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ID: 715

Fluid Monitoring in a Large Field in North of Sultanate of Oman to Maximize Ultimate Recovery

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ABSTRACT

Gas-oil gravity drainage (GOGD) is a highly efficient recovery mechanism in heavily fractured reservoirs, where gas is injected on the crest, and water is produced from the aquifer to allow the offtake of oil from the fracture network by horizontal wells. As the gas is injected on the crest of the field, the pressure of the gas column within the fracture network “pushes” oil out of the matrix blocks and drains down into the fracture network, where it drains down to be produced by the horizontal wells.

A key challenge to achieving the ultimate recovery (UR) during GOGD is monitoring the gas saturation as it displaces the oil within the matrix blocks. Maximum oil recovery results from displacing the oil from the matrix on the crest and replacing it with gas. The offtake from the horizontal wells, which are placed at the fracture oil rim, needs to be balanced to drain the oil from the fracture at an equivalent rate to the oil draining into the fracture from the matrix.

This variability provides opportunity and value to identify any bypassed oil within the matrix and determine ways to drain these blocks through adjusted injection and offtake, new well placement, or carrying out zone change in existing closed in wells either to produce oil or to pump off water.

This paper will outline the process used to track the gas displacement process within the Natih reservoir and visualize this in an integrated manner to define optimization opportunities. The dominant method to identify gas saturation within the matrix blocks is through Pulsed-Neutron logging, while new wells over the last 40 years allow extra gas saturation estimates from Open-hole logs.

It is particularly challenging to collate such a vast volume of data in a complex reservoir system and integrate this information from 1D into 4D throughout the field. The approach used includes division of the field into sectors and flow units as well as use of data analytics and Petrophysical software packages to create simple cross sections to illustrate the gas displacing oil and explain the performance of the wells.

This new integrated analysis identified significant new opportunities to raise the production level from the field and also reinstate some long term closed in wells.

EXTENDED ABSTRACT

Introduction

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Gas-oil gravity drainage (GOGD) is a highly efficient recovery mechanism in heavily fractured reservoirs. In a gravity drainage process, the technical limit of ultimate recovery (UR) is governed by capillary holdup, but it is a very slow process.

In order to optimize oil production and new well placement, it is required to assess the gas saturation within the matrix blocks as it replaces oil. In a brown field, locating the remaining oil requires the overall understanding of post-production fluid-fill. Fluid distribution over production time is very much affected by the local efficiency of the recovery mechanism, along with injection and offtake over time, which are both complicated by the heterogeneous reservoir architecture and structural aspects of the field.

To assess gas saturations and its displacement within the reservoir, we utilize Pulsed Neutron Logs quantitatively and qualitatively in combination with Open-hole logs that have been acquired at different times through the development. Various conceptual interpretations based on the vast volume of data are used to track the displacement of gas within the complex fractured reservoir.

This analysis allows better placement of new wells, improved understanding of why certain wells were gassing out or watering in, reinstatement of Long Term Closed in Wells (LTCiWs) and development of a secondary GOGD concept.

Field Background

The field is located in the North of Sultanate of Oman. It is a shallow 20km long NW-SE elongated carbonate monocline with an eroded fault escarpment and a hydrocarbon column of more than 450m (see cross section Fig.1).

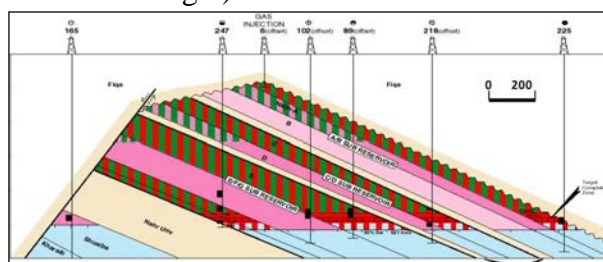


Figure.1- NE-SW Cross-section showing the main layers and the fluid contact/rim within the fracture column varies within each layer.

This carbonate reservoir consists of seven main layers which are separated by vertical permeability barriers, yet in dynamic connection via faults and fractures. The field is characterized by a well-documented structural history involving two major phases of deformation during the Alpine orogeny (as summarized in Stuart-Smith and Romine, 2004, and as illustrated in Fig.2). The reservoir subunits are highly fractured and exhibit 3 main fracture scales (as seen in Fig.3) - a) Background fractures b) Fracture corridors c) Fractured fault damage zones.

