Diagenesis and its impact on reservoir quality in a Triassic Sandstone, Berkine basin, North Africa

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Abstract

The TAGI reservoir was deposited in a Triassic braided fluvial system; it is widely distributed across the Berkine Basin of northern Africa. Reservoir quality across the basin is generally lower at depth due to compaction. However, production tests in the study area, which is located in the northern part of the Berkine Basin show that the TAGI in a deeper area has somewhat higher production rates in the lower part of the TAGI reservoir where it directly overlies the Hercynian Unconformity. This improvement in reservoir quality is thought to indicate a lack of compaction or some other diagenetic association. The mineral compositions, diagenetic components, intensities and sequences were analyzed using a combination of petrography, XRD, SEM, core porosity-permeability, well testing and conventional well log data. Much of the variation in production rates and reservoir quality is a result of the varying development of authigenic phases in the TAGI. The two most significant factors associated with improved reservoir quality at depth are the presence of chlorite rather than illite and dissolution porosity. That is, proportions of secondary dissolution pores and levels of grain-coating chlorite are more abundant in high flow wells, while illite, mixed-layer illite/smectite, anhydrite and carbonate cements are more abundant in low flow wells. The clay mineral types, chlorite versus illite, can be identified using spectral gamma ray cross plots. Much of the improvement in reservoir quality has occurred in the deeper burial realm where late-stage laterally-flowing highly-saline (dense) acidic basinal waters are being focused into the lower part of the TAGI sand. This is a region of pore-fluid cross-flow directly above the impervious fine-grained sediments that underlie the Hercynian Unconformity.

Keywords: Triassic Sandstone, diagenetic components, diagenetic intensity, reservoir qualities, chlorite pore lining, dissolution porosity

1. Introduction

TAGI reservoirs are widely distributed across the Berkine Basin. Reservoir quality is generally lower at depth due to compaction. However, production test results (Figure 1) in the study area located in the northern part of the basin indicated that a deeper area on the western side shows somewhat higher production rates and improved porosity-permeability values especially toward the lower part of the TAGI reservoir indicating a lack of compaction or some other diagenetic association.

This study focuses on the main diagenetic components, which likely influenced the reservoir quality but are not yet fully understand in the study area. It not only focuses on core-derived data, which provides information on diagenetic components, sequences and intensities, but also attempts to document any relationship to porosity-permeability, flow ability and wireline log character. In particular, this study reveals that the TAGI reservoirs show significant mineralogical changes in authigenic components from well-to-well, which is reflected in reservoir quality.

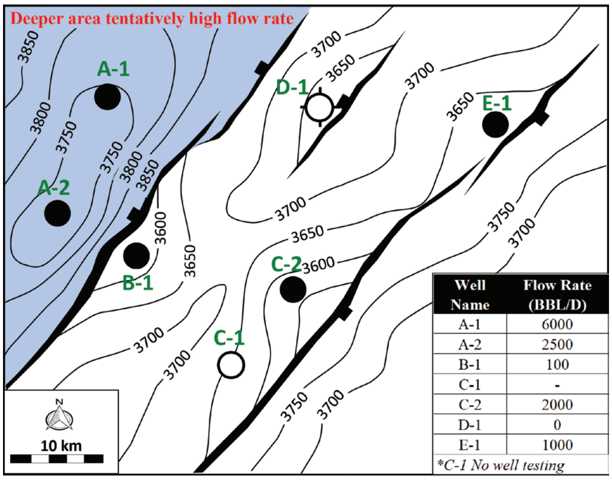

Figure 1. The TAGI depth structural map and the flow rates of the wells drilled in study area.

2. Locations and Geological Setting

The Berkine/Ghadames Basin is an intracratonic basin that developed during the Middle to Late Triassic on the margin of the Saharan platform. The basin lies to the east of the north-south trending Hassi Messaoud Ridge which separates it from the Oued Mya Basin to the west. The boundary between the Illizi and Ghadames (Berkine) Basins is defined by a break or hinge line in the slope of the basement rocks. The basin contains up to 6 km of Paleozoic and Mesozoic sediments and stretches over parts of eastern Algeria, western Libya and southern Tunisia (Fig. 2&3).

The structure of the Triassic basin is largely controlled by reactivation of NE-SW, NW-SE, Pan African and late Palaeozoic basement lineaments (Nedjari, 1994). The middle Cretaceous extensional reactivation of the NW-SE cross-cutting faults play a key role in the formation of a number of giant TAGI reservoir oil field (Pink et al., 1999).

The study area is located in northern part of the basin (Figure 1). The fluvial braided TAGI reservoirs are widely distributed with thickness is vary from 30 to 50 meters at the depth 3550 to 3780m (Figures 3, 4). In the study area, the reservoir temperature is approximately 100ºC, with pressures around 8,000 psia. The reservoirs thin to South East of the area toward the structural high, and thicken to North West of the area toward the basin depocenter. TAGI reservoirs are covered by volcanic and carbonate rocks; with the base bounded by Silurian shale (Figure 4). The bounding rocks are thought to significantly impact the intensity of diagenetic processes in the Berkine Basin (Morad et al., 2010).

