Lithofacies, Facies Association, and Depositional Environment of 34-1, 33-6, and 33-4 Sandstone, Wida Field, Gita Member, Talang Akar Formation, Asri Basin, Offshore Southeast Sumatra

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Abstrak – Tiga reservoir Anggota Gita (34-1, 33-6, dan 33-4) menunjukkan produksi minyak yang terbatas, penurunan tekanan yang cepat, dan *recovery factor* yang rendah akibat *solution gas drive*. Setelah mengalami dua kali *waterflooding* pengembangan lapangan tahap selanjutnya membutuhkan model statik dan dinamik. Akan tetapi, sebelum model tersebut dibuat karakterisasi reservoir perlu dilakukan guna mengetahui fasies dan lingkungan pengendapan untuk model stastik reservoir. Langkah awal melibatkan karakterisasi reservoir dengan integrasi data seperti *core*, *wireline log*, atribut seismik, petrografi, dll. Korelasi sumur untuk menyebarkan marker dilakukan dan diintegrasikan dengan atribut seismik untuk membuat *pie chart,* geometri reservoir, dan peta lingkungan pengendapan.Geometri eksternal dari atribut seismik menunjukkan adanya sungai distributari dan *point bar* sebagai reservoir. Fasies ini disusun oleh litofasies batupasir medium-halus *planar tabular cross bedding*, batupasir halus-sangat halus *mud drapes*, dan batupasir *ripple-wavy lamination*. Log sumur menunjukkan pola *fining upward*, batuan inti memperlihatkan banyak *channel rip up clast* serta kontak erosional, atau kontak tegas dengan litologi di bawahnya. Banyaknya struktur *mud drapes* pada batupasir *channel* mengindikasikan pengaruh pasang surut karena lingkungan pengendapan dekat dengan laut diduga pada *lower delta plain.* Bentukan *channel* berarah barat-timur (34-1) dan selatan-utara (33-6 dan 33-4). Asosiasi fasies (FA) lain mencakup laut dangkal, rawa-rawa, *interdistributary bay,* dan *tidally influenced interdistributary bay*.

Kata Kunci: Anggota Gita, Karakterisasi Reservoir, Sungai Distributari.

***Abstract** – Three Gita Member reservoirs 34-1, 33-6, and 33-4 produce from solution gas drive with rapid pressure decline and low recovery factor. After successful oil production enhancements through waterflooding injections prompt the need for a reservoir model in further field development. Before such model is built reservoir characterization was carried out to determine facies and depositional environment for facies modeling. The study integrated core, wireline log, petrophysical logs, seismic attribute, petrography, etc. Next, well correlation was carried out to distribute stratigraphic markers. Finally, seismic attribute and well correlation were integrated to construct pie chart and depositional environment map. External geometry from seismic attribute revealed distributary channel with point bars which act as reservoir and consist of medium-fine grained planar tabular cross bedding sandstone, mud drapes sandstone, and ripple-wavy lamination sandstone. Wireline log showed fining-upward pattern and core displayed abundant channel rip up clasts, sharp or erosional contact with underlying lithology. Frequent mud drapes found within channel sandstone indicate tidal influence in close proximity to marine environment probably in lower delta plain. Channels are trending west-east (34-1) and north-south (33-6 and 33-4). Other facies associations are shallow marine, swamp, interdistributary bay, and tidally influenced interdistributary bay.*

***Keywords**: Gita Member, Reservoir Characterization, Distributary Channel.*

BACKGROUND

Wida field is a very mature field discovered in 1988. The field is located in Asri Basin, Offshore Southeast Sumatra Block Northwestward form Jakarta. The structure is wide and broad anticline, faulted in the west part. The production started in 1989 with peak production up to 30.000 barrel oil/day from 7 reservoirs. These are sandstone reservoirs, part of Gita Member, Talang Akar Formation deposited in fluvial to delta environment having high porosity and permeability. Three shallowest reservoirs namely 34-1, 33-6, and 33-4 only supported from solution gas drive with rapid pressure decline and low recovery factor. Pressure and production decline were observed in late 90's thus in early 20's two water flooding injection has been applied and monitored through 4D seismic. Water flooding has successfully rebuild pressure and increase oil production. It has been estimated that untapped oil left in the reservoirs is still considerable.

The waterflooding trigger the need of 3D reservoir static dan dynamic model for next field development. 3D geomodelling of the reservoir can greatly help in estimating reserves and determining the efficient way to recover the hydrocarbon. Before such reservoir model is build, careful reservoir characterization is required especially in term of facies and reservoir geometry for use in reservoir facies modelling. The facies will be populated with petrophysical property such as porosity and water saturation which ultimately determine in place reserves. Therefore, facies and geometry of facies is very important in reservoir modeling. To determine the facies and its geometry reservoir characterization was done. The technique seeks all the relevant information that is required to describe a reservoir in terms of its ability of storing and producing hydrocarbons (Chopra and Michelena, 2011; (Yu et al., 2011). Understanding reservoir architecture such as its internal and external geometry, its static (distribution of reservoir properties such as porosity, permeability and net pay thickness) and dynamic (understanding the fluid flow within the reservoir is crucial. In reservoir characterization, wireline log patterns such as gamma ray are the basic subsurface data that are widely used. Interpreting depositional facies from a log pattern without sediment core is impossible. Thus, this study integrates a plethora of data that are available such as core, wireline logs, seismic attribute, petrophysical logs, and petrography. The information is incorporated for reservoir model subsequently. This research is part of reservoir characterization and modeling of Wida field for next stage development phase to drain untapped oil after waterflooding.

The purpose of this research is to:

1. Characterize the three reservoirs, in term of lithofacies, facies association, and depositional environment from various data set such as core, well logs, seismic data, petrophysical logs, and petrography.
2. To create depositional environment maps which can be used for facies or static modeling stage.

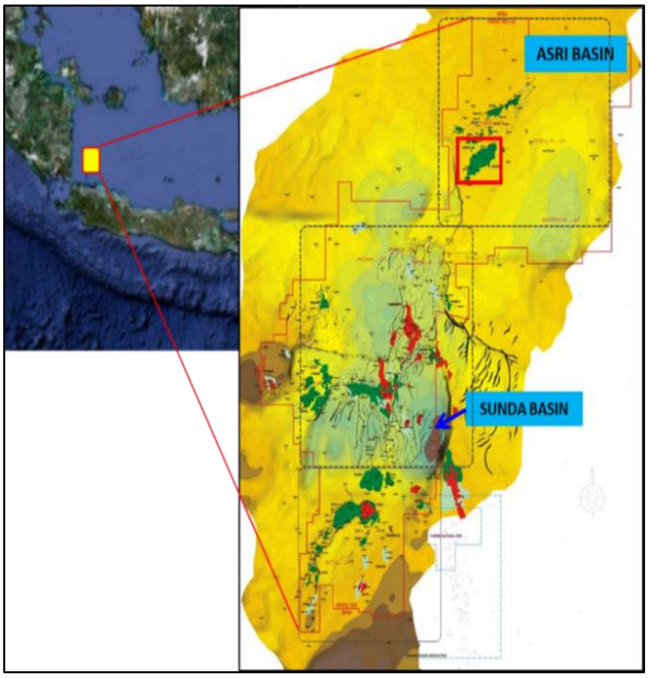

Figure 1. Location map of Wida field in Asri Basin northwestern of Jakarta Province (red box boundary).

History and Development of Wida Field

The field was found in April 1988 through exploration well Wid-01 in faulted anticline bounded by horse-tail faults. Before the discovery, Inta field which is located approximately 10 km northwestern from Wida field were drilled in 1987 and encountered similar reservoirs in faulted anticline with similar horse-tail structure. The similarity of structure between Inta and Wida lead to drilling in the latter structure. Total depth of Wid-01 is 3735 ft and it found 172 feet net pay sandstone in Talang Akar Formation. The well encountered seven separate reservoirs. Five DST tests were carried out with daily rate up to 17.905 BOPD. Fifty development wells were drilled across the field using five platforms and have mapped the area with ± 7500-acre and in place reserves staggering up to 500 million barrels. Peak production reach 30.000 BOPD. In the year of the discovery, Wida field was the biggest oil discovery in Indonesia since 1974.

In late 2000, pressure decline has been observed in 33-4, 33-6, and 34-1 reservoirs. These reservoirs were driven only by solution gas. This was different to lower reservoirs with strong water drive and showed no pressure decline. Laboratory-scale waterflood were conducted and first 4D seismic was acquired to map area with pressure decline. Waterflooding phase I was implemented in 2001 and successfully maintain production from the three reservoirs. Additional reserves from waterflooding phase I were condemned insufficient thus in 2004 the second 4D seismic was acquired. Waterflooding phase II was implemented to drain the bypassed oil from 4D seismic. Now, the field is very mature with number of wells >400. The next development phase is planned to use tertiary recovery method thus static and dynamic model are required to serve as field management tool and help making decision. Before such model is build, reservoir characterization in term of facies, external geometries, depositional environment is required to help in assisting facies modeling stage.

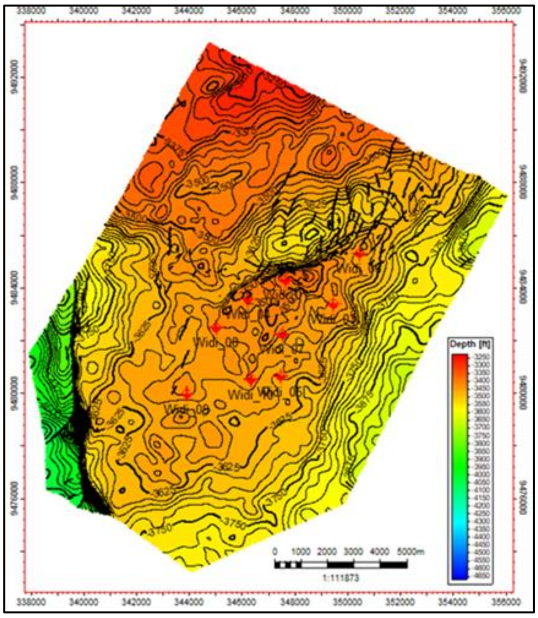

Figure 2. Depth structure map of top reservoir 34-1 depicting anticline structure of Wida field.

Geology of Wida Field’s Reservoirs

Wida field was in northwestern flexure margin of Tertiary back-arc Asri Basin. The field is a broad three-way dip anticline structure divided by fault which show horse-tail form into western and eastern part. The field produced from fluvial-deltaic sediments of Gita Member deposited during late synrift phase. Fluvial-deltaic deposits of Gita Member is main reservoir target in Asri Basin (Zhu et al., 2018). The stratigraphy of Wida field was summarized in Figure 3 (Young et al., 1995). Lower Creteceous metamorphic basement was penetrated only by wells in A-platform. Basement is onlapped and overlain by Zelda Member with lithology composed of sandstone, coal, and shale. The Lower Miocene Gita Member overlay Zelda Member unconformably above with lithology composed of sandstone, coal, carbonate, and shale. The boundary between Zelda and Gita Member is unconformity over most of the Asri Basin. However, at Wida field, the boundary is probably a discontinuity associated with field-wide coal marker namely Coal “A”. The overlying Baturaja carbonate deposited unconformably above Gita Member. Top of Talang Akar Formation is a high gamma ray marker associated with an unconformity.

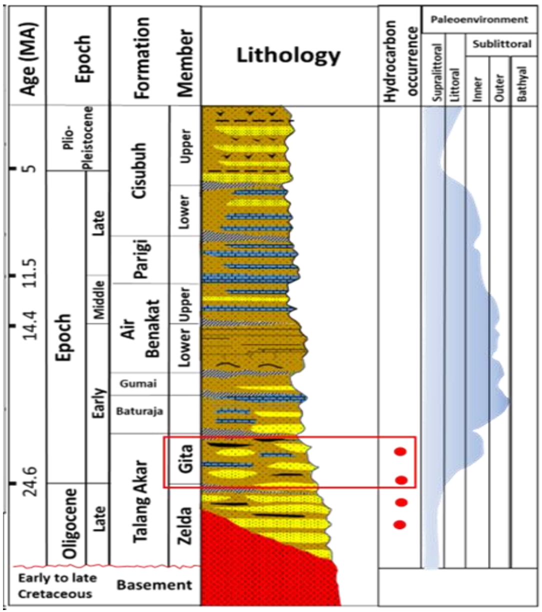

Figure 3. Statigraphy of Wida field (Young et al., 1995). The red rectangle shows Gita Member which has reservoirs under study.

Wida field has seven separate reservoirs from oldest to youngest. These are 36-1, 35-2, 35-1, 34-2, 34-1, 33-6, and 33-4. The fluvial body geometry showed gradual change from braided fluvial channel in lower reservoirs to meandering channel toward top. Stratigraphy of Talang Akar reservoirs in Wida field was summarized in Figure 4 (Carter, 2003). 36-1 sandstone is the lowermost reservoir. The reservoir is dominated by coarse grained sandstone, sheet-like, multistorey, and multilateral braided fluvial deposits. Oil was trapped in structural attic without stratigraphic component. In Wida-01 exploration well, the sandstone lies unconformably above metamorphic basement. The sandstone is thick. The base of the reservoir shows erosional contact, while the top shows a distinct contact with rootlet siltstone and coal indicating floodplain deposits. The sand grains are coarse to very coarse, with sedimentary structures predominantly is through cross-bedding. The gamma-ray log character exhibits a thick blocky pattern with boundaries between individual sandstone units difficult to ascertain due to both vertical and lateral amalgamation.

