Hanifa-Tuwaiq Mountain Zone: The Edge between Conventional and Unconventional Systems?*

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Abstract

Hanifa-Tuwaiq Mountain zone is a Jurassic section of dark, organic-rich carbonates and thick, slightly dolomitized shallow-marine limestone that serves as a source rock to the overlying Jurassic and Cretaceous conventional reservoirs. Hanifa Formation is slightly younger than Tuwaiq Mountain Formation; however; in Bahrain both formations coexist and act as one self-sourcing system. Conventionally, this system has relatively lower hydrocarbon storage capacity and deliverability, whereas unconventionally, the system appears to be prospective over a regionally broad area, lies within the oil maturity window, and has good organic richness. Although, in areas like Awali field, Hanifa-Tuwaiq Mountain zone acts as a moderate-quality conventional reservoir, the average reservoir properties, such as porosity and permeability, are considerably higher than typical unconventional units. Therefore, it is thought that Hanifa-Tuwaiq Mountain zone sits at the edge between conventional and unconventional systems. Basin modeling, petrophysical and geomechanical analyses were performed to evaluate the potential of the rock-rock intervals in Hanifa-Tuwaiq Mountain zone. Basin modeling, along with present-day TOC and HI measurements from a number of wells, were used to evaluate the maturity of the unconventional intervals at varying depths. The results suggest that these zones have unconventional, self-sourcing reservoir potential with zones of good organic richness, oil saturations, and porosities. Petrophysical and mineralogical analyses show that Hanifa-Tuwaiq Mountain zone is dominated by carbonate minerals with very low clay content. Based on the carbonate mineralogy and the anisotropic stress models built to understand the geomechanical characteristics and fracture stimulation potential, it is expected to be highly conducive to hydraulic fracture stimulations. Porosities and permeabilities of Hanifa-Tuwaiq Mountain zone were also analyzed using core and cutting samples. In addition, the reservoir intervals within Hanifa-Tuwaiq Mountain zone were evaluated, using 3D seismic vintages by extracting attributes from interpreted horizons and seismic time-slices. This approach enabled mapping of the distinctively strong seismic amplitude response interpreted as porous facies within the zone.

Introduction

Hanifa-Tuwaiq Mountain zone consists of a mixed section of dark, laminated organic-rich carbonates and thick, slightly dolomitized limestone. It serves as a source rock to the overlying Jurassic and Cretaceous conventional reservoirs in Bahrain and is bounded on the top by the

Kimmeridgian to Oxfordian-age Jubaila Formation and on the base by the Bathonian to Bajocian Dhruma Formation. In 2012, light oil of 43° API was recovered from Hanifa-Tuwaiq Mountain source rock in a vertical well offshore Bahrain. Subsequently, a number of technical studies were carried out to understand and evaluate the source-rock potential of Hanifa-Tuwaiq Mountain zone.

Depositional Environment

Hanifa and Tuwaiq Mountain formations were deposited in intrashelf basin which formed within the interior of a broad epeiric, shallow-water carbonate platform (Aigner, et al., 1989). Most of the infilling sediments in the intrashelf basin consist of sequences of upward-coarsening and upward-fining storm-generated (Awad, 2015) deposits derived from the surrounding platforms (Droste, 1990).

The reservoir intervals exhibit tan to dark grey wackestone, mud-dominated packstones and cryptocrystalline to very fine microcrystalline carbonates. Grains include pelloids, mollusk and echinoid fragments, dasyclad algae, benthonic forams, the hydrozoan *Cladocoropsis*, composite grains, and rare corals. Presence of pre-existing topographical highs in the basin led to carbonate mounds or build-ups within Hanifa, resulting in favorable reservoir properties. The source rock intervals in the same zone consist of cyclic, interbedded, grey bioturbated wackstones to mud-dominated packstones, black, laminated and massive sections of organic-rich carbonates. Associated sedimentary structures include bioturbation in organic-lean beds, erosional bases, parallel laminations, ripples, and cross laminations. The observed cyclicity and the amount of preserved organic matter have been linked to the pycnocline in the water column; this resulted from variations in relative sea level, restricted circulation conditions, or both. (Lindsay et al., 2015). The upper part of Hanifa commonly consists of dolomitized limestone due to diagenetic processes which included dolomitization, leaching, and chalkification. These diagenetic processes are linked to some of the intercrystalline and interparticle porosities.

Source-Rock Properties

The source rock richness and the commercial viability are typically controlled by various factors, including organic richness, maturity, porosity, permeability, fluid saturation, and volume. Geochemical and basin modeling studies, petrophysical analysis, and geomechanical evaluation were conducted to investigate these primary controls and to better understand the unconventional resource potential in Bahrain.

Organic richness was quantified by measuring Total Organic Content (TOC) in core and cutting samples; it varies between 0.5 and 4 % in upper Hanifa and 0.5 and 7 % in lower Tuwaiq Mountain. The kerogen-rich zones in these units occur over an average thickness of 130 and 85 ft., respectively. The computed density and resistivity-based TOC models and log measurements are consistent with values obtained from core measurements (Figure 1a).

