PETROGRAPHIC CHARACTERISTICS AND RESERVOIR QUALITY OF SANDSTONE RESERVOIRS FROM ENRECA-3 WELL IN BACH LONG VI ISLAND

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Summary

This paper presents the relation of petrographic characteristics and diagenetic process to the reservoir quality of sandstone units in the Enreca-3 well. The results of petrographic study show that almost all studied sandstones are fine- to medium-grained ones. All studied sandstones are quite clean and classified as arkose sandstone. The detrital grains of studied sandstones are mostly angular, subangular to subrounded in grain shape and mostly poor to moderate sorting. Arkose sandstones are composed of mostly quartz and feldspar with much smaller amount of rock fragments such as granite, volcanic, quartzite, schist, and sandstone. The sediments were derived mostly from continental block provenance. The sandstones were in the early diagenetic stage. The petrographic study also reveals that the visible porosity of studied sandstones has been strongly damaged by cementation, whereas the mechanical compaction has not significantly affected the visible porosity of these reservoir sandstones. The visible porosity of studied sandstones is fairly good with mostly well preserved intergranular pores (7.6 - 19.4%, average ~15%) and minor micropores within clay patches (~1.0 - 2.0%), and further enhanced with secondary pores (1.4 - 1.8%) due to the dissolution of uncertain grains such as feldspar and lithic fragment.

Key words: *Origin, diagenetic process, reservoir quality, sandstone, Enreca-3.*

1. Introduction

The ENRECA-3 well is located in Bach Long Vi island in the northeast of Song Hong basin. This is a fully cored well with approximately 500m in the interval from 0m to 500m. According to legacy data, the sediments in this studied interval belong to late Oligocene and were deposited within the deep water lacustrine [1]. The reservoir quality of sandstones is often controlled by diagenetic processes (i.e. cementation, compaction, dissolution and mineral conversion) and by the rock texture such as grain size, grain shape and grain sorting. After sand has been deposited and buried, sediments begin to undergo diagenetic processes, which turn the unconsolidated materials into a sedimentary rock. To predict the reservoir quality of sandstone reservoir rocks, we need to measure the effects of diagenesis on porosity and permeability. This requires a quantitative understanding of what cements occur in the reservoir rock and how they are distributed.

This study programme, with a total of twenty core samples in the interval from 101.25m to 371.93m and from 18.30m to 499.68m, was carried out using thin section analysis and XRD analysis for clay fraction, respectively. Thin section analysis helps to estimate the rock-forming minerals, rock texture, rock name, post-depositional alteration as well as the relation of other characteristics of the rock to the reservoir quality. The determination of mineral composition and visible porosity has been performed by the modal analysis of 500 counting points in each thin section after the method of L.Van der Plas [4]; Soloman and Green [5]. The sandstone is classified using R.L.Folk's classification [7]. The grain size distribution of sandstones was measured by long diameter of 100 grains per thin section. The textural terminology such as mean grain-sized (Mz), grain sorting (δ1), grain size distribution (SK1) and the peakedness of grain size distribution (Kg) is based on the classification of R.L.Folk and W.C.Ward [6]; F.J.Pettijohn [3]. The classification of the forming provenance is based on plate tectonic and sandstone composition of Pettijonh, 1973 and Dickinson [10]. Assessment of the relationship of the compaction process and cementation to damages of porosity in sandstones is after David W.Houseknecht [2]. The clay fraction analysis determines the volume percentage of each individual clay mineral of sandstones and helps to define the burial diagenetic evolution of the rocks.

2. Results and discussion

Petrographic analysis shows that all studied samples in the interval between 101.25 - 371.93m are arkose sandstones according to R.L.Folk's classification (Fig.1). The classification of the forming provenance of the rock is displayed in Fig.2, which reveals that arkose sandstones were mostly originated from continental block provenance.

