Characteristic of Pore Pressure at the Sub Surface Sedimentary Rock in Deep Water Part of Kutai Basin, East Kalimantan, Indonesia

Ginanjar[1], Dicky Muslim[2], Hendarmawan[3], Ildrem Syafri[4]

[1]Student at Faculty of Geology, Padjadjaran University, Bandung, West Jawa, Indonesia
[2]Lecture at Faculty of Geology, Padjadjaran University, Bandung, West Jawa, Indonesia
[3, 4]Profesor at Faculty of Geology, Padjadjaran University, Bandung, West Jawa, Indonesia

Abstract: ***The Kutai Basin is the biggest Tertiary basin in Eastern part of Indonesia, contains a significant amount of hydrocarbon accumulation, proven by the discovery of giant oil and gas fields. Currently, the majority of hydrocarbon exploration activities in Kutai basin is still concentrated on onshore, shelf, and Mahakam delta. Drilling activities at deep water part of Kutai basin is still slow due to high cost and limited of geological data information regarding to the petroleum system and geopressure of this part of the basin. In hydrocarbon exploration, information about geopressure within a basin is very important. For a geologist, information about subsurface geopressure is useful to look at the maturity and the migration of hydrocarbon in a basin. For a petroleum engineer, the subsurface geopressure information is useful to manage the production rate of hidrocarbon from the well. For a drilling engineer, this information is useful to design the type and density of drilling mud weigh and also casing pipe that will be used to prevent a blowout. In this research, the geopressure study at the deep water part of Kutai basin, particularly along Makassar Strait as of recent condition has been done. The objective of the research is to study the characteristics, vertical distribution, and the cause of overpressure within the area by using integration of geological and geophysical data. The research shows that in this area exists four main geopressure zones vertically. According to its depth, they are normal hydrostatic pressure occuring at a normal compaction where sedimentary rock layer lies, continue by abnormal pressure due to disequilibrium compaction, clay mineral diagenesis, and at the deeper section was expected by hydrocarbon generation.***

Keywords: Pore Pressure, Deep Water Kutai Basin

1. Introduction

Proven hydrocarbon reserve in Indonesia seems to be declining since majority of giant oil and gas fields have been exploited. Meanwhile, the demand of fossil energy keeps increasing day by day. This matter is enforcing the exploration activities should be more down slope by entering the frontier area such as deep water area like in offshore Makassar Strait, East Kalimantan, Kutei Basin (Figure 1).

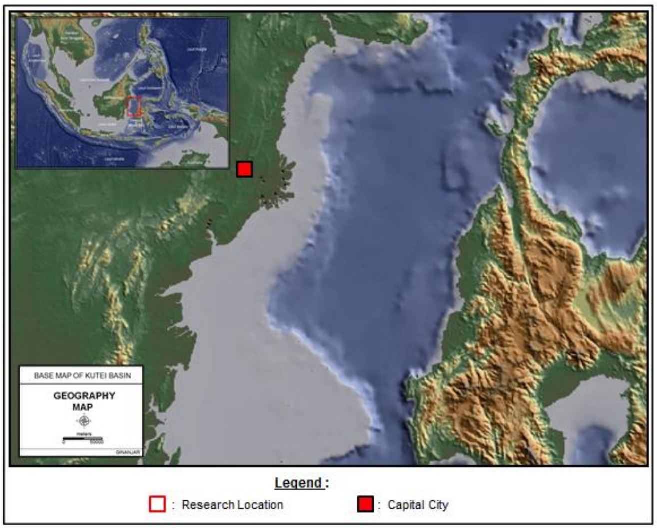

Figure 1: Deep Water Kutai Basin, Makassar Straits, Offshor East Kalimantan, Indonesia

Kutai Basin is one of the largest tertiary basin in eastern Indonesia and hold voluminous number of hydrocarbon. It is proved by the discovery of giant oil and gas fields in this area. Kutai Basin is estimated to have 30 MMBOE of oil and 30 TCF of gas in which only one third have been exploited (Bates, 1996).

