[PS]DFN Modeling Approach and Development Strategies of Fractured Reservoirs in Minagish Field, Kuwait*

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Search and Discovery Article #40896 (2012)**
Posted March 31, 2012

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

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Abstract

This paper describes how Discrete Fracture Network (DFN) models for the Mishrif and Rumaila reservoirs were built. It highlights the approach and methodology that was used for understanding the reservoir connectivity and its drive mechanism. Ultimately, based on these findings, a phased development strategy is proposed.

Mishrif and Rumaila are tight, carbonate, oil bearing, layered fractured reservoirs of Cenomanian-Turonian (Upper Cretaceous) age developed over an asymmetrical anticline, dipping from east to west. Three depositional models through time showed the impact of facies on the primary porosity nature.

The horizontal wells showed good production rates followed by a sharp decrease in pressure and production. This has prompted a detailed integrated study to fully understand the recovery mechanism and increase the well productivity.

A conceptual model has been developed for the reservoir connectivity by integrating static and dynamic data. This comprehensive study combines transient well testing and production data with cores, image logs and a fracture-oriented seismic facies analysis in order to characterize and map the fracture networks occurring in the reservoir units. It has resulted in improving the understanding of reservoir connectivity and flow mechanism.

Based on the findings, 3D DFN models were developed. These models include large-scale fracture corridors and four sets of diffuse fractures oriented EW, NS NW-SE and NE-SW.

The fracture corridors are modeled as single large-scale fractures crosscutting all of the reservoir units. Their position, orientation and extent are controlled by the results of all the seismic analyses. The diffuse fractures are modeled as bed-bounded fractures with a density controlled by the rock shaliness. The hydraulic properties of fractures were determined through a calibration of the DFN models against the available well test data. The KH of well tests were compared with the KH of the DFN models and the conductivities of fractures in the models were adjusted so that a good match between the observed and modeled KH was obtained. Finally, the calibrated DFN models were upscaled in order to compute full-field equivalent fracture properties usable in dynamic simulations. Two successful horizontal wells were drilled recently via completion of the study, and all the results obtained were integrated in order to improve development strategies and propose better well locations.

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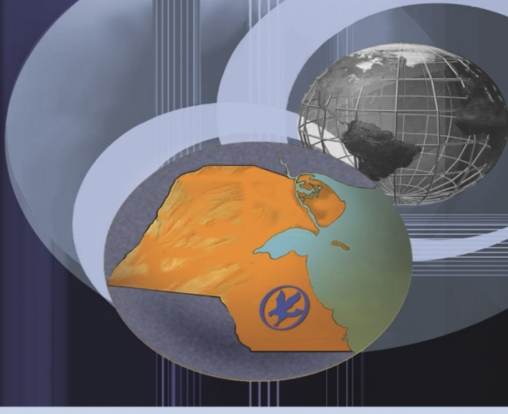
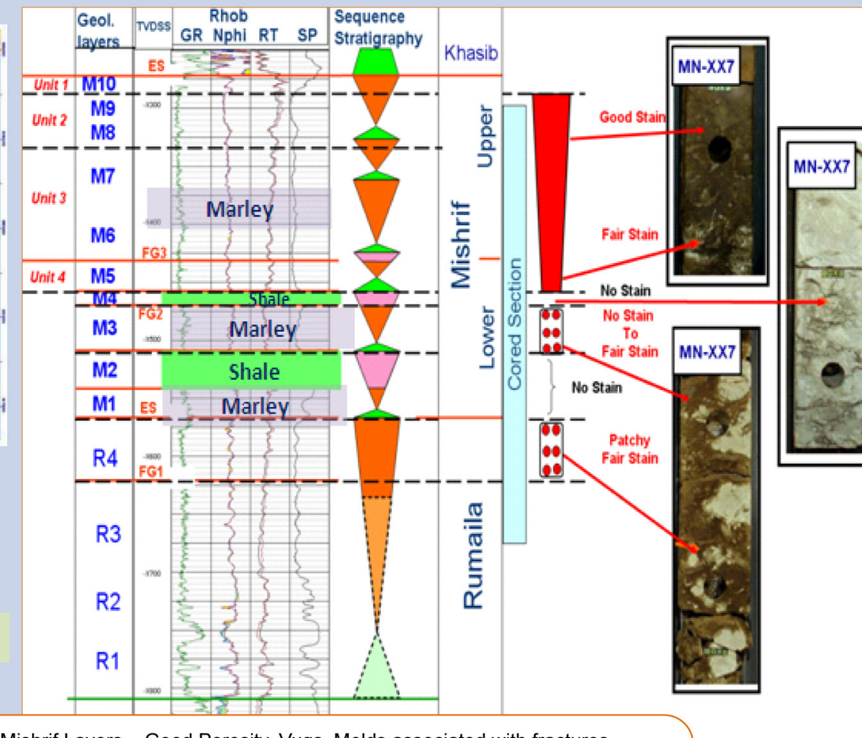