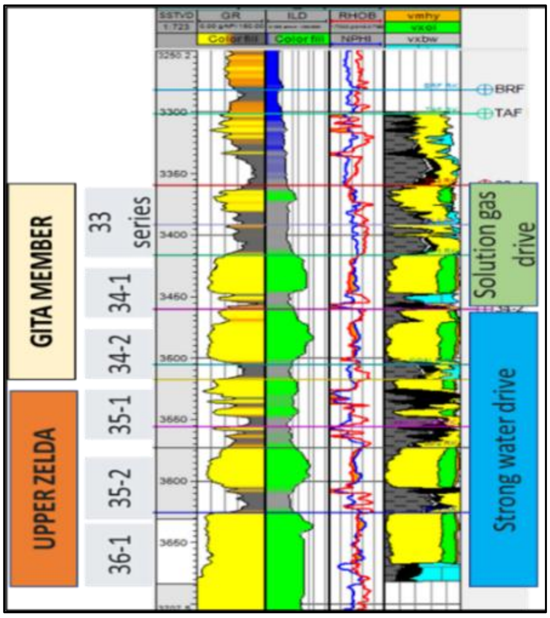

Figure 4. Stratigraphy of Wida field's reservoirs based on Wida A-01 well (modified from Carter, 2003). The sheme was modified by adding reservoir's drive and using mulitmineral log instead basic logs. Reservoirs under study are solution gas drive wiht low reccovery factor while lower reservoirs are strong water drive with high recovery factor.

35-2 sandstone overlay conformably above 36-1 and is separated from 36-1 by deposits of mudstone, siltstone, and coal. 35-2 sandstone exhibits similar characteristics to reservoir 36-1, but there are some differences, such as slightly finer grain size (coarse to medium) and greater variability. Sedimentary structures are predominantly characterized by through cross-bedding. The layer contact is sharp (abrupt), indicative of multistorey and multilateral stacking. Isopach net maps of sandstone beds show smaller thickness and a narrower extent compared to reservoir 36-1.

Reservoir 35-1 deposited conformably above reservoir 35-2 and is separated by floodplain deposits consisting of mudstone, siltstone, and coal. At its base, this reservoir exhibits an erosional surface, sedimentary structure is dominated by through cross bedding, medium to fine grain size with finer grain size compared to 36-1 and 35-2. The multistorey character is marked by several erosional contacts in the middle part of the sandstone.

Reservoir 34-2, situated above reservoir 35-1 and separated by a regional coal marker, displays a basal section with an erosional contact believed to have caused thinning of coal in some wells (Carter, 2003). The dominant lithology is quartz sandstone with sedimentary structures predominantly characterized by trough cross bedding. The sand grain size ranges from medium-coarse at the base to fine sandstone with mudstone lamination towards the top (Young et al., 1995). Net isopach maps indicate a narrower lateral distribution compared to reservoir 35-1. The interpretation of a meandering fluvial reservoir is not applicable, but it also cannot be fully categorized as a sheet sandstone deposited in a braided fluvial environment because the geometry of reservoir 34-2 is not as massive as units 35-1, 35-2, and 36-1 (Allen, 1965).

Reservoir 34-1 is conformably deposited above the 34-2 reservoir unit. Sedimentological studies of core rock reveal that the reservoir lithology consists of fine-grained sandstone with excellent sorting, exhibiting a general fining-upward log character. Planar tabular cross-bedding sedimentary structures are common, but towards the top, they transition to laminations of parallel ripple and wavy bedding. Coal laminations and intense bioturbation are found at the upper part of this unit. Core rock samples from wells Wid-01 and Wida B-08 reveal sporadic occurrences of mud drapes sedimentary structures from middle to top, indicative of tidal influence. Above the reservoir, there are carbonate-rich rocks rich in shell fragments and carbonate mudstones forming a transgressive lag. This records a period of shallow marine deposition (Armon et al., 1996). The sandstone morphology from seismic attributes as seen in Figure 5, log character, and core sedimentological analysis indicates that reservoir 34-1 is a meandering single-story distributary channel deposit influenced by tides(Young et al., 1995)

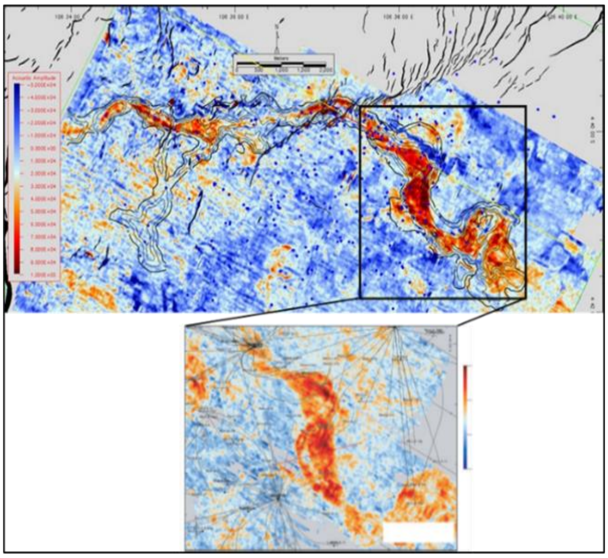

Figure 5. Sesmic amplitude attribute of 34-1 sandstone shows meandering channel with point bar development seen as ampliutde band (Carter, 2003)

The 33 series (33-6 and 33-4) consists of a series of reservoirs that occupy slightly different stratigraphic positions but are often found together. Seismic attributes at the same horizon encompass numerous 33 series channels, but well correlations show slightly different stratigraphic positions due to tuning thickness. The 33 series sandstones have a lithology of fine to very fine sandstone with a well-defined base, planar tabular cross-bedding sedimentary structures,

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thicker and more frequent mud drapes. Above the sandstone frequent laminations of carbonate mudstone are encountered. The log character shows fining upward pattern which is consistent across the field. The thickness of this reservoir is relatively thin compared to older reservoirs. Seismic attributes show a highly sinuous meandering fluvial distributary channel shape. Core data indicates an increasingly intensive tidal influence characterized by more frequent carbonate fossils and bioturbation structures upwards in the reservoir. The upper part of this unit contains shallow marine transgression deposits in the form of carbonate rocks, which have many fragments of carbonate organism shells and carbonate mudstone. The depositional environment interpretation is a distributary channel (Young et al., 1995) and point bar associated with a highly sinuous meandering fluvial distributary channel (Smith et al., 1996). Reservoir 33-4 is separated from 33-6 by a carbonate streak, mudstone, or carbonaceous siltstone. This reservoir shows similar characteristics to the 34-1 unit, but with a stronger indication of tidal influence. Reservoirs 33-4 and 33-6 exhibit highly sinuous meandering channel geometry and the development of scroll bars, clearly visible in seismic attribute as seen in Figure 6 and Figure 7.

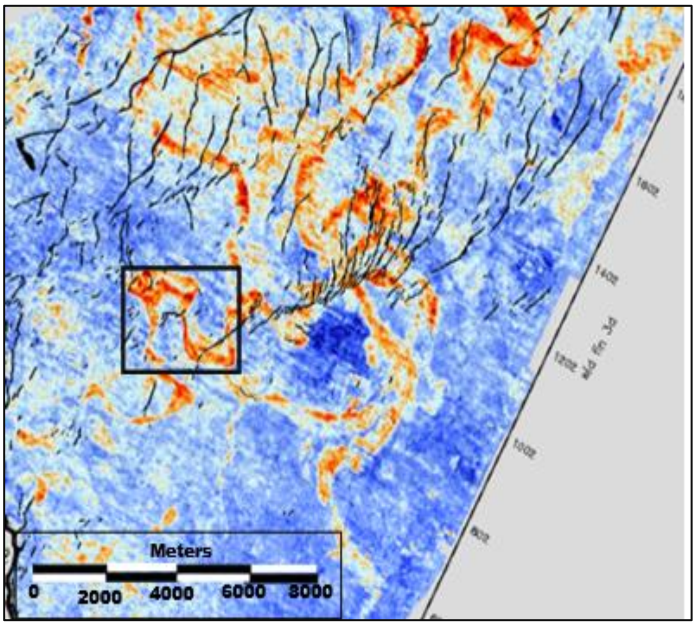

Figure 6. Seismic amplitude attribute of 33 series sandstone. Many 33 channels are imaged at same horizon attribute due to insufficient thickness although these channels have slightly different stratigraphic position (Carter, 2003)

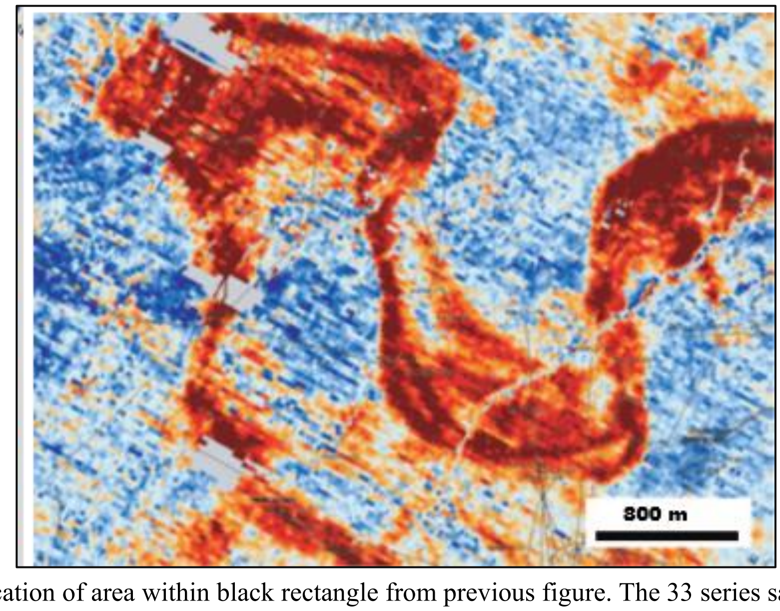

Figure 7. Magnification of area within black rectangle from previous figure. The 33 series sandstone’s point bar development is clearly imaged as amplitude band (Carter, 2003).

METHOD

Data

Four (4) full diameter core are available from Wid-01, Wida-B10, Wida-B08, and Wida-C02. Among these wells, only Wid-01 exploration well has full diameter core representing 36-1 to 34-1 sandstone. Core for 33-6 sandstone is available in Widi B-08 well. Core for 33-4 sandstone is not available and characteristics of 33-4 sandstone is regarded more or less similar to 33-6 sandstone. 33-6 and 33-4 sandstone are frequently found together in Wida field and surrounding field. The full diameter core forms the basis for sedimentological analysis. Additional data from these cores are available such as biostratigraphy, petrography, and SEM. Petrophysical multimineral logs include shale volume, porosity, water saturation, and mineral composition are available in 104 wells and have been quality controlled previously.

Table 1 summarized key wells data availability used in this research for sedimentological study while Table 2 summarized data availability for field wield data such seismic attribute, stratigraphic markers, and wireline logs. All data are proprietary of PT. PHE OSES and used here under confidentiality agreement. All data listed in the Table 1 and Tale 2 are secondary data while the primary data resulted from this research are sedimentological analysis such as lithofacies, facies association, and depositional environment maps which were translated into discrete facies log (vertical trend) and facies probability maps (horizontal trend) for facies modeling in facies modeling stage.

Table 1. Key wells data availability.

No	Data / Well	Widi-01	Widi-B8	Widi-B10	Widi-C2
1	Full Diameter Core	3507’-3769’	4380’-4580’	4440’-4503’	3382’-3941’
2	Core Photo	✓	✓	✓	✓
3	Petrography	3509’-3768’.	-	4440’,4445’, 4452’,4457.4’, 4461’,4468’, 4474’,4478’, 4486’, 4501’	3889.5’, 3893.8’, 3899.7’,3908.5’, 3918’, 3939.4’
4	SEM	3509’-3746’	-	-	
5	Palynology	3509.5’, 3533, 3538’, 3541.5’, 3592’, 3617’, 3640’, 3689’, 3708’, 3744’, 3751’.	4388.7’-4475’,4520’, 4589.3’.	4440.4’- 4520’	3914.7’-3937.3’
6	Foraminifera	1470’-3820’			3914.7’-3937.3’
7	Wireline and Multimineral Log	✓	✓	✓	✓
*	Reservoir units	34-1 to 36-1	34-1 to 35-1	33-6 to 33-4	33-6 to 33-4

Table 2. Field wide data availability

No	Data type	Availability remark
1	Seismic attribute thickness maps	1 map for 34-1, 1 map for 33-6, 33-4. Already in thickness depth domain
2	Stratigraphic markers	Include some wells in Wida field and surrounding fields such as Inta, Inda, and Aida
3	Wireline logs	All wells in Wida field and surrounding fields. Already environmentally corrected.
4	Multimineral logs	103 wells. Logs include shale volume, porosity, water saturation, and etc.

Methods

This research is part of an attempt to build static model for the three reservoirs especially in the facies modeling stage. The main method employed in this research is describing cores from key wells in Table 1. Core sedimentological analysis is integrated with wireline logs, petrophysical logs, petrography, seismic attribute, and biostratigraphy to understand lithofacies, facies association, and finally depositional environment. Firstly, the full diameter cores were used to determine lithofacies and examined sedimentary structure along with other characteristics. The lithofacies were then grouped to facies association. The description encompasses both primary and secondary sedimentary structures, sediment grain size, sorting, and the presence of fossils or bioturbation. Additionally, petrographic analysis is undertaken to better understand reservoir characteristics. Petrographic analysis involves the identification of constituent minerals (matrix and major grains), percentage composition of minerals, grain shape, sorting, diagenetic processes, porosity, and other components such as fossils, carbon content, etc. SEM and XRD analysis results from petrography samples were also included to better understand sandstone character. Palynology and foraminifera result analysis were used to further help in determining depositional environment. The facies analysis from key wells is used to create discrete facies log.

