Addressing the Geological Challenges in Tight Gas Sandstones with Advanced Borehole Imaging Solutions, Sultanate of Oman*

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Search and Discovery Article #40902 (2012)**
Posted March 31, 2012

*Adapted from poster presentation at GEO-2012, 10th Middle East Geosciences Conference and Exhibition, Manama, Bahrain, March 4-7, 2012

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Abstract

In tight gas sandstones, detailed geological understanding of the reservoirs is imperative in preparing optimal exploration, appraisal and development plans. The distribution of sand bodies, their textures, orientation and paleocurrent directions need to be understood in the context of sedimentary depositional environments to assist in the prediction and identification of reservoir architecture, reservoir quality variability and sweet spots. The use of high salinity mud, providing a highly conductive logging environment, affects the quality of borehole images. Additionally, tight formations are highly resistive, which limits traditional image interpretability for textural, structural and sedimentological analysis and petrophysical interpretation. Advances in borehole imaging in recent years have significantly helped in addressing the geological challenges in hostile borehole environments.

In the tight gas clastics of northern Oman, hyper saline mud (~300,000 ppm) and highly resistive formations (>20,000 ohm-m in some cases) have had a significant deleterious impact on the traditional imager quality. Image quality is of utmost importance in undertaking detailed sedimentological analyses and poor image quality reduces the confidence in the interpretation of reservoir architecture and textural variations. This is particularly the case in Oman's high net-to-gross continental tight gas successions. The latest borehole imager with improved signal-to-noise ratio and tolerance to high mud salinity has been deployed to acquire good quality images that help in the interpretation of these sandstone reservoirs.

The new imager is supported by new hardware configuration and improved downhole signal processing compared to the traditional imagers. Its 16-bit data quality provides better image visualization because of improved signal-to-noise ratio in hostile environments. Subtle

geological features which were masked with the traditional imager can be studied with the improved imaging for enhanced interpretation. Three wells, logged with this new imager, have provided a good understanding of reservoir geology in the tight gas reservoirs of Northern Oman where the reservoir facies were deposited in arid fluvial sheet flood/sand flat, sabkha and aeolian environments where sedimentary distinction between facies is subtle.

GEO 2012 Bahrain International Exhibition and Convention Centre

10th Middle East Geosciences Conference and Exhibition

ID: 1121471

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Schlumberger

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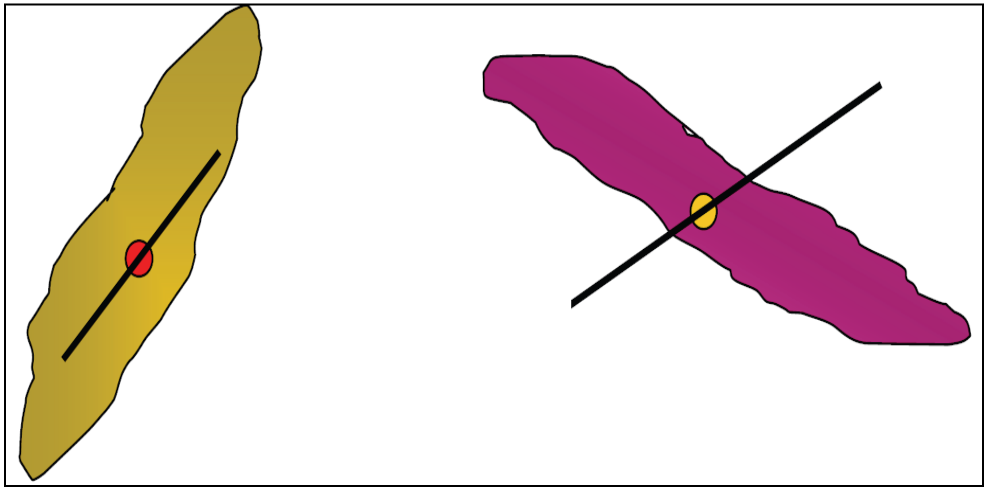
Introduction

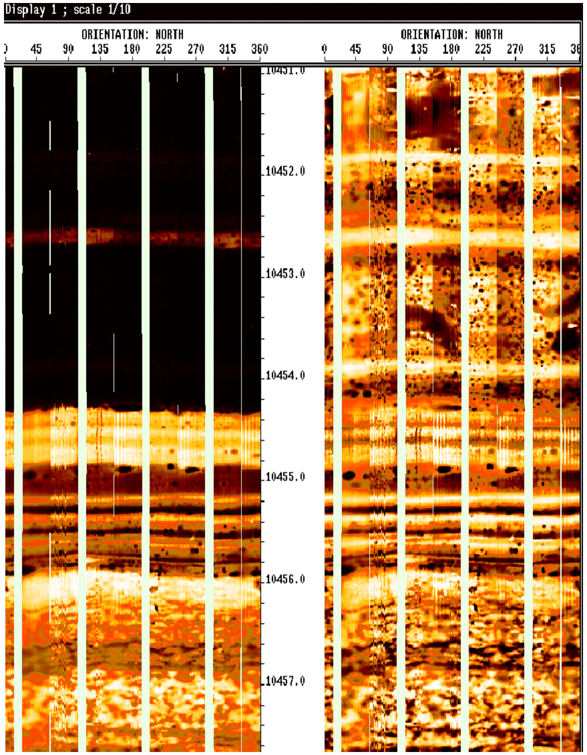
- Focus on the Tight Gas Exploration in the Sultanate of Oman; in the Paleozoic sequences.
- Geological complexities need to be understood
- Depositional, Structural and Diagenetic Effects
- Borehole Images are Key to Sub-surface understanding
- Borehole Image Logs also instrumental in Hydro-frac Design; 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
- Image Logging needs to be planned according to the Downhole conditions