Thermal maturity, another early screening criterion for the assessment of unconventional potential, was characterized using vitrinite reflectance (VRo) measured from a number of core and cutting samples. These measurements helped calibrate 1D and 3D basin models constructed to understand the burial and temperature histories of the source-rock intervals (Figure 2a). The results from basin modeling and VRo analysis indicate that Hanifa-Tuwaiq Mountain zone in the prospective areas has VRo values between 0.7 and 1.1 (Figure 2b), which lies in the peak oil maturity zone. This is consistent with results from present-day TOC and Hydrogen Index (HI) measurements used as a proxy for determining source-rock maturity (Figure 2c).

Favorable mineralogy and geomechanical properties of source rocks are essential in estimating the limits to economic production and calculating the volume of recoverable reserves. Hanifa-Tuwaiq Mountain zone is dominated by carbonate minerals (calcite and dolomite) with very low clay content (Figure 3). Quartz and pyrite are also present as accessory minerals. Minimal clay content and abundance of carbonate minerals tend to make formations more brittle, thus increasing the hydraulic fracture potential of the formations. Moreover, anisotropic stress models were built using dipole sonic log data to better understand the minimum horizontal stress (fracture closure stress), which provides a good measure of the hydraulic fracturing effectiveness (Figure 1). Zones with lower minimum horizontal stress gradients tend to have wider fractures under the pressure and, as a result, tend to deliver more proppant during the stimulation process.

Considering the factors mentioned above, the source rock intervals and zones of net pay were defined based on the following minimum parameters: effective porosity > 2 %; effective hydrocarbon saturation > 55 %; nearly contiguous/continuous reservoir thickness of > 25 ft.; zone thickness > 50 ft.; and Total Organic Content > 2%. As a result, two main source rock intervals were identified in Hanifa-Tuwaiq Mountain zone (Figure 4). The organic-rich interval in Tuwaiq Mountain shows better source-rock potential compared to that in Hanifa.

Reservoir Properties

It was observed in a number of wells drilled across Bahrain that Hanifa-Tuwaiq Mountain zone produced hydrocarbons conventionally. This suggests that the porous intervals of Hanifa-Tuwaiq Mountain zone can exhibit properties of a prospective conventional reservoir. High-pressure mercury-injection capillary pressure analysis conducted on core plugs and cutting samples of Hanifa-Tuwaiq Mountain zone from a number of wells show that the average porosities and matrix permeabilities range between 6 to 12 % and 0.01 to 0.7 mD, respectively. These porosity ranges are consistent with the neutron-porosity logs.

The reservoir quality of Hanifa-Tuwaiq Mountain zone is enhanced by natural fractures observed in FMI logs and conventional cores. This is further supported by oil samples successfully recovered from vertical wells, drilled in source-rock kitchen areas, without fracking.

A strong seismic amplitude response due to a relative increase in porosity is a useful approach to predict areas of relatively good reservoir qualities in Hanifa-Tuwaiq Mountain zone. Several 3D seismic vintages, along with more than 30 wells, were used to confirm the trend between RMS seismic amplitude and the porosity of Hanifa Formation. Cross-plotting both variables suggests that increasing porosity results in an increase in seismic amplitude (Figure 5). Mapping the seismic amplitude response can help to qualitatively predict the lateral extent of porous pockets, possibly carbonate buildups or mounds within the formation, which can form conventional traps (Figure 6). In addition, the overlying Jubaila Formation, due to lithological/facies changes, can act as a localized barrier to hydrocarbon migration, enhancing the prospectivity in existing structural and stratigraphic traps.

Discussion

The evaluations and results discussed above indicate that Hanifa-Tuwaiq Mountain zone is comparable to successful unconventional plays in North America. The closest analogy on the basis of lithology, organic richness, and similar reservoir properties is the Eagle Ford Shale. The thick sequence of kerogen-rich mudrocks interbededded with carbonates in Hanifa- Tuwaiq Mountain zone is similar to that of the Eagle Ford Shale (Figure 7). Both plays consist of type II-S kerogen and comparable TOC range, varying between 1-10% (Pearson, 2012). The Hanifa-Tuwaiq Mountain zone has average porosities of 6-12 % and permeabilties of 0.01-0.7 mD (Figure 8). By comparison, Eagle Ford Shale shows ranges in average porosities and permeabilities between 2 and 11 % and 7 and 1000 nD, respectively (Walls and Sinclair, 2011). The similarity between Hanifa-Tuwaiq Mountain zone and Eagle Ford Shale play highlights the high potential of the unconventional resource play in Khalij Al-Bahrain Basin west of Bahrain (Figure 9).

In the Arabian Basin and for the age-equivalent sediments, the Jafurah play in Saudi Arabia is known to be an emerging unconventional play. The Tuwaiq Mountain Formation in the Jafura basin has calcite-dominated source rocks, containing 1% to 14% TOC, abundant organo-pores, very low to no clay content, and limited pyrite minerals (Lindsay et al., 2015). On the other hand, northwest of Bahrain, Hanifa is a major conventional producer in the Abqaiq field where it has average core porosities of 17% and average matrix permeabilities of 1 mD (Al-Awami et al., 1998).

In Bahrain, Hanifa and Tuwaiq Mountain formations coexist laterally, and both consist of calcite-dominated mineralogy with similar geochemical and geomechanical properties. The additional relatively organic-lean intervals in Hanifa add to the main source interval in Tuwaiq, resulting in an increase in the overall source-rock potential and the generation capacity of the system. The porous intervals within Hanifa Formation can increase the hydrocarbon storage capacity. It is, therefore, reasonable to consider Hanifa and Tuwaiq mountain formation as one play system.