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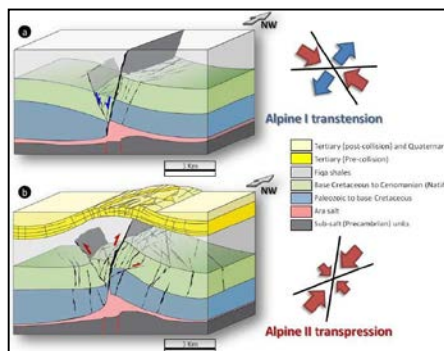


Figure. 2-Structural Evolution of the field and development of fractures and fracture corridors



Figure.3- Sketch illustrating the concept of faults & fracture corridors (in red) and background fractures (in grey) with respect to the presence of shales at the bottom of the depositional cycles.

The oil is relatively light with a viscosity of 2.1 cp and a density of 870 kg/m³ (31° API). The reservoir has been under production since 1967 and has undergone multiple phases of production including: pressure depletion, simultaneous gas and water injection within different units and sectors, in addition to steam injection trial. The dominant recovery mechanism historically (and up to date) is Gas-Oil Gravity Drainage (GOGD).

Gas-Oil Gravity Drainage (GOGD) in a Fractured Reservoir

Fractured carbonate reservoirs are characterized by a low permeability matrix (permeabilities in the order of 1-50 mD) and a highly permeable fracture system (effective permeabilities in the order of 500 – 10,000 mD). Due to the high permeabilities in fractures, viscous forces do not play an important role in highly fractured reservoirs.

In GOGD,

- Gas is injected at the crest of the field to maintain the fracture gas cap.
- Due to the high permeability of the fracture system compared to the matrix, gas preferentially invades the fracture network. The gas fills the fracture system to a deeper level than the oil in the matrix.
- The resulting disequilibrium drives the GOGD engine: the matrix oil has to move in a lower position than the gas in the fractures to obtain fluid equilibrium.
- As a consequence, the matrix oil (and mobile water) drain downward under the influence of gravity and into the fracture network creating an oil rim in the fracture

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network that supplies the producing wells.

- e) Produced gas is re-injected into the crest of the reservoir to maintain fracture gas cap therefore maintaining reservoir pressure as well as feeding oil into the oil rim.
- f) The aim is to obtain a dynamic equilibrium between the draining oil rate and the fracture oil rim thickness such that the gravity head is sufficient to push the draining oil to the producers with minimal coning of water or gas.

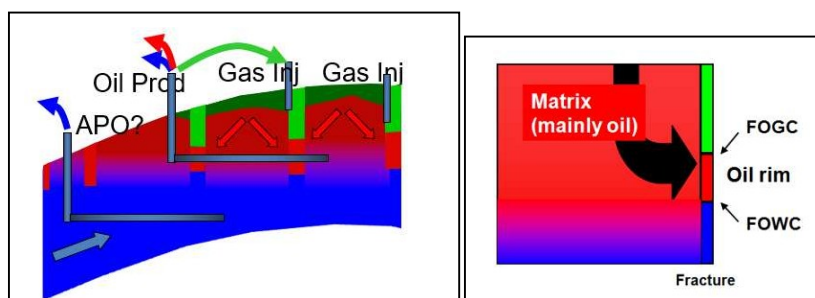


Figure.4- Schematic showing main features of development

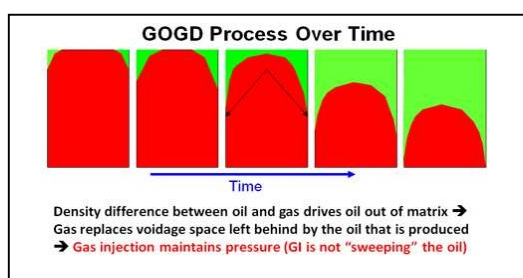


Figure. 5- GOGD process over time

Tracking Gas Displacement Through Data Analysis

It is highly challenging to understand the fluid distribution within various sectors of the field, with stacked reservoir subunits of different matrix permeabilities, and variable extension and connectivity of the different fracture systems. However, this integration and understanding is critical to support the ongoing GOGD development within each subunit.

