TO EXPLAIN THE NATURE OF CORE POROSITY USING RESULTS OF PETROGRAPHY ANALYSIS

by
Junita Trivianty Musu

ABSTRACT

The Permian to Triassic Tirrawarra Sandstone succession in the Cooper Basin of Central Australia is characterized by its low permeability. Ambient core porosity averages 8.96% and ambient permeability 0.9 mD. Most samples studied have permeabilities less than 3mD. Despite its overall poor reservoir characteristics, the Tirrawarra Sandstone is one of the major oil and gas targets in Australia. A total of 17 core plugs from 6 wells were studied petrographically using optical petrography, SEM and XRD. These results were integrated with core analysis data.

Petrographic study revealed the diagenetic events, mainly mechanical and chemical compaction, cementation and alteration have modified the reservoir quality. Ductile components such as rock fragments, clay and matrix influence mechanical compaction, which are the main cause of reservoir quality reduction. Quartz cementation and clay distribution also affected the porosity, but particularly permeability. Mechanical compaction as well as quartz cementation have reduced and blocked pore-throats to isolate intergranular pores. The alteration of feldspar to kaolin has changed intergranular porosity to microporosity. Illite occurs as either cement, alteration of rock fragments or kaolinite. All of these diagenetic events also affect fluid movement in the reservoir.

This paper presents the evaluation of the determination of effectiveness of porosity in the delivery of gas from sandstone reservoir in the Cooper Basin using integrated petrography analysis and core measurements.

Key words: core porosity, core permeability, petrography analysis, diagenesis.

I. INTRODUCTION

Assessment of low permeability gas reservoir sandstone of the Cooper Basin has been problematic for the operator in the area. Although many reservoirs sandstone have good porosity, the permeability of these rocks is highly variable. This study is an evaluation for the determination of the effectiveness of porosity in the delivery of gas from sandstone reservoir. The scope of the study is to asses the core results including porosity, permeability and irreducible water saturation with the result from petrography analysis.

II. STUDY AREA

The Cooper Basin, extending from northeastern South Australia into southwestern Queensland, covers an area of approximately 130,000 km2 (Figure 1). The basin contain Late Carboniferous to Middle Triassic sedimentary rocks and overlies unconformably Cambrian-Ordovician sediments of the Warburton Basin and are overlain unconformably by Jurrasic and Cretaceous strata of the Eromangga Basin (Battersby, 1976; Hill and Gravestock, 1995; Gravestock & Jensen-Schmidt, 1998).

The main petroleum reservoir in the basin is within Permian section, including the Tirrawarra Sandstone (Heath, 1989). About 85% of the oil reserves are reservoired in the Tirrawarra Sandstone of the Tirrawarra Field, whereas one-third of South Australia's Cooper Basin gas reserves are in the Big Lake and Moomba gas fields (Heath, 1989; Laws and Gravestock, 1998).

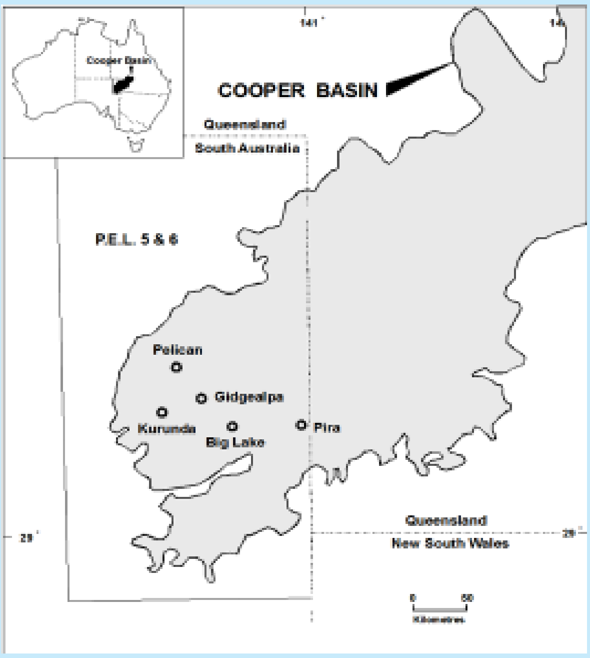

Figure 1
Location map of Big Lake, Gidgealpa, Kurunda, Pelican and Pira Fields of the Cooper Basin (after Rezaee, 1996)

Tirrawarra Sandstone consists mainly of fine to coarse-grained sandstones intercalated with thin siltstone, shales and coal beds (Thornton, 1979). The sandstone are mostly *arenites* with highly diagenetic influenced towards reservoir quality (William & Wild, 1984). The age of the Tirrawarra Sandstone is Late Carboniferous (Stephanian) to Early Permian.

