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LITHOFACIES, MINERALOGICAL, PETROPHYSICAL AND MECHANICAL PROPERTIES ANALYSIS OF RESERVOIR AND SEAL ROCKS FOR CARBON CAPTURE STORAGE (CCS) SYSTEM. PILOT STUDY IN GUNDIH FIELD, CENTRAL JAVA, INDONESIA

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Sari – Di Cekungan Jawa Timur Indonesia, Batupasir Ngrayong telah ditargetkan sebagai reservoir untuk *Carbon Capture Storage* (CCS). Pada sistem CCS ini, batugamping dan batulempung Formasi Bulu dan Wonocolo diharapkan berfungsi sebagai batuan penyekat. Tujuan dari penelitian ini adalah untuk mengetahui sifat litologi, mineralogi, dan mekanik dan petrofisika Formasi Ngrayong, Bulu dan Wonocolo dari litologi permukaan sebagai studi analog, dan selanjutnya akan diadaptasikan pada sumur injeksi bawah permukaan (Jepon-1) untuk karakterisasi potensinya sebagai reservoir dan segel fungsional dalam sistem CCS. Dua sampel pengeboran inti dangkal dan sampel singkapan yang diturunkan dari Formasi Ngrayong, Bulu dan Wonocolo dideskripsikan menggunakan kombinasi analisis petrografi, difraksi sinar-x, petrofisika dan mekanik. Analisis ini menunjukkan bahwa Formasi Ngrayong, Bulu dan Wonocolo mengandung tujuh litofasies yang berbeda (batulempung dengan batupasir kuarsa tipis, batupasir kuarsa bersih, batulumpur, batugamping biokistik, batugamping kalkarenit, napal berpasir, dan batu butir) dengan heterogenitas skala halus pada kain dan mineralogi yang sangat mempengaruhi sifat petrofisika. Porositas, permeabilitas, dan sifat petrofisika lainnya menunjukkan bahwa memiliki kemampuan untuk berfungsi sebagai segel CCS yang sesuai. Mineral autigenik yang melimpah dan tekstur disolusi menunjukkan bahwa interaksi fluida telah terjadi di dalam Formasi Ngrayong, Bulu dan Wonocolo. Mineral yang berpotensi reaktif dalam sistem CCS (termasuk karbonat dan klorit) banyak terdapat di Formasi Ngrayong dan Wonocolo

Kata kunci: Reservoir dan penyekat CCS, Ngrayong

Abstract *- In the East Java Basin Indonesia, the Ngrayong Sandstone has been targeted as a reservoir for carbon capture and storage (CCS). In this CCS system, the limestone and mudstone of Bulu and Wonocolo Formation is expected to serve as the primary seal. The purpose of this study is to investigate the lithological, mineralogical, mechanical and petrophysical properties of the Ngrayong, Bulu and Wonocolo Formations from surface lithology as an analogue study, and later will be adapted to subsurface injection well (Jepon-1) to characterize its potential as a functional reservoir and seal in a CCS system. Two Shallow core-drilling and outcrop sampling derived Ngrayong, Bulu and Wonocolo Formation samples are described using a combination of petrography, x-ray diffraction, petrophysical and mechanical properties analyses. These analyses show that the Ngrayong, Bulu and Wonocolo Formation contains seven different lithofacies (claystone with thin quartz sandstone, clean quartz sandstone, mudstone, bioclastic limestone, calcarenitic limestone, sandy marl, and grainstone) with fine-scale heterogeneities in fabric and mineralogy that greatly influence the petrophysical properties. Porosity, permeability, and other petrophysical properties suggest that could serve as a suitable CCS seal. Abundant authigenic minerals and dissolution textures indicate that multiple generations of past fluid-rock interactions have occurred within the Ngrayong, Bulu and Wonocolo Formations. Minerals that would be potentially reactive in a CCS system (including carbonate and chlorite) are common in the Ngrayong and Wonocolo Formations.*

Keywords*: Reservoir and Seal CCS, Ngrayong*

1. INTRODUCTION

The exsists of the growing accumulation of greenhouse gases impacting the global climate around the world. Proposed solutions include creating a system to keep CO_2 permanently underground (geosequestration) means directly reducing the emissions related to the application of CCS technology (Carbon Capture and Storage) also commonly referred to as the Carbon Sequestration (IPCC, 2005). This effort coincides well with Indonesia's commitment, which has been delivered in 2009 during the G20 meeting in Pittsburg and in 2010 during the COP-15 meeting in Copenhagen, i.e. to reduce 26% of CO_2 emissions by 2020 and up to 41% if international support forthcoming.

The objective of this study was to review available information about the physical characteristics of Ngrayong Formation as reservoir and Bulu and Wonocolo Formation as seal for CO_2 storage system in East Java basin. Outcrop observation and laboratory studies have been done to conduct the reservoir and seal properties includes porosity, permeability and mineral content that affect the trapping capacity of CCS system.

Several representative samples that came from outcrop andtwo shallow core drilling (ITB-1 and ITB-2). Investigations on petrophysical properties of sediments such as porosity and mineral content, may respond to the macro and microstructuralimage. For that reason outcrop observation, core description, petrography, x-ray Diffraction, and porosity analysis responds to achieve the goal. Jepon-1 was the first candidate to be an injection well and need more correlation about surface to subsurface characteristic of reservoir and seal rocks.