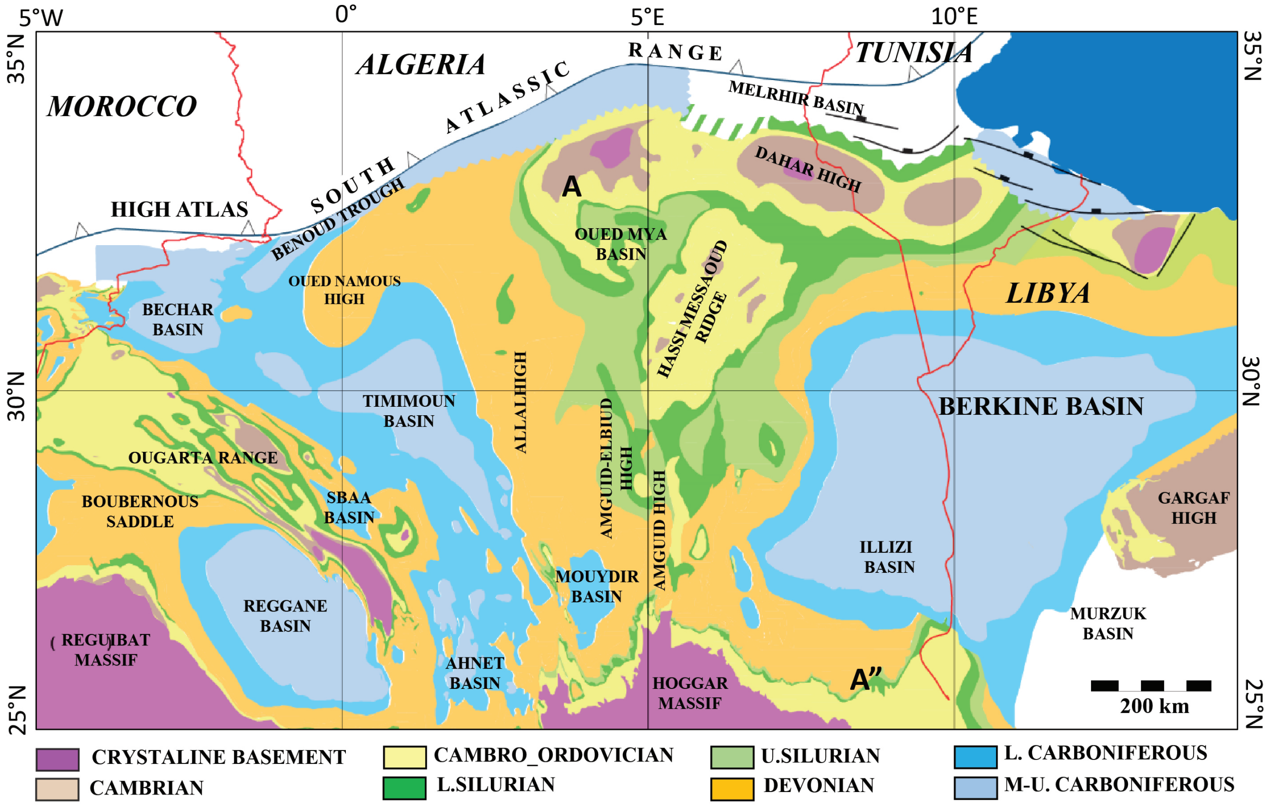

Figure 2. Pre-Mesozoic subcrop map of the Saharan Platform, showing the main Late Palaeozoic (mostly "Hercynian") to Early Mesozoic tectonic elements. After D.G. Roberts and Bally, 2012.

3. Methodology

The mineral compositions, diagenetic components, intensities and sequences were analyzed using a combination of petrography, X-ray powder diffraction (XRD), Scanning Electron Microscopy (SEM). Conventional core plug samples were collected in Triassic TAGI sandstone, which is the main reservoirs in the

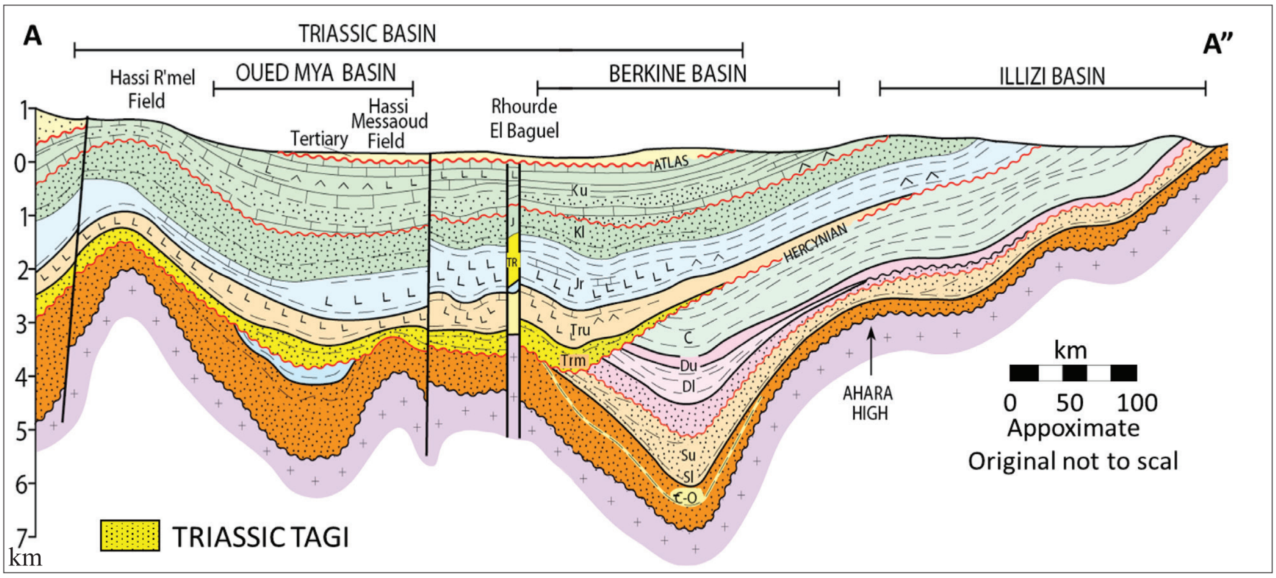

Figure 3. North-central Africa cross section from north to south, showing USGS-defined geologic provinces and major structures, modified from Popescu, 1995

