Carbonate shoal microfacies characterization using the interdependent of depositional systems and diagenesis of Kais Formation in the Matoa Field, Salawati Basin

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ABSTRACT

Matoa Field in the Salawati Basin, Papua, Indonesia was discovered in 1991. Oil production commenced in 1993, yielding a cumulative production of more than 21 MMBO by 2015. In the latest POD that was approved in 1999 and was valid until 2019, it was recommended to drill six additional wells within three integrated structures. By 2018, a static model was built, incorporating present-day island analogues and the latest interpretation from reprocessed 3D seismic data, paleontological data, and petrographic analyses. The latest static model renews the understanding on reservoir characteristics (geometry and microfacies) for the purpose of further field development.

This paper discusses field analogues in correlation with an interplay of carbonate depositional environment with diagenetic evolution in the Matoa Field. Three candidates for possible present-day analogues of Matoa Field were screened i.e., Java Sea's Thousand Islands, Kapoposang Islands of Spermonde Archipelago, and the Great Barrier Reef of Australia. The objective was to improve understanding of the conceptual geological model in the regional sense. Based on palaeogeomorphology (morpho-arrangements, shelf geometry and sedimentary architecture), the present-day Central Reef Zone of Wet Tropic at the Great Barrier Reef is fit to be utilized as an analogue to the continental, Miocene Salawati carbonate complex.

Well-tied 3D seismic data, from which several multiple attributes were analysed, have been reprocessed twice. Attributes such as RMS Amplitude, realized RMS Amplitude, Sweetness and Relative Acoustic Impedance were analysed and extracted to understand the diagenetic features of Matoa Carbonate reservoir. The result shows that RMS Amplitude, in combination with petrographic – paleontological data, exhibits the most likely attribute to characterize sedimentology and top diagenetic picks of the carbonates.

It is concluded from four reservoir zones in Matoa's static model, that present-day analogues and distinct interplay among lithology, depositional and diagenetic systems

are key aspects to revise the development strategies. The most significant interdependent factors can be quantitatively measured and modelled, such as the dual porosity system which was synthesized by Phi separate vug from the RFN Lucia porosity model.

Keywords: *Matoa Field, Salawati Basin, Kais Formation*

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INTRODUCTION

Matoa Field was discovered by SEO-1 well (later named as M-1 well in the POD) in 1991 with an oil flow test of 3,500 BOPD from two perforated intervals (9,516–9,570 ft and 9,607–9,694 ft) within the Kais Formation. The commerciality of Matoa discovery was confirmed after drilling two delineation wells, namely Matoa-2 and Matoa-3 in the same year. The oil is predominantly produced from a Miocene platform carbonate reservoir and is trapped within a three-way dip anticlinal closure of the Matoa complex. Reefal carbonates were occasionally found within the Matoa complex, such as those drilled by Matoa-20 well in August 1996, which flowed 1,085 BOPD. By 2015, cumulative oil production from the field had reached 15.26 MMBO.

Forty wells have been drilled by the end of POD validity in 2019 (and thus contract expiration in 2020.) Several wells are still producing, including 12 wells with artificial lift from platform carbonates and three naturally flowing wells from reefal carbonates. To arrest the increasing rate of production decline, several initiatives were taken. A static model was first built in 2006 and then a dynamic model was run in 2008. Petrophysics was re-analysed in 2013 and was validated by production data until 2015. In 2018, the static model was updated by incorporating all the results. The static model update also included the results from

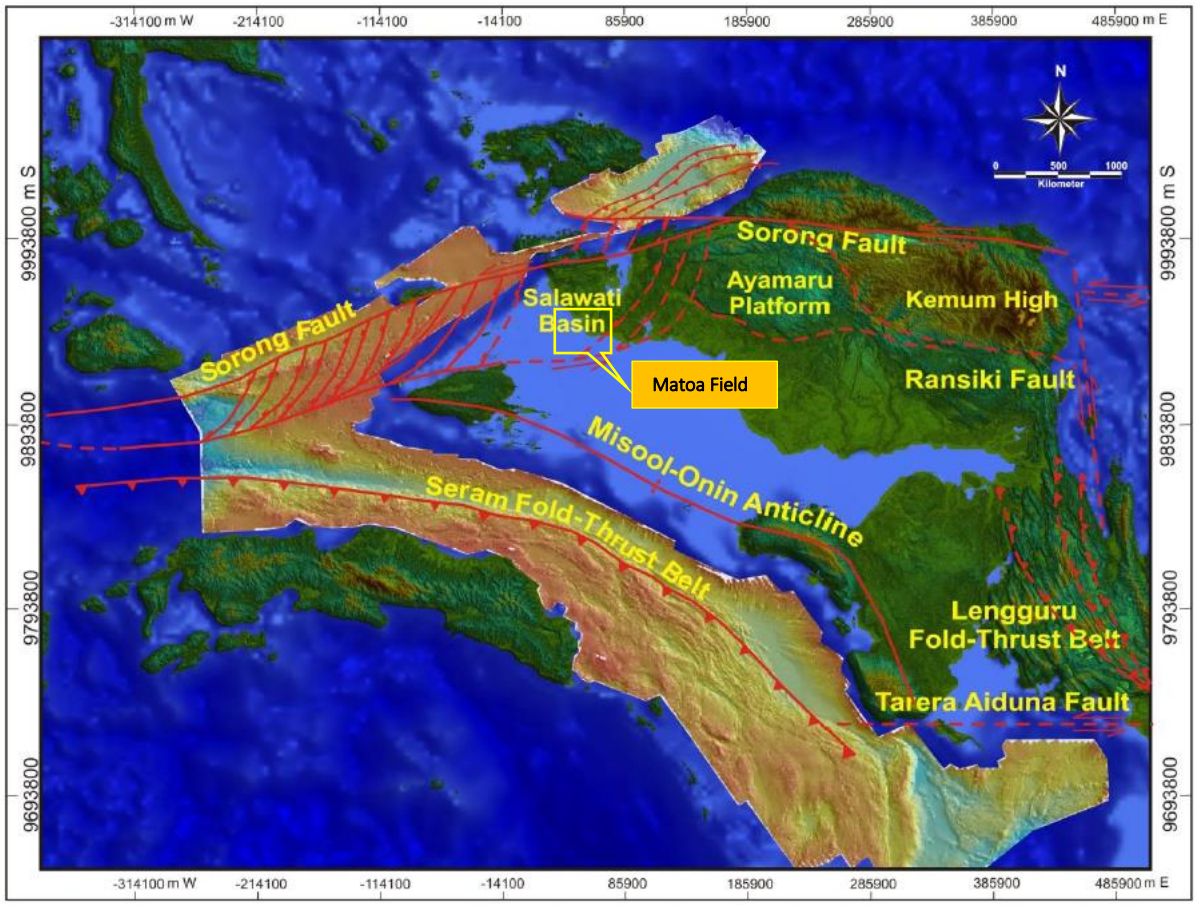


Figure 1: *Major tectonic elements surrounding the Matoa Field area, Salawati Basin (Riadini and Sapiie, 2011)*

the latest fault interpretation and updated depositional environment from analogues. Specific attention was taken about the interplay of the depositional systems and diagenesis with comparable regional geological events. Its application to quantitative petrophysical analysis resulted in new porosity and net pay values. The latter is discussed in detail in the following sections.

GEOLOGICAL BACKGROUND

The Salawati Basin is an asymmetric, E–W trending foreland basin, located on the northern margin of the Indo-Australian Plate. The basin is terminated to the South by the uplifted Miocene carbonates of the Misool – Onin Anticline and to the East by the Ayamaru Platform. The Salawati Basin has stratigraphic and tectonic history dating from Palaeozoic time to Recent (Riadini and Sapiie, 2011). The tectonic configuration of Salawati Basin is shown on Figure 1. The most prolific oil reservoir in the Matoa Field occurs stratigraphically within the thick Miocene Kais Formation carbonate, which can be subdivided into two main sequences of Early Miocene and Middle-Late Miocene age. During the Early Miocene, reef build-ups of Kasim Reef, Cendrawasih Reef, Linda Reef and Moi Reef developed as patch reefs surrounded by lagoonal carbonates. Basin-ward shoal

