RESERVOIR QUALITY REDUCTION CAUSED BY CLAY INDUCED DUCTILITY

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ABSTRACT

Ductile components including rock fragments, clay, and matrix material are often considered as the most important factors that control quality of shaly sandstones, which are usually characterized by low porosity and permeability. In presence of ductile components, the degree of quality reduction is affected mainly by distribution, occurences, and amounts of the ductile components. Therefore, the presence of ductile components affects rock petrophysics, and consequently has effect on fluid movements in reservoir during production.

This paper presents results of the study on plug samples taken from five wells from various fields in Cooper Basin (Tirrawarra Sand), South Australia. The samples were studied petrographically using x-ray diffraction, optical petrography, and scanning electrone microscope. The results were integrated with routine and special core analysis data. The overall results show that the distribution and the amount of ductile components have significantly reduced porosity, hence the quality of the reservoir. However, the effect is different for different types of porosity, and this certainly is valuable addition to our understanding over permeability behavior of shaly sandstones.

Keywords*: reservoir quality reduction, shaly sandstone, clay, ductility, compaction.*

I. INTRODUCTION

It has been long acknowledged that finding out the diagenetic history of sedimentary rocks such as sandstones is apparently of general interest to many earth scientists. In a more specific way, it is also increasingly realized that differences in diagenetic processes and mechanisms may differ in their way of modifying rock properties. This certainly affects the petrophysics of the rocks of interest, which in turn may influence many aspects of field development strategy. One product of a diagenetic process is the formation of minerals that are mechanically categorized as ductile material, thanks to their near plastic behavior under stress. In this light, presence of ductile components (i.e. rock fragments, matrix, and clay cements), as might be resulted from certain mechanisms in the diagenesis process, in reservoir rocks may have adverse effect on the rock's quality.

Ductile materials, as stated previously, and in accordance with the description by Beard and Weyl (1973) are undoubtedly found in many formations throughout the world including the Cooper Basin - Australia, which is the main focus of this study. Some investigators have conducted study on sandstone diagenesis including for the Cooper Basin shaly sandstones (Schulz-Rojahn & Phillips, 1989; Stuart *et al*., 1990; Tingate & Luo, 1992; Rezaee, 1996; and Rezaee & Lemon, 1996). In general, however, their studies were focused at investigating states of lithology, mineralogy, petrography, depositional environment, and compactions across the basin and its rocks. Not much attention was spent on the effect of the stressed ductile materials on the basin's reservoir rocks.

Considering the potentially significant state of compaction on the ductile materials in this basin, it is therefore the purpose of this paper is to review and

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study the effect of this compacted ductile material on reservoir rocks' petrophysical properties such as porosity and permeability. From this study it is hoped that relation between the presence of ductile material and petrophysical properties of reservoir rocks, shaly sandstones in this case, and their effect on the reduction of reservoir quality, can be shown. The experience on the ductile components present in the Cooper Basin shaly sandstones is hoped to be of some use for comparison to similar cases that may be found in other places.

II. METHODS

This study involved 17 sandstone core plug samples taken from five wells in several different fields in the Cooper Basin, South Australia. All samples were studied through dyed thin section, scanning electron microscope (SEM), and x-ray diffraction (XRD) analyses. Apart from the integrated petrographic analysis, special core analysis (SCA), routine core analysis, and mercury-intrusion capillary pressure (MICP) tests were also applied. Output data that include porosity, permeability, and water saturation at different conditions were integrated to the results obtained from petrographic analysis and then used to understand the effect of ductile components towards reservoir quality reduction.

III. CORE DESCRIPTION

A. *Mineralogy composition*

Compositional point counts from image analysis and the standard techniques (Pettijohn *et al*., 1978) were performed on all samples in order to quantify the mineralogy composition, grain size and thin-section porosity.

The sandstone samples studied are generally quartz-rich with additional rock fragments and minor components including micaceous and heavy minerals. Feldspar is absent from all samples, although it is suspected that much of the kaolinite was originally feldspars. All of the sandstone samples in term of present mineralogy composition are classified as *sublitharenites* (Folk, 1974).

Quartz is the predominant framework constituent in all the samples (48% to 68.6%, with an average of 57.8%), followed by rock fragments (4.5 to 15% with an average of 11.1%) including sedimentary and metamorphic grains (schist, shales, and cherts), which can be divided into ductile and non-ductile types. Feldspar is absent; it is assumed that feldspar has totally been altered to kaolinite (nil to 19%, with an average of 4.1%). The amount of detrital clay matrix is mainly illite (1 to 8% with an average of 3.78%). Minor components of the sample (less than 1%) include micas, organic matter, and heavy minerals (i.e. zircon and tourmaline) (Table 1). Siderite is mostly found as a minor component. Kaolinite dominates illite in all samples.