Next, wireline logs and multimineral logs were used to help pick stratigraphic markers, determine facies (discrete log) in un-cored wells, and well correlation. For well correlation, stratigraphic markers for some wells in Wida field and surrounding field are used and quality controlled. For wells with no stratigraphic marker, existing stratigraphic markers were extended (picked). Therefore, stratigraphic markers are available for all wells in Wida and surrounding fields. Facies discrete log, stratigraphic markers, and seismic attribute thickness maps of 33 series sandstone and 34-1 sandstone were combined to create facies pie chart map. The facies pie chart maps were then used to delineate reservoir external geometries and create depositional environment maps.

RESULTS

The lithofacies described from core were grouped to facies association. The lithofacies scheme for distributary channel is used in this research (D. Payenberg, 2003). Other lithofacies found in this research not included in the research are named accordingly.

Delta Distributary Channel Facies Association

This facies association serves as the reservoir in the Wida field. It consists of lithofacies planar tabular cross bedding sandstone (Sp), mud drapes sandstone (Sd), and wavy-ripple sandstone (Sr) at the top section of the reservoir. Both 34-1 and 33 series sandstone show distinctly sharp contact with underlying lithology. Lithofacies Sp only occurs in 34-1 sandstone while lithofacies Sd occurs both in 34-1 and 33 series sandstone. The 34-1 sandstone is medium to fine grain, moderately well sorted sand, friable to lose, and good visible porosity. The core is oil stained with brown to yellow color when examined under UV microscope. Within 34-1 sandstone frequent coal and shale rip up clasts are found having size of granule to pebble parallel to cross bedding direction. Planar tabular cross bedding occurs in the lower section while moving upward, mud drapes sandstone becomes more dominant. Mud drapes often occur as couplets. No bioturbation is found in lithofacies Sp and Sd. The cross-bedding structure is indicative of unidirectional traction current. Associated mud drapes couplet is dark grey color alternating with cross bedding. Mud drapes deposited trough suspension fall out during slack water periods (Reineck and Singh, 1980).

Wavy-ripple lamination fine grain-very fine grain sandstone occur at top 34-1 and 33-6 reservoir associated with mud drapes sandstone. Locally carbonaceous lamina with black color is preserved. Thalassinoides or Teichichnus type burrow structures occurred in this lithofacies with near vertical to random in orientation. Low-diversity and high-density occurrences of Teichichnus characterize marginal-marine (paralic) environments with reduced salinity (brackish water) and oxygen (Knaust, 2018).

33-6 sandstone show slightly different characteristics from 34-1 sandstone. In core, 33-6 sandstone shows more frequent and thicker mud drapes than 34-1 sandstone. The structure is found throughout 33-6 sandstone core while in 34-1 sandstone core mud drapes structures occurred from middle to top reservoir. The grain in 33 series sandstones is also finer, sortation also is better than 34-1 because no channel rip-up clast is found. Furthermore, no cross bedding is found or at least not identified as clearly seen as 34-1 sandstone even though there is indication of occurrence of low angle cross bedding. The top reservoir in core coincides with top of oil saturation. At the top, lithofacies is composed of ripple

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lamination sandstone with bioturbation probably from Thalassinoides and Ophiomorpha. Therefore, 33 series sandstone showed tidal effect which is more intense indicated by more sporadic mud drape structure occurred in couplet throughout sandstone unit. Abundance of mud drapes toward top of reservoir and bioturbation indicate the increasing influence of shallow marine and tidal effects on the Wida Field, as the depositional environment consists of a distributary channel system near marine environment in lower delta plain (Young et al., 1995). Wavy-ripple lamination and bioturbation at top of the reservoir may indicate abandonment phase of channel. Overall, the wireline log of this facies association shows a fining upward pattern with some blocky pattern at the base of channel. Porosity log shows high value and water saturation is low. The sandstone is clean sandstone and has low shale volume as shown by multimineral log.

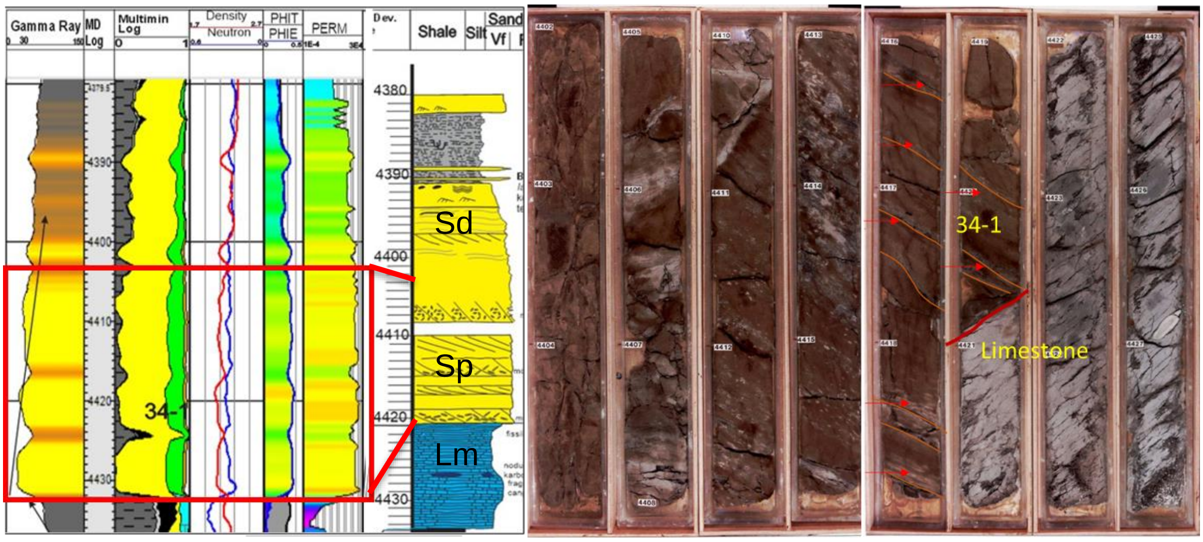

Figure 8. Core of Wid-B08 showing planar tabular cross bedding (orange line) and erosional contact (red line) between sandstone 34-1 and the underlying skeletal limestone (Lm). The cross bedding plunge to the right of core photograph. Numerous rip-up shale clasts and coal were observed, oriented parallel to cross bedding indicative of ancient flow direction (orange lines).

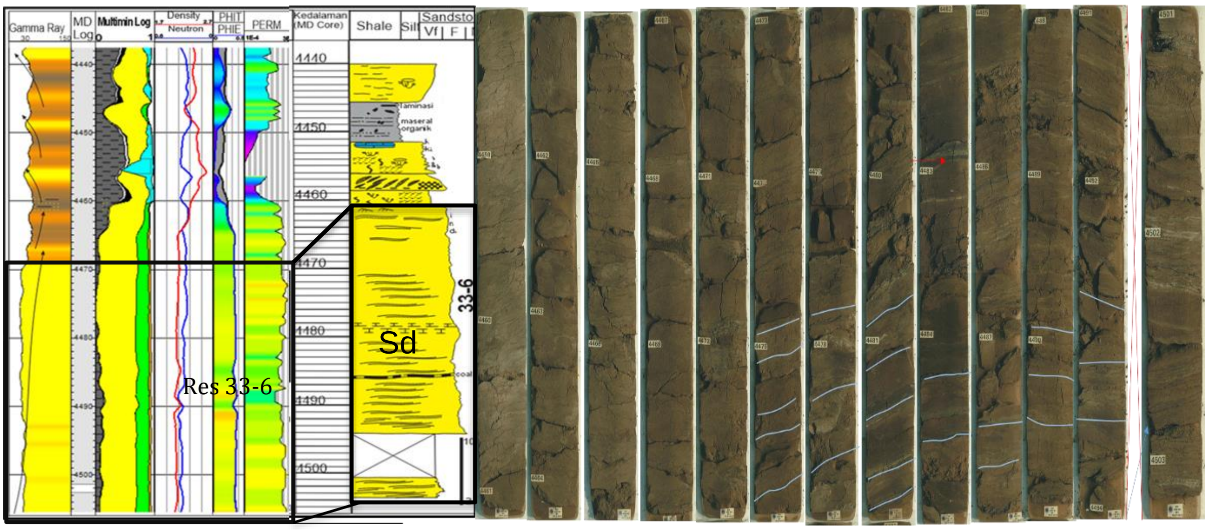

Figure 9. Core of Wida-B10 shows lithofacies mud drapes sandstone (Sd) of 33 series sandstone (black rectangle). The mud drapes structure are observed from the bottom to the top and is more pronounced in the 33 series sandstone compared to the 34-1 sandstone.

Shallow Marine Facies Association

This FA consist of skeletal limestone (Lm), calcareous mudstone (Fc), and calcareous sandstone (Sc) as seen in Figure 10 and Figure 11. This facies association has distinctive characteristics such as high diversity and high amount of calcareous fossil fragments from various fauna including platy corals, red algae, large benthic foraminifera, mollusks, and echinoderms. This lithofacies is non reservoir quality.

Based on core Wid-01, Wida-B08, and Wida-B10 it is found below sandstone 34-1 and above 33-6 (Sc) (between sandstone unit). In Wid-01 the limestone is skeletal mudstone-wackestone to calcareous mudstone underlying sandstone 34-1. The limestone is grey mixed with dark brown. It grades from limestone into calcareous shale which shows fissility in some parts. Fossil is highly fragmented and hard to identify species. The fossil is well oriented near parallel to bedding. The bed thickness is relatively thin.

Calcareous sandstone found above 33 series sandstone in Wida-B10 is very fine grain sandstone, moderately sorted with few flat shale clasts. It has numerous large foraminifera Leptocyclina sp up to 3 cm long which show approximately horizontally aligned to bedding. It also has a few small mollusks. Horizontal burrows are present approximately 1 cm in diameter. Calcareous concretion also occurred in the top of this unit. In wireline log, lithofacies Lm, Fc, and Sc have distinctive pattern. Coarsening upward log pattern and PEF log are good diagnostic tool as high PEF from 3.5 to 4 value is due to carbonate mineral composition.

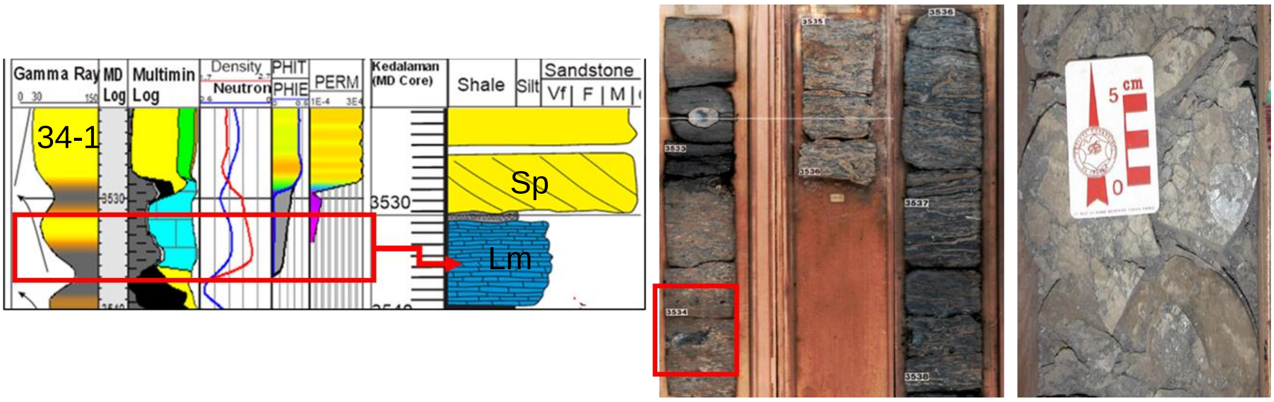

Figure 10. Core Wid-01 showing lithofacies skeletal limestone and calcareous mudstone underlying 34-1 sandstone (red rectangle). Magnification of the core reveals highly fragmented mollusk shell.

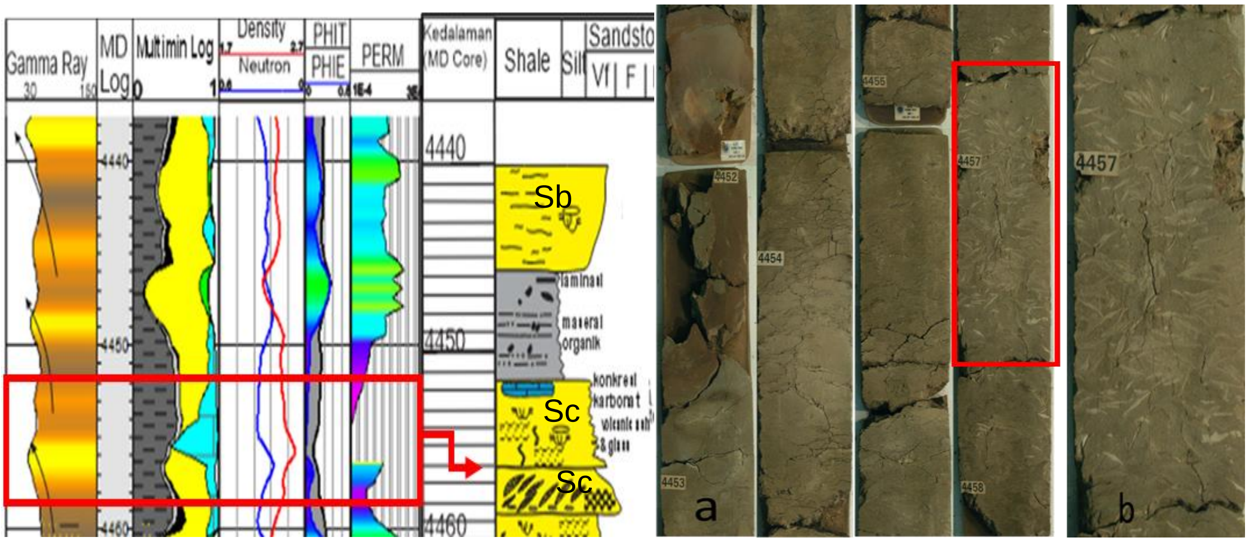

Figure 11. Well Wida B-08 core showing (a) Calcareous sandstone (Sc) above 33-6 sandstone (red rectangle) with abundant shell fragment and calcareous concretion. (b) Magnification of core at **(**red rectangle from figure a**)** 4457' MD reveal very abundant Leptocyclina sp shells up to 3 centimeters.