The combination of Hanifa and Tuwaiq as one system results in thicker and areally larger sweet spots, with increased volumetrics. The porous intervals in the presence of conventional traps, within the sweet spots of Hanifa-Tuwaiq Mountain play, make targeting small, otherwise uncommercial structures an added value to the unconventional target. Therefore, an effective exploration well placement strategy would be to target structural or stratigraphic traps within the unconventional sweet spots to reduce risk and increase production per well.

Conclusion

Hanifa-Tuwaiq Mountain zone has average rock properties (porosities and permeabilities) that are at the higher end of the source rock plays, yet at the lower end of conventional reservoirs. Consequently, Hanifa-Tuwaiq Mountain play can be considered to lie at the edge of conventional and unconventional systems. This has the advantage of an increased sweet-spot area and volumetrics. Furthermore, targeting stratigraphic or structural traps, where present in sweet-spot areas, can reduce the exploration risk.

Acknowledgements

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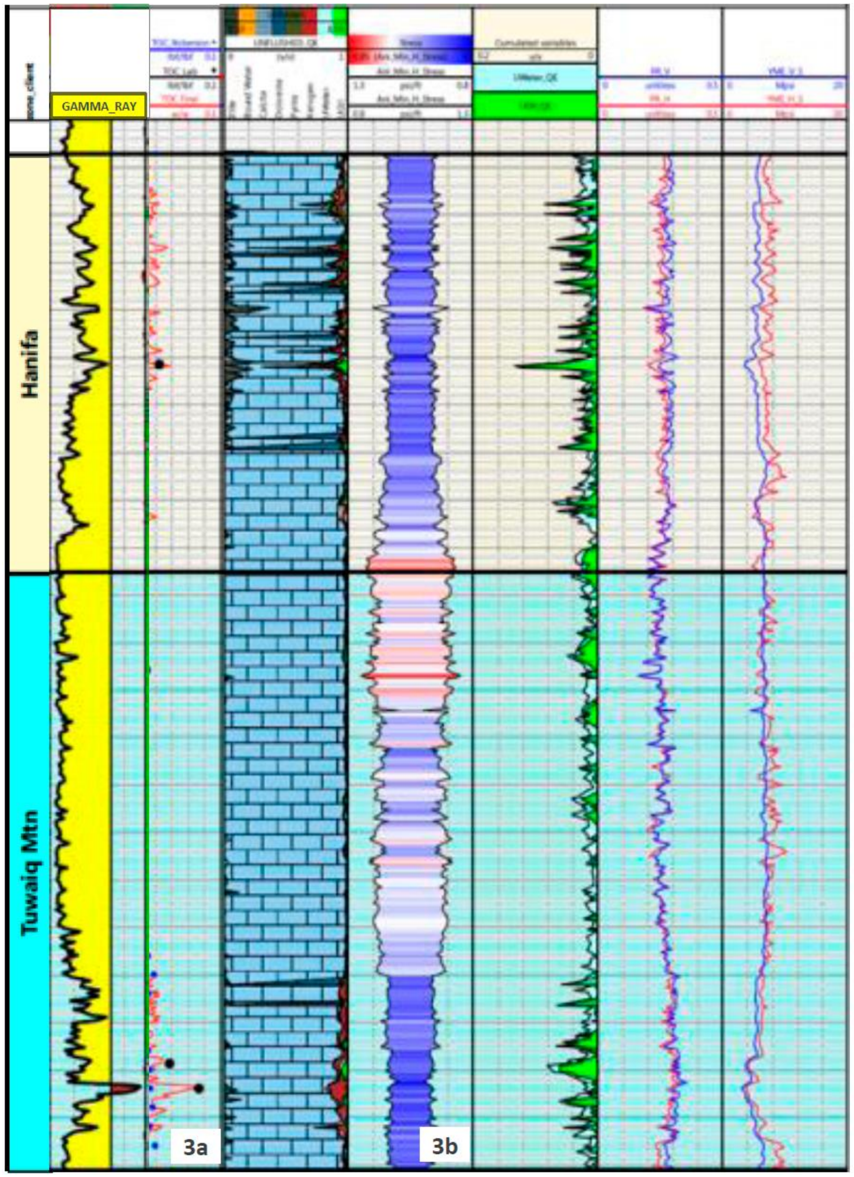

Figure 1. (a) Continuous TOC model (red curve) and TOC from core (black points) and cutting (blue points) measurements, indicating a range of 0.5–7 %. (b) Minimum horizontal stress profile from analysis conducted, independent of petrophysical analysis, using sonic dipole logs. Dark blue and dark red colors represent zones of high and low stresses, respectively. Lithology type, porosity, pore pressure affect the minimum horizontal stress profile.

