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Shallow Carbonate for Underground Gas Storage in West Java, Indonesia

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Abstract
The Parigi Formation has been a significant gas exploration in West Java Basin. This is due to their abundance, and they occur at shallow depths (800-1000 m). The main objective of this study was to focus on the characteristics and distribution patterns of the shallow carbonate to be used for gas storage. The case will be focused on Parigi Formation as a reservoir carbonate in the depleted oil and gas field in West Java Basin. These build-ups are better developed in onshore West Java Basin, where they exhibit coral reef frameworks and reach over 450 m in thickness. Moreover, Parigi Formation carbonate is well exposed in Palimanan, West of Cirebon City, and it is divided into four types of lithofacies. Preservation conditions, storage capacity, effective injection, and production are important factors in underground gas storage. In the geological site, factors that need to be evaluated are as follows: a reservoir, trap sealing, and tectonic activities in the surrounding area. However, in the USA and Europe, the porous reservoir formations such as sandstone or carbonate at depths of 500 - 1800 meters are common in storing natural gas in large volumes size. Ultimately, according to this case study, it has been found out that the most influential parameters for storing natural gas are porosity and permeability (petrophysical properties).

Keywords: Gas Storage, Carbonate, Reservoir, Porosity, Permeability.

Introduction

A depleted gas reservoir may be used as underground gas storage. It is an economical and effective for storing gas, which guarantees continuous safety and supply of gas. Gas storage technologies have been applied in Europe, Australia, the USA, and China, but not in Indonesia [1,2]. This study is an effort to introduce the underground gas storage to be applied in depleted oil and gas fields in Indonesia. It is an early stage of underground gas storage study, so designing, evaluating, and operating gas storages must be discussed until a project is implemented in a depleted field in Indonesia. Carbonate rock is one of the potential reservoirs for underground gas storage. In this study, Parigi carbonate is selected as a candidate because it is a shallow carbonate (800 m below the ground surface), and has been proven as a hydrocarbon reservoir in a few fields in West Java Basin areas. Several elements that characterize storage reservoirs, such as porosity, permeability, shape body, type of caprock, size of the volumetric area, and depth location of the reservoir, will be discussed in this paper.

Materials and Methods

Feature of Parigi Carbonate

At the end of the Early Miocene, there was a period of structural stability that led to the widespread deposition of Parigi carbonates. The Parigi build-ups in the West Java Basin were deposited in a shallow marine platform setting during regional tectonic quiescence [3]. Moreover, the development of Parigi build-ups is on the paleo-highs which are not necessarily associated with basement paleo-structural features. These build-ups are better developed in onshore West Java Basin, where they exhibit coral reef frameworks and reach over 450 m in thickness. Parigi Formation carbonate is well exposed in Palimanan, west of Cirebon City, and it is divided into four types of lithofacies [4].

In offshore, Parigi carbonate can be subdivided into two types, namely Lower Parigi and Upper Parigi. The Lower Parigi (6-9m) that was deposited as a biostromal wackestone to packstone, and it is overlain by a thick (12-60m) claystone unit, which in turn is overlain by the Upper Parigi carbonate (85m). It is a good marker horizon on the wireline logs and possibly acts

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as a chronostratigraphic unit, at least in the east-west direction parallel to depositional strike. The Upper Parigi carbonate is the build-up unit in which most known gas is trapped. Base on a few wells that drilled by Arco, the thickness ranges from a few meters to over 120 meters in the offshore West Java area [5,6]. In onshore Java, Upper Parigi carbonate reaches a thickness of over 400 meters in various wells drilled by Pertamina, as shown in Figure 1.

The Upper Parigi build-up is composed of fine to medium grain, the sorting is moderate of skeletal-foram wackestone, packstone and grainstone, with packstone being the more frequent lithology. Grain types are mostly larger benthonic foraminifera, including Amphistegina sp., rotaliids, and fragments of red algae, mollusk and an echinoderm. It is common to observe intervals with abundant Amphistegina foraminifera fragments, referred to as form hash. In addition, Parigi build-ups are oriented north-south and well-developed along an east-west belt near the platform/shelf margin setting.

Depositional Environment of Parigi Carbonate

The majority of the Parigi build-ups that have been deposited in a shallow marine platform setting in a general north-south orientation is shown in Figure 1.

