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Prediction of carbonate rock facies from core probe permeability measurements and well log data: a case study from carbonate reservoirs, Phu Khanh basin

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ABSTRACT

Probe permeameter (also known as Mini-permeameter) has been widely used in many field and laboratory applications where in-situ measurements and spatial distributions of permeability are needed. Mini-permeameter measurements have become popular techniques for collecting localized permeability measurements in both laboratory and field applications. It is designed to obtain fast, cheap, intensive and non-destructive permeability measurements and to describe the spatial arrangement of permeability. Currently the probe permeability meter is designed and manufactured as a portable air permeability for field applications and to be used in outcrop and core samples. In this instrument, the permeability is measured by air that flows from the samples to be measured into an air chamber through the vacuum created by increasing the volume of the chamber. In carbonate reservoirs, permeability predicted from pure porosity-permeability empirical relationship is often difficult due to complex rock pore systems leading to poor porosity-permeability relations. Once the relationships between permeability and textural rock properties are clearly established in carbonates, they can provide better permeability predictions from porosity data. Rock texture is an important parameter for the understanding of the porosity and permeability characteristics of carbonate reservoirs. In addition to predicting carbonate rock facies from routine core plug porosity and permeability measurements, there is an approach to determine carbonate reservoir facies based on core-plug probe permeability. The results of the probe permeability measurements, in this paper, can be used in combination with the porosity values derived from the well logs to classify and predict rock facies in carbonate cored or uncored reservoirs in Phu Khanh basin.

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1. Introduction

In the world, up to now, 60% of oil reserves and 40% of gas reserves are in carbonate rocks, especially in the Middle East with 62% of the world's oil reserves, of which over 70% is in carbonate rock; with 40% of the world's gas reserves, of which 90% is in carbonate rocks and many large carbonate reservoirs are likely to have a production lifetime beyond 50 years (Sadeq and Yusoff, 2015). Thus, carbonate-bearing rocks are always the leading object of exploration and exploitation of many countries in the world. It is no coincidence then that the petroleum industry has been the primary source of funding and promoting research into carbonate rocks and depositional systems, often with impacts extending well beyond oil and gas exploitation. Oil carbonate reservoirs are considered a subject of interest in the petroleum industry because it can be difficult to predict the quality and ensure high recovery factors from this carbonate rock.

In Vietnam, the oil and gas prospection, exploration, and production on the continental shelf have so far only focused on three main objects, which are Oligocene, Miocene sediments, and pre-Cenozoic basement rocks. Carbonate rock is also an object with great oil and gas potential in Nam Con Son basin, Tu Chinh - Vung May basin, and Phu Khanh basin.

Carbonate rock has become an object containing oil and gas that many companies are interested in and want to study and evaluate in petroleum exploration and production. However, due to the limitation of seismic, geological, and geophysical data of wells and core samples, there have not been detailed studies on the characteristics, quality, and permeability of carbonate-bearing rocks in Phu Khanh basin.

2. Geological setting of the Phu Khanh basin

The Phu Khanh basin, offshore central Vietnam (Figure 1), comprises the typical elements of a rifted margin: rifted basement, a syn-rift unit, a break-up unconformity, and a thick post-rift unit. The syn-rift sediments have been interpreted to consist of lacustrine and fluvial deposits, alluvial fans and fan deltas. The post-rift sedimentation is characterized by a gradual change from a transgressive ramp phase to a regressive shelf-slope phase. (Nguyen and Nguyen, 2010). Petroleum objects were discovered in the Phu Khanh basin in carbonate-bearing rocks of the Miocene age. The features of carbonate rock here are mainly black pepper limestone interspersed with biological limestone and shelf limestone, shallow marine environment to open sea. Carbonate rock is considered as one of the objects capable of containing the interest in the Phu Khanh basin. However, up to now, due to limited seismic, geological, and geophysical data of wells and core samples, there have not been meticulous and detailed studies on the characteristics, quality, and properties of the core samples, as well as the permeability of carbonate rocks in the Phu Khanh basin. Therefore, a complete and systematic study on carbonate rocks in Vietnam in general as well as in the Phu Khanh basin, in particular, is necessary, partly to accommodate the development needs of oil and gas exploration and production in Vietnam.