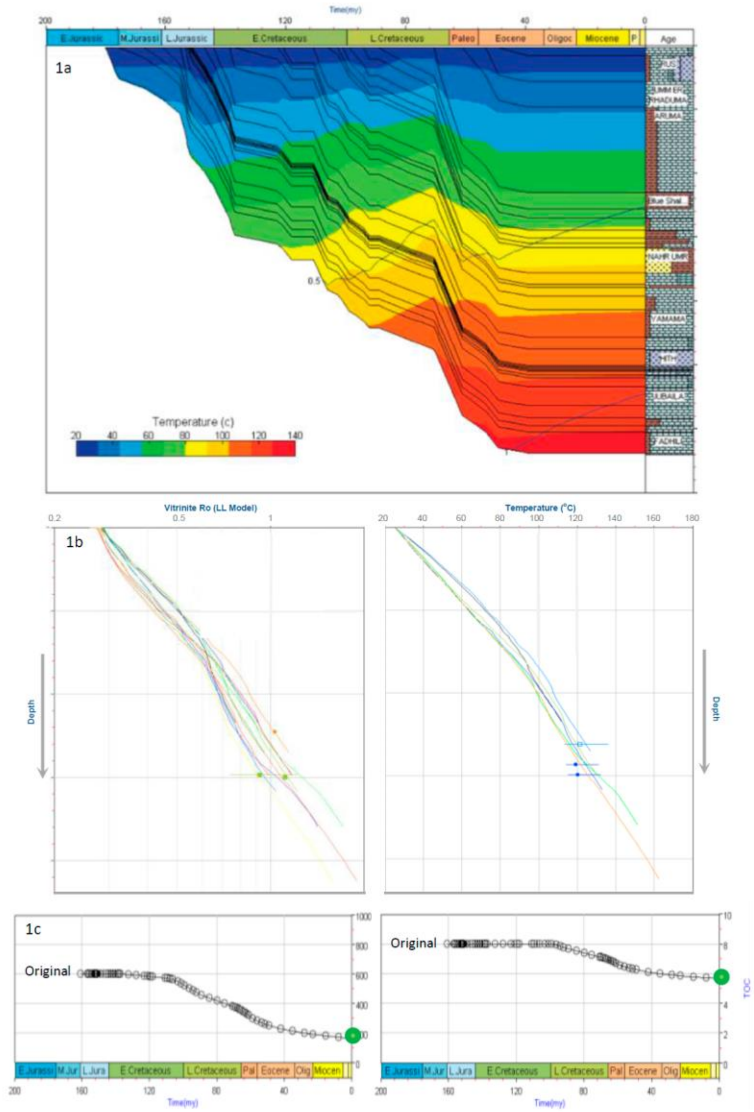

Figure 2. Basin modeling results: (a) The figure illustrates the stratigraphic input and the resulting burial-history plot for one of the basinal wells along with a temperature estimate overlay as a function of time and burial depth.

(b): Equivalent vitrinite reflectance (Ro) and temperature plots, products of thermal maturity modeling, were calibrated using geochemical and Rock-Eval data from well control. The figure shows a good fit between the plots of measured (symbols) vs. modeled (lines) values for Ro and temperature. The difference in the final Ro in the various wells is a reflection of the differences in stratigraphic section and tectonic history among the wells.

(c) Present-day TOC (~5-6%) and HI (~200 mg/gTOC) measurements were used as a proxy for maturity. Original TOC (8%) and HI (~600 mg/gTOC) were back-calculated to understand the generative capacity of the source rock. The distribution of HI was used as a measure of maturity, where lower the HI values, the higher the expected maturity.