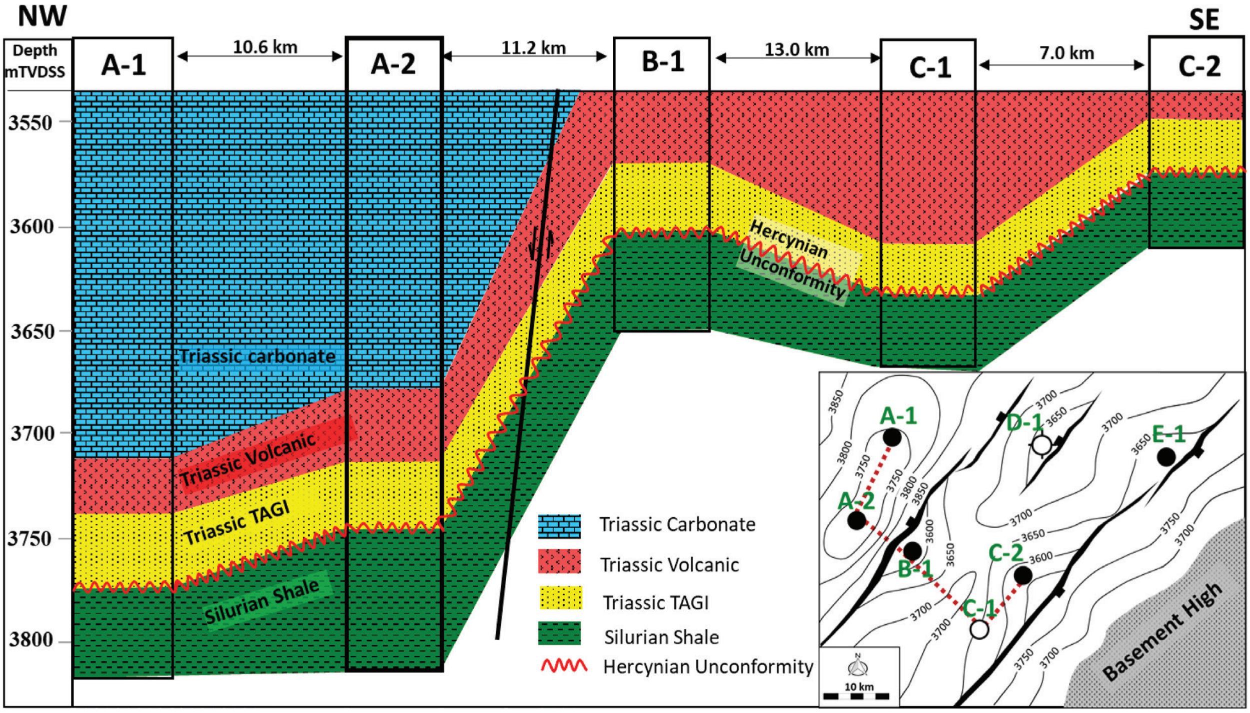

Figure 4. Structural correlation from NW-SE across the study area, showing the TAGI reservoir is thickening to the northwest and toward basin depocenter.

study area. In total, seven cored wells were selected, namely; A-1, A-2, B-1, C-1, C-2, D-1 and E-1. Petrographic analyses are summarized using percentage of each minerals observed in a sample. The X-ray powder diffraction (XRD) are used to confirm the results from petrographic analysis and to define other minerals, which cannot be identified by petrographic analysis. The XRD results are listed via separation into 100% clay minerals and 100% non-clay minerals.

Diagenetic components and intensities are investigated in both lateral (between well) and vertical dimensions (in well) in order to evaluate the variation across each diagenetic components from well to well and from bottom to top of the reservoir. The mineralogical results from petrography, XRD and SEM are integrated with porosity-permeability values from routine core analysis (RCA), well testing (DST) and wireline logs (spectral gamma ray).

4. Results

4.1 Detritral Components and Intensities

Detrital components are mainly quartz with minor feldspar (plagioclase and orthoclase), mica and heavy minerals (zircon, tourmaline and leucoxene). Most of the studied Triassic TAGI sandstone is a quartz arenite, with one sample of sub-arkose (Figure 5).

There is no significant variation in the dominant level of detrital quartz in all wells in the study area. The amount of detrital quartz ranges from 50% to 90%. The average grain size ranges from 0.1mm to 0.9 mm and most sands are medium to well sorted. Grains are generally sub-angular to rounded. Dominant contacts are mostly floating with straight to concave-convex contacts.

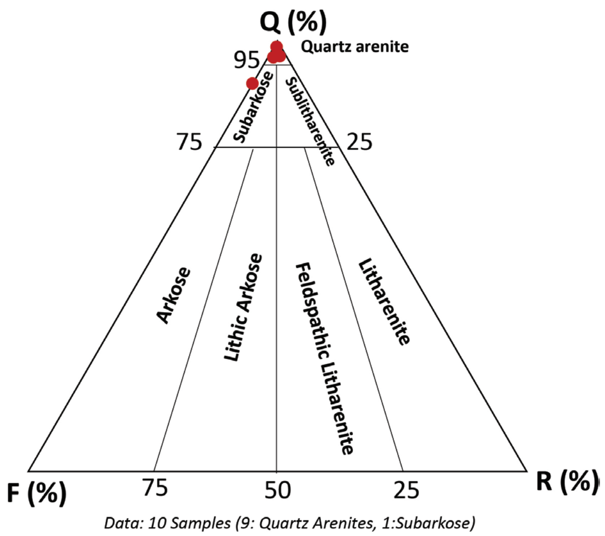

Figure 5. QFR diagram of well D-1, showing mainly quartz with minor feldspar. Triassic TAGI sandstone is mainly classified as Quartz Arenite (9 from 10 samples).

4.2 Diagenetic Components and Intensities

Quartz Overgrowth

Quartz cement mainly occurs as grain overgrowths, but microcrystalline growths cannot be observed using a standard petrographic microscope. The authigenic syntaxial overgrowths occur in the studied wells, they are discontinuous around quartz detrital grains (Figure 6). There are two possibilities for a silica source in quartz overgrowth; 1) an external origin linked to the circulation of waters supersaturated with silica or, 2) an internal origin related to pressure-dissolution of quartz grains at their contact points.

Quartz overgrowths are abundant in all studied wells and constitute one of the main cementing materials in the TAGI, with proportions ranging from 0% to 20%. However, there are no obvious relationships in the intensity of quartz overgrowth in the vertical and lateral dimensions as the proportion of quartz overgrowths are not significantly different from well to well or from bottom to top of The of the reservoirs.

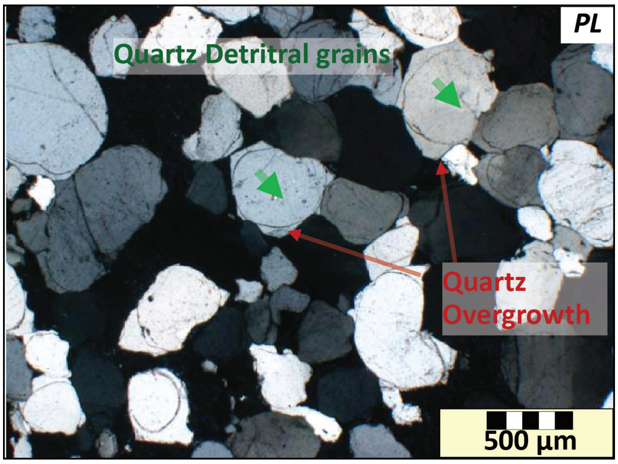

Figure 6. C-2 well petrography sample at 3694.3m (cross-polarized light), showing the abundance of syntaxial quartz overgrowths surrounding detrital grains.

