

DIAGENETIC CONTROLS ON CARBONATE RESERVOIR QUALITY: A CASE STUDY OF THE SRH WELL, KAIS FORMATION, SALAWATI BASIN, SOUTHWEST PAPUA

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ABSTRACT

The Kais Formation carbonate reservoir is the main hydrocarbon-producing rock in the Salawati Basin, Southwest Papua. The reservoir quality of this carbonate reservoir is highly heterogeneous due to post-depositional diagenetic processes. This study assesses the influence of diagenesis on the carbonate reservoir quality in the SRH well by integrating conventional core description, petrographic observations, scanning electron microscopy (SEM), X-ray diffraction (XRD) routine core analysis (RCAL), and petrophysical analysis from well log data. Two carbonate facies were identified, there are bioclastic packstone and bioclastic wackestone, deposited in back-reef lagoon environment. The results of petrographic and SEM observations indicate that dissolution, compaction, replacement, and cementation are diagenetic processes that affect the reservoir quality. Core porosity ranges from 2.51% to 29.65% with an average of 19.74%, while permeability ranges from 0.01 to 257.98 mD with an average of 38.27 mD. Based on petrophysical analysis, the effective porosity (PHIE) values vary from 1.79% to 29.95% with an average of 11.93%. Although porosity values are relatively consistent across several intervals, permeability values show significant variations, indicating that pore connectivity is more strongly controlled by diagenetic processes than pore volume. Dissolution and fracturing enhance reservoir quality through the development of secondary pore systems and increased pore connectivity, while compaction and cementation reduce permeability by decreasing pore connectivity. Replacement associated with micro-intercrystalline carbonate textures may locally maintain or enhance the pore connectivity depending on the extent of recrystallization and cementation. These findings indicate that post-depositional diagenetic processes are the primary controls on carbonate reservoir quality in SRH well and highlight the importance of integrating geological observations, core analyses, and petrophysical data for reliable carbonate reservoir characterization.

Keywords: permeability, petrography, pore connectivity, routine core analysis, scanning electron microscopy

INTRODUCTION

Carbonate reservoirs store a large share of the world's hydrocarbon resources and continue to be major targets for petroleum exploration and production. Carbonate reservoirs are generally more heterogeneous than siliciclastic reservoirs because their pore systems are influenced not only by depositional facies but also by a series of post-depositional diagenetic processes (Rosid et al., 2021). Diagenetic processes such as dissolution, cementation, recrystallization, and fracturing gradually modify the original pore network of the rock, resulting in significant variations in the reservoir quality of

the carbonate rock, even over relatively short distances. Consequently, the characterization of carbonate reservoirs is generally more complex than siliciclastic reservoirs (Rosid et al., 2021; Kusuma & Kalimi, 2019).

Reservoir quality can be assessed through its porosity and permeability characteristics because these properties determine the reservoir rock's ability to store and transmit fluids, particularly hydrocarbon. In carbonate reservoirs, both parameters can be modified by diagenetic processes before metamorphism. Diagenetic processes, such as dissolution and fracturing, generally increasing the pore spaces and its connectivity

that can enhance fluid flow, while cementation, compaction, micritization, and recrystallization generally reduce pore connectivity, thereby degrading reservoir quality (Kusuma & Kalimi, 2019; Alfayed et al., 2020; Irzon, 2022). Therefore, a comprehensive understanding of the influence of diagenesis on reservoir quality is crucial for reliable reservoir characterization and effective hydrocarbon field development.

The Salawati Basin, located in the Bird's Head region of Southwest Papua, is recognized as one of the most productive hydrocarbon-producing basins in East Indonesia. Commercial oil production began with the discovery of the Klamono Field in 1936, and since then, carbonate deposits have served as the basin's primary hydrocarbon reservoir (Putra & Jambak, 2021). Within the basin's stratigraphic framework, the Miocene Kais Formation is the primary reservoir due to its extensive coral reef development and favourable reservoir properties (Handoyo et al., 2024). However, variations in carbonate facies and diagenetic modifications have resulted in highly heterogeneous pore systems and reservoir quality across the formation (Putra & Jambak, 2021; Rosid et al., 2021).