Recently, the majority of exploration activities in Kutai Basin is still concentrated onshore, deltaic, and shelf area. High operating cost and limited of geological data particularly in reservoir property and pore pressure interrupt the drilling activity within the area.

Thick sediment and rapid sedimentation during the deposition within this basin resulted in a remarkable phenomenon to be studied. Studies about overpressure in the area have been conducted by several scientists and practitioners such as Bois et al. (1994), Bates (1996) and Burus (1998). However, the study merely concentrates in onshore, deltaic, and shelf area. One of the essential conclusions from previous researches was the overpressure in Lower Kutai Basin was due to disequilibrium compaction or loading mechanism during the deposition, when the rate of sedimentation is higher than the rate fluid escaping from the rock.

In contrast to the previous researchers above, Ramdhan (2010) in his dissertation thought that the cause of overpressure in Lower Kutai Basin was due to the existent of high temperature which generates unloading mechanism. This conclusion is based on his observation of wireline log data and vitrinite reflectance which have never been done before by the previous researchers. This contradicts with the hypothesis of disequilibrium compaction stated by previous researchers.

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2. Case Identification

The prior research in overpressure that had been conducted only covers the Lower Kutai Basin and Mahakam delta area, which geographically situated on the onshore part, deltaic, and shelf part of East Kalimantan province. Also, the observation only based on drilling data and wireline logging.

Furthermore the main focus issues for this research are:

- How the characteristic of pore pressure within the study area particularly trends and distributes downward to deep water?
- What is the main cause of overpressure in deep water area?

3. Geology of Deep Water Kutai Basin

Geologically, Kutai Basin is situated in between two continents: Asia and Australia and two oceans: Indian and Pacific. In addition, the basin is positioned nearby on the ring of fire which creates distinctive gradient thermal and heat flow compared to other basins in Indonesia. Having 165.000 kilometer square of area. Kutai Basin spreads along Makassar Strait in the eastern part, and Cretaceous Kuching High in Western part, which supplies sediment for Kutai Basin in Neogen era. In the northern part, the basin is bounded by Mangkalihat high and Sangkulirang Fault which separates the area from the Tarakan Basin. However, in the southern part, the basin is bordered by Adang Fault and Paternoster platform. The depths of the basement reach up 14 Kilometers (Rose and Hartono, 1971 and Mora, 2001).

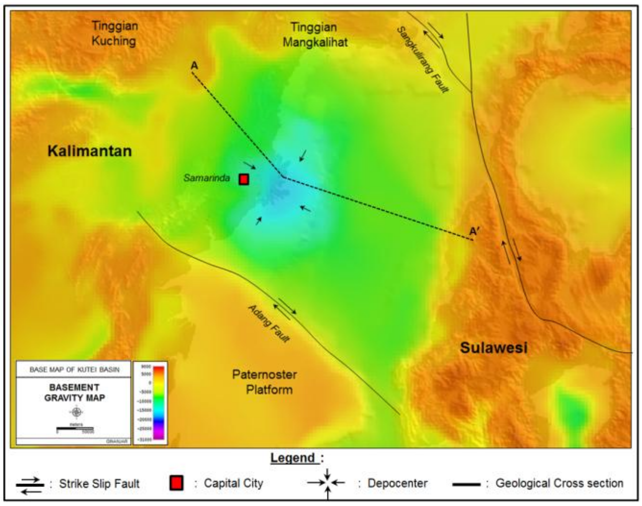

Figure 2: Geometry of Kutai Basin based on gravity map

Figure 2 shows the geometry of Kutai Basin based on gravity data, illustrated with dark orange color as high morphology and blue color as low morphology. According to the picture, the depocenter of the Kutai Basin is located exactly underneath of the Mahakam Delta at present time. Figure 3 shows the vertical section model of Kutai Basin in northwest to southeast direction based on gravity and wells data. This section represents the structure and lithology distribution of sedimentary rock passing through the depocenter of the basin (section A-A' on the gravity map).