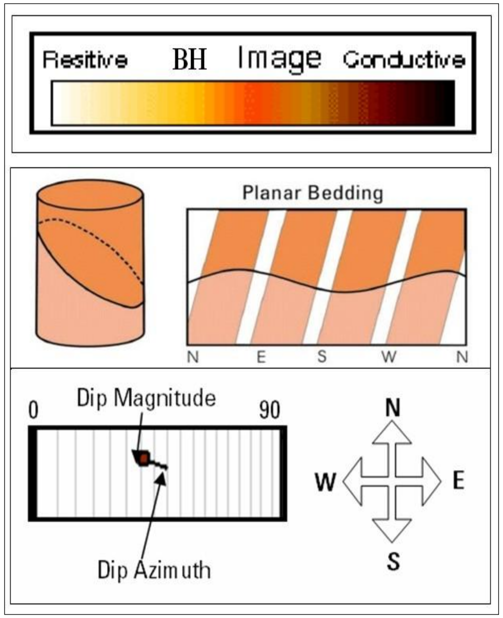


If the red arrow shows the max horizontal stress direction, the frac would be aligned in that direction.

This directional attribute is taken from Image logs.

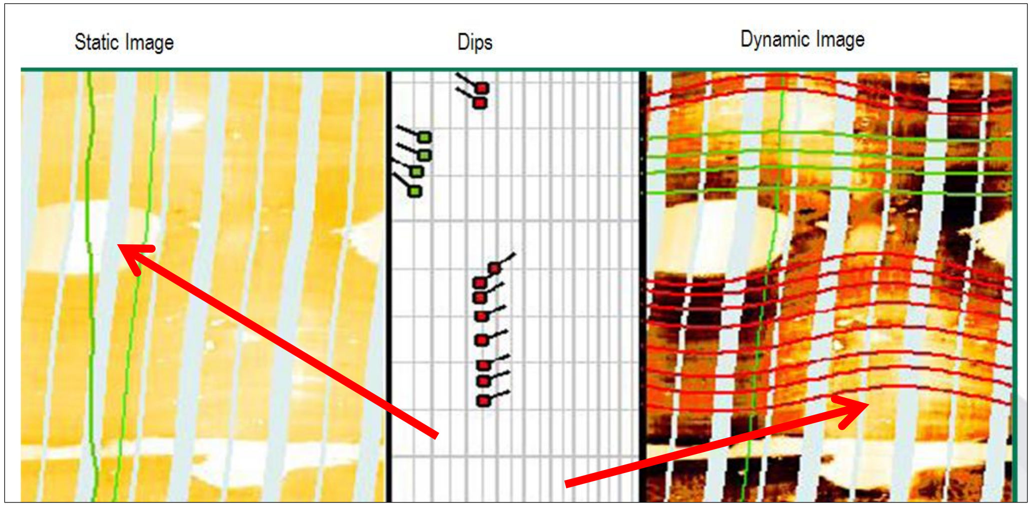
Borehole Images: Micro-resistivity Imaging in Campaign





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.

