Seismic Interpretation and Depositional Model of Kais-Lower Klasafet Reservoirs in Walio Area of Kepala Burung PSC, Salawati Basin, West Papua, Indonesia

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Abstract. Kepala Burung PSC is located at onshore portion of Salawati Basin. The PSC area is divided into two area(s) namely Walio Area and Arar Area at the south and north, respectively. Numerous exploratory wells had been drilled at Walio Area which resulted several economical discoveries of oil reservoired within the reefal Kais Formation and the overlying mixed-siliciclastics carbonate of Lower Klasafet reservoirs namely U-Marker and Texturalia Intervals. The latest discoveries at this area was in 2010 by the drilling of North Walio-1 well which encountered oil reservoirs within Kais Formation. With consideration of exploration success ratio, proven petroleum system elements and the broad distribution of Miocene Kais and Lower Klasafet; exploration in this area is still promising. Moreover, two three-dimensional (3D) volume of seismic which acquired in 2004 and 2007 are beneficial in improving the geological understanding in this area. This study is providing seismic interpretation which weighted to seismic facies analysis within Kais-Lower Klasafet reservoirs and the depositional model of these two associated reservoirs. Seismic facies analysis within the studied reservoirs are focused to reflection characteristics such as; seismic reflection termination, continuity, amplitude, frequency and internal reflection configuration. The internal seismic reflection characteristics are compared between the successful and unsuccessful exploration drilling. Subsequently, a sketched depositional model at the times of Kais and Lower Klasafet deposition is constructed. Three seismic reservoir facies are recognised in this area; pinnacle reef-patch reef which associated to narrow topography high(s), reefal carbonate bank which associated to broad or extensive topography highs, and drowning package of carbonate-mixed-siliciclastics at the top of Kais reef(s). These types of carbonates are interpreted to be deposited within five stages of major sea level rise. The antecedent topography of the reefs is mapped to be used as reef fairways in Salawati Basin, which means will be tied to neighbouring northern Arar Area and the other adjacent areas.

1. Introduction
The study area namely Walio Area is located at the Kepala Burung PSC in onshore Salawati Basin, West Papua, Indonesia (Fig 1). The basin is located in the western part of Bird’s Head which hosts other sedimentary basins; Bintuni Basin and North Irian Basin (Figure 1) [1].

The Bird’s Head area was part of the northern promontory of the Australian continent termed Sula Spur during the Paleogene [2]. The earliest recorded Neogenetectonic in Salawati Basin is the formation of Sorong Fault Zone (SFZ) (Figure 1) which related to clockwise rotation of the Philippine
Sea Plate at approximately 20 Ma (e.g. early Burdigalian, late Early Miocene), causing the subduction contact between Philippine Sea Plate and northern promontory of Australian continent changed to sinistral strike-slip [2]. Subsequently, the SFZ became the northern margin of the Salawati Basin [3].

This tectonic event resulted east-west folds and complex interplay of strike-slips and extensional faults. The SFZ formation was within the time of (e.g. contemporaneous) a larger tectonic event affecting the whole northern promontory (e.g. including North Irian Basin and Bintuni Basin) of Australian continent. The event was marked by Early Miocene Unconformity (EMU) at the top of Sirga Formation (Figure1) [4]. EMU occurred as a response to arc-continent collision (e.g. between Indo-Pacific arc and Australian continent) that produced a subaerial, erosional and angular unconformity in the Bird’s Head area.

The features resulted from the contemporaneous EMU and SFZ tectonic events are major east-west folds and strike-slip fault (e.g. Cendrawasih fault). In Walio Area, they are known as Walio fold, Kasim-Jaya fold, Linda-Sele fold, Wakamuk fold and Cendrawasih strike-slip fault (Figure1). Cendrawasih fault is an envelope of strike-slip with associated lower-order normal faults.

Consequently, during Middle Eocene, significant increase in the rate of sea level rise and thermal basin-sag caused a regional subsidence across the basin [5].

Extensional tectonics due to thermal basin-sag was amplified by the continued convergence of the Pacific and Australian Plates which converged WSW at ~248° relative to the Australian Plate [6]. Minimum compressive stress propagating NW-SE produced normal faults (e.g. extensional faults) striking NE-SW or N-S inmost locations.

Stratigraphic Framework on The Miocene sediments (e.g. Kais Formation and Klasafet Formation) were deposited during the tectonic event that has been described earlier. The deposition can be staged into several phases as the followings:

1.1. Late Oligocene (Chatian) to Early Miocene (Aquitanian)
During this time, the deposition of Sirga Formation (e.g. medium-grained siliciclastics – to – cobble-sized conglomerates) ceased due to uplift (Figure1). The tectonic event of EMU and SFZ affected basin configuration prior to the deposition of Kais Formation, as the formation’s antecedent topography.