III. METHODS AND MATERIALS

Seventeen core plug samples were selected on the basis of their low permeability from 6 wells in several different fields included Big Lake-31, Gidgealpa-49, Kurunda-2, Pelican-2, Pelican-3 and Pira-2. The samples were provided by Santos Ltd. These samples were characterized by dyed thin section, scanning electron microscopy analyses (SEM), X-ray diffraction analyses (XRD) analyses. Core analyses data was provided by Santos Ltd. The data includes porosity, permeability and water saturation at different conditions.

Table 1
Composition of the sandstone samples. The modal analyses are based on the point counting between 200 to 400 points per thin sections. QM = monoxtall quartz, QP = polyxtall quartz, NDRF = non ductile rock fragments, DRF = ductile rock fragments, AK = alteration kaolinite, M = mica, H = heavies, O = organic matter, Mat = matrix, QC = quartz cement, KC = kaolinite cement, SC = siderite cement, IC = illite cement, IP = intergranular porosity, MP = microporosity

Sample	QM	QP	NDRF	DRF	AK	M	H	O	Mat	QC	KC	SC	IC	IP	MP
JM-03	30	19	6	9	19	tr	tr	tr	5	9	1	1	0	0	0
JM-05	39	17	5	5	12	tr	tr	tr	8	6	3	3	1	0	0
JM-11	67.6	1	3	3	2	tr	tr	tr	4	3.5	1	1	1	10.4	2.5
JM-12	68.3	0	2	3	1	tr	tr	tr	4	4	2	2	1	11.5	1.2
JM-26	56.1	0	10.5	2	0	tr	tr	tr	1.4	15.6	2	0	0	11.1	1.3
JM-42	52.3	0	2.7	2.4	15.8	0.5	tr	tr	2	1.6	2	8.3	1.1	6.1	5.2
JM-46	45	10	4	8	10	tr	tr	tr	4	5	5	2	1	3	3
JM-48	52	12	4	5	4	tr	tr	tr	5	7	4	1	0	4	2
JM-49	50	8	5	8	5	tr	tr	tr	3	6	6	2	1	3	3
JM-50	62.6	3.2	4	4.2	3	tr	tr	tr	3	4.9	1	4.3	1	5.8	3
JM-51	47	12	1	4	4	tr	tr	tr	2	14	5	1	1	4	5
JM-53	63.3	3	2.5	2	1	tr	tr	tr	1	11	3.17	1.53	0	9.6	1.9
JM-55	39	11	3	5	2	tr	tr	tr	3	19	5	2	1	7	3
JM-56	38	3	9	5	3	tr	tr	tr	2	20	7	2	1	5	5
JM-126	39	20	3	10	4	tr	tr	tr	8	2	7	1	0	3	3
JM-127	30	27	5	7	3	tr	tr	tr	4	3	12	0	0	3	6
JM-128	43	14	5	8	2	tr	tr	tr	5	12	4	0	1	4	2

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IV. RESERVOIR PROPERTIES

A. *Texture*

Petrography revealed the grain size of the samples varies from very fine-grained to pebbly sandstones of about 0.12 to 0.27 mm or 1.9 to 3.1 using the *phi* scale. Grain size parameters were calculated based on statistical formulae by McManus (1988). Sorting in the Tirrawarra Sandstone sample set ranges from poorly sorted to well-sorted. Based on the visual comparison charts (Powers, 1953), the roundness of the samples varies from subangular to subrounded. Some subangular grains are quartz grains with overgrowths.