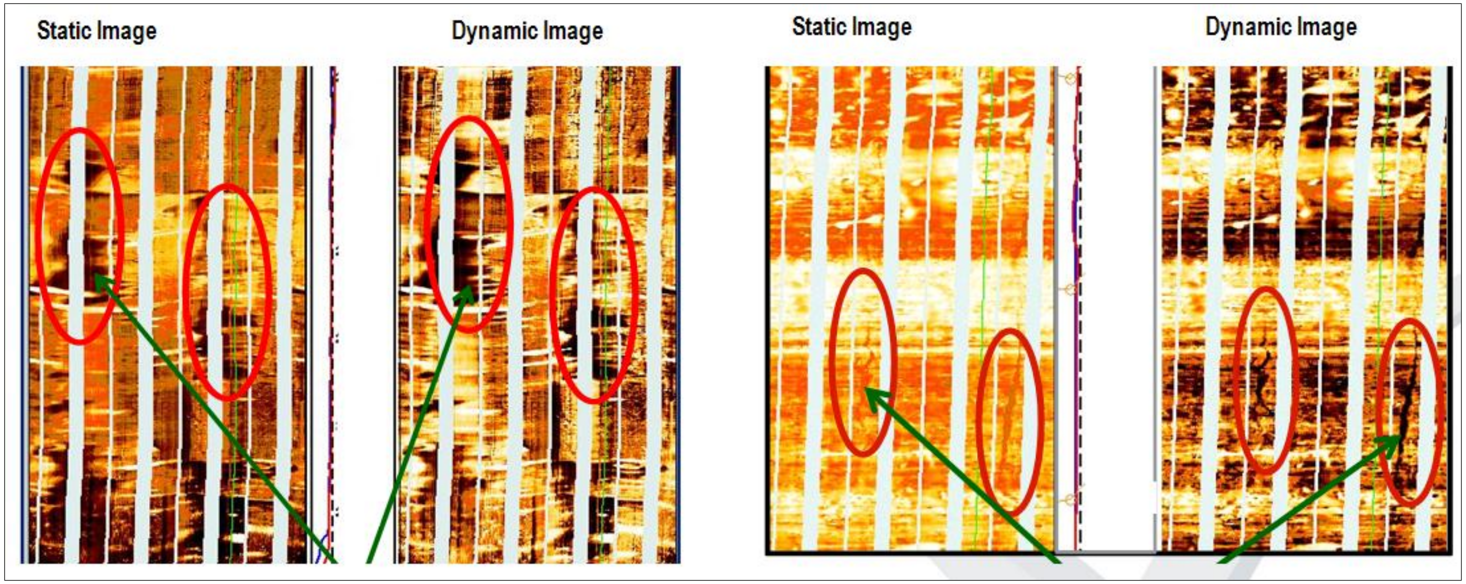
Borehole Images in Tight Gas Exploration



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

Micro-resistivity Images and Downhole Conditions: WBM

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.

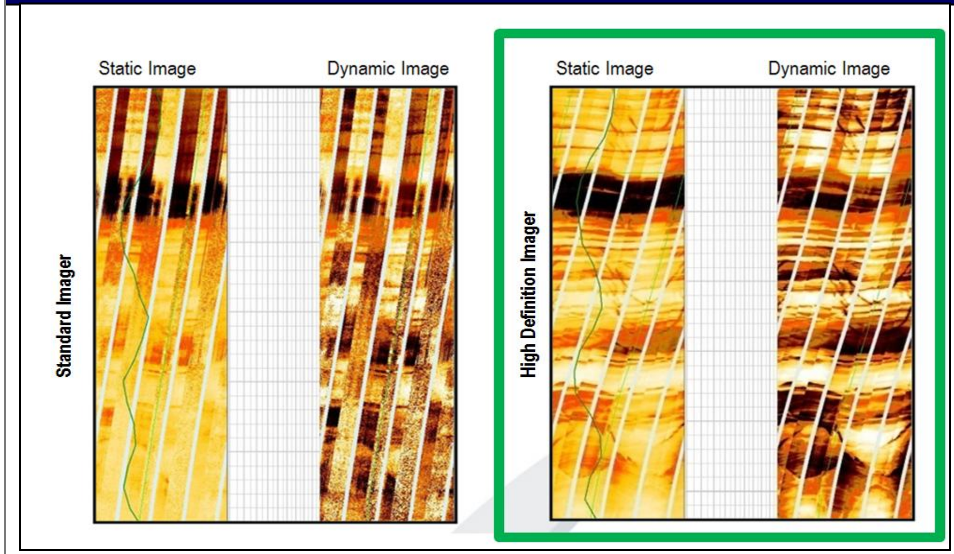
Moreover, if the contrast between the formation resistivity and mud resistivity is too high (Rt/Rm> 2000), the imaging tends to deteriorate in quality.

- 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.

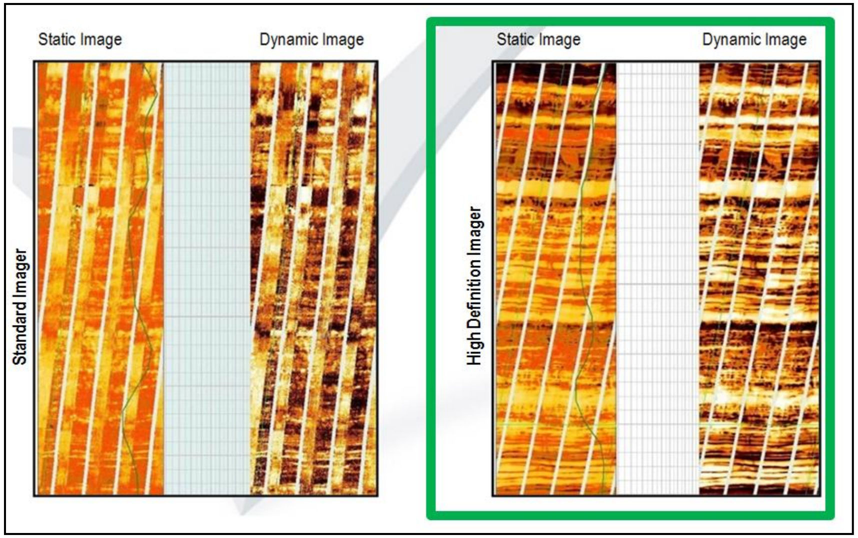
- The phase of the Alternating Current (AC) injected by the tool may shift relative to the optimum signal phase that the electronics are tuned to measure. In mild cases this results in reduced signal and higher susceptibility to noise. In extreme cases, this may result in apparent resistivity contrasts that are inverted compared to the reality.

