Back to the Rocks: New Petrophysical Model for Siliciclastics Engaging Old Petrological Techniques*

Melissa Vallee[1]

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[1]Santos and The Australian School of Petroleum - The University of Adelaide, Adelaide, SA, Australia (melissa.vallee@santos.com)

Abstract

Providing reliable petrophysical interpretations in complex reservoirs can be particularly challenging. These challenges are exacerbated when the sediments are rich in lithic grains and subsequent diagenesis has modified the pore structure by filling the pores with a variety of clays and other cements. In order to constrain the petrophysical models for the oil reservoirs in the Eromanga Basin, an extensive petrological study was proposed, incorporating different techniques to quantify the mineralogy and pore structure and redefine the petrophysical model used in the area. The results of this work will provide a robust framework for the petrophysical models and will provide more reliable interpretations in future.

Introduction

Recognizing the diagenetic processes and how they influence the physical and chemical properties of the reservoirs has become an essential task in the oil industry. Whilst previous studies have defined the overall structure of the oil reservoirs in the Jurassic-Cretaceous succession in the Eromanga Basin in East-Central Australia, the presence of smectite and other clays and the influences of diagenesis have not been completely understood. Therefore, the development of a refined mineralogical model constitutes a very important input for the understanding of these reservoirs.

This paper documents the differences in the key oil reservoirs with regard to the composition of the original sediment and the diagenetic changes that influence each reservoir using X-Ray Diffraction analysis, Scanning electron microscopy (SEM) and thin section analysis. This, in turn, was used to redefine the petrophysical models for the area. The target sandstones were the Hutton, Birkhead, Westbourne, Namur and Cadna-Owie/Wyandra formations.

Objectives

1) Perform X-ray diffraction analysis (XRD) in conjunction with scanning electron microscopy (SEM) to identify and redefine the mineralogical composition of the reservoirs.
2) Build quartz feldspar rock fragments (QFR) plots on the framework composition for each reservoir sand to document provenance evolution through the succession.
3) Identify clay mineralogy by formation and depth.
4) Re-define the petrophysical model.

Procedures

Thin Sections Analysis

Wells with core data across the Eromanga Basin were selected to prepare twelve petrographic thin sections in order to identify the mineralogy and to expose the origin and evolution of the rocks. They were analysed using a polarizing petrographic microscope. The samples were positioned across the basin as follows:

- 1 sample in Well A in the Cadna-Owie Formation.
- 6 samples in Well B as representative of the Namur and Birkhead formations.
- 2 samples in Well C as a typical Westbourne Formation.
- 3 samples in Well D as a characteristic Hutton Sandstone.

Modal analyses were performed based on 200 counts per slide in different random traverses in order to construct a quartz-feldspar-rock fragments plot or QFR diagram using the Gazzi-Dickinson point counting method (Gazzi, 1966; Dickinson, 1970; Dickinson, 1985; Ingersoll et al., 1984). QFR plots are commonly used to classify sandstones based on the relative abundance of quartz, feldspars and rock fragments. These components are the principal poles in the ternary graph with the main components normalised to 100%.

X- Ray Diffraction Analysis

This is an analytical technique used to identify the crystallographic structure and physical properties of materials by comparing diffraction data against a database maintained by the International Centre for Diffraction Data (ICDD).

Two sets of samples were prepared for each interval; one to conduct the XRD analysis on the fine fraction in order to determine clay mineralogy, and the other one to carry out the analysis for the whole rock.

The XRD results from the laboratory were processed separately and the resulting charts were interpreted. The first step was the identification of the peaks as all minerals have a unique X-ray diffraction pattern. Subsequently, data for each well was displayed in the same chart to analyse where the changes in clay minerals occur with depth.

Scanning Electron Microscopy

The scanning electron microscope (SEM) scans the sample surface with a high-energy beam of electrons. The electrons interact with the atoms of the sample, producing signals that provide information about the surface topography and composition of the sample. Scanning electron micrographs have a very large depth of field, and can thus yield a three-dimensional image useful for understanding the structure of a sample (Trewin, 1988).