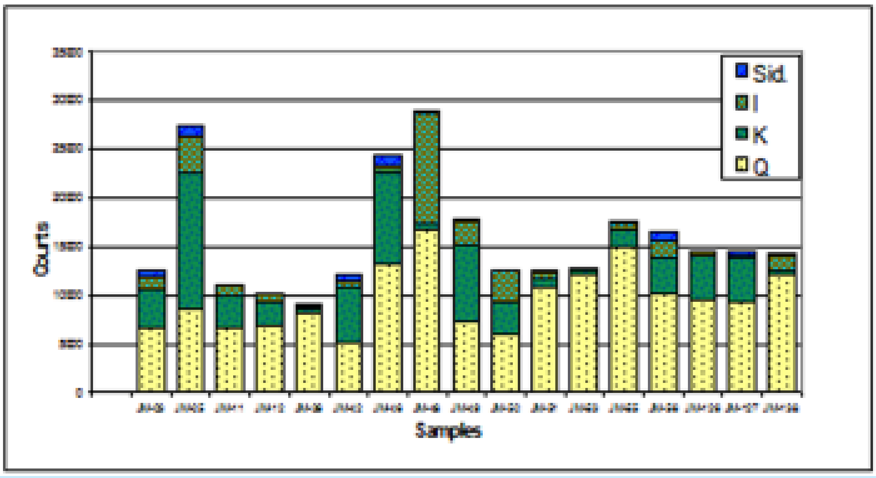

Figure 2
Semi-quantitative bulk XRD analysis showing relatively proportions between samples of the main minerals in the Tirrawarra Sandstone suite. (Note that the 4.26 Å peak of Q was used as the reference)

The samples show a variety of grain contacts, from tangential to concavo-convex. In the Tirrawarra Sandstone, grain contact style is dependent on the degree of compaction, a function of the amount of quartz cementation and the framework composition, especially the ductile components including ductile grains; matrix and clay cement (Rezaee, 1996). The degree of compaction will increase as the proportion of ductile components increase.

B. *Framework grain composition*

The Tirrawarra Sandstone studied samples are generally quartz-rich with additional rock fragments and minor components including mica and heavy minerals (Table 1). All of the Tirrawarra Sandstone on present mineralogy are classified as *sublitheranites* (Folk, 1974).

Quartz - is dominant (48% to 68.3%, with an average of 57.8%), mostly monocrystalline (53 to 100%). Hydrothermal and reworked sedimentary quartz grains are identified in minor amounts.

Rock fragments - including sedimentary and metamorphic grains (schist, shales and cherts). They are divided into non-ductile and ductile types. The proportion varies from 4.5 to 15% (average 11.1%). The proportion of rock fragments, especially the ductile types compared with quartz grains is one of the main controls on porosity and permeability.

Feldspar - is absent; it is assumed that feldspar has totally been altered to kaolinite. The amount of detrital clay matrix is mainly illite (1 to 8% with an average of 3.78%). Most of the kaolinite patches still show the original shape of the feldspar grains unless they dissolved. Feldspar alteration has an important role in the precipitation of quartz cement. Early alteration of feldspar grains in the Cooper Basin is one source of early silica cementation.

Detrital clay matrix - varies from 1 to 8% with an average of 3.78% by the total rock volume. Matrix is mainly as illitic clay. Similar to ductile rock fragments, the presence of matrix influences the reservoir quality. An increase of matrix mat lead to increased compaction.

Minor components - of the sample (less than 1%) include micas, organic matter and heavy minerals i.e. zircon and tourmaline.

XRD diffraction shows that the major components of the Tirrawarra Sandstone are quartz, kaolinite, illite and siderite. Based on the relative proportion of quartz and clays the samples were divided into two groups. The first group includes samples in which quartz is the dominant component compared to clays. This group includes most of the samples, except

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samples JM-05, JM-42, JM-49 and JM-50. In this group, kaolin dominated illite in most of the samples except sample JM-48 and JM-138. The amount of illite of JM-48 is relatively high. The second group has samples where clay is the dominant component compared to quartz according to the measured used. Kaolinite dominates illite in all samples. Siderite is found as minor component in both groups. The relative proportion of quartz and clays between samples in the suite provided useful information to assess the extent of compaction. Samples JM-26, JM-51, JM-53, JM-55 and JM-56 have quite high amount of quartz compared to clays, which also show relatively low compaction index (Figure 2).