Mixed layered Illite/Smectite and Illite

The amount of mixed layers illite/smectite from XRD analysis ranges from 0-30% of total clay (Figure 9a), and is directly proportional to the amount of illite in the sample, where the amount of illite in the clay proportion ranges from 0 - 100% (Figure 9b). The amount of the mixed layered illite/smectite and illite are relatively high in wells B-1, D-1 and E-1. The mixed-layer illite/smectite and illite (Figure 8a & 8b) occur as grain coats and occupy much of the intergranular pore space, so contributing to the deterioration of reservoir quality.

Early meteoric diagenesis can drive the infiltration of smectite clay coatings in a sandstone (Morad et al., 2000, 2010). The transformation of smectite into illite (Figure 8a & 8b) can take place at temperatures between 47 ºC and 68 ºC in a potassium-rich environment (Weibel, 1999). The smectite clay coatings were likely subjected to partial to complete illization in the presences of mixed layers illite/smectite (Figure 12a & 12b) during burial diagenesis.

Chlorite

The amount of chlorite ranging from 0 to 100% of total clay from XRD analysis. The amount of chlorite is tentatively high in wells A-1, A-2 and C-2 (Figure 9c). A chlorite versus quartz overgrowth plot indicates that high proportions of quartz overgrowths occur when the proportion of chlorite is low (Figure 7), this suggests that chlorite was formed before quartz overgrowth.

Chlorite probably precipitated by chemical alteration of feldspar as volcanic lithics, rich in Fe and Mg materials, were dissolved and released Fe2+ and Mg 2+ into the pore waters during burial diagenesis, especially toward the top of TAGI reservoirs that underly Triassic volcanics. Another possible way to form chlorite is by chemical alteration of precursor grain-coating smectite (Morad, 2010). Chlorite typically occurs as grain coats (Figure 8c), likely reducing porosity losses by inhibiting precipitation of otherwise widespread quartz overgrowths (Ehrenberg, 1993; Bloch et al., 2002; Ajdukiewicz and Larese, 2012).

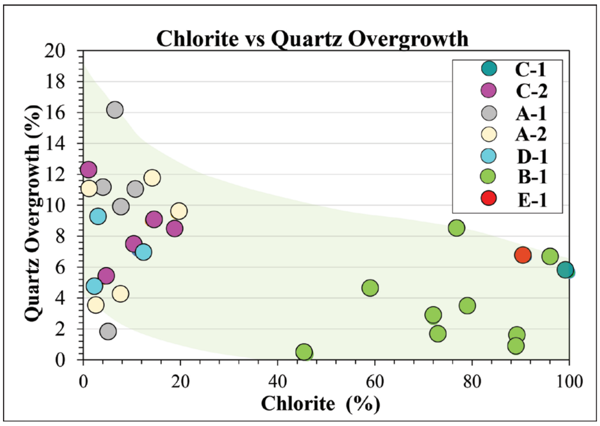

Figure 7. Cross plot, quartz overgrowth vs. chlorite, showing that the level of quartz overgrowth tends to be low when there is a high proportion of chlorite.

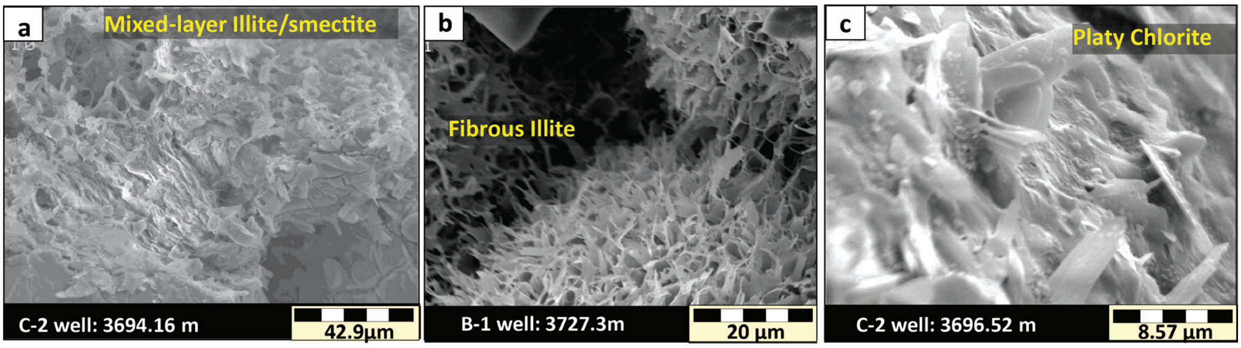

Figure 8. The spectroscopic analysis (SEM) of B-1and C-2 wells, showing abundant of (a) mixed layers illite/smectite, (b) fibrous illite and (c) platy chlorite.

Carbonate cement in the studied TAGI wells is either calcite or dolomite. Carbonate cements are generally present in all wells and is one of the main matrix cement in the study area. The amount of carbonate cement can be up to 20%, from petrographic analysis (Figure 11). Dolomite is usually associated with calcite occurrence and tends to replace it (Figure 10b) which implies a later stage diagenetic process. Dolomite was originally deposited as calcite that was post-depositionally altered by magnesium-rich pore water to form dolomite.

The petrographic results indicate the early cementation as the evidence that quartz detrital grains encased in calcite are not well compacted (floating) once calcite filled in the matrix (Figure 10a). Calcite cement is interpreted as an early precipitate from brine flushed from the overlying Triassic carbonate layers. Another possible source is the brine flushed from underlying Silurian marine mudstone (Morad, 1994).

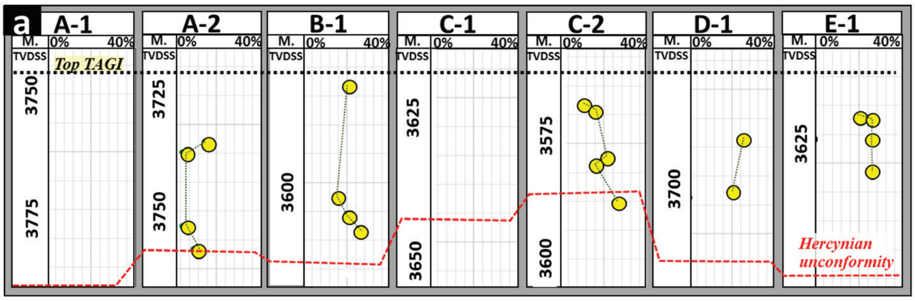

Figure 9a. The proportion of clay minerals distribution re-plotted from XRD analysis, showing mixed-layer illite/smectite range from 0 to 30% and no mixed-layer illite/smectite observed in A-1