Previous research conducted in the Salawati Basin has mainly emphasized regional geological evolution, facies distribution, seismic characterization, pore-type prediction, and the evaluation of hydrocarbon potential (Muhartanto et al., 2019; Handoyo et al., 2024). Specifically related to the Kais Formation, previous studies have focused on carbonate composition, lithofacies characteristics, pore system development, and reservoir quality evaluation. The relationship between carbonate composition and reservoir performance in one of the fields in the Kais Formation, namely the Walio Field, shows that higher reservoir quality is associated with abundant dolomite minerals and lower coral fragment content. The distribution of lithofacies and diagenetic characteristics of the Kais carbonate reservoir indicate variations in porosity and permeability characteristics among different lithofacies (Sompie et al., 2018).

Prananda et al. (2020) also revealed that carbonate reservoir of the Kais Formation is strongly affected by diagenetic processes, including cementation, dolomitization, and dissolution, which affect pore characteristics and secondary porosity development. Similarly, Munawaroh et al. (2022) showed that diagenetic processes such as compaction, dolomitization, dissolution, and fracture control pore development and reservoir

quality variations in different intervals of the Kais Formation.

Although previous studies have provided information on the depositional framework, facies distribution, petroleum systems, and diagenetic evolution of the Kais Formation, the specific influence of diagenetic processes on carbonate reservoir quality remains poorly understood. Previous studies have largely focused on regional characterization, lithofacies analysis, and reservoir distribution, while integrated studies evaluating the relationship between diagenetic changes, pore system development, and reservoir properties at the individual well scale are limited.

The SRH well provides a comprehensive dataset, including conventional core descriptions, petrographic observations, routine core analysis (RCAL), scanning electron microscopy (SEM), and wireline log data, allowing for an integrated assessment of each data point on diagenetic controls on reservoir quality. Therefore, this study aims to evaluate diagenetic processes in controlling reservoir quality, particularly in terms of porosity and permeability of carbonate rocks within the Kais Formation at the SRH well in the Salawati Basin, Southwest Papua. The results of this study are expected to improve understanding of carbonate reservoir heterogeneity and provide geological insights for reservoir characterization and hydrocarbon field development.

REGIONAL GEOLOGY

Regional Physiography

The Salawati Basin is one of the principal sedimentary basins in the Bird's Head region of Southwest Papua, Indonesia. It is located along the northern margin of the Indo-Australian Plate and extends predominantly in an east-west direction. Tectonically, the basin belongs to the Bird's Head region, which has undergone a complex geological evolution driven by the interaction of the Indo-Australian, Pacific, and Philippine Sea plates (Satyana, 2003).

From a physiographic perspective, the Salawati Basin is surrounded by several major regional geological features (Figure 1). The Salawati Basin is bounded by the Sorong Fault Zone along its northern and western margins, the uplifted Misool-Onin Geanticline to the south, and the Ayamuru Platform to the east, which separates it from the Bintuni Basin. These regional tectonic and physiographic features have significantly influenced the basin architecture, sedimentary distribution, and hydrocarbon accumulation within the Salawati Basin (Satyana, 2003).

The basin is characterized by a foreland depression that provided an accommodation space for the development of a carbonate platform during the Miocene. The combination of shallow marine conditions, a relatively stable carbonate shelf environment, and sufficient accommodation space favoured the growth and accumulation of carbonate-producing organisms, resulting in the development of an extensive carbonate platform. In this setting, the Miocene Kais Formation was deposited as a carbonate platform system consisting of coral reef structures, carbonate sandbars, and lagoonal facies (Ontosari et al., 2023). This depositional environment contributed to the formation of a thick carbonate succession, which later became one of the main hydrocarbon reservoirs in the Salawati Basin.

The reservoir quality of the Kais Formation was subsequently modified by post-depositional diagenetic processes. The interaction between depositional facies and diagenetic evolution plays a crucial role in controlling reservoir heterogeneity within the carbonate system. Ontosari et al. (2023) highlight that the characterization of Kais Formation carbonates is closely related to diagenetic evolution associated with depositional changes a sea-level fluctuation. Diagenetic processes can modify the original pore system by affecting pore development and connectivity, thereby influencing the present-day reservoir quality of the Kais Formation.