C. *Diagenesis*

Diagenetic modification affecting the present *sublitharenite* sandstone includes compaction, cementation by silica, clays and siderite, alteration of feldspars, rock fragments and micas. The important factors controlling the

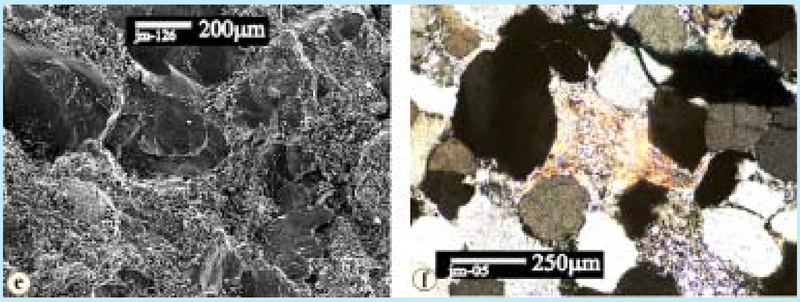

Figure 3
Photomicrographs of SEM (left) and thin section (right) shows the plastic deformation of matrix and ductile grains by mechanical compaction, squeezing the ductile components to the adjacent pore spaces

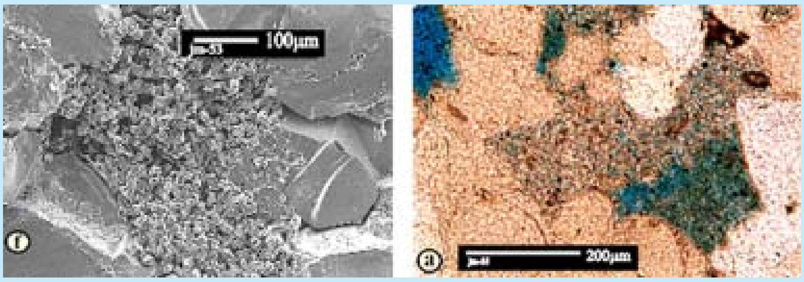

Figure 4
Photomicrographs of SEM (left) and thin section (right) shows quartz and kaolinite as the most common cement in most samples

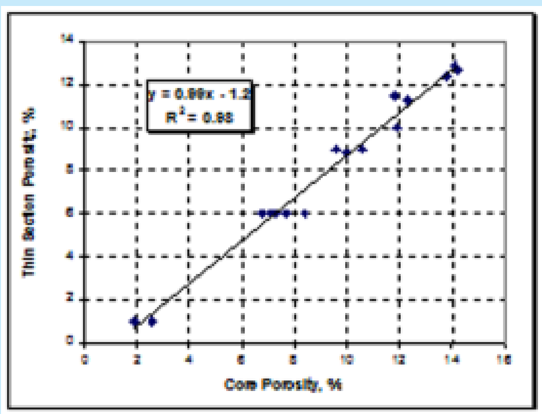

Figure 5
Ambient core porosity plotted against thin section porosity in the Tirrawarra Sandstone (Musu 2000)

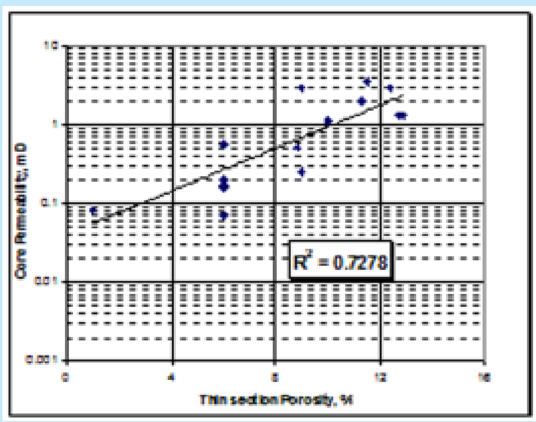

Figure 6
Semi-log cross plot of thin section and core porosity against ambient corepermeability (mD) of the Tirrawarra Sandstone (Musu 2000)

