Impact of Clay mineral type on sandstone permeability based on field investigations: case study on Labuan island, Malaysia

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Abstract. Permeability is a petrophysical parameter that can indicate the economical value of sandstone as a hydrocarbon reservoir. In presence of Clay minerals in sandstone composition, permeability can be affected significantly according to the Clay mineral type. Therefore, understanding the impact of Clay on the permeability of sandstone has a big importance in scientific research and industry as well. Although well-logs can provide very good data quality, it is not cost-effective as a preliminary tool. However, field investigations and observations are basic tools to collect valuable data in a short time at a very low cost. In this paper, 30 intervals from 10 outcrops in Labuan island were selected to be described and investigated in the field using air permeameter and portable gamma-ray spectrometer with no additional lab investigations except 3 thin-sections for validation. Tinyperm II was used to determine the permeability, while gamma-ray spectrometer was used for Clay minerals typing. Results of lithofacies, permeability, and gamma-ray have shown a lack of relation between facies and permeability in the selected outcrops while showing a significant impact of the authigenic Clay minerals on permeability according to their types and morphologies. This paper can provide a good reference for preliminary reservoir field studies.

1. Introduction
In sandstone reservoirs study, one of the challenging problems is to evaluate the reservoir quality accurately in the presence of Clay. Clay minerals in sandstone can be found as primary or/and diagenetic components. In terms of form and composition, they can be found as detrital shale, structural clasts, and dispersed matrix shale. In terms of composition, those forms include kaolinite pore-filling, chlorite pore-lining, and illite pore-bridging [1]. The presence of Clay cement and its morphology, stability, and wettability plays an effective role in affecting reservoir porosity and permeability directly, and pore fluids geochemically through reactions [2]. Therefore, the petrophysical properties of sandstone can be strongly influenced by Clay content [3].

The present paper focuses on the impact of Clay minerals, and their type on the permeability of sandstone in Labuan island as a case study. The main purpose of the paper is to present a low-cost workflow to investigate outcrops for reconnaissance reservoir studies. Labuan island is believed to be in a very strategic location, connecting the geology of Sabah, Brunei, and the offshore geology of Sabah stages in a very small area [4]. The island is located inside Brunei-Sabah Basin [5]. That is the main advantage to study Labuan island outcrops, which will provide a good picture as an analog for Sabah subsurface reservoirs.
1.1. Geological Setting

Labuan island as our case study is a part of the Brunei-Sabah basin. It is located to the NW of Borneo island [6]. It is considered as a plunging asymmetric anticline. Such a structure controls the topography creating nearly flat geomorphology, where the highest elevation is 85 meters [7]. Labuan stratigraphy is a good representation of the NW Sabah basin. It is situated about 8 km to the west of Sabah, to the north edge of Brunei bay, and to the south of the South China Sea (Figure 1).

Sabah region is located in the northern part of Borneo island (Figure 1). It covers an area of about 73,000 km² [8]. Geomorphologically, it consists of four provinces, the western lowlands, the western cordillera, the central uplands, and the eastern lowlands [9]. The complicated geology of Sabah is a reflection of the South China Sea region’s high complexity.

Figure 1. Sabah and Labuan location map.

Labuan island’s geologic exposures show two main groups; an older deep marine sequence deposited from Late Eocene to Middle Miocene and a younger fluvio-marine rich clastic sequence from Middle Miocene to Pliocene. The older deep marine is represented by Crocker and Temburong Formations. The younger shallow marine is represented by Setab shale and sand-rich Belait Formation (Figure 2). The two groups are separated geologically by regional unconformity of the Middle Miocene age, known in the oil industry as the deep regional unconformity (DRU) [10].

The region is considered to be inverted since Miocene. The inversion of the region had forced the shallow marine deposits to prograde seaward [11] (Figure 3). Considering the latest studies of Labuan stratigraphy, this study will focus on 2 of Labuan Formations from older to younger; Temburong and Belait Formations regarding their importance for this study. These formations specifically in Labuan island are most likely to reflect more details about their offshore equivalent stages; II, IV respectively [12].
Figure 2. Labuan island geological map, modified from [13].