Siliciclastic of Ngrayong Formation, hemiplegic marl of Wonocolo Formation and dominant reefal limestone of Bulu Formation occurred in northern part of onshore area in East Java (Van Bemmelen, 1949; Koesoemadinata, 1969; Pringgoprawiro, 1983). As reservoir and cap rock of geological CO_2 storage, the integrity depends of many factors one of them depend on intrinsic transport properties, which include flow through its primary and secondary porosity, permeability, abundance of mineral that most likely to be involved with rock brine- CO_2 interactions (Sribudiyani *et al.,* 2003).

Sandstone interval in Ngrayong Formation is a clean quartz sandstone with fine to medium, well sorted grained and with cross bedding. Sandstone intercalated with mudstone, limestone and coal.

From outcrop data alone this is a valid description, white colour and friable nature. However, thin section shows that many of the quartz grains are very angular, not what would be expected from 'mature' sand recycled and transported over long distances. There are embayments indicative of volcanic sources with melt inclusions in several grains (Smyth, 2003) . Clay mineral analysis by XRD shows significant proportions of quartz, montmorillonite, albite, sanidine, and kaolinite, appearance of kaolinite means there is weathering process from plagioclase.

2. DATA AND METHODOLOGY

2.1 Outcrop Observation

Outcrop observation is located in the eastern part of Gundih Field (**Figure 1**). Administratively situated in Wukiharjo village, Parengan sub-district, Tuban district, East Java Province. Based on traverse line canbe divided into two parts, namely: western part and eastern part sections

2.1.1 Western Part Section

The Stratigraphy of western part (from oldest to youngest) begin with, Sandstone, shale, and intercalation of coal from Lower Part of Ngrayong Formation, Quartz sandstone from Upper Part of Ngrayong Formation, Calcarenite from Bulu Formation, Claystone and intercalation of sandstone fromWonocolo Formation (**Figure 2**).

Ngrayong Formation divided into two part: Lower Part and Upper Part. Lower part of Ngrayong Formation consists of sandstone, shale, intercalation of coal and intercalation of limestone. Sandstone has white yellowish color, very fine to fine grain size, calcareous, close fabric, good sorted, good porosity and permeability, medium hard, mineralogy by quartz, feldspar, and lithic. Shale has black grey in color, very fine to fine in grain size close fabric, good sorted, good porosity and permeability, soft-medium hard. Coal has black in color, non-calcareous, has parallel lamination of sediment structure. Wackestone (limestone that still has mud matrix) has white colour, medium hard and compact.

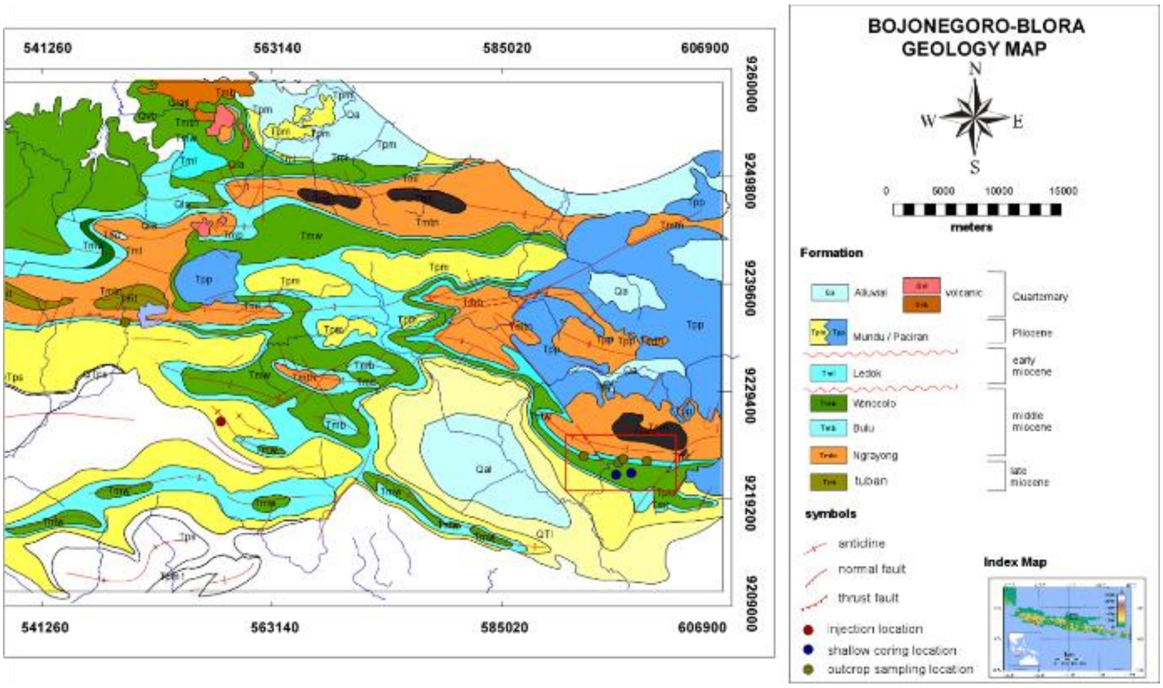

Figure 1. Geology map around Gundih Field, red box was the observation area

Upper Part of Ngrayong Formation consists of sandstone that has white yellowish colour, fine to medium grain size, non-calcareous, close fabric, good sorted, verygood porosity and permeability, compact, mineralogy by quartz, feldspar, and lithic. Thick bed: 30 - 60 cm. Bulu Formation consists of calcarenite. Calcarenite has yellow in color, clastic texture, fine to medium in grain size, good sorting, closed fabric, compact, massive -well bedded. Wonocolo Formation consists of sandy marl dominant and very fine sandstone. Marl, grey yellowish in color, calcareous, consist of foraminifera. Sandstone has white yellowish in color, fine to medium in grain size, calcareous, close fabric, good sorted, good porosity, compact, mineralogy by quartz, feldspar, and lithic. Thick bed: 30 - 60 cm.