This facies association is regarded as transgression lag and picked as stratigraphic marker characterized by high abundance of carbonate fossil fragments in relatively thin layers. It records transgression occurred after fluvial-delta sedimentation in each reservoir parasequence thus finalizing paralic sedimentation and subsequently change into shallow marine depositional environment. Bathymetric condition interpreted as deepening upward. These lithofacies also picked as a stratigraphic marker for marine flooding zones. Transgressive lags suggest a sediment-starved environment, as a significant portion of sediments accumulates in terrestrial environments during sea level rise (Zecchin et al., 2019).

Transgressive lag deposits typically consist of mollusk fragments, rip-up clast rock fragments, carbonate or phosphate nodules, gravel-sized siliciclastic clastics, glauconite, and carbonate cement (Cattaneo & Steel, 2003). Fine-grained sediments undergo backwash (Zecchin et al., 2019). These sediment layers are generally thin, although layers several meters thick are also reported (Zecchin et al., 2019).

Swamp Facies Association

This facies comprises of coal (C) grades downward into coaly mudstone with abundant coal material as seen in Figure 12. The coaly mudstone is black in color due to the high organic content. The lithofacies is found beneath the skeletal limestone (Lm) and above interdistributary bay facies association. Both facies association of swamp and interdistributary were encountered concurrently. This indicates that the interdistributary bay sediment as living environment for coal forming vegetation to grow. The coal forming vegetation leave rootlet structure in interdistributary bay deposits. Coal is stratigraphic marker, and it can be correlated across entire field.

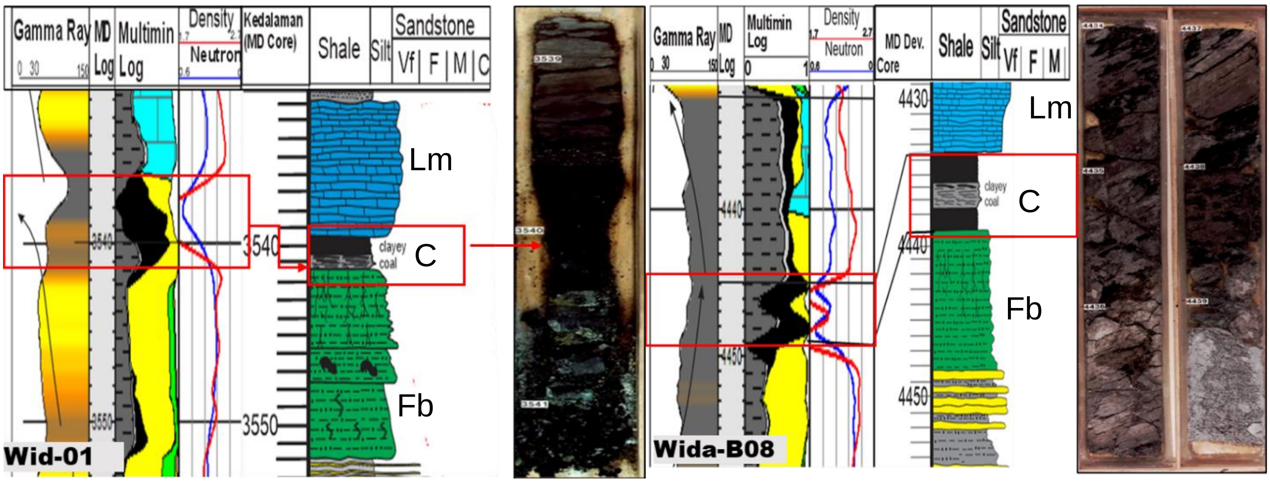

Figure 12. Coal and coaly mudstone lithofacies in (a) core Wid-01 and (b) Wida-B08 lithofacies forming swamp facies association. The coal is found below limestone and above rootlet mudstone indicative of vegetated interdistributary bay which change into swamp environment.

Interdistributary Bay Facies Association

This facies association consists of rootlet mudstone lithofacies (Fb) with some indication of soft sediment deformation structure and interlamination of carbonaceous mudstone with very fine-grain sandstone (Fl) as seen in Figure 13 and Figure 14. The rootlet mudstone is in the upper part while interlamination of carbonaceous mudstone-very fine grain sandstone is situated in lower part. This facies association is found beneath coal and coaly mudstone lithofacies. The sedimentary structures within the sandstone laminae include mud flaser, parallel laminations, and ripple mark. The distinctive features of this facies association include a high content of organic carbon material, presence of plant root structures, and interlamination between fine grain and coarser grain sediments forming a heterolytic unit.

Rootlet structure is indicative of vegetated environment. The wireline log shows serrated log pattern. This facies association is deposited in a tide-influenced interdistributary bay environment. Swamp facies association and interdistributary bay facies association were found concurrently. The indistributary bay provide environment for coal forming plant to grow above creating a swamp environment and lead to rootlet structure on top of rootlet mudstone.

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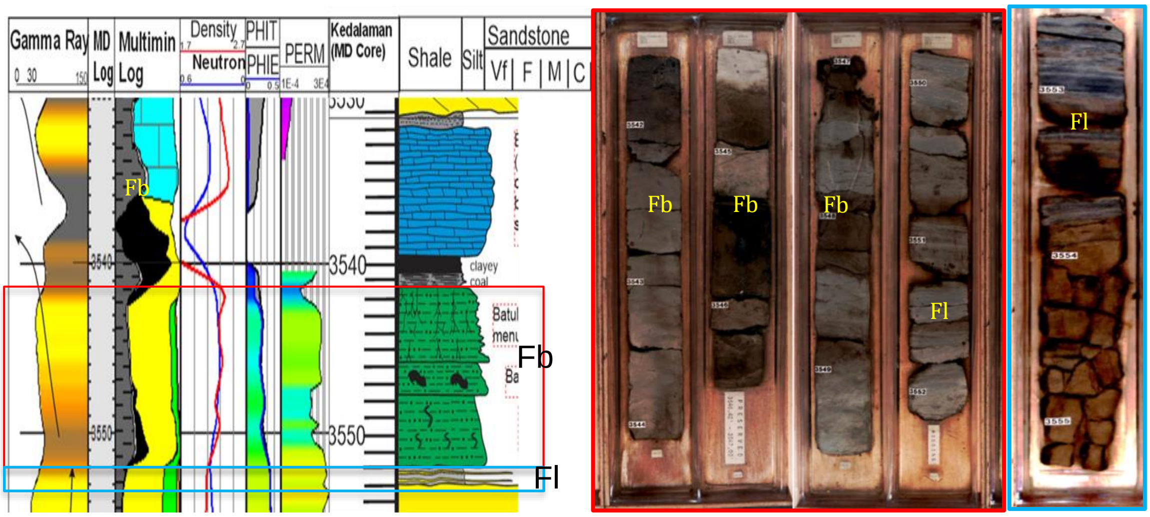

Figure 13. Well Wid-01 showing interdistributary facies association with lithofacies rootlet mudstone (Fb) (red box) above and mudstone interlaminated with very fine-grained sandstone (Fl) below (light blue box). Below this lithofacies is 34-2 sandstone.

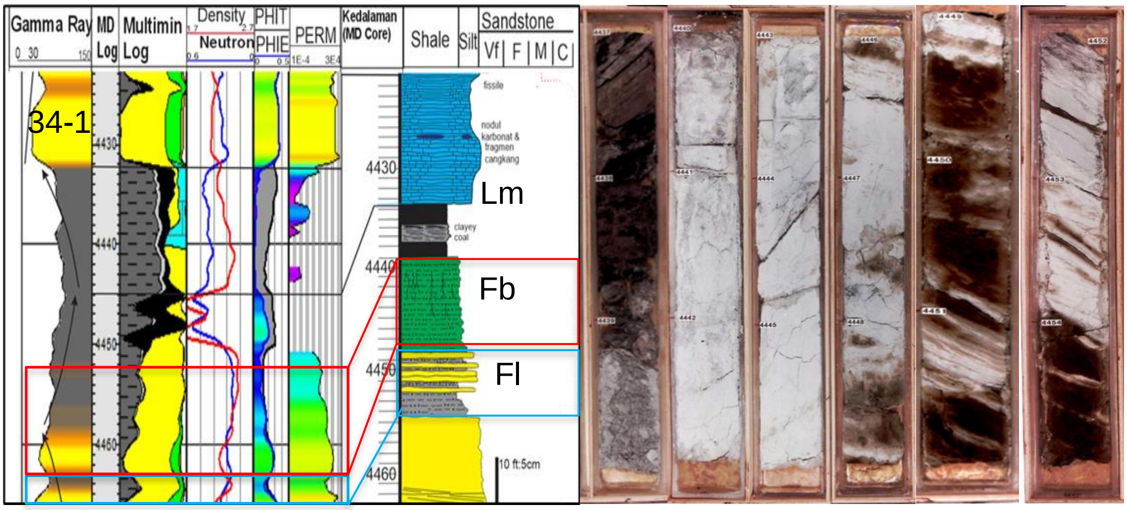

Figure 14. Well Wida B-08 showing interdistributary facies association with lithofacies rootlet mudstone (Fb) (red box) above and mudstone interlaminated with very fine-grained sandstone (Fl) below (light blue box).

Mouth Bar Facies Association

This facies association is found above the distributary sandstone unit. It consists of mudstone-sandstone laminations (Fb) intensively bioturbated that coarsen upward into fine to fine-medium-grained bioturbated sandstone (Fb) as seen in Figure 15. The bioturbation formed pipe like structure, horizontal, diameter 0.5-3 cm filled with fine sand and pyrite cemented. The bioturbations probably are Thalassionoides or Teichichnus. The base of this unit is very poorly sorted, laminated to wavy-bedded, composed mainly of quartz silt/sand and minor coalified plant fragments

Coarsening and thickening upward log pattern correlated with coarsening of sediment grain size in mouth bar toward the top or sandstone unit. The base of the sandstone is somewhat finer than the top part. Vague lamination delineated by orientation of elongate carbonaceous debris with possible minor soft-sediment-deformation. The sandstone is composed mainly of quartz with minor coalified plant fragments. The coalified plant fragments indicate proximity to vegetation source.

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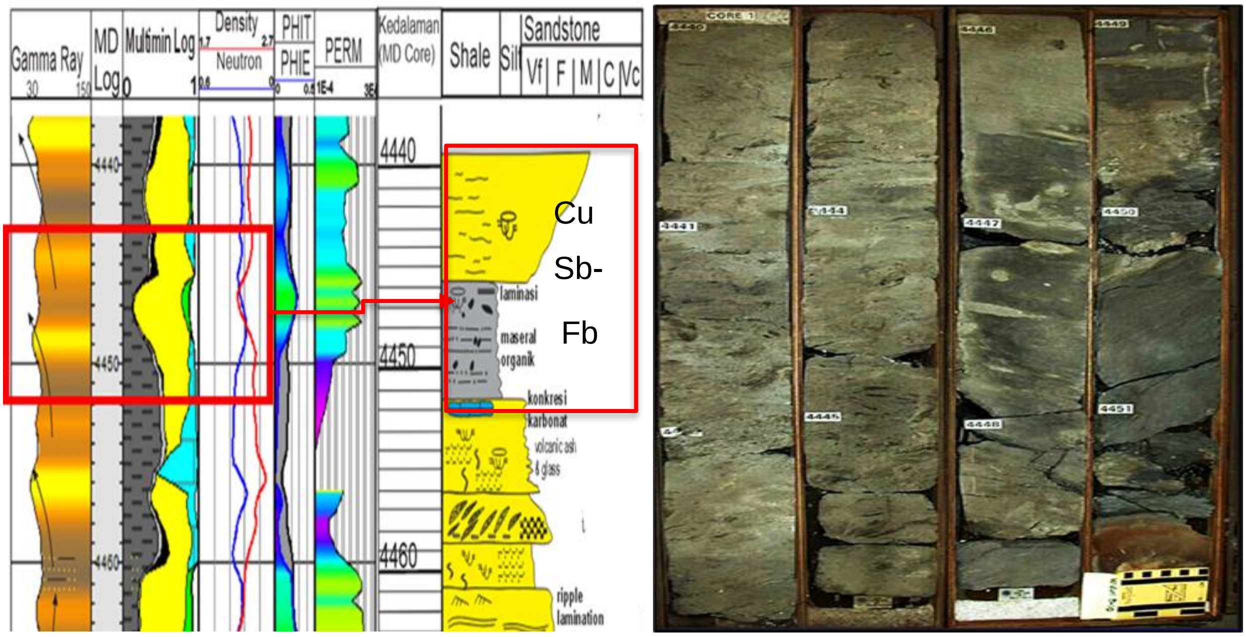

Figure 15. Mouth bar facies association above 33-6 sandstone in core Wida-B10. It consists of mudstone interlaminated with sand layers in lower section grade into bioturbated fine-medium sandstone in upper section.