Figure 3. Structural map and cross-section for Labuan and the surrounding region [4]. The map and the cross-section show the complication of the different structures which led to the development of Labuan Island as an anticline.
Labuan stratigraphy had been developed by the contribution of many previous authors (Figure 4). Temburong Formation is the deep marine formation below the DRU [14]. It has been suggested to be the argillaceous part of Crocker Formation. It was described as a shaly sand turbidites [15]. Temburong Formation has been deposited during the Oligocene to the Early Miocene. Stratigraphically, Temburong Formations are forming the core of Labuan Island. It is well exposed in the southern part of the island [14]. Setap Shale was proposed as a shallow marine dark argillaceous shale with some intercalations of siltstone and limestone [16]. It was formed during the period from the Early to Middle Miocene [7]. It is covering the central part of Labuan Island [13], but it is hardly exposed due to the differential erosion for shales [10]. On the contrary, some authors have said that Setap Shale is just a part of Temburong as a coarsening upward of the Layang-Layang Beds [9].

Belait Formation is a fluvial fining upward formation. Its texture starting from conglomerate to pebbly sandstone at the bottom till reaching the shale and coal at the top [9]. It has been deposited during the Middle to Late Miocene [20]. Belait Formation is forming the limbs of Labuan anticline as the youngest unit of the succession [14]. It is well exposed in Labuan along the northeastern and western coasts of the island [4]. The base of Belait Formation is considered as erosional because it is correlated with the DRU in the offshore [14].

2. Methodology
The main objective of this paper is to understand the impact of Clay minerals on the permeability of Labuan sandstone using field observation and investigations. The reason to do so is to get the most from the reconnaissance trip. Because having additional information during the fieldwork can uncover areas of interest easily, reduce undirected efforts, and reduce the cost during and after the field trip. An outcrop description has been carried out to outline the general lithofacies. Tinyperm II (air-flow permeameter) was used to measure permeability for selected intervals from the outcrops. The Spectral gamma-ray instrument was used to investigate the presence of Potassium (k), Uranium (U), and Thorium (Th). Thin sections were used later after fieldwork for results validation.
An outcrop field description has been conducted for 10 outcrops. 8 outcrops were representing Belait Formation namely L1, L4, L5, L6, L6B, L8, L10, and L12 with a total of 23 intervals, while 2 outcrops were representing Temburong Formation namely L3 and L7 with a total of 7 intervals. A preliminary facies study was carried out based on field observation of lithology, and sedimentary structures.

Air permeameter was used in this study to provide low cost, fast, non-destructive, and high-resolution measurements of permeability. Moreover, it was able to be applied to poorly consolidated and tiny beds which can be a problem for traditional lab permeability instruments. Measurements were taken using Tinyperm II manufactured by (NER, Inc.). The instrument measures the permeability of rock by injection of air through rock surface and waits until the pressure inside the instrument is normalized. It is able to detect the permeability with (1 to 1000 mD) range [21]. A total number of 30 intervals were investigated using Tinyperm II from the above-mentioned outcrops. The average of two to four readings was taken on and around the spot of interest in the sample for a representable result. Readings were converted from the instrument readings into millidarcy (mD) using equation (1) [22]:

$$\text{Tinyperm II Reading} = -0.8386 \times \log_{10}(K_{air}) + 12.967$$

Spectral gamma-ray spectrometry was used as a non-destructive Clay typing method. The tool used in this study was Gamma Surveyor II manufactured by (GF Instruments). The instrument measures K in (%), U in (ppm), Th in (ppm), and total gamma-ray in (nGy/h). The measurements were carried out on the outcrop scale for the same chosen intervals by the gamma-ray instrument with three minutes per interval [23]. Three readings were taken, the higher and the lower values were neglected.

Thin sections were used in this study for validation of Clay minerals typing results. Only representative three thin sections were presented in this paper for Clay mineral identification and validation of gamma-ray results. The effect of Clay minerals present in sandstone was understood based on the different morphologies of authigenic Clay minerals and characteristics of Quartz under polarized microscope. Blue epoxy impregnation was applied to thin sections to indicate pore spaces under microscope for better identification of Clay minerals positioning.

3. Results and Discussion

3.1. Outcrop Description

The outcrop description has shown a wide range of variations. As a preliminary lithofacies analysis, 7 lithofacies were identified based mainly on lithology, grain size, sedimentary structure, and presence of coal lenses (Table 1) (Figure 5).

