# West Kuwait Unconventional Hydrocarbon Potential Evaluation of the Najmah Formation - Phase 1 Project Summary*

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Search and Discovery Article #80658 (2019)**
Posted January 14, 2019

*Adapted from oral presentation given at the GEO 2018 13th Middle East Geosciences Conference and Exhibition, Manama, Bahrain, March 5-8, 2018
 DOI:10.1306/80658Al-Murakhi2019

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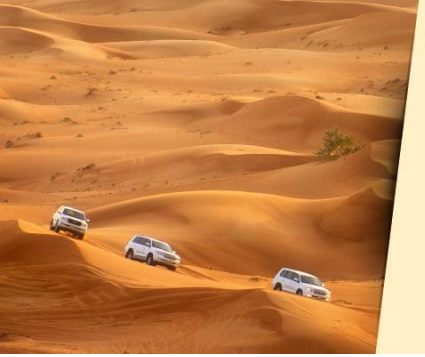
## Abstract

This study has investigated the 'unconventional' shale oil / gas potential within the Najmah Formation of West Kuwait. The unconventional potential has been characterised, quantified and ranked across a study area encompassing the Dharif, Abduliyah, Minagish and Umm Gudair Fields. A multi-disciplinary approach was utilized integrating analyses derived from core data, petrophysical data, image log and geomechanical analysis. The Najmah Formation has a consistent stratigraphy across the study area within which organic-rich argillaceous wackestones and mudstones of Najmah Unit III form the primary target. Limestones (Najmah Units II and IV) encase Najmah Unit III. Najmah Unit III is generally high in TOC, whose original form is dominated by pore filling pyrobitumen. TOC increases overall from South to North across the study area.

RockEval data and vitrinite reflectance confirm the expected overall increase in present day thermal maturity with depth within the Najmah, but variation within individual fields is also notable. The Najmah Formation is in the (peak to late) oil generation window across the study area. A ranking and 2D composite risk mapping exercise of the target Najmah Unit III has determined the most prospective areas for further appraisal and exploitation. Lateral porosity increases are offset by additional trends in depth, thickness and TOC requiring an understanding of all parameters. In a vertical sense, a stratigraphic 'sweet-spot' is noted in the upper half of the Najmah IIIC and overlying IIIB with uniformly high TOC and porosity.

Geomechanical analysis sought understanding on rock and stress behaviour across the Najmah Formation. High stress contrasts between target, organic rich Unit III and the bounding organic poor limestones provide very good stress barriers for hydraulic fracture containment in certain fields, but not in others. Strong stress barriers will reduce the risk of out of zone propagation of hydraulic fractures and increases the treatment efficiency required to generate a stimulated reservoir volume (SRV). Notably it is the organic unit that remains the target Formation, not any juxtaposed organic poor horizons. Depletion effects related to existing production were also investigated and found to severely reduce the stress barriers in those fields because of poro-elastic effects. Pore pressure in reportedly depleted Najmah intervals is a development risk and should be confirmed via testing.

Available image analysis shows that a dominant NE-SW trend can be established for SHmax orientation. Certain natural fractures in the Najmah Formation are critically stressed under current reservoir pressure and in situ stress and other will become conductive following stimulation caused by hydraulic treatment. Relative comparison of wells and fields was performed based on weighted contribution of several geomechanical parameters that have direct impact on hydraulic fracture containment, complexity and ease of fluid flow for a given permeability.



GEO 2018
13th Middle East Geosciences Conference and Exhibition

CONFERENCE:
5 – 8 March 2018

EXHIBITION:
6 – 8 March 2018

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# West Kuwait Unconventional Hydrocarbon Potential Evaluation of Najmah and Dhruma – Phase 1 Project Summary

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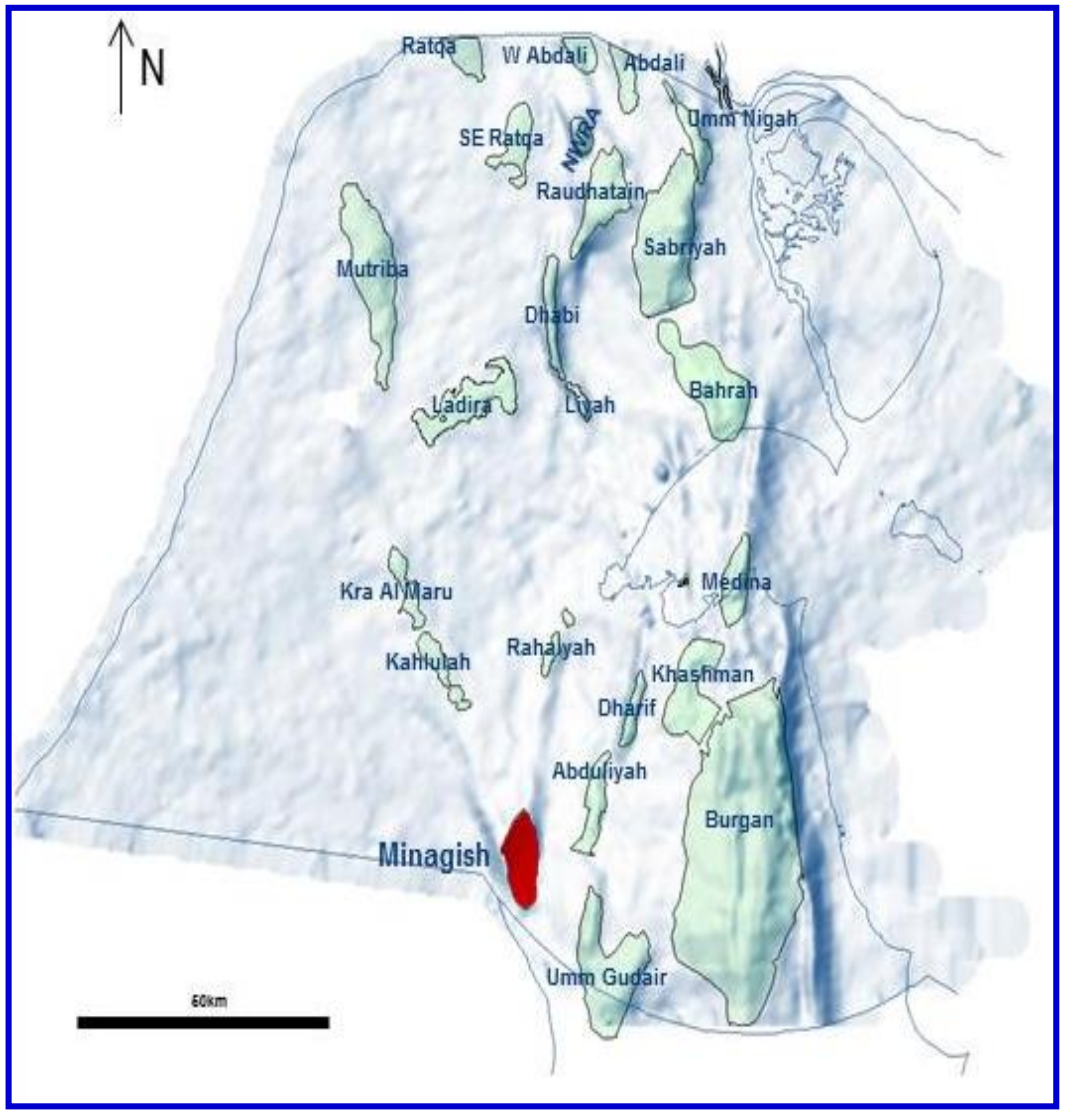
Kuwait Oil Company
إحدى شركات مؤسسة البترول الكويتية
A Subsidiary of Kuwait Petroleum Corporation