The texture and the detailed composition of the reservoir sandstones are shown in Table 1 and the

Table 1. *The petrographic data of sandstones from Enreca - 3 well*

Depth (m)	Rock Classification	TEXTURE								MINERAL COMPOSITION (%)																									Visible porosity		
		Grain size (mm)				Sorting(δ1)	Sorting class	Roundness	Grain contacts	Framework grains									Accessory minerals					Matrix/ Pseudo-matrix			Cement and authigenic minerals										
		Max	Min	Mode graln sire	Mean grain size (Mz)					Quartz	K-Feldspar	Plagioclase	Mica	Granitic	Volcanic	Schist	Quartzite	Sandstone	Apatite	Zircon	Tourmaline	Epidote	Sphene	Clay minerals	Volcanic ash	Organic matter	Kaolinite (illitised)	Chlorite	Muscovite/sericite/other clays	Calcite	Dolomite	Siderite	Quartz	Albite	Opaque mineral	Intergranular	Intragranular	Micropores
101.25	Arkose	1.50	0.10	0.25-0.5	0.40	1.01	P	A-SA/SR	P-L	27.2	20.8	1.6	2.0	2.0		0.2	0.8	0.6	Tr	Tr	Tr	Tr	Tr	2.0		Tr	6.2	2.0	5.8	0.4	0.8	2.0		3.8	Tr	19.0	1.0	1.8
113.57	Arkose	0.80	0.03	0.125-0.25	0.14	0.53	M-G	A-SA/SR	P-L	30.0	18.0	3.0	4.0	Tr	1.2	1.0	0.8		Tr	Tr	Tr	Tr	Tr	2.6			5.0	1.2	7.8		1.4	1.2	Tr	1.0	1.0	19.4	0.4	1.0
121.87	Arkose	1.50	0.05	0.25-0.5	0.29	1.12	P	A-SA/SR	P-L	30.2	20.6	3.8	1.8	3.0			1.0	1.0	Tr	Tr	Tr	Tr	0.2	Tr			4.6	1.4	9.0		1.2	2.0	0.4	1.2	1.4	15.0	1.2	1.0
204.74	Arkose	2.20	0.10	0.25-0.5	0.47	1.04	P	A-SA/SR	P-L	29.8	19.4	3.2	2.8	3.8	0.4		2.0	1.0		Tr	0.2	Tr		Tr			6.0	1.0	6.8	0.8		1.2	0.8	1.0	1.0	16.0	1.8	1.0
230.02	Arkose	0.80	0.05	0.25-0.5	0.27	1.00	P	A-SA/SR	P-L	29.6	21.0	4.2	3.0	4.2		0.6	1.0		Tr	Tr		Tr					5.8	1.2	4.2	1.4		1.8	1.2	1.0	1.0	15.8	1.0	2.0
262.40	Arkose	1.20	0.05	0.25-0.5	0.28	0.96	M	A-SA/SR	P-L	30.4	19.8	5.0	1.0	4.0	1.0	1.0		1.0	Tr	Tr	Tr	Tr					5.0	1.0	5.2	1.0		2.0	1.0	1.2	1.0	17.0	1.4	1.0
281.39	Arkose	0.40	0.05	0.125-0.25	0.19	0.57	M-G	SA-SR-R	P-L	31.0	18.2	5.2	3.0	2.0	0.4	Tr	1.0		Tr	Tr	Tr	Tr					5.6	1.4	6.8	Tr	2.8	1.0	1.8	1.0	1.0	15.0	1.0	1.8
297.60	Arkose	0.60	0.05	0.25-0.5	0.33	0.79	M	SA-SR-R	P-L	32.8	20.0	4.8	1.2	2.8			1.0		Tr	Tr	0.2	Tr					5.0	1.0	6.6	Tr	Tr	2.8	2.2	1.2	0.4	16.0	1.2	0.8
300.68	Arkose	1.20	0.05	0.25-0.5	0.25	0.71	M	SA-SR-R	P-L/C	31.8	20.8	4.0	1.4	2.0			1.0			Tr	Tr	0.2			2.0		5.2	1.4	5.8	Tr	1.2	2.0	2.0	1.0	1.0	15.0	1.0	1.2
371.93	Arkose	0.50	0.05	0.125-0.25	0.17	1.00	P	A-SA/SR	P-L/C	33.0	21.0	3.8	3.0	1.0			1.0		Tr	Tr	Tr	Tr		3.0	4.2	1.6	5.0	1.2	6.2	Tr	1.0	1.6	1.6	1.0	1.0	7.6	1.2	1.0