The platform was dissected by relatively deeper water which separates the offshore Parigi trend from the onshore Parigi trend. The orientation of the Parigi build-ups appears to have been controlled by the combined effects of current/wind directions and the morphology of the platform margins [7]. The build-ups are elongated parallel to the inferred current direction. The current direction at an angle to the platform margins resulted in the NNW trending build-ups in the offshore area and NE-SW trend in the adjacent part of the coastal area. It is shown in Figure 1. This paleogeography map is controlled by Top Parigi depth, which is gridded from regional well tops using Petrosys software.

The build-ups on the offshore Platform are spaced close together and are separated by narrow tidal current channels, no build-ups are present, and the Lower Parigi is overlain by claystone with limestone stringers. The outline of the Parigi build-ups is well-defined on the seismic due to their sharp dipping flanks [8,9]. Top Parigi is expected to have a strong positive amplitude while in a gas bearing carbonate, the top Parigi shows seismic amplitude much weaker than in a water-bearing case.

The gas/water contact can be easier to identify in Parigi carbonate. A shallow hazard and site surveys indicate very clearly a flat spot anomaly representing a gas/water contact shown in Figure 2A. Analyses of sidewall core samples from the offshore wells indicate that these build-ups do not have distinct lithological differences between the windward and leeward part of the build-up [10]. This is probably due to 1) an extensive diagenetic overprinting on the depositional fabric and hence the obliteration of facies and 2) merging of the flanks of several smaller build-ups to form large build-ups with a mixture of various facies [11].

The Parigi build-ups in the offshore are predominantly skeletal foraminifera packstone with rare coralline material and little or no framework structure. However, this differs from the Parigi trend in onshore Java to the south where build-ups are higher in relief and comprise a coral-algal framework, as shown in Figure 2B.

A Parigi carbonate outcrop study in Palimanan onshore showed that this carbonate is divided into 4 major lithofacies [4]. The lithofacies are: 1) Mudstone-wackestone facies (upper part) with porosity between 5 and 25% and as a marine-phreatic diagenetic environment, 2) Wackestone-packstone facies (middle part) with thickness reaches more than 170 m and porosity between 15 and 28%. It is believed to be influenced by diagenetic environments, such as vadose – freshwater phreatic, and also the tectonic process, 3) Packstone-grainstone facies (below part) is mostly composed of medium to fine-grain limestone [12]. The porosity is as a vuggy and moldic with porosity between 10 – 25% and 4) Mudstone-wackestone facies (bottom part) similar to mudstone-wackestone facies in the upper part is formed under a diagenetic regime with porosity ranges between 5 and 20%.

Parigi Carbonate Reservoir Evaluation

Parigi carbonate form excellent reservoirs owing to the presence of high porosity (average 30%) and permeability (up to 650 mD). The widespread distribution of build-ups in offshore and onshore West Java Basin is an important factor in analyzing the carbonate facies of high-quality carbonate reservoirs in this area [9,13].

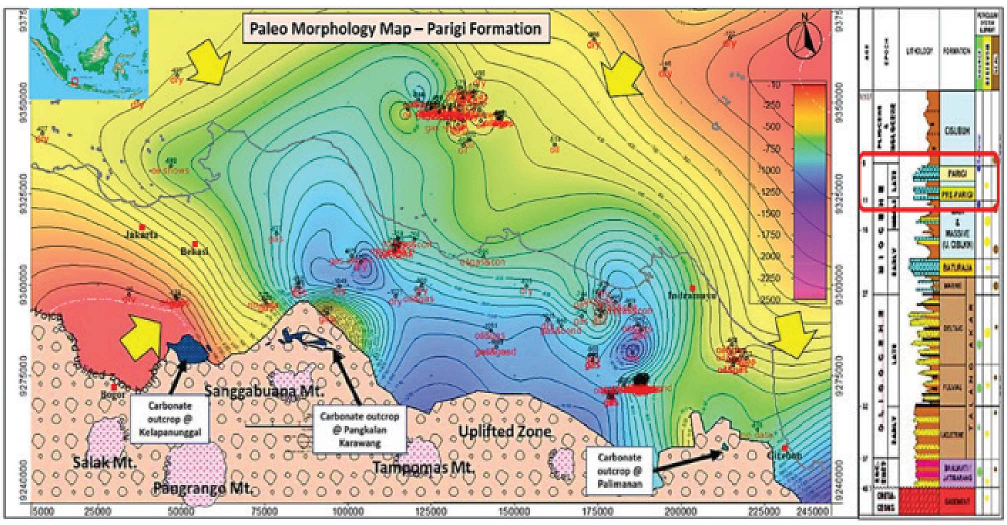

Fig. 1 Parigi build-up depositional setting in offshore and onshore West Java Basin.