Abstract

This paper describes how Discrete Fracture Network (DFN) models for the Mishrif and Rumaila reservoirs were built. It highlights the approach and methodology that was used for understanding the reservoir connectivity and its drive mechanism. Ultimately, based on these findings, a phased development strategy is proposed. Mishrif and Rumaila are tight, carbonate, oil bearing, layered fractured reservoirs of Cenomanian- Turonian (Upper Cretaceous) age developed over an asymmetrical anticline, dipping from east to west. Three depositional models through time showed the impact of facies on the primary porosity nature. The Upper Mishrif is mud-dominated but with occurrence of fine-grained sediments. The Lower Mishrif and Upper Rumaila are dominated by microporosity. The muddy sedimentation and disappearance of porosity due to heterogeneous cementation (nodules) led to a very poor reservoir potential. The first Mishrif vertical producer has intersected a NE-oriented, fluid conductive fault. This fault boosts the system permeability from an average of 1-2 mD to about 60 mD. Three horizontal wells were drilled later with good production rates followed by a sharp decrease in pressure and production. This has prompted a detailed integrated study to fully understand the recovery mechanism and increase the well productivity. A conceptual model has been developed for the reservoir connectivity by integrating static and dynamic data. This comprehensive study combines transient well testing and production data with cores, image logs and a fracture-oriented seismic facies analysis in order to characterize and map the fracture networks occurring in the reservoir units. It has resulted in improving the understanding of reservoir connectivity and flow mechanism. Based on the findings, 3D DFN models were developed. These models include large-scale fracture corridors and 4 sets of diffuse fractures oriented EW, NS NW-SE and NE-SW. The fracture corridors are modeled as single large-scale fractures crosscutting all of the reservoir units. Their position, orientation and extent are controlled by the results of all the seismic analyses. The diffuse fractures are modeled as bed-bounded fractures with a density controlled by the rock shaliness. The hydraulic properties of fractures were determined through a calibration of the DFN models against the available well test data. The KH of well tests were compared with the KH of the DFN models and the conductivities of fractures in the models were adjusted so that a good match between the observed and modeled KH was obtained. Finally, the calibrated DFN models were upscaled in order to compute full-field equivalent fracture properties usable in dynamic simulations. Two successful horizontal wells were drilled recently via completion of the study, and all the results obtained were integrated in order to improve development strategies and propose better well locations.

Kuwait Map shows the location of Minagish Field

Mishrif & Rumaila Reservoir Layering

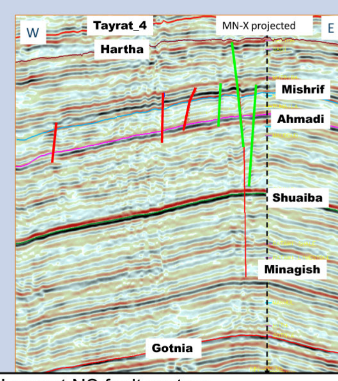


- Upper Mishrif Layers – Good Porosity, Vugs, Molds associated with fractures.
- 15 Geological time surfaces at field scale.
- Two Major Sequence boundaries created with exposure time.
- 14 reservoir layers for Mishrif and Rumaila.
- Lower layers are mainly mud dominated with thin inter-bedded brittle layers.

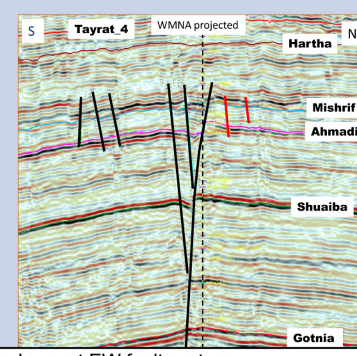
Structural Analysis

- Faults and horizons interpretation using 3 different Q land cubes.
- Edition of seismic horizons near the faults, some horizons had to be regularized, then fault polygons were computed.
- Once fault pattern were identified, they were analyzed in order to determine the main fault families, the fault types, timing of faulting and the possible origin of faults.
- 4 fault families with EW, NS, NE-SW and NW-SE orientations were identified.
- All faults have a normal sense of shear and show no evidence of reactivation.
- Main phases of development of Minagish anticline since Gotnia time. Faulting was due to folding.
- Timing of oil generation coincides with timing of faults generation and activity in the reservoirs.
- The main fault families could be responsible for oil migration upwards to Mishrif and Rumaila reservoirs are EW and NS fault families. Other faults confined to shallow units and disconnected from deeper units.
- Analysis of the present day conditions.

