

# **PS Understanding Reservoir Properties of the Organic-Rich Qusaiba Shale, a Potential Shale Gas Reservoir, Northwest Saudi Arabia: An Outcrop Approach\***

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## **Abstract**

The reservoir properties of the Lower Silurian Qusaiba Shale (QS), a potential unconventional shale gas reservoir in Saudi Arabia, are not completely understood. One way to better understand the vertical and lateral variations which significantly control the reservoir properties of QS is an outcrop study. Sedimentological and geochemical analyses were carried out on ~ 31 m thick outcrop section of QS at the northwestern region of Saudi Arabia to determine its lithofacies, paleo-redox conditions and to re-construct the depositional environment of QS. Based on the organic matter richness of QS, there are two broad units; the basal 20 m thick, comprised of organic-rich dark grey to black shale, and the overlying 10-12 m thick, consists of organic-lean variegated shale and siltstone to fine-grained sandstone beds. Lithologically, QS is mainly a siliciclastic sediment with traces of carbonates (average 0.5 %). The main mineral components are clay minerals (~ 55%) and quartz (~ 24%) with common proportions of K-feldspar (~7%) and plagioclase (~4%).

LECO TOC analysis showed high organic content in the basal unit (range: 1.09 - 6.1 wt. %, ~ 2.61 wt. %). The TOC content decreases drastically in the upper silty/sandy unit (range: 0.04-0.5 wt. %, ~0.2 wt. %). QS is predominantly characterized by type III (gas prone) kerogen with a considerable amount of type IV, which was likely sourced from reworked and oxidized materials with low H content and high O content. Tmax values with an average of 425° C, vary between 414° C and 452° C. The studied section of QS presents a general trend of upward shifting from anoxic-euxinic, distal and deep marine during the deposition of the basal unit to oxic, high energy, proximal and shallow marine settings for the upper silty/sandy unit. The kerogen type and maturity level of the organic matter suggest that the QS can be a self-sourced shale gas reservoir. The depositional settings, sedimentary influx and the vertical lithological variation, were the main controls on the organic matter distribution and ultimately the quality of source rock in the Qusaiba Shale. Qualitative evaluation of porosity showed that there are three different types of porosity: inorganic porosity, organic porosity and natural fracture porosity. Quartz, feldspar and pyrite contents significantly contribute to the brittleness character of the basal unit which further control the reservoir quality of the QS.



# Understanding Reservoir Properties of the Organic-Rich Qusaiba Shale, a Potential Shale Gas Reservoir, NW Saudi Arabia: An Outcrop Approach

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## ABSTRACT

Qusaiba Shale is one of the widely distributed lower Silurian source rocks in the Middle East. It has a potential for unconventional shale gas resources in Saudi Arabia. This work presents full sedimentological, geochemical characterization to evaluate the reservoir potential of the organic-rich Qusaiba Shale section, which crops out through 31m thick at Tabuk Basin in the northwest of Saudi Arabia.

Six different lithofacies have been identified; (1) Laminated organic-rich shale (2) Graptolitic concretion lithofacies (3) Massive organic-rich shale lithofacies (4) Variegated Shale facies (5) Siltstone-Shale interbedded lithofacies and (6) Cross-stratified Siltstone/Sandstone lithofacies. Qusaiba Shale is mainly dominated by clay and silica, with minor occurrence of carbonate. The vertical profiles of Mo, Cu, Ni, U, and V are very consistent with the TOC enrichment and clearly differentiate between the organic-rich shale and the variegated shale. TOC in the dark-grey laminated and massive shale ranges between 0.5 and 6.1wt % (average 2.52 wt. %) then becomes lean (0.04-0.35 wt. %) in the overlying variegated shale and siltstone interval. The obtained results indicate that the depositional settings, sediment influx and the vertical lithological variation of the Qusaiba Shale in Tabuk Basin control the quality and distribution of TOC.

The kerogen is mainly of type III (gas prone) with considerable content of Type IV (inert gas). Qualitative evaluation of porosity showed that the pore system is consists of three types of porosity including inorganic porosity, organic porosity and natural fracture porosity. The brittle minerals (Quartz, Feldspar, and Pyrite) form an average of 42 % which exhibit a uniform distribution of brittleness in the organic-bearing interval. Natural fracture density reaches up to 7.7 fracture/m<sup>2</sup> in the basal organic-rich lithofacies, which indicate their high potential for effective hydraulic fracture.