In order to apply this technique, samples must be electrically conductive, at least at the surface; therefore the rock samples were coated with a conductive material as such graphite (carbon) to avoid the accumulation of static electric charge at the surface during electron irradiation and to increase signal and surface resolution. After this, the carbon coated samples were place in the microscopy chamber to be analysed.

Petrophysical Modelling

The presence of various clays in reservoir rocks can significantly affect the evaluation of a formation as they can have a unique influence in some petrophysical parameters, such as porosity, often reducing it in a significant way. Subsequently permeability is also affected as a result of this reduction.

The wireline log interpretations conducted in each new well within the Eromanga Basin rely on the assumption than only certain types of clays are present in each formation. A robust petrophysical model needs to integrate the sedimentological environment, core and fluid analyses, production history and wireline log data. The last stage of this project was the construction of a petrophysical model in each formation that could reflect a more precise mineralogy, once all the framework and clay minerals were identified with the methods as described previously. This was achieved using wireline log data acquired in the wells employed for this study (density log, neutron, sonic transit time log, photoelectric factor, gamma ray and resistivity) and a multi-mineral approach in GEOLOG Multimin software by Paradigm™.

Results

Framework grain mineralogy was identified by examination of thin sections and QFR plots were built to understand composition and provenance evolution. Quartz and K-feldspars are dominant throughout the formations, with a higher occurrence of rock fragments in the Birkhead Formation and with minimal amounts of accessory minerals such as micas and zircon.

Results from the QFR plot suggest that the eleven rock samples fall in the arkose, subarkose and lithic arkose categories, but the Birkhead samples are feldspathic litharenites following the QFR classifications from Folk (1974).

The analyses of eleven plots of XRD results (Figure 1) and 120 SEM photomicrographs (i.e. Figure 2 and Figure 3) revealed the presence of smectite, kaolinite, illite, chlorite and mixed clay layers as the main authigenic clays. They occur in the formations as follows:

- Smectite, chlorite, and kaolinite in the Cadnaowie Formation.
- Chlorite, smectite altering to illite (I/S) and kaolinite in the Namur Formation.
- Chlorite, illite and kaolinite in the Westbourne Formation.
- Chlorite, illite, smectite/chlorite and kaolinite in the Birkhead Formation.
- Chlorite, smectite/illite, illite and kaolinite in the Hutton Formation.

The depth at which smectite is completely altered to illite differs from one basin to another. In the current study, the transformation from smectite to a mixed layer clay I/S starts at depths greater than 2171' and is fully altered at the next tested depth of 4315'. The transformation from mixed layer clay I/S to illite is likely to occur between 4871' and 5543'.

Additionally, the XRD results and thin section analyses identified the presence of siderite and calcite as the main cements in the Westbourne and Birkhead formations, whilst the major cements in the Namur and Hutton formations were silica and kaolin. The new petrophysical model adjusted the clay minerals through the formations and included smectite and chlorite for the Cadna-Owie Formation and chlorite for the Namur, Westbourne, Birkhead and the Hutton formations. Kaolinite and illite remained common compared with the former model. Although more minerals were identified in minor amounts, the petrophysical evaluation was restricted to model the same number of minerals as electrical logs acquired less one; five in this case. The remaining log available was used to calculate water saturation. Table 1 shows the mineralogy employed in the previous and new petrophysical models. Table 2 and Table 3 compare the results for petrophysical properties of the rocks using the former and new petrophysical models.

Overall, an increment of the volume of clays was observed within the formations as a consequence of the modifications in the clay mineralogy, thus increasing the volume of the water bound to the surface of the clays and diminishing total porosity. However, a slight increase of effective porosity values was noticed. This is possibly due to the addition of chlorite to the new model which has decrease the content of illite and kaolinite.

Porosity and water saturation represent important inputs for the volumetric calculation of hydrocarbons in place. Therefore, variations to these values from the original model will result in modifications if a new estimation of reserves is carried out.