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

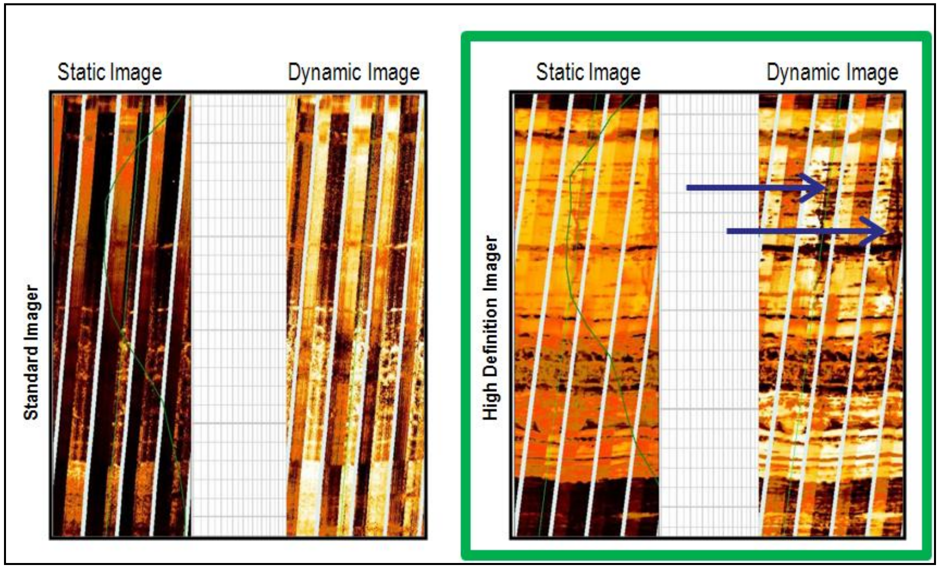
Standard Imager & High Definition Imager in WBM