3. Methodology and data

There have been many authors such as Archie, Lucia, and Choquette-Pray who classified carbonate rocks using different methods, yet they are all based on the distribution and association between the pores in the carbonate rock. In this study, some of the methods that have been compared for rock typing and grading are Lucia, Global hydraulic elements (GHE), and permeation probes on core plugs.

3.1. Probe Permeametry

The permeability data are often collected from the probe permeameters on a compact support volume. Typically, a probe permeameter is operated by injecting gas (e.g. compressed nitrogen) into a permeable porous media at constant pressure (i.e. P = Pi). In this technique, the gas is injected through a circular tip with an inner radius ri. To prevent the leakage of gas between the injection tip and the surface of the sample, a tip seal of outer radius ro (ri < ro) is used. Outside the tip seal, the sample surface is kept at atmospheric pressure (i.e. $P = P_{atm}$) (Brown & Smith, 2013; Dinwiddie et al., 2003; Ayan et al., 1994).

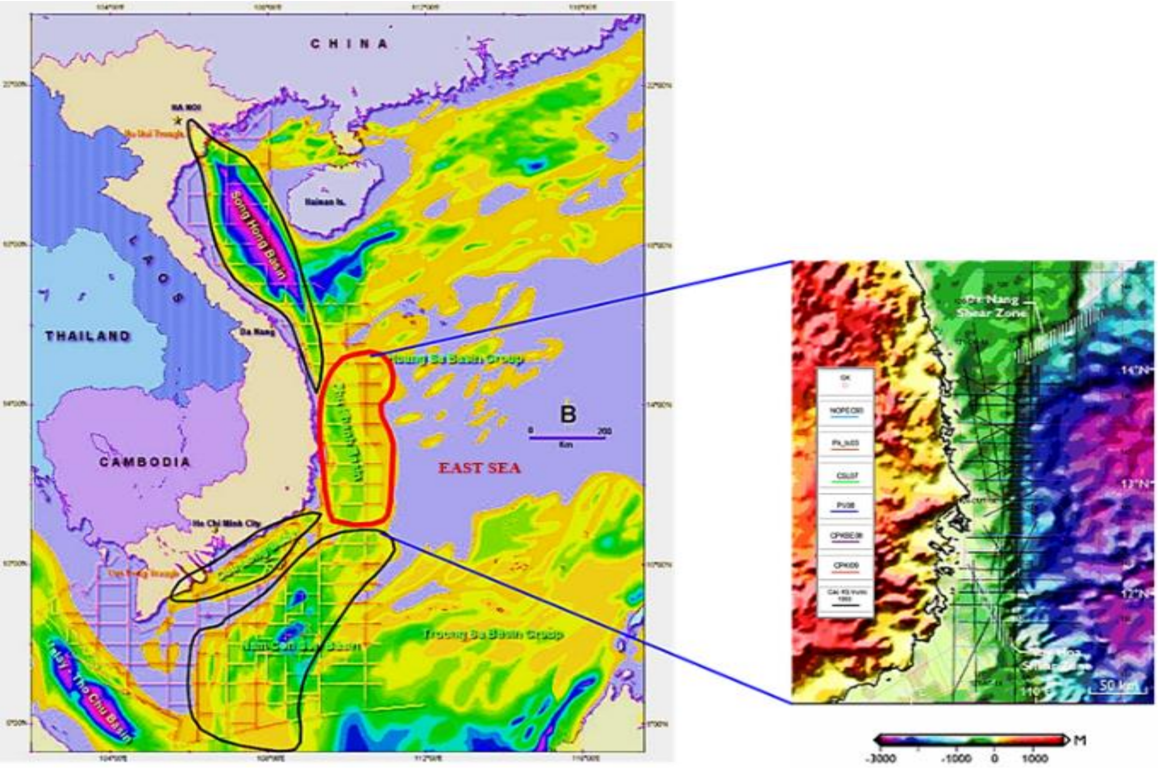

Figure 1. Location map showing the study area.