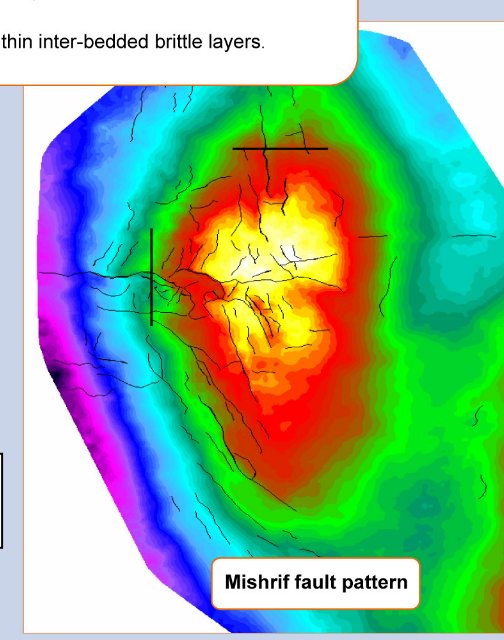
Detection & Mapping of Faults



- Largest NS fault system
- Goes down to Minagish, and could have assisted the migration of oil up to Mishrif and Rumaila in relay with other, deeper faults



- Largest EW fault system
- Goes down to Gotnia, and could have formed a conduit for the migration of oil up to Mishrif and Rumaila



Mishrif fault pattern

Folding Summary

The EW and NS folding possibly have the same history:

- Quiet and regular folding during the period Gotnia to Mishrif
- Accelerated folding during the period Mutriba to Hartha
- Quiet and regular folding during the period post-Hartha

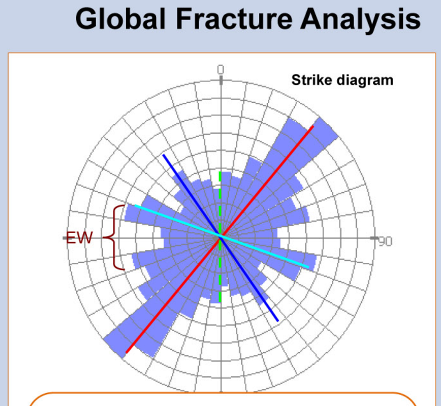
Faults Summary

FAULT FAMILY	TYPE	AFFECTED UNITS	SYN-SEDIMENTARY ACTIVITY	POSSIBLE TIMING
EW	Normal	Up: Sadi Down: Gotnia	Yes, syn-Mishrif	Syn-Mishrif to Sadi
NS	Normal	Up: Hartha Down: Minagish	No	Hartha
NW-SE	Normal	Up: Sadi Down: Zubair	No	Sadi
NE-SW	Normal	Up: Mutriba Down: Ahmadi	No	Mutriba

Fracture Analysis

- Detection of fractures based on geometrical characteristics and electrical properties.
- Fracture analysis from BHI data of 12 inclined and vertical wells.
- Four different sets of diffuse fractures and fracture clusters: NS, EW, NW-SE, and NE-SW.
- The orientation of the in-situ stress in the reservoirs was carried out based on the bore hole breakouts.
- Core analysis data were integrated with the results of the bore hole image analysis.
- The dynamic data were used to qualitatively assesses the impact of fractures in production.
- These results are fully consistent with core observations and the results of the fractures characterization based on BHI image interpretations.

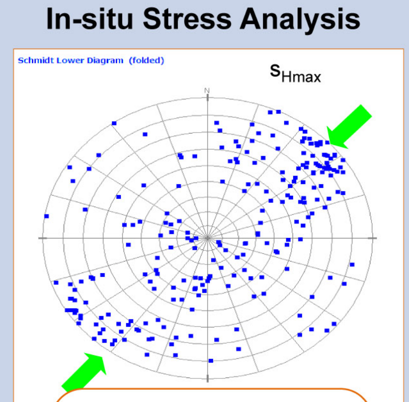
Global Fracture Analysis



- 3108 fractures were interpreted in the 12 wells studied.
- Three main fracture orientations dominate: NE-SW, NW-SE, EW, (ESE-WNW) and ENE-WSW).