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## MOTIVATION & OBJECTIVE

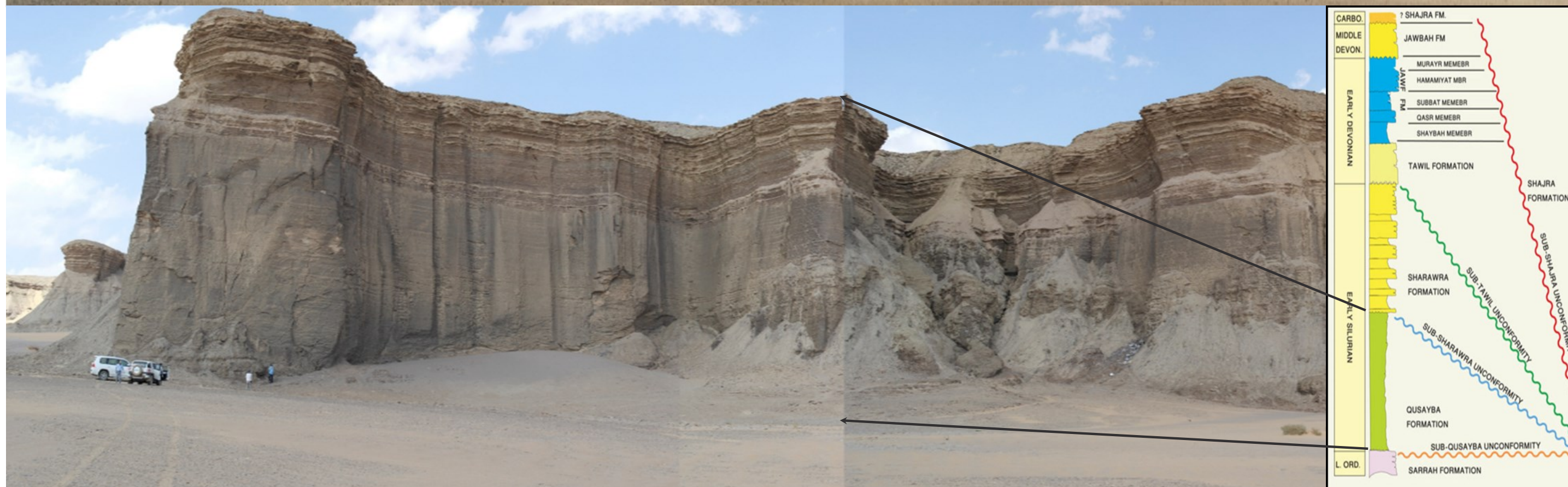
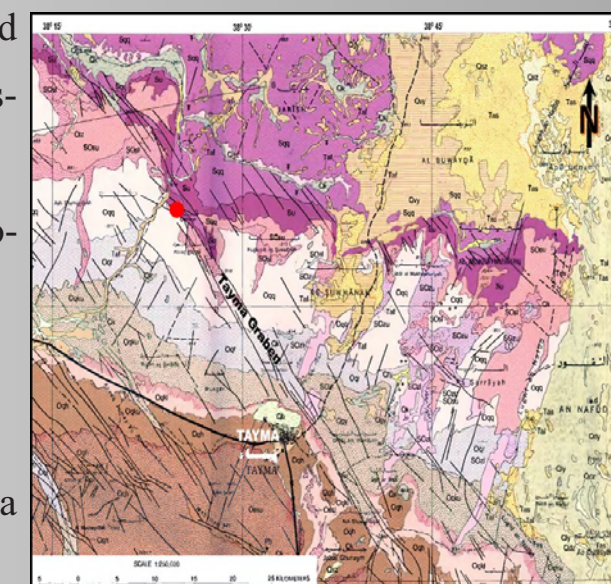
- ♦ Though the QS is considered as a potential unconventional shale gas reservoir, the understanding of its possible reservoir properties remains very limited.
- ♦ An outcrop study was undertaken to facilitate a better understanding of the vertical and lateral lithofacies variations and the effects of such variations on reservoir properties of potential oil and gas shale reservoirs.

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## GEOLOGIC SETTING

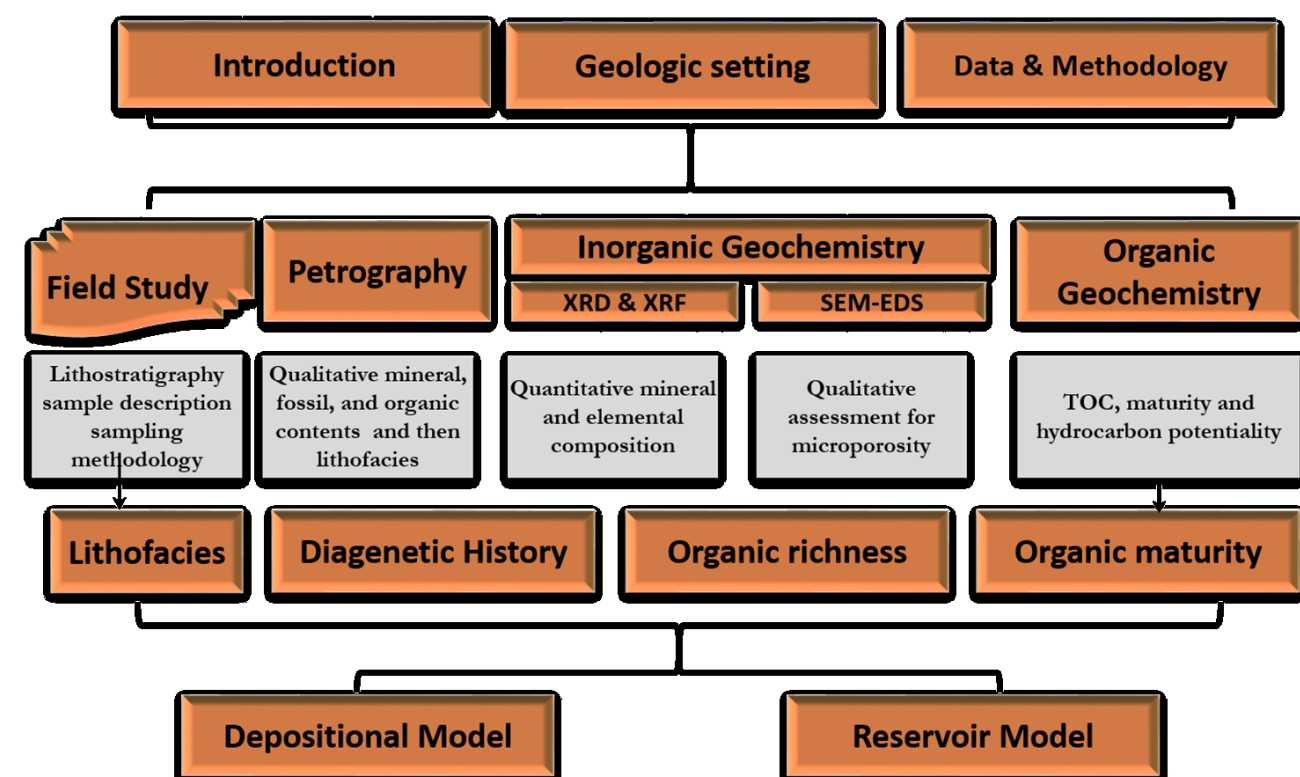


- ♦ Tabuk basin, located in NW Saudi Arabia and extends into Jordan and Iraq in the north, is considered as part of a broad Gondwana stable Paleozoic shelf, which was covered by the Tethys Sea transgression during the Silurian.
- ♦ Qusaiba shale interpreted to represent the delta-toe clays, dominates the Silurian-Carboniferous depositional setting of the Arabian Plate.
- ♦ Megafaunas including graptolites, molluscs, brachiopods and trilobites are diverse and abundant.
- ♦ Across the eastern Arabian, the basal part of the Qusaiba “hot shale” contains up to 14 wt% of TOC.
- ♦ The studied outcrop is ~ 31 m thick and extends laterally for ~ 3 km to form the NW side of Tayma rift and is located to the northwest of Tayma City.