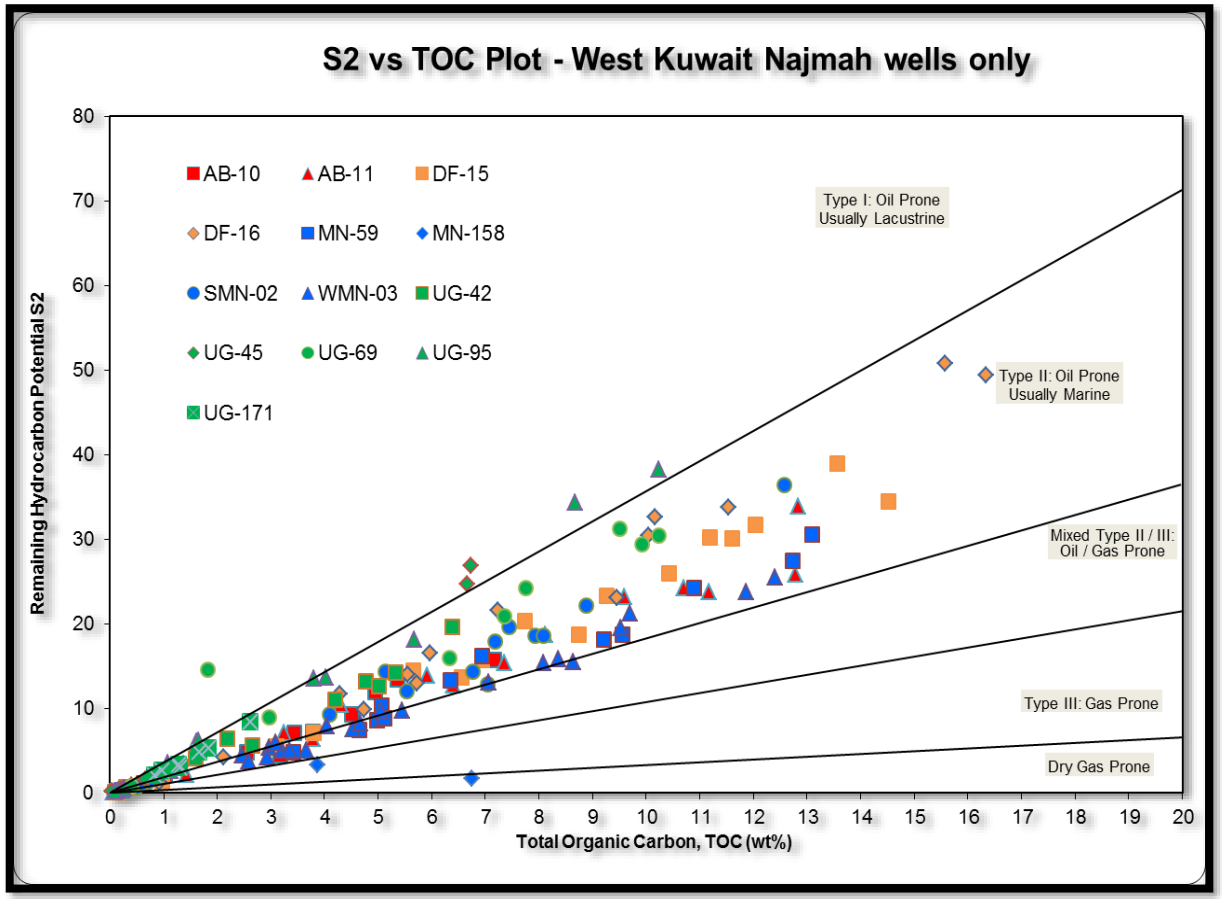

- 4 fields included in study
- 34 wells included in study
- Cores from 11 Najmah wells
- Cuttings from 3 Najmah & 4 Dhruma wells

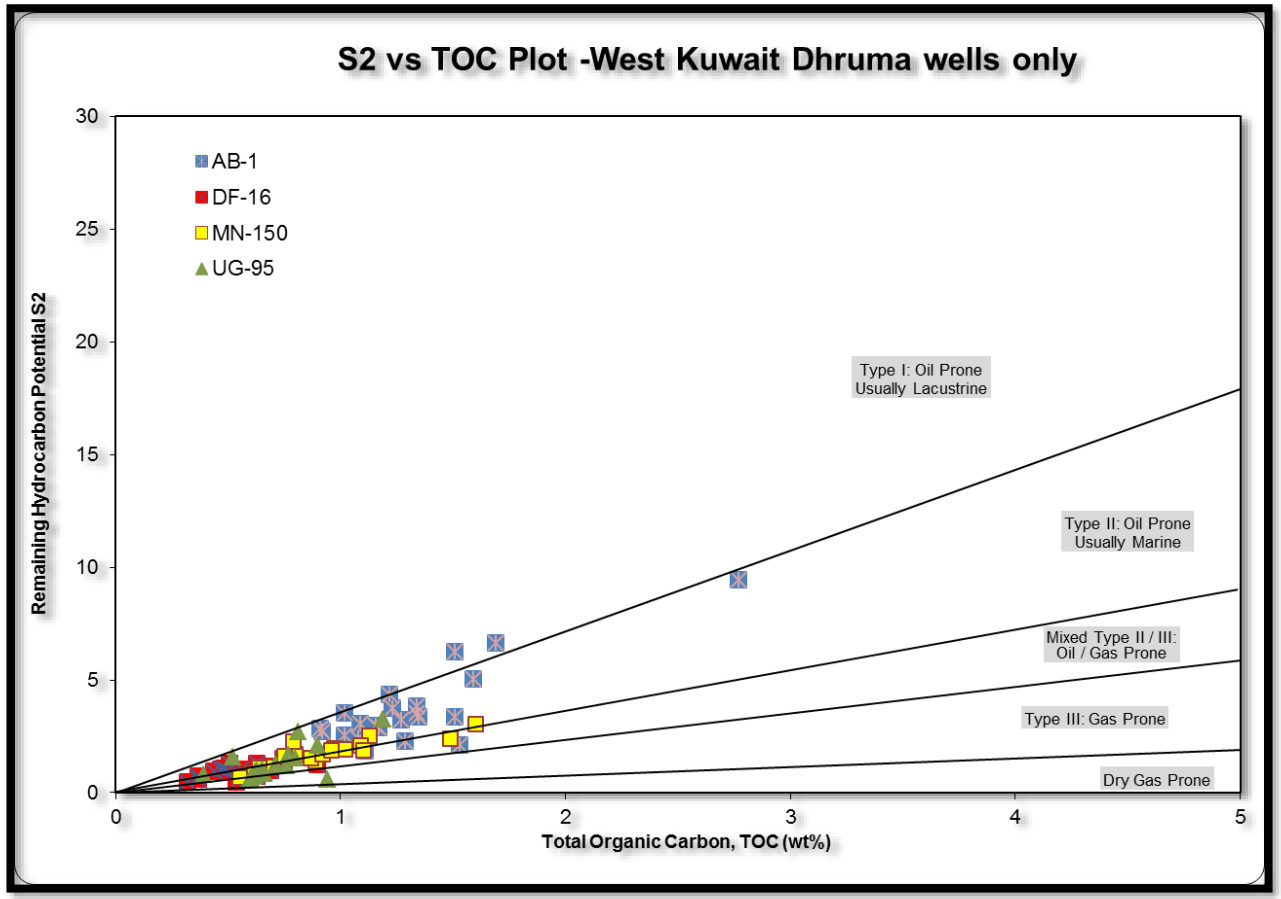
- North to South
- DF - Dharif
- AB - Abduliyah
- MN - Minagish (including WMN & SMN)
- UG - Umm Gudair