Figure 2 shows a schematic of the probe permeameter configuration. For small samples, the injected gas escapes from its other exposed surfaces, but for any surface that is almost four times the radius of the probe away from the center of the injection tip, the boundaries have no significant influence on the permeability calculations. Figure 3 shows an image illustrating the probe permeameter during the permeability measurements.

Although the measured probe permeability is the representative of a relatively small rock mass (the PPP-250 probe has a diameter of 1cm), but remarkably probe permeability can be measured at a density with a thick, sparse density depending on the purpose. When measured probe permeability is equivalent to the measurement recorded in the conventional petrophysical data (15 cm or 0.5 ft), the data can be used to replace the measured permeability on the conventional core when combined with porosity calculated from the material of logs.

3.2. Lucia method

Lucia (1883,1995, 2007) classified carbonate rocks according to their porosity-permeability characteristics, which is the most common and widely used distinction today and can be used to assess the quality of aquifers based on the porosity relationship - permeability of carbonate-containing rocks.

It is possible to use multiple linear regression to show the correlation between porosity, permeability, and carbonate rocks according to well geophysical parameters.

Equation (1) can be used to classify rock type:

$$Log(k) = (A - Blog(rfn)) + ((C - Dlog(rfn)) Log(\Phi)) \quad (1)$$

Where, A = 9.7982, B = 12.0838, C = 8.6711, D = 8.2965, and rfn is the number of architectures of the rock varying from 0.5÷4.

Lucia defined three main carbonate rock classes (Figure 4) defined by their Rock Fabric Number (RFN) below:

- Class 1: grain dominated Fabric - Grainstone. RFN's of 0.5÷1.5.
- Class 2: grain dominated Fabrics - Packstone. RFN's of 1.5÷2.5.
- Class 3: Mud-dominated Fabrics - Packstone, Wackestone, Mudstone. RFN's of 2.5÷4.0.

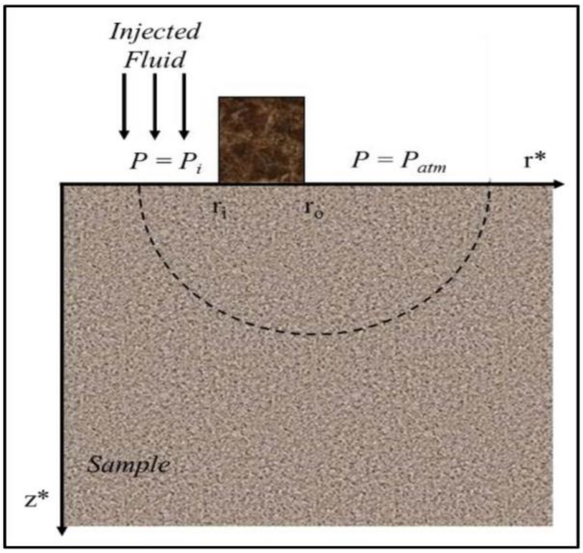

Figure 2. Schematic of the Probe Permeameter Configuration (Al-Azani et al., 2019).

Figure 3. Probe-Permeameter During Permeability Measurements (Meyer, 2002).

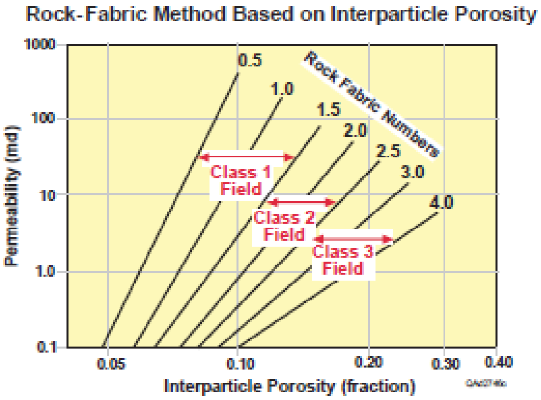

Figure 4. Lucia classify rock type based on rock fabric (Lucia, 1983; 1995).