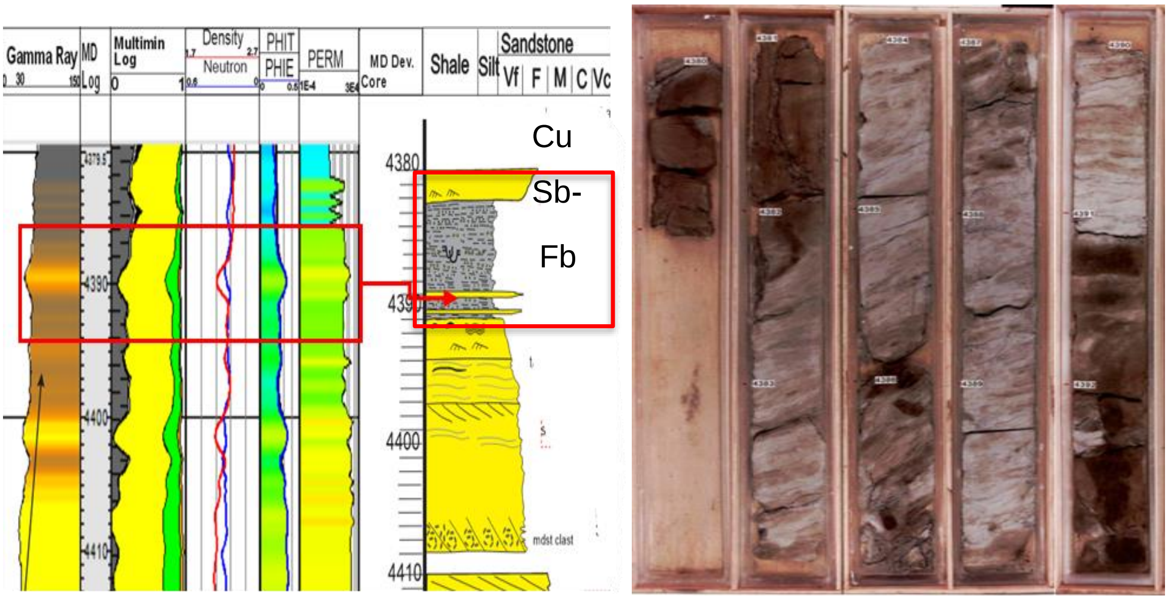

Figure 16. Mouth bar facies association above 34-1 sandstone in core Wida-B08. The unit grades from mudstone interlaminated with sandstone layers to fine sandstone in upper part.

Tidally Influenced Interdistributary Bay Facies Association

The facies association is only encountered in core Wida C-02 occurred in 33-6 and 33-4 parasequence. It consist of lithofacies carbonaceous laminated mudstone with sandstone laminae (Flb) less bioturbated, intensively bioturbated carbonaceous laminated mudstone, finely interlaminated mudstone-very fine grain sandstone (Fl), and black massive fissile carbonaceous mudstone (Fm). The facies association distinctive feature is the regular interlamination of very fine-grained sandstone with mudstone, forming a finely laminated mudstone-sandstone heterolytic deposit. Ripple or lamination structure is frequently observed in the very fine grain sandstone.

Carbonaceous laminated mudstone (Flb) in Figure 17 is less bioturbated and has low to high carbon composition ranging from 10%-30%. The sandstone laminae are olive grey in color and have primary sedimentary structure ripple-wavy lamination. Burrows are low to intensive probably from Planolites sp. filled with silt-very fine sand sediments oriented parallel to bedding. The intensively bioturbated carbonaceous laminated mudstone in Figure 19 is similar to lithofacies in Figure 17 except the bioturbation is more intense and carbonate content is low to moderate from 10%-20%. Finely interlaminated mudstone-very fine grain sandstone (Fl) in Figure 18 is light olive to yellowish gray in color. Minor sedimentary structure occurred such as mud flaser, wavy-ripple. Minor burrows probably from Planolites sp. filled with silt-very fine sand sediments. Moderately abundant coalified plant fragment parallel to laminae. The sandy layer only has minor visible porosity.

Carbonaceous laminated mudstone with sandstone laminae (Flb), intensely bioturbated carbonaceous laminated mudstone (Flb), and finely laminated mudstone-very fine grain sandstone (Fl), form a heterolithic deposit. These lithofacies indicates deposition by alternating traction current and suspension settling. Ripple structures and wavy laminations observed in the sandstone laminae are attributed to the traction of high-velocity flows, while the mudstone layers are formed by the settling of suspended particles during periods of weakened flow or slack water (Reineck & Singh, 1980). High-frequency alternations between mudstone and sandstone laminae are interpreted to reflect cycles of rising and falling tidal currents (Dalrymple et all., 1990). Each mudstone-sandstone couplet records a cycle of diurnal or semidiurnal tidal fluctuations (Archer, Kuecher, & Kvale, 1995). The wireline log for this facies association is serrated indicating alternation of thin sandstone-shale interval. Black shale is high in carbon content (20%-30%) with few very fine grain sandstone laminae as seen in Figure 18. Sedimentary structures in sandstone laminae are ripple-wavy lamination. Minor burrows occurred probably from Planolites sp. filled with sand sized quartz. Highly carbonaceous black mudstone is the result of deposition in quiet environments, such as overbank, channel abandonment, or delta front-prodelta settings.

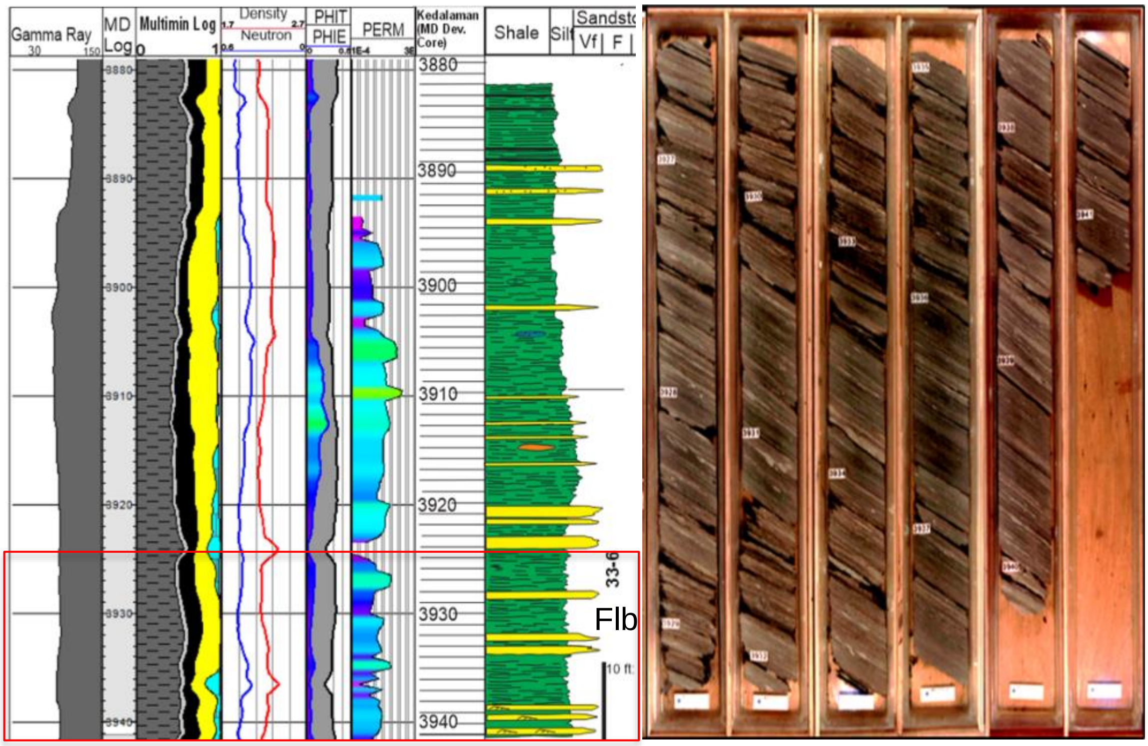

Figure 17. Well Wida C-02 showing carbonaceous laminated mudstone with sandstone laminae (Flb) less bioturbated and high carbon composition 10%-30%. The lithofacies found in the base of the core.

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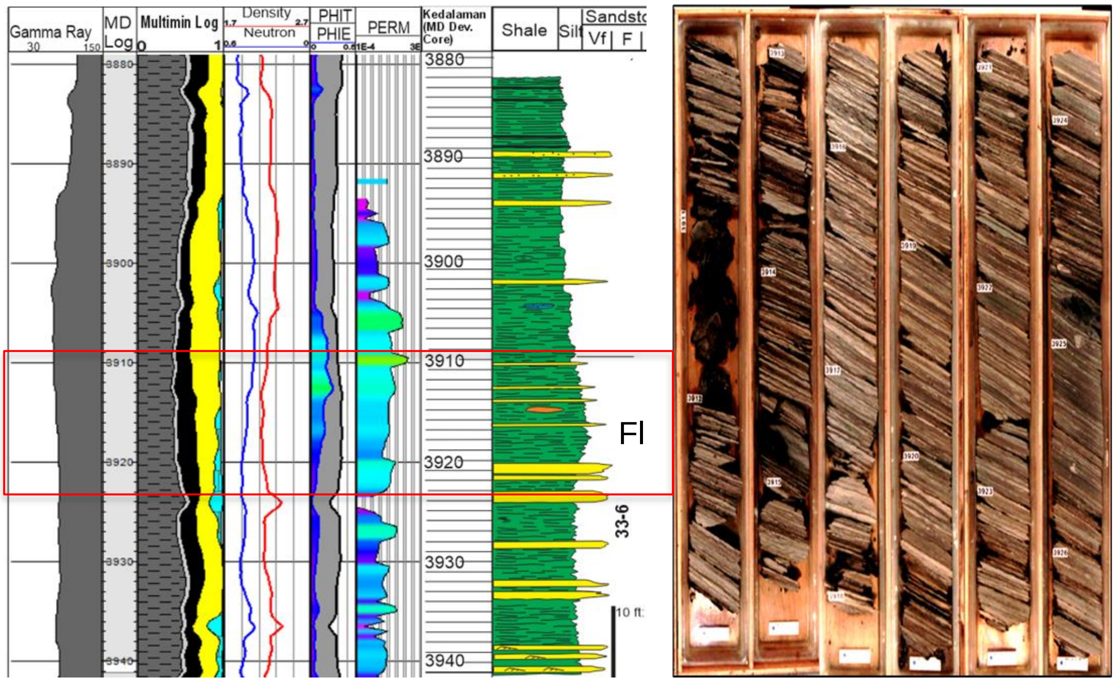

Figure 18. Well Wida C-02 showing finely interlaminated mudstone-very fine grain sandstone (Fl). The alternation of mud and sand layers in this lithofacies is more frequent and thinner than in carbonaceous laminated mudstone below and above indicating more intense tidal effect.

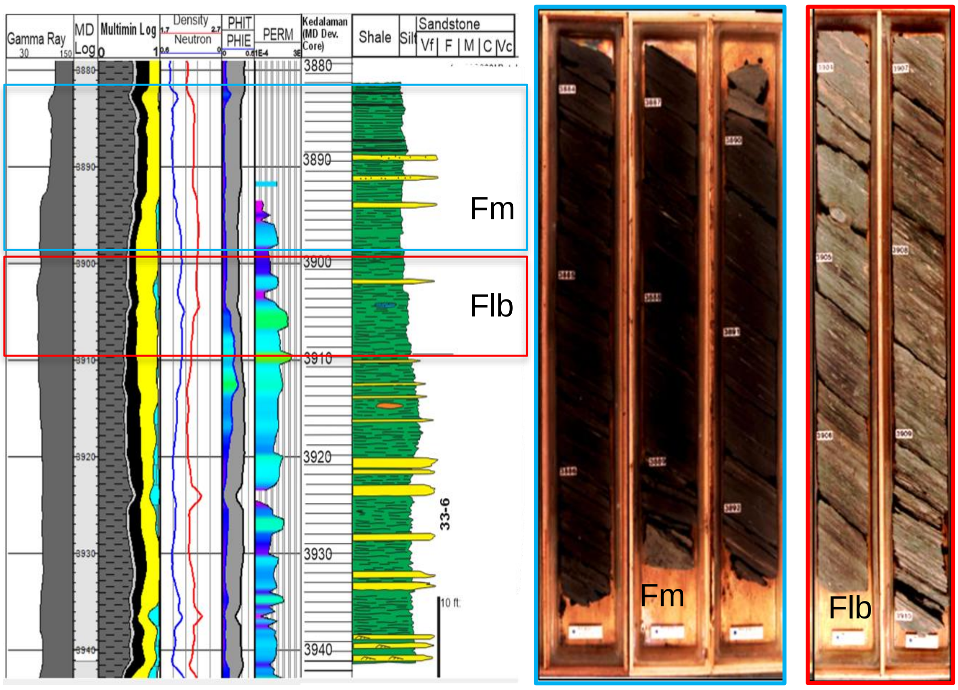

Figure 19. Well Wida C-02 showing black carbonaceous shale (Fm) high in carbon content (light blue box) and intensively bioturbated carbonaceous laminated mudstone (Flb) with medium carbon composition (red box).