## Phase I Achievements:

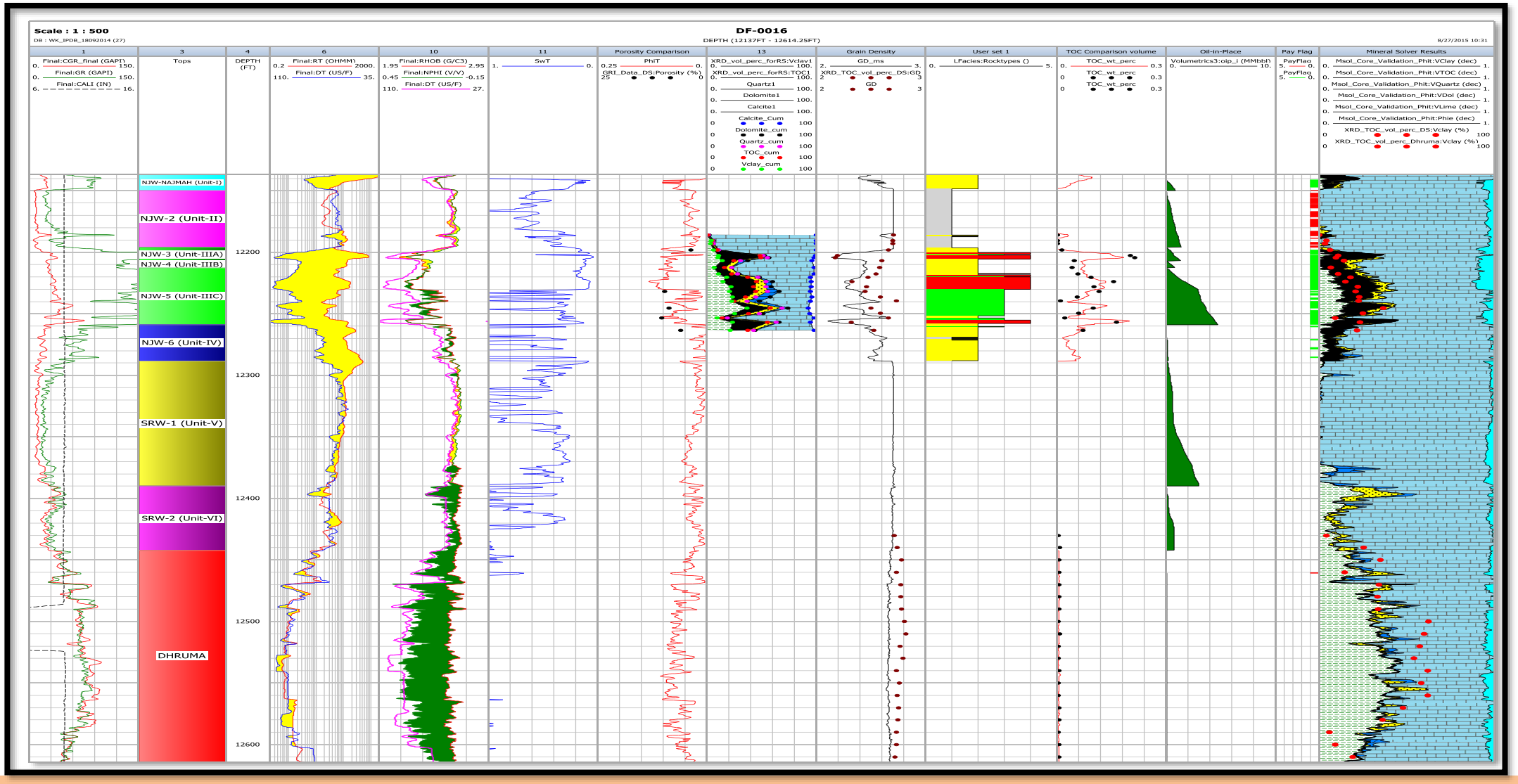
- Porosity (pore system) distribution and relationships with TOC established – good unconventional shale oil potential is recognised in Najmah
- First order reservoir parameter trends mapped and sweet-spots identified
- The results show Dharif and Abduliyah are more prospective regions/ fields compared to Minagish and Umm Gadair
- Oil Storage Capacity based on the assumptions of PVT properties for each field