1.2. Early Miocene (Burdigalian) to early Late Miocene (Tortonian)
Slow rate of sea level rise produced topography highs (e.g. resulting folds from EMU-SFZ tectonic events) and developed shallow marine where Kais Formation and Lower Klasafet Formation termed U-Marker and the overlying Textularia intervals were deposited. Kais deposition was initiated in Burdigalian. However, in Langhian, the increasing rate of sea level rise and thermal basin-sag induced rapid creation of accommodation space. In some parts of Walio Area, carbonate deposition ceased and changed into mixed clastic carbonates of Lower Klasafet. Therefore, the deposition of Kais Formation and Lower Klasafet were contemporaneous until Tortonian age (Figure1).

1.3. Late Miocene (late Tortonian) to Pliocene
Interplay of rapid sea level rise, thermal basin-sag and extensional tectonic due to the converging Pacific and Australian Plates lead to the ceasing of Kais and Lower Klasafet deposition (e.g. rapid subsidence). It developed into pelagic deposits of deeper marine of Klasafet Formation. The convergence of Pacific and Australia Plates was accommodated by a series of normal faults trending N-S or NE-SW and occurred prior to Pliocene whilst deposited Upper Klasafet shale (e.g. stratigraphy column in Figure1). The local normal faults along the Cendrawasih strike-slip fault were also reactivated during this event.
2. Data and Method

2D seismic lines and two volume(s) of 3D seismic are used for interpretation seismic facies and depositional model (Figure 1). Numerous exploratory wells are used to confirm the seismic facies determination. The interpretation begins with understanding the regional tectonostratigraphy of the Salawati Basin from published studies. This knowledge is then used to summarize the local tectonics and corresponding stratigraphy in Walio Area, particularly during Miocene to Early Pliocene.

Then, the seismic is interpreted into several key horizons: Top Sirga, Top Kais and Top Textularia (e.g. Text-II). Hereafter, seismic facies(s) are conceived by analyzing the seismic reflection termination, internal reflection configuration, continuity, amplitude and frequency.

Typical reefal seismic reflections usually moudy, chaotic and low-moderate amplitude. They are delineated and grouped to analyze the pattern of distribution. The combination of distribution pattern sand seismic facies analysis are then used to construct depositional model. The model is calibrated with existing exploratory wells. The following section is to discuss Walio Area’s typical seismic facies and its interpretation.

3. Result and Discussion

There are three results that are observed: the antecedent topography during Kais Formation deposition, seismic facies analysis, and depositional model and its implications.

3.1. Antecedent Topography during deposition of Kais – Lower Klasafet Reservoirs

Pre-depositional antecedent topography of Kais Formation was produced by EMU and amplified by SFZ tectonic events. These events developed subaerial exposure, folding, strike-slip fault complex with smaller normal faults and folds and contemporaneously ceased the deposition of Sirga Formation, marked by regional EMU. These structural features formed antecedent topography, such as Walio High, Sele Embayment, Payao Local High, Linda-Wakamuk High, Kasim-Jaya High, Walio-Kasim
Syncline, Kasim Utara Terrace, Cendrawasih Terrace, Moi Deep, and Klamono Ramp (Figure 2). Between Cendrawasih Terrace and Moi Deep, Cendrawasih sinistral strike-slip fault with local splays of normal faults and folds developed with limited extend. Top Sirga, Kais and Textularia Formations were interpreted to delineate the antecedent topography (Figure 2).

Figure 2. (A) antecedent topography during deposition of Kais and Lower Klasefet. (B). Seismic section illustrates the antecedent topography reflected by top sirga (green horizon). (C) seismic section, as above with different angle.

Figure 3. (A) typical seismic character at Walio High representing amalgamation of part reefs creating reefal-bank. (B) typical seismic character at Kasim-Jaya High representing pinnacle reef (e.g rimmed carbonate) with slope c.a 50°. (C) typical seismic character of drowning carbonate of Lower Klasafet reservoirs at the crest of Kais reef.
3.2. Seismic Facies Analysis

Seismic reflection characteristics were analyzed in all local topographies (Figure 3). There are three seismic facies of Kais-reefal from the seismic. Their shapes (e.g. reefal bank, patchy or pinnacle) are influenced by the antecedent topography.

3.2.1. Facies-1 reefal bank and patch reefs (Kais Formation)

Reefal carbonate bank is an amalgamated patch reefs and extend laterally to a broad plain antecedent topography. The reef body tends to build-out rather than build-up. They are mainly located on a broad topography high (e.g. Cendrawasih terrace, Moi Deep, Figure 3). The seismic facies typifies moundy to relatively flat top, weak amplitude, moderate frequency, discontinuous to chaotic internal seismic reflection, has bilateral onlap reef canal. In the northern part of Walio High, reefal bank is common. The boundary of individual patch reef is rather difficult to be recognized. “Pseudo individual patch reef” is sometimes present to be bounded by normal fault, however it is ambiguous. The normal faults accentuate the reef boundary; however, it is not always the case. In the southern part of Walio High, individual patch reef is more noticeable (e.g. Klaserai Field).

