Refining the Facies Model to Address Reservoir Heterogeneity: Application of New Borehole Imager in Sandstone Reservoirs of Oman*

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Abstract

The geological complexities of the clastic reservoirs in Northern Oman pose difficult challenges in understanding the distribution of reservoir facies for proper delineation of the gas bearing formations. The latest borehole imager helped a great deal in overcoming the limitation of traditional imaging in high salinity mud and detailed sedimentological interpretation could be performed to understand the architecture of the reservoir.

Proper understanding of reservoir sand distribution and its genetic relationship in one of the larger clastic reservoirs of Northern Oman has not been accomplished. The high salinity mud environment downhole was affecting the data quality of borehole images for detailed sedimentological description and the structural elements that offset the reservoir sand bodies. The latest borehole imager with improved signal-to-noise ratio and tolerance to high mud salinity (~300,000 ppm) acquired good quality images to help in interpretation of sandstone reservoirs.

The detailed analysis of borehole images in the sands of the field suggested the presence of a fault that juxtaposed the sands of probable aeolian environment against the fluvial sands. The reservoir properties and their distribution are different for these sands, which were earlier interpreted to be part of the same fluvial stack. The earlier understanding of these sands was not able to explain the variations in the dynamic response of the reservoir.

Different architectural elements were identified as dunes and inter-dunes of aeolian deposition where high-angle cross-bedded sands could provide a good permeability zone. Similarly, the different fluvial elements were also identified on borehole images. A comprehensive sedimentological evolution was understood in terms of depositional environments, and the impact of faulting was understood with the help

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of nearby well data. The integrate faulting explained the different to	ted interpretation in the fram flow units for production.	ework of geological evol	ution and distribution of sa	nd bodies affected by the



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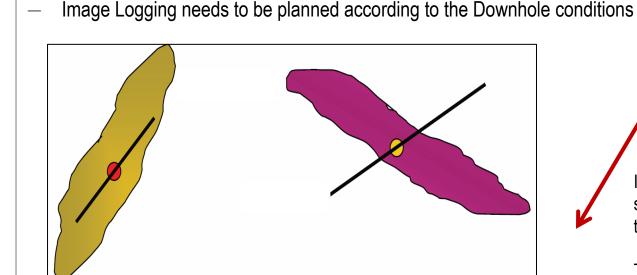


Outline

- Introduction
- Borehole Images in Tight Gas Reservoirs
- Micro-resistivity Images in WBM
- High Definition Imager
- Standard & High Definition Images
- Study Area
- Structural Elements and Facies Associations
- Observations and Interpretations
- Summary

Introduction

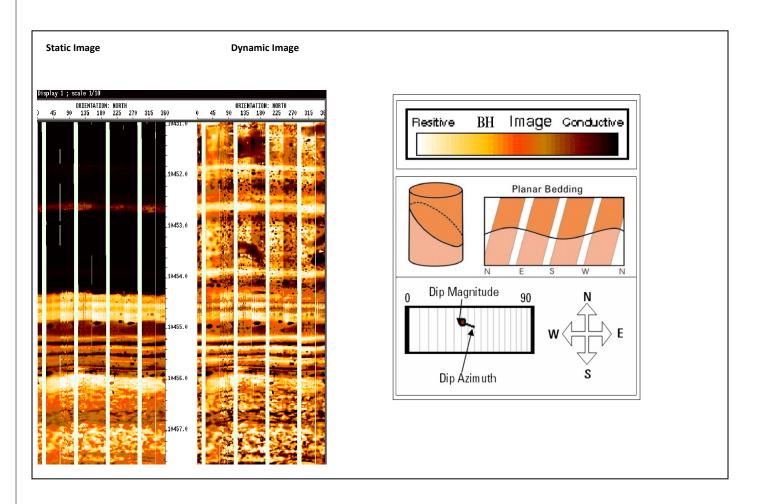
- Focus on the Tight Gas Reservoirs in the Sultanate of Oman; in the Paleozoic sequences.
- Geological complexities need to be understood
- Depositional, Structural and Diagenetic Effects
- Borehole Images are Key to Sub-surface understanding
- Borehole Image Logs also instrumental in Hydro-frac Design; frac planned to generally align in the direction of max horizontal stress direction; and frac length honoring the sand body geometry.
- The varying stress regime and differential hardness of rocks in the Gas exploration acreage makes acquiring borehole images a very important part of the log acquisition.
- These two information can be had with the help of image logs.
- Micro-resistivity image more suited for tight sands exploration, than ultrasonic or other measurements