3.3. GHE method

Corbett et al. (2003) proposed the rapid and more straightforward approach to plot the porosity and permeability data on the pre-determined global hydraulic elements (GHE) template which is constructed on the basis of equation 1. A systematic series of a priori FZI values was arbitrarily chosen to define 10 porosity-permeability elements. Only ten were chosen in order to split the wide range of porosity and permeability parameter space into a manageable number of GHEs.

$$K = \Phi_e \left[\frac{FZI.\frac{\Phi_e}{1-\Phi_e}}{0.0314}\right]^2 \qquad (2)$$

The series of FZI values (0.0938÷48) corresponds to the lower boundary of Global hydraulic elements (Table 1) (Potter and Le, 2003). This allows any core plug to be rapidly classified in terms of GHEs merely by plotting its porosity and permeability values on the template. The GHE approach also permits the selection of representative samples even when core data availability is limited.

Table 1. FZI mean value for each GHE by Corbett et al. (2003).

GHE	FZI	GHE	FZI
10	48	5	1.5
9	24	4	0.75
8	12	3	0.375
7	6	2	0.1875
6	3	1	0.0938

3.4. Data set

In this study, some core plug data from four wells A-1X, B-2XST, B-2X-ST1, B-1X, and thirty-three meters of carbonate well core have been analyzed and measured.

4. Results and discussions

The permeability measurement method is performed under normal conditions, the research depth of the permeability measurement method is also relatively shallow, and the value of measured permeability represents only a small cross-section of the sample. In this study, samples for pointed permeability measurements were stored for a long time, for example, well A-1X was drilled more than ten years ago and stored under normal conditions. Therefore, errors still exist when comparing the permeability measured by the two methods at two different times. However, the results of permeability measurement are reliable and can be applied for further studies.

Figures 5 and 6 compare the permeability from the laboratory samples analysis and the measured probe permeability recorded. In general, the trend of permeability is unchanged. However, due to the difference in measurement conditions, the nature and representativeness of the measured rock's volume in these two methods are different and depend on the heterogeneity of the rock, and the results of permeability measurements are often detailed and highly reliable. Especially when measuring the spot permeability on newly obtained core samples that have not yet been drilled for conventional core (core plug).

By combining measured probe permeability and porosity determined from petrophysical data, it is possible to predict rock facies for uncored