Petrographic Examination

Petrographic observations for 34-1 reservoir are based on Wid-01 exploration well. It was taken from 3515’, 3520’, and 3530’ MD. These samples revealed that the sandstone exhibits excellent sorting, subangular to subrounded grain shape, and the framework dominated by quartz. Grain-to-grain contacts are dominantly characterized by floating contacts, with minor clay matrix and cement occurring infrequently as minor components. Floating contacts suggest low compaction and lithification levels, resulting in loosely packed intergranular highly visible porosity. Pore throats are wide and interconnected without internal barriers within the rock pores as seen in Figure 20 to Figure 21. Three samples analyzed are quartzarenite.

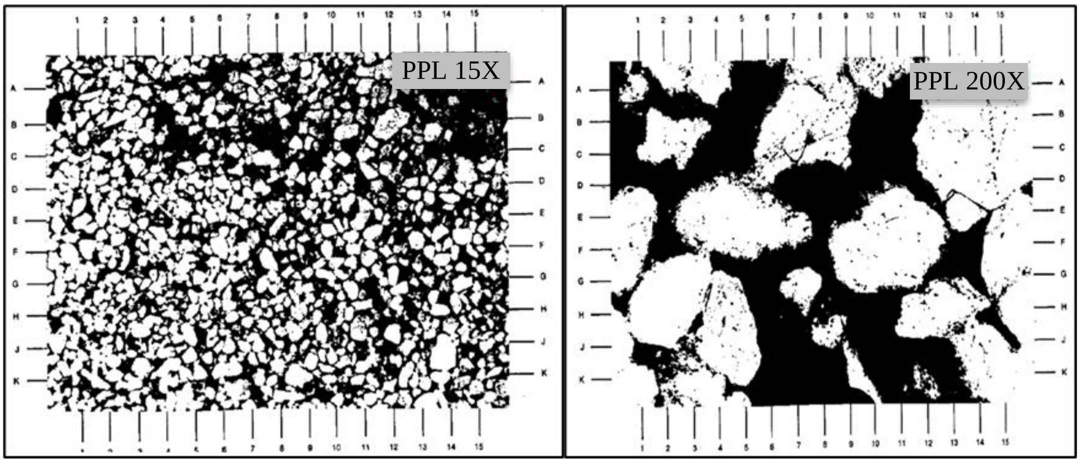

Figure 20. Petrographic thin section of sample 3520' Widi-01 34-1 sandstone reservoir. 15x PPL magnification reveals fine to very fine-grained sandstone with excellent sorting, subangular-subrounded subangular-subrounded rounded grain roundness, friable texture, and a framework grain dominated by quartz. PPL 200x examination showed floating contact and wide interconnected pore throat.

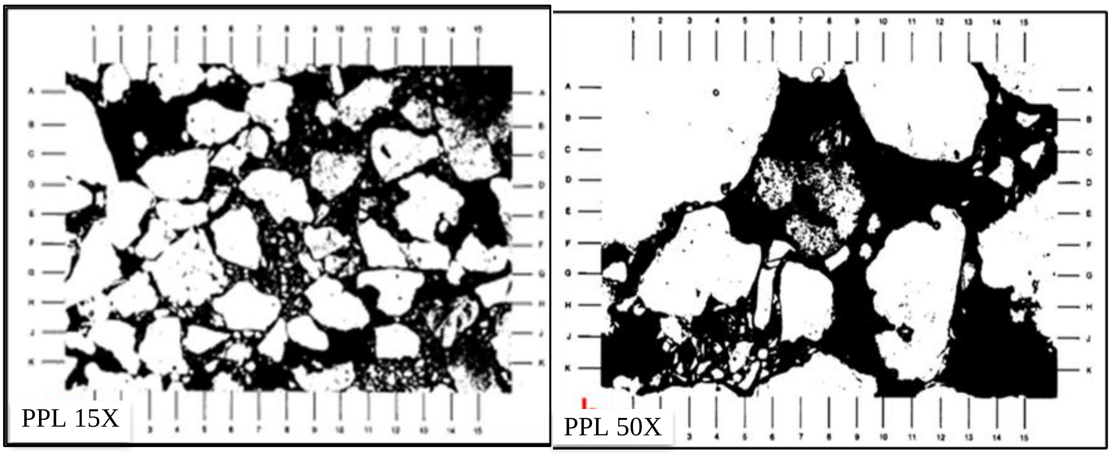

Figure 21. Petrographic thin section of Widi-01 sample 3530' 34-1 sandstone reservoir. 15x PPL magnification showed the framework grain is dominated by quartz minerals with excellent visible porosity. Matrix is notably sparse, and the grain arrangement appears loosely packed. 200x PPL showed wide pore throat and interconnected porosity.

Petrographic analysis of mud drapes sandstone for 33 series sandstone reservoir involves 6 (six) Wida-B10 core samples (plugs) taken from 4461', 4468', 4474', 4478', 4481', dan 4501' MD. One sample is shown in Figure 21. The sixth observation of the mud drapes sandstone lithofacies from 33-6 sandstone indicates the presence of quartz arenite, sublithic arenite, and felspathic sublithic arenite with quartz as the dominant framework grains. The average grain size is 0.15 mm (fine sand), exhibiting good to exceptionally good sorting and subangular to subrounded grain shape. Grain-to-grain contacts are of the floating contact type.

The detrital quartz mineral is of a composite type with a source originating from gneiss/schist. Other framework components include orthoclase, microcline, plagioclase, muscovite, zircon, tourmaline, chert fragments, and mudstone fragments. Intergranular porosity predominates, averaging 35%, with a small amount of moldic porosity. The detrital quartz source is interpreted to be from metamorphic basement rocks that were elevated during deposition. Cement is present in minor amounts, and in some samples, there are traces of quartz cement on mineral surfaces. This cement does not bridge grain-to-grain contacts and does not block pore throats. The rock exhibits a friable-loose compaction, indicating the absence of early cementation and insignificant compaction effects of burial.

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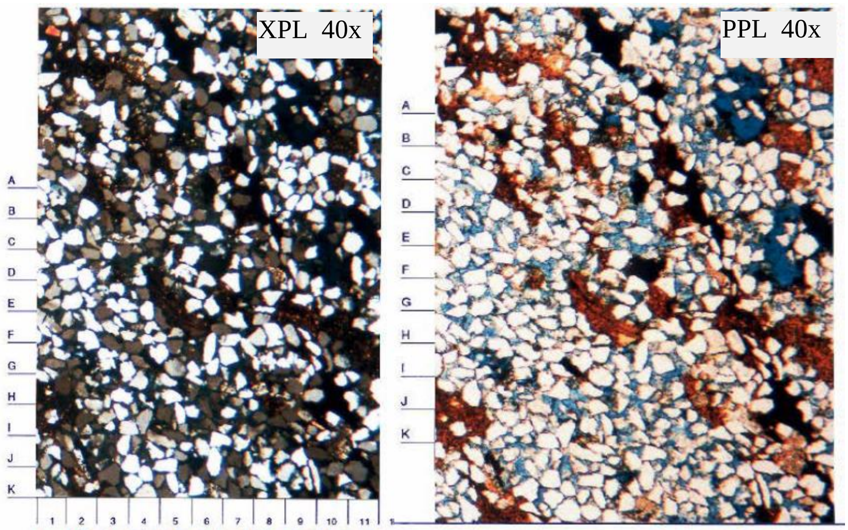

Figure 22. Petrographic section of Widi B-10 samples 4501'. XPL 40x showed the sample is predominantly composed of quartz (quartzarenite) with some feldspar, rock fragments, and laminated organic material. Blue color in PPL 40x indicates dominance of intergranular porosity with floating contacts. Matrix and cement are rarely encountered.

From petrographic examination and QFL diagram in Figure 23 it can be concluded that 34-1, 33-6 and 33-4 sandstone are mature sandstone consisting of majority quartz arenite with few sublitharenite and subarkose. The sandstone is both mature texturally and compositionally with dominance of rounded well-sorted quartz as framework grains. Mature sandstone commonly deposited in downstream area such deserts, shoreface, or delta. Petrographic examination supports the interpretation of distributary channel origin of these sandstones.

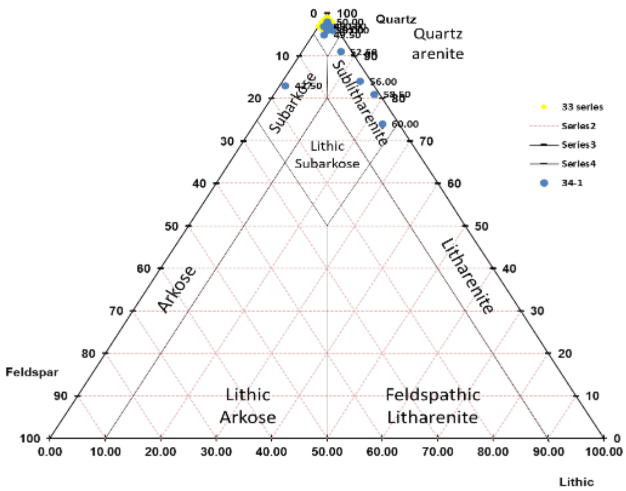

Figure 23. QFL diagram of petrographic sample 33 series and 34-1 sandstone.

Biostratigraphy Analysis Review

Review of biostratigraphic analysis of the sandstone 34-1 lithofacies planar tabular cross bedding sandstone was taken from Widi B-08 core. Samples analysis from depths of 4400'-4420' MD were reviewed. The review found presence of *Zonocostites ramonae, Discoidites borneensis*, and *Pandaniidites sp*. *Zonocostites ramonae* is mangrove pollen (Rhizophora) commonly found in Miocene-Pliocene-aged sediments (Germeraad, Hopping, & Muller, 1968). The pollen characterizes coastal environments, distal delta plains, or lower delta plains influenced by tidal effects, often with salinity ranging between 10-35 ppt (Morley and Morley, 2013).

Review of biostratigraphic analysis of the lithofacies mud drapes sandstone taken from Widi B-10 core, The core analyzed represented 33 series sandstone. The core contained pollen assemblage predominantly dominated by Casuarina spp and

Pandanus spp, indicating paleoenvironment of freshwater coastal environment. The presence of Pandanus spp and Spinizonocolpites echinatus suggests a mangrove-backmangrove environment, likely influenced by the tide (Morley & Morley, 2013). Other mangrove pollen assemblages were found such as Verrucatosporites usmensis and Dicolpopollis sp. Palynological study conclude sedimentation occurred in a terrestrial-transitional environment.

Pie Chart and Depositional Environment Maps

The stratigraphic marker was correlated throughout the entire field and facies were interpreted using discrete facies log. The correlation was helped by seismic attribute thickness available for 34-1 and 33 series reservoirs. The facies pie chart was constructed for the three reservoirs. The pie chart map shows the distribution of distributary channel facies in wells. When seismic attribute was overlaid by pie chart both data will help delineate reservoir external geometry of distributary channel. The depositional environment map can subsequently be drawn from this. Only reservoir units were mapped due to seismic attribute maps for delineating external geometry were only available for reservoirs.

34-1 Cycle Reservoir

The seismic attribute thickness in Figure 24 clearly imaged the main distributary channel in the center of mapped area. It trends west-east. The pie chart also indicates distribution of the distributary channel in wells. Seismic attribute amplitude in eastern part of main 34-1 distributary channel in Figure 25 showed the development of point bar as dimmer amplitude band in some parts than the surrounding point bar for example near Wida-B06. Furthermore, the seismic attribute also imaged small channels southern and northern from the main distributary channel. These small channels are wet. One well, Wida-F08 intersected the southern channel, but it was wet and above regional oil water contact.

The flow of sedimentation can be interpreted confidently from west to east based on the seismic attribute observation (Carter, 2003). The depositional environment map of 34-1 reservoir is distributary channel in origin as seen in Figure 26. To simplify depositional environment based on the potential as reservoir the depositional environment was divided to distributary channel facies association and interdistributary bay/tidally influenced interdistributary bay.

33-6 and 33-4 Reservoir

Seismic attribute thickness in Figure 27 showed many channels were imaged at the same horizon due to tuning thickness of 33 series sandstones. To differentiate between these channels, well correlation was utilized, and pie chart maps of distributary channel facies from wells were constructed as seen in Figure 27. 33-6 and 33-4 channels were seen trending north to south. Similar to 34-1, development channel point bar is clearly imaged in seismic attribute.

In well correlation 33-6 and 33-4 channel sandstone were differentiated based on carbonate streak between the two reservoirs. 33-6 is stratigraphically lower than 33-4 and in seismic attribute image, the channel appears below 33-4. This observation is very obvious in the central part of the mapped area as if 33-6 distributary channel were laid below the imaged 33-4 distributary channel. Similar to 34-1 attribute image, 33-4 distributary channel shows point bar development as amplitude band in areas such as near Wina Platform as shown in Figure 27. In well section, the thickest sandstone correlates to brightest area in the inner bend of point bar for example in Wina-A20 well.

The depositional map of 33-6 and 33-4 reservoir were shown in Figure 28 and Figure 29. These maps were used to construct facies model of 34-1, 33-6, and 33-4 for static reservoir models. Simplification was done where all rocks outside distributary channels were combined to form interdistributary bay deposits/tidally influenced interdistributary bay and where there is indication of shaly sandstone occurrence in this facies association the facies is assigned as heterolytic sandstone. These shaly sandstones are probably sandstone laminae in facies association interdistributary bay/tidally influenced interdistributary bay which were frequently found in core.