If the red arrow shows the max horizontal stress direction, the frac would be aligned in that direction.

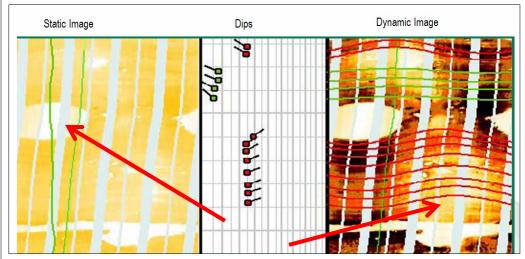
This directional attribute is taken from Image logs.

Borehole Images: Micro-resistivity Imaging in Campaign



Reading Borehole Images and Dips, on Micro-resistivity image logs. The Micro-resistivity images provide all information on structure, stress regime and diagenetic, stratigraphic with high resolution data in this campaign.

Borehole Images in Tight Gas Exploration

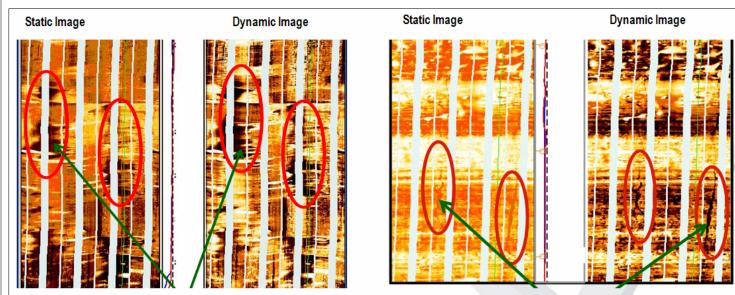


Cementation nodules

Diagenetic imprints of cementation can be observed on the images. The break-out and induced fractures are suggestive of prevalent stress regime. The cross-beds in red tadpoles suggest the paleo-current direction.

Drilling Induced fractures develop in the direction of max horizontal stress and,

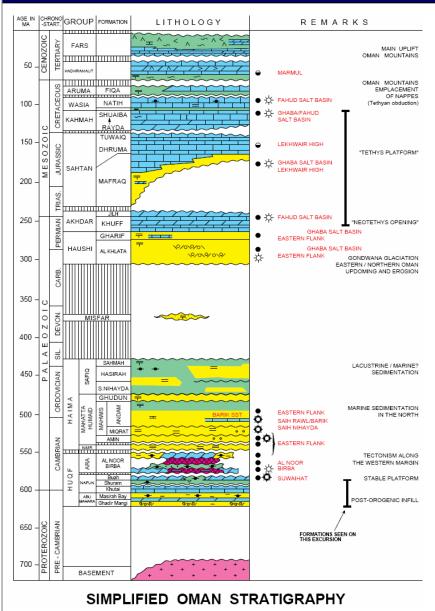
Break-outs in the direction of min horizontal stress; as seen in the images from vertical wells.

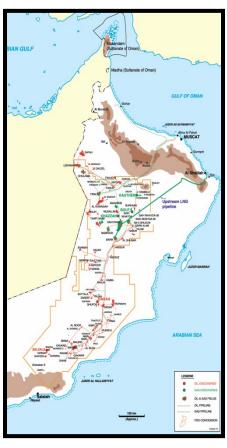


Break-out

Drilling Induced fractures

Study Area





The study area is located in the North Oman; where wells are drilled in the Paleozoic sequences of Haima group to exploit the Gas reserves in the tight sandstones.