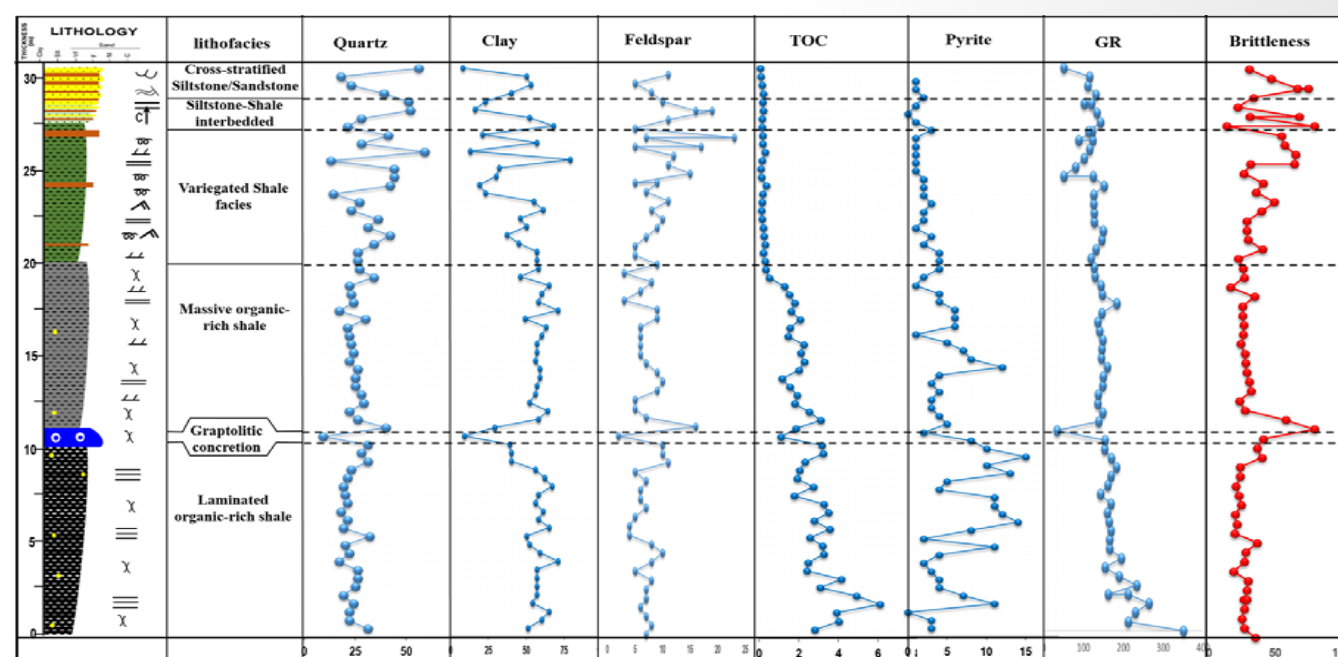
A comprehensive, multiscale, integrative methodology involving detailed field and laboratory investigations was used to fully characterize the QS and evaluate its reservoir potentials as a silica/organic-rich unconventional shale-gas reservoir (Fig. 2). For instance, X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and petrographic analysis (thin section) were used to determine mineralogy and microfabric of the identified lithofacies in QS.



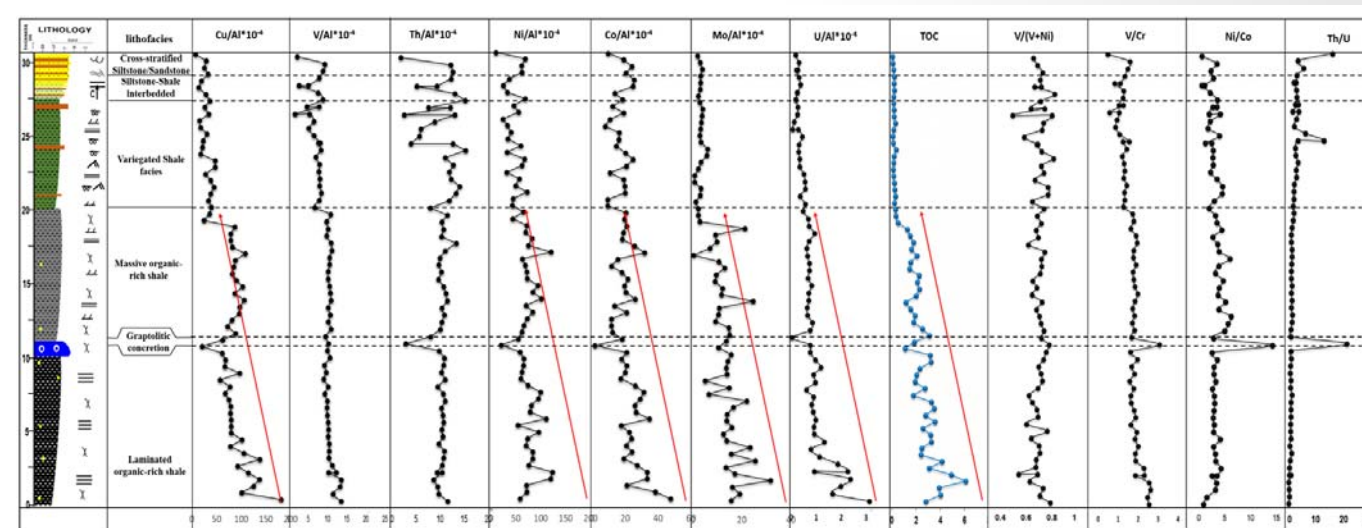
A ~31 m thick sequence described at the outcrop is subdivided into two broad units based on the visual organic richness. The basal 20-m thick section of the outcrop consists of a dark grey to black, hard, fissile and thinly laminated shale. This lower section is subdivided into two units separated by a graptolite-bearing concretion interval. The overlying top 10-12 m thick upper section of the outcrop is organic-lean, laminated variegated shale intercalated siltstone to fine grained sandstone beds. Six lithofacies association have been identified.