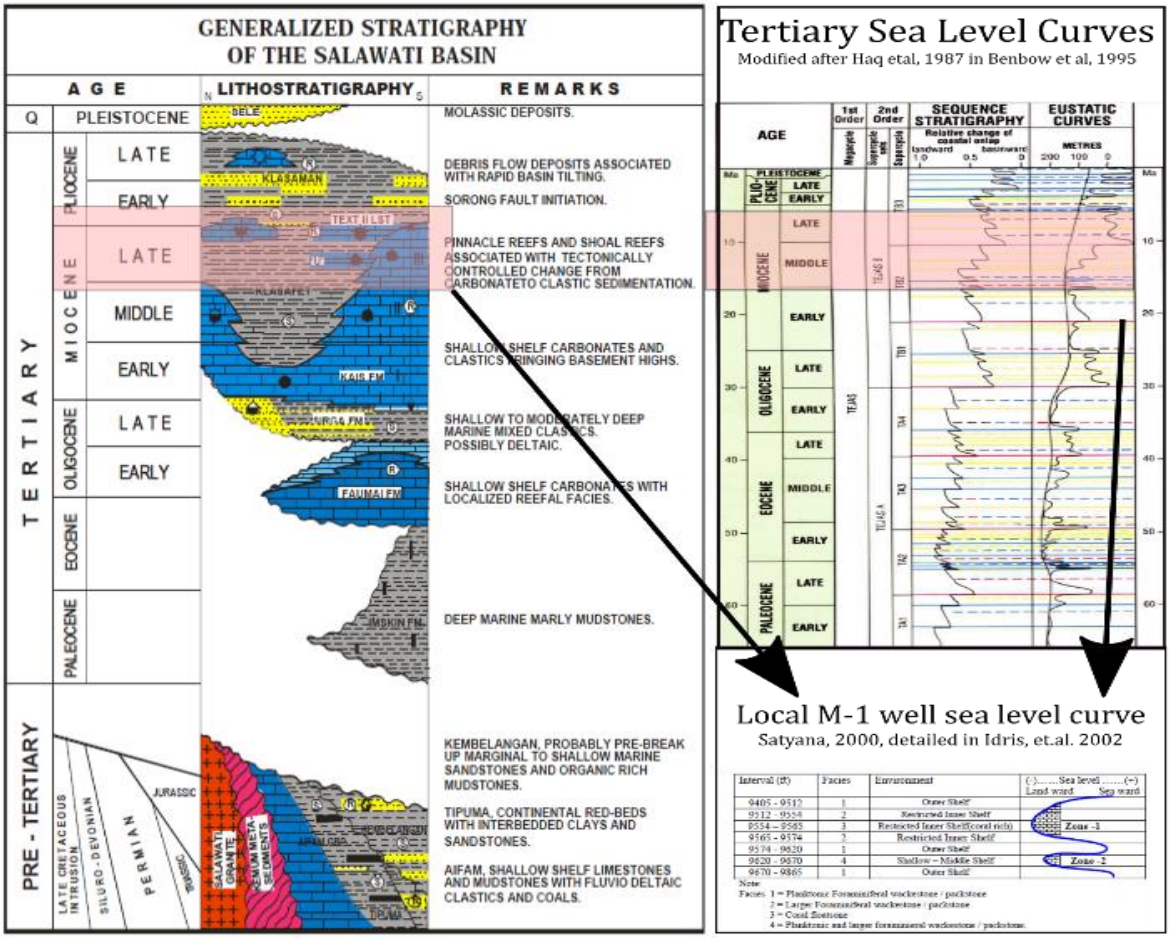


Figure 2: *Regional stratigraphy of the Salawati Basin (Satyana, 2003) in comparison with Tertiary Sea Level Curves (Benbow et al., 1995) and Local Sea Level Curves derived from Matoa-1 well (Idris et al., 2002) in the Miocene interval of the Matoa Field*

carbonates developed throughout a shelf margin towards open sea. At the distal, pinnacle reefs were deposited on a drowned shallow water platform margin. This took place during a transgressive phase, with the sea rising towards the north-west. A subsequent drop of sea level occurred during late Early Miocene time and marked the uppermost boundary of Early Miocene sedimentation (Satyana, 2003).

During the Middle-Late Miocene time, the sea level rose, marked by landward movement of the shoreline. Carbonate reefs of Matoa Field, Salawati Reef, North Sele Reef and Arar Reef were deposited in open lagoon settings during this process. The whole interval lies within the Kais Formation, as shown on Figure 2.

DATA

Integrated field development of the Matoa structural complex, which consists of the Matoa Field, SWO Field and M-29 (Amuk) Field, was documented in the 1999 POD, entitled "Integrated Matoa Field POD Revision". Six development wells were proposed, including two in the SWO Field. The obligation to drill four wells was completed with eleven additional development wells drilled by 2007. During 1991–2007, 40 exploration and development wells were drilled and a 3D seismic cube covering the Matoa Field was acquired. The seismic cube covers 8.5 km of length in NE-SW direction and 3.5 km of width in NW-SE direction.

The existing 40 wells contain various datasets, given in detail in Table 1. The following data have been integrated during this study: wireline logs (36 wells), check

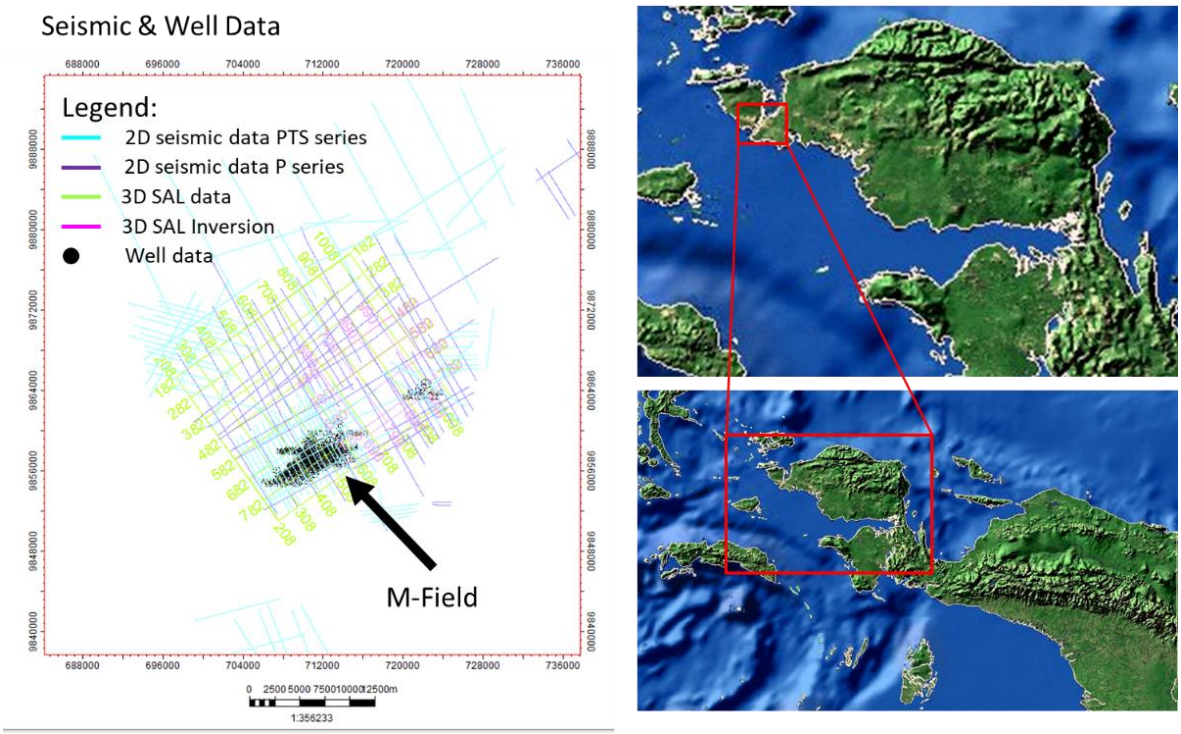


Figure 3: *Location area and data coverage.*

Table 1. *Distribution of Well Data.*

Well	Porosity Effect. (PHIe)	Secondary Porosity (POR)	Porosity Total (PhiTot)	Porosity	Water Saturation (Sw)	Permeability	Petrography	RFN	Checkshot	Well Test	SCAL	RCAL	Top Kais	Intra Kais	Base Kais	Lithofacies	Depositonal Environmen	Diagenesis
M-1	V	V		V	v		V	V	V	V	V	V	V			V		
M-2	V	V		V	v			V	V	V	V		V		V	V		V
M-3			V	V	v			V	V	V						V		V
M-4				V	v			V	V	V	V		V					V
M-5	V	V		V	v	V	V	V	V	V					V	V	V	V
M-6	V	V		V	v	V		V	V	V						V		
M-7				V	v			V	V	V			V			V		V
M-8	V	V		V	v	V		V	V	V			V			V		
M-9			V	V	v			V	V	V								V
M-10				V	v	V		V	V	V		V	V					V
M-11	V	V		V	v	V			V	V		V	V					V
M-12	V	V		V	v	V		V	V	V		V						V
M-13	V	V		V	v	V		V	V	V		V	V					V
M-14	V	V	V	V	v	V		V	V	V		V	V					V
M-15																		
M-16	V	V	V	V	v	V	V	V	V	V			V	V		V	V	V
M-17	V	V		V	v	V		V	V				V					V
M-18				V	v			V	V	V		V						V
M-19	V	V		V	v	V		V	V	V						V		V
M-20	V	V	V	V	v	V	V	V	V	V			V	V		V	V	V
M-21	V	V		V	v	V		V	V				V					V
M-22									V									
M-23	V	V		V	v	V		V	V	V								
M-24	V	V		V	v	V	V		V				V			V	V	V
M-25								V	V				V			V		
M-26	V	V	V	V	v	V		V	V	V			V			V		V
M-27	V	V		V	v	V		V	V									V
M-28	V	V		V	v	V	V	V	V	V						V	V	V
M-29									V				V					
M-30	V	V		V	v	V		V	V	V			V					
M-31	V	V	V	V	v			V	V	V			V					
M-32	V	V	V	V	v			V	V	V								
M-33	V	V		V	v			V	V	V								V
M-34	V	V	V	V	v			V	V				V	V		V	V	
M-35									V									
M-36									V									
M-37									V									
Sum	24	24	9	30	30	19	6	29	36	25	3	7	20	3	2	15	6	22

shots (4 wells), SCAL data (2 wells), well tests (28 wells), RCAL & DST (7 wells), various formation tops/markers (5 wells each for Intra Kais and pre-Kais markers), porosity logs (5 wells), rock type log (1 well), pressure data (8 wells) and petrographic data (8 wells).

In 2013, petrophysical analysis was performed on the 36 wells with wireline logs yielding an updated log of interparticle porosity (Phi_{ip}), separate vug porosity (Phi_{sv}), permeability and S_w logs. Data availability, distribution, and area location can be seen on Figure 3.