Notes:
M-G: Moderate - good
M: Moderate
P: Poor
A: Angular
SA: Subangular
SR: Subround
R: Round
P: Point
L: Long
C: Concavo-convex
Tr = Trace
/: With some

Table 2. *The statistical parameters of grain size analysis for sandstones from Enreca-3 well*

Depth (m)	101.25	113.57	121.87	204.74	230.02	262.40	281.39	297.60	300.68	371.93
Median diameter - ϕ scale (Md = ϕ 50)	1.29	2.84	1.59	0.95	1.70	1.72	2.37	1.55	1.90	2.55
Median diameter- mm scale (Md = P50)	0.41	0.14	0.33	0.52	0.31	0.30	0.19	0.34	0.27	0.17
Mode diameter-ϕ scale (Mo-ϕ)	1.04	2.65	1.63	0.83	1.69	1.63	2.20	1.36	1.77	2.33
Mode diameter-mm scale (Mo-mm)	0.49	0.16	0.32	0.56	0.31	0.32	0.22	0.39	0.29	0.20
Mean diameter - ϕ scale (Mz-ϕ)	1.32	2.86	1.80	1.08	1.88	1.84	2.42	1.61	1.99	2.57
Mean diameter - mm scale (Mz-mm)	0.40	0.14	0.29	0.47	0.27	0.28	0.19	0.33	0.25	0.17
Standard deviation (σ1)	1.01	0.53	1.12	1.04	1.00	0.96	0.57	0.79	0.71	1.00
Skewness (SK1)	-0.09	-0.13	0.10	-0.02	0.06	-0.02	-0.10	-0.06	-0.04	-0.07
Kurtosis (KG)	1.42	1.19	1.04	1.16	0.88	1.08	1.11	1.04	1.13	0.97

Note:

Median diameter: The size is most readily determined from the 50% line of the cumulative distribution curve
Mode diameter: The mode size is the commonest grain size in a distribution
Mean diameter: The best measure of average grain size.

summary of petrographic component is shown in Fig.3. Table 2 shows the detailed result of grain size analysis. These results indicate the arkose sandstones are mostly fine-grained to medium-grained sandstones with several of fining-upward cycles, in which the mean grain size (Mz) ranges from 0.14mm to 0.47mm. The detrital grains are common angular, subangular to subrounded in grain shape and typically poor to moderately good sorting, in which the standard deviation value (σ1) ranging from 0.53 to 1.12. The compaction is commonly weak to moderate with mostly point to point and long type in grain contacts (Fig.4 & 5). The compaction tends to increase downward from the depth of 300.68m with concavo-convex grain contact type.

Figs.3, 4 and 5 show that the arkose sandstones are predominantly made up of quartz (average ~31%), k-feldspar (average ~20%) with subordinate amount of plagioclase (average ~4%) and mica (average ~2%). Rock fragments are present in a considerable amount as mainly granite (average ~3%) with other minor lithics as volcanic (scattered ~1%), schist (scattered ~1%) and quartzite (average ~1%). Studied sandstones in this interval are quite clean without detrital matrix materials or negligible (scattered ~2 - 4%). The detrital matrix materials are predominately made up of clay minerals, intermixing with volcanic ash and organic matters. The detrital matrix materials partly filled up the intergranular pores.