**Table 1.** General lithofacies of Belait and Temburong Formations in Labuan island.

| Facies                      | Symbol | Interval ID          |
|-----------------------------|--------|----------------------|
| Flaky siltstone             | Fl-S   | L1-01                |
| Massive sandstone           | M-SS   | L1-03, L4-01, L4-03, L6-02, L7-03, L10-02, L10-03 |
| Massive sandstone with coal lenses | M-SSC | L1-02, L5-03, L7-02, L8-02, L8-03 |
| Interbedded sandstone       | Ib-SS  | L3-01, L3-02, L3-03, L6B-01, L6B-03, L8-04, L12-01, L12-02, L12-03 |
| Interbedded sandstone with coal lenses | Ib-SSC | L6B-02 |
| Laminated sandstone         | Lm-SS  | L4-02, L6-01, L7-04, L10-01 |
| Cross-laminated sandstone   | Cr-SS  | L5-02                |
Figure 5. The seven representative facies from Labuan island outcrops. (A) Laminated sandstone of L6-01 overlain by massive consolidated sandstone of L6-02. (B) Interbedded consolidated sandstone of L12-01. (C) Interbedded consolidated sandstone with coal intercalated lenses of L5-03. (D) Massive semi-consolidated white sandstone with coal lens of L1-02. (E) Cross-laminated semi-consolidated sandstone of L5-02. (F) Flaky siltstone of L5-01.
3.2. Permeability
Permeability measurements of the 30 intervals have been converted into (mD), which have shown a wide range of permeabilities of Labuan sandstones. Permeability has a range of (1.4 to 512) mD. Measurements were classified into 4 classes of permeability as a quantitative evaluation for reservoirs; Poor to Fair, Moderate, Good, and Very Good permeability according to [24] as shown in Table 2. Classification of permeability values shows that most of the samples are evaluated as good with a range of (68.05 to 218.58) mD, followed by poor to fair with a range of (1.4 to 13.28), then moderate with a range of (31.54 to 45.7) mD, and finally the very good quality represented by 3 samples only with a range from (378.54 to 512.01) mD as shown in the box plot diagram (Figure 6).

The data also shows that Temburong Formation samples have poor to fair permeability in 6 samples out 7, with only one moderate permeability value. While Belait Formation samples are mostly good permeability with only 3 samples with poor to fair permeability out of 23 samples. In terms of lithofacies and sedimentary structures, the described facies did not show a notable pattern or relationship with permeability variation.

| Interval ID | Tinyperm II Reading | Permeability (mD) | Class       | Interval ID | Tinyperm II Reading | Permeability (mD) | Class       |
|-------------|---------------------|-------------------|-------------|-------------|---------------------|-------------------|-------------|
| L1-01       | 12.05               | 12.23             | Poor to Fair| L6B-02      | 11.01               | 218.58           | Good        |
| L1-02       | 11.57               | 45.70             | Moderate    | L6B-03      | 11.15               | 146.79           | Good        |
| L1-03       | 11.37               | 81.34             | Good        | L7-01       | 12.03               | 13.28            | Poor to Fair|
| L3-01       | 12.85               | 1.40              | Poor to Fair| L7-02       | 11.57               | 45.70            | Moderate    |
| L3-02       | 12.35               | 5.44              | Poor to Fair| L7-03       | 12.20               | 8.22             | Poor to Fair|
| L3-03       | 12.09               | 11.27             | Poor to Fair| L7-04       | 11.71               | 31.54           | Moderate    |
| L4-01       | 11.04               | 195.85            | Good        | L8-02       | 11.03               | 204.08           | Good        |
| L4-02       | 11.61               | 42.09             | Moderate    | L8-03       | 10.80               | 378.54           | V. Good     |
| L4-03       | 11.69               | 33.33             | Moderate    | L8-04       | 11.43               | 68.05            | Good        |
| L5-01       | 11.36               | 82.47             | Good        | L10-01      | 12.09               | 11.11            | Poor to Fair|
| L5-02       | 11.27               | 105.59            | Good        | L10-02      | 11.22               | 119.47          | Good        |
| L5-03       | 11.13               | 155.08            | Good        | L10-03      | 10.70               | 512.01           | V. Good     |
| L6-01       | 10.72               | 478.04            | V. Good     | L12-01      | 12.31               | 5.99            | Poor to Fair|
| L6-02       | 11.04               | 195.85            | Good        | L12-02      | 11.16               | 40.87           | Good        |
| L6B-01      | 11.23               | 117.84            | Good        | L12-03      | 11.25               | 111.55          | Good        |
3.3. Spectral Gamma-ray

Only Potassium and Thorium values were used as shown in Table 3 for identifying the dominant Clay mineral in each interval. Intervals investigated with spectral gamma-ray have shown almost a tight range of K <1.9 %. However, the Th range was wider with values of (2.76 to 13.8) ppm. Th/K ratio was presented on Th/K cross-plot indicate the dominant Clay minerals. The cross-plot was plotted considering the different permeability classes to present the type of Clay mineral at each permeability level (Figure 7). The chart shows 4 clusters; poor to fair Kaolinite dominated cluster, poor to fair mixed layer Clay dominated cluster, moderate to good Montmorillonite dominated cluster, and good to very good Chlorite dominated cluster. Permeability changes are related to Clay cement morphologies [1]. The general morphologies of authigenic Clays can be outlined according to [25,26]. Kaolinite cement which mostly found as pore-filling plates, Chlorite which is found as Quartz grain coats, Illite which can be found as lath-like blades and in fibrous form, and Smectite which can be found as grain coats and pore bridging.