The petrophysical work carried out can be grouped into three phases:

- 1) Data collection/gathering to prepare a fluid contact database
- 2) Data Analysis – conceptual models built to understand the gas displacement and visualize it over time
- 3) Impact/Value addition to business based on the outcome of this work

Data Collection/Gathering to Prepare a Fluid Contact Database

There are three main sources of gathering information related to fluid contacts/ fluid distribution:

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- 1) Open hole Density Neutron logs acquired while drilling → to provide matrix Gas Oil Contact (GOC) at the time the well is drilled.
- 2) Pulsed Neutron Log acquired through casing over time → to monitor hydrocarbon saturation changes and to provide quantitative and qualitative information on matrix GOC
- 3) Gradio surveys in observation wells → to provide information on Fractured Gas Oil contact (FGOC) and/or Fractured Oil Water contact (FOWC).

The process to collate the data into a database required tracking of gas, oil, and water contacts within the matrix over time. While collating this information we recognized several complexities.

Complexity #1: For modelling and reservoir management purpose, the field is divided into numerous sectors (see Fig 7). Each reservoir subunit was managed by different teams with different sector boundaries (see Fig. 8). These differing sectors for each layer were therefore merged into a single zonation system through the whole reservoir.

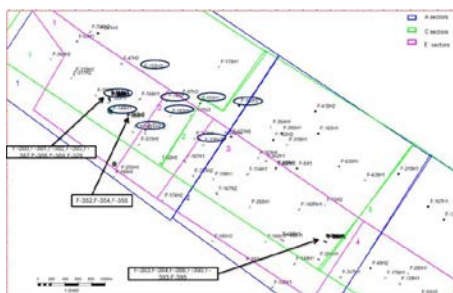
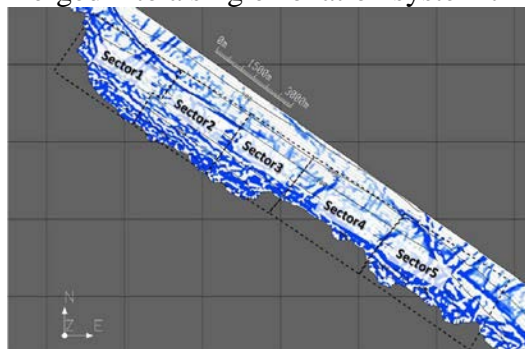


Figure. 6- Geographical definition of the field sectors Figure. 7- Sectors for different reservoir subunits

Complexity #2:

The hydrocarbon storage resides within the porous matrix) with relatively low fracture volume despite the overwhelming influence of fractures on fluid transport. These matrix blocks which are surrounded by fractures have stacked, laterally continuous reservoir quality, with highly variable permeability between each layer. This vertical permeability contrast has strong control over whether the gas laterally moves along the layer or vertically through the different layers

The result of this permeability contrasts was matrix being saturated by gas to a deeper level in more permeable layers, while oil saturation is seen significantly shallower in lower permeability layers. This complexity required the further sub-division of the main reservoir layers into sub-zones based on permeability. Each and every sub-zone then required identification of gas, oil, and water contacts. An example of some of this variability is shown in Figure 9.

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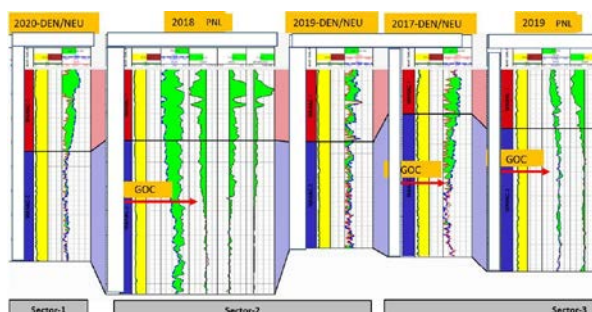


Figure. 8- Example of variable GOC in different sectors within the same subunit.

Complexity #3: Despite the vast amount of well penetrations (over 500) and active surveillance of the field, given the dimensions of this field (18km long, 4km wide and 450 m tall), saturation data is not as extensive as might be hoped. Due to the dip of the structure and the highly variable reservoir quality and fracture connectivity, wells that were ideal for monitoring gas saturation earlier in development life become redundant as the gas moves past the well location. This requires new wells to be identified to monitor the gas movement downdip. The result of this is that there are time gaps in gas saturation data within certain sectors and certain subzones.