There is also a secondary NS orientation

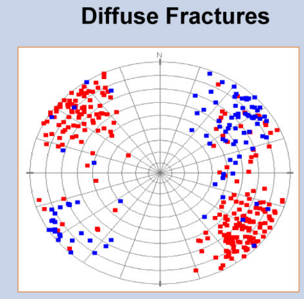
In-situ Stress Analysis



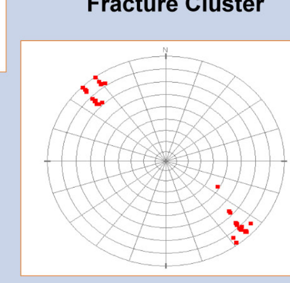
- A NE-SW orientation of shmax is consistent with the fact that most of the resistive/closed fractures are oriented NW-SE.
- Breakout data, combined with the knowledge of the regional tectonic regime, indicate that the maximum horizontal stress shmax is oriented NE-SW.

Fracture Components

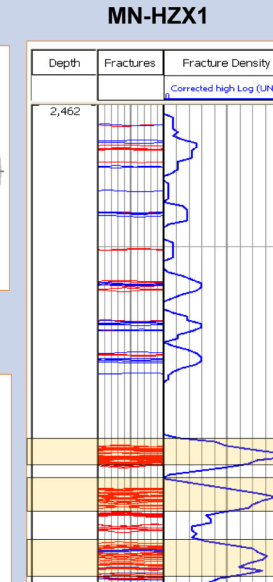
Diffuse Fractures



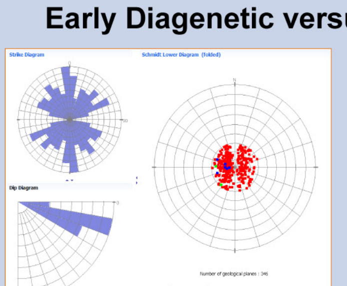
Fracture Cluster



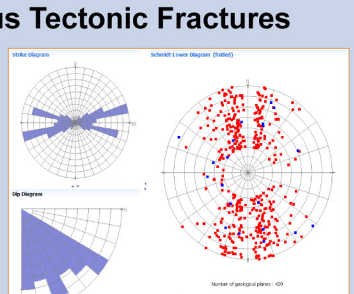
MN-HZX1



Early Diagenetic versus Tectonic Fractures

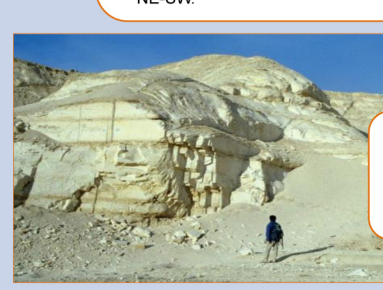


Early diagenetic
Low-angle fractures (dip < 30°).
Scattered orientations, consistent with an early-diagenetic origin, i.e. with a formation in a material not fully compacted and dewatered.



Tectonic fractures
High-angle fractures (dip > 30°).
Preferential orientations, consistent with a tectonic origin, i.e. with a formation under stress.

Diffuse fracture densities were computed anywhere possible. They are systematically higher in horizontal wells than in vertical wells (better sampling of fracture networks) and range from 0.04 to 1 fractures per meter.



Fracture clusters share three same orientations as the diffuse fractures and large-scale faults: EW, NW-SE and NE-SW. Their apparent thickness ranges from 0.5 to 25 m.
Fracture densities in the clusters are much higher than in diffuse fracture sets and range from 1 to 12 fractures per meter.

Dynamic Data Analysis

Analyze all of the dynamic data available in order to assess the impact of diffuse fractures (characterized from borehole image analysis) and fracture corridors (identified from seismic analysis) on fluid flow in the Mishrif and Rumaila reservoirs.

Qualitative analysis was made by comparing typical Mishrif reservoir core permeability with interpreted well-test permeability.

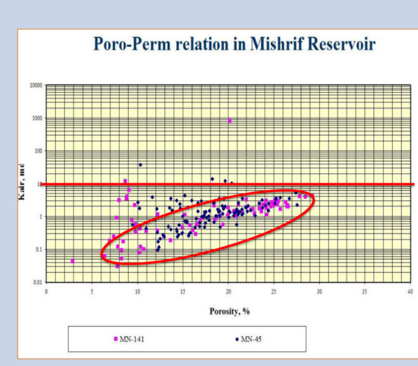
Core permeability ranges from 0.1 to 10 mD (Average 1-2 mD).

Well test interpretation indicates 50-58 mD, which is much higher than the core permeability.