# West Kuwait – Najmah Only :TOC - Kerogen Quality



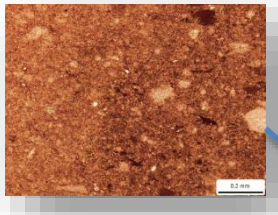



# Najmah v/s Dhruma Intervals – DF 16 (key well)

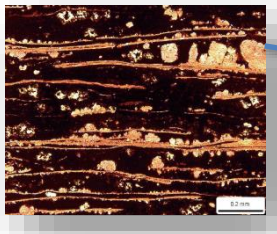


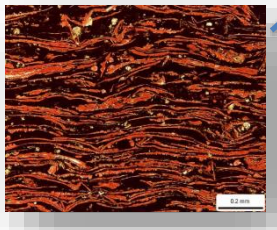
# Summarized XRD & Key Facies

Peloidal limestone – v.low TOC



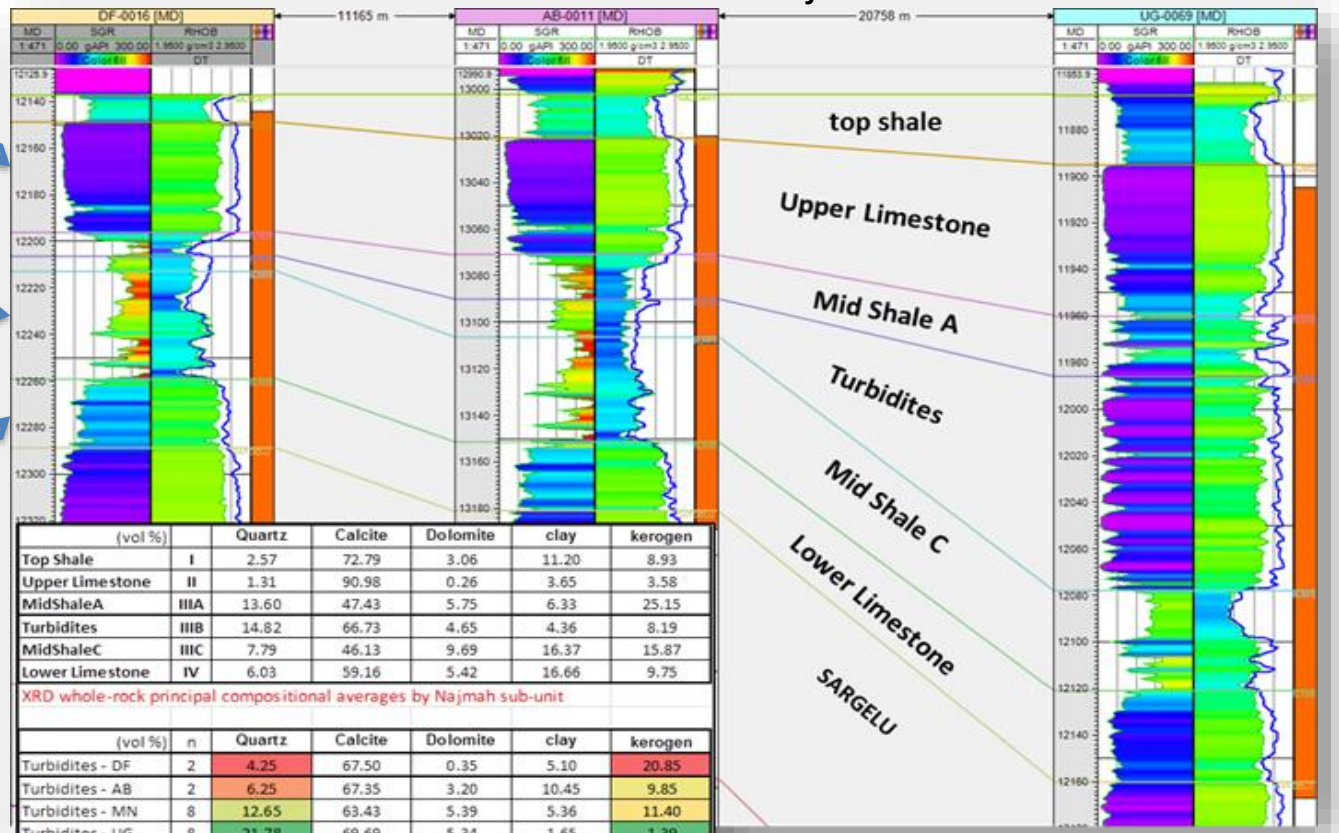
Bituminous, argillaceous skeletal limestone





argillaceous skeletal limestone

Target facies for unconventional consideration are the bituminous argillaceous limestones of Najmah III



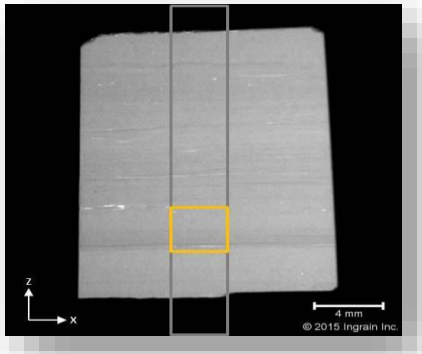

| (vol %) | | Quartz | Calcite | Dolomite | clay | kerogen |
|---|---|---|---|---|---|---|
| Top Shale | I | 2.57 | 72.79 | 3.06 | 11.20 | 8.93 |
| Upper Limestone | II | 1.31 | 90.98 | 0.26 | 3.65 | 3.58 |
| MidShaleA | IIIA | 13.60 | 47.43 | 5.75 | 6.33 | 25.15 |
| Turbidites | IIIB | 14.82 | 66.73 | 4.65 | 4.36 | 8.19 |
| MidShaleC | IIIC | 7.79 | 46.13 | 9.69 | 16.37 | 15.87 |
| Lower Limestone | IV | 6.03 | 59.16 | 5.42 | 16.66 | 9.75 |

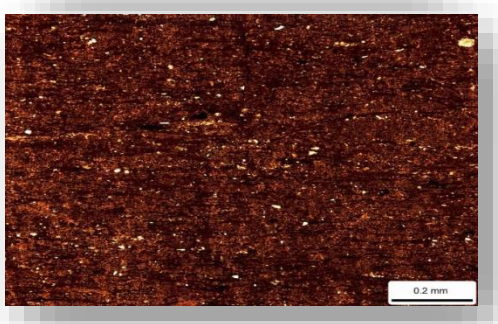
XRD whole-rock principal compositional averages by Najmah sub-unit

| (vol %) | n | Quartz | Calcite | Dolomite | clay | kerogen |
|---|---|---|---|---|---|---|
| Turbidites - DF | 2 | 4.25 | 67.50 | 0.35 | 5.10 | 20.85 |
| Turbidites - AB | 2 | 6.25 | 67.35 | 3.20 | 10.45 | 9.85 |
| Turbidites - MN | 8 | 12.65 | 63.43 | 5.39 | 5.36 | 11.40 |
| Turbidites - UG | 8 | 21.78 | 69.69 | 5.34 | 1.65 | 1.39 |