B. *Ductile components*

Ductile components included in the study are ductile rock fragments, matrix and authigenic clays mainly kaolinite and lesser amount of illite. The amount of ductile component presents in the sample varies from 5.4 to 34% (Table 1). The presence of ductile components (Beard and Weyl, 1973) tends to create microporosity and isolated macropores, which serves as the explanation for the low permeability of the sandstone samples (Figure 1). The presence of ductile components appears to consistently reduce porosity and permeability, as shown in Figures 2a and 2b.

C. *Texture*

Texture includes grain size and sorting. The grain size of the samples varies from very fine-grained to pebbly sandstones of about 0.12 to 0.27 mm. Sorting of the sandstones sample set ranges from poorly sorted to well-sorted. The roundness of the samples varies from subangular to subrounded. The samples show a variety of grain contacts, from tangential to concavo-convex. Grain contact style is dependent on the degree of compaction, a function of the amount of quartz cementation and the framework grain composition, especially the ductile components including ductile grains, matrix, and clay cements. The degree of compaction will increase as the proportion of ductile component increases.

IV. DIAGENETIC EVENTS

Diagenetic modification affecting the present *sublitharenites* sandstones include compaction, cementation by silica, clays and siderite, alterations of feldspars, rock fragments and micas. The sandstones sample set was originally deposited as *litharenite*, *feldspathic litharenite*, *lithic arkose* and *arkose*. The alteration of feldspar into kaolinite has changed the original framework grain composition.

Table 1
Compositions of the sandstone samples. The modal analyses are based on the point counting between 200 to 400 points per thin sections.

SAMPLE	QM	QP	NDRF	DRF	AK	M	H	O	Mat	QC	KC	SC	IC	IP	MP	DC
JM-03	30	19	6	9	19	tr	tr	tr	5	9	1	1	0	0	0	34
JM-05	39	17	5	5	12	tr	tr	tr	8	6	3	3	1	0	0	29
JM-11	67.6	1	3	3	2	tr	tr	tr	4	3.5	1	1	1	10.4	2.5	11
JM-12	68.3	0	2	3	1	tr	tr	tr	4	4	2	2	1	11.5	1.2	11
JM-26	56.1	0	10.5	2	0	tr	tr	tr	1.4	15.6	2	0	0	11.1	1.3	5.4
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	23.3
JM-46	45	10	4	8	10	tr	tr	tr	4	5	5	2	1	3	3	28
JM-48	52	12	4	5	4	tr	tr	tr	5	7	4	1	0	4	2	18
JM-49	50	8	5	8	5	tr	tr	tr	3	6	6	2	1	3	3	23
JM-50	62.6	3.2	4	4.2	3	tr	tr	tr	3	4.9	1	4.3	1	5.8	3	12.2
JM-51	47	12	1	4	4	tr	tr	tr	2	14	5	1	1	4	5	16
JM-53	63.3	3	2.5	2	1	tr	tr	tr	1	11	3.17	1.53	0	9.6	1.9	7.17
JM-55	39	11	3	5	2	tr	tr	tr	3	19	5	2	1	7	3	16
JM-56	38	3	9	5	3	tr	tr	tr	2	20	7	2	1	5	5	18
JM-126	39	20	3	10	4	tr	tr	tr	8	2	7	1	0	3	3	29
JM-127	30	27	5	7	3	tr	tr	tr	4	3	12	0	0	3	6	26
JM138	43	14	5	8	2	tr	tr	tr	5	12	4	0	1	4	2	19

Note : QM : mono-x-tall 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, DC = ductile components

Most of the diagenetic events in the sandstone sample set have reduced the porosity and permeability except the dissolution of the unstable grains and cements. The most important factors controlling porosity reduction, mainly primary porosity and also permeability, are the mechanical compaction followed by cementation. The extent of compaction and cementation also depends on the grain size and sorting and sediment framework.

A. *Compaction*

Mechanical compaction in the sample set is identified in thin section by the presence of bent mica flakes, plastic deformation of ductile grains and re-orientation of non-ductile grains as shown in Figure 1. Finer grained samples tend to have higher mechanical compaction compared to coarser grained samples, which is obviously seen by the greater amount of ductile grains and detrital clay matrix. Mechanical compaction has not only reduced the intergranular volume but also framework grain volume, which occurs with significant amount of ductile grains (Houseknecht, 1987).