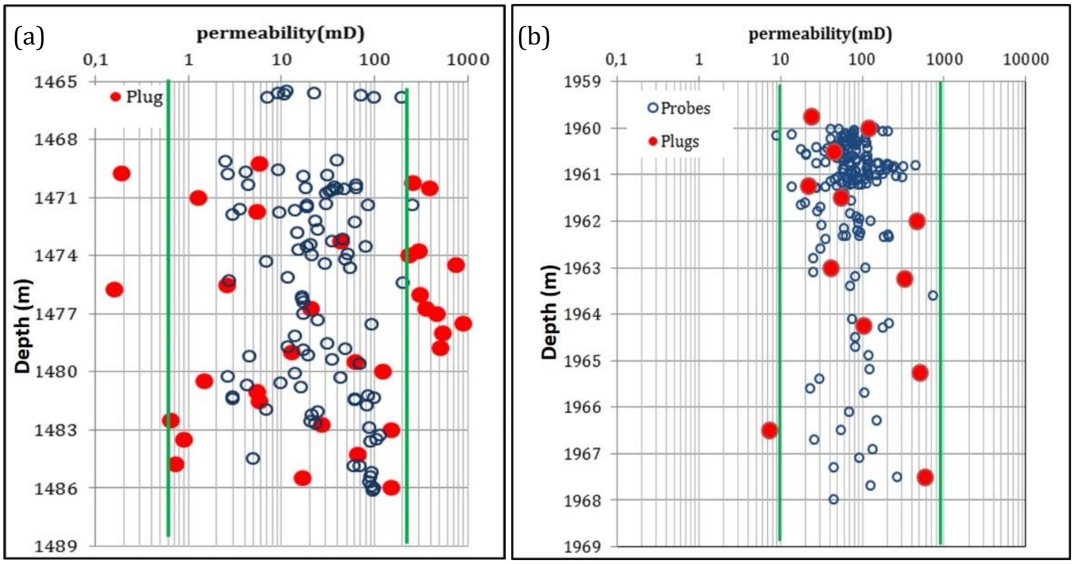

Figure 5. (a) Comparison of Plug permeability, well A-1X; (b) Comparison of Probe permeability, well A-1X.

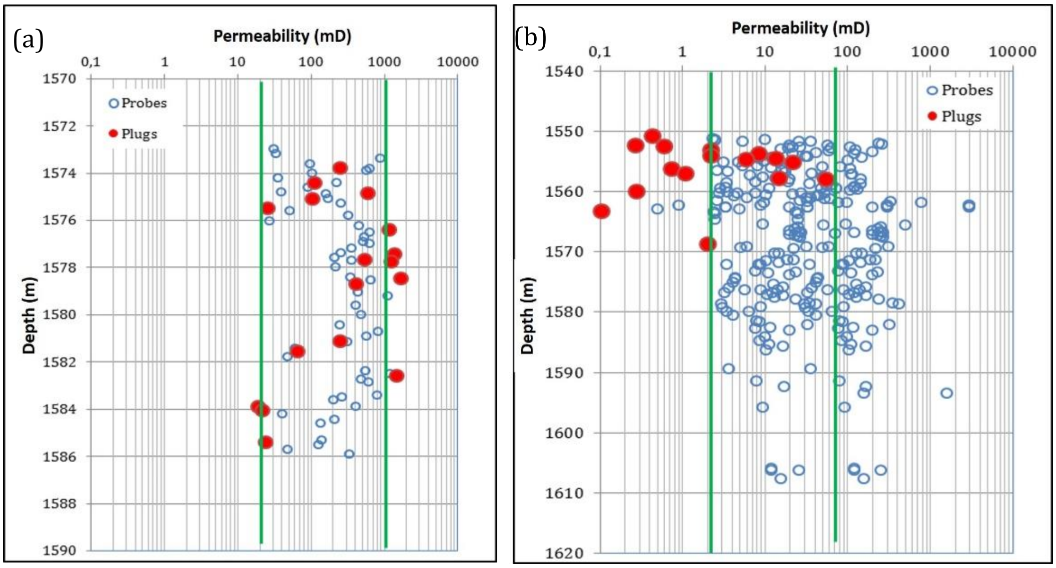

Figure 6. (a) Comparison of Probe and Plug permeability, well B-1X; (b) Comparison of Probe and Plug permeability, well B-2XST.

carbonate reservoirs in the study area as well as sample analysis. The results are shown in Figures 7 a, b and Figures 8 a, b. Therefore, it is clear the carbonate rocks (as Lucia, 1995; Corbett et al., 2003), according to the sample analysis results and the probe permeability measurements combined with porosity measurements from the unit, are typically equivalent. By applying the classification from the probe permeability combined with the porosity derived from well logs to predict the rock type for the zones without conventional core. By comparing the predicted results from the probe permeability measurement data and the core sample measurements, the results are quite similar in Figure 9.

5. Conclusion

The use of probe permeability measurement in combination with well-log data shows efficiency in rock typing for carbonate reservoirs in the Phu Khanh basin, using Lucia (1993) and Corbett et al. (2003) approach.