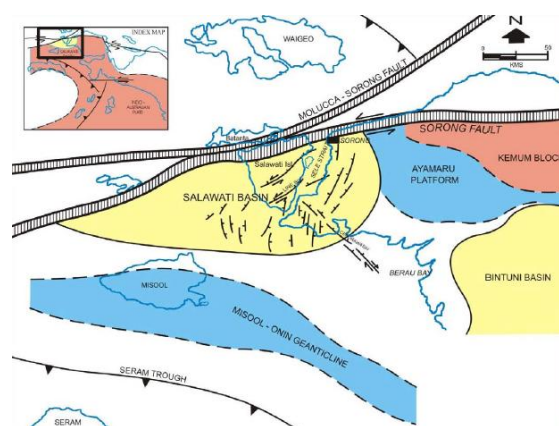


Figure 1. Regional Setting of the Salawati Basin (Satyana, 2003).

Regional Stratigraphy

The stratigraphic succession of the Salawati Basin records sedimentation from the Paleozoic to the Quaternary and reflects the tectonic evolution of the Bird's Head region of Southwest Papua (Figure 2). The oldest rocks comprise the Siluro-Devonian Kemum Metamorphic Complex and the Carboniferous-Permian Aifam Group, which form the pre-Tertiary basement. These units are unconformably overlain by the Mesozoic Tipuma and Kembelangan Groups, although their distribution is largely restricted to the southern part of the basin due to Late Cretaceous uplift and erosion in the northern region (Satyana, 2003).

Tertiary sedimentation commenced with the deposition of deep-marine marly mudstones of the Imskin Formation during the Paleocene, followed by the transgressive carbonate deposits of the Faumai Formation in the late Eocene-early Oligocene. These carbonates are conformably overlain by shallow-marine siliciclastic deposits of the Sirga Formation. During the Miocene, widespread carbonate sedimentation led to the development of the Kais Formation, which represents the principal hydrocarbon reservoir within the Salawati Basin. The Kais Formation was deposited across a range of depositional environments, including lagoonal, carbonate bank, reef, and locally deeper-water settings. Carbonate deposition occurred contemporaneously with the accumulation of fine-grained siliciclastic sediments of the Klasafet Formation. Subsequently, the basin was filled by the Pliocene Klasaman Formation and Pleistocene Sele Formation, marking the transition from carbonate-dominated to siliciclastic sedimentation associated with tectonic uplift and basin inversion (Satyana, 2003).

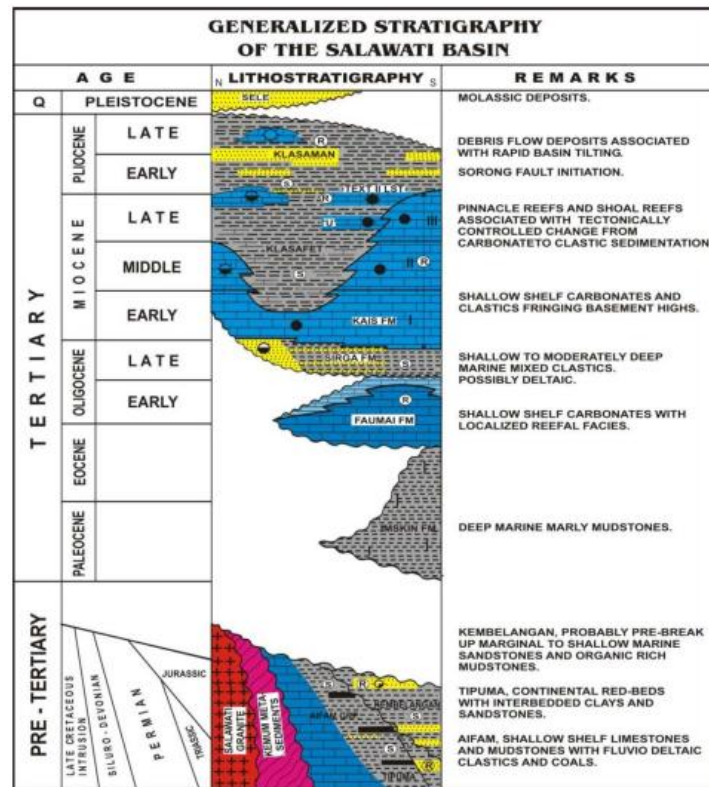


Figure 2. Regional Stratigraphy of the Salawati Basin (Satyana, 2003).

Regional Tectonic Setting

The tectonic evolution of the Salawati Basin can be divided into three major phases (Figure 3): pre-basin inversion, syn-basin inversion, and post-basin inversion, which collectively controlled basin development, carbonate platform evolution, and hydrocarbon accumulation (Handoyo et al., 2024).