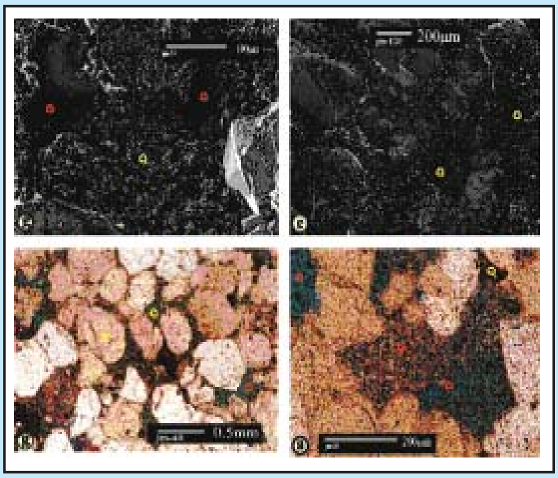

Figure 1
SEM photomicrographs show effect of mechanical compaction on ductile components. Primary intergranular pores are isolated due to compacted ductile components and quartz cement and also the pore lining clays. Yellow circles show ductile component, whereas red circles show isolated pores and micropores.

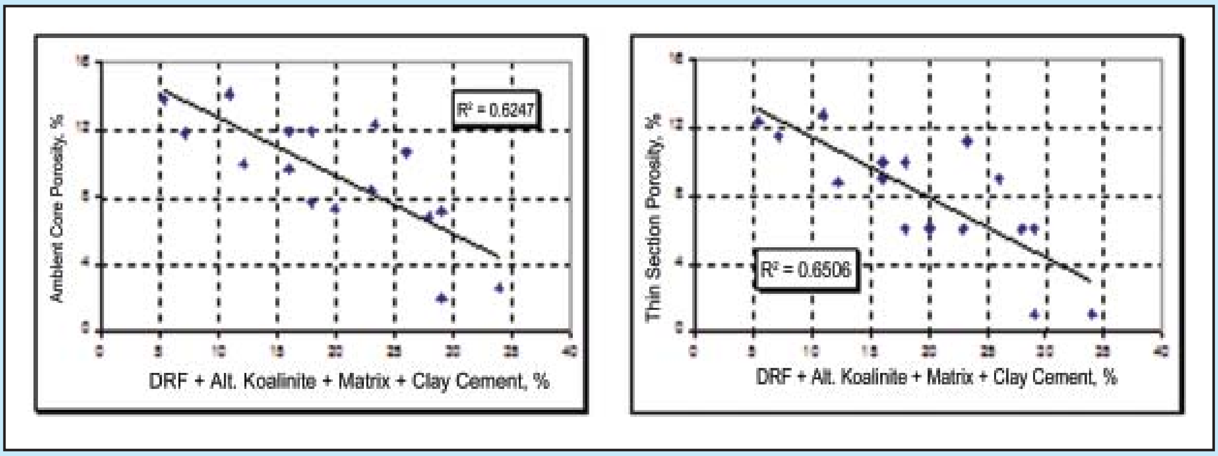

Figure 2a
Effect on ductile components on porosity, core (left) and thin section porosity (right). (DRF=ductile RF; Alt. kaolinite=alteration kaolinite).

The loss of the original porosity as a result of compaction was done by using Compaction Index of Rezaee and Lemon (1996). The following equation was used to measure the compaction index:

$$\text{Compaction Index} = \left[\frac{IGVo - IGV}{IGVo}\right] \times 100 \qquad (1)$$

Where IGVo is the original inter-granular pore volume at the time of deposition and the IGV is the presence of inter-granular pore volume.

The IGVo was estimated for individual sample by using the methodology of Beard and Weyl (1973) based on grain size and sorting. The IGV is the sum of inter-granular porosity and total cement. IGVo in the sandstone suite varies from 31.4 to 39.4%. Applying the above equation, the compaction index of the sample suite ranges from 11.2% to 67% as tabulated in Table 2. The amounts of ductile grains, matrix, and clay are the main factors controlling the compaction index. The presence of quartz cement in controlling the compaction index is obvious in quartz-rich sandstones (Figure 3).