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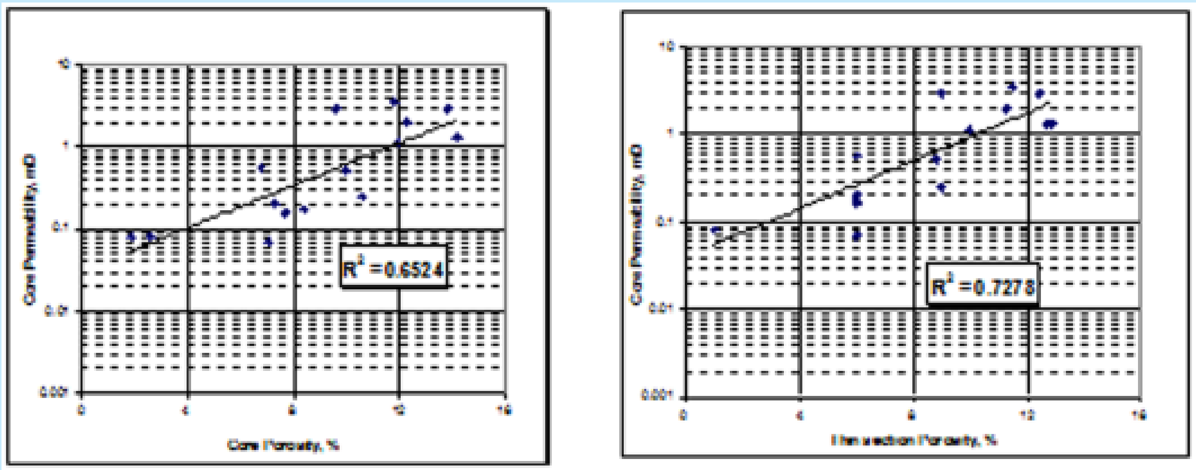

Figure 7
Semi-log cross plot of ambient core and thin section porosity (%) plot against ambient core permeability (mD) of the Tirrawarra samples

porosity reduction, mainly primary porosity and permeability are mechanical compaction and quartz cementation. The extent of compaction and cementation also depends on the grain size and sorting and sediment framework.

- Compaction

Mechanical compaction - is identified by the presence of bent mica flakes, plastic deformation of ductile grains and reorientation of non-ductile grains (Figure 3). Finer grained samples have higher mechanical compaction compared to coarser grained samples, which is obviously seen by the greater amount of compacted ductile grains and detrital clay matrix. It has not only reduced the intergranular volume but also the framework grain volume. This occurs with significant amounts of ductile grains (Houseknecht, 1987).

Chemical compaction - is recognized in lesser amount by the presence of concavo-convex and sutured grain contacts, stylolites and pressure dissolution seams, which are also more obvious in the finer grained samples where clay is associated with carbonaceous material. The sands with higher quartz cementation have fewer chemical compaction features.

- Cementation and alteration

Quartz - is the most common cement (Figure 4). Quartz cementation increases as any grains other than quartz decrease. Quartz cementation can be both destructive and preservational with regard to porosity and reservoir quality. Early precipitation of quartz overgrowths in quartz-rich sandstone provided a resistant framework and minimized further compaction to preserve porosity. In contrast, late stage quartz cement reduces the remaining primary porosity. Quartz overgrowths are recognized in thin section and SEM by euhedral faces and straight contacts between adjacent grains and dust rims over the detrital quartz grains.

Kaolinite - is the most abundant authigenic clay, mainly found in finer sands, mostly filling pores and blocking pore-throats (Figure 4). Two types of authigenic kaolinite were recognized, kaolinite as cement and alteration kaolinite. The kaolinite cement was the product of direct precipitation from pore-fluids, whereas alteration kaolinite is the total replacement of feldspar grains. Precipitation of pore-filling kaolinite cement alters intergranular porosity to microporosity. Fifteen to 40% of the total volume of occupied by authigenic kaolinite is observed as microporosity. The quartz and kaolinite are co-genetic, related to the alteration of feldspar in the presence of carbon dioxide.