AGE	FORMATION	Elevation (m)	Lithology	Lithofacies	Lithofacies Remarks	Lithofacies Bulk Mineralogy	Total Organic Carbon Wt. %
EARLY SILURIAN	QUSAIBA FORMATION	30		Cross-stratified Siltstone/Sandstone (29.05-31m)	Intercalation of silt and sandstone with trough cross stratification, fining upwards sediments at the base and hangs to hummocky cross stratification at the top.	Factor 1: 40% Silica, 40% Organic, 20% Clay	0.5-1.0
		25		Siltstone-Shale Interbedded (28-29.05m)	Grey, laminated siltstone/sandstone and shale intercalation characterized by micaceous siltstone to fine sandstone facies.	Factor 2: 30% Silica, 30% Organic, 40% Clay	0.5-1.0
		20		Variegated Shale facies (20.5-28m)	Colorful olive green, purple, brownish shale that are intercalated with thin siltstone to very fine sandstone beds. There are horizontal, convolute and cross ripple laminations. The shale laminae are generally fissile but become highly indurated at some intervals.	Factor 3: 20% Silica, 20% Organic, 60% Clay	0.5-1.0
		15		Massive organic-rich shale (11.5-20.5m)	Dark grey to black shale with some nodular intraformational mud clasts. It is highly dissected by natural fracture network mainly filled with gypsum. Cross lamination and soft sediment deformation of laminae are observed immediately above the concretion-bearing interval.	Factor 4: 10% Silica, 10% Organic, 80% Clay	0.5-1.0
		10		Graptolitic concretion (10.5-11.5m)	Discontinuous, fractured, calcareous concretion lenses. It represents a good marker bed exhibit soft sediment deformation structures.	Factor 5: 10% Silica, 10% Organic, 80% Clay	0.5-1.0
		5		Laminated organic-rich shale (0-10.5m)	Green, dark grey, black, laminated, organic-rich, silty and clayey shale. The shale which is generally fissile at the base becomes highly indurated towards the top. This part is intensively fractured with gypsum filling mineralization. The gypsum occurrences decrease towards the top of the interval.	Factor 6: 10% Silica, 10% Organic, 80% Clay	0.5-1.0

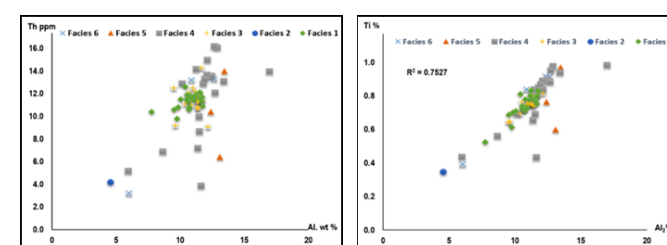
Qusaiba Shale, like other organic-rich shales, is mainly dominated by two end-member oxides; SiO<sub>2</sub> as a function of detrital quartz origin (no petrographic evidences show silica cementation) and Al<sub>2</sub>O<sub>3</sub> which represents the clay fractions. With the exception of the graptolitic concretion lithofacies (> 70 % carbonate), minor occurrence of carbonate characterized the outcrop section. Pyrite has a distinctive existence particularly in the lower organic-rich lithofacies with an average of 5-7 %.



- ◆ The trace elements show good correlation with the TOC in the outcrop.
- ◆ The laminated and massive organic-rich shale lithofacies exhibit higher concentrations of Co, Ni, Cu, Mo, and U than in the overlying variegated shale.
- ◆ The concentrations of V, Cr, Zn, Rb, Zr, Nb, Ga, Y and Sr show uniform distribution throughout the entire section.

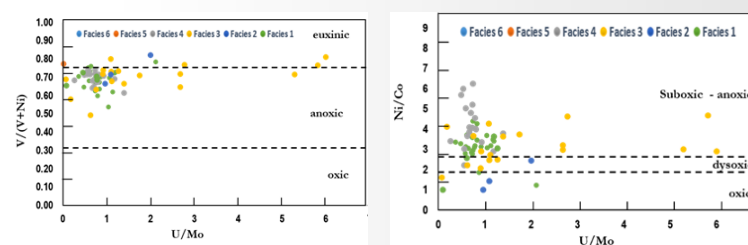


The abundances, enrichments and depletion ratios of trace elements are interpreted based on their geochemical behavior through three main subcategories: detrital, paleoredox and paleoproductivity proxies (Tribouvillard et al., 2006).