Discussion

The suggested classification of Dickinson and Suczek (1979) supposes that the sediments are derived from a single source. Only the Birkhead Formation plots in the feldspathic litharenite zone. This indicates two sediment sources into the Eromanga Basin. The Hutton, Namur and Westbourne formations have a cratonic-transitional continental origin, whilst volcanic-fragment-rich sands are common in the Birkhead Formation and perhaps with some influence in Westbourne, Namur, and Cadna-Owie formations. The depositional models suggest an interplay between an eastern and a western sediment source with one or other dominant at different times.

Three different processes could be distinguished through the succession Cadna-Owie-Namur-Birkhead-Hutton in regard to the evolution of smectite. The early generation at shallower depths of smectite clays due to the degradation of volcanics, the conversion of this smectite to a mixed layered clay illite/smectite with depth and the possible more rapid conversion with temperature to illite if an elevated heat flow is present. Yet, kaolinite was widely seen in all the samples but less in the Cadna-Owie Formation.

The depth at which smectite is completely altered to illite differs from one basin to another. In the current study, the transformation of smectite to a mixed layer clay I/S starts at depths greater than 2188’ and is fully altered at the next tested depth of 4315’. The transformation of mixed layer clay I/S to illite is likely to occur between 4871’ and 5543’, but the exact depths where both changes may occur cannot be established due to the lack of samples within those ranges.
In general, illite and kaolinite are the most commonly observed clay minerals in this study, whilst chlorite and smectite are present but to a lesser extent. Since chlorite is the type of clay that contains iron and magnesium within its chemical structure, iron-magnesium

rich volcanolithics and/or mafic minerals (such as hornblende, pyroxene or biotite) can be typically inferred as being altered to chlorite.

The presence of chlorite was questioned at first, due to the difficulty of identifying its characteristic peak at the start of the XRD patterns. These difficulties were caused by noise and overlap with the kaolinite peaks. Although the signal/noise ratio for minerals like quartz and kaolinite/chlorite were acceptable, the signal/noise ratio for chlorite was very low as a result of the utilization of an old instrument for the analysis. However, the presence of chlorite was confirmed by SEM and a re-assessment of the sometimes bimodal peak around 29 degrees on the XRD plots.

Kaolinite and illite occur within the matrix of the sands, delivered along with the sand grains. All four clays, kaolinite, illite, smectite and chlorite, form as alteration products of the labile framework grains (feldspars and VRFs) and as cement. Kaolin, however, is the most common authigenic and allogenic clay.

Silica cement is present as quartz overgrowths in most samples investigated. Three main processes of quartz precipitation are identified through the succession. The first process generates silica cement by the alteration of feldspars to kaolin (Equation 1). The second process is related to pressure dissolution (stylolites), resulting from deep burial and late stage compaction. This process is more evident as depth of burial increases.

$$2((kNa)AlSi_3O_8 + H_2O + 2H^+ = Al_2[Si_2O_5](OH)_4 + SiO_2 + 2K^+2HCO_3^- \qquad (1)$$

Feldspar Kaolin Silica

In addition, the equation above illustrates that dissolution of feldspars also contributes to the formation of kaolin cement. However, another possible source could be the alteration of volcanic rock fragments.

The third process, the transformation of smectite to illite also releases silica (Equation 2). Besides the generation of illite and silica, this reaction also liberates sodium, potassium, magnesium and iron, which could contribute to the formation of different types of carbonate cements in later diagenesis.

$$Smectite + Al^{+3} + K^+ = Illite + Si^{+4} + Na^+ + Ca^+ + Mg^{+2} + Fe^{+2} + H_2O \qquad (2)$$

Based on XRD data, siderite is only present in the Birkhead Formation and in the top of the Hutton Formation. Usually this mineral precipitates in local reducing conditions in the presence of organic matter (Moore et al., 1992). The literature recognises the Birkhead Formation as being deposited in a lacustrine/coal swamp/floodplain environment (Paton, 1986); therefore, the reducing conditions are favourable and siderite is believed to be an early cement in this formation. This is significantly different to the formations above, such as the Namur Formation, where a fluvial environment and oxidizing conditions result in a very low probability of siderite precipitation.