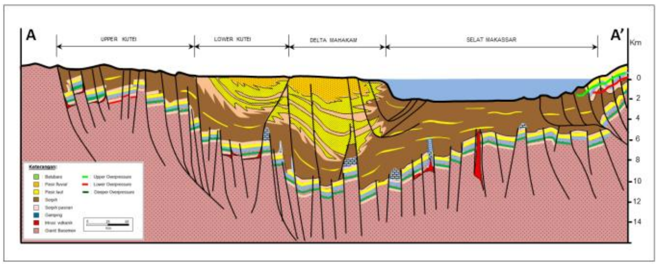

Figure 3: Geological cross section of Kutai Basin in Northwest to Southeast direction

3.1 Tectonic Framework

Tectonically, Kutai Basin situates in between two plates, Indian Australia southward and Eurasia northward. Kutai Basin was formed due to the interaction between those plates (Van de Weerd and Armin, 1992, McClay et al., 2000., Hall, 2002, 2009). Moss and Chambers (1999) and Chambers et.al. (2004) continuously observed the process of Kutai Basin restoration. In their conclusion, it is suggested that there are 4 following main periods, how Kutai Basin was formed:

- During Middle to Late Eocene, early formation of the basin begins with the occurrence of half graben system as the result of extensional regime in Southeast Asia, including Kalimantan (Hall, 2009). The process is followed by syn-rift sedimentation.
- In late Eocene until Late Oligocene is the period of basin sagging indicated by influx of marine mudrock sediment supply deposited into the basin and forms carbonate platform on basement high basin margin.
- Late Oligocene to Early Miocene is the early timing when the deltaic deposits were formed. The tectonic period comprises of two phases, firstly begins with the inversion process or uplift and volcanism activity, then secondly followed by spreading or extensional in the depocenter.
- In middle Miocene to present, as the result of the inversion of Samarinda anticlinorium was formed which is the main anticlinorium system within the basin. Nevertheless in Upper Kutai Basin the inversion during Late Oligocene was formed by Kuching high. This inversion creates the regression cycle of sedimentation in lower Kutai Basin and continues without any gap until present time. Delta progradation system commenced as thick deposits which comprises of mega-sequence dominated by sandstone. Coals in proximal area and claystone dominates marine distal area. The sedimentation rate is up to 500 ft/myr (Bates, 2006). At present time delta progradation continue downward to east.

3.2 Stratigraphy

In general stratigraphy column of Kutai Basin from hinterland to deep-water can be illustrated from figure 4.

However, the sedimentation pattern comprises of two sections: transgression during Paleogene (spreading filled up by sedimentation and sagging) and entire regression throughout Neogene time (progradation delta and aggradations) (Allen dan Chambers, 1998).

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The main process in Paleogene consists of spreading loaded by various sediments from Alluvial fan to deltaic and deep water deposits. At present time, in deep water part, sedimentation is dominated by material from Mahakam Delta.

The Neogene cross section showed the lithology in hinterland to shallow marine is dominated by fluvio-deltaic, marine deposits and down slope to deep water which comprises of sandstones, mudrocks, coals, and turbidities sandstones fining upward. Duva et al. (1998) conducted study on the subject of detail sequence stratigraphy in shallow marine.

Evolution of delta system, starting from delta plain down to delta front can be observed obviously in the cross section. At this point, the evolution tells us that in several area of the Late Miocene up to Pliocene, sediments were eroded and were left in Middle Miocene or even older. The shifted carbonate platform during Miocene becomes obvious indicators from deltaic progradation sequences in Neogene.

Figure 4 is the geological cross section which illustrates the comprehensive model of how the tectonic event controls the stratigraphy deposition sequence and sedimentation process in the deep water part of Kutai Basin.