2.1.2 Eastern Part Section

The Stratigraphy of eastern part section consist of (from oldest to youngest): Sandstone, shale, and intercalation of coal from Lower of Ngrayong Formation, Quartz sandstone from Upper Part of Ngrayong Formation, Calcarenite from Bulu Formation, Claystone and intercalation of sandstone from Wonocolo Formation (**Figure 3**).

Ngrayong Formation divided into two parts: Lower Part and Upper Part. Lower part of Ngrayong Formation consists of sandstone, shale, and interbedded sandstone . Sandstone has light grey colour, fine grain size, close fabric, good sorted, loose, mineralogy by quartz and lithic; concretion with carbon streak, load cast. Shalehas dark greycolour, clay in grain size, coal strike. Sandstone has light-dark brown colour,medium in grain size, open fabric, poor sorted,loose, mineralogy by quartz and lithic. Claystone has dark grey colour, fragments: Quartz, limestone, coal strike.

Upper part of Ngrayong Formation consists of sandstone and claystone. Sandstone has light brown in color, medium-coarse grain size, close fabric, poor sorted, loose, mineralogy by quartz and lithic; channel, crossbed, burrow, convolute. Claystone has brown colour, clay in grain size, non-calcareous. Bulu Formation

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consists of bioclastic limestone and mudstone. Limestone has light white in color, bio-clastic, calcarenite in type, fragment: shell, gastropode, spary calcite. Claystone has light grey colour, non-calcareous, clay in grain size.Wonocolo Formation consists of sandy marl and limestone. Marl has light grey colour, calcareous, foram fragment. Limestone has light brown, grainstone in type, grain supported, fragment shell, spary calcite, and micrite.

2.1.3 Lithofacies

Two main facies has been recognized for Ngrayong Formation: Dominant claystone with thin beds of fine quartz sandstone, and quartz sandstone. Claystone is commonly parallel laminated. Quartz sandstones are mostly free of mud, quartz up to 80%, the grain size mostly subangular shapes.

Bulu Formation are developed: mudstone facies that contains quartz-rich sandstone (less than 20% quartz grain) and bioclastic limestone (calcarenitic).

Lithofacies for Wonocolo Formation consist: foraminiferal-rich sandy marl and Limestone (Grainstone). Carbonate mud constituting about 50 % mainly as matrix, porefillings and micritisation of bioclast.

2.2 Shallow Core Drilling

Shallow drilling samples (not more than 100 meter) from ITB-1 and ITB-2 (location of the wellbore in red circle, see fig 2) will be used for certain analysis. The samples imply various lithology representing geology formation in the area starts with interbedded sandstone and claystone from the bottom layer and ends with limestonedomination at the top (see **Figure 4**). Imaginary line that divides the two different lithology placed as boundary between Upper Ngrayong and Bulu Formations.

Sandstone of Upper Ngrayong is descripted as light to dark grey quartz sandstone with very fine to fine grain, good sorted, has medium to good porosity, close fabric, non calcareous, some coal streak, has ripple lamination structure.

Furthermore, for the claystone characterized by claystone with dark to light grey colour, poor-good porosity, non-calcareous, ductile. Bulu Formation consists of limestone (wackestone) and mudstone. Wackestone has light-brownish yellow, medium-good porosity, and fossil fragment.

2.3 Petrography

Some samples in petrography were analyzed by thin section with blue-dyed. Petrography or optical microscopy was used to observe of fracture, pore distribution and structures. Most images were taken at 300-4000 times magnification with a 25 mm working distance.

Representative sandstone of Upper Ngrayong Formation (**Figure 5**) is generally composed of very fine-fine, subrounded-angular grains and is moderately well to well sorted. The quartz grain occurs predominantlyas monocrystalline grains (45% to 70%) with minor polycrystalline grains (3% to 7%), showing secondary quartz outgrowth. Authigenic clay and the secondary quartz, are the main cementing agents in this interval. The visible porosity varies between fair to very good (20% to 30%). The thinsections also showed that the primary porosity controlling factors are clay matrix and localized quartz overgrowth cement. Thepresence of pore-filling authigenic kaolinite, together with well-developed quartz overgrowths, have commonly reduced pores and locally blocked pore-throats.

Grain-to-grain contacts are tangential, straight to concavo-convex in the Upper Ngrayong intervals. The effect of strong post-depositional is indicated by the presence of deformed grains and intensive fine fractures crossing through several grains.

Petrography on limestone sample of Bulu Formation (**Figure 6**) described a bioclastic limestone, typified by abundance ofplanktonic foraminifera, crystalline sparrycalcite cement is well developed. It also contains quartz grains, commonly less than 20%. Carbonate minerals often undergo dissolution with intrinsic (from diagenetic) or secondary activity.