The source of calcium to precipitate calcite cement includes formation water, intrareservoir shales and carbonate grains from marine origin but, given that the Birkhead Formation was deposited in a non-marine environment, the most likely sources are the water that has been expelled from compacting clays in the alteration of smectite to illite (Equation 2) and the dissolution/alteration of plagioclase feldspar.

Petrophysical evaluations in a siliciclastic system with a high clay content tend to underestimate the saturation of hydrocarbons if the conductivity of the clays is not considered. By contrast, porosity values could be overestimated when petrophysicists do not have the appropriate understanding of the occurrence of the different clays through the formations, as each has a unique way of affecting porosity.

The replacement of chlorite by calcite in the model changes the total porosity only slightly as the tool response parameters for the two minerals are very similar (i.e. chlorite and calcite have similar densities). However, the addition of chlorite does have a considerable impact on water saturation, and effective porosity. Overall the water saturation increases by 5-10% and effective porosity increases by 0.1-1%. Two factors need to be considered: 1) of all the clay types, chlorite has less negative effect in the total porosity of the formations and could be deemed as having a small amount of effective porosity, and 2) the increase in water saturation is related to the water bound to the chlorite structure. However, the volume of the total water saturation that will be produced out of the reservoirs could be arguable. In other words, the relative proportions of free water and capillary bound water is something that still needs to be established.

Since water saturation and porosity represent important inputs for the estimation of oil in place, changes observed in this study will ultimately decrease the calculated oil in place and it will cause modifications in a new estimation of reserves. The identification of chlorite using only wireline logs could be very challenging since chlorite is not a radioactive clay (as it does not contain potassium), thus the gamma-ray log is not affected by its occurrence. This may be the reason why chlorite has not been modelled previously when analysing these formations.

Conclusions

Clay distribution is a function of sediment provenance, sediment maturity and depth. All of the three methods employed for this study were chosen to fully understand clay mineralogy and distribution with the sands and within the stratigraphic succession. XRD proved particularly useful in the identification of the clays through the succession analysed.

Clay identification and semi-quantification by XRD was found to support the observations made from thin sections and SEM. Kaolinite and illite occur within the matrix of the sands and also as authigenic clays. All four clays (kaolinite, illite, smectite and chlorite) have formed as authigenic clays from the alteration products of the labile framework grains (feldspars and volcanic rock fragments (VRFs)) and as cement. Kaolin, however, is the most common authigenic and allogenic clay, present as tightly and loosely packed booklets, partially filling open primary porosity.

Depth of burial and original grain mineralogy has controlled the evolution and precipitation of authigenic clays throughout the succession. At shallower depths, smectite from VRFs is more stable and is altered to a mixed layer clay I/S with depth. The high geothermal gradient of the Cooper/Eromanga basins (Lemon, 2006) causes a rapid transformation of this mixed clay layer to illite, reaching its total transformation at depths between 4871 ft and 5543 ft.

The samples with a high content of lithics (volcanic-arc derived sediments), seemed to be more affected by diagenetic processes and in general were poor quality reservoirs. They contained higher amounts of matrix, presented more signs of compaction and rock fragments were altered to a range of clay types that filled primary and some secondary pore spaces.

The application of petrological techniques to samples from different fields allowed the identification of significant factors that influence reservoir quality. The petrological study showed that the main controls on permeability were diagenetic processes, and to a lesser extent, sorting and grain size. Reservoirs with advanced compaction and high authigenic clay content, especially illite, tend to have lower permeability than those with less clay and less compaction. Samples with a high content of carbonate cement generally had lower permeability than those samples showing only silica cement. Finer grained, poorly sorted sediments also tended to exhibit low permeability values.