Chemical compaction was also observed in the studied samples under thin section. This is indicated by the presence of concavo-convex and sutured grain contacts, stylolites, and pressure dissolution seams. Stylolites are commonly parallel to the bedding plane (Figure 4). These features are more obvious in the finer grained samples where clay is associated with carbonaceous material. The presence of organic

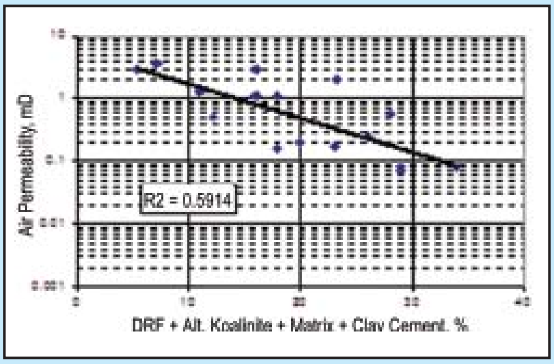

Figure 2b
Effect of ductile components on ambient permeability (DRF=ductile RF; Alt. kaolinite=alteration kaolinite).

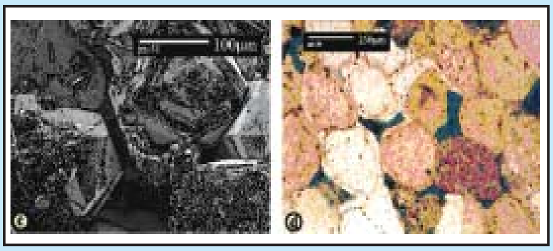

Figure 3
The presence of quartz cement in controlling the compaction index is obvious in quartz-rich sandstones.

matter catalysed pressure solution rather than the precipitation of quartz overgrowths (Pitmann, 1972). It is clear in the studied samples that sands with higher quartz cementation have less chemical compaction.

B. *Cementation and Alteration*

Cementation in the studied samples is the second main cause, after compaction, of intergranular porosity and permeability reduction. It includes quartz, clays, and siderite cementation. Quartz is the most common cement in the samples, varrying from 2% to 20%. Quartz cement increases as the presence of any other grains other than quartz decreases. In some samples, with fewer rock fragments, the precipitation of quartz cement preserved the original pores. The early precipitation of quartz overgrowths in quartz-rich sandstone has strengthened the grain framework against compaction, preventing destruction of the remaining intergranular porosity. In contrast, late stage quartz cement reduces the remaining primary porosity.

Intergrowths of quartz and kaolinite indicate that kaolinite precipitated during the development of quartz overgrowths. The co-genetic growths of quartz cement and kaolinite cement occur adjacent to the alteration kaolinite, as both are the products of early feldspar alteration.

Two types of kaolinite were recognized, kaolinite as cement and alteration kaolinite. Kaolinite cement was the product of direct precipitation from pore-fluids, whereas alteration kaolinite was the total replacement of feldspar grains. Kaolinite is the most abundant clay cement, up to 12% of total rock composition (Table 1). Kaolinite occurs as subhedral to euhedral booklets, which mostly fill pores and closes pore-throats. Precipitation of pore-filling kaolinite cement alters intergranular porosity to microporosity.

Illite is the second common authigenic clay minerals after kaolinite. There are three types of authigenic illite, namely illite as cement, alteration of rock fragments and illite as alteration of kaolinite. Under SEM authigenic illite is recognized by its fibrous lettuce-like habit (Figure 5, left). The occurrences of authigenic illite, together with other soft components including ductile rock fragments, matrix and kaolinite cement have reduced the reservoir quality by allowing significant compaction as in Figures 1 and 4.

Table 2
Compaction related to cementation, mechanical compaction and primary porosity

SAMPLE	CEPL	COPL	IGV	IGVo	CI
JM-03	35	65	11	31.4	65
JM-05	38	62	13	34.1	61.9
JM-46	38	53	16	34.1	53.1
JM-48	33	56	16	36.75	56.5
JM-49	41	51	18	36.75	51
JM-51	57	32	25	36.75	32
JM-55	69	14	34	39.4	13.7
JM-56	76	11	35	39.4	13.7
JM-126	25	67	13	39.4	67
JM-127	44	47	18	34.1	47.2
JM-138	43	47	21	39.4	46.7
JM-11	28	46	21.4	39.4	45.7
JM-12	33	38	24.5	39.4	37.8
JM-26	33	39	24.1	39.4	38.8
JM-42	30	54	18.1	39.4	54.1
JM-50	41	42	21.3	36.75	42
JM-53	53	21	31.1	39.4	21.1

Note :
CEPL : original porosity destroyed by cementation
COPL : original porosity destroyed by compaction
IGV : intergranular pore volume, IGVo : original intergranular pore volume and CI : compaction index (all in %).