#### Detrital proxies

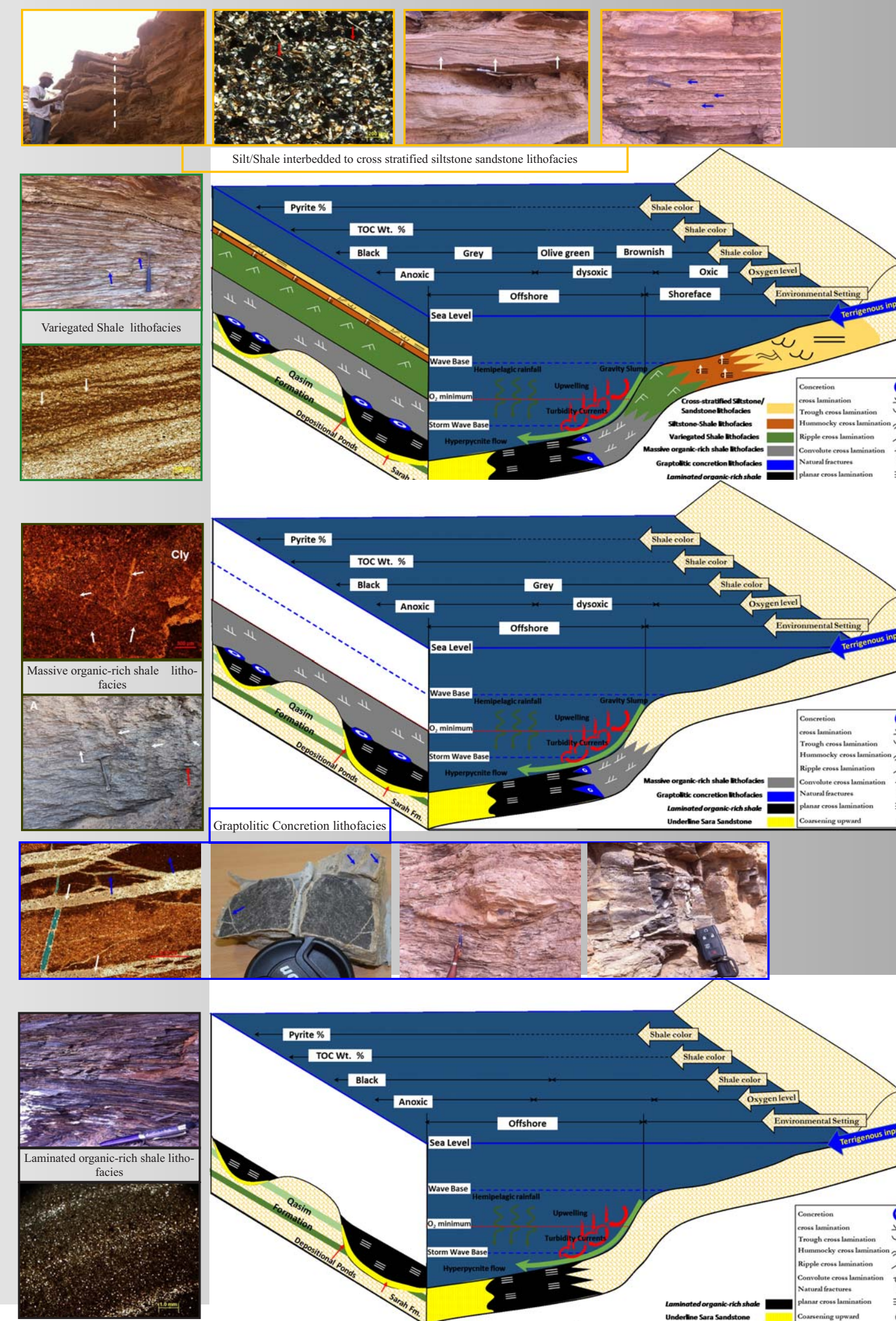
The positive correlations of Ti and Th with Al indicate the detrital source of these elements without authigenic enrichment.



#### Paleoredox proxies

The QS samples show intermediate values of the V/(V+Ni) ratio reflecting the prevalence of less strongly stratified anoxic water column and euxinic conditions during the deposition.

- ⇒ The paleo-topography, which was created during the Late Ordovician deglaciation event largely, controlled the deposition of QS and in particular, ponding of the lower organic-rich part (Sharland et al., 2001).
- ⇒ The laminated organic-rich shale lithofacies is characterized by well-preserved lamination, fine grain size, high clay content, and clear absence of bioturbation. These evidences indicate a deposition by suspension from hemipelagic sediments in a relatively low energy, quiet water (Abouelresh and Slatt, 2011 and 2012).
- ⇒ The sharp decrease of TOC from the underlying massive organic-rich facies to the overlying variegated shale facies is presumably due to a rapid uplift and/or landward shift of the depo-center during the deposition of this lithofacies.
- ⇒ The siltstone - fine sandstone facies in the topmost part of the studied section pointed to the dominance of high energy shallow oxygenated (probably middle to inner shelf) depositional settings.

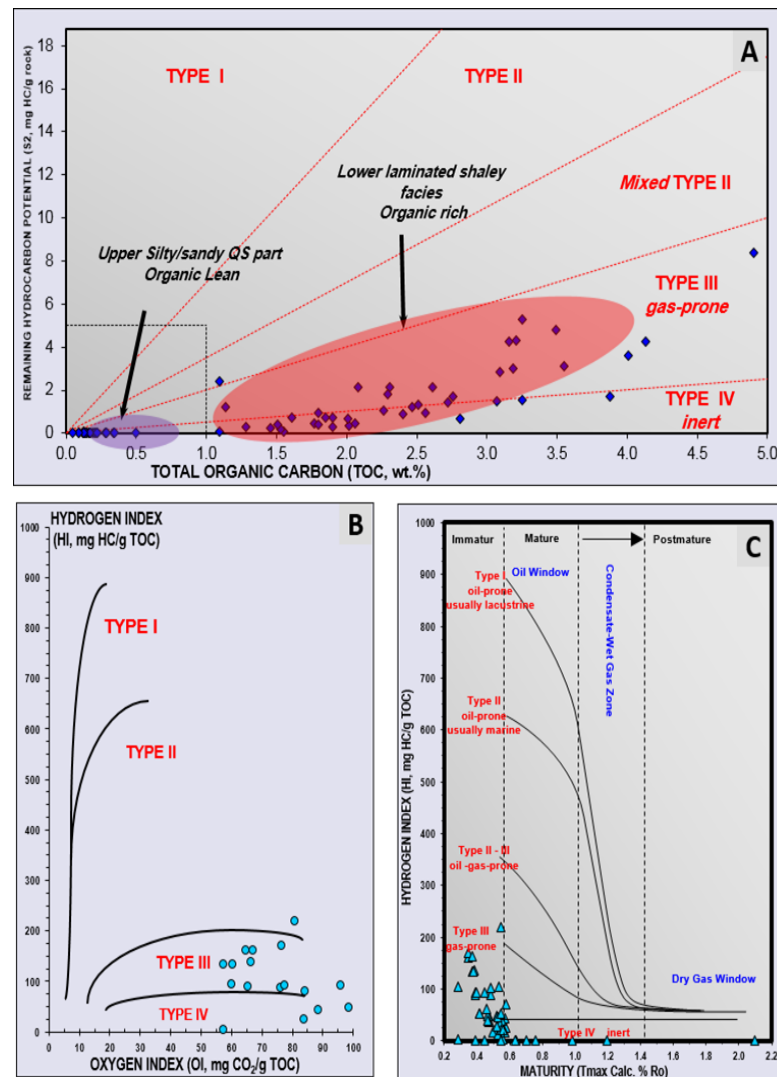




In the geologic contexts, the reservoir quality means the combination of properties that provide high storage capacity and good producibility. Among these properties, porosity, brittleness, and thermal maturation of organic matter are the top qualifications of any given organic-rich shale to be a potential shale gas reservoir (Curtis, 2002; Hammes et al., 2011; Slatt 2011).