Ultimately, good reservoir quality in the study area depends on rock composition at the time of burial. Quartz-rich sands provide a rigid framework that can preserve porosity and permeability whilst shaly-silty sands are more ductile and form rocks that are more susceptible to compaction.

A more thorough understanding of the current mineralogy allowed a more robust petrophysical model to be built, increasing the confidence of the rock properties results (porosity and water saturation). Partial dissolution of feldspars and lithics has created secondary porosity that can be detected by wireline logs. However, these secondary pores are not always connected and may not contribute to permeability and effective porosity.

The substitution of chlorite by calcite in the petrophysical model had only a minor impact on total porosity due to the very similar log properties for the two minerals. However, the change in both effective porosity and water saturation was significant. This was due to the effects of bound water associated with the chlorite. As a clay, chlorite has a high surface area per unit volume and will have some volume of clay-bound water, and this will contribute to the overall water saturation. Therefore, the impact of this increased water saturation will result in modifications to oil in place calculations.

Recommendations

Only five formations from the stratigraphic succession of the Eromanga Basin were included in this study due to time constraints. They were the Cadna-owie, Namur, Westbourne, Birkhead and Hutton formations. Additional studies should assess the Adori, McKinlay and Murta formations. Mineralogical variation within the studied formations was not addressed, and so a broader selection of samples in different fields across the basin and at closer vertical spacing should be chosen to determine more precisely the depth of conversion of smectite to illite.

K-feldspar-rich sands create high responses on the gamma ray tool, which usually causes an overestimation of clay content, so the employment of a spectral gamma ray tool for further drilling within the Eromanga Basin is recommended. This tool would provide a better assessment of the radioactive sands and non-radioactive clays.

In order to build a petrophysical model, assumptions are often made based upon the best available data. For example, there were no SCAL data available for any of the wells involved in this study. Consequently, suppositions were made regarding the appropriate Archie values (a, m and n) to be used in the calculation of water saturation, as regional SCAL results were used. These assumptions generate uncertainties in the petrophysical evaluation, so an appraisal of the sensitivity of water saturation and hydrocarbon pore volume calculations to variations in key parameters is recommended (sensitivity analysis) for further study.