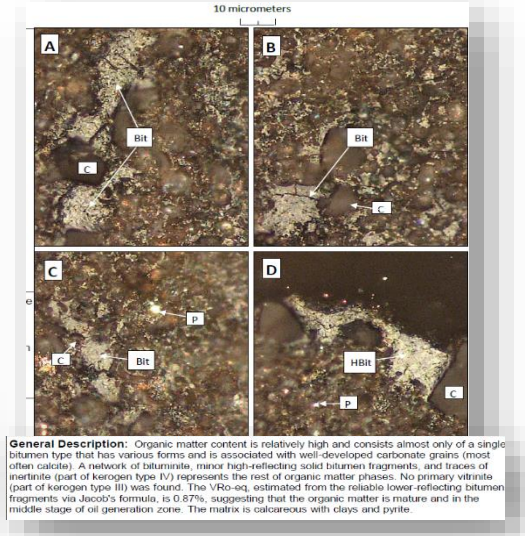
XRD whole-rock principal compositional averages - Turbidite sub-unit by field

# AB10 (13100ft) Micro-facies

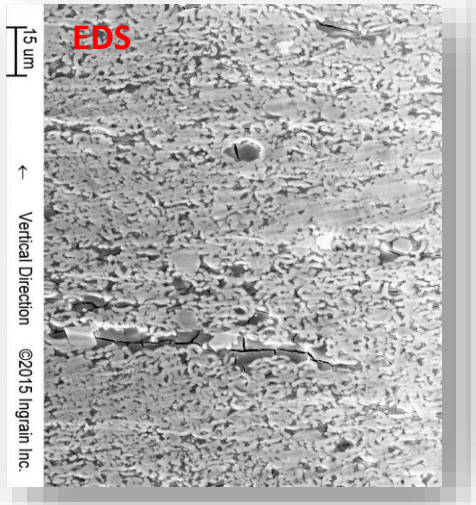


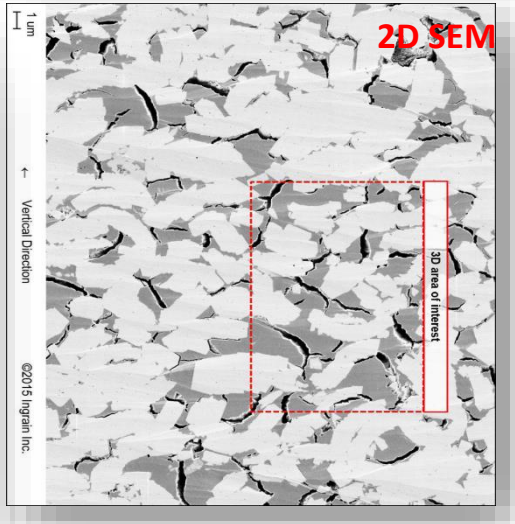




"No visible open macropores are observed, however some micropores may exist within the matrix and organic matter."




Vro slides show <10um scale OM textured fragments (many of which are original depositional material) with a background of pin point OM.



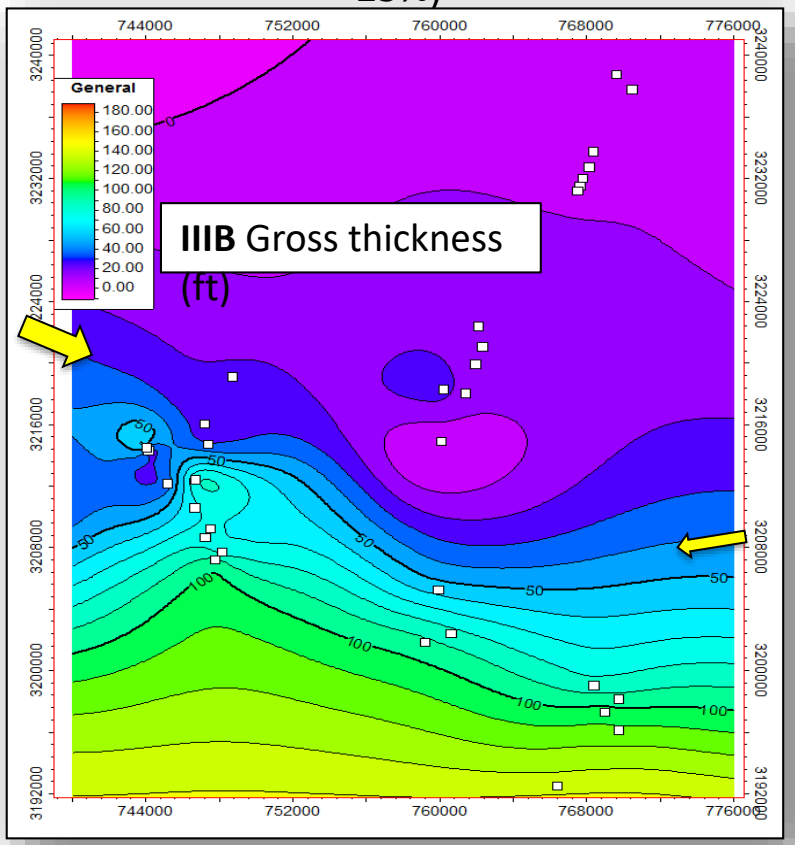



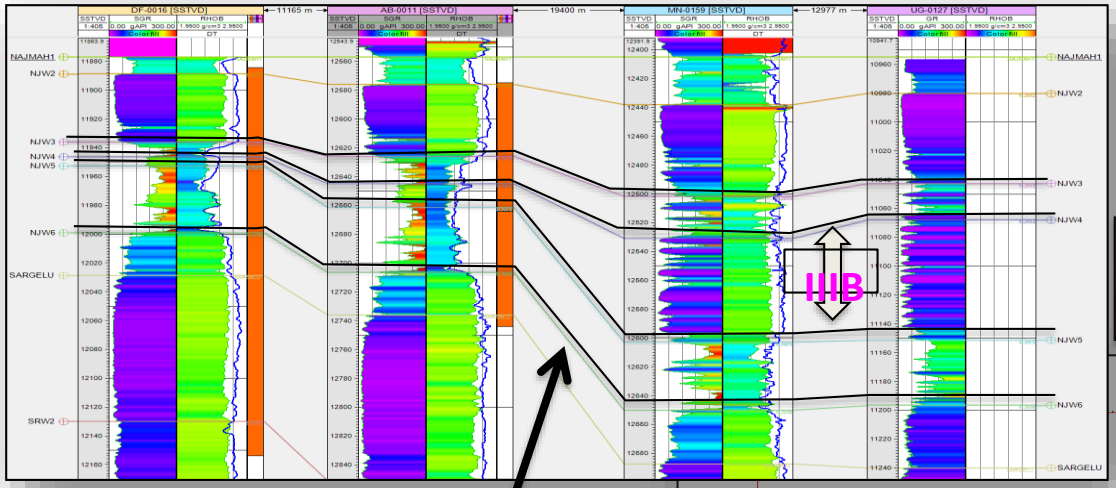

SEM show further detail – EDS samples show dominance of <5um scale OM with occasional >10um stratiform patches intimately bedded with peloidal and micro-vermicular calcite. 2D SEM scans show dominance of ?connected <5um amorphous bitumen with characteristic shrinkage pores

.. detailed integration of the various core datasets supports a consistent theme for TOC (bitumen) and associated porosity developed within the Najmah – this matches the characterisation of oil-prone source rocks at late oil maturity in other unconventional plays…..