The depositional environment has been envisaged to be aeolian to alluvial grossly.

However, a refined facies model is imperative to properly understand the depositional architecture and their bearing on the flow units.

The image logs acquired in this field help refining the facies model in the light of an established geological model.

Challenges

- A North Oman gas field is on production.
- The study well was logged to understand the productivity of Haima Group, and to gather data for better understanding of the gas reservoirs.
- The flow behavior was not responding to the simplistic model that was conceptualized earlier for the Paleozoic Haima group sequences.
- Well B was drilled 100m east of one previous well A and it posed interpretation challenges in terms of lateral extension of facies.
- High salinity mud system being used by was another challenge hindering the image quality.

Borehole Imaging: Challenges

Micro-resistivity imaging in Water-base mud provides the highest resolution of borehole imaging in the industry.

However, the more frequent usage of Hyper-saline mud (>150,000 ppm in this campaign) where the mud conductivity becomes very high, could be detrimental to getting useful images.

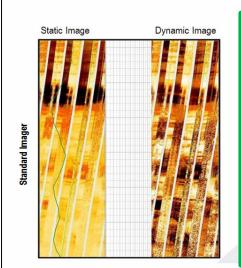
Moreover, if the contrast between the formation resistivity and mud resistivity is too high (Rt/Rm> 2000), the imaging tends to deteriorate in quality.

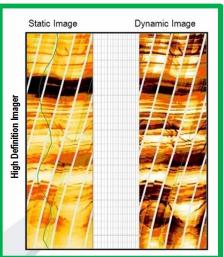
- The highly conductive borehole 'shorts' the tool measuring current. Relative to a fresh water-base mud, only a small proportion of measuring current flows in the formation. This results in decreased sensitivity to formation resistivity changes and overall lower button signal amplitude.
- ➤ The phase of the Alternating Current (AC) injected by the tool may shift relative to the optimum signal phase that the electronics are tuned to measure. In mild cases this results in reduced signal and higher susceptibility to noise. In extreme cases, this may result in apparent resistivity contrasts that are inverted compared to the reality.

A High definition imager was deployed to address such concerns and was put to trial in such hostile logging conditions in the tight sands exploration for Gas.

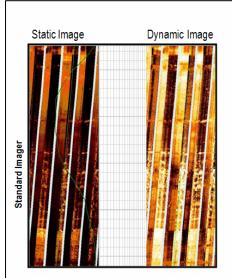
The imager not only acquires the best quality of data, it also provides 16-bit of data compared to the 10-bit data of regular imager for better dynamic contrast.

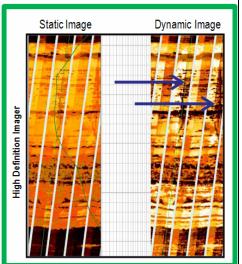
Standard Imager & High Definition Imager in WBM