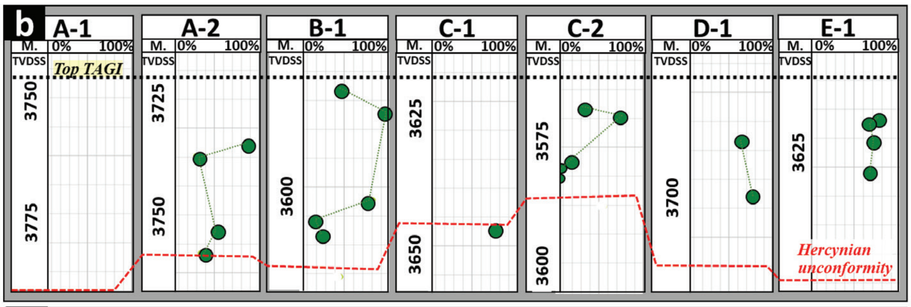

Figure 9b. The proportion of clay minerals distribution re-plotted from XRD analysis, showing illite range from 0 to 100% and no illite observed in A-1 well.

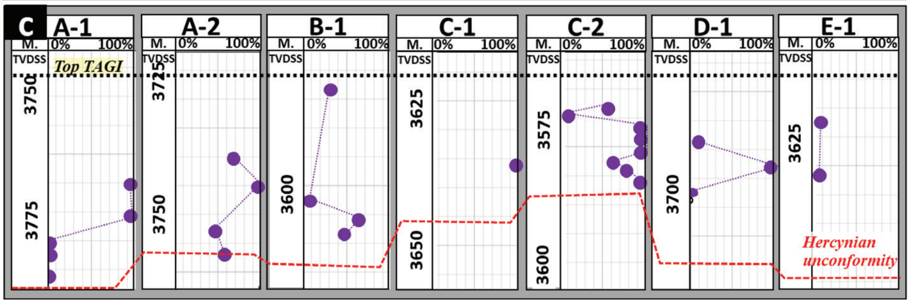

Figure 9c. The proportion of clay minerals distribution re-plotted from XRD analysis, showing chlorite range from 0 to 100%.

Anhydrite

Evaporitic cements observed from petrographic study are mainly sparry anhydrite (Figure 10b) with some halite and barite. Petrographic analysis shows the amount of anhydrite ranges from 0 to 25% (Figure 12). Anhydrite are generally present in all wells and constitute one of the main matrix cements in the study area.

Anhydrite cemented bands are usually found where calcite is present. The calcite appears to be chemically altered and replaced by anhydrite during burial diagenesis. There are low variations in the amount of anhydrite cement between wells. However, the proportion of anhydrite cement is high in the deep area (A-1 well), which is a well with a high proportion of secondary leachate porosity.

Sparry anhydrite is evidence of secondary precipitation and is usually a burial cement, perhaps tied to leaching of carbonate and thermochemical sulfate reduction (Warren, 2014). Anhydrite's presence is perhaps related to the movement of water rich in calcium sulfate from underlying Silurian marine mudstone (Morad, 1994). Another possibility of anhydrite forming related to the influx of dense brine flushed from overlying evaporite-prone Triassic carbonates.

Anhydrite cement levels are generally higher in the lower part of the TAGI reservoirs, which probably related to a dense sulfate-rich fluid flow mechanism focused above the Hercynian unconformity.

Dissolution of Matrix Cement

Dissolution (secondary porosity) is observed in all wells, especially on the lower part of the TAGI reservoirs (Figure 10c). Dissolution intensity tends to be high in the deeper part of the study area (A-1 and A-2 wells) and in the lower part of the reservoirs attached to Hercynian unconformity. The nature of the hydrodynamic flow system along Hercynian unconformity, which drove the leaching of matrix cement, is not fully understand. There is a greater likelihood of lateral fluid flow immediately above the unconformity, which is a permeability barrier underlain by impervious sediment. If the laterally flow waters were chemically aggressive, then this is a likely mechanism facilitating secondary leachate porosity created the secondary porosity in this area. Dissolution tentatively the major factor beside chlorite pore lining which help to enhance reservoir qualities. Another factors which may control the dissolution of carbonate cement in deeper area might be related to increase pressure. There are studies indicating that the solubility of CaCO3 when contacted by deep CO2 will be increased with increasing pressure as the pressure in the deep area is higher than the shallow area approximately 300 psi (Rukuni et al., 2012). Present-day water samples indicate high saline water at the reservoir level, with pH ranging from 1.5.0 to 5.0 and a specific gravity around 1.22 (Table 3). These, or similar saline and acidic waters, rich in sulfate probably flowed through the reservoir during the leaching process and removed calcite to form sparry anhydrite, as seen in the high proportion of anhydrite in the leached sediments of well E-1 (Figures 10b & 10c).

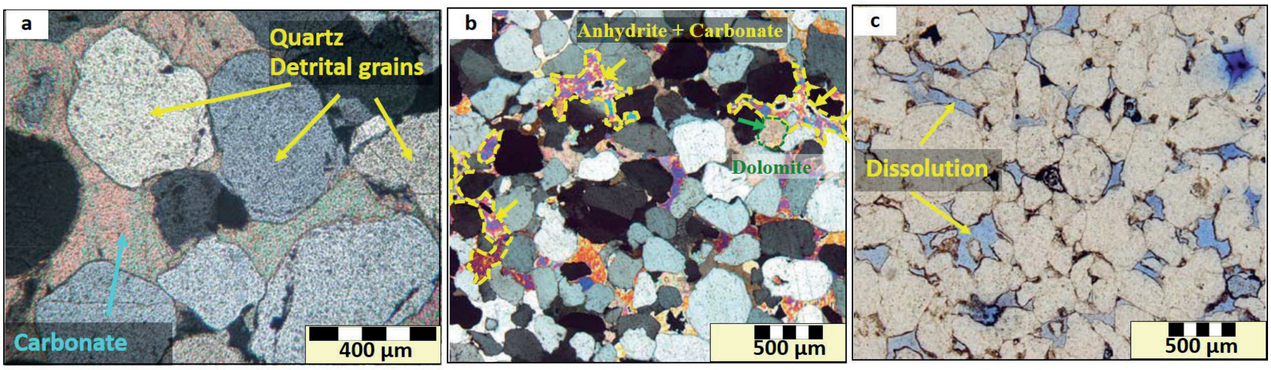

Figure 10. Petrographic analysis of (a) C-1 sample at 3763.5 m (cross-polarized light), showing floating of quartz detrital grains and abundant of carbonate cement filled in the matrix, (b) E-1 sample at 3739.4 m (cross-polarized light), showing anhydrite presence associated with carbonate cement, (c) E-1 sample at 3747.8 m (plane light), showing abundant dissolution in the bottom part of reservoirs, that are attached to Hercynian unconformity