The use of probe permeability measurement in rock research has many advantages: (i) fast recording time, (ii) uncomplicated and non-destructive operation of slabbed core samples, (iii) low cost, and (iv) it is possible to obtain a rapid assessment of the rock characteristics contained immediately after cutting the slabbed core sample or even measure it on the whole core sample after drilling.

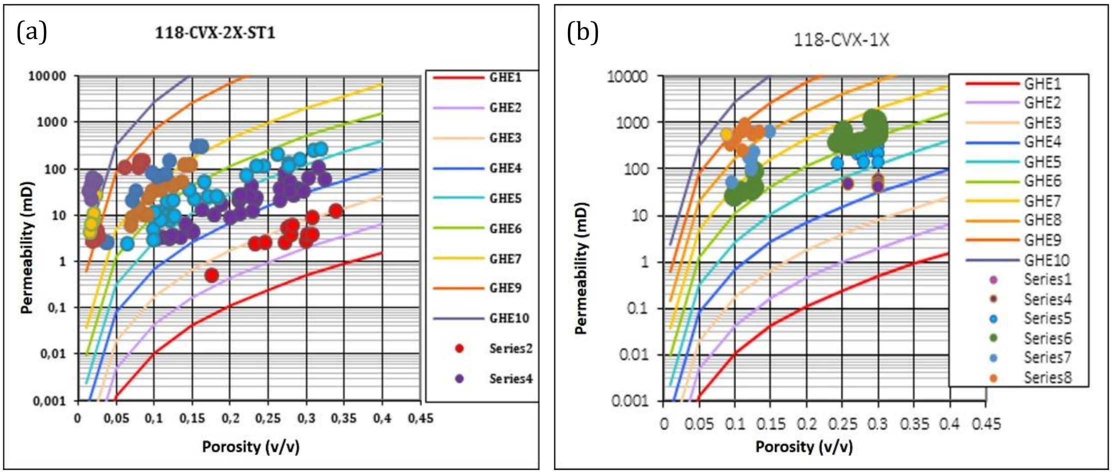

Figure 7. (a) Rock classification according to GHE and Lucia on probe permeability and porosity measurement documents from logs, wells B-2X-ST.; (b) Rock classification according to GHE and Lucia on probe permeability and porosity measurement documents from logs, wells B-1X.

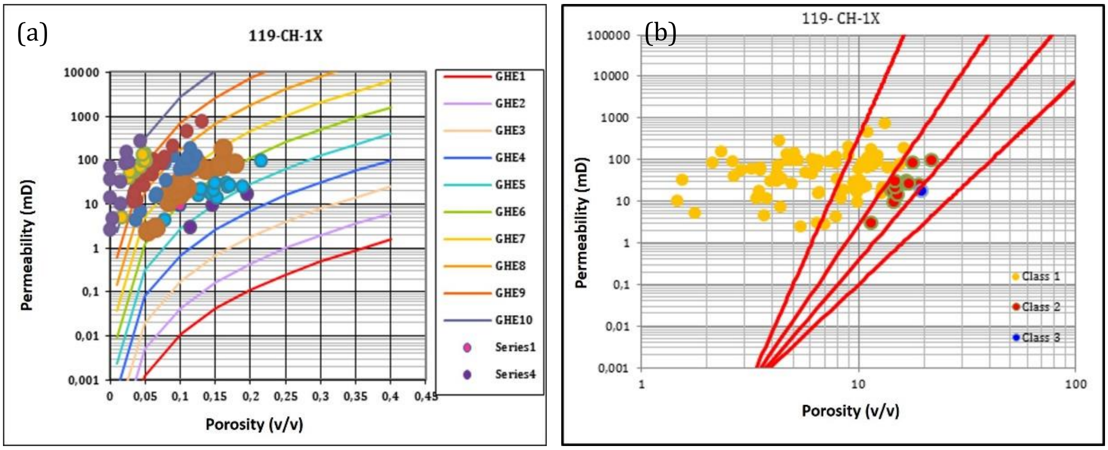

Figure 8. (a) Rock classification according to GHE on probe permeability and porosity measurement documents from logs, wells A-1X; (b) Rock classification according to GHE and Lucia on probe permeability and porosity measurement documents from logs, wells A-1X.