KH Analysis

Typically in a fractured reservoir

$$\frac{KH_{test}}{KH_{matrix}} > 10$$



Permeability enhancement due to fracture around the well

GEO 2012, 10th Middle East Geosciences Conference & Exhibition, Manama, Bahrain, from 4–7 March 2012

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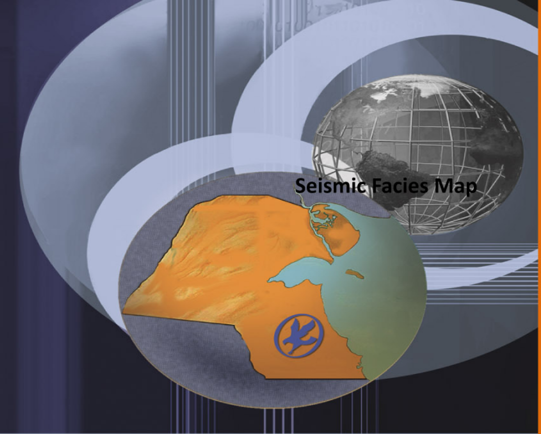


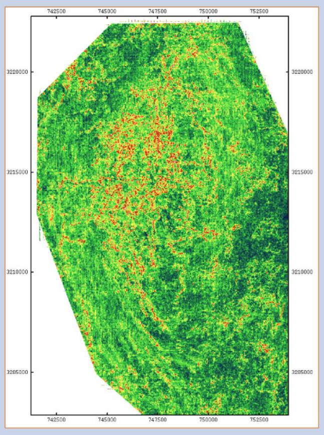
Structural Controls on Fracture Corridors & Layer Bounded Fractures

1) Basic Seismic Analysis

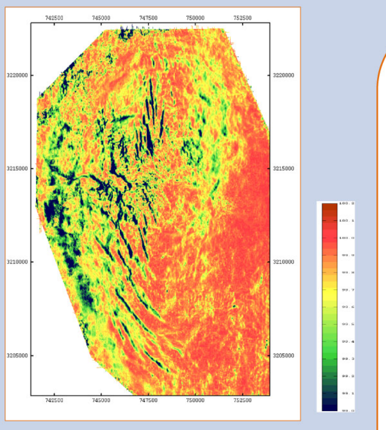
- Curvature analysis was used as a main technique for the detection and mapping of fracture lineaments that are small scale features than the seismic faults.
- The analyses carried out were finalized with the use of seismic attributes and the seismic facies map obtained from advanced seismic analysis.
- The major output is a complete map of major and minor faults occurring in the reservoir, which will be used for fracture modeling.

Analysis based on 6 seismic attributes:

- Edge after PCA
- 3D curvature
- Coherency
- Coherency on the 30Hz component
- Coherency on the 40Hz component
- Similarity on Energy



3D Curvature (absolute values)

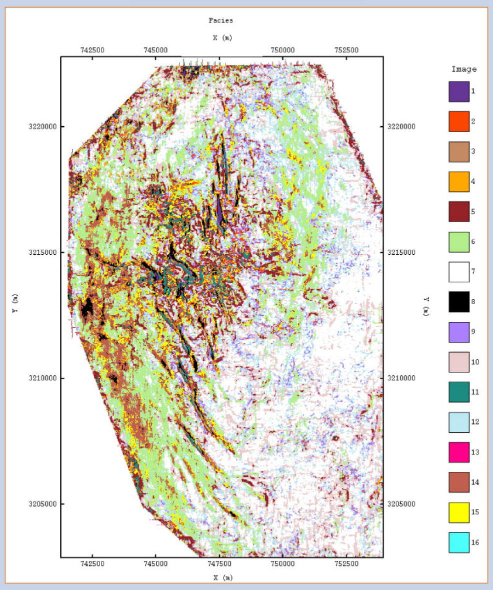


Coherency or Similarity : measures the local variability of seismic traces based on local distance calculations between traces within a short time window, along time slices or along horizons.

2) Advanced Seismic Analysis

- Building a fracture oriented seismic facies map based on post-stack discontinuity attributes computed from the inverted synthetic seismic cube.
- This analyses allowed detecting the large scale fractures with a high precision and possibly visualizing the width of the fracture corridors.
- The results obtained are in agreement with the findings of detailed structural analysis.
- The inversion process improving the seismic resolution and the advanced method used to filter the footprints impacting the attributes ensure the robustness and the quality of the results.
- The fractured- oriented facies map together with the geometrical and seismic attributes generated were used in the fracture modeling to constraint the distribution and extent of fracture corridors in the regions between the wells.