Natural Fractures seen on High definition images



Fine textural details on High definition images

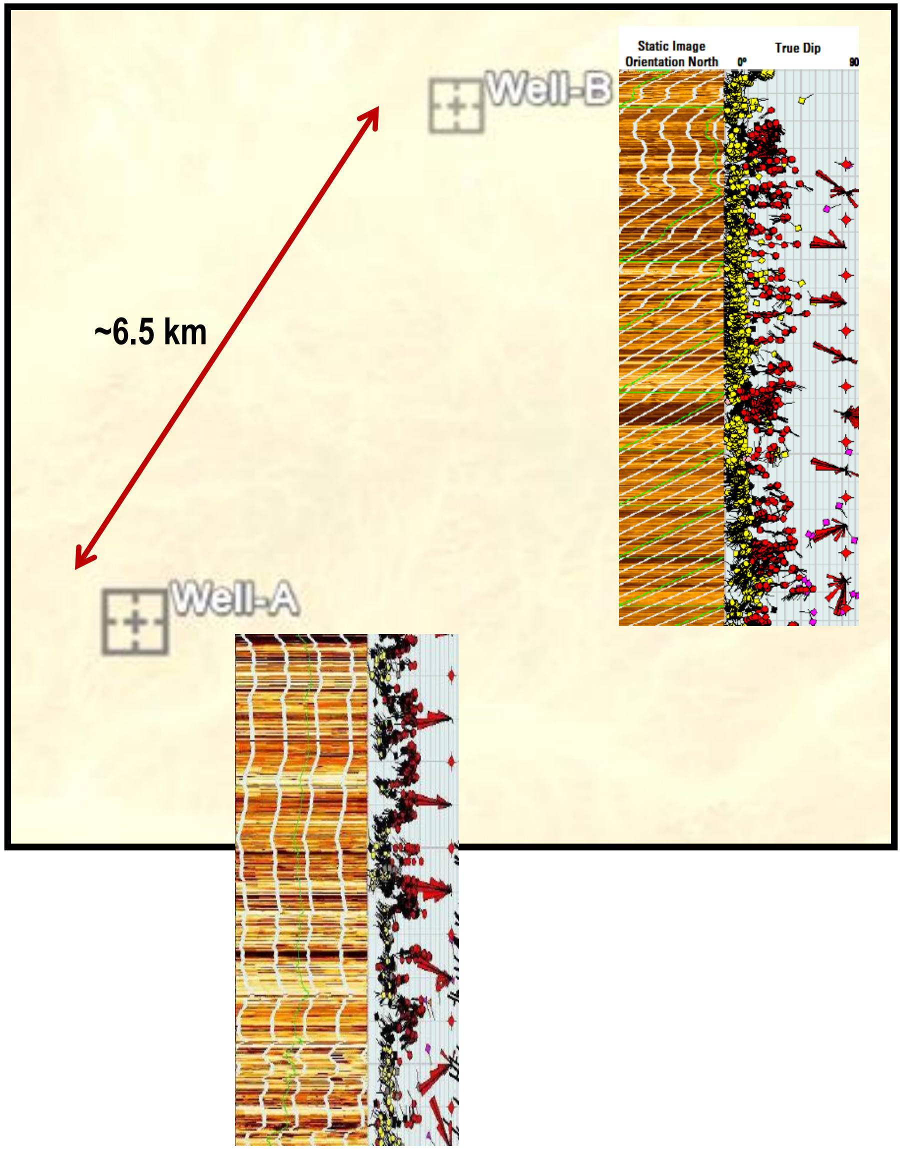


Induced Fractures seen on High definition images

Formation resistivity: 80-100 ohm-m
Rt/Rm: ~4000
Mud salinity: 240,000 ppm

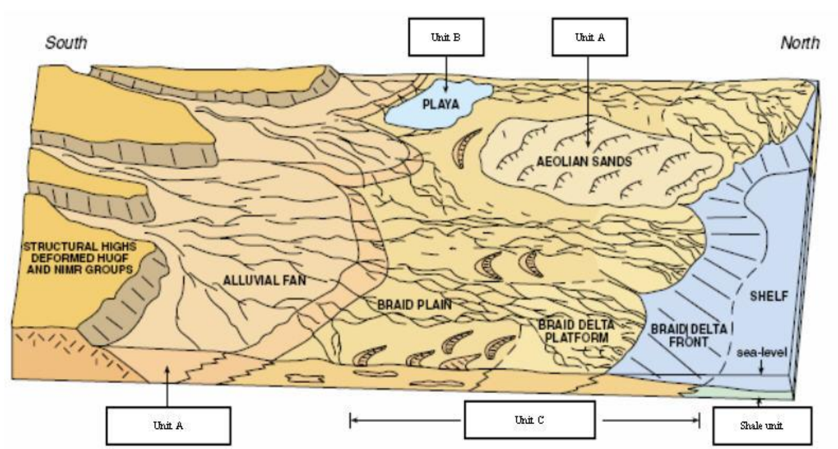
The High definition imager was run with the standard imager in the same well; showing better results with the high definition imager.