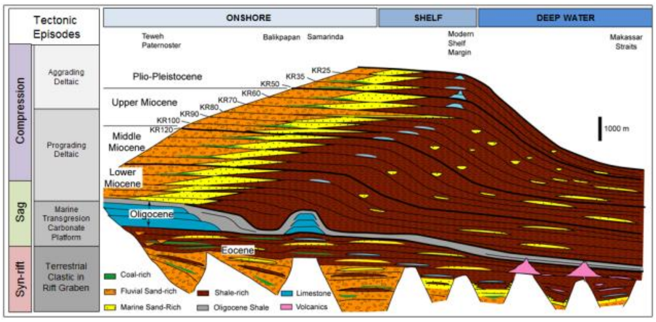

Figure 4: Tectonic, deposition sequence and Stratigraphy of deep water Kutai Basin (Seller, 2003).

3.3. Structure

Generally, structural pattern formed in Kutai Basin is a series of NE–SW anticline and syncline. Compression stress comes in NW-SE direction and constructs fold series of anticlinorium particularly in Samarinda City. This anticlinorium lies along the mainland to Mahakam Delta, then downward to shelf end up eastward in Deep-Water area.

Downward to marine area, the fold pattern demonstrates the occurrence of fan pattern from huge deltaic geometry. At this point, the structure tells us that the sediments from Mahakam Delta were deposited with high compression stress that created the fold pattern. Furthermore the folds acted as petroleum element where the hydrocarbons are trapped. Trust fold frequently observed exists along the axis in NE-SW direction. On the other hand, the normal fold observed is having a perpendicular trend against the trust fault.

4. Data Acquisition and Processing

Numerous data from geological survey from the field were acquired to conduct a pore-pressure study within deep water Kutai Basin, which consists of:

- Drilling data comprises of Repeat Formation Test (RFT), Drill Stem Test (DST) and Modular Dynamic Tester (MDT). These data are acquired from direct formation of pore-pressure measurements inside borehole. Furthermore, there are at least 820 observation points from 26 wells with various depth interval obtained from DST data.
- Well logging data such as gamma ray, density, neutron porosity, sonic and temperature logs were obtained to understand the petrophysical property of the formation
- X-ray Diffraction (XRD) data were applied to observed the composition of clay minerals
- Ro data from Vitrinite Reflectance were obtained to examine the rocks kerogen maturity

Data processing was begun by creating a pore-pressure (in Psi) versus depth (in ft) curve based on MDT and DST direct formation measurements inside the borehole. The curve was expected to illustrate pore-pressure profile of the study area vertically. Perfectly single pore-pressure curve per-well should be conducted with dense interval. In contrasts , the high cost in deep water becomes unattainable for this process. Thus sample data acquisition was conducted in particular interval, especially on the main zone. In order to deal with the limited data, consequently pore-pressure versus depth curve will collaborate the data from 26 wells then plot into one stack curve as showed in figure 5. Most of the wells used are located at the western flank of Makassar Straits.

This technique does not accurately describe pore-pressure profile per layer. However this is already sufficient to illustrate pore-pressure gradient of highly abnormal pressure or top of overpressure which obviously can interprets pore pressure distribution through the curve.

In pressure versus depth curve, measured pore-pressures are represented by green dots. Mostly, the pore-pressure measurement were conducted in overpressure interval, therefore the values of pressure are above normal hydrostatic pressure gradient (blue line).

According to data population, there are clearly three observed trends with distinct gradient which comprise of:

- Data population with gradient 0.465 psi/ft represented by blue line color.
- Data population with gradient 0.601 psi/ft represented by black line color. These two lines intersect each other at -3000 feet depth below mud line (DBML). This intersecting point was interpreted as the first peak of overpressure, named as top of upper overpressure.
- Data population with gradient 1.214 psi /ft represented by red line color, this line intersects with the black color line at -6000 feet depth below mud line (DBML). This intersecting point was interpreted as second peak of overpressure and named as top of lower overpressure.