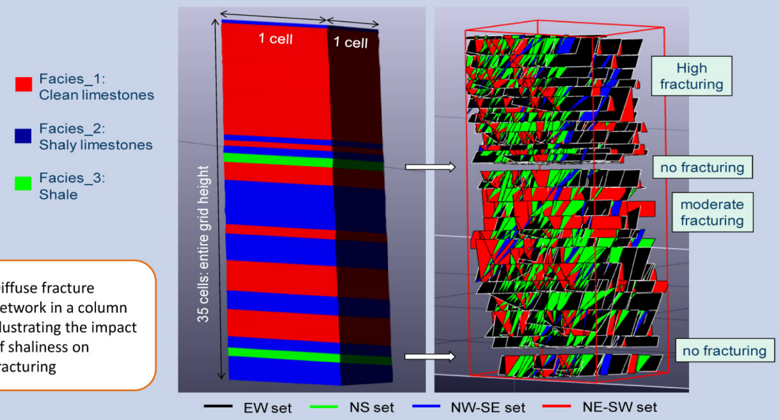
Seismic facies map



Stratigraphic Controls on Layer Bounded Fractures

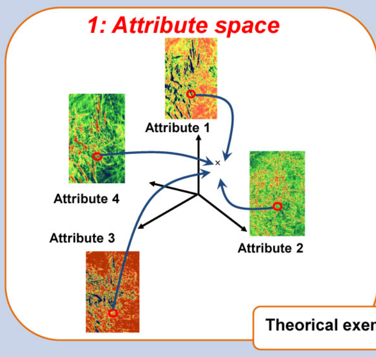
Drivers of Diffuse Fracturing

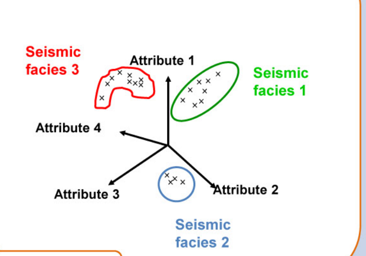
- The rock shaliness has an important impact of the degree of diffuse fracturing.
- In order to quantify this impact, three pseudo-facies were defined based on the shale content.
- Clean limestones with VSH<0.11 are significantly fractured.
- Shaley limestones with 0.11<VSH<0.39 are moderately fractured.
- Shaley units with 0.39<VSH show no diffuse fracturing.
- These results form the basis for modeling of diffuse fracturing in Mishrif-Rumaila reservoirs.



Diffuse fracture network in a column illustrating the impact of shaliness on fracturing

Fracture Seismic Facies Analysis: principle





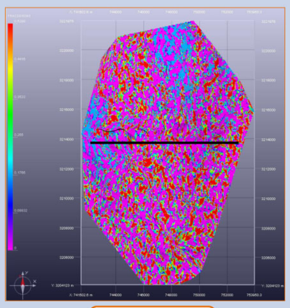
Theorical exemple with 4 Attributes

Model of Fracture Properties

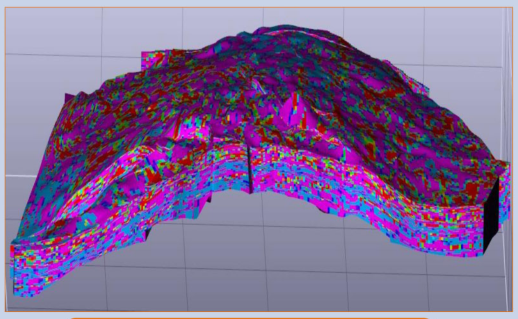
- The DFN models were built by integrating all the results in the project. They contained the large-scale fracture corridors detected from seismic analysis, together with 4 sets of diffuse fractures characterized on image logs interpretation.
- Fracture corridors were modeled as single objects cross cutting all the reservoir units whereas diffuse fractures were modeled as fractures with limited vertical dimension , bed bounded in essence. Their density was controlled by rock shaliness.
- The hydraulic properties of the fractures, i.e the conductivity and aperture of diffuse fractures and fracture corridors, were obtained through the calibration of DFN models based on the KH value obtained from well test of MN-V-1.
- Finally, the calibrated DFN models were upscaled in order to compute a model of equivalent fracture properties usable in dynamic simulations.
- The upscaled fracture properties include fracture porosity, fracture permeability and matrix block size.
- The fracture porosity was used for the computation of the STOOIP in the fracture networks.