Illite is another common authigenic clay mineral, occurring as cement and alteration of rock fragments and kaolinite. Illitization of kaolinite increases with depth as the amount of kaolinite and feldspar decreases (Hower et al., 1976). In the studied samples,

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it is also likely that the amount of illite cement increases with temperature gradient (pers. comm. Lemon, 2000), that can be related to the increasing of the burial depth regional and variations in the heat flux.

Siderite is the only carbonate cement as revealed by thin section, SEM and XRD. It is easily identified by its variety of forms including rhombohedral, blocky and radial forms, micrite and isolated blotches of pore-filling micro-sparry cement.

- Porosity and permeability

Porosity was evaluated using the integration of petrography, image analysis and core analysis data. Three types of porosity are recognized; primary intergranular porosity, secondary porosity and microporosity. Some samples also had a few fractures.

Primary intergranular porosity is the dominant porosity type. It mainly found in well-sorted high-quartz-cement sandstone. It is nearly absent in poorly

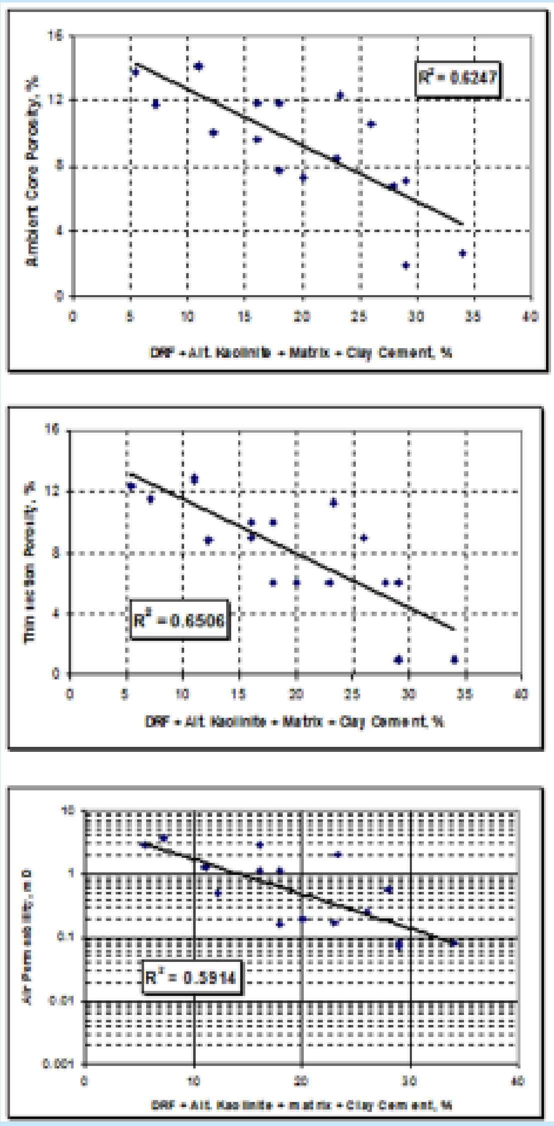

Figure 8
Effects on ductile components (minus non-ductile RFs) on porosity and permeability in the Tirrawarra Sandstone. (DRF=ductile RF; Alt. kaolinite=alteratio kaolinite