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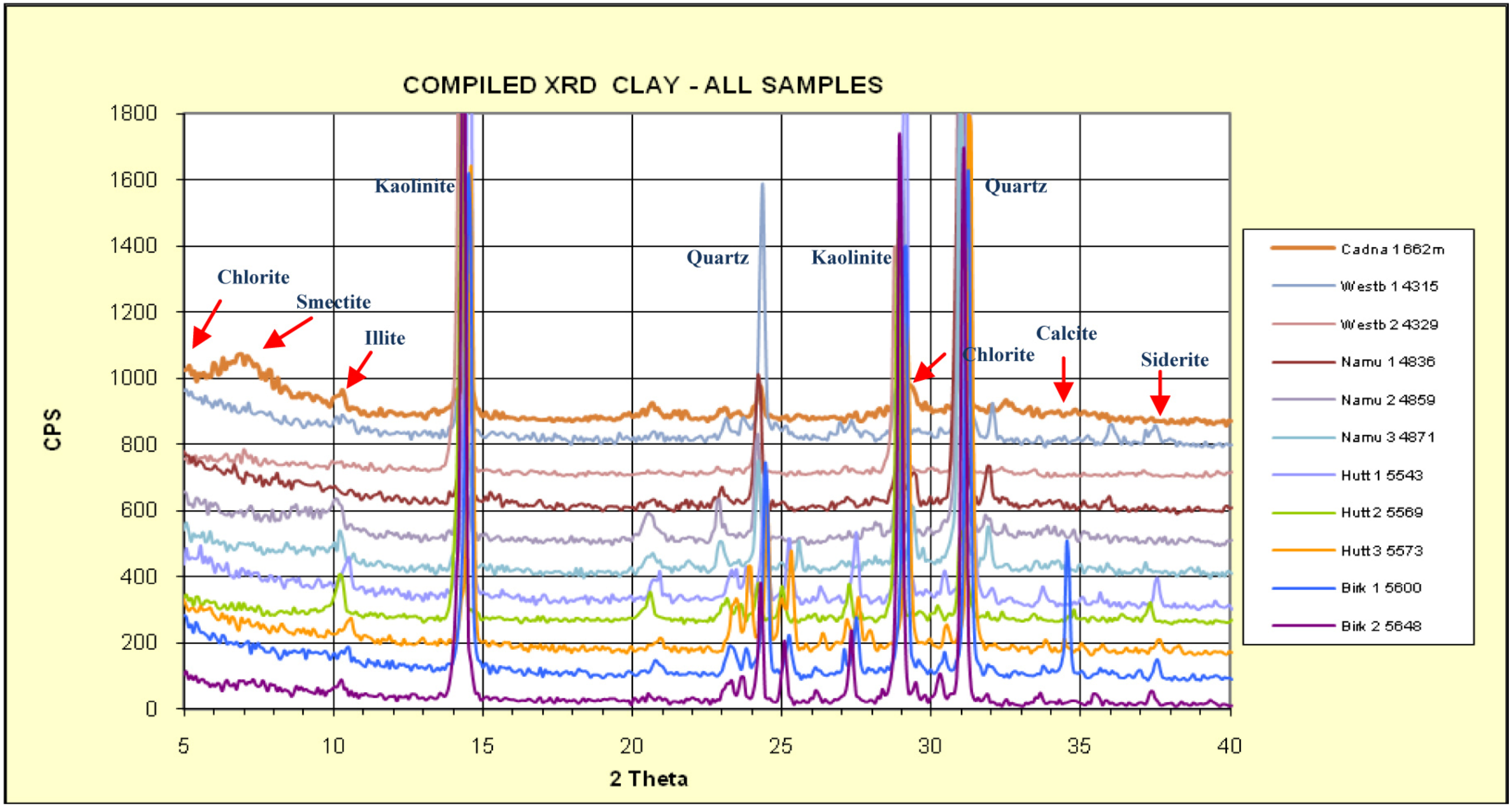

Figure 1. XRD plot showing the distribution of clay minerals and their evolution with burial depth.