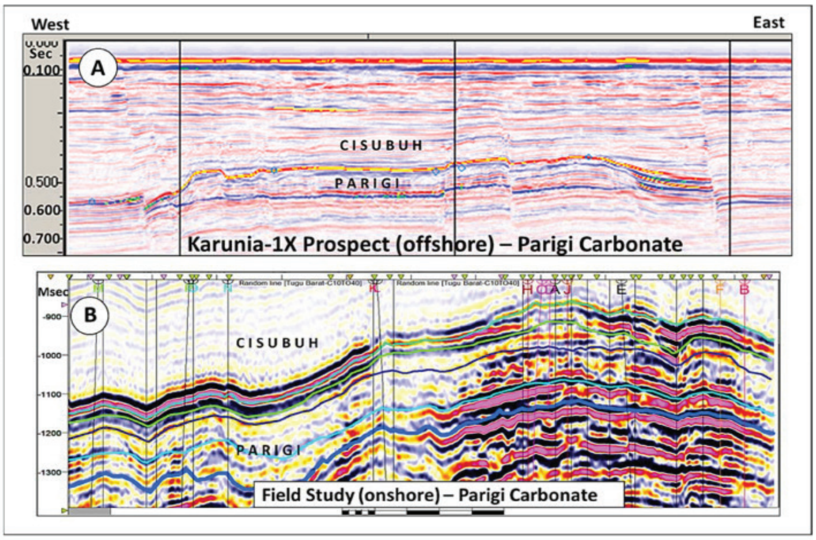

Fig. 2 (A) High resolution seismic indicates low relief the Parigi build-up in offshore West Java Basin [5,9], and (B) 3D seismic indicates high relief the Parigi build-up in the land area.

Infield study, the environment of deposition, facies, and diagenetic processes are studied using Well logs and 3D-seismic analysis. Furthermore, porosity logs and density logs are applied to understand the porous zones in the Parigi build up. In addition, the reservoir's historical pressure versus depth of each well in this field can be seen in Figure 3.

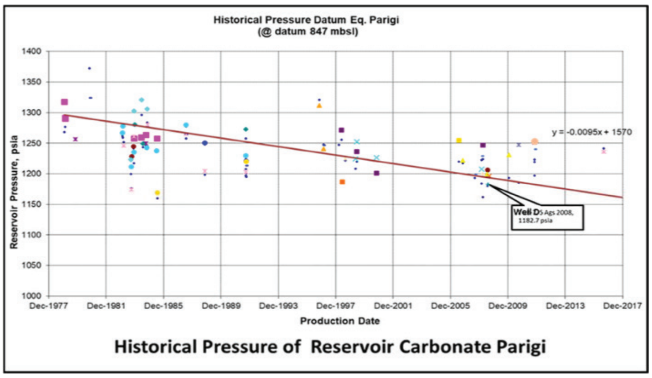

Fig. 3 Relationship between reservoir pressure of each well and production date of reservoir carbonate Parigi Formation.

Well Log Evaluation

The analyses of a few well data were done using GR, RHOB, NPHI, and Facies logs. GR log reflects the shale content of sedimentary formations. The clean sandstones and carbonates normally exhibit a low radioactivity, while the clay and shales show higher in the API unit [14,15]. The RHOB log is utilized to measure in-situ bulk formation density in g/cm^3, and it is defined as the overall density of rock. The Carbonate Facies log indicates wackestone-packstone in the bottom, and upper parts of the Parigi build up. The middle part of the build-up is dominated by packstone. Those logs analysis produced five different bed boundaries, such as Top Parigi, Parigi Zone-B, Parigi Zone-C, Parigi Zone-D, and Bottom Parigi, as shown in Figure 4. These tops are applied in seismic facies analysis. Moreover, the Parigi carbonate boundaries (top and bottom) can be differentiated clearly from the GR log. The NPHI-RHOB tools are utilized as a lithology indicators. When NPHI-RHOB separates the Parigi carbonate boundaries, it is indicative of karstic dolomite [16] (Figure 4). Also, it is worth noting that the carbonate facies log is not well interpreted due to very limited data from cores in the Parigi carbonate section. In addition, packstone and wackestone are the only lithofacies that can be applied for the whole Parigi section [12]. The outcrop study of Parigi carbonate in Palimanan identifies four lithofacies for the whole carbonate section, and these facies will be correlated with subsurface Parigi carbonate in this field.