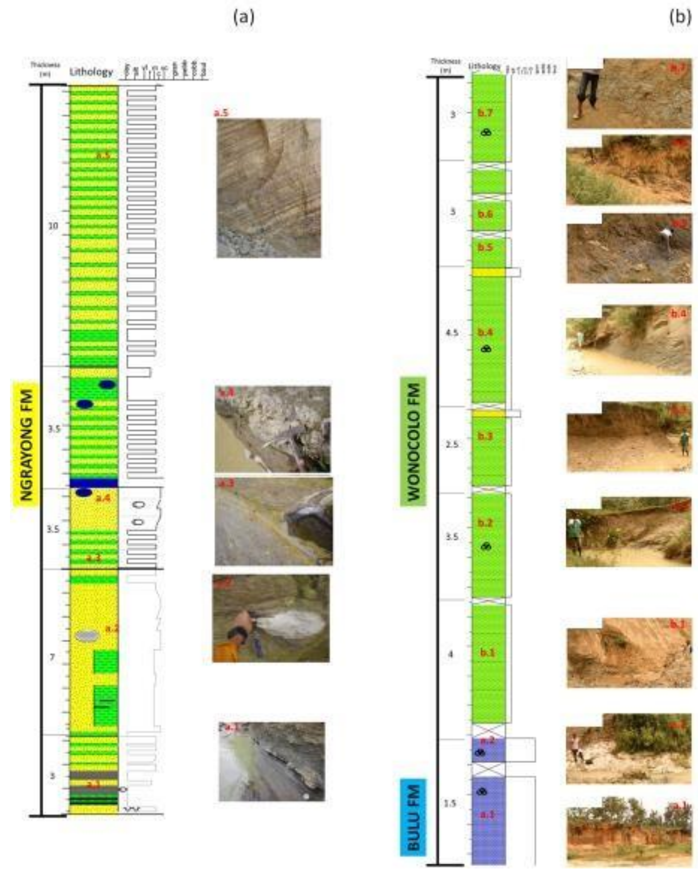

Figure 2. Stratigraphy in the western part section
(a) stratigraphy in Ngrayong Fm interval; (b) stratigraphy in Bulu and Wonocolo Fm interval.

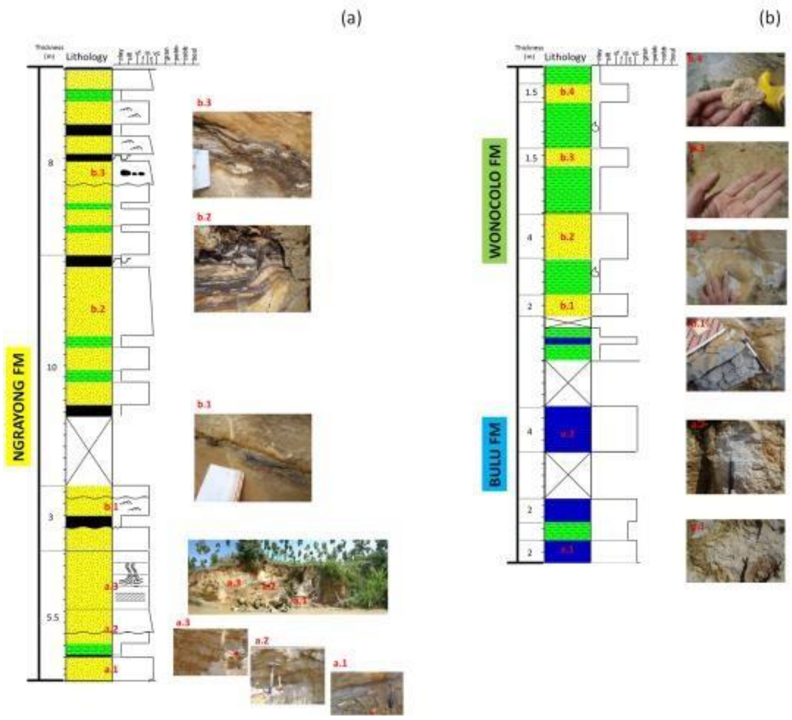

Figure 3. Stratigraphy in the eastern part section
(a) stratigraphy in Ngrayong Fm interval; (b) stratigraphy in Bulu and Wonocolo Fm interval.

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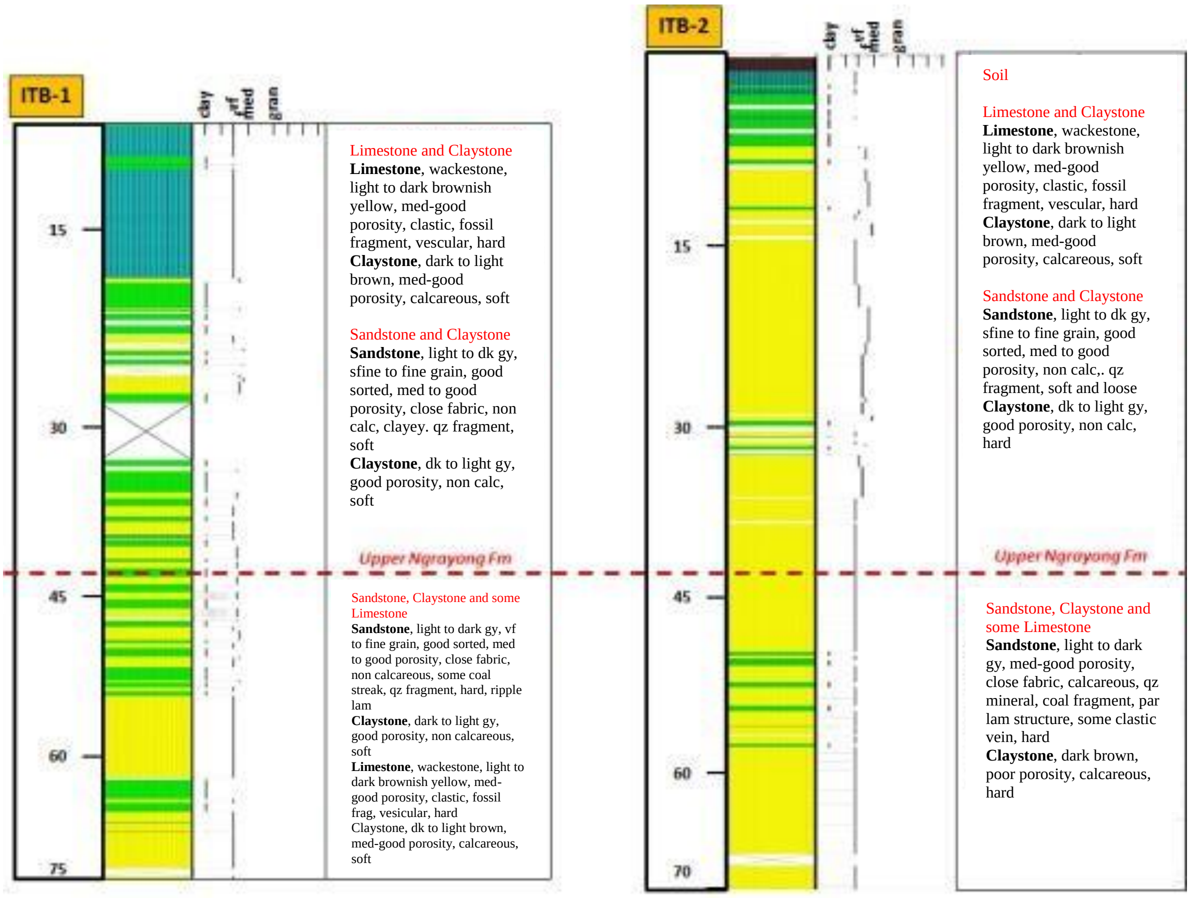