Study Area

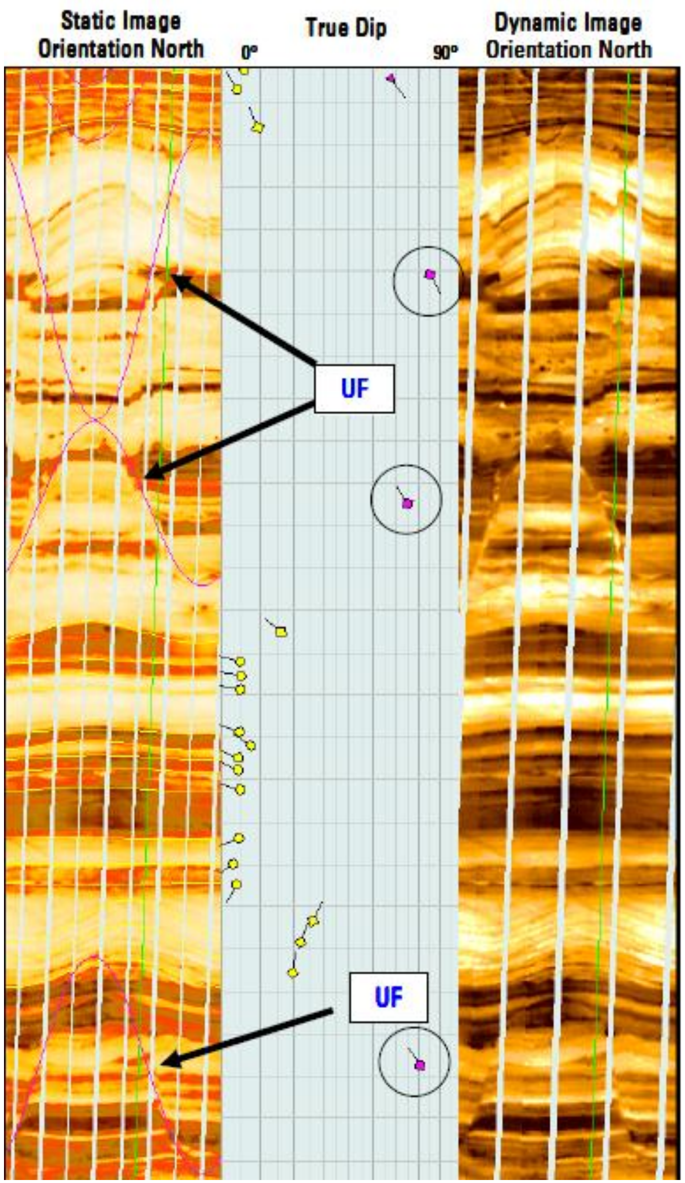


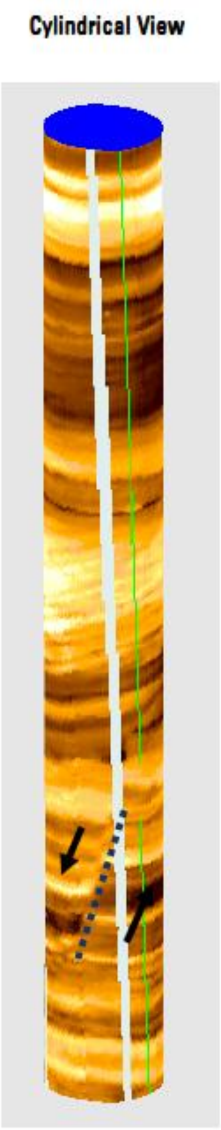
The study area is located in North Oman, where two wells were drilled in the Paleozoic clastic sequence with hyper-saline mud. High-definition borehole images were acquired to understand the architectural complexities of the depositional environment as they impact not only the fluid flow, but also the hydro-frac design to exploit the tight gas sandstone reservoirs.

Well B was drilled North-east of Well A; almost 6.5 Km away. The general depositional environment for the filed in the zone of interest is envisaged as shown in the diagram below.



Structural elements in the Field





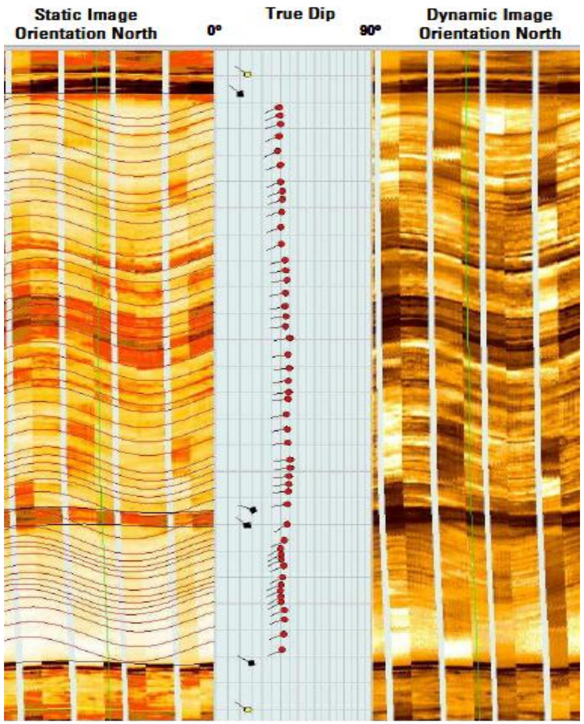
The high quality of images provides the means of interpreting the subtle micro-faults on the images.

These faults not only suggest the prevalent structural trend (NE – SW striking), but also can potentially offset the flow units in a reservoir. Their relation with the existing fault trend is very important to understand the existence of any splay faults that could potentially be the conduits for fluid for differential cementation, rendering theses sandstone units tight.

The examples shown here are classic text-book example of structure on image logs; and the faults picked do show displacement of beds.

The snapshot represents 5m of interval.

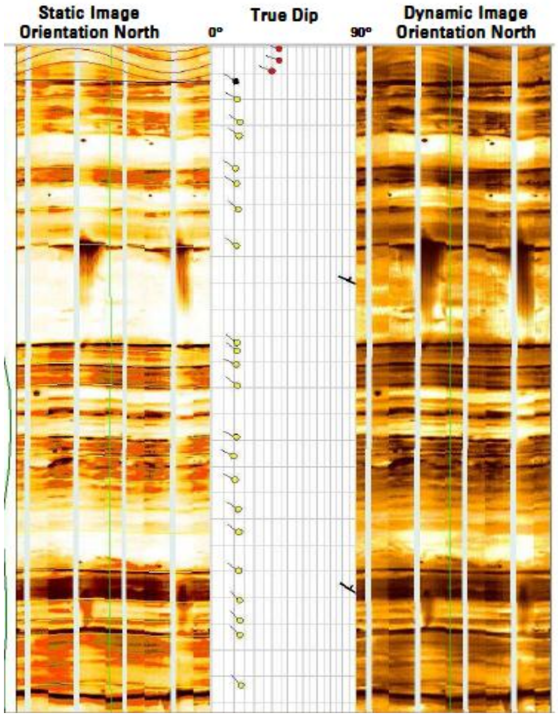
Facies Association in Well-A



Probably cross-beds of Aeolian environment. This 2m of sand section represents two sets of cross-bedded sandstones, with a westerly flow direction.