Figure 4
Chemical compaction was observed under thin section by the presence of concavo-convex and sutured grain contacts, stylolites and pressure dissolution seams. Stylolites are commonly parallel to the bedding plane

Siderite is the only carbonate cement in the studied samples. The proportion varies from 0 to 8.3% of rock volume (Table 1). Siderite is easily identified by its variety of forms including rhombohedral, blocky and radial forms, micrite, and isolated blotches of pore-

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filling micro-sparry cement (Figure 5, right). Minor siderite dissolution occurs in the studied samples creating insignificant secondary porosity.

V. POROSITY AND PERMEABILITY

Porosity is evaluated by using the integration of petrography, image analysis, routine, and special core analysis (SCA) data. Three types of porosity are commonly found, namely primary intergranular porosity, secondary porosity, and micro-porosity. Some samples also had a few fractures. Primary intergranular porosity is the predominant type (0 to 11.5%), mostly observed in well-sorted high quartz cement sandstone, and nearly absent in poorly and moderately-sorted sandstone with high amount of matrix and ductile-rock fragments.

Microporosity varies from trace amounts to 5%, commonly presents in association with kaolinite clays, mostly observed in samples with low to moderate compaction with significant amounts of quartz and quartz cement. Secondary porosity occurs insignificantly, where only a few samples exhibit this type of porosity. Core permeability is low, varying from 0.01 to 3.6 mD with an average of 0.9 mD at ambient conditions.

VI. RESULTS

A. *Comparison of Cementation versus Compaction*

Comparison of the amount of quartz cementation against the amount of ductile rock fragments and matrix allows the extent of mechanical compaction in the sample set to be divided into two catagories; low to moderate and moderate to high (Figure 6). According to Houseknecht (1987), porosity can be reduced to 26% in well-rounded, matrix free, ductile free sandstones by mechanical compaction. Most of the samples studied contain low to high amounts of both ductile grains and matrix. The extent of compaction in the studied samples could be predicted by applying the 26% IGV as the normal porosity reduction.

Modified Houseknecht plot (Houseknecht, 1987) was also used to asses the relative effect of compaction and cementation on porosity (Figure 7). The modified Houseknecht plot requires four main factors including the original intergranular pore volume (IGVo), the present intergranular pore volume (IGV),

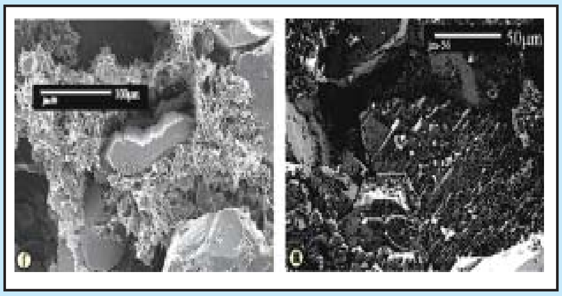

Figure 5
Illite cement substantially reduces pore-pthroats (left). Euhedral, blocky siderite spars cement filling porosity.

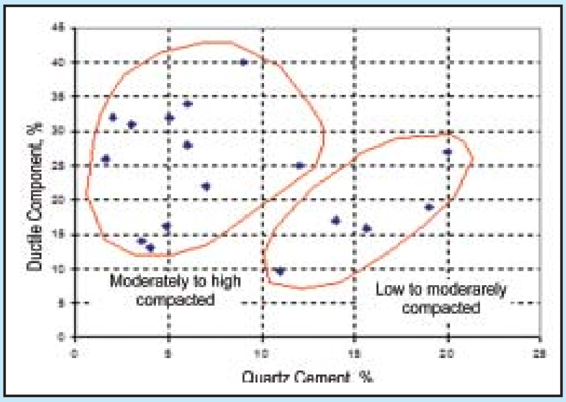

Figure 6
Two groups of samples based on the comparison between the proportion of ductile components and quartz cements

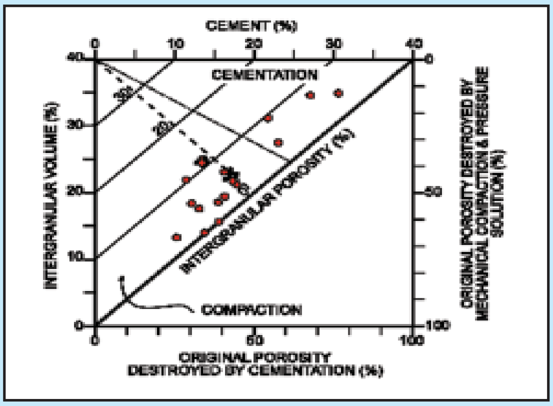

Figure 7
Modified Houseknect plot shows that the mechanical compaction has grater effect on porosity in most of the samples.