SEISMIC INTERPRETATION

A new interpretation of the reprocessed, high-resolution Matoa 3D seismic cube was completed, with updated faults and structure-depth maps of top/base reservoir and formation. The interpretation was initially done in time domain and tied to Matoa-1, Matoa-12, and Matoa-20 wells. Time to Depth Conversion was done by using the V_0+KZ equation ($V = V_0 + K*Z$, where V = instantaneous velocity, V_0 = reference velocity, K = velocity gradient, and Z = depth).

A single fault called the 'Line-Six fault' by Satyana (2011, 2013), was re-interpreted in this study. It is inclined towards the interior of the northwest-ward Pliocene generative kitchen and acts as the south-eastern bounding fault, giving the field its 3-way dip closure. This fault extends from the surface to Top, Intra and Base Kais markers.

CARBONATE VERTICAL SUCCESSION

Internal characteristics and vertical succession of the carbonate were obtained mainly from the core and associated data in Matoa-16 and Matoa-34 wells (Figures 4 & 5, respectively). Complementary and

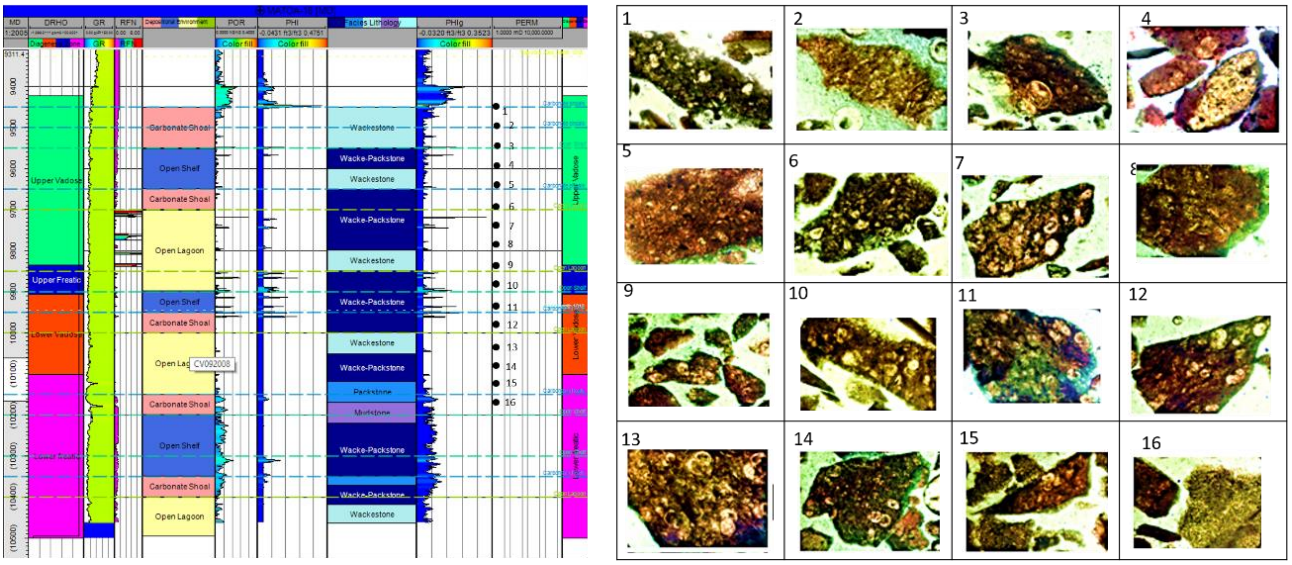


Figure 4: *Wireline Log Data, Plot Results and Petrography of the Matoa-16 Well.*

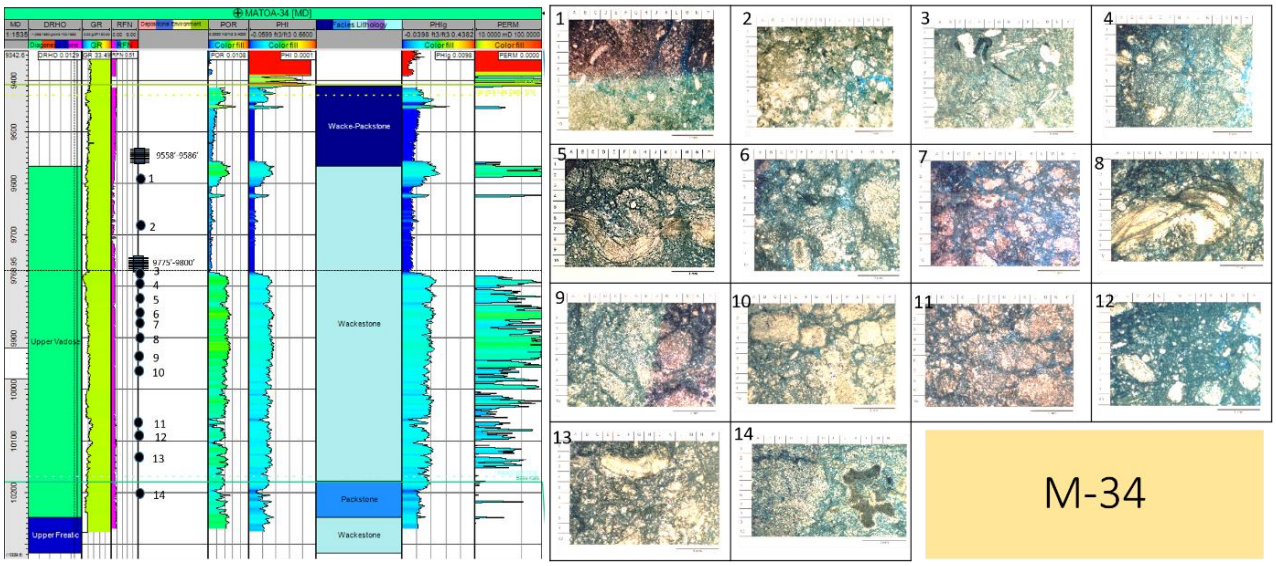


Figure 5: *Wireline Log Data, Plot Results and Petrography of the Matoa-34 Well.*

specific data of porous intervals with petrographic analysis were taken from Matoa-1, -20, -24, and -28 wells. However, since core data recovered from such wells became rubble, petrographic analysis became less conclusive. Reconstruction of depositional environments and vertical succession of lithological subdivisions were based on matching petrographic data with the wireline logs.

Furthermore, the diagenetic process experienced within intervals of Base Kais (=Top Pre-Kais) to Top Kais in Matoa Field can be synthesized. A summary of carbonate vertical successions with their associated depositional environments and diagenetic overprint in Matoa-16 and Matoa-34 is summarized in Figures 4 and 5. Several classifications have been employed, i.e. rock naming classification of Dunham (1962), the depositional environment

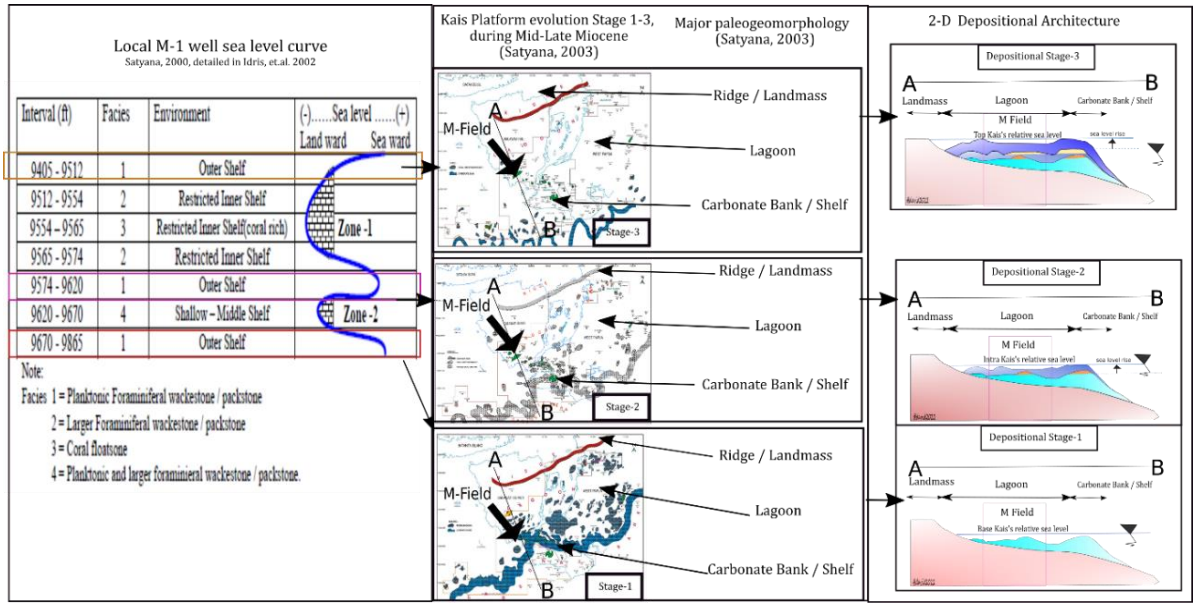


Figure 6: *The stage of deposition environment evolution based on previous studies (Satyana, 2003) and the use of Matoa-1 well data for calibration of eustatic curves (Idris et al., 2002).*

classification of Harris (2009), and diagenesis classification of Moore (1997).