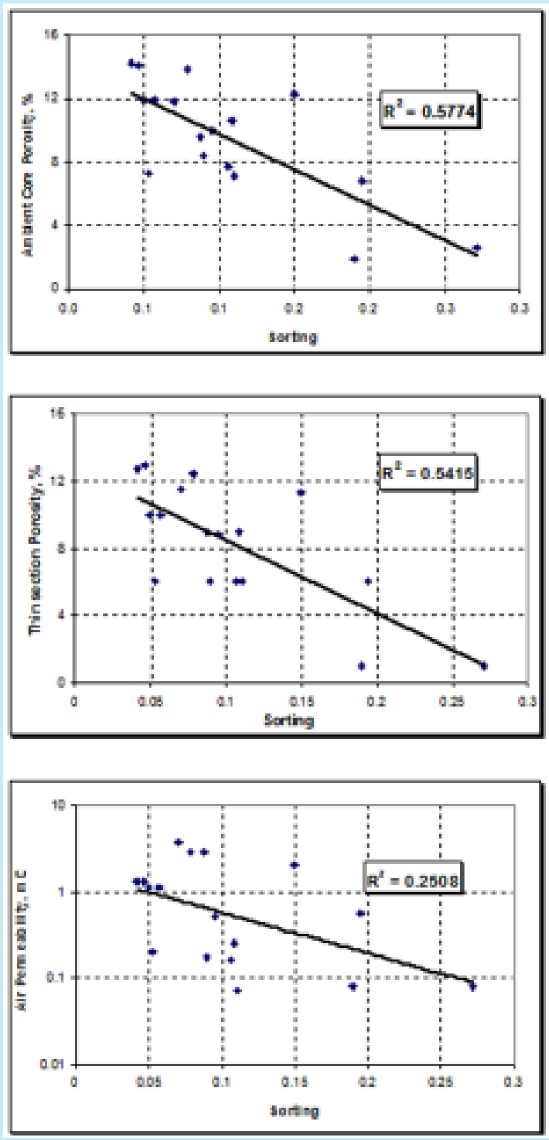

Figure 9
Effects on grain sorting on porosity and permeability in the Tirrawarra Sandstone samples

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and moderately sorted sandstones with high amount of matrix and ductile rock fragments. The pore diameter ranges from 0.06 to 0.14 mm with an average of 0.09 mm. Primary pores are often modified by partial filling with kaolinite. The remnant primary porosity between the quartz cement is clean and polygonal in shape.

Microporosity is the second most common porosity type. It is commonly present in association with authigenic kaolin clays. The diameters range from less than 1 mm to 30 mm with common diameters around 10 mm. It is mostly observed in samples with relatively low to moderate compaction with significant amounts of quartz and quartz cement.

Secondary porosity is insignificant. Most of the secondary porosity occurs as a result of labile grain solution, such as feldspar and rock fragment, siderite and clay dissolution. The sizes range from 0.3 to more than 0.5 mm.

- **Parameters controlling porosity and permeability**

Data from petrography and data from core analysis were compared. The plot of plug porosity versus thin section porosity indicates a consistent relationship (Figure 5). Porosity measured from thin section is usually lower than plug porosity and is usually explained by geometric factors such as undistinguished microporosity within the clay and ductile lithic grains. Thin section porosity often provides a better measure of effective porosity as it does not include micropores. The ambient porosity from core and thin section ranges up to 14.1 and 12.9% respectively, whereas the ambient air permeability reaches only as high as 3.6 mD with an average of about 0.9 mD at ambient conditions. Permeability in the samples studied is low, as the group was specifically chosen for the study.

Tirrawarra Sandstone samples at ambient air permeability show a good correlation with porosity, both ambient core and petrography porosity (Figure 6 and 7). In general the parameters, which influence porosity, also influence permeability. However, there are some other aspects that may also control the permeability separate from the porosity.

The porosity in the sample suite is dominantly controlled by mechanical compaction, an outcome of the occurrence of ductile grains; matrix and clay ce-

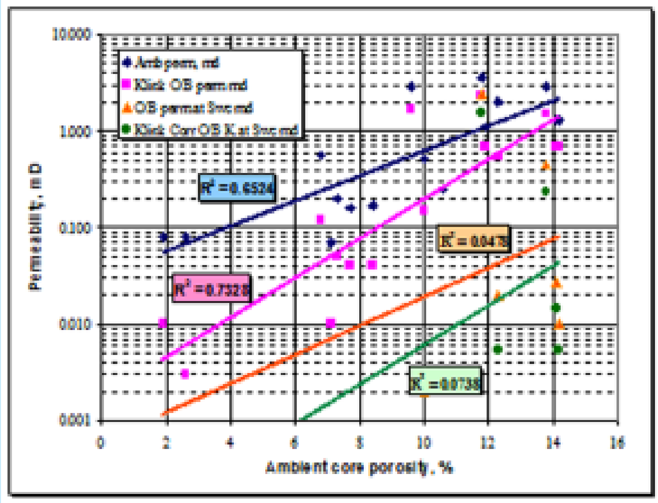

Figure 10
Semi-log cross plot of ambient core porosity (%) against permeability under different conditions (mD) of the Tirrawarra Sandstone samples