# IIIB TOC & Thickness

The (IIIB) turbidites show a very large N-S thickness variation across the study area – with a related variation in TOC (from 1-25%)

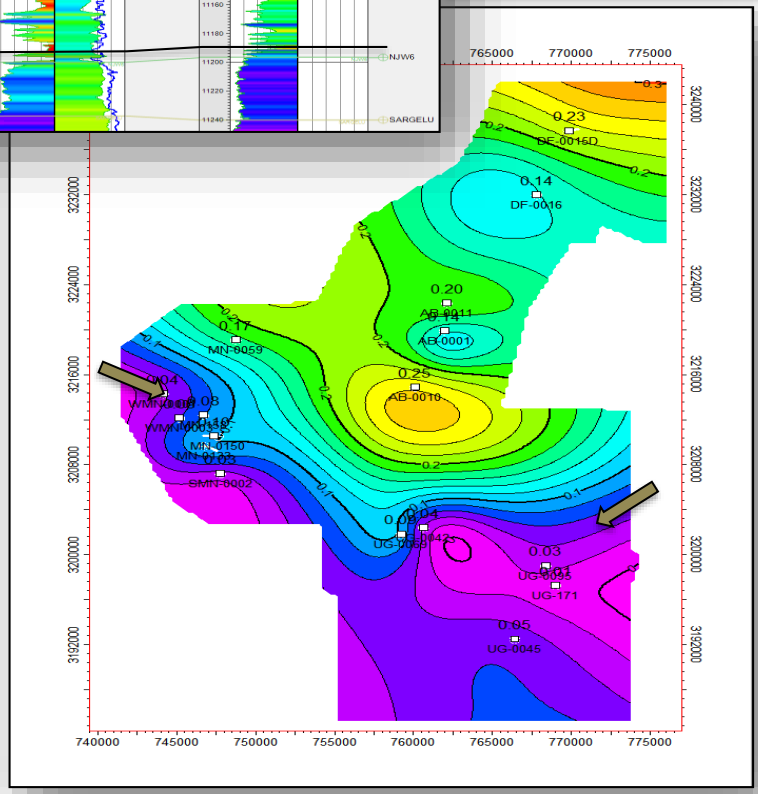



**IIIB** –net ave TOC v/v

The point at which the (IIIB) turbidites interval thickens up beyond 30ft matches that at which the average TOC falls from ~10%v/v to ~6%v/v - (this trend runs E-W across N Minagish Field)

this is taken as a cut-off at which point the 'target' changes from being a combined IIIA-IIIB-IIIC (as in AB-DF) to just a IIIC (as in UG)