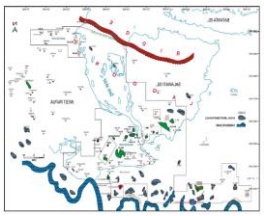
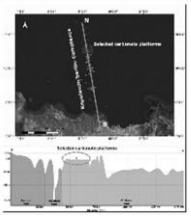
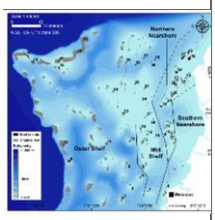
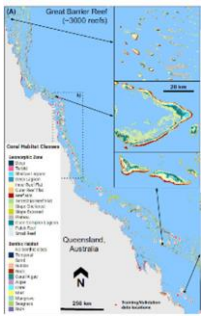
Carbonate Depositional Environment of Matoa Field

Broad discussions on the regional setting and depositional environment of Kais Formation have been made; the first by Redmond and Koesoemadinata (1976, in van Gorsel, 2018) then Suseno (2018, in van Gorsel, 2018). Abundant data related to Matoa Field has been analysed and revisited by Satyana (2003) and JOB PPS Internal Studies (2017). One of many essential results is the lateral distribution and heterogeneity of carbonate facies in Kais Formation. Advanced carbonate characterisations of Kais Formation were added to previous studies. They were related to diagenetic evolution during sea level fluctuations as illustrated by Figure 2. Figures 6 & 10 illustrate and explain the advanced characterization enhanced to the previous analysis as shown in Figure 2. This explanation can be seen in Figure 6.

Present-day Analogue

The regional NW-SE cross section illustrated in Figure 6 shows that the Kais Formation carbonate of Matoa Field consists of three major paleo geomorphological elements: ridge/ landmass, lagoon, and carbonate bank/shelf (Satyana, 2003). The ridge/landmass is the hinterland of the Bird's Head micro-continent, which is the northwestern part of the Australian Continental Crust. The lagoon paleo-geomorphology evolved in three stages of sub-environments of deposition, the younger being the widest (~30 km to ~60 km). Matoa Field itself is located within this lagoonal area. An extensive carbonate bank/shelf developed in the southern area, which is free of siliciclastic input, so giving ideal conditions for barrier reef formation.

Table 2. *Comparison of Present-day analogues with palaeogeomorphology of the Matoa Field.*

Kais's Major Paleo geomorphology	**Paleo-Morphometry (Length/width in km)**	**Seribu Island Platform Analogue**	**Spermonde Archipelago Analogue**	**Great Barrier Reef Analogue**
Ridge / Landmass	130 / 5	not available / uncomparable to Matoa Field	Limited landmass	Comparable to Matoa Field
Lagoon containing shoal & inter-reef lagoon	130 / 35-60	Lagoon intra-reef available	Comparable to Matoa Field	Comparable to Matoa Field
Carbonate Banks / Reef	130	Comparable to Matoa Field	most of them are drowning	Comparable to Matoa Field
Reference	Satyana (2003)	Amir et al. (2022)	Kench and Mann (2017)	Lyons et al. (2020)
Image				

Several regional candidates of present-day coral reef habitats which are assumed to fulfil paleo-geomorphological criteria have been selected for analogues, i.e., Thousand Islands, Spermonde Islands and Great Barrier Reef. By comparing all morphometric aspects of analogues as listed on Table 2. Comparison of Present-day analogues with palaeogeomorphology of the Matoa Field, the most likely match of environment to Matoa Field is the Great Barrier Reef.

Base Kais

Base Kais is defined as the boundary between Kais Formation and the underlying interval, observed from mud log and sonic log data at 10,855' MD (10,824' TVDSS) depth of Well B-1 (Figure 7). Meanwhile in Matoa-2, the Base Kais boundary was well defined by the sharp contact of carbonate and an underlying coal seam (member of Sirga Formation) at 10,700' MD (10,667' TVDSS) depth (Figure 8).

Stage-1 (Base Kais to Intra Kais) to Stage-3 (Top Kais) Cycle

By using Matoa-16 and Matoa-34 well data as shown on Figures 4 & 5, respectively, the carbonate depositional cycle of Base Kais to Top Kais (Stage-1 to Stage-3) can be observed from 3D seismic interpretation.

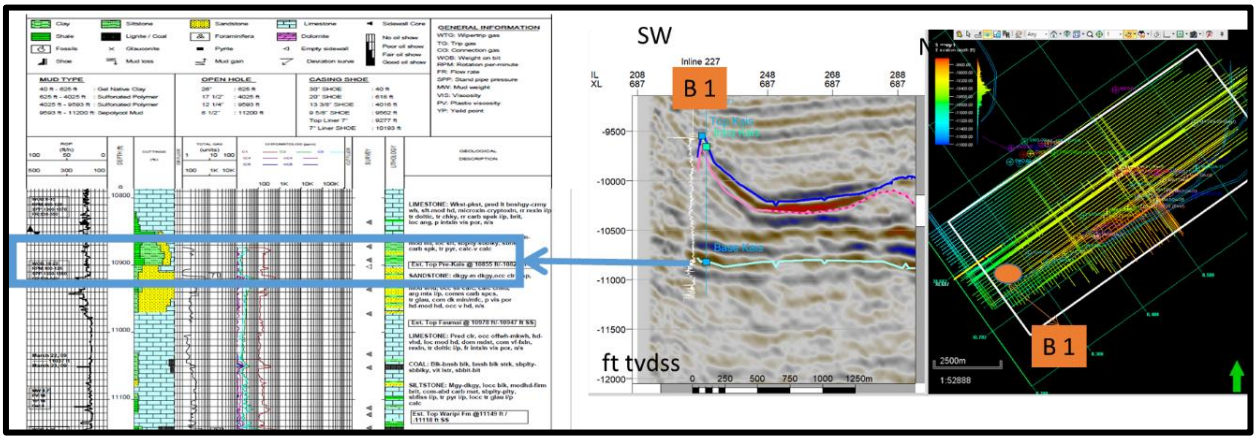


Figure 7: *Definition of Base Kais from Well B-1.*

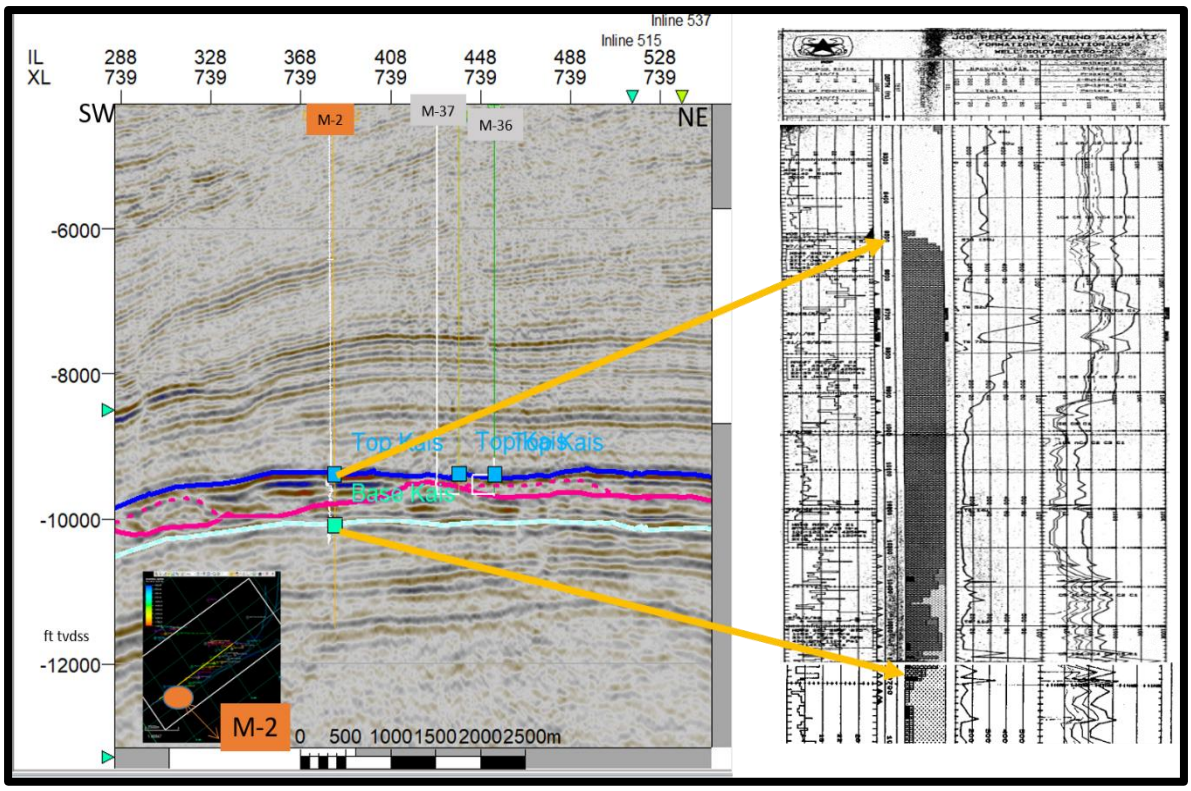


Figure 8: *Definition of top and base Kais from Well Matoa-2.*

Comparison between eustatic curves with well-tied seismic led to the interpretation that the deposition of shoal carbonate of Matoa Field occurred during sea inundation (sea level rise) as discussed on Figure 2. Based on isopach data and seismic time slices, there were three stages of (3D seismic) brief depositional cycles observed, as illustrated on Figure 9.