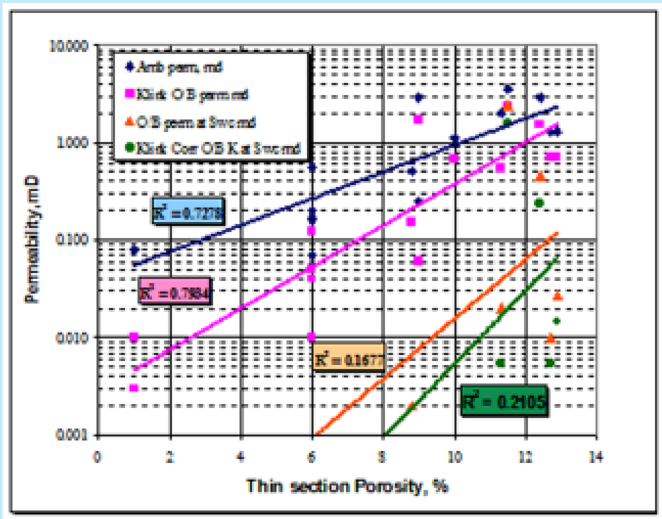

Figure 11
Semi-log cross plot of thin section porosity (%) against permeability (mD) of the Tirrawarra Sandstone samples

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ment (Figure 8). Well-sorted samples have higher porosity compared to poorly-sorted ones. Most of the primary porosity occurs in the well-sorted sandstone, and no primary porosity found in the poorly sorted sandstones. Figure 9 shows that the cross-plot of grain sorting versus porosity and permeability. The R^2 is relatively low for the permeability, but it demonstrate similar trend with the porosity. It is then believed that grain sorting also plays role in the presence of porosity and permeability. The grain size in the sample suite relative has similar size; therefore it does not show effect toward porosity.

The amounts of quartz cement do not show significant control on the amount of total porosity and permeability as seen by the weak correlation between the amount of quartz and quartz cementation and the amount of porosity. Although quartz cement has prevented the samples from significant mechanical compaction, but other factors such as pore-geometry and ductile components including rock fragments, clays have a greater affect on porosity and permeability reduction (refer to Figure 8). Quartz cement does influence microporosity that increases slightly with increased quartz content. Early quartz cementation protected the kaolinite from further compaction that also preserved the microporosity. At the same time the presence of ductile grains and illitization within the kaolinite plates or booklets proved to be the main influence for microporosity reduction.

Permeability shows a reasonable correlation with thin section porosity, because unlike core porosity, thin section porosity does not include the smallest micropores (Figures 10 and 11). Even so, ambient core porosity shows a slightly better correlation with overburden porosity in comparison with the thin section porosity. Ambient air permeability has also had good correlation with the overburden permeability. The differentiation of the porosity types has helped to estimate the cause of low permeability measurements. The size and packing density of kaolinite is a major control on permeability as all fluid movement needs to pass through masses of kaolinite plates.

Permeability decreases as compaction index increases. Overburden permeability shows a better correlation with compaction index in comparison with ambient permeability. This relationship suggests that the rock "decompacts" to some extent when core is brought to the surface. Other possibilities could be the collapse of very fine clay when the samples were dried. Therefore, the ambient permeability readings are artificially high. Because of this, it is necessary to compare the ambient reading to the overburden ones when assessing the permeability.

V. CONCLUSIONS

The main point of this study is to illustrate the usefulness of using diagenesis information to link petrographic information to core analyses data. Integrated petrography analysis supported by SEM and XRD has helped in assessing and evaluating core measurement results.

The main diagenetic event controlling the reservoir quality in the Tirrawarra Sandstone is mechanical compaction. Quartz cementation, however, in a few quartz-rich sandstones with low impurities, controls porosity reduction. The amount of ductile grains, matrix and authigenic clays controls the intensity of mechanical compaction, which in turn affects the porosity, particularly primary porosity. Generally, permeability is controlled by the same factors which control porosity but other factors such as clay types and their distribution, also play a part.

VI. ACKNOWLEDGEMENTS

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