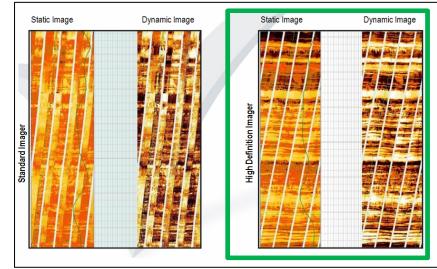




Natural Fractures seen on High definition images







Fine textural details on High definition images

Formation resistivity: 80-100 ohm-m

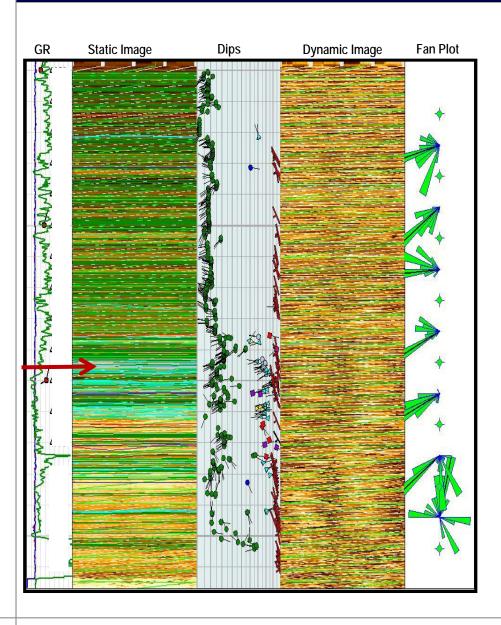
Rt/Rm: ~4000

Mud salinity: 240,000 ppm

The High definition imager was run with the standard imager in the same well; showing better results with the high definition imager.

Induced Fractures seen on High definition images

Study Well with Dip Information



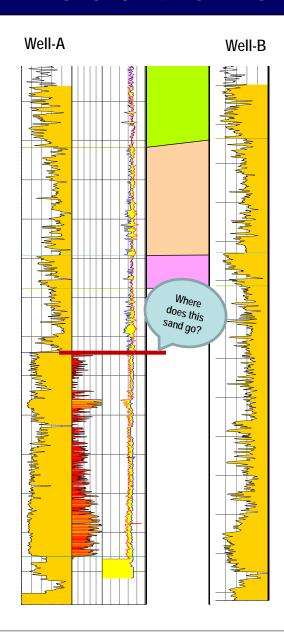
The snapshot illustrates 150m of data compressed on 1:500 scale to show the variation of Gamma Ray and the dip trends.

The logged interval represents the Paleozoic Haima group sequences in this well.

Faults were interpreted on the image logs, with associated fracture planes; shown by high angled colorful tadpoles in the dip track. The top of the sands unit is interpreted with fault plane

Stacking of sands were earlier interpreted to be one unit initially; of alluvial origin in the bottom part. However, the detailed analysis with borehole images suggest that there could actually be genetically different units juxtaposed together by a fault. Moreover, subtle facies variations were observed defining the architectural elements from aeolian to alluvial to sabkha deposits in an arid setting.

A Tale of two Wells



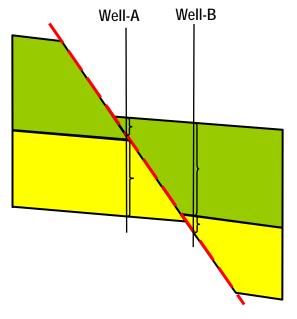
Well B was drilled 100m east of well A; and found a major sand section missing.

The red line sees a sand top in Well-A that goes missing in Well-B; 100m away!!

The seismic is a 2-D one; and does not really show any faults in the vicinity of Well-A and B. Another well, Well-C correlates nicely with Well-B though it is 11km farther from Well-B.

Options:

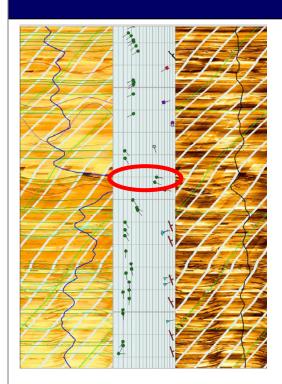
- 1. Facies Changes in the depositional system
- 2. Sands faulted out

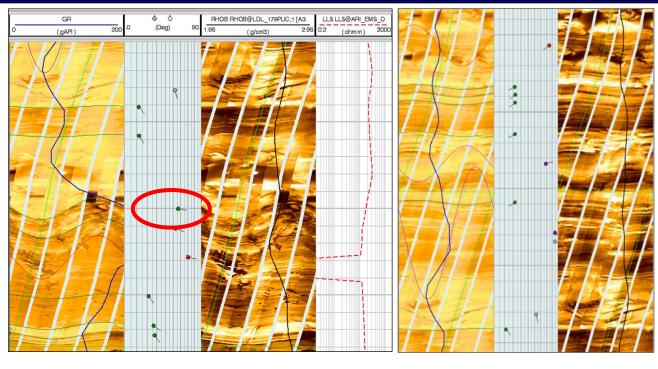


The high resolution borehole images from the improved imager in Well-B suggest the presence of fault plane that seems to have offset the sands in Well-B down the vertical depth. Well-A did not have the image logs!