Despite these complexities, the creation of the fluid contact database for the new unified sectors, and for each of the different sub-zones across this large field has allowed a step-change in the way the GOGD process can be visualized.

Data Analysis-Conceptual Models to Visualize Fluid Movement

Since 2016 there have been multiple attempts to visualize the fluid contact database to provide the reservoir plumbing understanding to allow for the optimal reservoir optimization. Analytics Approach: The first analytics visualization method was created to allow direct import of the fluid contact database into a commercially available analytics tool (see Fig.10). This visualization tool allows a very quick filtering of sectors, reservoir layers, and subzones over time to allow identification of deepest gas identification versus time. Due to the reservoir and fracture heterogeneity this easy filtering allows for highly flexible combination and separation of different sectors, layers and subzones to test different connectivity scenarios.

One key benefit of this visualization was to allow identification of ambiguous well logging results, and subsequent identification of new data gathering opportunities to add to the extensive database.

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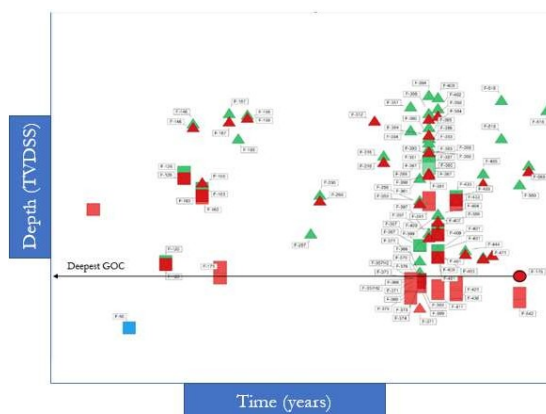


Figure. 9- Example of fluid distribution visualization in analytics tool -across a single subunit in the field

Conceptual Models: The Analytical tool is highly flexible for testing the different connectivity across the field, however, is not ideal to convey or visualize the movement of gas through the matrix blocks. Initially it was proposed to map gas saturation into the Static model and look at animating the changes over time, however due to the size and complexity of the connectivity this was not deemed to be practical.

To achieve the visualization of gas movement through the field it was decided that conceptual models would be appropriate to convey the gas movement through the layers. This was achievable due to the highly lateral homogeneity within each of the subzones which allow the grouping of sector data into conceptual snapshots per layer and field sector.

To illustrate the gas movement in C unit we consider two conceptual models. Conceptual model one assumes that there is connection between C1 and C2 layers and the gas is moving down at the same speed (see Fig. 11). The implications of this means that all the overburden layers are fully gassed out if we see gas at deep depth in C irrespective of C1 or C2 layer.

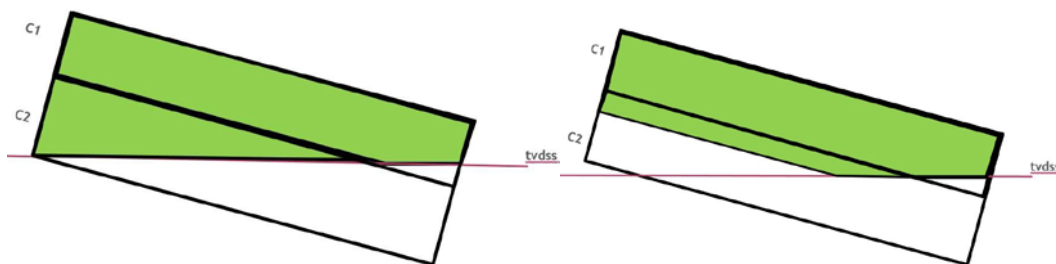


Figure. 10- Conceptual model one for C layer Figure. 11 - Conceptual model two for C layer

Conceptual model two allows for the gas to move from C1 to C2 layer but it stays at the top of C2 layer even in the shallow depths (see Fig. 12). This effect is driven by reservoir quality, with the C1 layer being significantly better quality. This model is the one that matches with both the fluid contact database as well as production data, suggesting that C1 is laterally connected but gas is only seeping into the top of C2 layer rather than actively driving the

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GOGD process. This analysis means that we have opportunity to improve recovery factor from C2 layers due to significant volumes of oil being left behind up-dip.