Figure 4. Lithology description of shallowcore drilling ITB-1 and ITB-2, red dash line was contact interpretation of started Ngrayong Formation

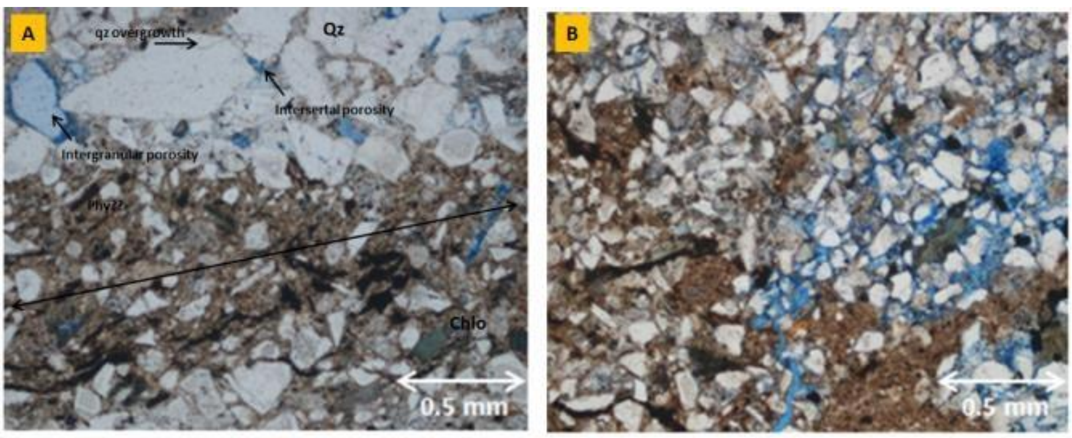

Figure 5. Thin section of Upper Ngrayong sandstone from ITB-1 well at depth 42 m, (1) showing parallel contact between grains and cement (double headed arrow); (2) showing intergranular porosity (blue colour) with secondary kaolinite (green colour)

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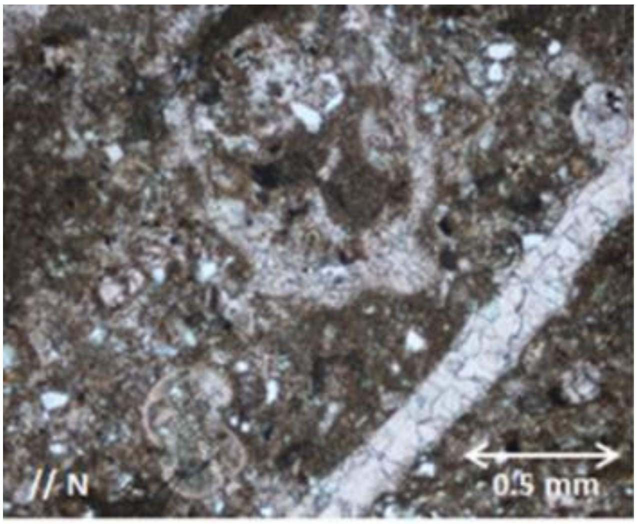

Figure 6. Thin section of BuluFormation, showing chamber of planktonic foraminifera and big vein calcite intersect the lithology

2.4 X Ray Diffraction

The available XRD analyses from the shallow core show that the clay content within the Upper Ngrayong sandstones is generally more legible than Bulu Formation. The predominantclay minerals within the Upper Ngrayong sandstone reservoirs are kaolinite, followed by albite, montmorillonite and sanidine (**Figure 7**). Similar to the mineralogy analysis, the contentof chlorite minerals is high in the Upper Ngrayong section. The plagioclase richness within the Upper Ngrayong reservoirs confirms the kaolinite content. It is interpreted that this kaolinite was formed from weathering or alteration processes of plagioclase.

Quartz detected in Bulu Formation has a similar appearance to those in Ngrayong and is suspected to be derived from similar source.