The brown line represents the fracture gradient or maximum horizontal stress, acquired from Leak of Test (LOT) in several wells which apparently demonstrates rock matrix

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strength to hold wellbore if horizontal force is applied. This line has gradient 0.898 psi/ft. The outer green line represents the overburden pressure, this line has gradient 1 psi/ft.

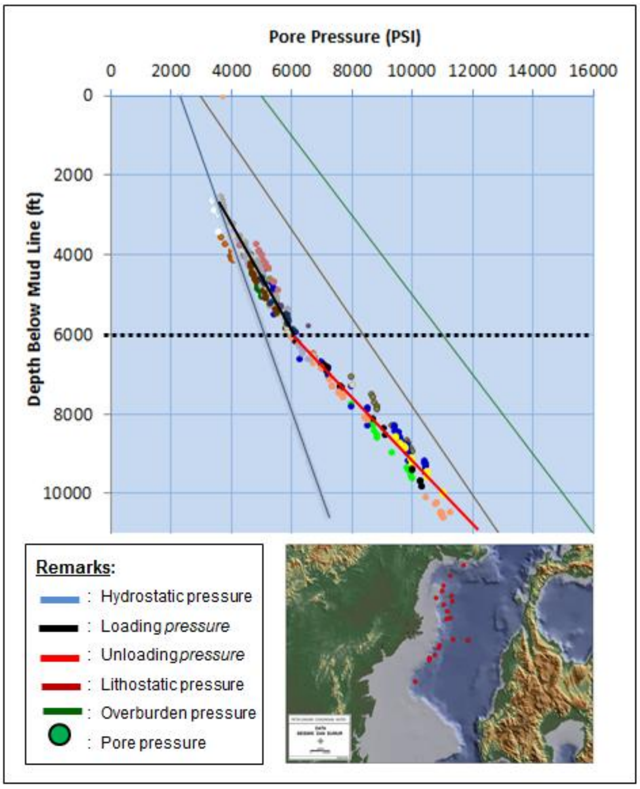

Figure 5: Pore pressure versus depth plot curve of 26 wells within deep water Kutai Basin.

5. Data Interpretation

In addition, there are following geological data assessments conducted to investigate the main cause of overpressure within study area and distinguish what the different between both overpressure are, such as:

- Observation to well log responses and characteristic of each well.
- Direct observation to core, particularly clay mineral in shale section.
- Observation to kerogen maturity using Vitrinite Reflectance data

Pore-pressure observation to well log responses and the characteristics were conducted in similar method as what we did in MDT/DST data. The observation collaborated 26 wells and was grouped based on the type of wireline data. They were then plotted into one curve as function petrophysical parameters versus depth (in feet DBML). Furthermore the analysis was conducted by observing and comparing each trend of well log data in curves. Figure 6 shows how data displayed from left to the right: ((i) geo-pressure log, (ii) neutron porosity log, (iii) sonic log, and (iv) density log. There is a following color index that tells us the quantity of data population in which blue represents low population data and red represents high population data.

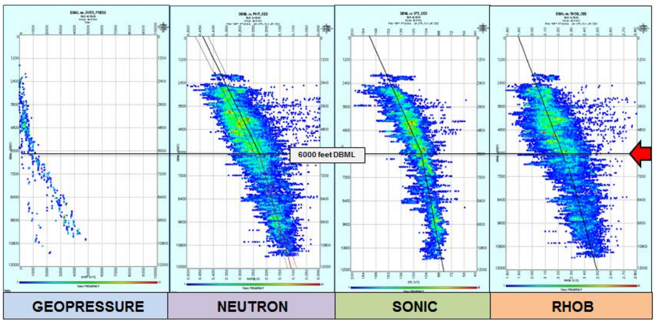

Figure 6: Well log response and their relation to the top of overpressure zone

The distinctive pattern observed started at depth -3000 to -6000' DBML. The geo-pressure curve begin shifting from normal hydrostatic trend. However, the respond of sonic and destiny log remained unchanged which indicated the cause of overpressure due to disequilibrium between fluid velocity trying to escape in pore-space and compaction rapidity during sedimentation, called as disequilibrium compaction.