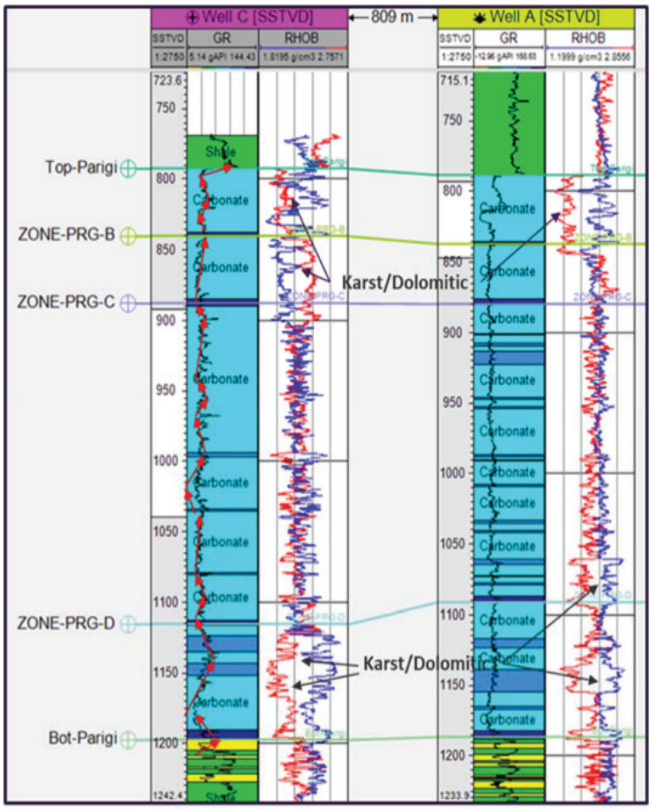

Fig. 4 Indicator of Top and Bottom Parigi carbonate from drilling and wireline logs. NPHI-RHOB separate curves in the upper part and the bottom part of Parigi carbonate indicate karst/dolomitic with good porosity and permeability indications.

Seismic Facies Analysis

Four wells with varied data suits, including wireline, mud logs, and completions reports, were used in the study to

establish regional correlations of 5 litho-stratigraphic surfaces (Top Parigi, Top Zone Parigi-B, Top Zone Parigi-C, Top Zone Parigi-D and Bottom Parigi). The 3D seismic data was incorporated in the workflow to aid in the interpretation of the relative position of depositional environments. The 3D seismic coverage in the study area was used to define overall build-up geometry and identify the potential reservoir closure for underground gas storage. The seismic facies boundaries of Parigi carbonate sequences were interpreted based on the log evaluations and characteristics of seismic reflections such as mounded, parallel, clinoform, progradation etc [17,18]. The geometry of Parigi carbonate is a product of shaping the depositional surface, changing base level, and accumulating sediment. Based on the seismic characteristic and distribution of Parigi carbonate, the surfaces can be divided as Parigi Zone-A, Parigi Zone-B, Parigi Zone-C, and Parigi Zone-D. Also, a seismic facies interpretation of the carbonate zones is shown in Figure 5A.
The interpreted facies can be seen in Figure 5B where the carbonate body is divided into four (4) stages: stage-1 of Parigi-D is Highstand System Tract, stage-2 and 3 are Parigi-B and C dominated by Transgressive System Tract, stage-4 is Highstand System Tract with quick transgressive as part of Top Parigi layer. To the surface, this seismic facies analogs from top to bottom as follows: 1) Mudstone-wackestone facies=Parigi zone-A, 2) Wackestone-packstone facies=Parigi zone-B, 3) Packstone-grainstone facies=Parigi zone-C, and 4) Mudstone-wackestone facies=Parigi zone D in the bottom part.

Geological Reservoir Modelling

A seismic attribute extraction was done to determine the porosity and density distribution in Parigi carbonate (Figure 5). In determining porosity through the logging tool, there are two calculations: (1) the first is the calculation of single porosity and (2) the second is a combination of the porosity. Comparative results of the porosity of logs with the core porosity for the well D can be seen in Figure 6. In the picture, it looks that almost all the methods, including of both single porosity and the porosity combination, have a good alignment when they are compared with the core porosity.
The results of the model porosity has been obtained based on the dissemination of modeling property, then they were continued with the creation of a permeability model. The method performed by using the equation cross plot result of permeability porosity of the core data [19] in Figure 7 shows a cross plot between permeability and porosity of the Parigi Reservoir.