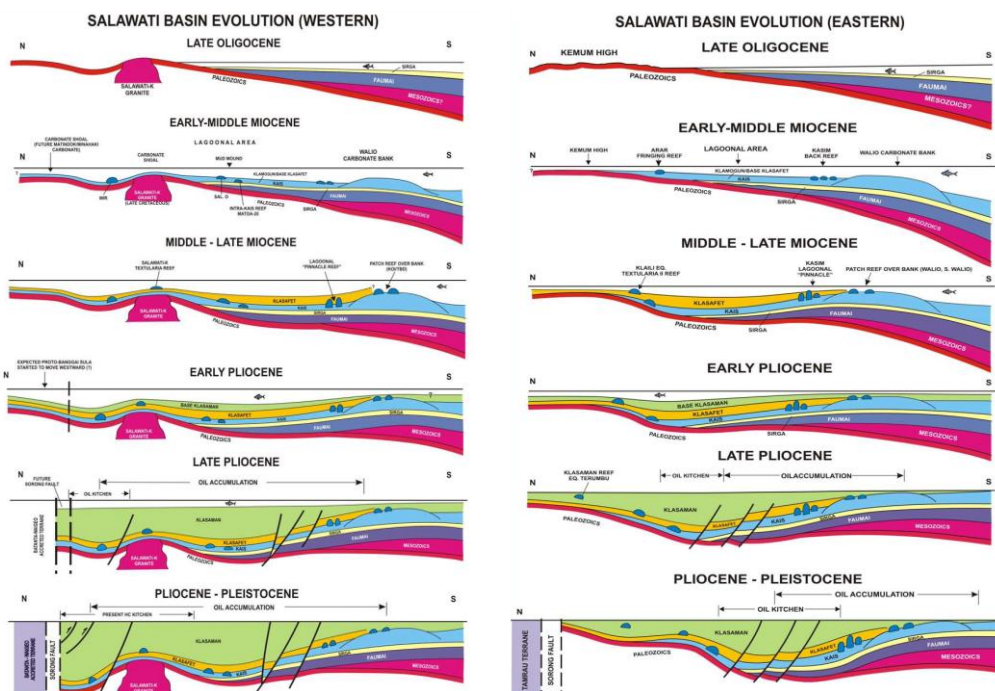


Figure 3. Schematic Section Showing the Evolution of the Salawati Basin (Satyana, 2003).

- 1) Pre-basin inversion phase. During this phase, the Salawati Basin developed

as a southward-dipping foreland basin under relatively stable tectonic

conditions. Sedimentation was dominated by the deposition of pre-Tertiary basement rocks followed by the Paleogene Imskin, Faumai, and Sirga Formations (Satyana, 2003).

- 2) Syn-basin inversion phase. During the Miocene, tectonic activity related to the Sorong Fault initiated basin inversion and promoted widespread development of the Kais carbonate platform. According to Satyana (2003), the platform evolved through three successive stages, from initial platform growth to reef aggradation and final termination of reef development due to increasing tectonic deformation and siliciclastic supply.
- 3) Post-basin inversion phase. Continued tectonic inversion during the Late Miocene-Pliocene reversed basin polarity, shifting the depocenter northward and terminating carbonate growth. Siliciclastic sedimentation became dominant with the deposition of the Klasaman and Sele Formations, establishing the present structural configuration of the Salawati Basin (Satyana, 2003; Handoyo et al., 2024).

RESEARCH METHOD

This study was conducted by integrating conventional core description data, petrographic thin section, scanning electron microscopy (SEM), X-Ray diffraction (XRD), routine core analysis (RCAL), and wireline log data from the SRH well in the SRH Field, Salawati Basin, Southwest Papua. Core observations and petrographic analysis were used to identify lithofacies, pore types, and diagenetic features. SEM and XRD analyses were used to characterize pore morphology and mineralogical composition, while RCAL measurements provided laboratory-derived porosity and permeability data. Wireline log data, including neutron porosity (NPHI) and bulk density (RHOB) logs, were integrated to evaluate effective porosity throughout the reservoir interval. The calculated effective porosity was subsequently integrated with petrographic observations and routine core analysis (RCAL) to evaluate the influence of diagenetic processes on carbonate reservoir quality.

Diagenetic interpretation was based on petrographic observations using the carbonate classification proposed by Dunham (1962), supported by SEM and XRD analyses. Reservoir quality was evaluated using laboratory-measured porosity and permeability from RCAL, while wireline-

derived effective porosity was used to examine the vertical distribution of reservoir quality within the studied interval. The overall workflow integrated geological, petrographic, and petrophysical datasets to assess the relationship between diagenetic processes and reservoir quality in the SRH well.