Another pressure gradient shifting occurs approximately in depth -6000' DBML (dash line), indicated by neutron porosity and sonic log shifting. The density log gradient was relatively unchanged. In nature, the porosity of sedimentary rock linearly declines by depth (overburden effect of beneath loading) then is hold by fluid increase within pore space and rock matrix.

There is a question, what is the cause of increasing fluid volume within the pore space in rock matrix? To answers that question, an analysis on mineral content in clay section were conducted. In addition, clay diagenesis Smectite to Illite in temperature 185^{0}F will produce water as chemical reaction (Boles and Franks, 1979), hereby the following formula:

Smectite + K^+ = Illite + Silika + H_2O

Generated water will increase fluid volume within the pore-space of rock matrix, thus additional overpressure potentially may occur in this section.

Another cause of increasing pore-pressure within sedimentary rock layers is due to hydrocarbon generation, bitumen generated oil, or cracking from oil which becomes gas. The chemical reaction of this process will produce fluids which comprises of gas, oil, and water. They increase the fluid volume within the pore-space of rock matrix and consequently will contribute overpressure.

The research was conducted using XRD and Vitrinite Reflectance (Ro) analysis from 26 six wells to further examine the cause of overpressure within depth -6000 feet DBML due to clay diagenesis or hydrocarbon generation. Furthermore XRD analysis tells us the percentage of Smectite and Illite mineral in shale section. Moreover, Vitrinite Reflectance (Ro) exhibits kerogen maturity. The maturity corresponds to temperature which is equivalent to depth. Thus Vitrinite Reflectance (Ro) will tells us where the hydrocarbon generation was generated. Figure 7, shows the percentage distribution of Smectite and Illite minerals in clay

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section versus depth that were analyzed from well core.

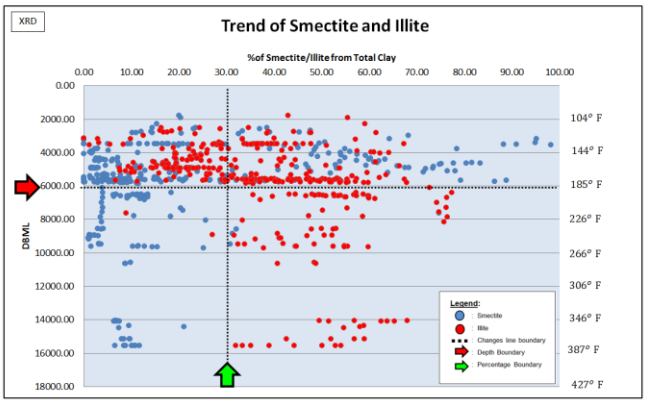

Figure 7: Percentage distribution of Smectite and Illite minerals within clay in deep water part of Kutai Basin.

Distinctive trend was observed in depth 0 to -6000' feet in DBML. The percentage of Smectite and Illite minerals within clay is relatively the same in scattered population. However, at depth -6000 to -16000 feet in DBML(red arrow), the population initiate a gather where the percentage of Illite significantly increases up to 30-80% (showed in green arrow). In depth -6000 feet in DBML, the temperature of the sedimentary layers is 185^{0}F or 80 ^{0}C, which is ideal for chemical reaction of Smectite to transform to Illite.

According to the comprehensive study and support by XRD, MDT/DST, and Well Logging analysis data, the provisional conclusion of the cause of overpressure in this section is due to impact of aquathermal to clay diagenesis.