This process was undertaken for all the sectors to determine the linkages of gas movement through the C unit to the injection and offtake within each sector.

The same work was carried out for other layers, subzones and sectors. The outcome of this work was identification of potential shallow oil opportunities, understanding of availability and lack of data and candidates where pulsed neutron log should be acquired.

GOGD Plumbing Diagram: From 2019 onwards the team identified that the gas and oil distribution in the matrix and fractures is more dynamic than expected, therefore the relevance of integrating the well data into 4-D (including the capture of newly recognized tectonic history post charge). The updated iteration of visual representation evolved into a more integrated “plumbing diagram” that included fracture extension and mechanical boundaries between subunits which provided clearest understanding for the level of gas in each sector (see Fig.13).

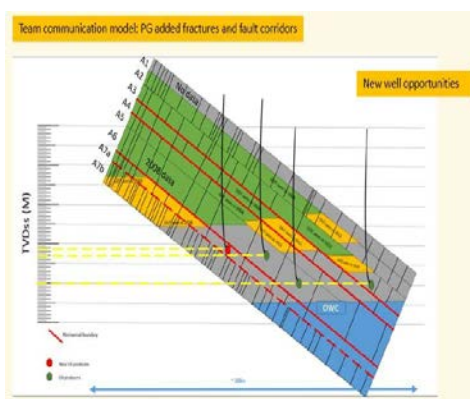


Fig. 12-Plumbing diagram showing the fluid distribution

The new plumbing diagram was first generated with a grey background indicating no available data for that sector or reservoir layer. Mechanical boundaries (which act as the vertical limits of the fracture system) between sub-layers were identified and marked by thick red lines. As seen in Figure 13, some subzones are connected vertically, while some have mechanical boundaries separating them. Finally, the fieldwide pre-production Oil Water Contact (OWC) was introduced in the cartoon. Sometimes, only Gas-down-to (GDT) and Oil-up-to (OUT) are known in a subzone. Where there was variability in gas contact within a sector, green shading was used to represent the shallowest gas in that sector and orange shading to represent the deepest gas seen in that sector, This representation allows for the team to identify potentially deep gas related to close proximity to gas filled fractures.

This sketch was then used by production geologist and seismologist to integrate further with available fault and fracture models and matured the model to provide further understanding of the GOGD process. This approach helped the team to de-risk drilling of new wells in already gassed out areas and also come up with ongoing data acquisition strategy for certain sectors and layers into the future.

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Maturation to Flow Units: In 2020, in order to further optimize production, the team adapted a new operating approach as part of WRFM (Well, Reservoir and Facilities Management) strategy where instead of sectors and layers, the reservoir was characterized further in to representative “flow units”. Within each previously defined sector, multiple flow units were defined (see Fig. 14). The flow unit is an open and connected system where flow is initially governed by gravity forces through the open fracture network. The boundaries of the flow unit are set by the top seal down to the oil water contact as the lower limit. The lateral boundaries are set by existing fracture corridors which provide high connectivity from the gas cap down to the lowest level in the reservoir.

This latest approach provides the subsurface team with a clearer picture for the tracking of the intake/offtake and oil rim within the GOGD system along with a surveillance strategy focus on reservoir optimization.

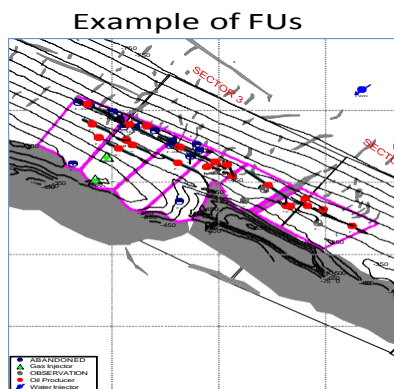


Figure. 13- The pink lines show boundaries of flow unit within a sector.

Flow unit definition leveraged the previously mentioned efforts into a full integration of available datasets including; structural, static properties, fluid contacts, volumetric analysis and dynamic properties. Figure 17 below summarizes the workflow followed by the integrated team to come up with flow unit definition and production optimization strategy for the flow unit.