Diagenetic Environment & Evolution

The diagenetic evolution can be interpreted by combining Matoa-34 (Figure 4) and Matoa-16 (Figure 5) well data with the eustatic curve from Matoa-1. It is interpreted as the product of multiple sea level drops as described in Figure 2. According to Moore's (1997) petrographic

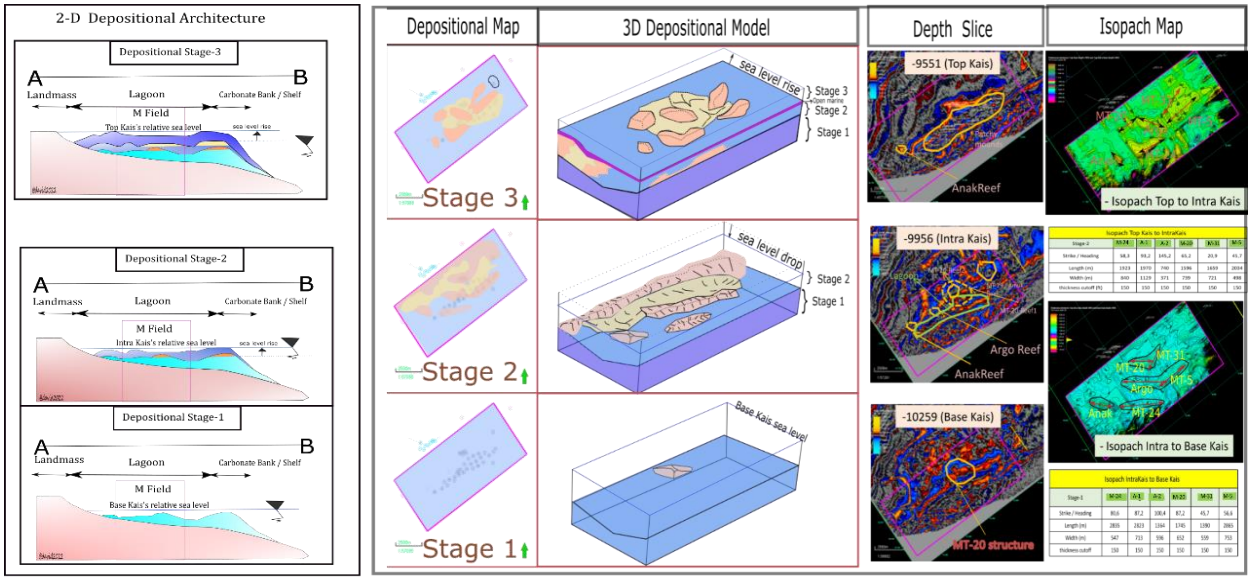


Figure 9: *Illustration of Kais Carbonate depositional stages from Stage-1 to Stage-3 using isopach and seismic time slice.*

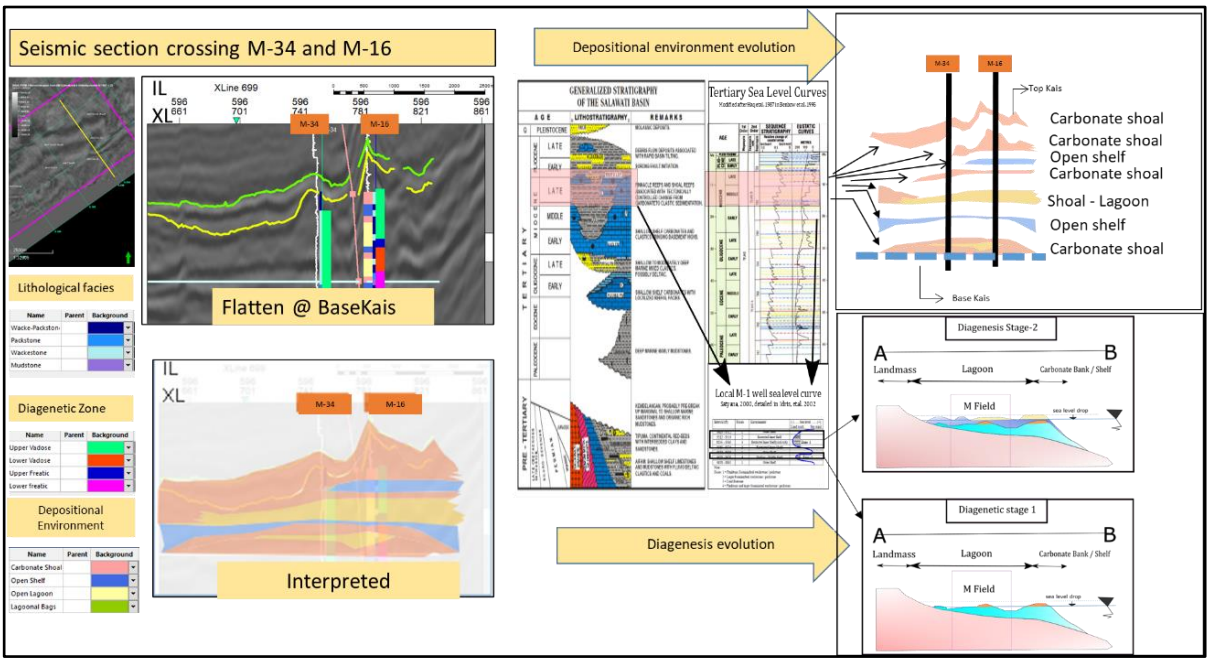


Figure 10: *Evolution of diagenesis in the Matoa Field in correlation with Sea Level Drop from Well Matoa-1*

classification, at the boundaries of Stage-1 to Stage-2 and Stage-2 to Stage-3, diagenesis was in the marine vadose zone. Our reconstruction of the interplay between diagenesis and deposition evolution is in Figure 10.

A seismic attribute analysis test was performed on x-line 760 to find any correlation between diagenetic expression in wells with seismic data and top diagenesis marker as the control for layering. After testing multiple attributes such as: RMS Amplitude, realized RMS Amplitude,

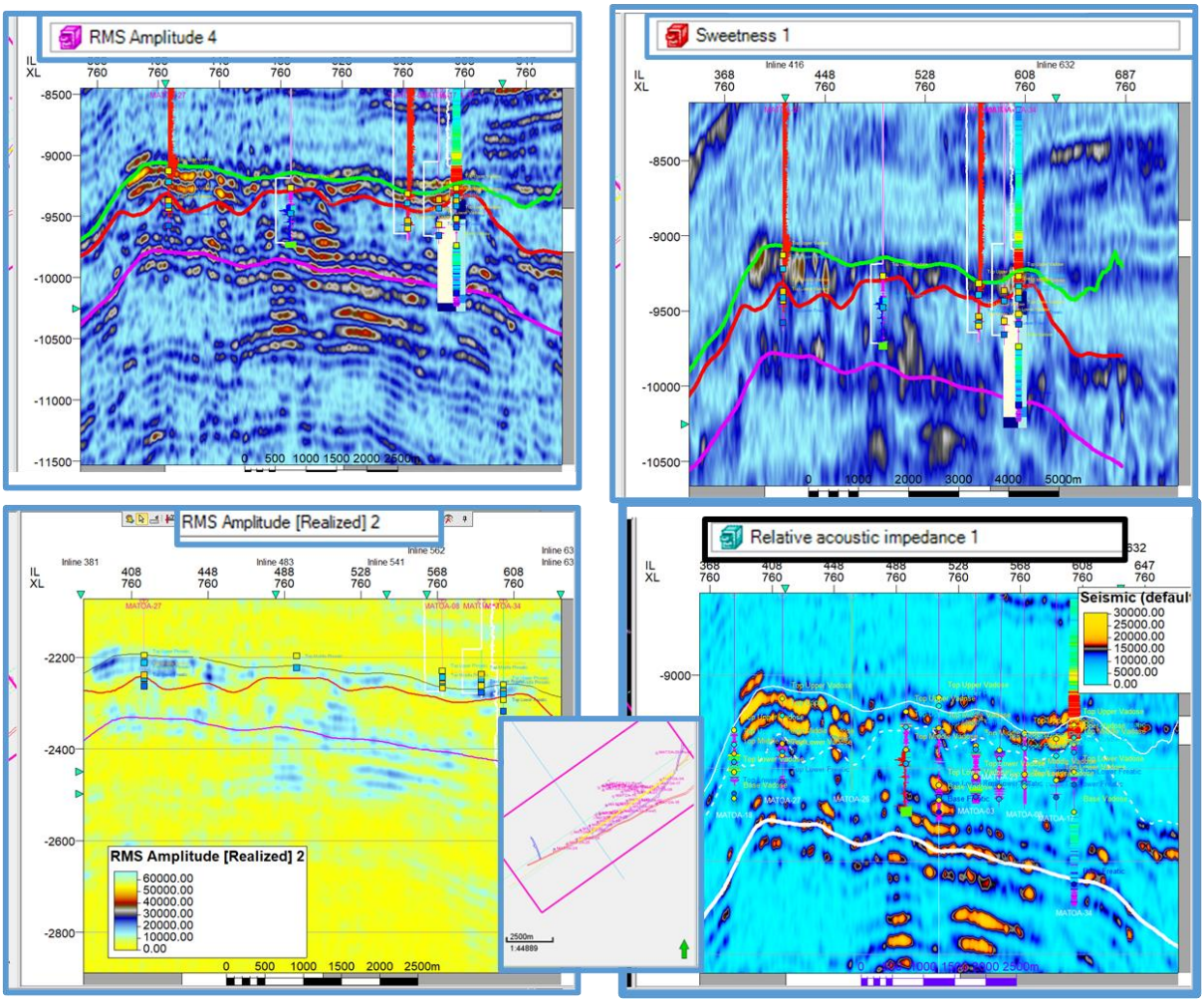


Figure 11: *Cross-sectional seismic attributes RMS Amplitude, RMS Amplitude (realized), Sweetness, and Relative Acoustic Impedance*

Sweetness and Relative Acoustic Impedance. Good correlation was obtained to determine diagenetic zonation/layering. From correlation analysis, the best fit attribute to be used is Relative Acoustic Impedance. Such integrated zonation/layering scheme based on Relative Acoustic Impedance was used in 3D modelling. The cross-sectional view of these four seismic attributes can be seen in Figure 11.