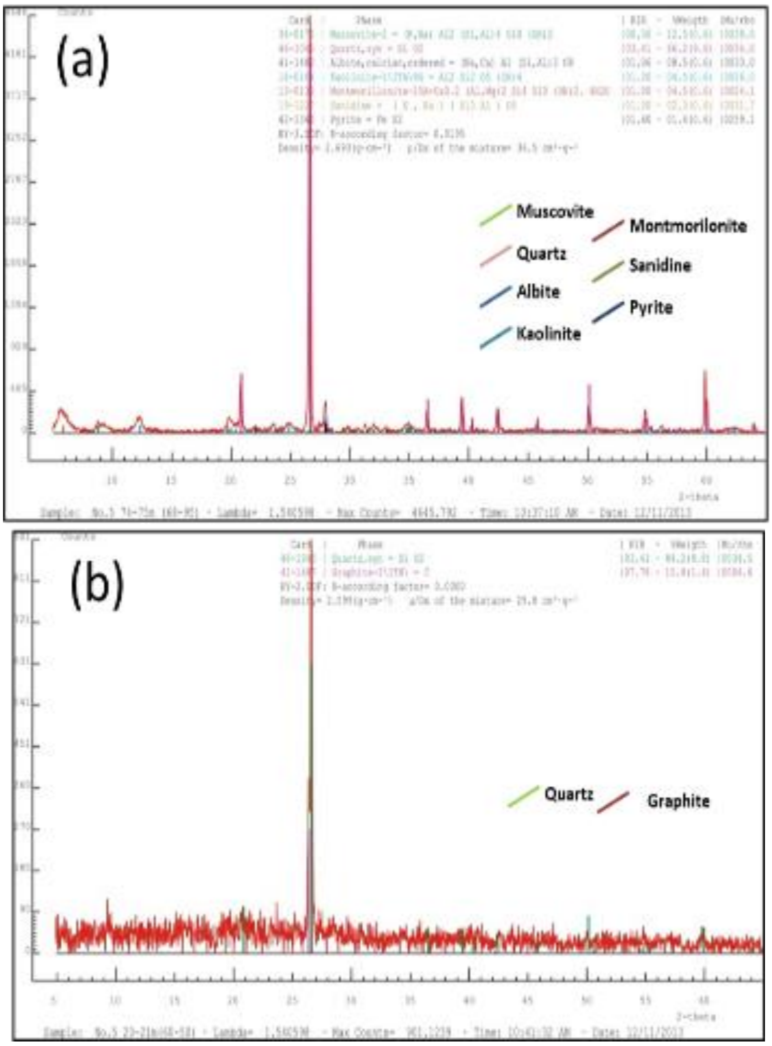

Figure 7. XRD result from shallow drilling (a)from Ngrayong Formation, (b) from Bulu Formatio

2.5 Spontaneous Potential (SP), resistivity and porosity measurement

Porosity of samples in the cored depth range shows diverse variations (**Figure 8**). Resistivity and SP that run along with porosity measurement in the ITB-1 well record a very interesting view. In general, between SP, resistivity and porosity seem to have pattern which describes the lithology. When meeting sandstone porosity value ranges bigger thanwhen meeting claystone or limestone. These trend of property showed that log SP, resistivity, and porosity correspond to lithology.

In summary,

- The average value of sandstone in NgrayongFormation: resistivity 111.6 Ω; SP 317.6 mV; porosity 33%.
- The average value of sandstone in Bulu Formation: resistivity 219 Ω; SP 338 mV; porosity 30%.
- The average value of claystone in Ngrayong Formation: resistivity 145 Ω; SP 354 mV; porosity 34%.
- The average value of claystone in Bulu Formation: resistivity 970 Ω; SP 327 mV; porosity 29%.
- The average value of limestone in Bulu Formation: resistivity 1032 Ω; SP 342 mV; porosity 28%

(a) (b) (c)