Figs.4 and 5 show poorly sorted medium-grained arkose sandstones. Detrital grains are mainly angular, subangular to subrounded and typically weakly compacted with point to point and long contacts. Detrital grains contain mostly quartz, feldspar, mica and rock fragments. Feldspar grains are present in a considerable amount as

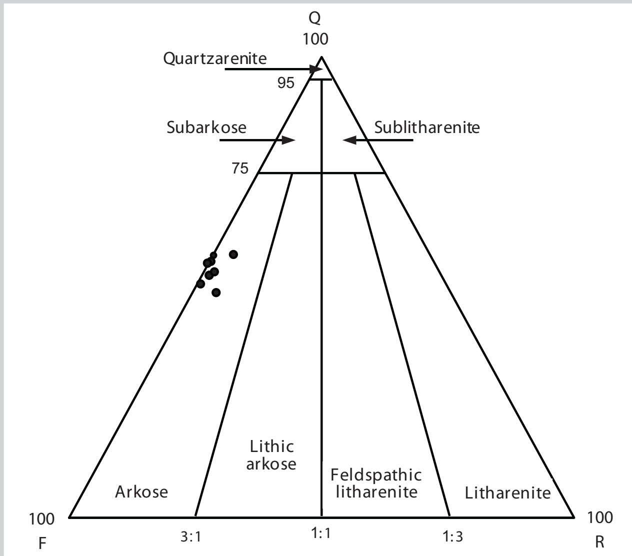

Fig.1. *The classification of sandstone with less than 15% fine-grained matrix. After R.L.Folk's classification, 1974*

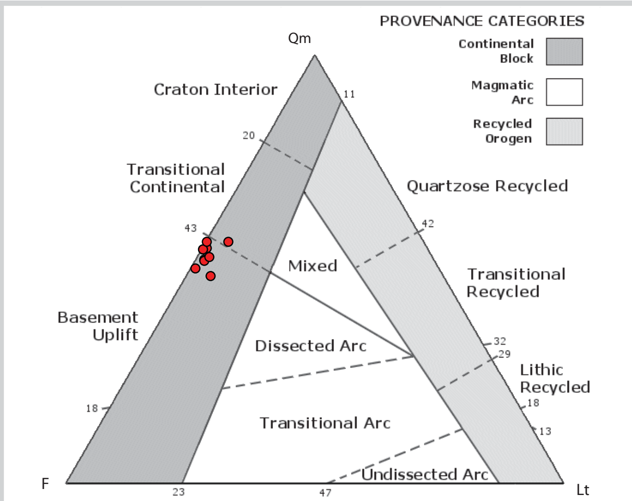

Fig.2. *The relation between tectonic settings and sedimentary materials of reservoir sandstones from Enreca-3 well. After William R. Dickinson, 1979*

k-feldspar (stained in yellow) and minor plagioclase, some of them have undergone partial dissolution and been locally replaced by sericite, muscovite and clay minerals. Minor detrital mica flakes are present as muscovite (Mus) and biotite, some of them have slightly been replaced by chlorite (Ch) minerals. Rock fragments are present as granite, schist, quartzite and sandstone. The sandstones are quite clean with minor detrital matrix materials. Authigenic minerals are present with moderate amount as pore-filling kaolinite (K), siderite, chlorite, calcite, dolomite, albite, sericite-muscovite-other clay minerals and opaque minerals. These authigenic minerals are not only replacing feldspar grains but also partly filling up pore spaces. Locally, kaolinite clays have been replaced by fibrous illite.