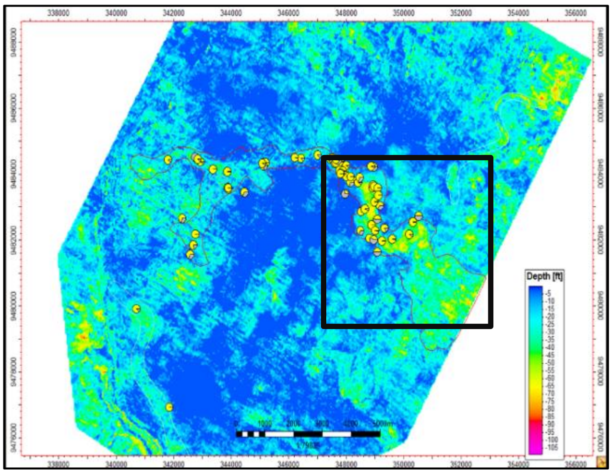

Figure 24. Seismic attribute thickness and pie chart map of 34-1 sandstone showing west-east distributary channel.

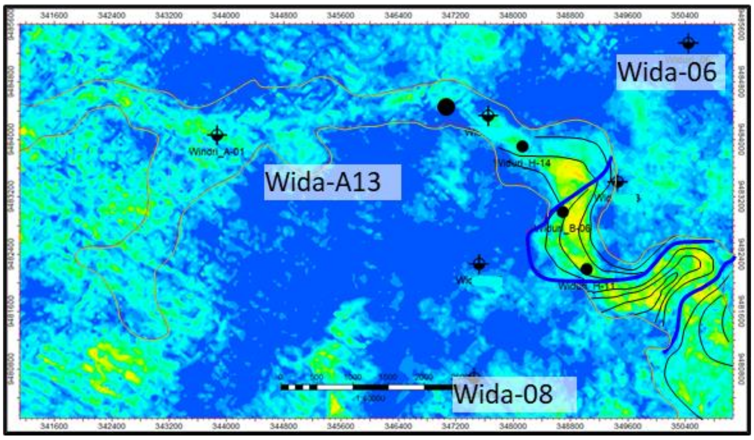

Figure 25. Seismic attibute in eastern part (black rectangle from previous image) of main 34-1 distributary channel showing point bar development and its interpretation.

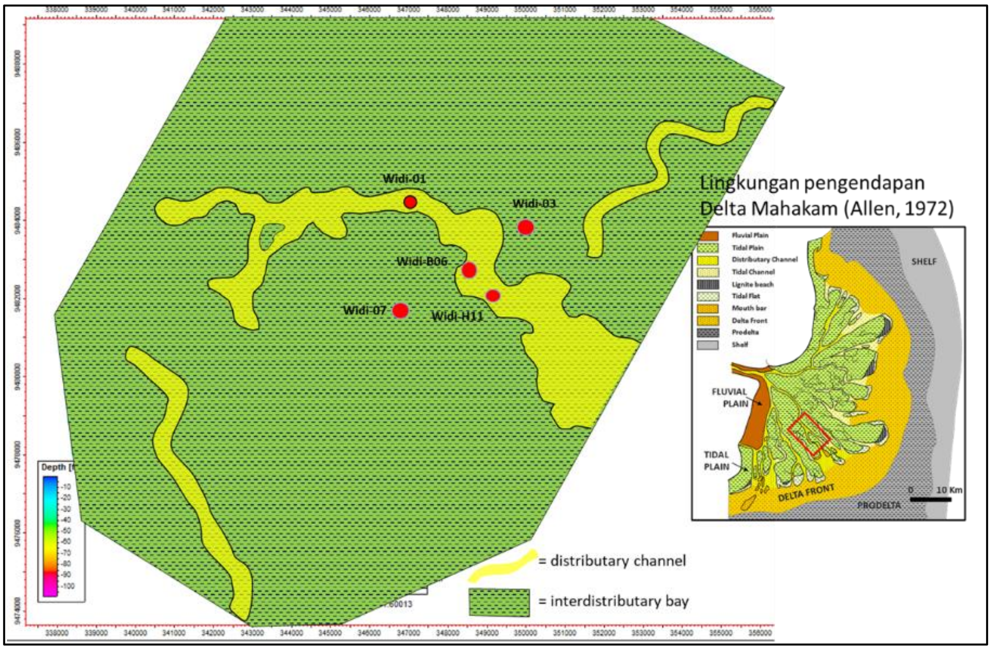

Figure 26. Depositional environment map of 34-1 reservoir. Using Mahakam Delta as modern analog (Allen, 1972), distributary channel interpreted to be deposited in lower delta plain (red box). This single channel is part of larger deltaic channels.

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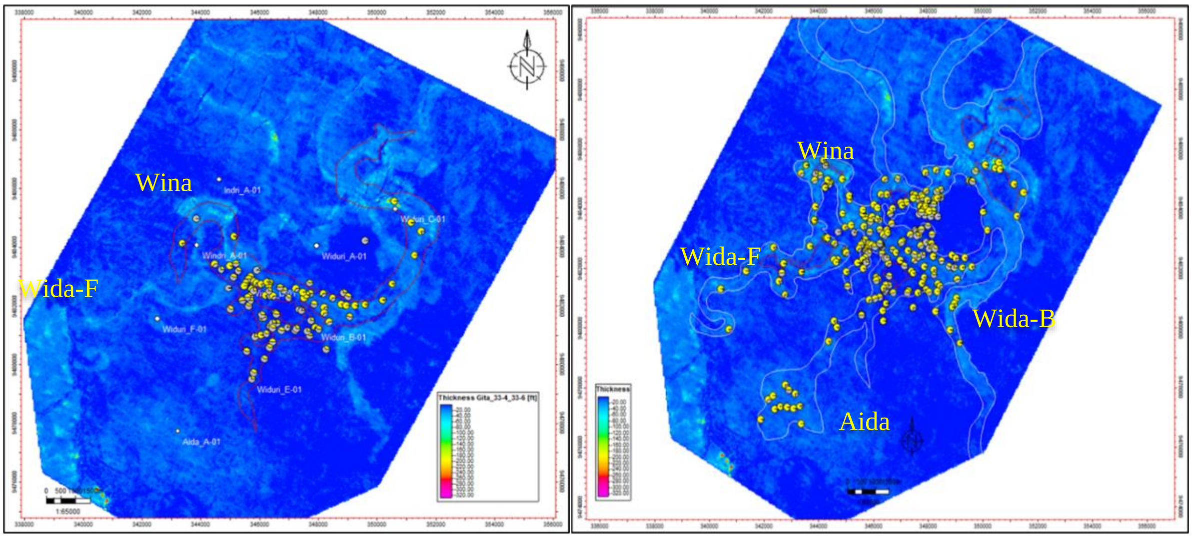

Figure 27. Seismic attribute thickness and pie chart map of 33-6 (left) and 33-4 (right) sandstone reservoir. Both are imaged concurently due to tuning thickness.

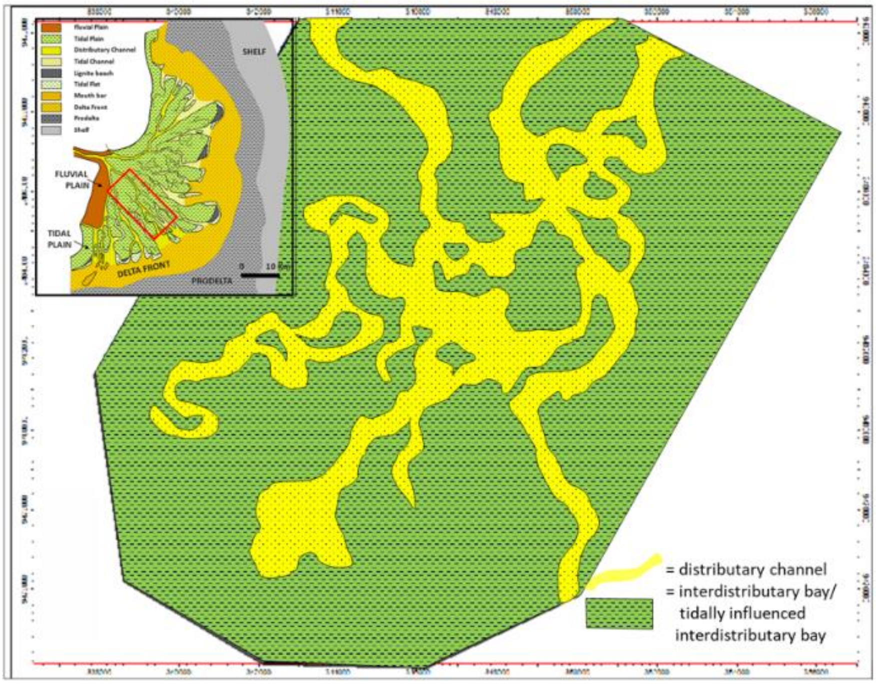

Figure 28. Depositional environment map of 33-6 sandstone reservoir. Mahakam Delta depositional environment as analog (Allen, 1972).The reservoir is interpreted to be distributary channel origin in lower delta plain (red box) and was part of larger deltaic channels.

Well Correlation

Well correlation in distributary channel and its associated facies will show lateral facies change as shown in Figure 26. If transected perpendicular to channel direction facies will change from interdistributary bay/ tidally influenced interdistributary bay deposits dominated by shale having serrated wireline log pattern to interdistributary channel having blocky wireline log pattern in innermost bend part of point bar and gradually change to fining upward. Above distributary channel deposit, clay plug, or abandonment channel deposits sometimes can be found in wireline log. From distributary channel deposits facies change to interdistributary bay again with shale dominated lithology. Crevasses splay may overlay. The wireline log pattern shows a coarsening upward pattern. Mouth bar can also be deposited above distributary channel indicating subsiding delta. It has a coarsening upward pattern as well.

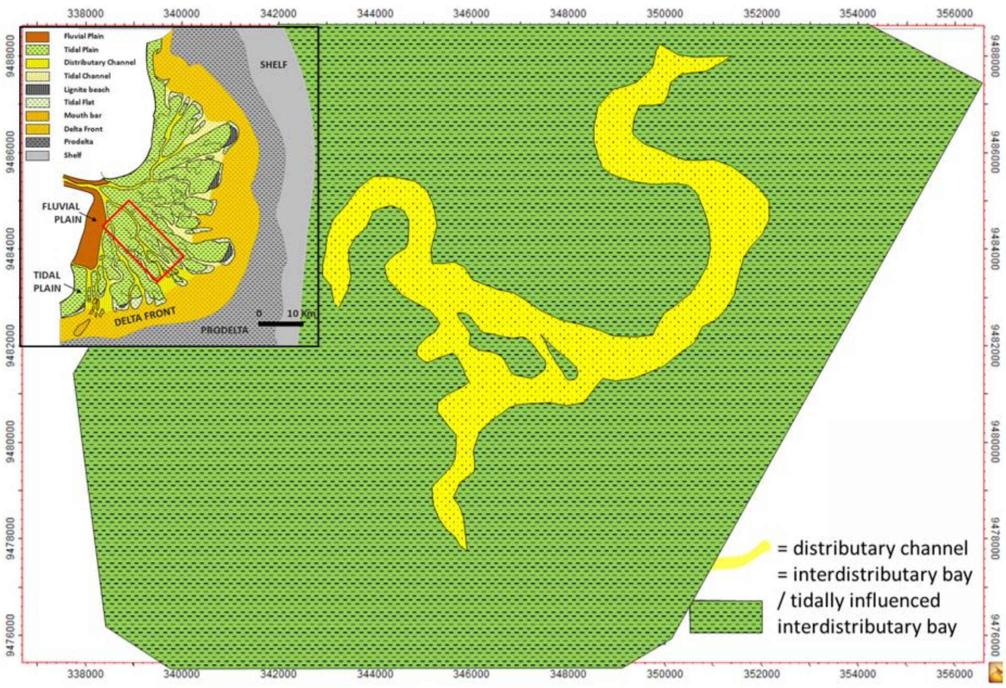

Figure 29. Depositional environment map of 33-4 sandstone reservoir. Mahakam Delta depositional environment as analog (Allen, 1972).The reservoir is interpreted to be distributary channel origin in lower delta plain (red box) and is part of larger deltaic channels.

If transected parallel to channel direction, the correlation will how thinning and thickening of distributary channel and facies change in more distal facies such as mouth bar or delta front mudstone.
Interdistributary bay/ tidally influenced interdistributary bay deposits may still have moderate sand content as shown in the core by lithofacies for example laminated mudstone with sandstone laminae and finely laminated mudstone-very fine grain sandstone. In wireline logs, these lithofacies are interpreted as heterolytic shaly sandstone.

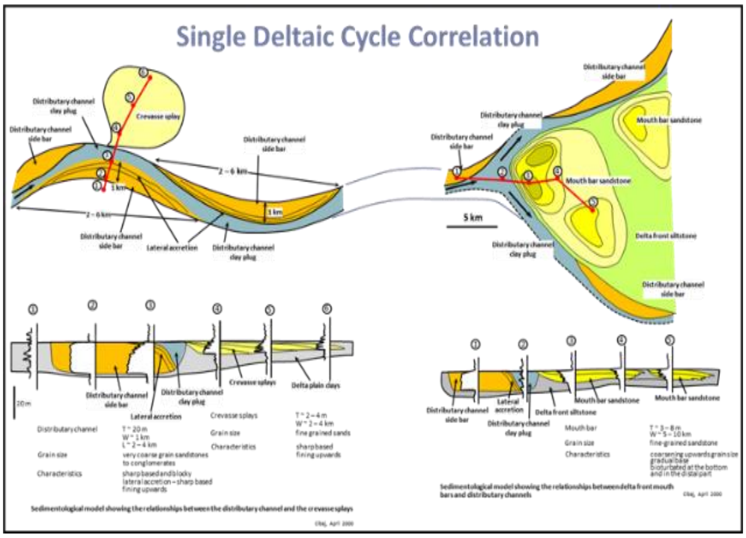

Figure 30. Correlation basis of fluvial distributary channels and its associated lateral environment (Cibaj, 2010).