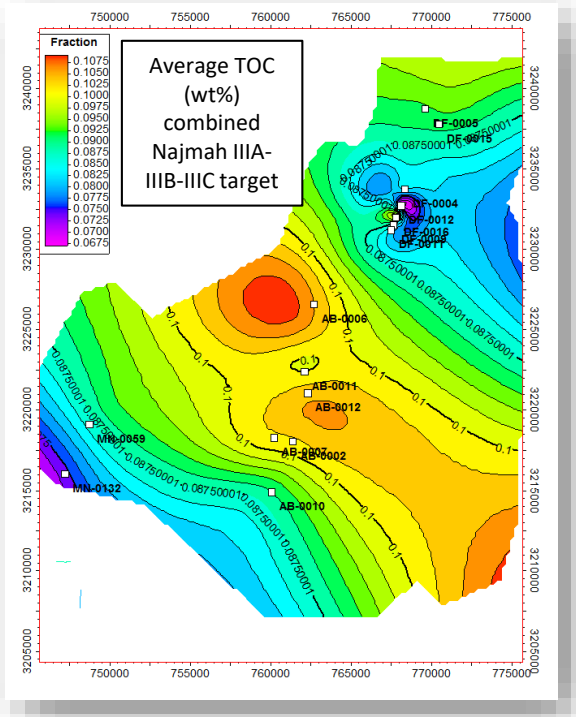


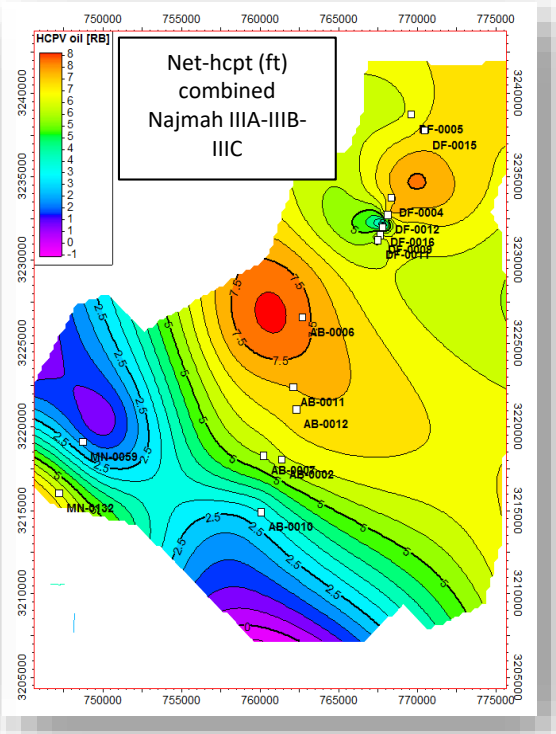
# Target Definition

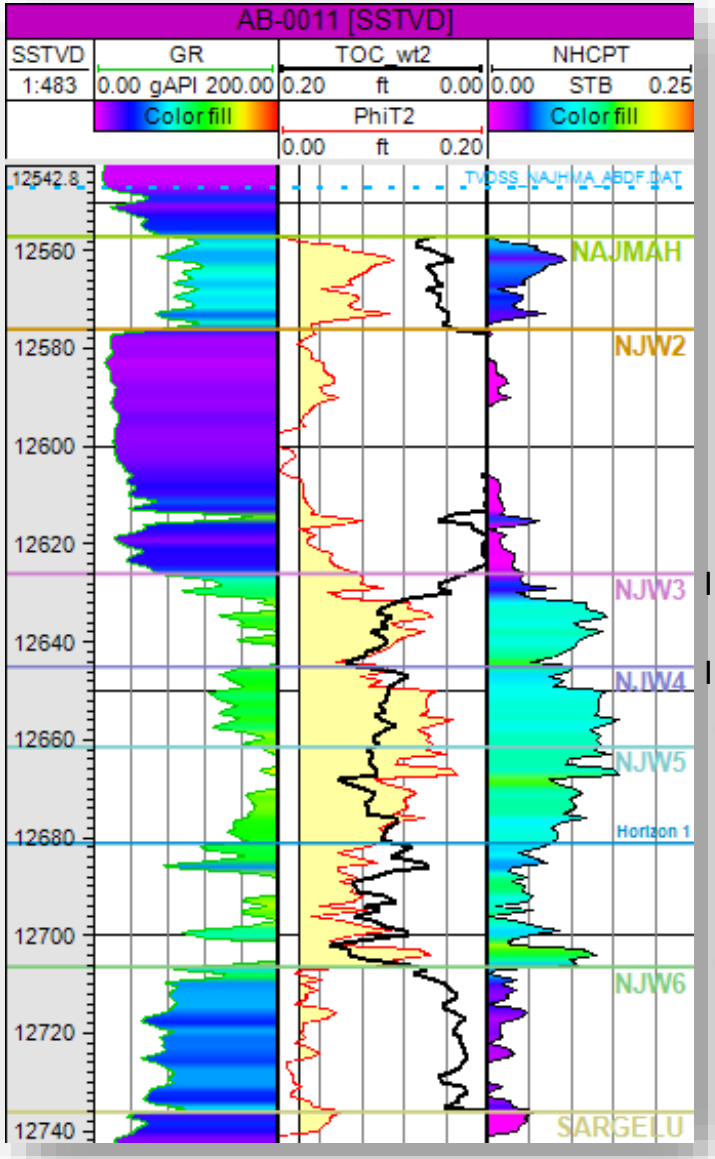
On the basis of NHCPT (net hydrocarbon pore-thickness) the hydrocarbon resource is concentrated in the Najmah Shale – with the thickest mapped resource in Abduliyah..

Within such a  target area the unconventional potential can be further divided on the basis of a more variable (TOC) lower half and a richer/more uniform upper half

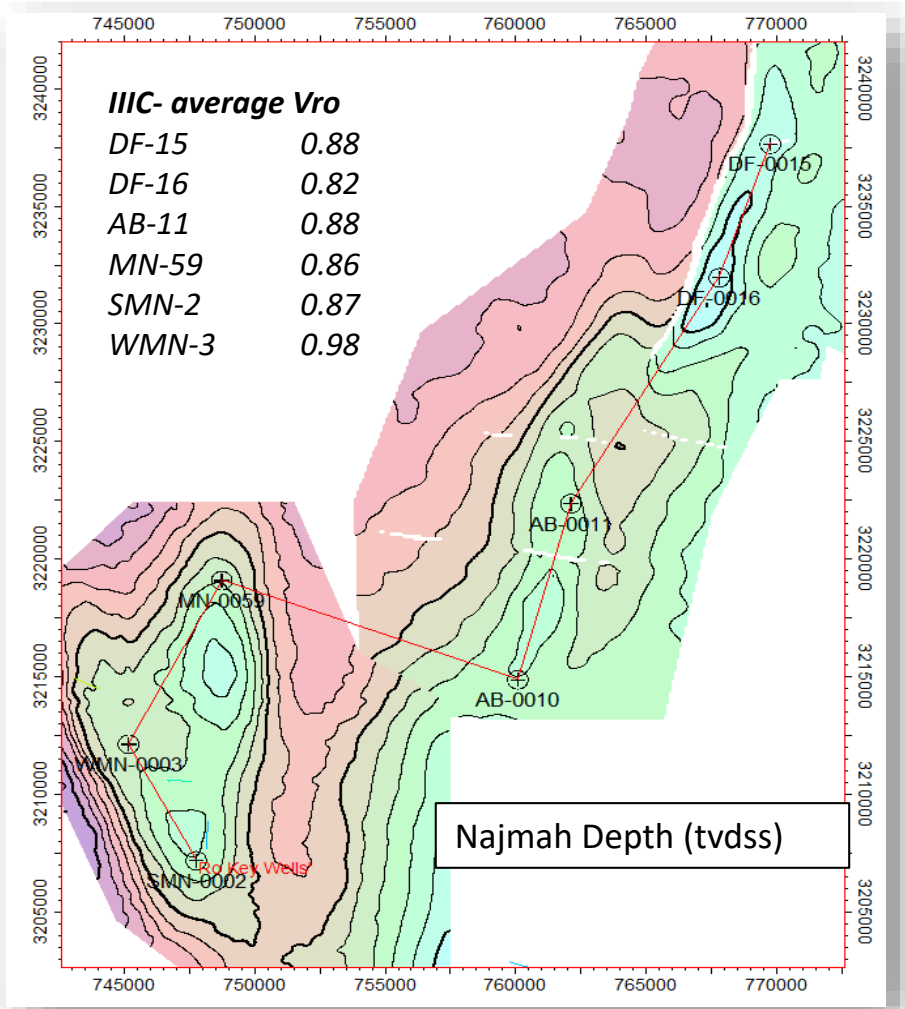
This further defines the most prospective sweet-spot for exploitation……