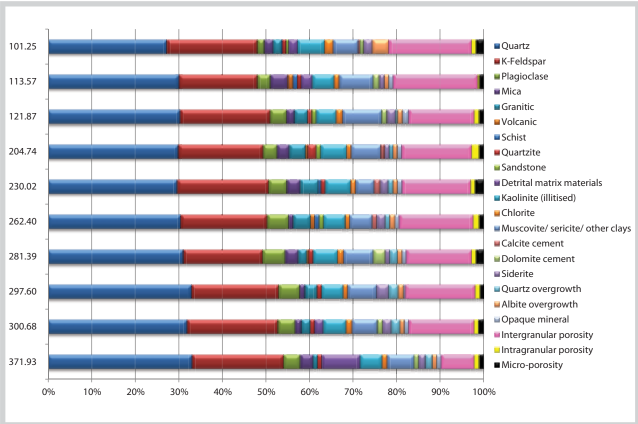

Fig.3. *The summary of petrographic data of sandstones from Enreca-3 well*

Cement and authigenic minerals are present in almost all sandstones in a considerable amount with mostly diagenetic clay minerals as kaolinite (average ~5.5%), chlorite (average ~1.3%), muscovite/sericite (average ~6.5%) and minor calcite (scattered from trace - 1.4%), dolomite (scattered from trace - 2.8%), siderite (average ~2.0%), quartz overgrowths (average ~1.4%), albite (average ~1.3%) and opaque minerals (average ~1.0%). Diagenetic minerals not only partly replaced feldspar grains but also filled up the intergranular pores and secondary pores.

These arkose sandstones have strongly been cemented with authigenic minerals such as diagenetic clay minerals, quartz overgrowths, opaque minerals, and carbonate minerals. Although the mineralogical maturity and textural maturity of these arkose sandstones are not

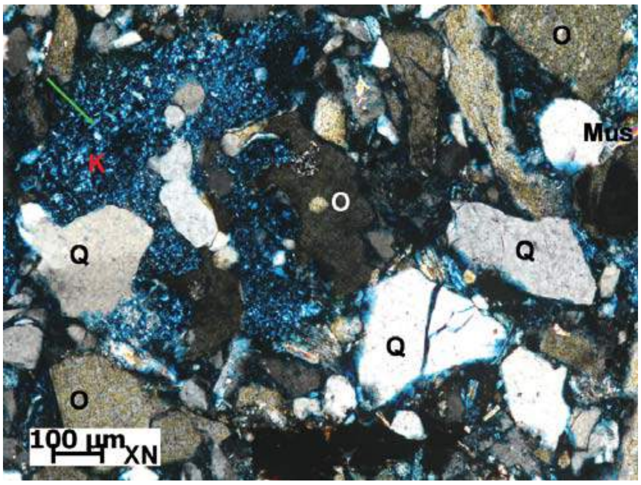

Fig.4. *121.87m depth from Enreca-3 well*

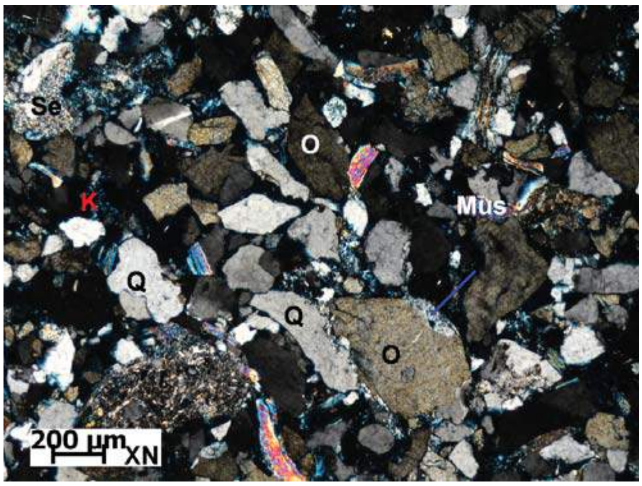

Fig.5. *230.02m depth from Enreca-3 well*

Table 3. *The XRD analytical result for clay fraction of samples from Enreca-3 well*

No	Depth (m)	Kaolinite	Chlorite	Illite	Smectite	Illite-smectite
1	101.25	17.4	5.7	45.7	29.0	2.1
2	113.57	31.0	5.0	54.7	4.5	4.9
3	121.87	20.2	7.9	54.1	12.4	5.4
4	204.74	20.7	5.8	47.6	21.8	4.1
5	230.02	22.4	8.1	52.9	6.5	10.1
6	262.40	20.6	7.3	59.9	6.4	5.8
7	281.39	20.5	8.1	61.2	5.8	4.5
8	297.60	20.1	6.3	42.9	8.7	22.1
9	300.68	18.0	8.2	50.5	4.5	18.8
10	371.93	17.4	8.4	63.1	5.4	5.6