Moreover, the sands that were earlier supposed to be stack of same genetic unit, are also found to be having different facies association, aeolian and fluvial juxtaposed with another fault!

Structural Elements in the Well



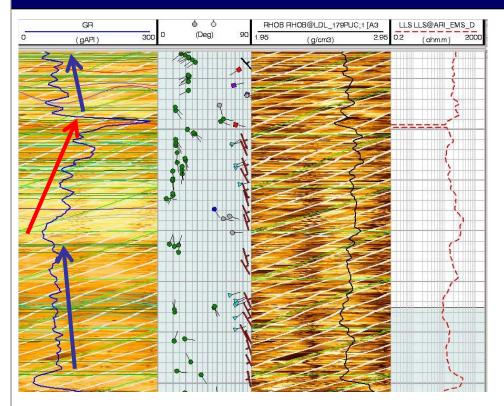


The snapshot above illustrates 8m of interval where in the middle of the section, a fault zone is interpreted, shown with a red ellipse.

A zoomed snapshot of 3m at 1:20 shows a fault plane, clearly marked on the image; with around 60 degree of dip towards east. A significant change in dip pattern is also observed across this fault.

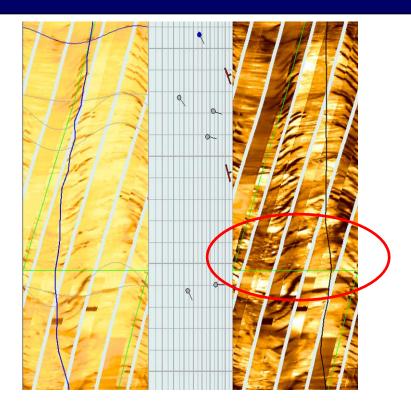
The fractures striking like the fault in intervals above and below the fault plane suggest a strong structural trend of NNE – SSW.

Stratigraphic Observations



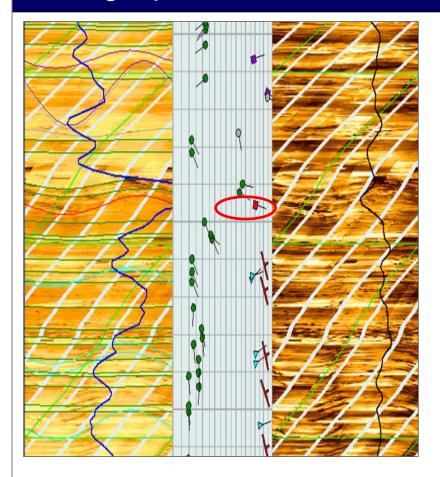
A feeble build-up of coarsening up (blue arrow) is followed by a fining-up sequence (red arrow); overlain again by a coarsening up sequence.

Some lag-like feature can be observed at the base of the fining up sequence in the next snapshot. This lag is indicative of a channel (confined flow) development in a fluvial sequence.

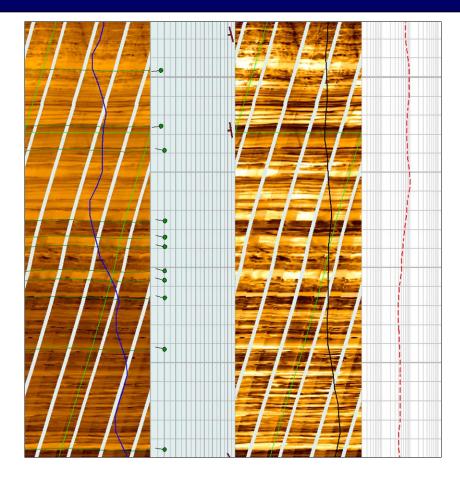


A zoomed snapshot at 1:20 for 3m interval shows the channel lag, circled in red ellipse. Drilling induced fractures obscured the image quality for interpretation

Stratigraphic Observations...