The number of samples used for each analytical method, such as conventional core description, petrographic thin section, scanning electron microscopy (SEM), X-ray diffraction (XRD), routine core analysis (RCAL), and wireline log data are summarized in Table 1. Sample selection based on the availability of representative carbonate intervals from the SRH well, taking into account the lithofacies variations, pore characteristics, and observed diagenetic features. Samples were selected to represent different carbonate textures and diagenetic processes, such as dissolution, cementation, compaction, replacement, and fracture development to evaluate their effects on reservoir quality.

Table 1. Dataset Availability in SRH Well

Dataset	Number of Samples	Application
Conventional core	11 intervals	Lithofacies description and macroscopic diagenetic observation
Petrographic thin sections	20 samples	Microfacies classification and diagenetic interpretation
SEM	9 samples	Pore morphology and diagenetic texture characterization
XRD	20 samples	Mineralogical composition analysis
RCAL	33 core plugs	Core porosity and permeability measurements
Wireline logs (RHOB & NPHI)	Continuous interval	Effective porosity (PHIE) evaluation

RESULTS

Carbonate Facies

The carbonate interval of the SRH well (1569.25-1579.00 m) is predominantly composed of limestone. Based on conventional core description and the Dunham (1962) classification, two carbonate facies were identified: bioclastic packstone and bioclastic wackestone. Among these, bioclastic packstone is the dominant facies throughout the studied interval, whereas bioclastic wackestone occurs only locally. The vertical distribution of the identified facies is presented in Figure 4 & Figure 5, while their main characteristics are summarized in Table 2.



Figure 4. Core Photographs of Bioclastic Wackestone (1572 m).



Figure 5. Core Photographs of Bioclastic Packstone (1571 m).

Table 2. Characteristics of Carbonate Facies in SRH Well

Facies	Texture	Main Components	Dominant Pore Types	Occurrence
Bioclastic Wackestone	Mud-supported	Small-medium bioclasts	Vuggy, fracture	Minor
Bioclastic Packstone	Grain-supported	Small-large skeletal bioclasts	Vuggy, fracture, moldic	Dominant

Bioclastic packstone is characterized by a grain-supported texture composed of abundant skeletal grains with calcarenite to calcirudite grain sizes. In contrast, bioclastic wackestone exhibits a mud-supported texture containing dispersed skeletal components within a micritic matrix. The carbonate succession generally consists of hard limestone with light gray to dark brown coloration. Oil shows were observed throughout most of the studied interval.

Integration of lithofacies observations with biostratigraphic data indicates that the studied carbonate interval was deposited in a back-reef lagoon setting. Bioclastic packstone is associated with the outer back-reef lagoon,

whereas bioclastic wackestone represents the inner back-reef lagoon facies.

Diagenetic Process

Petrographic observations integrated with SEM analyses identified several diagenetic features within the carbonate reservoir of the SRH well, including dissolution, compaction, replacement, and cementation. Petrographic observations show that dissolution (Dis) is represented by vuggy pores, compaction by irregular stylolite seams (Sty) and fracturing (Fr) that open discontinuities cutting across the carbonate fabric, and replacement (DolR) by partial substitution of carbonate constituents by dolomite (dolomitization). Representative petrographic photomicrographs are presented in Figure 6 & Figure 7. SEM observations reveal pore-filling calcite cement and micro-intercrystalline carbonate textures. Calcite cement occurs as euhedral crystals occupying pore spaces, whereas micro-intercrystalline carbonate forms a fine crystalline matrix within the carbonate rock. Representative SEM images of these features are presented in Figure 8.

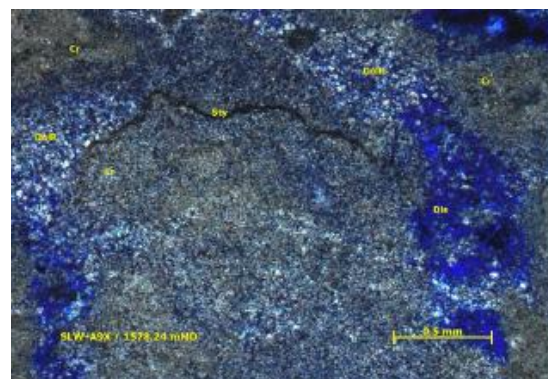


Figure 6. Petrographic Photomicrographs of the SRH Well Sample at 1578.24 m (LEMIGAS, 2023).