PETROPHYSICAL APPLICATION TO 3D STATIC MODEL

After successfully reconstructing microfacies vertically from well data and laterally from seismic 3D data, reservoir characterization was continued by quantifying factors that affect the porosity and property of carbonate reservoirs in the M-Field. Petrography data other than the M-16 and M-34 wells in Figures 4 & 5 used in this analysis include the M-1 well (Figure

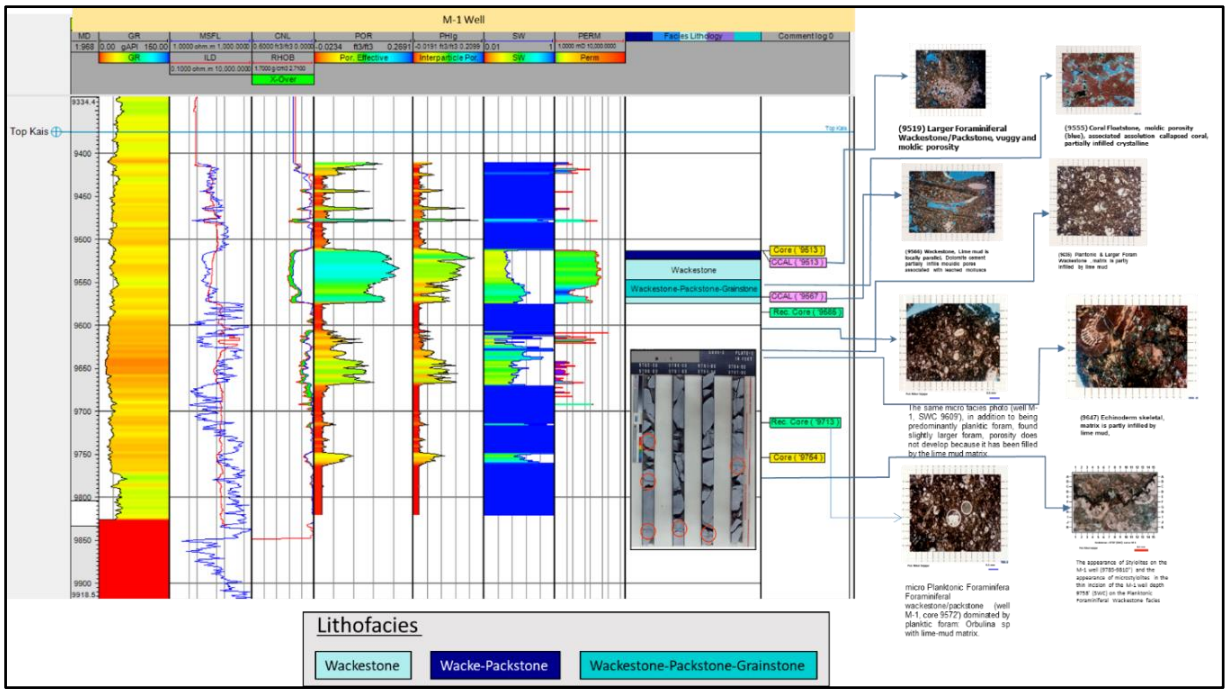


Figure 12: *Petrophysical characteristics in the Matoa-1 well with core data calibration.*

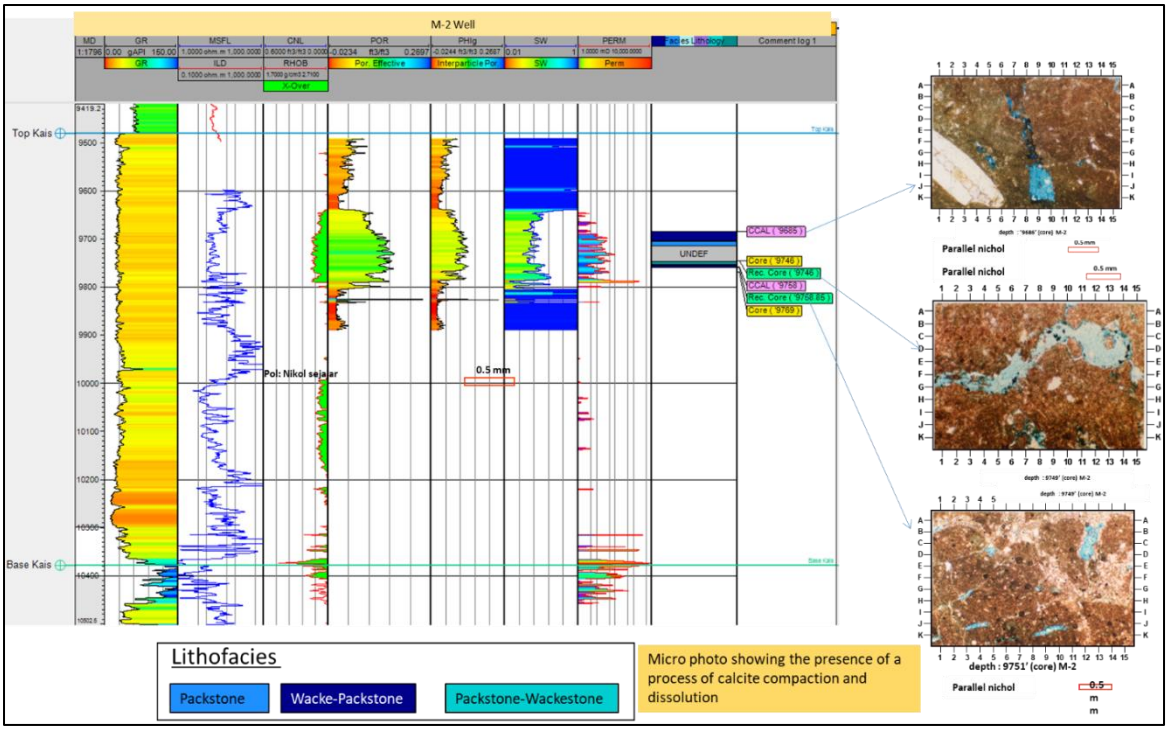


Figure 13: *Petrophysical characteristics in Matoa-2 well with core data calibration.*

12), the M-2 well (Figures 13 & 14), and the M-5 well (Figure 15). Petrographic data were used for the determination of effective porosity.

Calibration of petrography and log data can be used for the determination of RFN (Rock Fabric Number) logs, secondary porosity, diagenesis porosity (S_{vug}), to rock type modelling. In general, the flow of

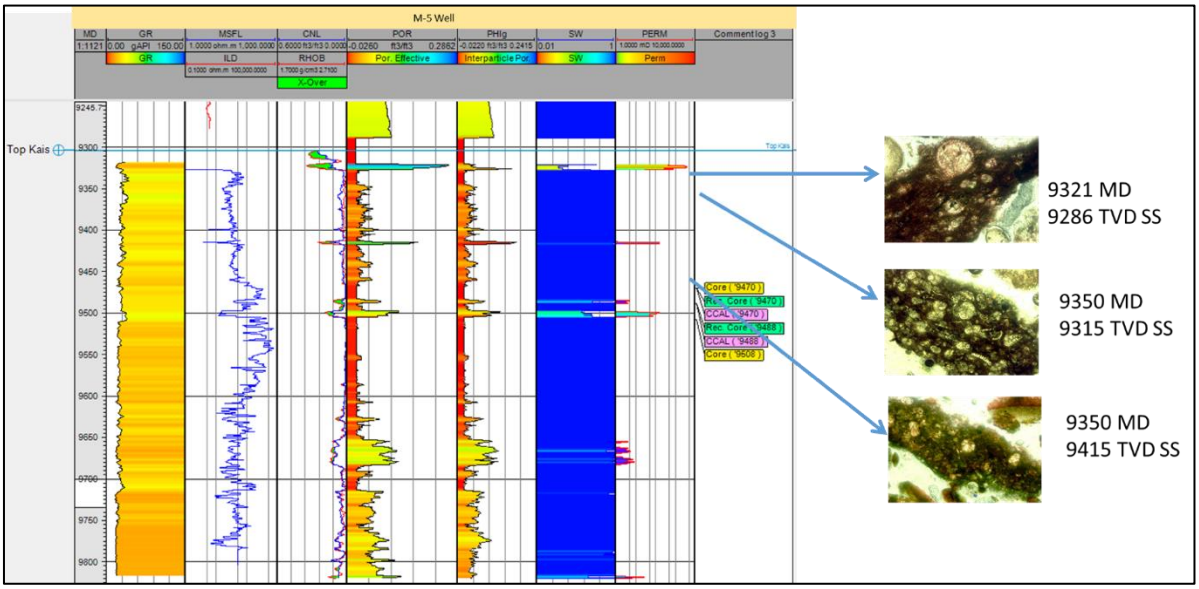


Figure 14: *Petrophysical Characteristics in the Matoa-2 Well with petrographic Data Calibration.*