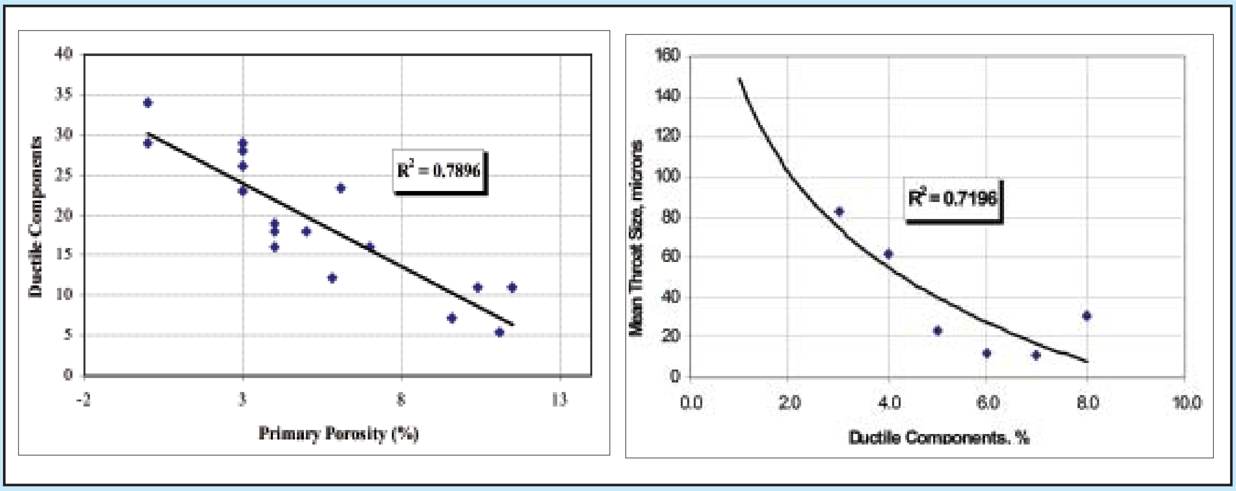

Figure 8a
Ductile components have different effect on porosity type i.e. primary intergranular type (left) and micro-porosity (right)

original porosity destroyed by cementation (CEPL), and original porosity destroyed by compaction (COPL). With sifgnificant amounts of ductile rock fragments and matrix, the IGVo based on Beard and Weyl (1973) was used for each sample instead of using 40% as the IGVo. The modified Houseknecht equations are expressed as follows:

$$IGV = Total\ cement + Primary\ Porosity \qquad (2)$$

$$CEPL = \frac{Cement}{IGVo} \times 100 \qquad (3)$$

$$COPL = \frac{IGVo - IGV}{IGVo} \times 100 \qquad (4)$$

The modified Houseknecht plot suggests that in this particular sample set mechanical compaction has greater effect on porosity compared to cementation in most of the samples. Nevertheles, ductile components as the main factors controlling mechanical compaction give different effect toward porosity types. It seems that ductile components have greater effect on primary porosity than on micro-porosity (Figure 8a). On the other hand ductile components also give significant effect on the mean throat size which in turn effect the permeability of the rocks. Mercury injection capillary pressure (MICP) data was only applied on 6 representative samples (Figure 8b).

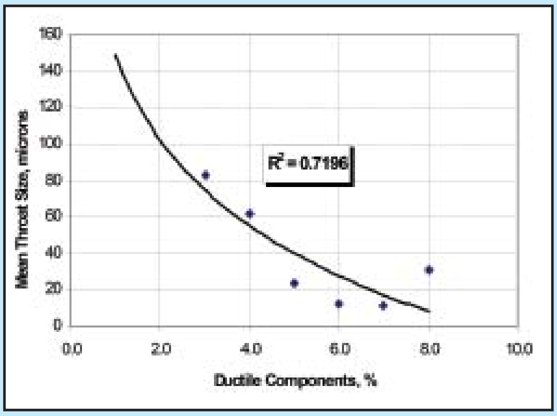

Figure 8b
Ductile components have significant effect on pore-throat size.

B. *Effect on Porosity and Permeability*

Data from petrographic analysis and data from core measurements were compared. The plot of plug porosity versus thin section porosity indicates a consistent relationship (Figure 9). 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.