The fault plane shown in the red ellipse seems to get a fining up sequence (with GR, dip patterns and texture) of a channel fill juxtaposed against the overlying coarsening up sequence of probable aeolian environment.



The coarsening up of GR (blue curve on static image), the build up of resistivity, the thin laminations to thicker laminations going up ... indicates a probable dune build-up starting on the inter-dune deposits of high GR.

Analogy with Outcrop and Subsurface



FITA

FILIVIA ORIGINATE FOR

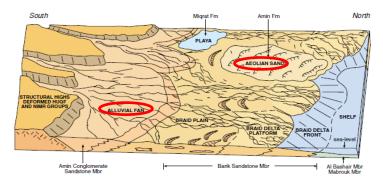
SAND SHEET

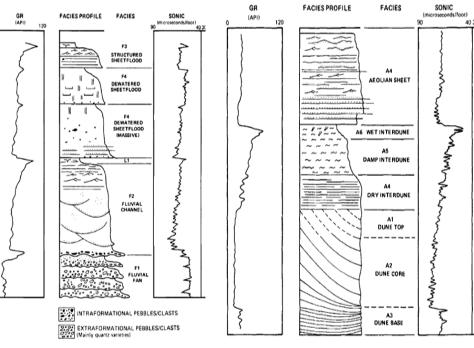
FULIVIA CONSILOMERATE FOR

ACOLIAN DUNE

(b)

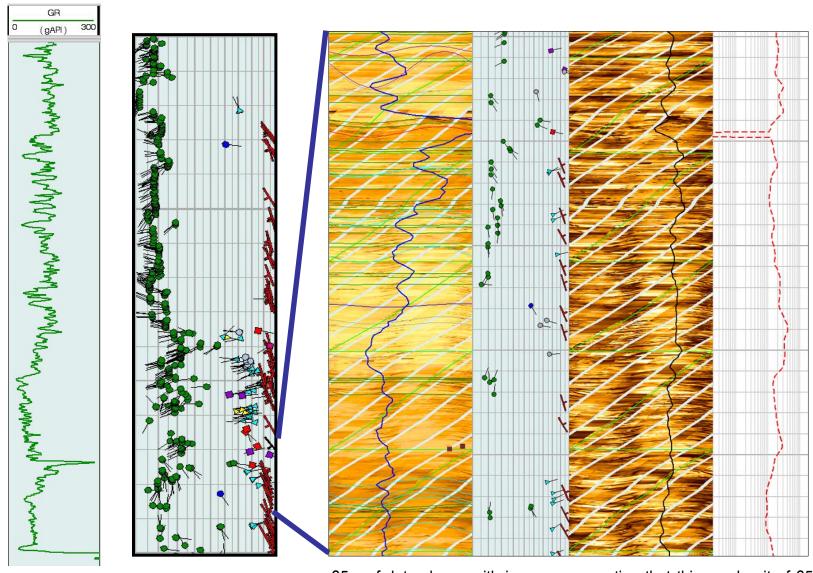
Rotliegendes of Permian, Southern North Sea, UK: Fluvial and Aeolian; An analogy





Typical Fluvial sequences Typical Aeolian sequences

Mixed Environment sands; with different reservoir properties



150m interval

GR Response in Dip patterns in the interval

25m of data shown with images; suggesting that this sand unit of 25m is not only different genetically, but also would work as different flow units

Conclusions

- Need to understand the depositional system and structural controls for optimal exploitation
- The flow behavior through Paleozoic Haima is governed by the complexity of depositional units from different processes and this information needs to be understood for proper exploitation.
- Borehole images are important for such detailed studies.
- The High definition imager acquires excellent images in challenging logging conditions of imaging in hyper saline mud and high resistivity formation.
- The image logs in the study area show facies variability and role the structure plays with the facies distribution;
 which controls the eventual producibility of the units.