Introduction

4 Industrial Revolution (4IR) assisted deep diagnostics for saturation mapping has assumed a crucial role in fractured reservoirs to more accurately map fracture channels, identify the flow corridors and target lagged hydrocarbons volumes in the interwell reservoir layers. Saturation mapping in the interwell area assisted by deep electromagnetic tomography is demonstrated to be a viable solution to achieve an enhanced understanding of the interwell reservoir volume, leveraging on resistivity contrast between water and hydrocarbons (Marsala et al., 2008). Additionally, crosswell electromagnetic tomography also has been a promising solution for enhancing reservoir history matching and fluid saturation mapping via complementing well logs and production information with interwell volumetric resistivity data (Katterbauer et al., 2014; Katterbauer et al., 2016).

Several crosswell electromagnetic (EM) surveys were conducted in recent years, demonstrating the significant potential of this technology for interwell saturation mapping. A crosswell electromagnetic survey was performed between two horizontal wells, a watered out oil producer and a water injector (Marsala et al., 2015a) in the reservoir section, followed by a 3D resistivity inversion (Marsala et al., 2015b) that was developed to derive a 3D resistivity cube in the interwell space. The main strength of this unique technology is how it offers an incomparable depth of investigation. It also provides a robust way to extract the water saturation distribution volumetric from an EM tomographic 3D resistivity inversion results (Marsala et al., 2017a).

Key challenge to obtain an accurate fluid distribution mapping using an analytical approach (i.e. Archie’s equation) from a tomographic 3D resistivity cube, up to few kilometers in size, is the lack of knowledge of the controlling parameters, such as water salinity, cementation factor, saturation exponent, porosity and fracture distribution, etc. in the interwell volume. The problem is mathematically ill-posed, as we do not have direct methods to measure the volumetric distribution of such quantities in the interwell reservoir volumes. Different approaches have been undertaken to tackle this problem, such as using advanced uncertainty analysis techniques (Saif et al. 2018), integration with history matching workflows (Marsala et al., 2017b) or data assimilation methods.

In this work a novel artificial intelligence framework was employed combining both well logs and EM tomography for the mapping of saturations in the interwell volume. The framework was tested leveraging on crosswell electromagnetic tomography, based on a realistic synthetic reservoir box model with two horizontal wells (one producer, one injector). The reservoir box model encompasses a complex fracture network distribution, commonly encountered in fractured carbonate reservoirs in the Arabian Peninsula, that are in production mainly by water injection assisted mechanisms.

AI Framework

In the regions close to the wellbores we typically have a complete characterization of the rocks and fluids, thanks to an extensive availability of well logs and production data. The uncertainty in term of fluid saturation occurs in the interwell volumes, where on the contrary only limited deep measurements are available, such as EM tomography.

The artificial intelligence developed framework workflow (Figure 1) utilizes a deep learning approach to relate resistivity and well logs to the saturation honoring both geology and reservoir dynamics. The training set was composed of well logs and resistivity data in the near-wellbore volume that subsequently trained the deep learning network.

The trained network is then utilized for the mapping of interwell saturation, deriving a 3D saturation profile for the interwell volume.
Figure 1: Artificial intelligence framework workflow for saturation mapping. Wellbore volume data are processed and then employed for the training of the network. Subsequently, the network then intelligently maps the saturation in the interwell region.

The initial data processing enables to combine well logs and resistivity profiles for the network training, and provides the flexibility to adapt it to different layers and reservoir sections if needed for a particular reservoir. This flexibility is crucial for many reservoirs that consist of different geological layers and where the distribution and saturation profiles are considerably different.

The trained network can also easily incorporate different wells and new data, and it does not require any re-training; it allows the fast and simple computation of the new saturation maps. For the study, 15 hidden layers in the network were utilized which was proved adequate for obtaining a good estimation of the results.

Case Study

The 4IR framework was used for interwell water saturation mapping on a realistic synthetic reservoir box model where the crosswell electromagnetic tomography was conducted in the interwell region. The resulting 3D resistivity cube is displayed in Figure 2. The resistivity cross-profile indicates a low resistivity zone in the interwell area that is next to higher resistive areas potentially outlining not yet-swept hydrocarbon zones that are intersected by a highly conductive fracture corridor.

Figure 2: 3D resistivity inversion cube (Rt apparent total resistivity) from a tomographic crosswell electromagnetic survey between a horizontal water injector (right) and an oil producer pair (left),
spaced 1.3 km apart (Marsala et al., 2015a). The water injection front is clearly not uniform in this case of relatively tight matrix carbonate reservoir with highly conductive fracture corridors.

The network training results on the processed data in the near-wellbore volume are outlined in Figure 3. The processed data were separated into a training, validation, and testing set with 70% of the data being allocated to the training set, 15% to the validation and 15% to the testing. Results show a strong ability to estimate the saturation profile around the wellbore area with the coefficient of determination being above 0.985. Taking into account that the output function is restricted to the range from zero to one, estimation quality at the boundaries to both zero and one may be marginally reduced. Small disparities at the lower and upper boundaries of the saturation profile are of negligible importance as an area with 90% water saturation may not be of interest to further produce. The resulting water cut from such a zone and cost of water treatment outweigh by and large the revenues resulting from the recovered hydrocarbons.

**Figure 3:** Network training results for the artificial intelligence approach.

The application of the trained network on the interwell area resulted in the interwell saturation map outlined in Figure 4. The saturation map exhibits the fracture channels that funnel the water from the injector to the producer well. Both to the left and right, stranded oil patches are observable that are bypassed by the injection water in the fracture channels. Water has propagated mainly in fracture channels and left partially un-swept other remaining oil patches in the interwell reservoir layers.

**Conclusions**

Utilizing an artificial intelligence method for mapping interwell saturation based on well logs and electromagnetic tomography provides a data-driven approach to deep diagnostics of the reservoir, honoring both geology as well as reservoir dynamics. The 4IR framework has exhibited a strong estimation quality of the water saturation profile for a realistic reservoir box model via training the network with well-log data in the near-wellbore zone. This AI framework can be readily supplemented with new data to improve the accuracy of the predicted saturation maps. The 4IR framework is flexible enough to be adapted to different geological structures and petrophysical relationships and the results from this reservoir box model study exhibited great potential in a broader application of the technique for interwell saturation mapping.
Figure 4: Water saturation map obtained from the AI framework.

References


Saif Sarah, Marsala Alberto [2018] Uncertainty Quantification Algorithms for Reservoir Characterization of Interwell Volumes, AAPG International Conference and Exhibition, Cape Town, South Africa, November 4-11, 2018