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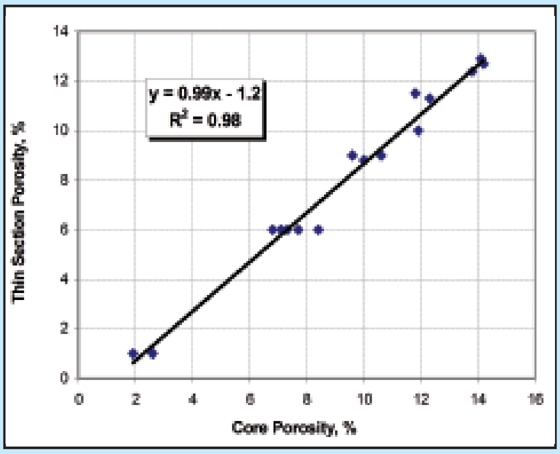

Figure 9
Ambient core porosity plotted against thin-section porosity in the Tirrawarra Sandstone

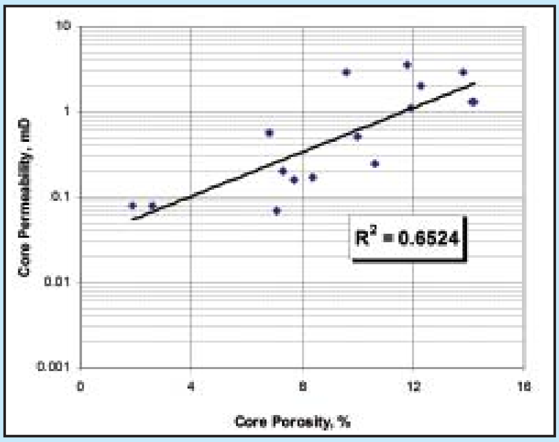

Figure 10
Semi-log cross plot of ambient core porosity (%) against ambient core permeability (mD) of the Tirrawarra samples.

The ambient air permeability shows a good correlation with porosity, both ambient core and thin section porosity (Figures 10 and 11). It could be assumed that in general the parameters, which influence porosity, would also influence permeability. However, there are some other aspects that may also control the permeability separate from the porosity. The porosity is dominantly controlled by mechanical compaction, an outcome of the occurrence of ductile grains including clay clasts, matrix, and clay cement as they show correlation as shown in Figure 2. This figure shows that thin section porosity has slightly better correlation with the ductile component compared to core porosity.

On the contrary, the amount of quartz cement does not show significant control on the amount of total porosity and permeability as indicated by the weak correlation between the amount of quartz and quartz cementation and the amount of porosity observed in the samples. As discussed before, quartz cement has prevented the samples from significant mechanical compaction, but other factors such as pore-geometry and ductile components (including rock fragments and clay both as matrix and cement) are believed to have a greater effect in porosity and permeability reduction.

Microporosity increases slightly with increase of quartz both as grain and cement, as early quartz cementation protected the kaolinite from further compaction. At the same time the presence of ductile

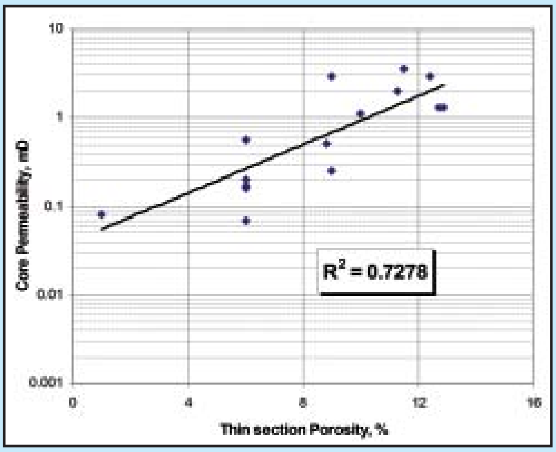

Figure 11
Semi-log cross plot of thin section porosity against ambient core permeability (mD) of the Tirrawarra Sandstone

grain including illitization within the kaolinite plates proved to be the main influence for microporosity reduction, as shown in Figures 3 and 5.

From thin section analysis, it is observed that permeability shows a reasonable correlation with porosity because, unlike plug porosity, thin section porosity does not include the smallest micropores (Figures 12 and 13). Nevertheless, ambient core porosity shows a slightly better correlation with overburden porosity in comparison to the thin section (Figure 14).

Ambient air permeability also has good correlation with the overburden permeability (Figure 15).

The various proportions of different types of porosity in shaly sandstone in the Cooper Basin would lead to the scattered plot between porosity and permeability that has helped to estimate the cause of low permeability measurements. 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 experienced decompaction to some extent when it was brought to the surface. Other possibilities for the better correlation of the overburden permeability when plotted against compaction index are that the movement or collapse of fibrous and very fine clay when the samples were dried. This leads to artificially higher permeability. Because of this reason, it is crucial to compare the ambient reading to the overburden ones when assessing the permeability.