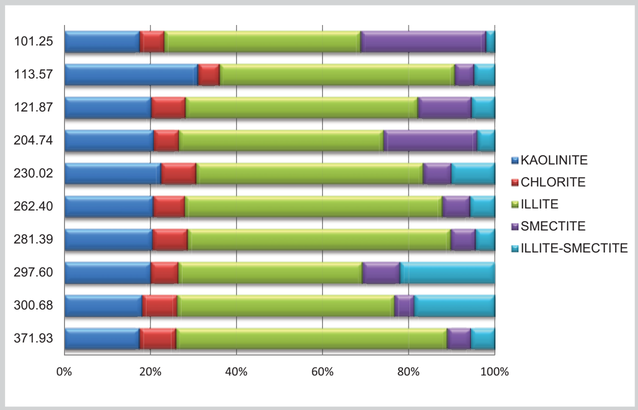

***Fig.6.** The summary of clay fraction data of samples from Enreca-3 well*

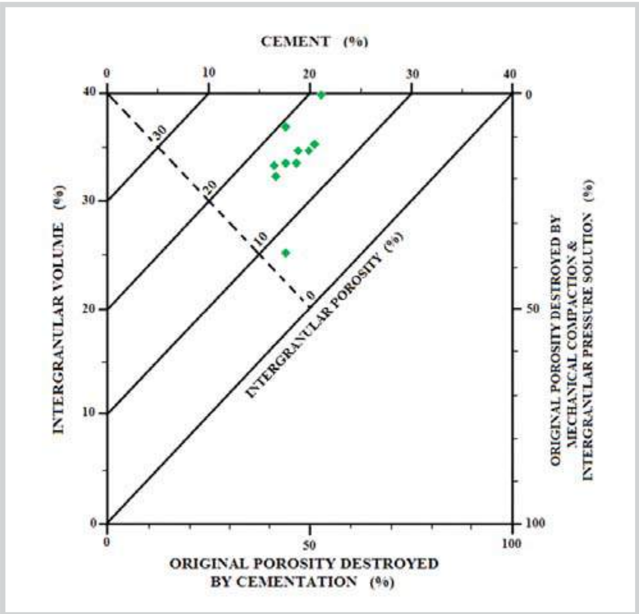

***Fig.7.** The original porosity destruction of reservoir sandstones from Enreca - 3 well due to mechanical compaction and cementation [10]*

high, the rocks have undergone a slightly mechanical compaction. Those help to preserve the pore size and pore throat size.

The XRD analytical result for clay fraction of the rocks in the studied interval from 18.30m to 499.68m is displayed in Table 3 and the data summary is shown in Fig.4. The result reveals that clay minerals are predominantly made up of illite (average ~53.0%), followed by kaolinite (average ~21.0%), smectite (average ~10.0%), chlorite (average ~7.0%) and mixed-layer clay minerals of illite-smectite (average ~8.0%). The clay analytical result indicates that all clay minerals have intermittently increased and decreased; this suggests that clay minerals in the studied interval were not significantly affected by high thermal condition or by the burial depth; whereas the clay minerals of rocks in studied interval have been formed by chemical weathering of minerals containing Al and Si. The rocks have been deposited in stable conditions and are probably in an early diagenetic stage. In this stage, the transformation of clay minerals is significantly controlled by the depositional environment and the source rock.

In general, with progressive increase in burial depth smectite has been converted into illite or chlorite [9]. The irregular increasing and decreasing of smectite in this interval indicate that the source of sediments was derived from volcanic ash. Clay mineral assemblage such as kaolinite, chlorite and illite tends to increase or decrease irregularly; this may suggest that the formation of clay minerals in this studied interval did depend on source rock, modes of sediment transport and sedimentation environment. The presence of chlorite