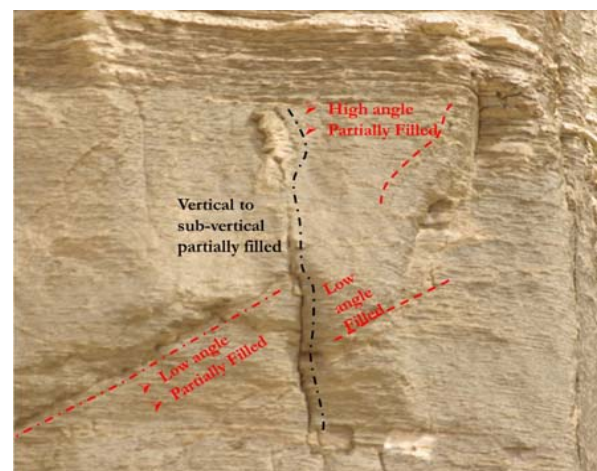
### Organic Geochemistry

The bivariate plots of TOC versus  $S_2$  shows that the kerogen in QS is mainly of type III (gas prone) with considerable proportion of Type IV (inert gas). Type IV is sourced from reworked and oxidized materials with low H content and high O content. In the studied section,  $T_{max}$  values show an average of 425°C, varying between 414 °C and 452 °C. The lower part of the studied QS section has the potential as a source rock and therefore, it is considered as part of the regionally distributed Qusaiba Hot Shale and, in particular, at central and eastern Saudi Arabia (Jones and Stump, 1999).

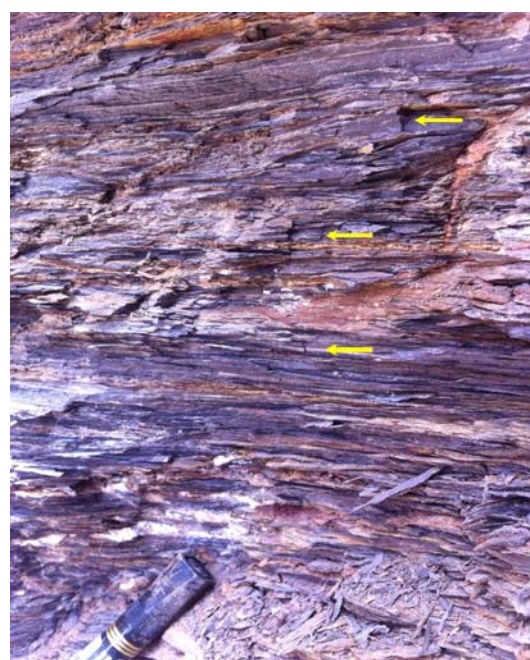


### Natural Fractures

- Are there natural fractures present?
- Are they of different types?
- Do they have different orientations?
- Do they have different angles with respect to the bedding planes?
- Are they connected?
- How abundant are they?
- What is their intensity?
- How long are they?



Vertical to Sub-vertical  
High angle ( $80^\circ$  -  $45^\circ$ ) - Low angle ( $10^\circ$  -  $44^\circ$ )  
Parallel to subparallel  
Filled- Partially filled - Open



These microfractures developed with this scale due to volume change in kerogen and hydrocarbon generated during thermal maturation