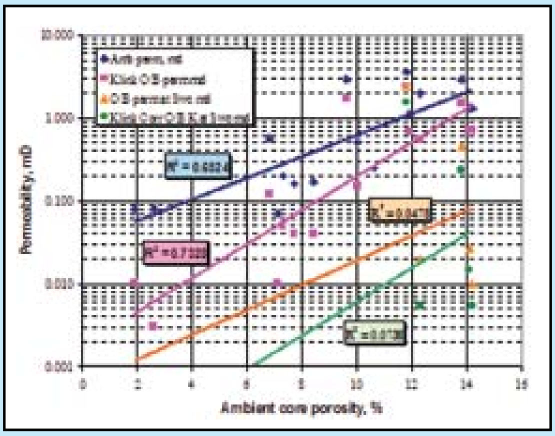

Figure 12
Semi-log cross plot of ambient core porosity (%) against permeability under different conditions (mD) of the Tirrawarra Sandstone samples

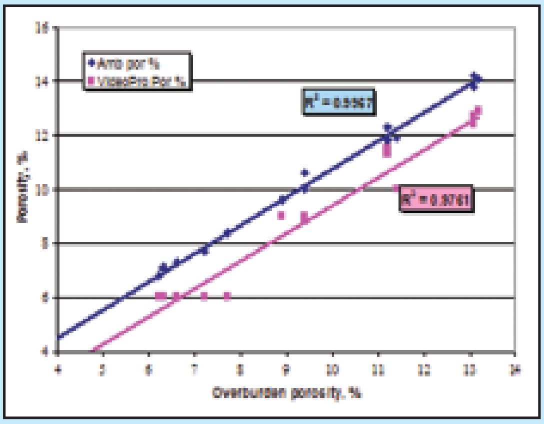

Figure 14
Overburden core porosity (%) plotted against ambient core porosity (%) and thin section (Videopro) porosity (%) of the Tirrawarra sandstone

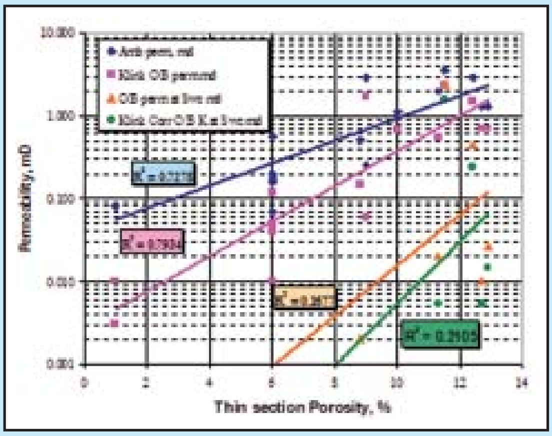

Figure 13
Semi-log cross plot of thin section porosity (%) against permeability (mD) of the Tirrawarra Sandstone samples

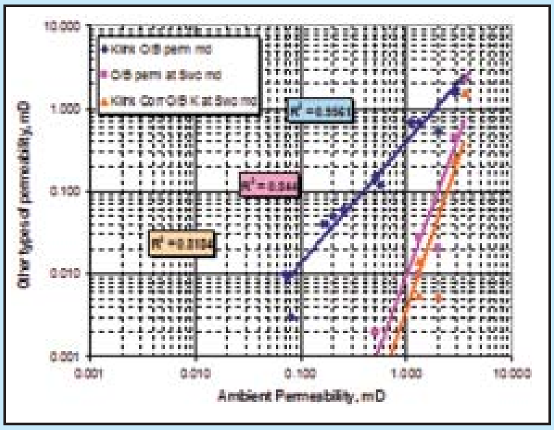

Figure 15
Log-log cross plot of ambient permeability (mD) versus overburden permeability at different conditions (mD) of the Tirrawarra Sandstone

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VII. CONCLUSIONS

From the study that has been conducted, several main conclusions can be derived. The main diagenetic events controlling the reduction of resevoir quality in terms of porosity reduction in most of the samples is mechanical compaction. Quartz cementation, however, in a few samples, particularly in quartz-rich sandstone with low impurities, controls porosity reduction. The amount of ductile grains including clay clasts, matrix, and authigenic clay controls the intensity of mechanical compaction, which in turn affects the total porosity, particularly primary porosity. However, in this particular sample set ductile component does not give significant effect to microporosity. Ductile component gives significant effect on pore-throat size, which also affects the permeability.

Generally permeability is controlled by the same factors which control porosity but other factors such as clay types and other ductile components and their distribution also play a part. Differentiation of the porosity types would help to estimate the cause of low permeability measurements.

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