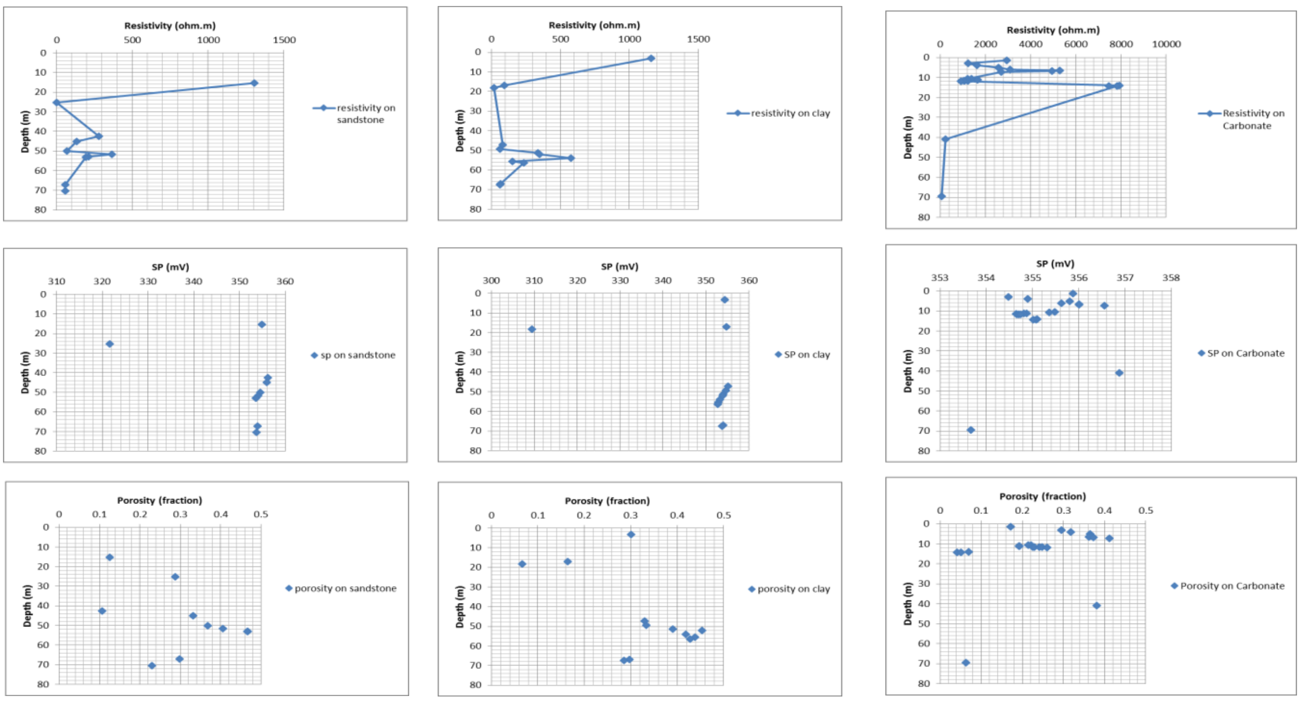

Figure 8. Resistivity-SP-Porosity composite log in ITB-1, (a) for sandstone (b) for claystone, (c) for limestone

2.6 Mechanical measurement

Triaxial test from Ngrayong and Bulu samples showed by 2D linear Mohr-Coulomb criterion. The Mohr-Coulomb criterion defines a linear relationship between the stressdifference ($\sigma 1$ and $\sigma 3$) at failure and the confining stress using two parameters: So the cohesion (Co the unconfined compressivestrength) and μi the coefficient of internalfriction, where $\mu i = \tan\theta$. The equation thatdefines the 2D linear criterion is $\tau = So + \sigma n\mu i$Result of triaxial compression in Ngrayong and Bulu formations (**Figure 9**) give very optimistic value of failure coefficient, μinearly 0.75 and 1 described that the rock has a high capability to held high stress/pressure.

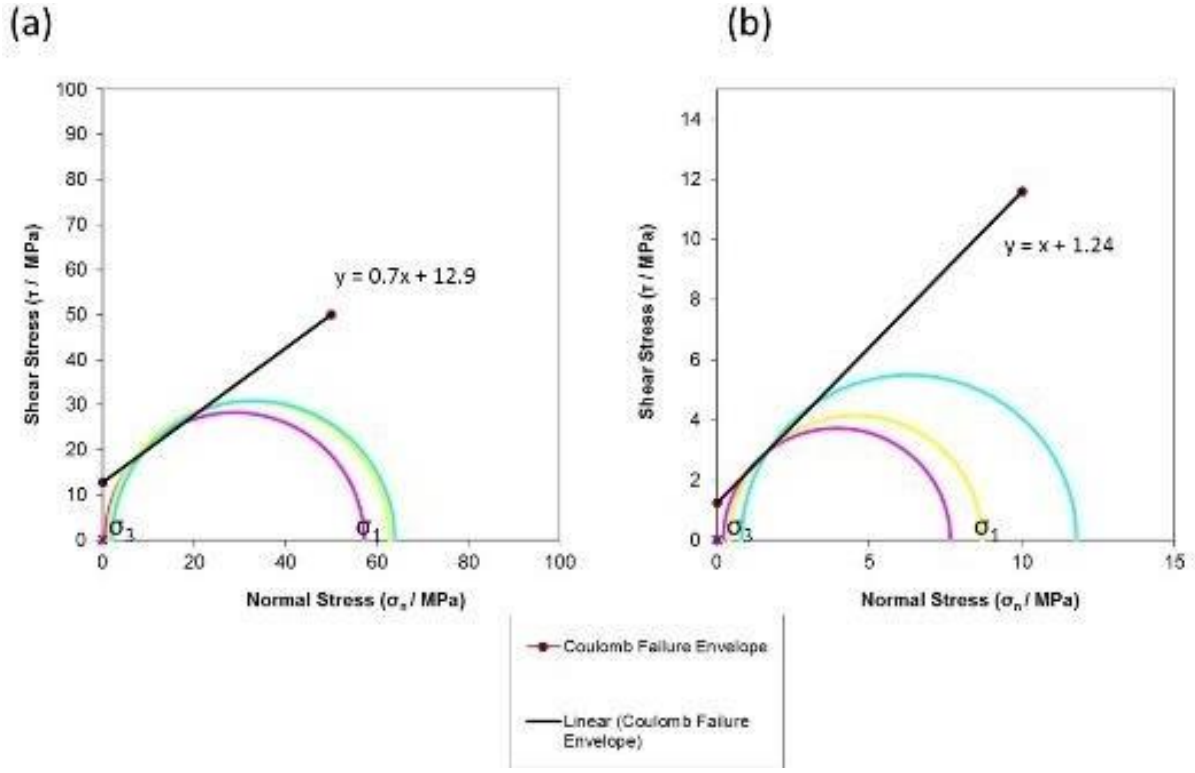

Figure 9. 2D Mohr-Coulomb criteria for (a) Ngrayong sample; (b) Bulu sample

3. DISCUSSION

Based on geological outcrops supported by core description and laboratory analysis provoke a big question about how this analyses result will affect the properties deep underneath the surface. Jepon-1 well which will be the first candidate to be an injection area, locatedmore than 20 kilometres towards the west from shallow drilling suspected has different internal characteristics in the rock. Regionally from surface and subsurface cross section (Fig 10) reveal the thickness and depth of Ngrayong Formation changing become relatively thinning because of the slope gently southward direction (Sapiie *et al*., 2006). This factor can be bad or be good in terms of reservoir or for CO_2 itself. One issue must be addressed is not only about the top sealing (Bulu and Wonocolo Formations) but structure must also be concerned, whether is leaking or sealing.