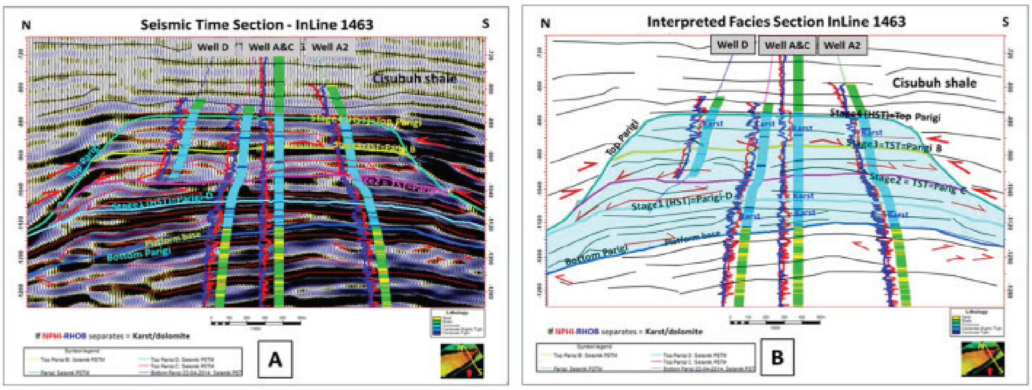

Fig. 5 Seismic facies of Parigi carbonate interpretation: (A) it indicates platform margin facies, clinoform, down lap, platform base, parallel, and mounded and (B) the upper part of NPHI-RHOB separate curves indicate karstic/dolomitic.

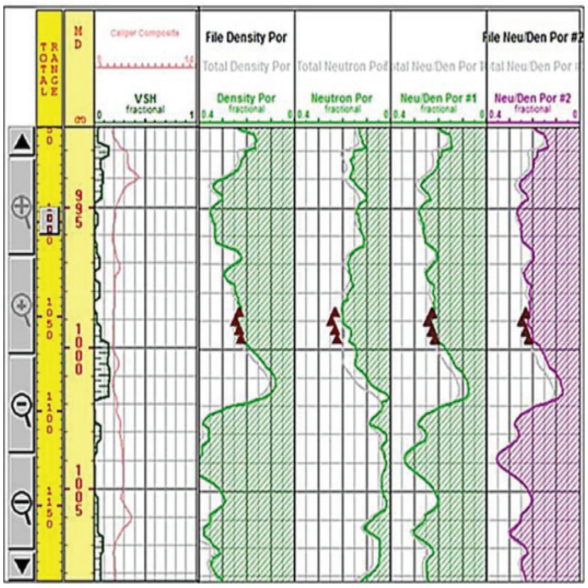

Fig. 6 Calibration results between the porosity of the Log with the Core porosity on the well D in the field location.

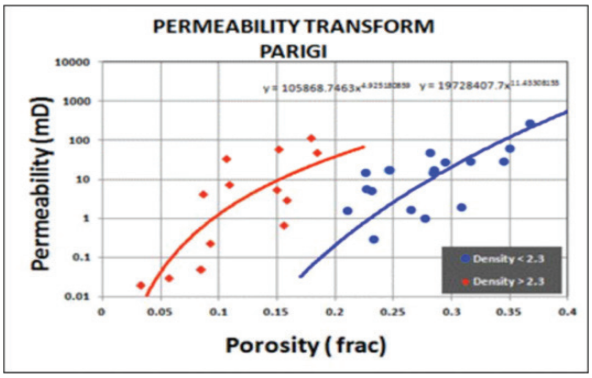

Fig 7 Cross plot permeability and porosity separated using density of the reservoir carbonate Parigi.