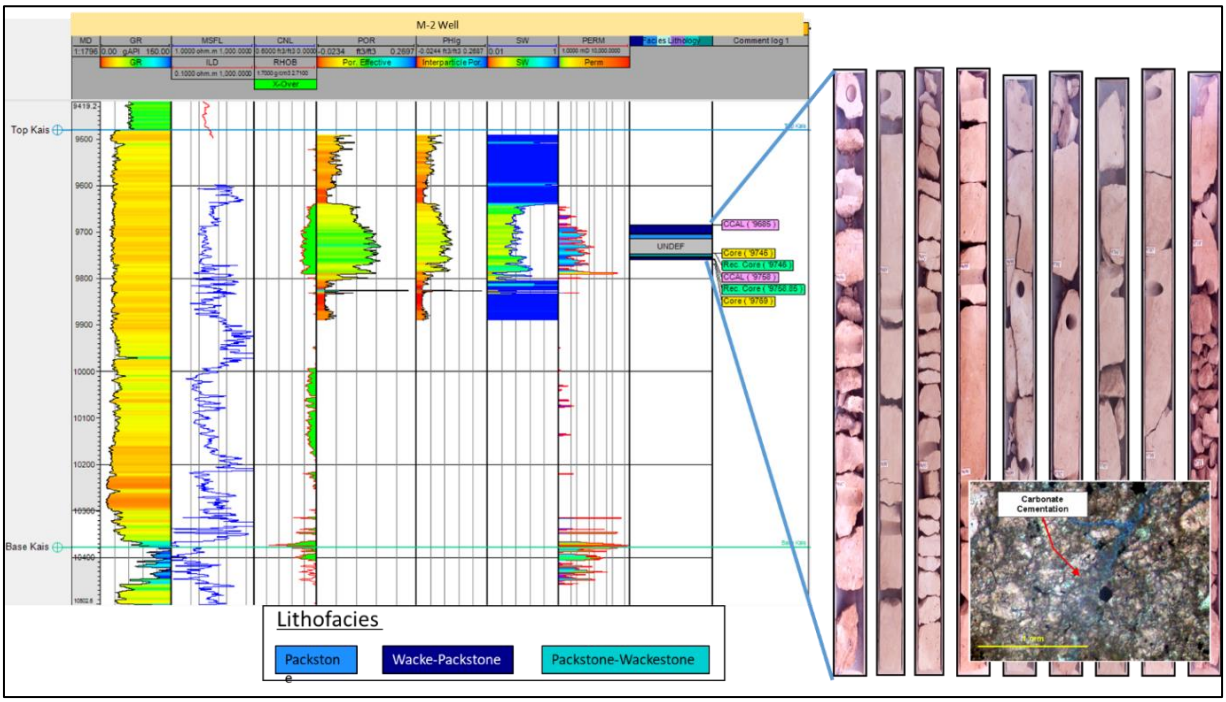


Figure 15: *Petrophysical Characteristics in the Matoa-5 Well with Petrography Data Calibration*

petrophysical analysis based on Lucia (2007) is from the creation of RFN logs, the determination of the effective porosity values, secondary porosity, diagenesis porosity (S_{vug}) shown in Figure 16. The petrographic data above shows that the RFN log correlates with Phig. The RFN calculations were made based on the cross plot between porosity and initial water saturation (Swi) with the formula:

*RFN=Exp ((7.163+1.883*Ln (Phig)+Ln (SW)) / (3.063+0.610*Ln (Phig))), with a range of values 0 – 2.5.*

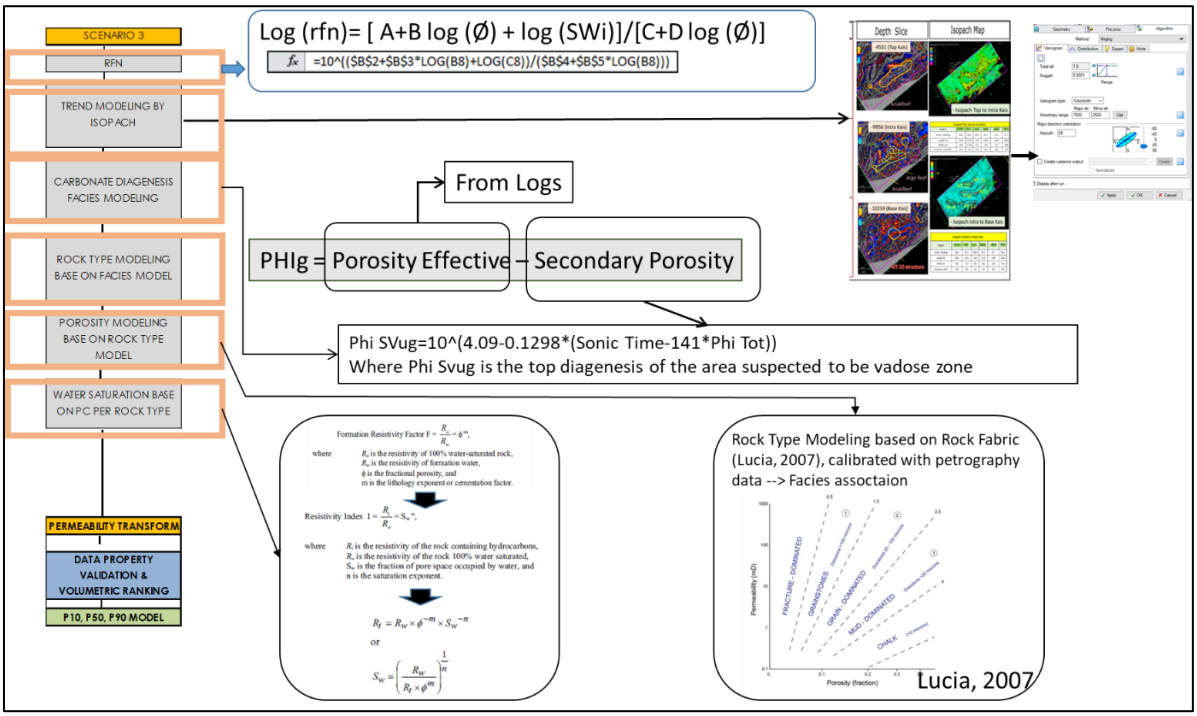


Figure 16: *Flow of Petrophysical Analysis in the Matoa Field.*

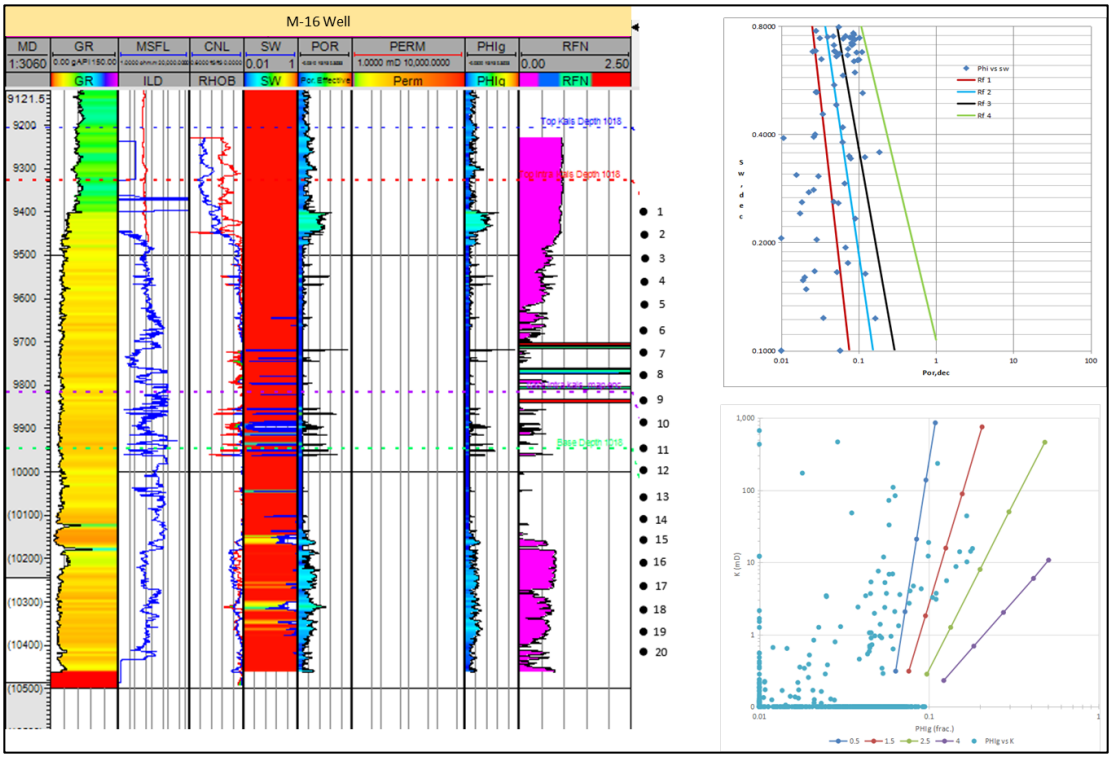


Figure 17: *Petrophysical log and cross-plot determination of rock type.*

From the results of such cross-plots, rock types based on lithology, depositional environment and diagenesis were obtained (Figures 17 & 18).