Lithofacies distribution is very close related to sedimentation history, assessment of middle to late Miocene sedimentation in the Rembang zone was carried out using seismic stratigraphic interpretation (lateral facies) collaborate sedimentological data from wellbore (vertical facies). Ardhana (1993) recognized pattern of sediments in small basinal areas resulting from basement fragmentation were derived from the north (Bawean Arch). Sediments are mostly deposited in shelf areas during changing rapidly of sea level highstands. Wonocolo Formation, which mostly foraminiferal-marl, the existence of deltaic deposition probably occurred.

Physical properties in each lithofacies convenient enough to keep and hold CO_2. CO_2 must-act as supercritical state (volume of CO_2 decreases dramatically with depth) in the subsurface. Suitable depth thickness must be reached for injection, depth elevation average of 800 meters or more with assumed gradient temperature in basinal area around 25^{o}C per km (based on the density data of Angus *et al*., 1973). Special attention is addressed more to porosity and permeability. Both of these factor are related to fluid movement within the rock. Even though there is no direct connection between porosity and permeability, our results show a good connection between those with facies of lithology.

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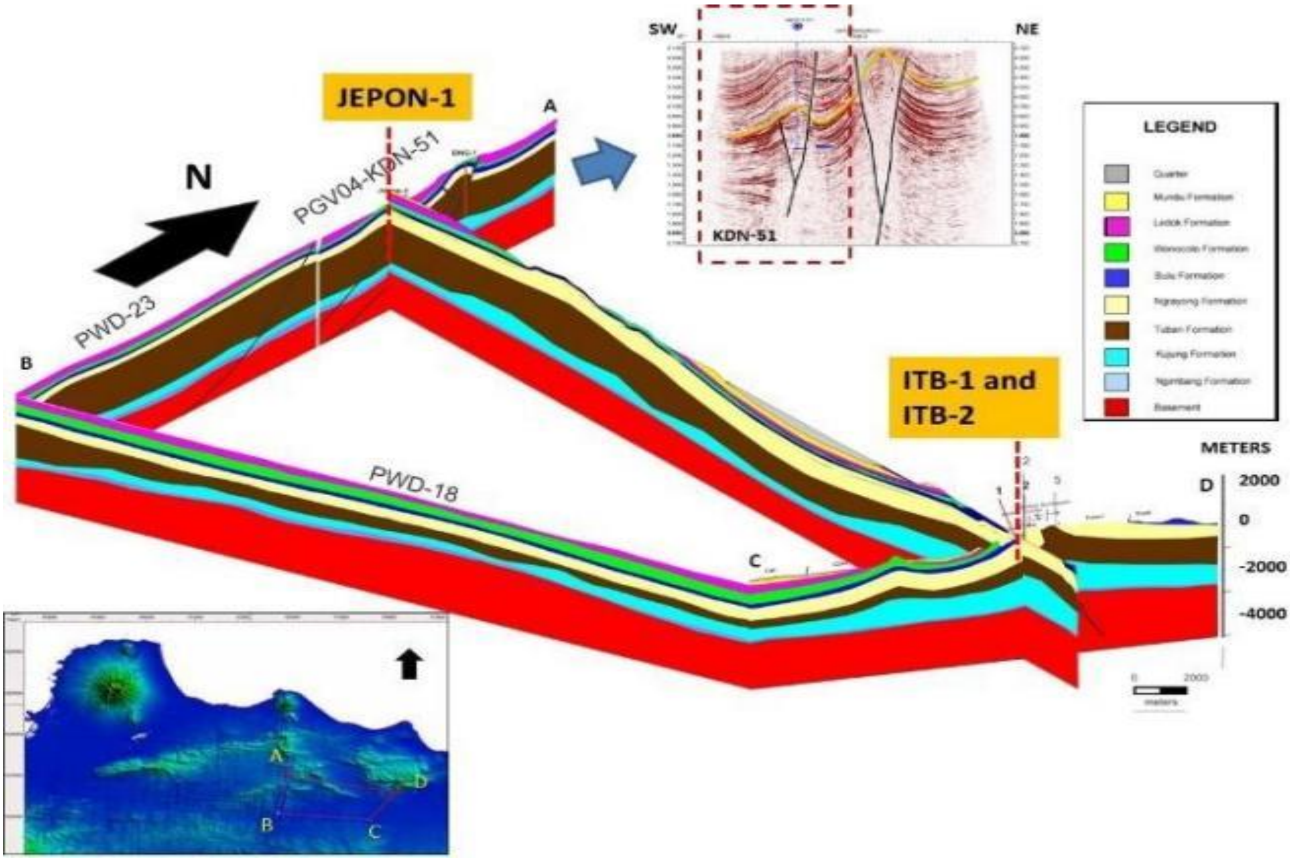

Figure 10. Surface to subsurface cross sectionfrom shallow drilling data (ITB-1 and ITB-2) to seismic data that located Jepon-1 as an injection well

5. CONCLUSION

Ngrayong, Bulu and Wonocolo Formation contains seven different lithofacies (claystone with thin quartz sandstone, clean quartz sandstone, mudstone, bioclastic limestone, calcarenitic limestone, sandy marl, and grainstone).

1. Ngrayong Formation as reservoir storage for CO_2 has adequate capacity in terms of thickness, depth, porous and permeable rock that can contain (a mixture of) gas and liquid. Overlain by a seal (non permeable rock) layer.
2. Surface and subsurface correlation reveals diminishing in thickness of reservoir Ngrayong Formation toward Jepon-1.

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