During the geological reservoir modelling, seismic data have been used to identify porosity and permeability in the reservoir distribution in the target horizons. Four surfaces (horizons) have been identified in Parigi carbonate from a seismic section in Figure 5, and two seismic attributes of porosity and permeability have been generated, as shown in Figure 8. In Figure 8A, the porosity value distribution in Parigi carbonate is shown. The Parigi-A and Parigi-B more porous (0.24 frac - 0.30 frac). Figure 8B shows the permeability value distribution, where Parigi-A and B are more permeable (3.2 - 320 mD). The lower part is relatively tighter (0.0 frac – 0.10 frac) and impermeable (<0,1mD). Moreover, the high capacity of reservoir for gas storage requirements demands high-matrix permeability and good vertical and lateral reservoir continuity [5,12,17]. After assessing permeability and porosity values using geological reservoir modelling, it is determined that there are good permeability and porosity zones in the upper part of Parigi carbonate, as seen in Figure 8. After running the geological reservoir modelling, according to the obtained results, it sounds that the upper zone is a porous porosity/moderate permeability zone, and the lower zone is a tight porosity/weak permeability zone. The Upper zone is a reef build-up that has been developed on the platform limestone (Lower zone). The growth of the build-up sequence was periodically interrupted by marine transgression and erosion/karstification, as seen in Figure 4. This Parigi carbonate build-up expanded better at the area platform within the inner-middle neritic area. The Parigi carbonate was overlain by onlapping the Cisubuh Formation shale, as shown in Figure 5.

In Figure 9, a good correlation across the field and the Cisubuh Formation, which acts as a seal for reservoir Parigi Carbonate are shown. The Cisubuh formation is dominated by shales with minor intercalation of sandstone, conglomerates, and calcareous streaks. The thickness of this formation ranging from 200 - 400 m with shale density ranging from 2.0-2.21 g/cm^3. The shales are the main seal for sealing hydrocarbons in the Parigi carbonate reservoirs [20,21]. The Cisubuh contains an abundance of foraminifera, such as Globigerinoides ruber, Rotaliia, and Mollusks. Moreover, it seems that this formation has been deposited in a shallow sea.

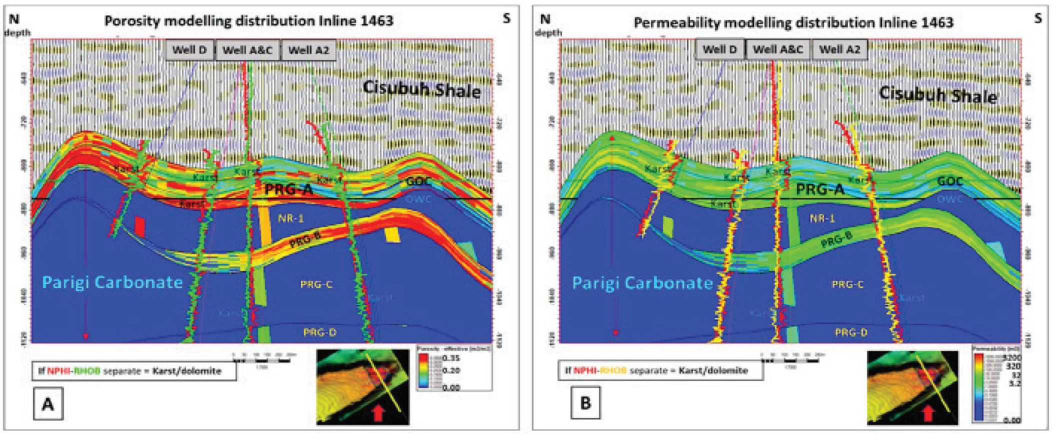

Fig. 8 Geological reservoir modeling of Parigi carbonate indicates (A) medium to high porosity and (B) medium permeability in the upper part of the build-up carbonate (B), and Karst zone is identified from log crossing of NPHI and RHOB.