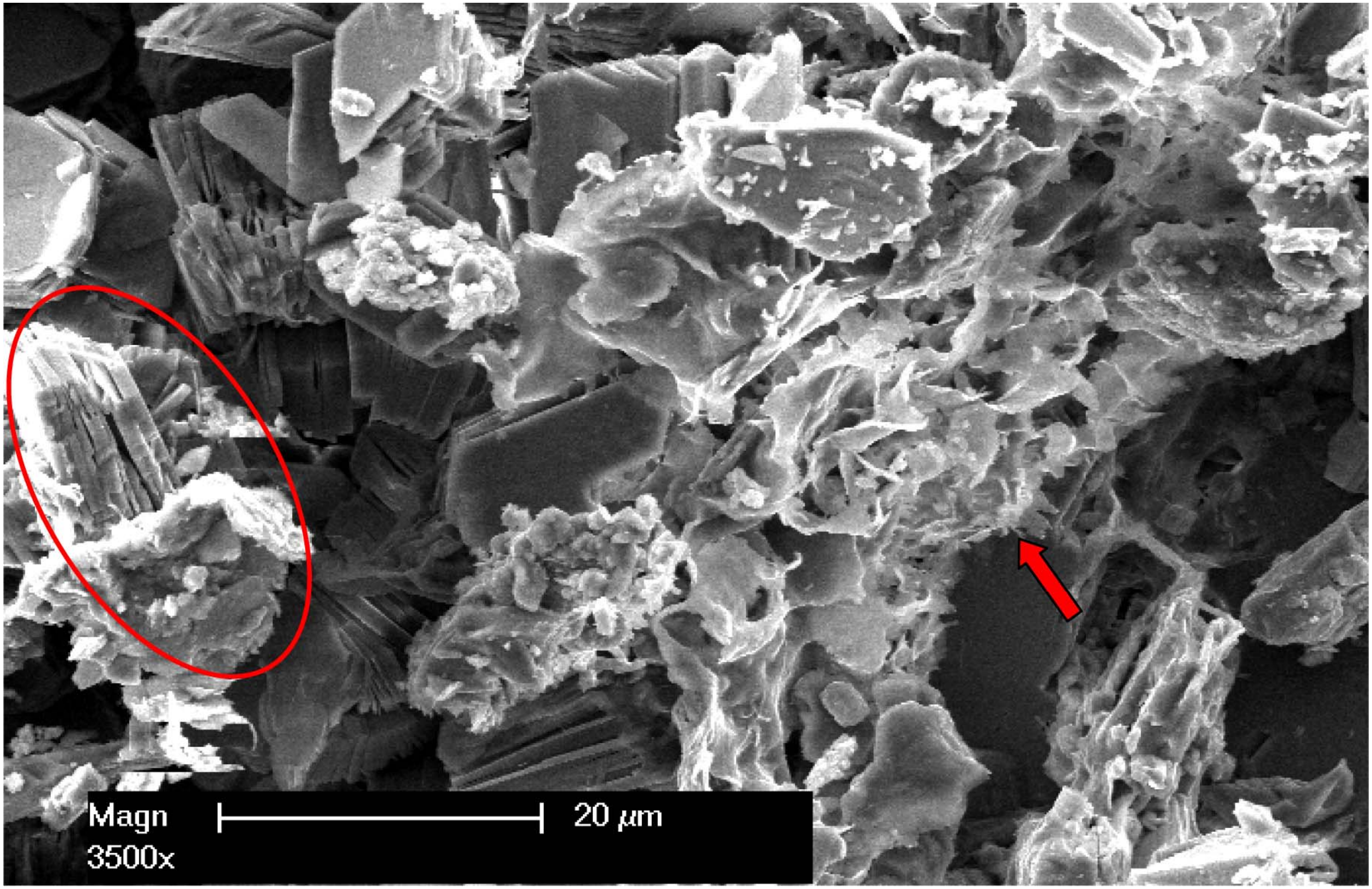

Figure 2. Booklets of kaolinite filling porosity (red circle). "Lettuce-like" smectite and chlorite (red arrow) are also part of the clay alteration, replacing a framework grain, of probably volcanic origin.