The correlation section A-A’ in Figure 31 show lateral facies change from interdistributary bay/tidally influenced interdistributary bay deposit to distributary channel 34-1 and moving back to interdistributary bay/ tidally influenced interdistributary bay. At the top of interdistributary bay in Wida-03 there is heterolytic shaly sandstone. Correlation B-B’ parallel to channel direction in Figure 31 showed thinning of 34-1 sandstone in western part and thickening toward eastern

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part. B-B' section in Figure 32 shows no facies change as it only transects in distributary channel. Both correlations are hung in transgressive surface at the top of 34-1 sandstone.

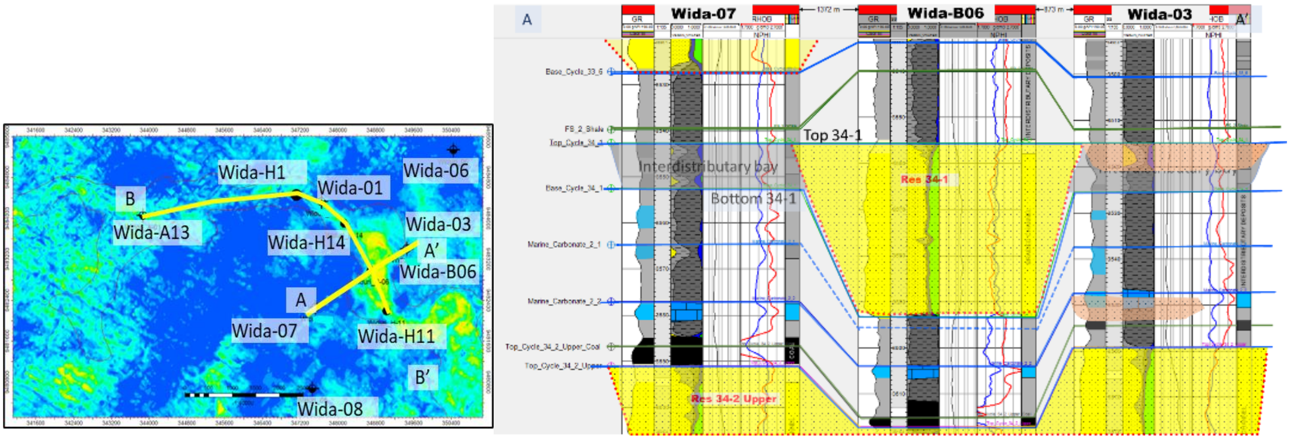

Figure 31. Well correlation section A-A' showed lateral facies change perpendicular to distributary channel. The correlation was flattened at transgressive surface above 34-1 sandstone.

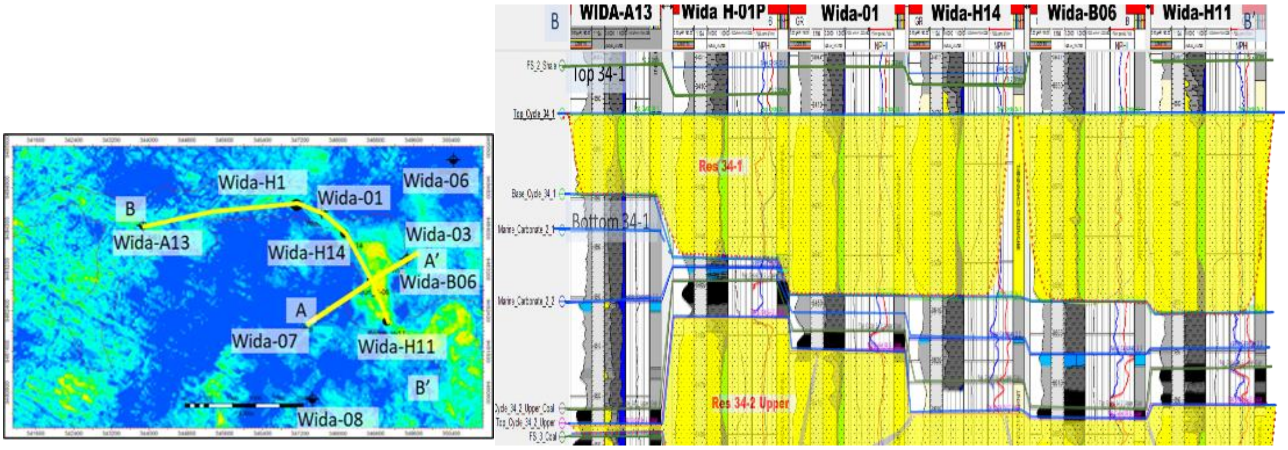

Figure 32. Well correlation section B-B' showed thinning of 34-1 sandstone in western part and thickening toward east.

Correlation section A-A' made perpendicular to 33-4 sandstone in Figure 33 also show similar condition. The correlation results showed facies change from interdistributary bay dominated by shale to distributary channel sandstone and moved back to interdistributary bay where the top is overlaid by heterolytic sandstone/ shaly sandstone. The thickest 33-4 sandstone was found in Wina-A20. In areas away from the inner bend of point bar the sandstone thickness is less from well drilled in inner bend areas.

The correlation section B-B' and B1-B1' were made within 33-6 distributary channel as shown in Figure 34 and Figure 35. Correlation B1-B1' in 33-6 distributary channel also shows facies change from interdistributary deposit to distributary channel and moved back to interdistributary deposit when transected perpendicular to channel direction. Based on correlation B-B', 33-6 channel showed contrary to 33-4 distributary channel, the 33-6 distributary channel showed thinning in western part such as in area of Wina Platform while thickening toward eastern part in Wida B Platform.

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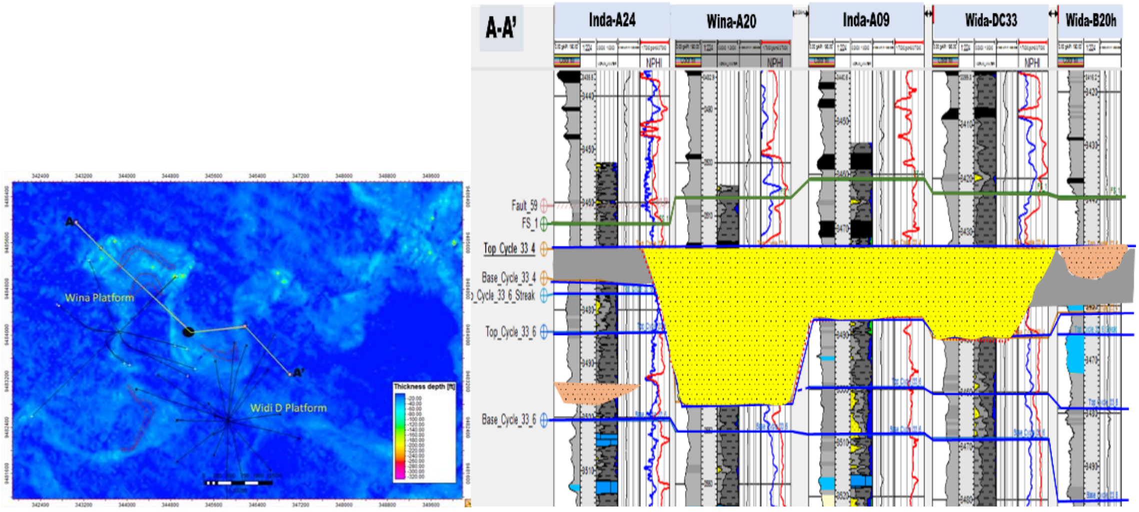

Figure 33. Correlation section A-A' perpendicular to 33-4 distributary channel. It showed lateral facies change from interdistributary bay to 33-4 distributary channel.

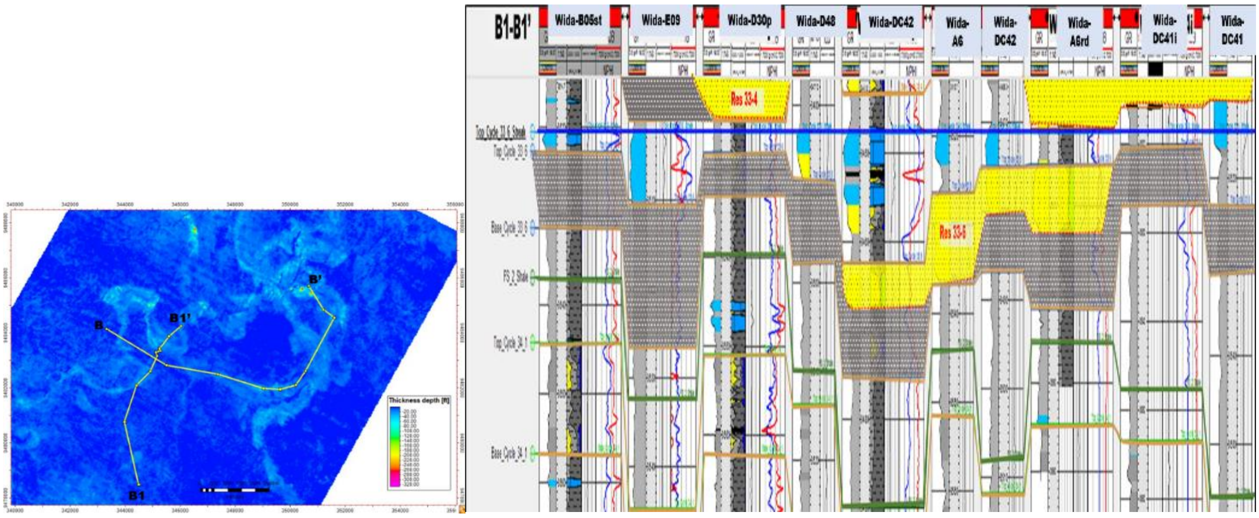

Figure 34. Correlation section B1-B1' made in 33-6 distributary channel. The correlation is perpendicular to channel. The facies change from interdistributary bay to distributary channel and move back to interdistributary. The correlation was flattened at carbonate streak above 33-6 sandstone as flooding surface.

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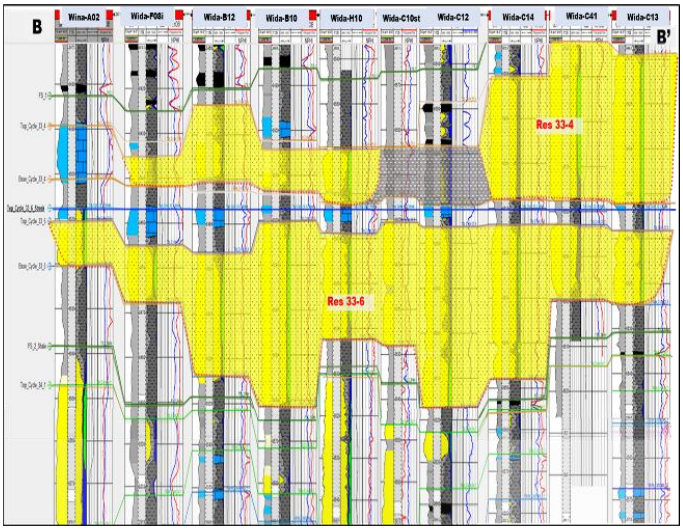

Figure 35. Correaltion section B-B' in 33-6 reservoir parallel to channel direction. The correlation only transects distributary channel and showed thinning of sandstone in western part and thickening toward eastern part.

CONCLUSIONS

Based on this research there are some conclusions that can be drawn as listed below:

1. Distributary channel facies association served as reservoir in Wida field and consist of lithofacies medium-fine grain planar tabular cross bedding sandstone, fine to very fine grain mud drapes sandstone, and ripple-wavy lamination fine to very fine grain sandstone. The distributary channels were deposited in tidally influenced delta as indicated by sporadic mud drapes in channel sandstone.
2. Non reservoir facies association (FA) found laterally, below, and above distributary channel are shallow marine, swamp, interdistributary bay, and tidally influenced interdistributary bay. Shallow marine facies association consist of skeletal limestone (Lm), calcareous mudstone (Fc), and calcareous sandstone (Sc) which have abundant calcareous shell fragments and large foraminifera Leptocyclina sp interpreted as transgressive lag deposits. Interdistributary bay FA consists of rootlet mudstone (Fb) and interlamination of carbonaceous mudstone with very fine-grain sandstone (Fl) found below skeletal limestone and calcareous sandstone. Swamp facies association consist of coal (C) and coaly mudstone above interdistributary bay. Tidally influenced interdistributary bay FA consist of carbonaceous laminated mudstone with sandstone laminae (Flb) less bioturbated, intensively bioturbated carbonaceous laminated mudstone (Flb), finely interlaminated mudstone-very fine grain sandstone (Fl), and black massive fissile carbonaceous mudstone (Fm).
3. The 34-1. 33-6, and 33-4 reservoir sandstone are mature sandstone texturally and compositionally. It constists dominantly of quartz arenite with few sublitharenite and subarkose. Framework grain dominantly consists of quartz, grains are subangular to well rounded, moderate-very well sorted. Grain-to-grain contacts are dominantly characterized by floating contacts, with minor clay matrix and cement, and highly visible porosity. Intergranular porosity dominated with minor dissolution porosity, pore throats are wide and connected. In the core, the sandstones are friable to lose.
4. The depositional environment maps of three reservoirs were constructed with the aid of seismic attribute, well correlation, and pie chart maps. The external geometry of 34-1 showed distributary channel trending west-east while 33-6 and 33-4 showed north-south distributary channel. Clear point bar development of channels was imaged as amplitude band. The depositional environment was divided into distributary channel and interdistributary bay deposit for helping facies model construction in static reservoir model.

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