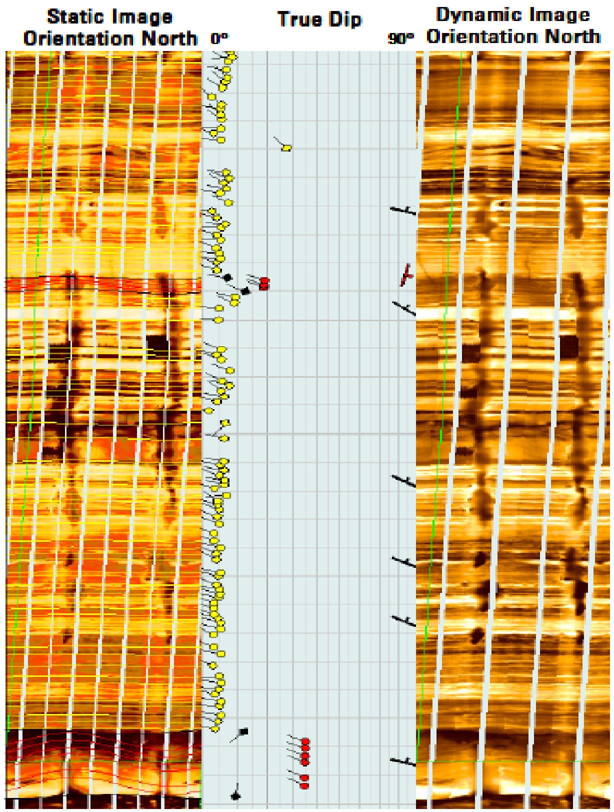
The scale of the cross-beds with the texture observed within is indicative of a probable **sand dune depositional environment** where high energy deposits could provide better path-ways for fluid flow; if not differentially cemented.

The high resolution images suggest no cementation in this interval; where a change of direction from south-west to west going towards top is indicative of the change in wind direction.



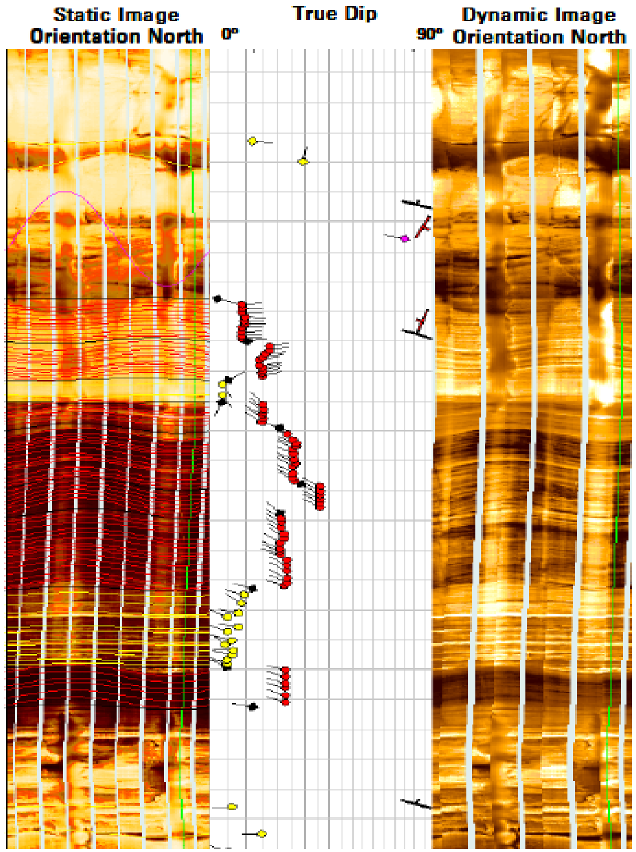
This 2m of interval with planar sand beds is probably indicative of a **sand flat environment of an unconfined flow** in an arid environment. The north-westerly dips might represent the direction of the flow..

Facies association in Well-B



5m of planar sands (yellow tadpoles) overlie the cross-bedded sand dunes (red tadpoles) in this snapshot.

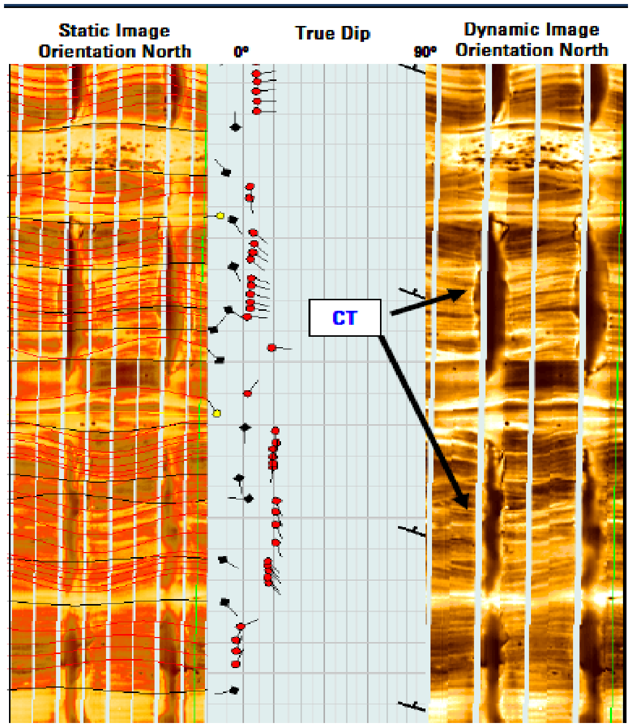
High resolution images are crucial to understand this change in facies. Also, break-out running on the image as conductive streaks suggest a maximum stress direction of NNE – SSW. The facies association suggests a **probable unconfined sheet flood on top of an aeolian sand dunes.**



The snapshot to the right shows a 5m thick sequence, probably 3 facies.