Two Models of Diffuse Fracturing

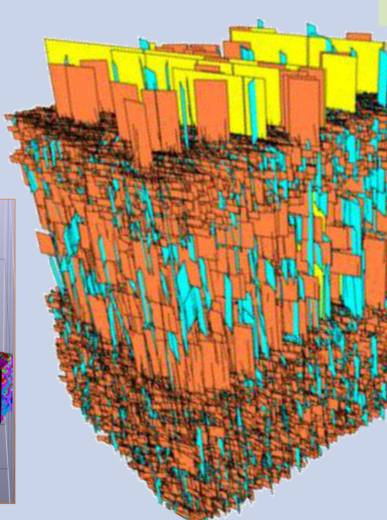
- **Because shaliness does not explain all of the fracture density** variations in the reservoirs, 2 different modeling approaches are used.
- Model 1 is an average model that uses the average fracture parameters computed, with the fracture density controlled by pseudo-facies.
- Model 2 is a more variable model based at the same time on average fracture properties, pseudo-facies, and geostatistical analyses of spatial variations of fracture density.



Map view



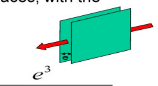
Cross-sectional view of NS fracture density distribution obtained by SGS simulation (Model 2)



3-D DFN Model view

Results of DFN Calibration

Aperture (e): computed from conductivity (Cf) by considering fractures as planar surfaces, with the Poiseuille's law



Results:

Diffuse fractures: 0.038 mm

Corridors: 10.8-12.4 mm

$$Cf = \frac{e^3}{12 * 0.98.10^{-6}}$$

	Diffuse fractures	Fracture corridors
Fracture Model 1 Aperture (mm)	0.038	10.8
Fracture Model 2 Aperture (mm)	0.038	12.4

Hydraulic conductivity: much higher in fracture corridors than in diffuse fractures, consistent with the role of corridors as drains in the reservoirs

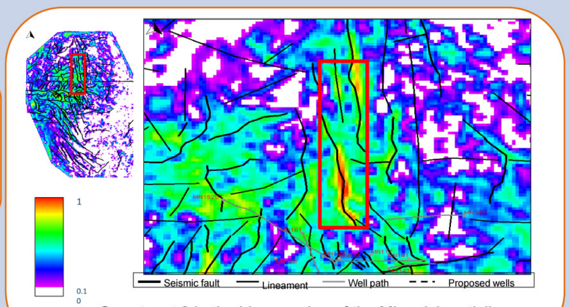
Diffuse fractures: 16.4 mD.ft

Corridors: 34449-53642 mD.ft

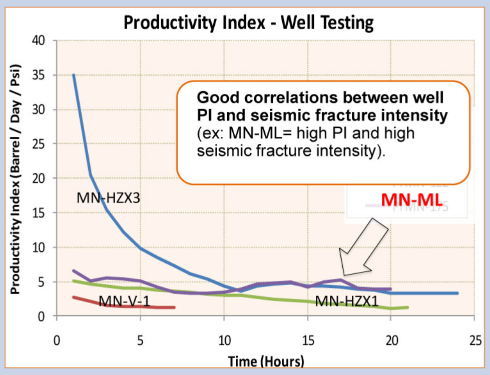
	Diffuse fractures	Fracture corridors	interpreted KH (mD.ft)	computed KH (mD.ft)
			MN-14	MN-14
Fracture Model 1 Conductivity (mD.ft)	16.4	34449	10777	10819
Fracture Model 2 Conductivity (mD.ft)	16.4	53642	10777	10770

Development Strategies

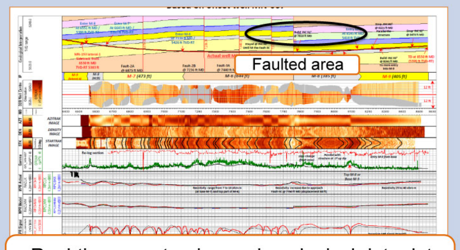
The knowledge acquired in terms of distribution, organization and dynamic performance of fracture networks was used in order to propose recommendations regarding the position of new wells and development strategies.