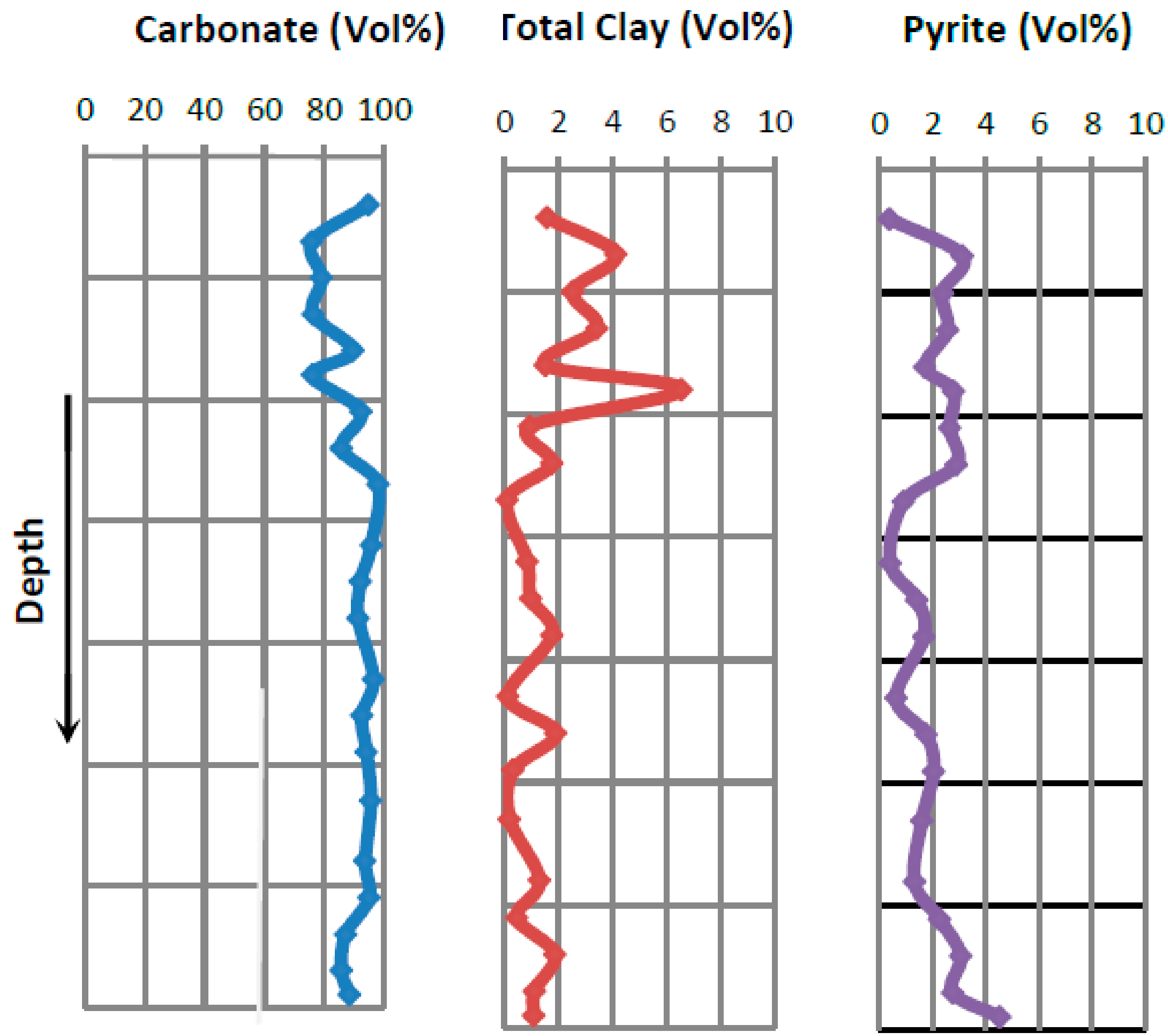

Figure 3. Bulk mineralogy of Hanifa-Tuwaiq Mountain zone from cutting samples, showing dominant carbonate minerals along with pyrite and total clay content.

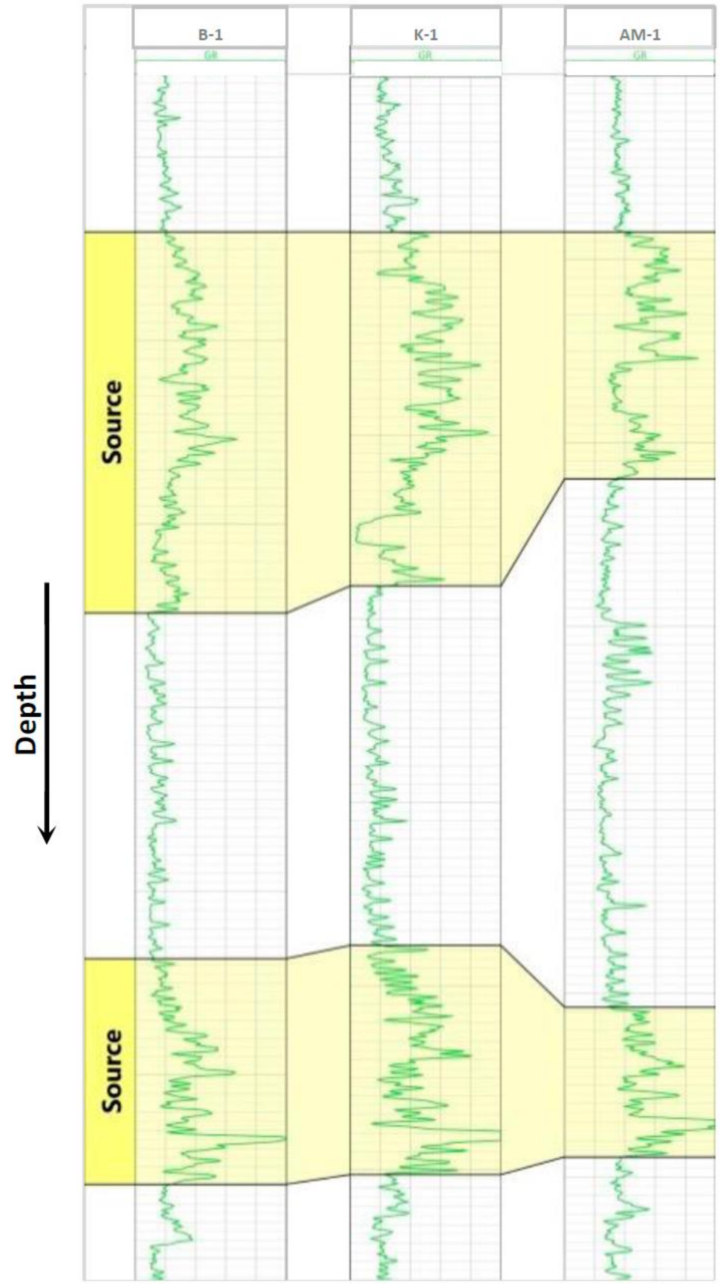

Figure 4. Source rock intervals within Hanifa-Tuwaiq Mountain zone.