The Petrophysical component of this work included review of each flow unit (~70 flow units across the field) and each well within the flow unit to generate fluid distribution plots for each flow unit in order to explain the movement of fluid over time. The visual representation arranges wells from shallowest to deepest within the flow unit versus their spud year. The drilling history, well status, well test results, overburden fluid contacts and any potential opportunity is shown in the same plot.

Impact/ Value addition to the Business

The various approaches used to track gas displacement have helped understand fluid movement within each layer/sector/flow unit. During the evolution of each approach limitations were experienced due to the complex nature of the reservoir. This complexity is complicated by the fact that there is inherently some areas and subzones lacking information

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on fluid contacts. The new characterization has allowed identification of gaps allowing planning of data acquisition in new wells or through pulsed neutron log acquisition in existing wells.

Translating the reservoir and fluid characterization efforts into business value, the efforts employed have resulted in a step-change in proactive management of the GOGD process within the field, including:

- 1) To understand why certain wells are gassing out or watering in.
- 2) Support re-instatement of LTCiWs
- 3) Zone change in poor performing wells
- 4) Opening multilaterals which have been shut-in for a long time
- 5) Derisking drilling of new wells
- 6) Additional volumes added based on deeper OWC or shallower GOC in some areas
- 7) Supporting secondary GOGD/trans development.

Table 1: Opportunity type and number

Opportunity Type	Number of wells executed	Number of wells pending
Reinstatement of LTCiWs	6	7
Zone Change in poor performing wells	4	5
Re-opening multi-laterals	2	
Additional new wells based on deeper OWC or shallower GOC	10	35

Figure 14 and Figure 15 show an example of Reinstatement of LTCiWs. Where shallower wells in a flow unit are impacted by high water cut, an existing LTCiW sits deeper in the flow unit within the depth and zone of interest for it to be utilized to pump off additional water from the flow unit and optimize the GOGD process in that flow unit.

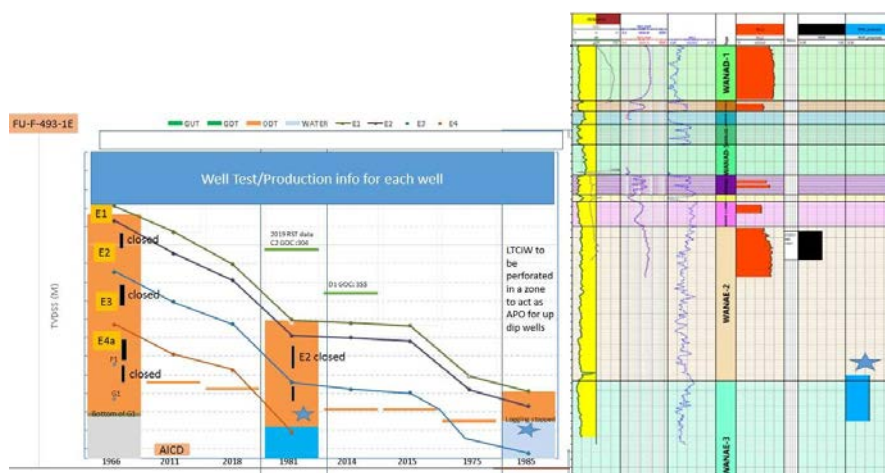


Fig. 14- Fluid distribution plot

Fig. 15-LTCiw proposed for zone change to act as an APO

Conclusion

GOGD is a very effective recovery mechanism in fractured carbonates but it is a slow process. In order to optimize production and well placement, it is important to track gas displacement. Integration of the gas displacement process is complex when dealing with a large, stacked reservoir with variable reservoir quality and extensive fracturing, necessitating novel methods of data capture and visualization. When dealing with a highly complex issue with large volumes of data, we found benefit in starting with simplistic visuals and follow a path of continuous improvement through adding complexities in a sequential manner until reaching the optimal required characterization to influence the day-to-day business decisions. The efforts have yielded a step-change in the management of the GOGD process and have yielded opportunities to increase production.

Acknowledgment

The views and opinions presented in this article are those of the authors. We would like to thank the Ministry of Energy and Minerals and Petroleum Development Oman for granting permission to publish these data. We would like to thank the project reviewers for their input (Olanrewaju Oladiran, Nabil Al Bulushi) and management for their continuous support (Issa Mahruqi, Mohamed Yarabi and Mohamed Salhi).

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