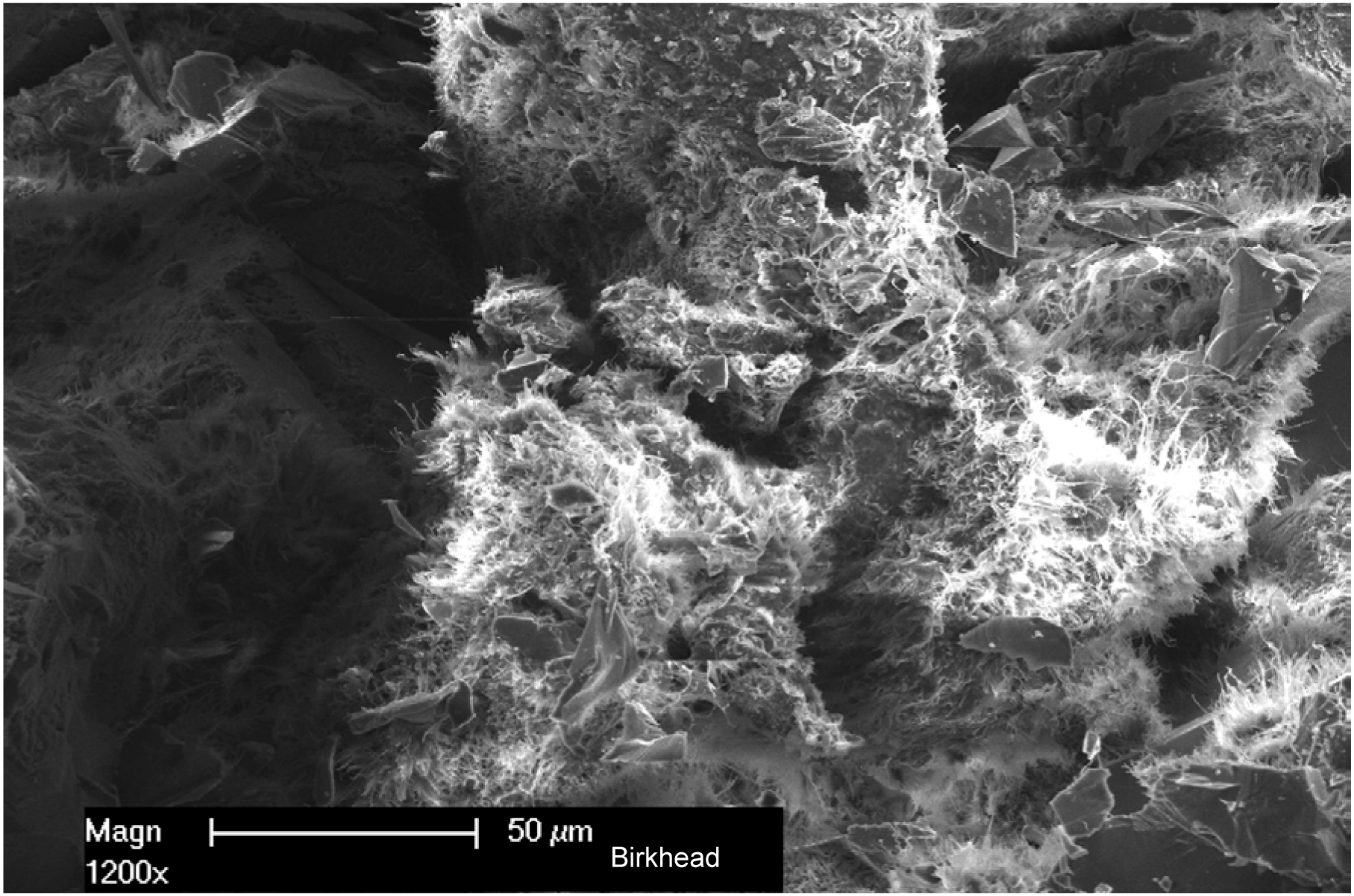

Figure 3. Fibrous illite growing into pore space in the Birkhead Formation.

Formation	Old petrophysical model	New Petrophysical model
Cadna-Owie	Quartz, calcite, illite, kaolinite, glauconite.	Quartz, illite, kaolinite, smectite, chlorite.
Namur	Quartz, calcite, feldspars, illite, kaolinite.	Quartz, feldspars, smectite/illite, chlorite, kaolinite.
Westbourne	Quartz, calcite, feldspars, illite, kaolinite.	Quartz, calcite, feldspars, illite, chlorite or kaolinite.
Birkhead	Quartz, calcite, feldspars, illite, kaolinite.	Quartz, siderite or calcite, feldspars, illite, chlorite or kaolinite.
Hutton	Quartz, calcite, feldspars, illite, kaolinite.	Quartz, siderite or calcite, feldspars, illite, chlorite or kaolinite.

Table 1. Comparison of minerals employed prior and currently.

WELL/FORMATION	AVG PHITp (%)	AVG PHIEp (%)	WT.AVG SW (%)
- Cadna-owie	21.7	8.4	98
- Namur	18.1	11.4	61
- Westbourne	18.2	12.6	61
- Birkhead	17.2	13.0	49
- Hutton	15.2	13	54

Table 2. Summary of petrophysical properties – former interpretation.

WELL/FORMATION	AVG PHITp (%)	AVG PHIEp (%)	WT.AVG SW (%)
Cadna-owie	21.5	9.1	95
Namur	17.9	12.3	67
Westbourne	17.8	13.2	67
Birkhead	16.7	13.1	58
Hutton	14.9	12.9	53

Table 3. Summary of petrophysical properties – new interpretation.