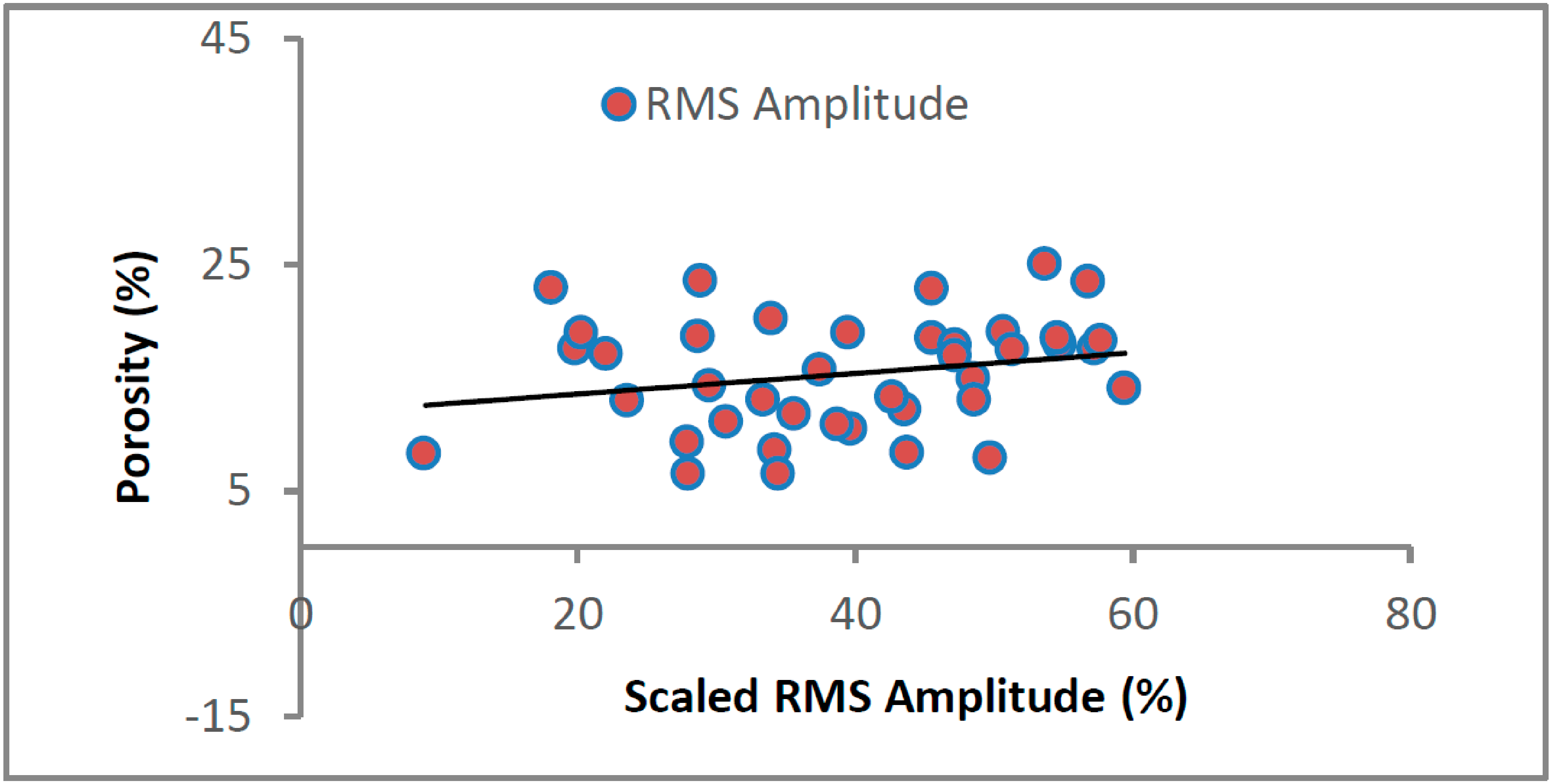

Figure 5. Cross-plot of porosity values derived from Neutron Porosity logs of 39 wells with the scaled amplitude response from 5 3D seismic vintages. This suggests a positive trend between porosity and seismic amplitudes.