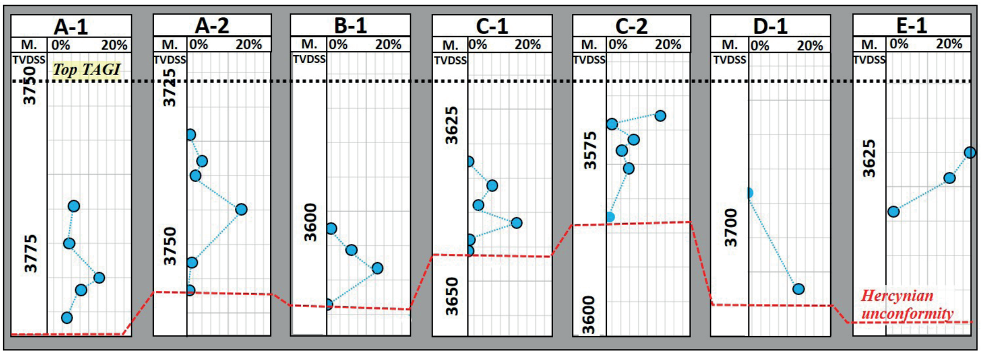

Figure 11. The proportion of carbonate distribution re-plotted from petrographic analysis, showing carbonate cements range from 0 to 20%.

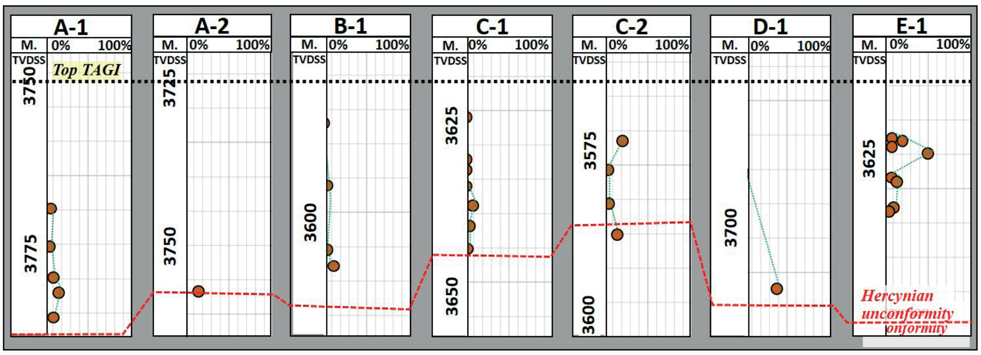

Figure 12. The proportion of anhydrite distribution re-plotted from petrographic analysis, showing anhydrite cements range from 0 to 25%.

4.3 The relationship of diagenesis to flowability, porosity-permeability and wireline log signatures

Diagenesis and Flowability

Reservoir performance can be directly measured by flow rate as quantified by drill stem testing (DST). Results, when tied to core-derived observations, show that diagenetic components are key to flowability values in each well. The high flow wells tend to be high chlorite, while the low flow wells tend to show higher levels of illite, mixed-layer illite/smectite and carbonate. Chlorite levels are higher in the A-1, A-2, C-2 and D-1 wells (Figure 13), which are mostly are the high flow wells except D-1 (no flow). The reason that the D-1 well does not flow is the high amount of illite. The amount of mixed-layer illite/smectite is also high and the high levels of these fibrous clay at the reservoir level, compared to the other wells, has greatly impeded its ability to flow. Likewise, the other high illite wells show low flow rates (Figure 13). The average carbonate cement level is high in the B-1 well, which is also reflected by a low flow rate (100 bopd).

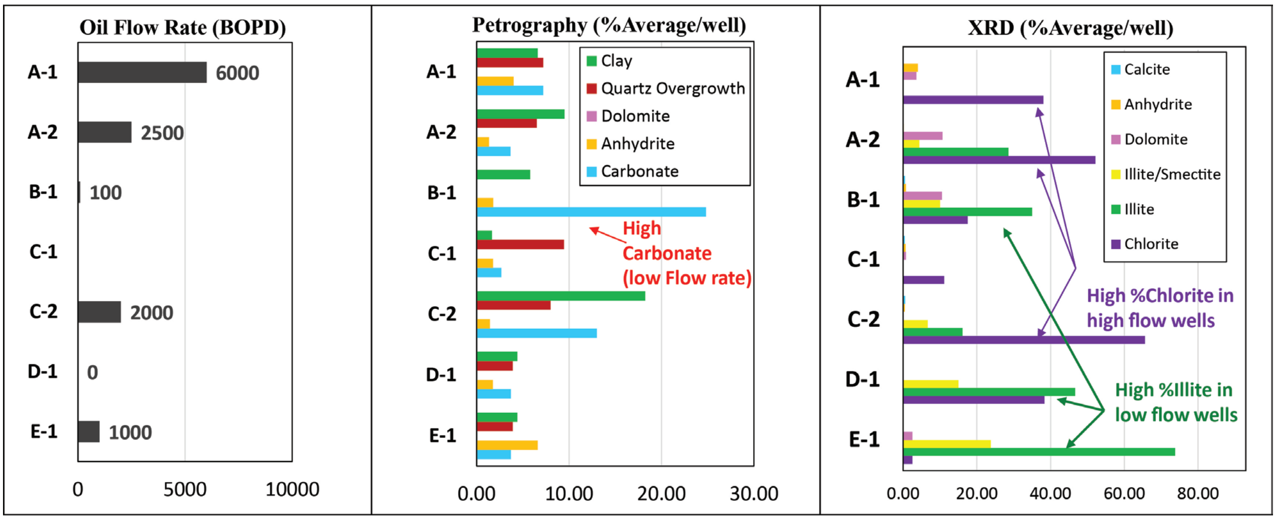

Figure 13. Flow rate and diagenetic components, showing high flow rate with high chlorite and low flow rate with high carbonate, illite and mixed layers illite/smectite

Diagenesis and Porosity-Permeability Relationship

There are correlations of illite pore-filling clay and porosity- permeability using exponential functions (Figure 14a). Helium porosity values are inversely tied to illite concentration in a general way. The concentration of illite is up to 100%, which is reflected by porosity lower than 4% in high illite samples. The permeability values are moderately inversely correlated with illite concentration. Once again, when the concentration of illite is up to 100%, the permeability in high illite samples is lower than 0.1 mD (Figure 14b).