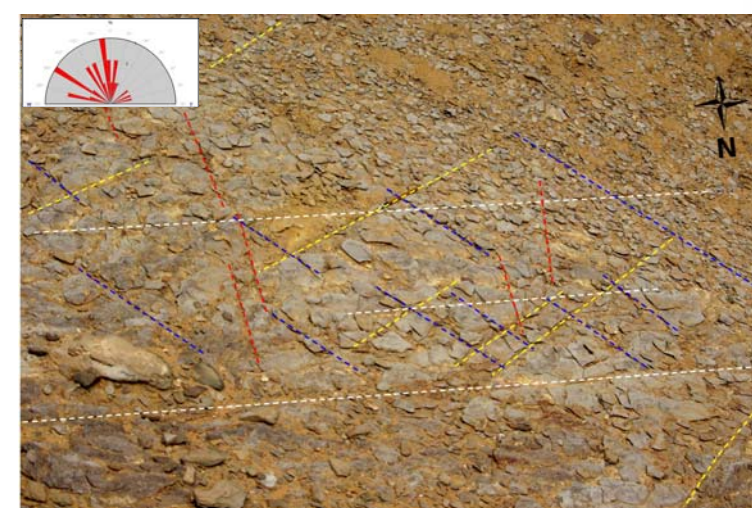
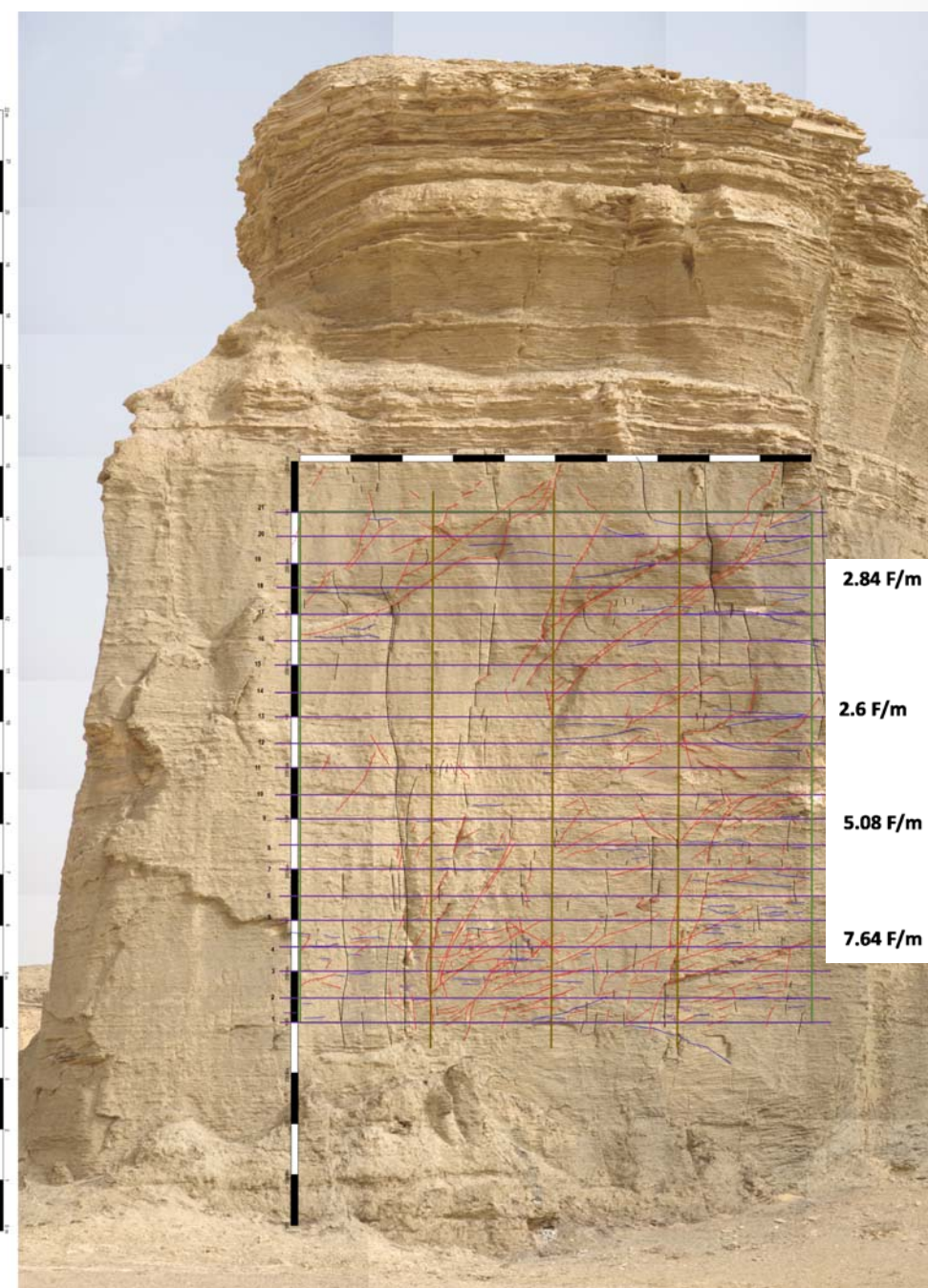


Gypsum-lined fracture without apparent displacement of low angle to bedding plane, QHS.

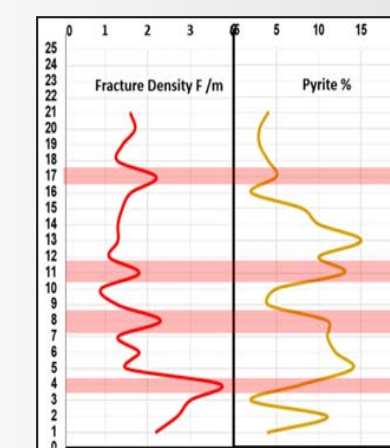
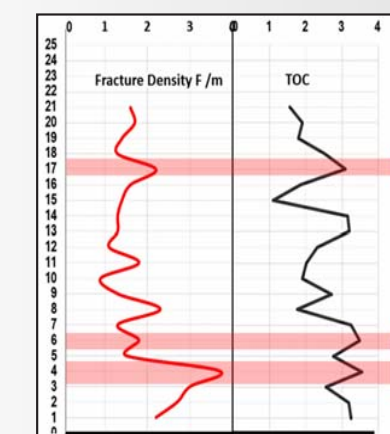
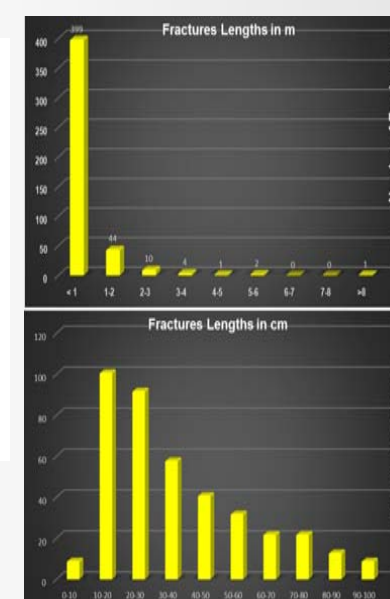
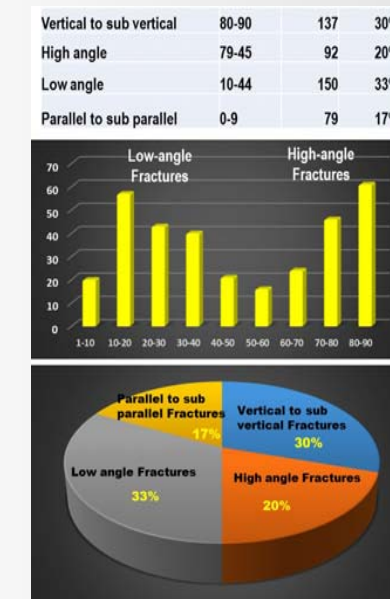
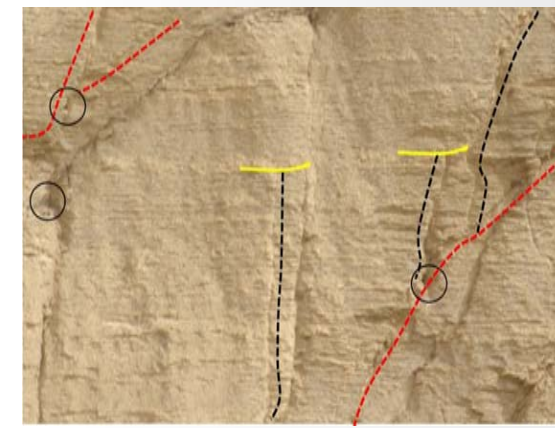
The fractures terminated against:

- I- Other youngest fractures
- II- Major tectonic –related fracture
- III- Lithofacies changes boundary.