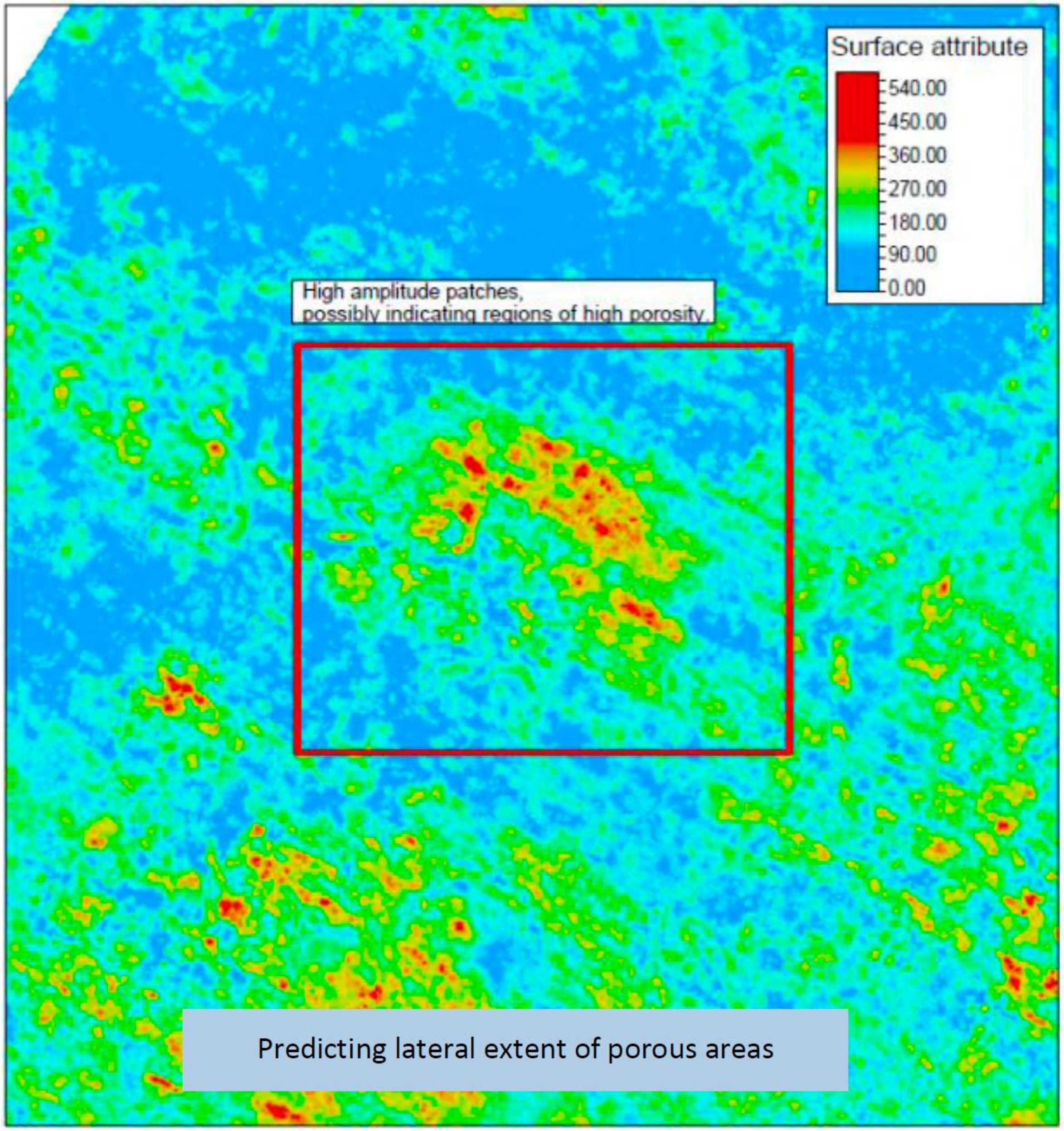

Figure 6. A window-based seismic RMS amplitude map derived from a 3D seismic vintage. Warmer colors show higher amplitudes and thus potentially higher porosity regions.