The lowermost section probably represents a **sheet flood sand, overlain by high angled cross bedded sands of probably aeolian dunes**. The top of the snapshot shows massive sands, probably a **fluvial dump**.

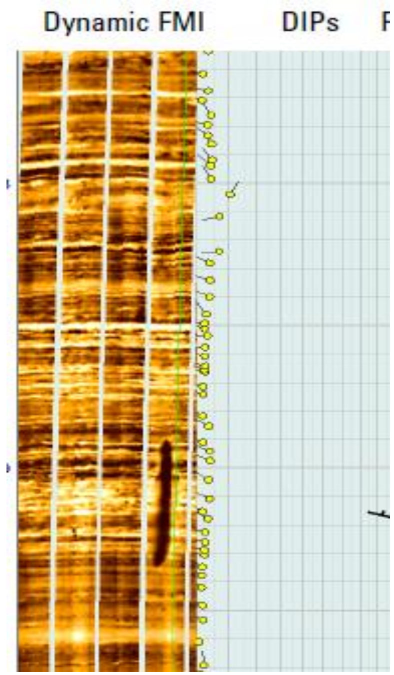
Facies Association in Well-B



Though the conductive vertical patches (break-out) on the image are very dominant in this interval; still the reactivation surfaces could be picked in this aeolian environment of deposition.

The **pebbly lag at the set-boundary of cross-beds is the reactivation surface** signature where the aeolian agency changes its direction slightly and deposits another set of dune sands.

These are excellent examples of facies identification on the high quality images, in an interval of 3m.



This flat-bedded snapshot of image log in 2m of interval probably suggests an **inter-dune on distal facies of a sheet flood**. The interpretation with respect to the facies association is suggestive of a distal sheet flood deposit here.

Observations and Interpretations

In this field, the wells A and B show the difference in the facies encountered in the Paleozoic rocks.

The wells are around 6.5 km apart; Well B being north east of the well A.

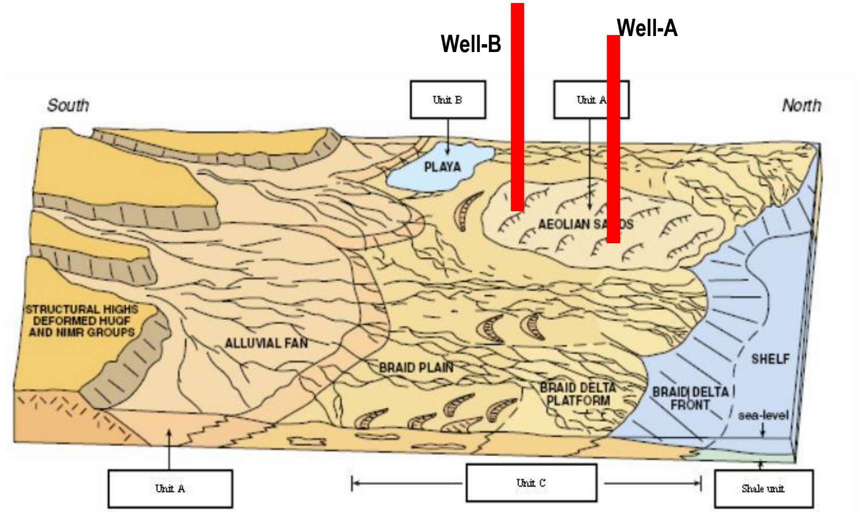
Both the wells have the main sandstone facies in probably aeolian environment

Well B has fluvial incursion in the facies sequence more than Well A.

Well B shows more directional changes in the aeolian deposition as well.

Modeling from well A to B would need introducing complexities in the static model.

The refinement of depositional environment in this light is imperative to understand the main reservoir quality intervals and their possible contribution to the production later on, when hydro-fractured. The geometry and extent of the sands is important to understand for each unit in this complex environment of deposition.



Summary

➢**Borehole image logs play a highly important role in the exploration of tight gas sandstones in the Sultanate of Oman.**

➢**Confident sedimentary and structural interpretation of image logs to understand the depositional environment, diagenesis, faults and fractures, and stress regime requires the highest available level of image detail and quality.**

➢**A new high-definition imager has been introduced and successfully proven in the Sultanate of Oman, satisfying the above requirements in even the most challenging wells drilled with salt-saturated water-base muds.**

➢**The facies association in the field studied with the help of image logs is suggestive of quite variations where different geological agencies contribution to the deposition of reservoir units is varied.**

➢**A refinement of the static model is imperative on a higher resolution with more wells drilled in this field.**