Sweetspot 2 in the hinge region of the Minagish anticline (background: fracture intensity from seismic)



Well Placement: 1st "Multi-lateral" Well

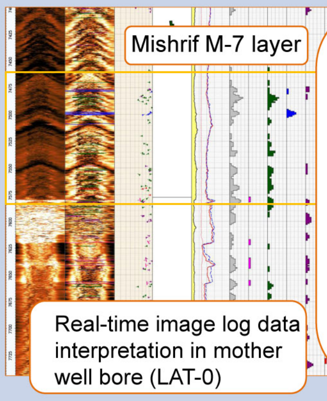


Real-time geosteering and geological data data interpretation in mother well bore **(LAT-0)**

Real-time geosteering and geological data data interpretation in 2nd lateral hole well bore **(LAT-1)**

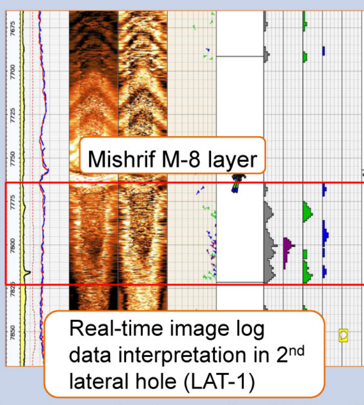
Production Data Analysis

- All the dynamic data including production data, well test data, static pressure measurements and productivity index (PI) measurements were analyzed in order to assess the role of diffuse fractures and fracture corridors on production in Mishrif and Rumaila reservoirs.



Real-time image log data interpretation in mother well bore (LAT-0)

- Fracture cluster (possible corridor) in **MN ML (LAT-0) in M07 reservoir layer**, near the faulted zone. This possible corridor has total of 64 fractures. These fractures are dominated mainly by conductive and Partial Conductive fractures with mean orientation is toward N-S (hinge zone of the field). The fracture density in the cluster are much more high than in diffuse fracture sets (1.9 fractures per meter).



Real-time image log data interpretation in 2nd lateral hole (LAT-1)

- Fracture cluster (possible corridor) in **MN ML (LAT-1) in M08 reservoir layer**, near the faulted zone. This possible corridor has total of 53 fractures. These fractures are dominated by conductive and partial conductive fractures with mean orientation is toward NNE-SSW (hinge zone of the field). The fracture density in the cluster are much more high than in diffuse fracture sets (1.54 fractures per meter).

Summary & Conclusions

- There are four families of faults in the Mishrif and Rumaila reservoirs with NS, EW, NW-SE and NE-SW orientations. Faulting developed in a relatively narrow time window between the deposition of the Mishrif and Hartha formations. Fault development coincides with pulses in the development of the Minagish anticline, suggesting that faults mainly owe their existence to folding. Oil is thought to have formed in the Najmah/ Sargelu source rocks and to have migrated upwards to the Cretaceous reservoirs in the period ~85 to 53 My.
- The timing of oil migration coincides with the timing of fault development and activity in the Mishrif and Rumaila reservoirs. The largest NS and EW faults have sufficient vertical persistency to have assisted the migration of oil upwards to the reservoirs.
- Fracturing in the Mishrif and Rumaila reservoirs is composed of four sets of diffuse fractures and fracture clusters. Fracture orientations are similar to that of larger-scale faults: NS, EW, NW-SE and NE-SW.
- The statistical properties of each of the fracture components were characterized, and served as a basis for fracture modeling. Qualitative analysis was performed mostly based on well-test data available. Results indicated that the Mishrif is fractured in the vicinity of the well, and that fractures enhance fluid flow.
- The detailed seismic analyses carried out allowed completing the fault detection carried out in the first part of the study. A final map of large-scale fractures occurring in the reservoir was produced, which constitutes a major input for the modeling of fracture corridors.
- The analysis of dynamic data available allowed concluding that natural fractures have a clear local impact on well productivity. Each producer seems to have a limited drainage area suggesting that fractures are either poorly connected, poorly conductive or both. The analysis of log data allowed identifying rock shaliness as a driver for diffuse fracture occurrence. Three pseudo-facies characterized by distinct fracture density properties were defined and used for fracture modeling.
- Fracture corridors were modeled as single objects and their geometry and position was imposed by the results of seismic analyses. Two models of diffuse fractures were developed. Model 1 is an average model where diffuse fracture density is controlled by shaliness whereas Model 2 is a more variable model integrating geostatistical results. The DFN models built were calibrated against the KH obtained from the well test in well MN-14, and equivalent full field fracture properties were computed for both Models 1 and 2.
- Based on the results of the study, 5 sweet spots were identified and evaluated. We achieved the remarkable success of drilling two horizontal and "Multilateral" wells in terms of increased sustained oil production rates. These wells were drilled by non-damaging water based mud system with sized CaCo3 as weighing agent. Also, the filter cake was effectively cleaned by new innovative VES based acid stimulation system to remove the formation damage. Additionally the two micron filtered brine was used to minimize the chances of pore throat blocking.

GEO 2012, 10th Middle East Geosciences Conference & Exhibition, Manama, Bahrain, from 4–7 March 2012