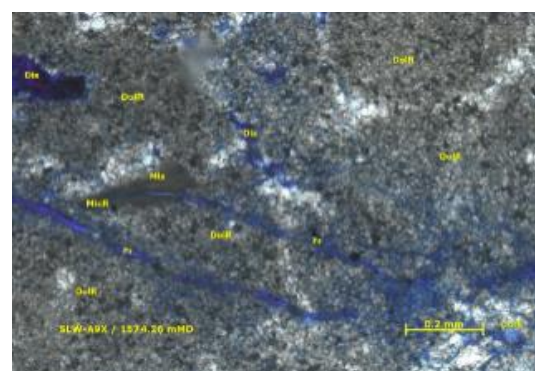


Figure 7. Petrographic Photomicrographs of the SRH Well Sample at 1574.26 m (LEMIGAS, 2023).

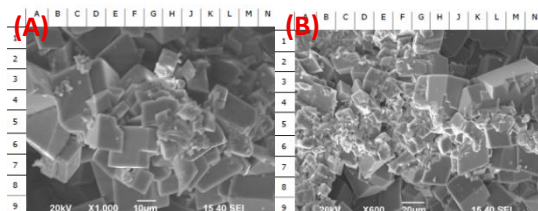


Figure 8. SEM images showing calcite cement and micro-intercrystalline carbonate textures in the SRH well: (A) Sample at 1577.84 m and (B) Sample at 1575.03 m (LEMIGAS, 2023).

Porosity and Permeability Characteristics

Porosity and permeability characteristics of the SRH well were evaluated using routine core analysis (RCAL), including core porosity and core permeability measurements, together with wireline-derived effective porosity (PHIE). A total of 33 core plug samples were analyzed to determine porosity and permeability, while PHIE was used to describe the continuous vertical distribution of porosity within the studied interval. Summary statistics of the measured properties are presented in Table 3 and the vertical distribution of PHIE is shown in Figure 9.

Core porosity ranges from 2.51% to 29.65%, with an average value of 19.74%. Core permeability ranges from 0.01 to 257.98 mD, with an average value of 38.27 mD. Effective

porosity (PHIE) ranges from 1.79% to 29.95%, with an average value of 11.93%. The porosity and permeability measurements exhibit vertical variation throughout the studied interval. The statistical distribution of reservoir properties indicates significant heterogeneity within the Kais carbonate reservoir interval. Although core porosity and effective porosity show relatively similar ranges, permeability shows a much wider variation, indicate that fluid flow capacity is controlled not only by total pore volume but also by pore connectivity and pore system characteristics. The occurrence of high permeability values within a given interval indicates the presence of a well-connected pore systems, likely related to constructive diagenetic processes such as dissolution and fracture development. Otherwise, intervals from low permeability values likely reflect decreased pore connectivity caused by destructive diagenetic processes, including cementation and compaction.

Table 3. Summary Statistics of Porosity and Permeability Measurements in the SRH Well

Parameter	Minimum	Maximum	Mean
Core porosity (%)	2.51	29.65	19.74
Core permeability (mD)	0.01	257.98	38.27
Effective porosity (PHIE, %)	1.79	29.95	11.93