Permeability and porosity cross plots can also be used to investigate variations in diagenetic intensity. If there is only intergranular porosity present, a linear correlation in porosity-permeability values can be seen. However, when primary intergranular porosity is affected by the overprint of diagenetic components and dissolution voids, there is either a deterioration or enhancement of reservoir quality. There are low variations of the porosity-permeability cross plot on the high cemented and low dissolution wells. The high cementation area, especially by carbonate cements, illite and mixed illite/smectite pore filling can be observe as the narrowed cross plot on porosity- permeability. In contrast, intervals with dissolution can be observed by the elevated permeability above the high cemented area (Figure 15a & 15b).

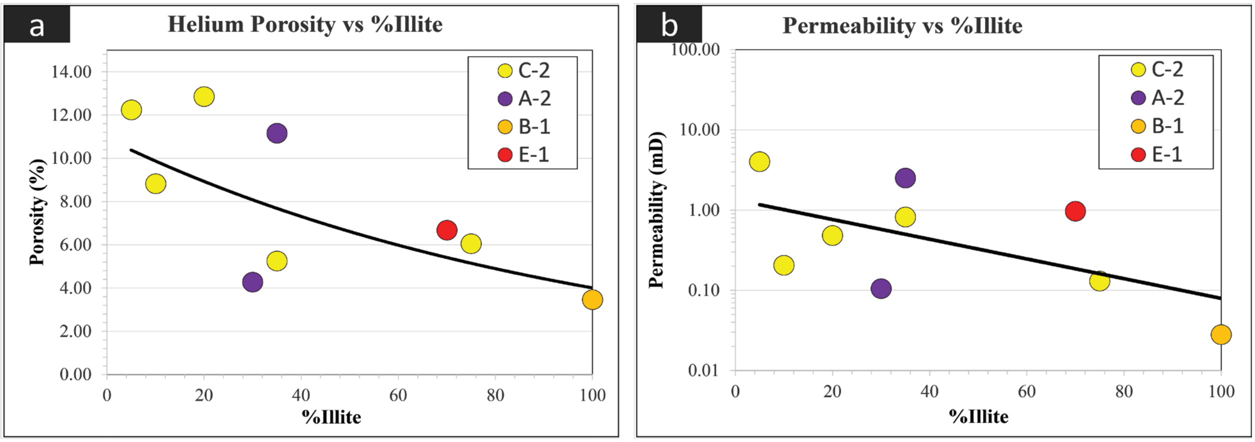

Figure 14. Illite vs. porosity/permeability plots, showing low poro-perm with high proportion of illite.

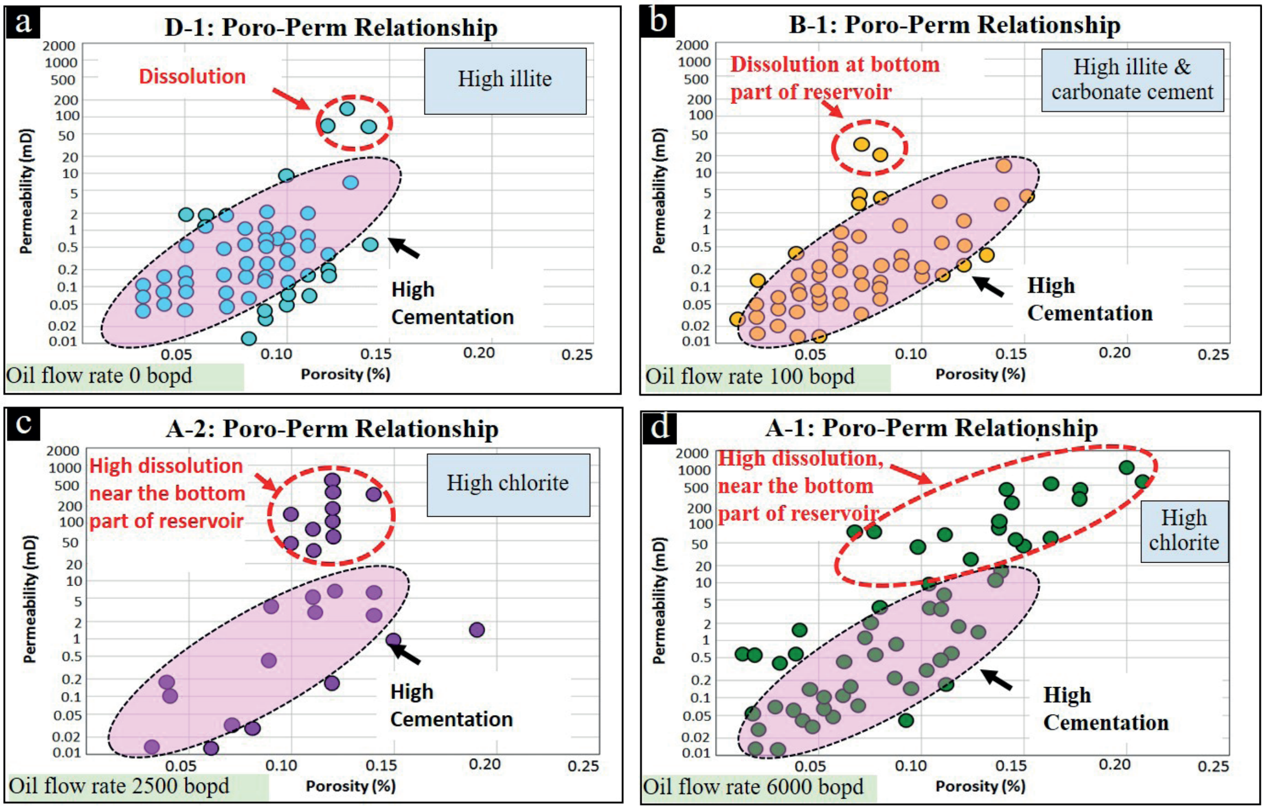

Figure 15. The porosity-permeability cross plot tied to significant diagenetic components, (a,b) D-1, B-1 (low flow) wells and (c,d) A-2, A-1 (high flow) wells, showing highly cemented areas are indicated by characteristic zones in a porosity-permeability cross plot. High dissolution/ chlorite wells are indicated by broad spreads in the porosity-permeability cross plot and can be predicted to be the elevated permeability areas in the cross plot above the high cementation plot areas.