Moreover, to ensure whether the overpressure is caused by hydrocarbon generation or not in this section, the analysis of kerogen maturity was conducted by using Vitrinite Reflectance (Ro) from several wells and then were plotted into curve versus depth (feet TVDSS) as showed in figure 8. On the curve, peak of lower overpressure due to temperature represented by red arrow altered the clay mineral from Smectite to Illite as discussed above. In addition, measured Vitrinite Reflectance (Ro) is represented by multicolored dots as per depth where the data were acquired.

The dots of data sample demonstrate a well-ordered trend with certain inclination. If a line were put on the dots as average line which represents whole sample through statistical linear regression, the well will attain an equation which relates Ro todepth as showed by black line.

Based on the preceding researches, Ro value in deepwater Kutai Basin for oil is 0.6 and 0.9 for gas (Satyana, 2014). Subsequently Ro values [were] plotted into the curve (figure 8), as represented by green dash line for oil and red dash line for gas

If both Ro equation and Ro windows line were plotted and were collaborated on the same curve, subsequently in depth approximately 14,000' DBML, there will be an intersection which was interpreted as depth where hydrocarbons were generated. Hydrocarbon generation causes an increase of pore-pressure in sedimentary rock layers.

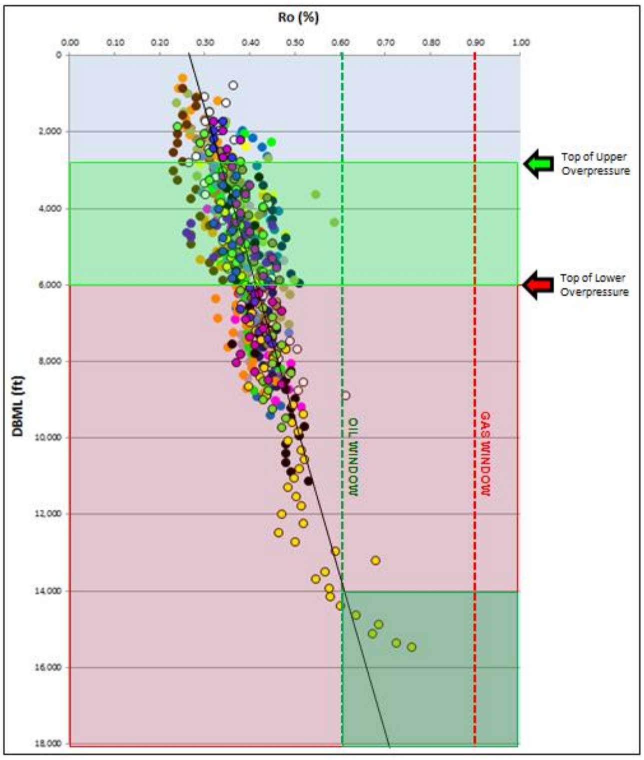

Figure 8: Vitrinite Reflectance versus depth from several wells in deepwater Kutai Basin.

Thus, we can conclude that top hydrocarbon generation is equivalent with the top overpressure for deeper overpressure section.

6. Conclusion

Based on the research that has been done, there are three main zones of overpressure in deepwater of Kutai Basin, comprise of:

- **Upper overpressure zone**, expected to be found at depth starting at -3000 (+/-500) feet DBML. This overpressure is due to disequilibrium between fluid velocity trying to escape in pore-space and compaction rapidity during sedimentation (loading mechanism), called disequilibrium compaction. According to the curves, the pressure is approximately at 2500 up to 5500 psi
- **Lower overpressure zone**, expected to be found at approximately depth of -6000 (+/-500) feet DBML. This overpressure is due to disequilibrium compaction with additional pressure that comes from clay diagenesis, (from smectite to illite. The pressure range is approximately at 5500 up to 10000 psi..
- **Deeper overpressure zone**, expected to be found at approximately depth of -14000 (+/-500) feet DBML. The main cause of the overpressure is due to hydrocarbon generation. The gradient pressure is approximately above 10000 psi.

The conclusion above can be simplified using the following table.