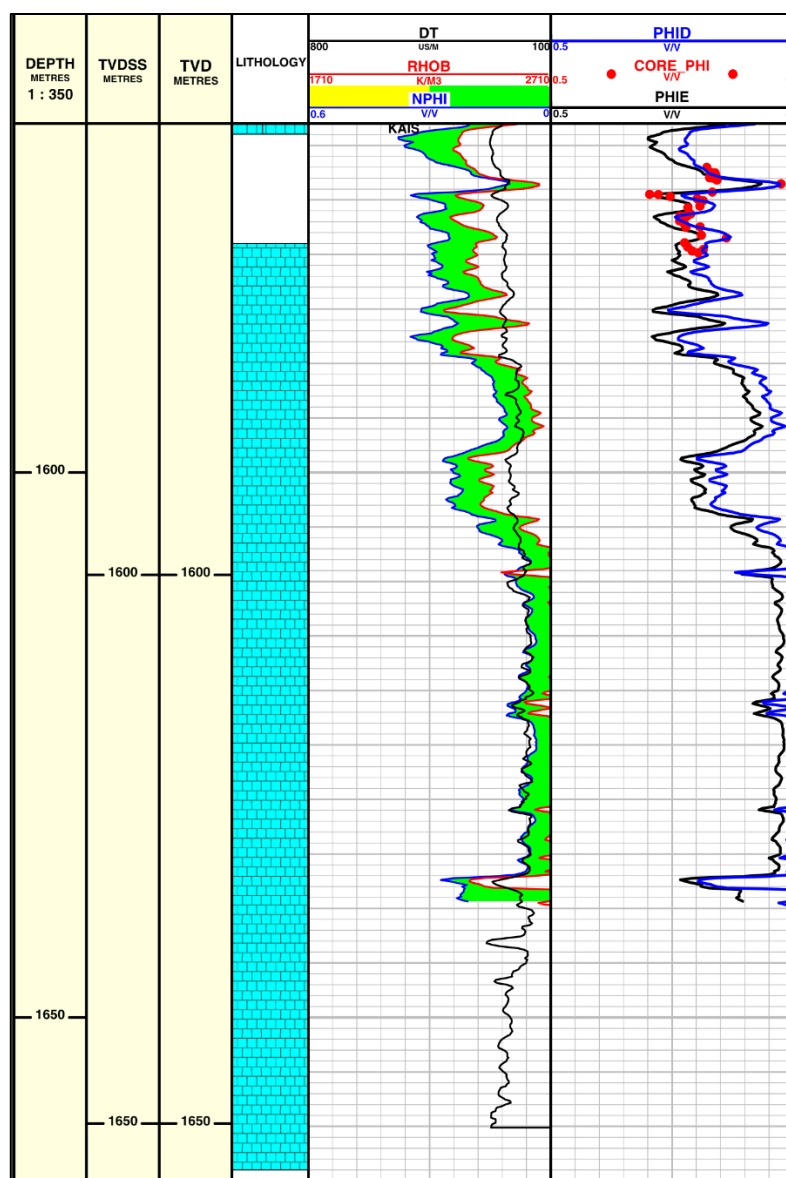


Figure 9. Vertical Distribution of Wireline-derived Effective Porosity (PHIE) in the SRH Well

DISCUSSION

The results indicate that carbonate reservoir quality in the SRH well is controlled predominantly by post-depositional diagenetic processes rather than depositional facies. Although the studied interval consists of bioclastic packstone and bioclastic wackestone deposited in a back-reef lagoon environment, both facies exhibit similar diagenetic features, indicating that diagenetic modification exerts a stronger influence on porosity and permeability than the original depositional texture. This observation suggests that the heterogeneity of the Kais Formation reservoir is primarily governed by the intensity and distribution of diagenetic processes rather than facies variations (Fengfeng et al., 2023).

Despite relatively small variations in porosity, permeability exhibits substantially greater variability throughout the studied interval, indicating that pore connectivity rather than pore volume only exerts the primary control on fluid flow. This relationship is consistent with Natasia et al. (2017), who demonstrated that carbonate reservoir characterization requires consideration of pore geometry and pore distribution because depositional facies may be strongly overprinted by diagenetic modification. The study emphasized that variations in pore types can result in different permeability responses despite similar porosity values. For example, the samples at 1574.26 m and 1578.24 m display comparable core porosity values (21.74% and 20.81%) and similar wireline-derived effective porosity (PHIE) values (20.4% and 19.4%), whereas permeability decreases markedly from 150.64

mD to 35.49 mD. Petrographic observations indicate that the interval at 1574.26 m is characterized by abundant dissolution and fractures, whereas compaction and replacement are more evident at 1578.24 m. A similar relationship is observed between the samples at 1577.84 m and 1575.03 m, where porosity values remain relatively comparable (19.42% and 23.31%) while permeability differs considerably (11.91 mD and 293.48 mD). These observations indicate that diagenetic modification plays a major role in controlling pore geometry and connectivity, leading to significant variations in permeability despite relatively similar porosity values.

Among the identified diagenetic processes, dissolution, replacement by dolomitization, and fracturing represent the main constructive processes controlling reservoir quality. Similar enhancement of carbonate reservoir properties through diagenetic processes has been reported in dolomitized carbonate systems, where dolomitization and dissolution may generate secondary pore systems and modify reservoir potential (Putra, 2018). Dissolution generates secondary pore systems, particularly vuggy pores, while fractures enhance pore connectivity, thereby improving fluid flow pathways. Consequently, intervals dominated by these processes generally exhibit higher permeability than intervals where dissolution is less developed. Similar relationships have been widely documented in carbonate reservoirs, where dissolution is regarded as one of the most effective mechanisms for enhancing reservoir quality through the development of secondary porosity and improved pore connectivity (Fengfeng et al., 2023).