There are high variations as shown in the porosity-permeability cross plot in the low cemented, high chlorite and high dissolution wells. There are abundant of elevated permeability areas in the plot field above the high cemented area, which is the results of dissolution and those same porosity-permeability characteristics are observed in most of the high flow wells (Figure 15c & 15d).

Clay contents and Spectral Gamma Ray Relationship

Each clay mineral is strongly linked with the variable content of radioactive isotopes, mainly potassium and thorium (Klaja and Dudek, 2016). The thorium/potassium ratio depends on the crystal structure of the mineral, its dimensions, concentration of radioactive ions during formation of the mineral and the weathering and diagenetic processes taking place from the moment of mineral formation.

Clay typing from well log data is usually accomplished by using cross-plots of potassium and thorium data (Table 1) from the spectral gamma ray log and the photoelectric effect.

Cross plot was constructed for PE versus thorium potassium ratios (Figures 16) and thorium vs.

Table 1. Thorium/potassium ratios vary with clay types (Modified from Halliburton, 1985)

	Th/K Ratio in Clay
High	Kaolinite
	Chlorite
	Montemorillonite
	Illite
	Mica
	Glauconite
	Feldspar
Low	Potassium evaporites

Potassium indicated three main types of clay minerals, which are; mixed-layered clays, chlorite and illite. The results from the wireline cross plot is supported in the studied TAGI reservoir by results from XRD and SEM analysis. Accordingly, this plot can be used as a semi-quantitative guide to which clay minerals are present in the study area, prior to performing core analysis.

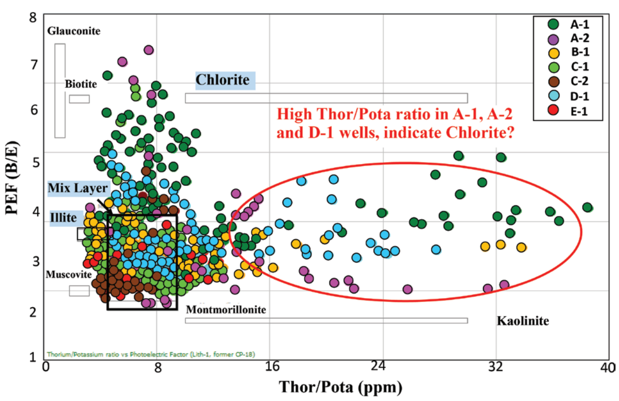

Figure 16. Schlumberger PE and thorium/potassium ratio cross plot, showing mainly mixed-layered clay, chlorite and illite clay minerals.

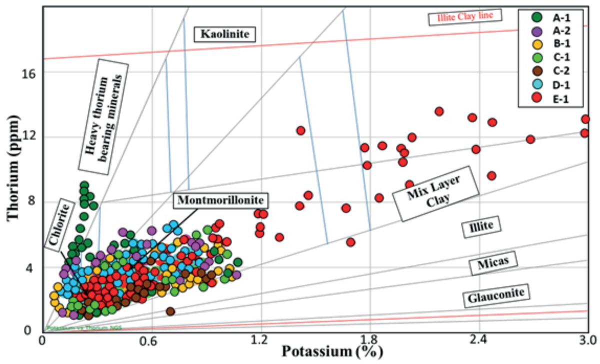

Figure 17. Schlumberger thorium vs. potassium cross plot, showing mainly mixed-layered clay, chlorite and illite clay minerals and montmorillonite.

5. Conclusions

Triassic TAGI sandstone is mostly a quartz arenite composed dominantly of quartz with minor feldspar. The authigenic components are mainly quartz overgrowth, clay minerals (mixed-layer illite/smectite, illite and chlorite), carbonate cement (calite and dolomite), anhydrite with dissolution of the carbomnate and anhydrite cement.

Higher production flow rates, porosities, permeabilities are tentatively associated with intervals with evidence of pervasive dissolution, elevated chlorite, and low levels of carbonate, illite and mixed-layer illite/smectite. Chlorite typically occurs as grain coatings that reduced porosity loss by inhibiting the precipitation of pore-filling quartz overgrowths. Dissolution can be observed in all wells, especially in the lower part of the TAGI reservoir attached to Hercynian unconformity, and is most obvious in the deeper part of the study area.

The reason that the deeper areas on the western side show higher production rates is related to more intense dissolution. This dissolution may be controlled by the hydrodynamic flow system above the Hercynian unconformity, where focused deep cross-flows drove the leaching of matrix cement. Another reason for elevated flow rates might be related to the effect of increased pressure during calcite cement dissolution. Today, the reservoir pressure in the deep area is higher than the shallow area by around 300 psi.

A porosity-permeability cross plot can be used to predict diagenetic intensity. Highly cemented areas are indicated by restricted zones in a porosity-permeability cross plot. High dissolution/ chlorite wells are indicated by broad spreads in the porosity-permeability cross plot and can be predicted to be the elevated permeability areas in the cross plot above high cementation areas.

Thorium/Potassium ratios indicate three main types of clay minerals in the TAGI, which are; mixed-layer clays, chlorite and illite, as confirmed by results from XRD and SEM analysis. It is prior information for clay minerals identification that can be ascertained before performing core analysis.

6. Future Work

The clay behavior are not yet fully quantified, especially the expansion capacity of the various clays. A study on which expansive clay components are present and in what proportions is important and future results should be used to support further production plans. The study on glycolation/CEC to identify expansive clay minerals is proposed and should be considered.

Modern and past brine flows through the TAGI reservoir have exerted a significant impact on reservoir quality. Varying pore brine chemistry drives secondary precipitates in pore space and this can dramatically reduce reservoir quality. Further analysis (stable isotopes?) on the timing and extent of carbonates in the TAGI should be performed to test the tentative conclusions from this study.

Sources of brine flushing the TAGI reservoir are not fully understand. Sources probably tie back to underlying Silurian marine mudstones or overlying Triassic evaporite-prone carbonate. The study on the sources of the brine should be conducted. Moreover, the hydrodynamic model, which controlle the leaching of matrix cements is still not fully quantified. Dissolution is known to significantly enhance reservoir quality in the study area. A better understanding of hydrodynamic model, including the effect of pressure to calcite cement dissolution, will help to predict the areas with higher dissolution levels and improved reservoir qualities.

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