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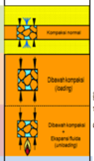
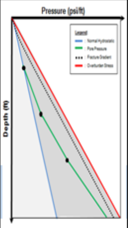
NO	PROG DEPTH DBML (ft) (AVERAGE)	PRESSURE (PSI) (AVERAGE)	CURVE GRADIEN (Psi/ft) (AVERAGE)	GEOLOGICAL CAUSES	GEOLOGICAL MODEL	GEOPHYSICAL MODEL
1	0-3000 (+/- 500)	0 - 2500	0,465 Normal Hydrostatic Pressure	Normal Compaction		
2	3000-6000 (+/- 500) (Upper)	2500 - 5500	0,601 Overpressure	Disequilibrium Compaction (DEC)		
3	6000-14000 (+/- 500) (Lower)	5500 - 10000	1,214 Overpressure	DEC+Diagenesis Smectite to Illite (DEC + DS2E)		
4	14000 - ? (Deeper)	> 10000	? Overpressure	Impact of Hydrocarbon Generation	?	

If all of above overpressure zones that have been discussed are plotted on the Kutai Basin facies models, it will look like those in Figure 9 below.

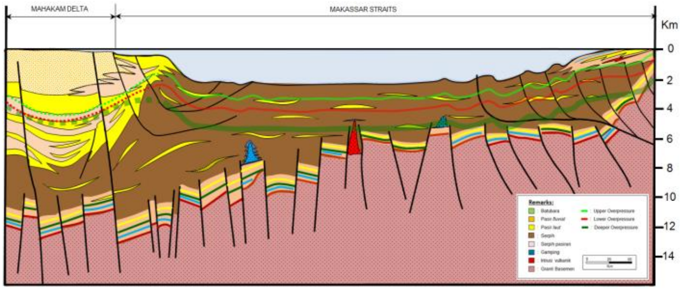


Figure 9: Facies model of Kutai Basin plotted with top of overpressure zones

On the figure above, the top of upper overpressure is represented by horizontal light green line then followed by red line as top of lower overpressure. The green line represents top of potential deeper overpressure. These lines are relatively paralel to water bottom, it is based on the wells correlation result..

7. Other recommendations

The majority of the data is particularly from the eastern part of Makassar Strait or East Coast Kalimantan Island. In order to have a more holistic research, data from West Sulawesi are required. Thus, it can be applied to the exploration for the entire deepwater area of Kutei Basin. In addition, further study within this area should be continued.

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Author Profile

Ginanjar received the B.Sc. in Geophysics from Padjadjaran University, Bandung, Indonesia in 1990 and M.Sc. degrees in Reservoir Geophysical from Indonesian Univeristy, Jakarta, Indonesia in 2000. He has 25 years experiences in oil and gas exploration and production in Indonesia. He is interest on the seismic imaging technology, reservoir geophysics and geomechanics as well especially on the pore pressure prediction and modelling using seismic data.

Hendarmawan, Professor of hydrogeology, Graduated from Geology Department, Padjadjaran University for BS degree in 1992, master and doctor degree from Geoscience Department, Osaka City University, Japan in 2005. Now, as the Dean of Postgraduate School, Padjadjaran University. At least during 25 years research focused on groundwater isotopes, and also on pore pressure interest in oil field. Some publications were established in some journals and during 12 years latest, stable

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isotope of deuterium and oxygen mapping have been conducted on the volcano field in the West Java, Indonesia.

Ildrem Syafri, Professor of petrography, Padjadjaran University who interst as well on the geopressure study in sedimentary rock. He received his bachelor degree from Padjadjaran University, master and doctor degree from Marie-Curie University in France.

Dicky Muslim, Senior lecture for Geologycal Engineering at Padjadjaran University, Bandung, Indonesia. He received his Bachelor Degree in Geology from Padjadjaran University, Bandung, Indonesia, master and doctor degree from Geoscience Departement, Osaka City University in Japan.

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