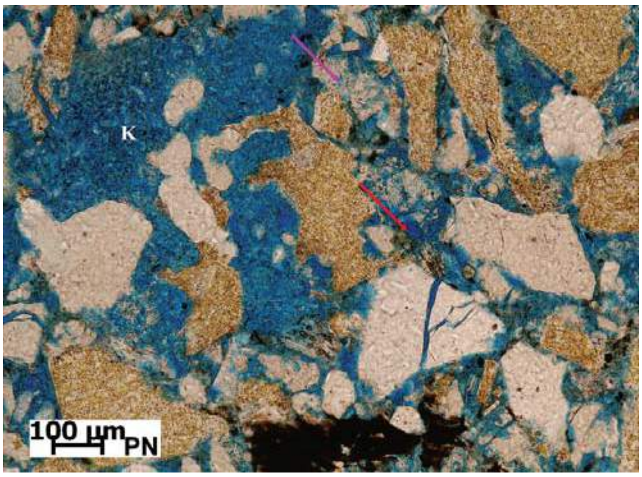

***Fig.8.** Depth 121.87m*

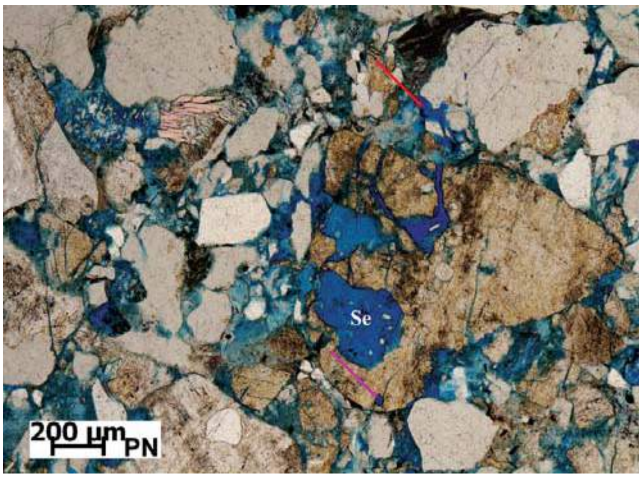

***Fig.9.** Depth 204.74m*

The figures indicate reservoir sandstones have very good reservoir quality. High levels of visible porosity are present as mostly preserved intergranular pores (red arrows) with minor micropores within kaolinite patches (K) and significantly enhanced by secondary macropores (Se, pink arrows) due to the dissolution of unstable grains as feldspar grains.

suggests that the source rock is probably from the weathering of intermediate and basic crystalline rocks or low grade metamorphic rocks. The presence of illite and kaolinite suggests their deviation from crystalline rocks containing feldspar and mica or from pre-existing soils and sedimentary rocks. The other hypothesis is that the presence of kaolinite is probably from the subsequent leaching of the minerals from granitic and basis rocks in the hinterland. The irregular increasing and decreasing of illite may suggest that there appears intermittent transgressive trend in this studied interval.

Normally, at the depositional surface, the sandstone has roughly 40% porosity [2], which will be reduced by burial diagenesis such as compaction, intergranular pressure solution and cementation. Fig.5 reveals that roughly 50% of the original porosity of reservoir sandstones in the studied interval 101.25 - 371.93m from Enreca well has been destroyed due to cementation; whereas only ~15% of the original porosity of reservoir sandstone has been damaged due to compaction. The petrographic analysis also supports these results, as the sandstones contain a considerable amount of authigenic minerals and almost all detrital grains display point to point and long grain contacts.

Figs.8 and 9 indicate that the sandstone with high levels of visible porosity is present mostly as preserved intergranular pores (average ~16%) with minor micropores (roughly 1%) within clay patches and significantly secondarily enhanced by partial dissolution of feldspars and lithics (roughly 1.5% of secondary pores).

3. Conclusions

The analytical results of this study have indicated that:

- Reservoir sandstones from Enreca-3 are fine to medium grained arkose sandstones with low mechanical maturity and mineralogical maturity;

- The detrital framework modes of sandstones were derived from continental block provenance and sporadically from uplifted basement provenance;

- The original porosity of reservoir sandstones has been severely damaged due to cementation and furthermore by compaction;

- High levels of the visible porosity of reservoir sandstones are present mostly as preserved intergranular pores with minor micropores and secondary pores.

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