Table 3. Average of the spectral gamma-ray K and Th measurements.

| Sample  | K (%) | Th   | Sample  | K (%) | Th   |
|---------|-------|------|---------|-------|------|
| L1-01   | 0.80  | 11.68| L6B-02  | 0.6   | 8.04 |
| L1-02   | 1.10  | 10.96| L6B-03  | 0.33  | 7.69 |
| L1-03   | 0.98  | 10.20| L7-01   | 1.71  | 8.63 |
| L3-01   | 1.96  | 13.8 | L7-02   | 1.35  | 7.99 |
| L3-02   | 0.78  | 12.5 | L7-03   | 1.92  | 7.96 |
| L3-03   | 0.81  | 9.78 | L7-04   | 1.06  | 8.52 |
| L4-01   | 1.46  | 11.08| L8-02   | 0.76  | 6.3  |
| L4-02   | 0.23  | 6.11 | L8-03   | 1.1   | 9.74 |
| L4-03   | 0.31  | 4.7  | L8-04   | 0.34  | 6.83 |
| L5-01   | 0.29  | 4.89 | L10-01  | 0.88  | 11.17|
| L5-02   | 0.47  | 8.68 | L10-02  | 0.21  | 4.61 |
| L5-03   | 0.27  | 5.74 | L10-03  | 0.4   | 4.47 |
| L6-01   | 0.26  | 6.7  | L12-01  | 0.74  | 11.63|
| L6-02   | 0.29  | 2.76 | L12-02  | 0.59  | 4.3  |
| L6B-01  | 0.23  | 3.22 | L12-03  | 0.8   | 5.66 |
3.4. Thin section Analysis
According to the Th/K cross-plot, it is obvious that Chlorite and Smectite (Montmorillonite) were able to preserve permeability from other cementation processes like cavity filling, Quartz cementation, and overgrowth. On the contrary, Kaolinite and mixed-layer Clay were responsible about blocking permeability and pore throats.

Authigenic Clay minerals morphologies and features were able to be identified in thin sections under a polarized microscope for results validation. Sample L1-01 which is dominated by Kaolinite and poor permeability shows Kaolinite pore-filling domination under microscope (Figure 8). Sample L3-01 which is characterized by the domination of mixed-layer Clay and poor permeability, shows pore-filling Kaolinite, Quartz cement, Quartz overgrowth, and Illite pore-lining clearly (Figure 9). Sample L5-01 which represents Chlorite domination with good permeability value shows a high percentage of Chlorite coats and a small amount of Kaolinite filling with clear pore spaces in the thin section (Figure 10).

Figure 7. Th/K Clay mineral identification chart plotted according to permeability classes [27].

Figure 8. Thin section image showing morphological features of L1-01. (Q) Quartz grain, (P) Pore space, (KF) Kaolinite pore-filling.
4. Conclusion
The sandstone permeability of Temburong and Belait Formations in Labuan island is strongly affected by Clay minerals according to their types. Lithofacies of Labuan island with their varieties in the studied outcrops have no obvious impact on sandstone permeability, which confirms that the impact of Clay minerals is authigenic and not allogetic. Chlorite and Montmorillonite coatings have a good impact on permeability, unlike Kaolinite pore-filling and mixed-layer Clay of Kaolinite, Illite, and Montmorillonite which have reduced sandstone permeability dramatically. Belait Formation has shown better quality in terms of permeability, while Temburong has poor quality in almost all samples. Expected reservoirs of Belait Formation offshore equivalent (Stage IV) appear to be promising rather than Temburong Formation offshore equivalent (Stage II) according to permeability results. Field observation and investigation can provide information more than expected with high accuracy if the right methods and tools were applied. For further studies, samples from offshore Sabah Stages should be studied alongside with Labuan outcrops for correlation. More laboratory analysis like XRD, SEM, poro-perm analysis, and micro CT should be applied to samples for a better picture of the area.
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