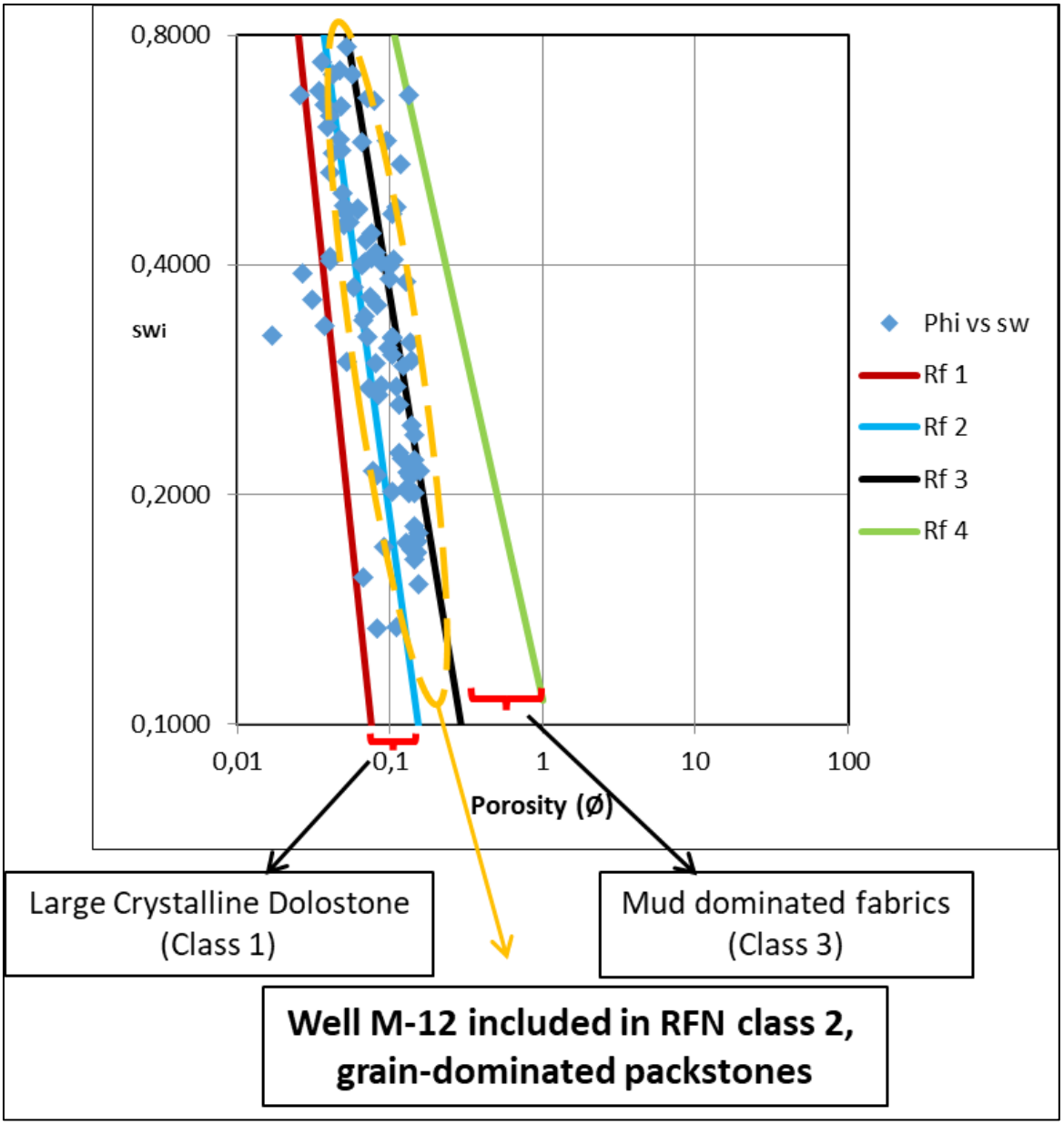


Figure 18: *Cross-plot Between Porosity and Swi for Rock Types Classification.*

MODELLING APPLICATION

Characterization of microfacies, cores, logs and seismic data created 3D geological static models including rock type models (Figure 19), porosity models (Figure 20), permeability models (Figure 21) and water saturation models (Sw, Figure 22).

CONCLUSION

Since 2002, no diagenetic characterization was done in Matoa Field. This paper illustrates that a combination of high-resolution core, log, and 3D seismic could characterize the reservoir sedimentology, depositional environments, and diagenetic evolution of the carbonates. Comparing with the Great-Barrier Reef analogue, Matoa Field was paleo-geomorphologically a

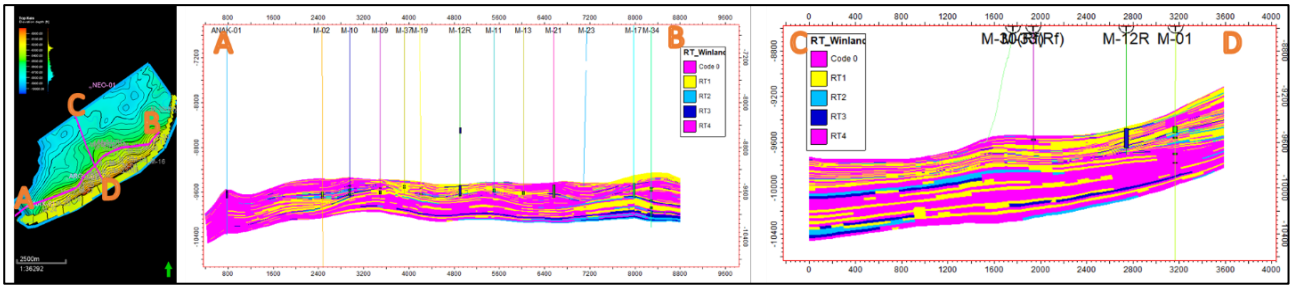


Figure 19: *Rock type model of Matoa Field.*

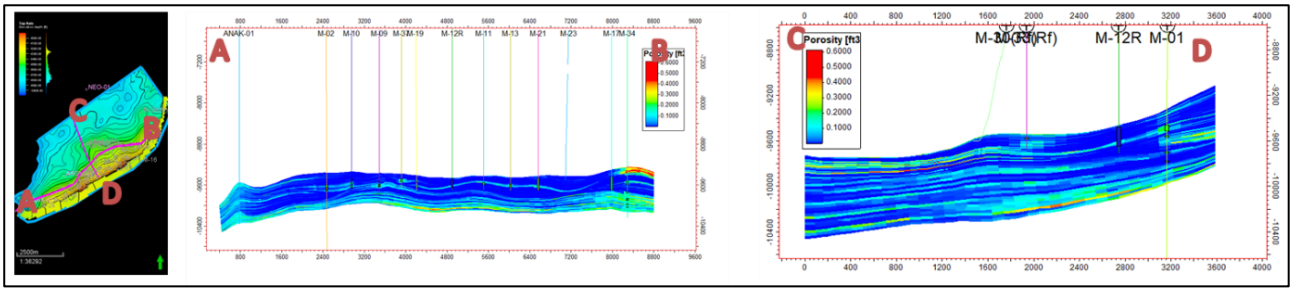


Figure 20: *Porosity model in Matoa Field*

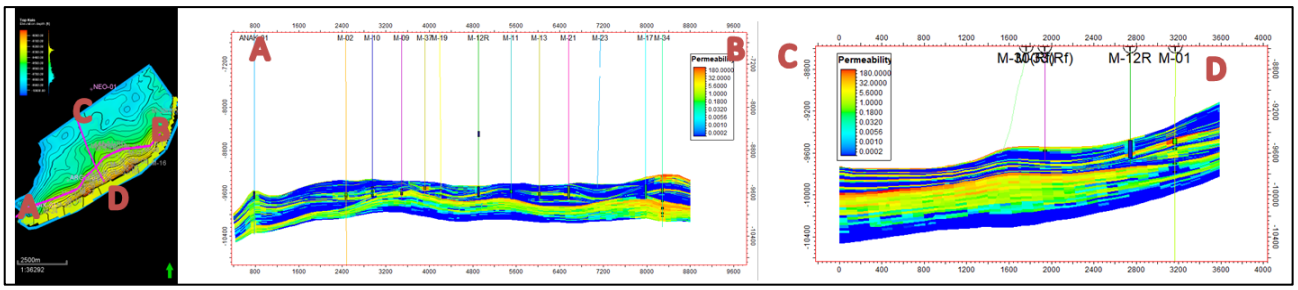


Figure 21: *Permeability model in Matoa Field.*

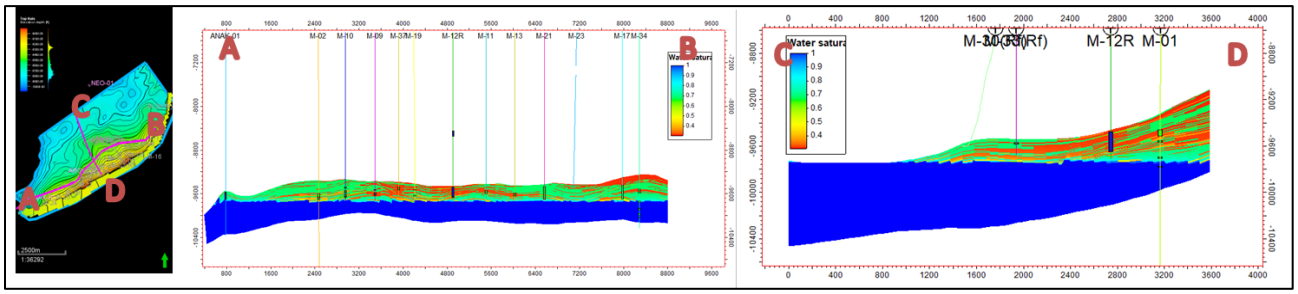


Figure 22: *Sw model in the Matoa Field.*

carbonate shoal lying within a lagoon during Miocene time. This carbonate shoal grew from Base Kais to Top Kais times, undergoing three stages of deposition and two cycles of marine vadose diagenesis.

All data, analogues and analyses have enabled conclusions from integrated geophysics, geology-to-reservoir modelling, with advanced analysis of the carbonate microfacies. This work enabled generation of porosity models based on RFN, as a combination of lithology, deposition and diagenetic environments, permeability models, rock-type models, and water saturation. From all models, it is evident that the Matoa Field reservoir consists of four productive intervals.

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