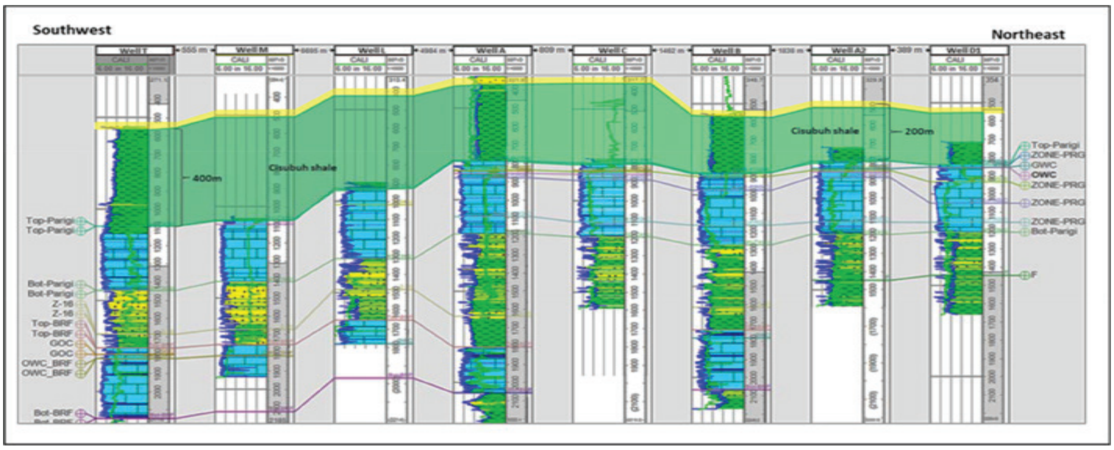

Fig. 9 Well correlation section across the field structure shows the thickening of Cisubuh shale from NE (200m) to SW (400m).

Results and Discussions

Well log evaluation results

Five different bed boundaries have been produced by using GR, ILD, NPHI, and RHOB log analysis; in addition, and the boundaries which are used as well top info in Parigi Carbonate seismic interpretation are as follows: Top Parigi, Zone PRG-B, Zone PRG-C, Zone PRG-D and Bot-Parigi. The GOC and OWC well have been determined in the upper part of carbonate build-up. The carbonate facies log is not properly exposed because of a lack of fossil data (all sections interpreted as packstone and wackestone-packstone only). The lithofacies sequence is correlating to the Parigi carbonate outcrop in Randegan/Palimanan [4,22,23].

The calibrated NPHI-RHOB tools are used as a lithology indicator [20]. When NPHI-RHOB curves show a separation, it indicates the karstic dolomite and when these two curves are superposed, it indicates limestone, as seen in Figure 4.

Seismic Facies Evaluation Result

The formation tops from wells were applied to seismic data by using synthetic seismograms. And based on seismic internal reflection characters, the Parigi carbonate section is interpreted and divided into four surfaces from top to bottom: Parigi zone A is identified as HST (a lot of karst/dolomite zone), Parigi zone-B and zone-C are identified as TST (limestone), and Parigi zone D is identified as HST in the bottom part (Figure 5). The Zone-A is characterized by mounded facies and dominated by wackestone and packstone facies. This zone is interpreted as a good porosity and permeability layer, and the oil gas contact/oil-water contact is clearly identified within this zone at about -860 m. In addition, the facies identification is also carried out by the distribution of FMI data from W-38 well and core data.

Geological Reservoir Modelling Evaluation Result

The multi-attribute has been generated to see the distribution of effective porosity and permeability on Parigi horizons; in addition, the results of this distribution are already validated with production data on the wells in this structure. The produced wells have a sizable porosity value. Moreover, the result indicates that the Parigi Zone-A (upper part) is relatively more porous (high porosity value 0.24 frac – 0.30 frac) and less dense 2.2 gr/cc with the permeability of 1 – 320 mD as shown in Figure 8.

Total Volumetric of Parigi Reservoir

A technical review of the geophysical, geological, and reservoir aspects of the Parigi build-up structure results in a total volumetric of OOIP, which is estimated to be 66.13 MMstb, and IGIP is estimated to be 53,209 MMscf (53.2 Bcf). This is based on a fine model calculation where the Bulk volume is equal to 254.332E+6m^3; Net Volume is equal to 247,032E+6m^3; Pore Volume is equal to 53,471E+6m^3; HCP Voil is equal to 15,829E+m^3; HCPV gas is equal to 8,372E+m^3; NP is equal to 9.71MMSTB; GP is equal to 13,674 Mscf (13.7Bcf); RF oil is equal to 14.68%, and RF gas is equal to 25.70%. Based on a decline curve analysis (DCA), estimated reserves in 2017 are 153,000 barrel oil and 12.6 Bcf of gas, moreover, in this field, the oil and gas production is estimated to be stopped by 2025 due to uneconomic production cost.