Conversely, stylolite development (compaction) and calcite cementation generally reduce reservoir quality by decreasing pore volume and pore connectivity. Stylolite represent pressure-solution during burial, whereas calcite cement precipitates within pore spaces, partially occluding the pore network. Petrographic observations also indicate replacement of the original carbonate constituents, accompanied by micro-intercrystalline carbonate textures identified in SEM images. The development of these micro-intercrystalline textures may locally preserve or enhance intercrystalline pore networks; however, their contribution to reservoir quality depends on the extent of recrystallization and associated cementation. Where cementation becomes more extensive, pore connectivity is progressively reduced, resulting in lower permeability. Similar effects of stylolite development (compaction) and

cementation on carbonate reservoir quality have been reported in previous studies of deeply buried carbonate reservoirs (Paganoni et al., 2016).

The higher sensitivity of permeability compared to porosity to diagenetic modification is related to the characteristics of carbonate pore systems, where fluid flow is primarily controlled by pore throat, connectivity, and the presence of interconnected secondary pores, rather than total pore volume alone. In carbonate reservoirs, diagenetic processes can significantly change pore characteristics without producing significant changes in total porosity. For example, dissolution can enlarge existing pores and create interconnected pore systems, while fractures can provide additional flow pathways. Otherwise, cementation and compaction can reduce pore throat connectivity by filling pore spaces or destroying pore systems, resulting in significant permeability reductions even when porosity remains relatively unchanged.

In the Kais Formation, carbonate deposition in coral reef, sandbar, and lagoonal environments produced heterogeneous primary pore fabrics that were subsequently modified by multiple stages of diagenesis. As a result, the initial depositional fabric was overprinted by dissolution, cementation, replacement, and compaction, leading to substantial variations in pore connectivity and reservoir quality. Consequently, the permeability variations observed in the SRH well are interpreted reflect differences in diagenetic intensity on the original depositional fabric rather than differences in total pore volume alone. Therefore, intervals with comparable porosity values may exhibit markedly different permeability depending on the extent to which pore connectivity has been enhanced or reduced by diagenetic processes.

This finding is consistent with previous studies of carbonate reservoirs that emphasize that diagenetic processes such as dissolution and fracturing can improve reservoir quality, while compaction and cementation generally reduce pore connectivity. However, this study is limited to observations from a single well, and therefore the lateral variability of diagenetic characteristics across the SRH Field cannot be fully evaluated. Future studies integrating additional wells and reservoir-scale characterization are recommended to better constrain the spatial distribution of diagenetic heterogeneity within the Kais Formation.

CONCLUSION

The results of this study indicate the influence of post-depositional diagenetic processes on carbonate reservoir quality in the Kais Formation at the SRH well, Salawati Basin, Southwest Papua. The findings indicate that reservoir quality is primarily controlled by diagenetic modification of pore systems rather than depositional facies variations. Although two carbonate facies, namely bioclastic packstone and bioclastic wackestone, were identified within the studied interval, both facies exhibit similar diagenetic characteristics, suggesting that diagenetic processes gave a stronger control on reservoir heterogeneity.

Dissolution and fracturing represent the main constructive diagenetic processes that enhance reservoir quality by generating secondary pore systems and improving pore connectivity. In contrast, compaction and cementation reduce reservoir quality by decreasing pore connectivity and restricting fluid flow pathways. Replacement associated with micro-intercrystalline carbonate textures may locally preserve or modify pore networks depending on the degree of recrystallization and associated cementation. These findings indicate that permeability variations in the SRH well are more strongly influenced by diagenetic controls on pore geometry and connectivity than by porosity alone.

This study contributes to geological sciences and applied geology by improving the understanding of diagenetic controls on carbonate reservoir heterogeneity and highlighting the importance of integrating petrographic observations, SEM analysis, routine core analysis, and petrophysical evaluation for carbonate reservoir characterization. Further studies involving additional wells and reservoir-scale analysis are recommended to better evaluate the spatial distribution of diagenetic heterogeneity within the Kais Formation.

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