In Moi Deep, Kais reef is patchier in comparison to Walio High, despite the antecedent topography is relatively broad, similar to the Walio High. This is due to higher rate of sea level rise than the rate of reef growth. The reef tends to build-up rather than build-out.

3.2.2. Facies-2 pinnacle reefs (Kais Formation)

Pinnacle reefs are mainly located on a narrower topography high (Figure 3). The observed seismic facies are profoundly mounded (e.g. rimmed carbonate look-alike with reef slope c.a. 50°), moderate amplitude, moderate frequency, parallel and continuous internal seismic reflection, and has distinctive bilateral onlap reef canal (Figure 3). In Kasim Utara pinnacle, the angle of reef mound could reach ~50°.

3.2.3. Facies-3 Drowning Carbonate (Mixed Siliciclastic and Carbonate of Lower Klasafet)

This facies is characterized by high amplitude, high frequency parallel, onlap termination onto Kais Formation, local chaotic seismic reflection near to crest of the underlying Kais reef, and flat-to-moundy top (Figure 3).

3.3. Depositional Model and Reef Fairways

The deposition of Kais carbonate can be divided into five (5) stages, strongly controlled by relative sea level rise. Prior to these stages, the basin underwent tectonics due to arc-continent collision between Pacific Island Arc and Sula Spur, and clockwise rotation of Philippine Sea Plate (Gold et al, 2017). As the results, angular unconformities formed and Sirga Formation ceased contemporaneously created east-west folds were present (e.g. Walio, Wakamuk, Linda-Sele, Kasim-Jaya and Klamono Ramp). The entire Walio Area was exposed subaerially. The five stages of Kais-Lower Klasafet deposition are described as follow (Figure 4):

3.3.1. Stage-1

Following the subaerial exposure, the rise of sea level flooded Moi Deep into subaquaueous environment (shallow marine). Meanwhile, other areas (e.g. Walio-High, Cendrawasih Terrace, etc) were still exposed subaerially. Kais Formation was deposited during this stage with patchy distribution due to relatively flat and broad depositional antecedent topography. Moi Reef is one of the examples deposited during this stage.

3.3.2. Stage-2

Relative sea level continued to rise, the carbonate reefs within Moi Deep gave up and subsequently drowned. Cendrawasih Terrace became subaqueous (e.g. shallow marine environment) and deposited
patchy Cendrawasih reef, due to relatively broad depositional antecedent topography. However, the presence of sinistral strike-slip Cendrawasih Fault with minor splays of normal faults in some particular location along the strike slip made it possible to expect rimmed carbonates. These carbonates are present near splays of normal faults within Cendrawasih Terrace. It is similar to pinnacle reef type. In the eastern part of Walio Area (Figure 4), within Klamono Ramp, the Kasuari reef was contemporaneously deposited.

3.3.3. Stage-3

Sea level continued to rise, Cendrawasih Terrace drowned, and shallow marine shifted to higher area, the Kasim Utara Terrace. Kasim Utara reef with pinnacle morphology grew with compliment to narrower antecedent depositional topography.

3.3.4. Stage-4

Subsequent relative sea level rise induced the drowning of Kasim Utara Terrace to which shallow marine environment shifted to Kasim-Jaya High and Walio High. It began by the deposition of “South Kasim drowned-pinnacle reef” and pinnacle reef of Kasim Barat. Prior to the maximum sea level rise, the entire Walio High and Kasim-Jaya High were in subaqueous condition. Jaya pinnacle reef, Kasim pinnacle reef and Walio reefal-bank took place during this stage. It is important to note that during the growth of South Kasim reef and Kasim barat reef, the reefs in Walio High were likely to be patchy-deposited in the southern part, unlike the northern part of Walio High that accumulated amalgamated reefal bank.

3.3.5. Stage-5

During this stage, Walio reefal-bank and Jaya reef were drowned due to their incapacity to catch up the rise of relative sea level. However, Kasim reef remained to grow. Thereafter, the entire area of Walio (including Kasim reef) was drowned and environment changed to a deeper marine setting with pelagic deposits.

Figure 4. Antecedent topography during deposition of Kais Formation, (B) Transgressive reef development model of Kais Formation. The deposition was initiated at the lowest point of area called Moi Deep and backstepping to higher area contemporaneously with the rise of relative sea level.
4. Conclusion
The antecedent topography constraints the reef fairways and its seismic characteristics. In the Walio Area, Moi Reef is the oldest reef (Stage-1), followed by Cendrawasih Reef (Stage-2), Kasim Utara Reef (Stage-3), Walio-Kasim-Jaya Reefs (Stage-4) and Kasim Reef (Stage-5). These reef fairways can be used to further navigate the mapping of reef distribution within the geological time (e.g. stages of carbonate development). It will then be tied to surrounding areas within the Salawati Basin in order to define yet-to-find carbonate reefs and new play types within Kais-Lower Klasafet intervals.

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