Parigi Reservoir Gas Storage Assessment

The Parigi Reservoir, including “cushion” natural gas, is used for providing pressure in the reservoir.After depleting oil and gas production in 2014, the underground gas storage capacity of the Parigi Reservoir is approximately 12.7 Bcf. During this time, the reservoir pressure has dropped by some 160 psi below its initial value (1330 psi); and in other word, in 2017, the reservoir pressure is equal to 1170 psi, as seen in Figure 3. The reservoir pressure trend indicates that this field is subjected to a combination drive reservoir. The carbonate is buried in about 800 m below sea level, and a thick shale layer covers it; therefore, it sounds that it is feasible for gas storage [1,2,24], as seen in Figure 10. Moreover, it seems that the parameters of this reservoir are within the range of the parameters that are applied or used in America and European countries [19,22,25,26]. In Table 1, a comparison has been made between the parameter values of field and the others.

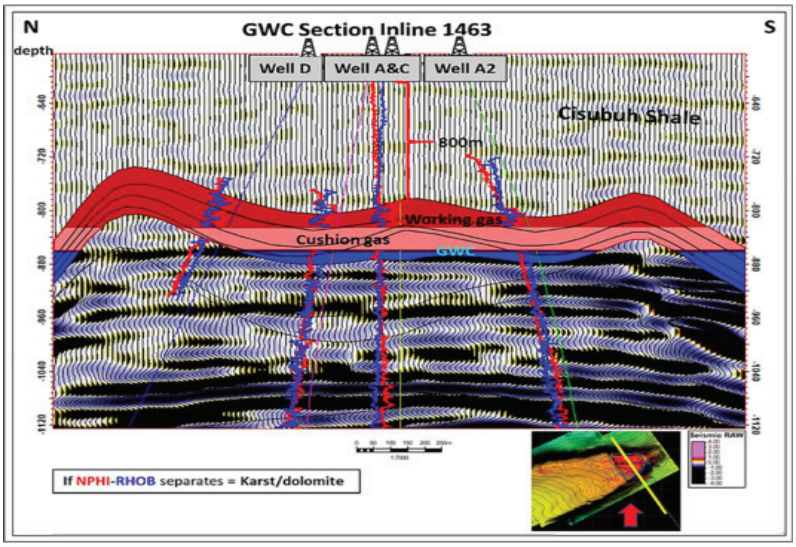

Fig. 10 Shallow Parigi Carbonate is feasible for an Underground Gas Storage in a depleted field in onshore West Java.

Tabel 1 Parameter comparison among USA, Europe, and field location study.

Main Parameter	Depleted field (Europe)	Depleted field (USA)	Depleted field Formasi Parigi
Total Volume (BCF)	59	26-55	53.2 (IGIP)
Working Gas Capacity (BCF)	35	13-28	19 (based on cumulative production of 5 active wells)
Storage Pressure (psi)	1247-1957.5	499-4335	1170-1330
Number of existing wells	25	23-28	28
Gas Cushion	%45	%51	%50
SW(%)	<%45	<%45	>%45
Porosity(%)	10-30%	15-23%	24-30%
Permeability (mD)	1 mD-800 mD	1 mD-200 mD	1 mD-320 mD
Top Reservoir Depth (m)	650-1300	1400-2862	800
Reservoir Thickness (m)	4.5-100	3-150	80

Conclusions

The Parigi carbonate has buried in a depth about 800 m below the ground surface. Based on seismic interpretation, this carbonate build-up is approximately 4,100 m wide and 13,000 m long, and the best estimate thickness is 80 m. Moreover, an effective carbonate build-up reservoir of 25% from the whole build-up in the North-East part, where the effective closure area approximately equal to 4,75 km2, is assumed.

The overlying cap rock of Cisubuh Formation clay is estimated more than 200 m thick and forms a thick clay sediment, and it has been distributed widely in West Java Basin. The bottom part of Parigi carbonate is tight limestone. The bottom part probably has low permeability, and seismically, it is classified as parallel seismic reflection, and it is known as base platform carbonate.

With an effective carbonate reservoir of 25% (top build-up), a gas storage pressure of 1170 psig, and a build-up area capacity of 1173 acre (4,75km^2), and the effective thickness of 80 m, the estimated gas storage capacity is approximately 53.2 Bscf. Moreover, this large scale gas storage has the potential to make a major contribution to the development of a more flexible, dynamic gas market for West Java Province [27,28].

Ultimately, by making a comparison between the main parameters of the underground gas storage fields in this area, Europe, and America, this field is feasible for underground gas storage (Table 1). The underground gas storage method is a new and constructive technique in developing countries such as Indonesia.

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Nomenclatures

DCA: Decline curve analysis

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