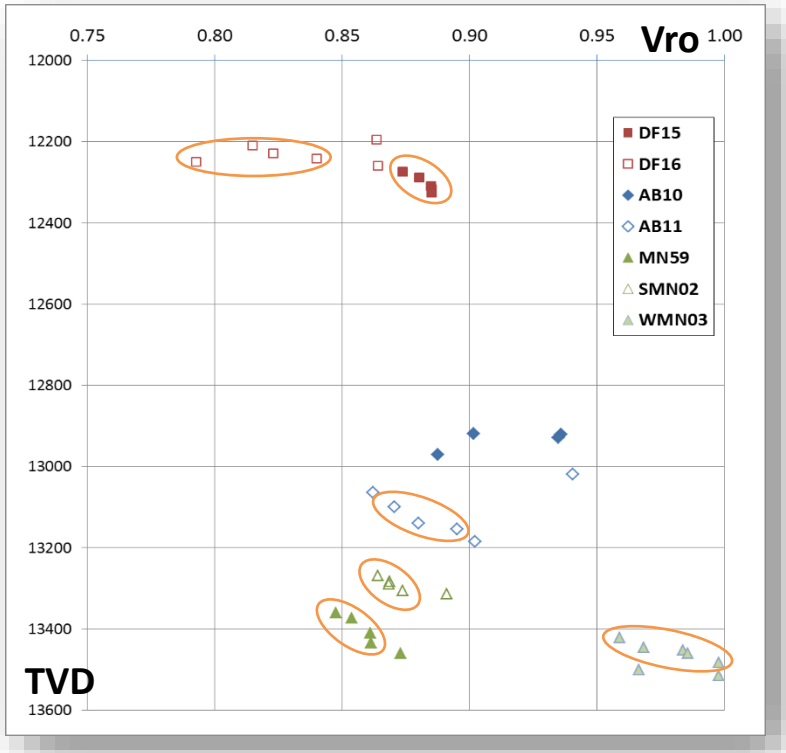



# Refining Potential at Field Scale

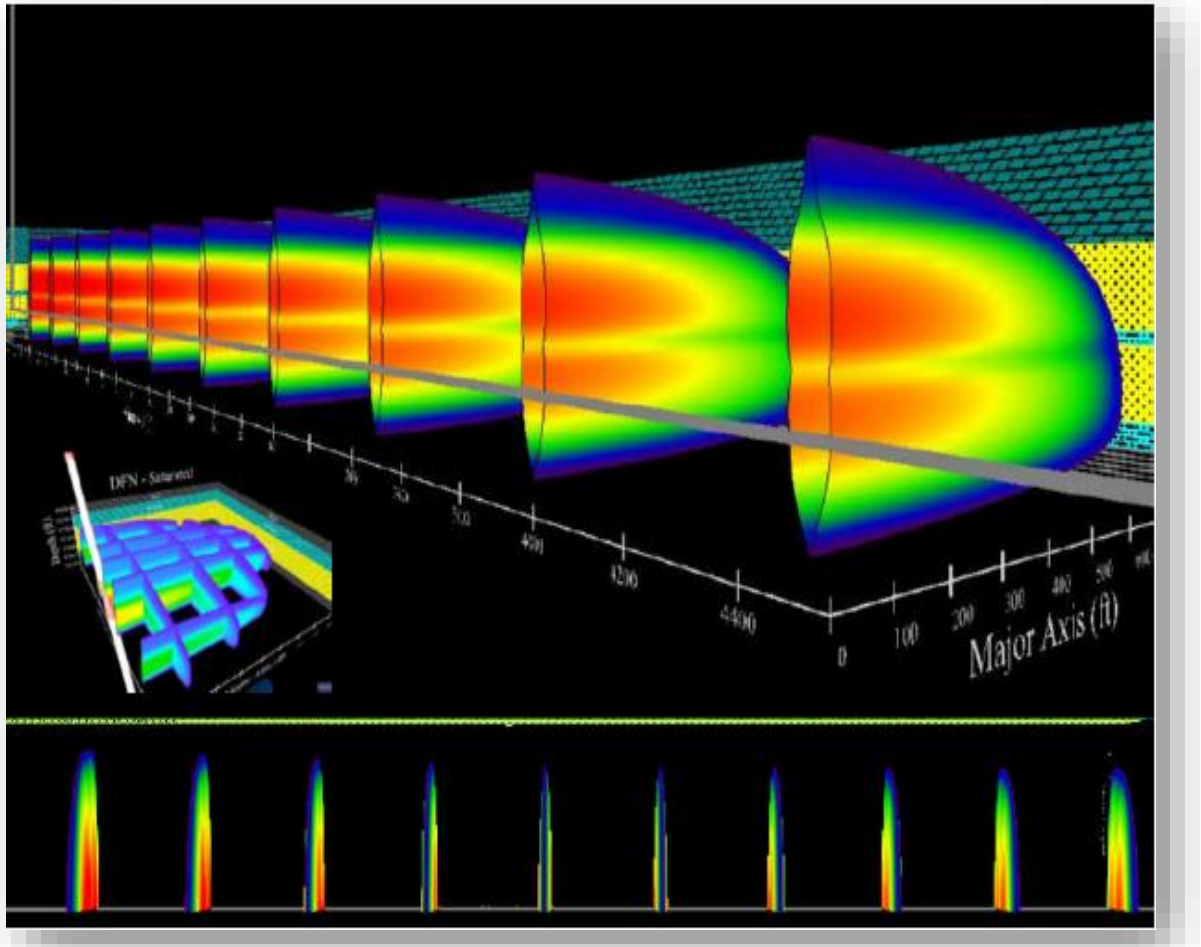



Source rock maturity data (Vro) QC'd from separate data sets shows significant variation within the same field areas (A simple Vro-depth relationship can thus not be used to map away from wells). This suggest a significant control on maturity from local structural elements (faults, fault blocks) and requires further investigation aligned to Geomechanical study.



# Geomechanics Applications : Unconventional Reservoirs

- Low porosity and low permeability rocks
- Stimulation is required for economic production from the reservoir.
- Geomechanical Parameters play vital role in effective implementation of stimulation techniques:
  - Elastic properties of reservoir rock
  - In-situ stress state in the reservoir rock
  - Identification of Stress barriers
- Critically Stressed Natural fractures identification and analysis for production enhancement.



# Geomechanics Work Completion

= Ongoing

= Completed

| Rock Mechanical Testing | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|
| Full-Core CT Scan | | | | | | | | | | |
| Plugging and Plug CT Scan, Preparation of Test Samples | | | | | | | | | | |
| Tri-Axial Testing | | | | | | | | | | |
| Brazilian and Scratch Testing | | | | | | | | | | |

| Geomechanical Modeling | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|
| Umm Gudair Field (8 Wells) | | | | | | | | | | |
| Dharif Field (7 Wells) | | | | | | | | | | |
| Minagish Field (12 Wells) | | | | | | | | | | |
| Abduliyah Field (7 Wells) | | | | | | | | | | |

| Critically Stressed Fracture Analysis | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|
| CSF Analysis | | | | | | | | | | |

| SHmax Orientation from Image Logs | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|
| All Available Data | | | | | | | | | | |

| Presentation and Report | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|

# Geomechanical Summary: West Kuwait (Najmah Formation)

- Upon basic screening of well based geomechanical parameters of west Kuwait fields, following conclusions can be drawn.
- These conclusions are preliminary and they need to be further verified with field data, 3D geomechanical model additional rock mechanical testing for sweet spot evaluation.

| Geomechanical Property | Preliminary play ranking | Comments |
|---|---|---|
| **Relative Brittleness Index** | **Favorable** | Based on rock mechanical tests, elastic properties and mineralogical constituents, target intervals in Najmah formation seems favorable and comparable with known unconventional plays. |
| **High Pore Pressure** | **Favorable** | Najmah formation in west kuwait fields is overpressured (~16.5-18.0 ppg). Higher pore pressure is very favourable for fluid flow in unconventional reservoirs. (It is assumed that no depletion has taken place from Najmah-IIIA&IIIC layers). |
| **Stress Contrast for Frac Containment** | **Favorable based on field / interval.** | In Abdulliah & Dharif where there is no significant depletion in Najma Limestone reservoir units, Najmah-2 (upper) and Najmah-VI/Sargelu-I (Lower) provide very good stress barriers for fracture containment. |
| **Critically Stressed Natural Fractures (if present)** | **Favorable** | If any natural fractures exist within target Najmah-III layers, they are likely to be critically stressed for enhanced permeability and stimulated reservoir volume with generation of complex fracture network. |