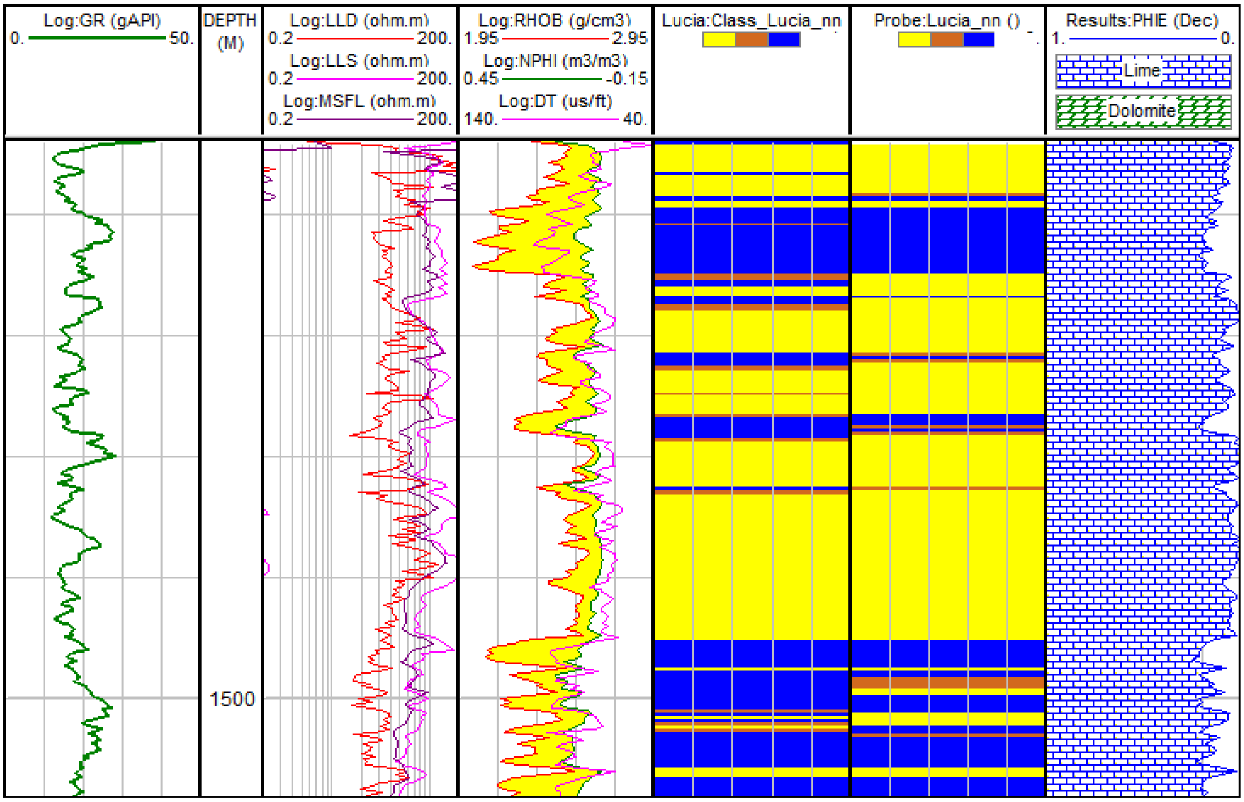

Figure 9. Rock-type prediction from core analysis and from probe permeability measurements in combination with well log data.

The probe permeability measurements can be used in combination with the porosity values derived from the well logs to classify and predict rock facies in carbonate sediments.

Rock classification based on probe permeability data in combination with the porosity derived from well logs can be effectively used to predict the rock types for the uncored zones.

Contribution of authors

Hong Minh Thi Nguyen - designed ideas, wrote the article draft and finalized the checking manuscript. Hong Thi Pham - analyzed samples and prepared pictues and database.

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