*Termination can create local porosity*

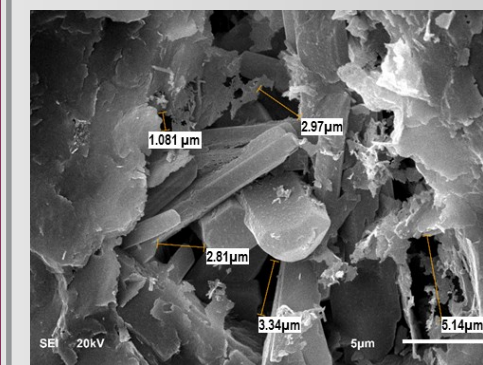


E-W major set (white) running parallel to the main plateau trend.  
NE-SW (yellow) abundant, shorter.  
NW-SE (blue) more abundant and shorter  
NNW-SSE (Red) less abundant medium length

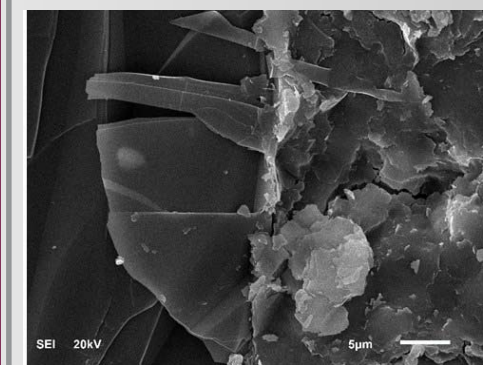
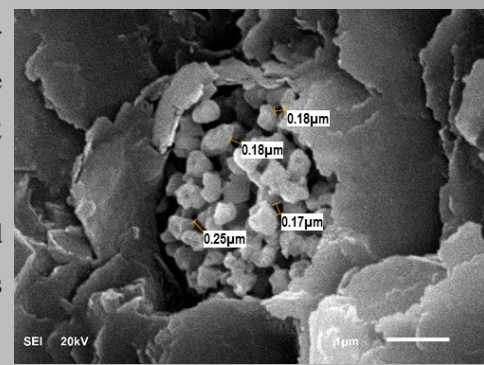


### Micro Porosity

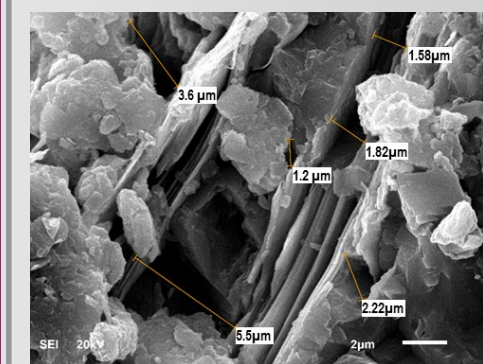
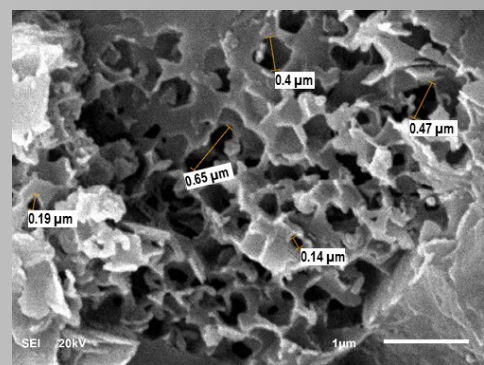
Qualitative evaluation of porosity has been carried out on the QS using thin section petrography and SEM imaging. Three types of porosity including inorganic porosity, organic porosity and natural fracture porosity have been identified.



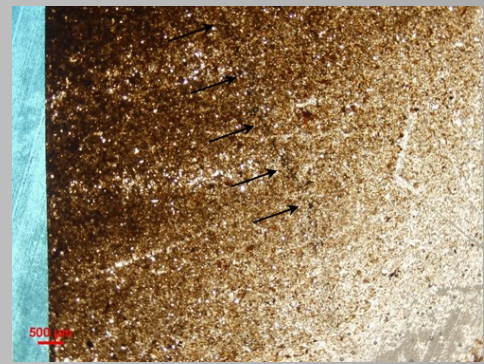
- Random orientation of platelet-like mineral grains (clay and mica) creates a large number of pore size ranges, between 2 and 20 μm.
- Pyrite framboids have diagenetic-related micro-porosity with an average size less than 1 μm.



Organic-related porosity does not have that high fraction of the total porosity due to the low maturity levels of these samples. However, in few cases, the organic particles with relative maturity show a significant micro-porosity with pore size ranging between 0.2 and 0.6 μm, and show a high level of pore connectivity which is expected to substantially contribute to the potential permeability.



- Right: microfracture filled with hydrocarbon (Black arrows) in the laminated organic-rich shale lithofacies.
- Left: long narrow space between clay (mica ?) particles which might work as permeability channels.



### SUMMARY & CONCLUSIONS

- Qusaiba Shale consists of six lithofacies: (1) Laminated organic-rich shale (2) Graptolitic concretion lithofacies (3) Massive organic-rich shale lithofacies (4) Variegated Shale facies (5) Siltstone-Shale interbedded lithofacies and (6) Cross-stratified Siltstone/Sandstone lithofacies.
- TOC characterized by an upward decrease from the basal black to dark grey laminated organic-rich shale to the topmost cross-stratified silty/sandy lithofacies.
- The kerogen in QS is mainly of type III (gas prone) with a considerable amount of Type IV (inert gas) which is sourced from reworked and oxidized materials with low H content and high O content.
- Qualitative evaluation of porosity in the QS showed that there are three types of porosity: inorganic porosity, organic porosity and natural fracture porosity.
- Natural fracture density reaches up to 7.7 fracture/m<sup>2</sup> in the basal organic-rich lithofacies, which indicate their high potential for effective hydraulic fracturing.

### ACKNOWLEDGMENT

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