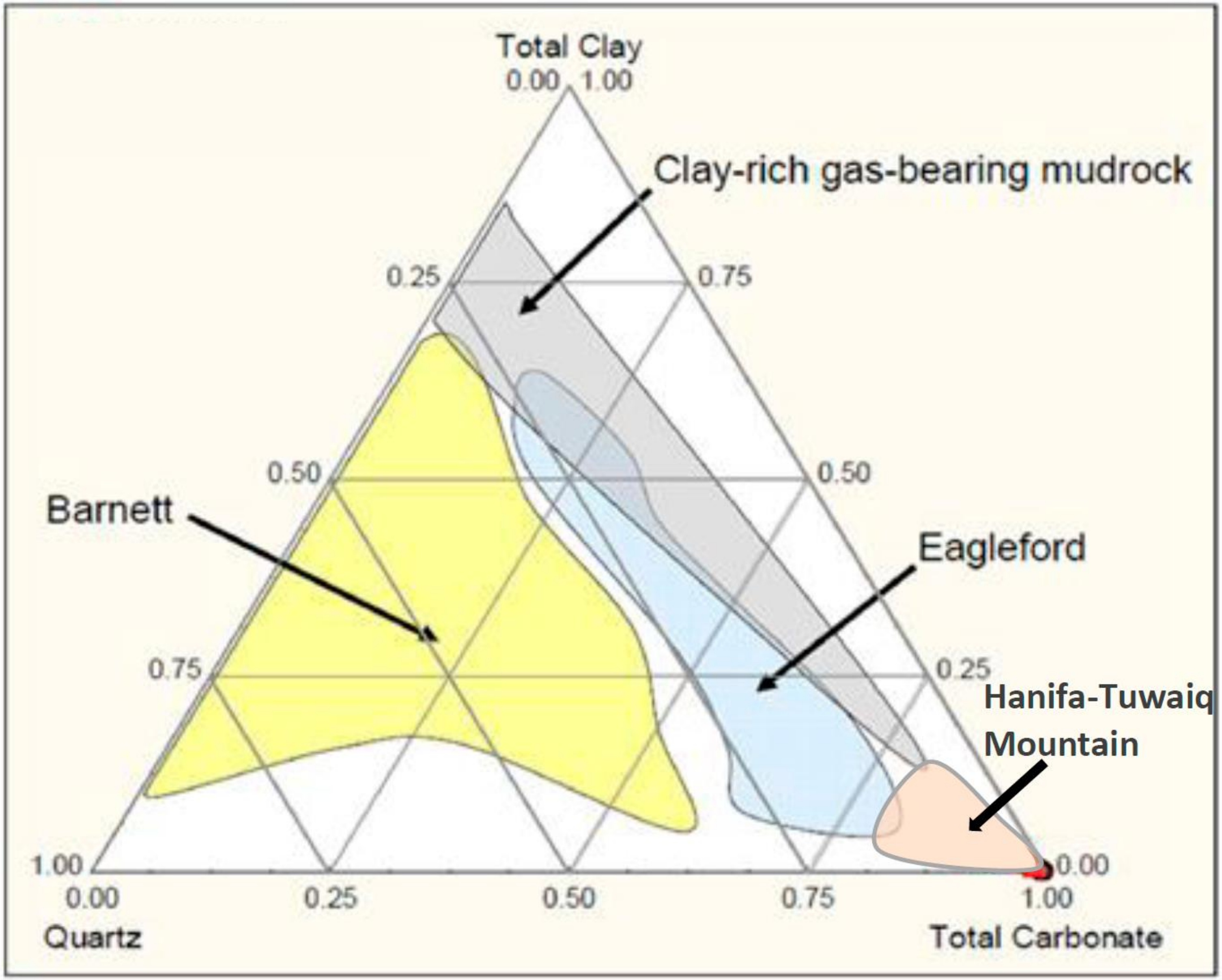

Figure 7. Ternary plot showing the mineralogy of Hanifa-Tuwaiq Mountain source rock intervals compared to Eagle Ford and Barnett shale plays in North America. Hanifa-Tuwaiq Mountain has comparable carbonate mineralogy with lower clay content. Modified from (Passey, 2010)

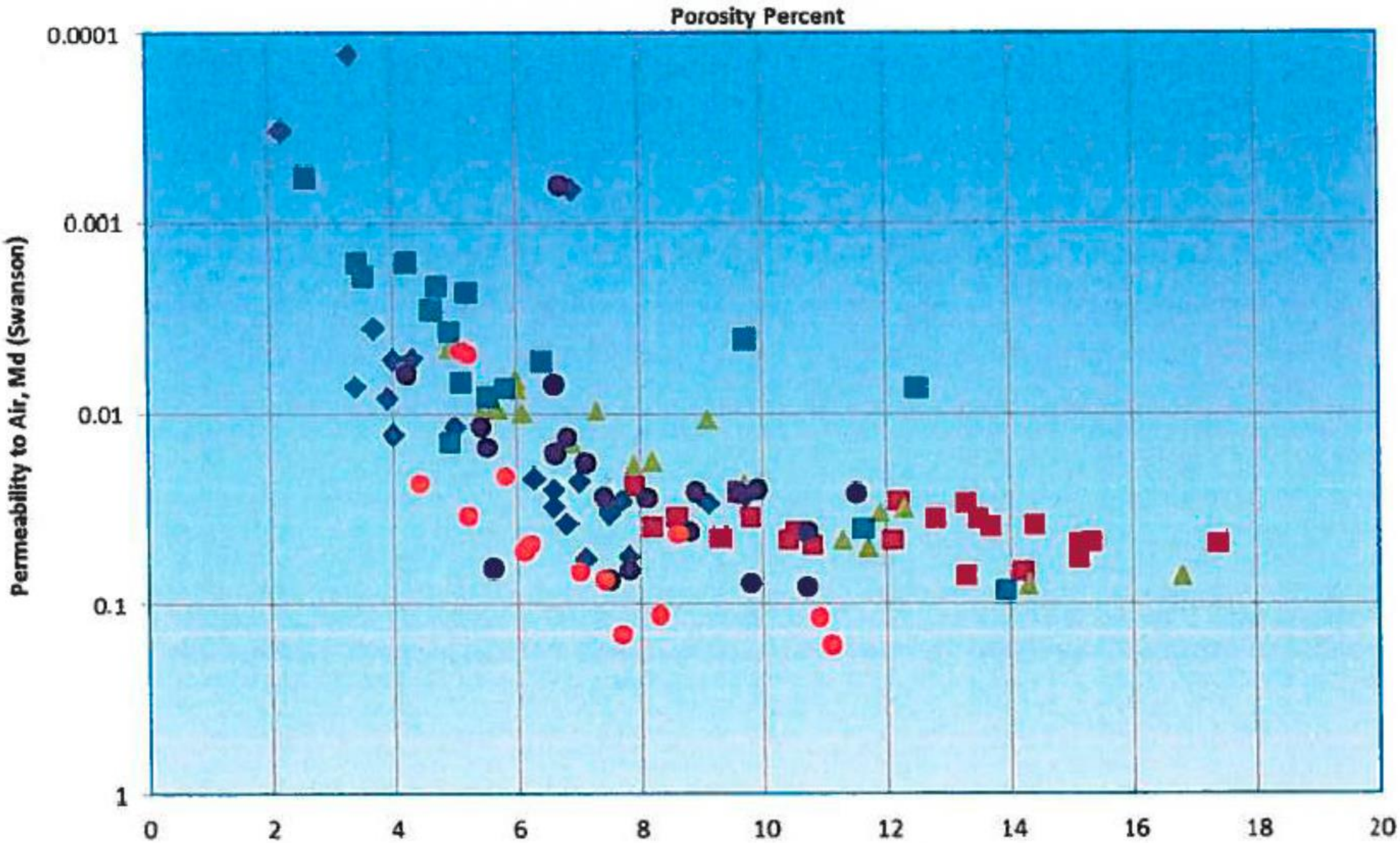

Figure 8. Porosity and permeability cross-plot showing the reservoir properties of Hanifa-Tuwaiq Mountain zone in a number of wells across Bahrain, based on MICP analysis conducted on core and cutting samples.

Figure 9. The base map highlights the close vicinity of Bahrain to the major unconventional play area for Tuwaiq Mountain and a major field producing conventionally from Hanifa in Saudi Arabia. The red polygon delineates the potential area in Khalij Al-Bahrain Basin for unconventional light oil/condensate.