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Lateral Reservoir Drainage in some Indonesia's Sedimentary Basins and Its Implication to Hydrodynamic Trapping

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Abstract - Lateral reservoir drainage is a hydrodynamic flow type driven by the difference in overpressure. It can lead to hydrodynamically tilted hydrocarbon water contact, and open an opportunity of finding oil and gas in places where previously are not considered as potential traps. In this paper, some examples of the presence of hydrodynamic traps in Indonesia's sedimentary basin are discussed. Tilted hydrocarbon water contacts are present in some fields in the Lower Kutai Basin, and our interpretation is that regional lateral reservoir drainage is present in this basin and is responsible for the tilted contacts. It is also interpreted that lateral reservoir drainage leading to tilted hydrocarbon water contacts may be present at the Arun Field - North Sumatra Basin, Vorwata Field - Bintuni Basin, and BD Field - offshore East Java Basin. As most Indonesia's sedimentary basins are overpressured, the presence of lateral reservoir drainage driven by overpressure difference in the same stratigraphic unit is very plausible to occur, opening the opportunity for hydrodynamically tilted hydrocarbon water contact to be present.

Keywords: overpressure, hydrodynamic, lateral reservoir drainage, tilted hydrocarbon water contacts, Lower Kutai Basin

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Introduction

The term lateral reservoir drainage, coined by O'Connor and Swarbrick (2008), is used to describe active hydrodynamic flow in a reservoir caused by overpressure dissipation. In principle, this hydrodynamic flow is similar to 'classical gravity-driven hydrodynamic flow' (*e.g.* Hubbert, 1953). The difference is only in driving mechanism and its associated source of fluid for the fluid flow. In the lateral reservoir drainage, the source of fluid is overpressured mudrock, while in the classical gravity-driven, the source of fluid is meteoric water entering the reservoir from higher elevation.

Hydrodynamic trapping leading to tilted hydrocarbon water contacts is not a new idea in petroleum exploration. The benchmark paper discussing this trapping mechanism has been published in 1953 by Hubbert. Hubbert (1953), by combining some physics principles with mathematical treatment, shows that in response to active groundwater flow within a reservoir, the contact between hydrocarbon and water should be tilted, to the contrary the most commonly assumed flat hydrocarbon-water contact in rest hydrostatic environment (Figure 1). He gives some solid evidences of the presence of tilted hydrocarbon-water contacts, mainly from the North American basins, as well as from some basins world-wide in strengthen his idea of hydrodynamic trapping. The examples given by Hubbert (1953) are mainly classical gravity-driven hydrodynamic flow.

The lateral reservoir drainage has proven to produce tilted hydrocarbon water contact world-wide. Dennis *et al.* (2000) gave a comprehensive discussion on how active lateral reservoir drainage trapped oil in the North Sea area. Grosjean *et al.* (2009) also gave an example how this lateral drainage trapped oil in the South Caspian Sea, and O'Connor *et al.* (2008) gave a convincing evident of the presence of lateral reservoir drainage in the forms of tilted hydrocarbon water contact in the North Sea area. Recently, Robertson *et al.* (2013) discussed comprehensively the lateral reservoir drainage in the UK Central North Sea and its associated hydrocarbon accumulation.

In this paper, the lateral reservoir drainage in some Indonesia's sedimentary basins is discussed. The discussion will start by giving brief introductory and theoretical review of hydrodynamic trapping, then followed by description of hydrodynamic trapping in some Indonesia's sedimentary basins. Several interesting points are discussed afterwards, followed by conclusions of this paper. It is demonstrated here the opportunity of the presence of tilted hydrocarbon water contact that may previously have been overlooked in petroleum exploration in some overpressured basins in Indonesia.

Theoretical Overview

Hydraulics of Groundwater Flow

The fluid will flow in response to the difference in hydraulic potential. The equation of the fluid flow in porous media is given by the following Darcy's equation:

$$v = K\frac{dh}{dl} \quad (1)$$

where:

v = velocity (LT-1)

K = hydraulic conductivity (LT-1)

h = hydraulic head (L)

l = distance between hydraulic head point (L)

$\frac{dh}{dl}$ = hydraulic gradient

Hubbert (1940 and 1956) further demonstrates that the hydraulic head is another form of potential, so it can be said as hydraulic potential. It is the sum of two components contributing to the hydraulic head, namely the elevation head and the pressure head (Figure 2). The equation describing this relation is:

$$h = z + \gamma \quad (2)$$

where:

z = elevation head (L)

γ = pressure head (L)

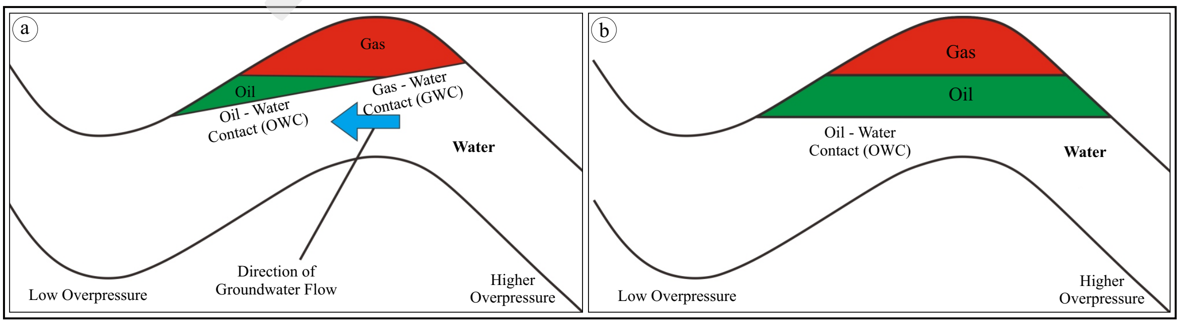

Figure 1. Cartoon of (a) tilted hydrocarbon-water contact (b) the most commonly assumed flat hydrocarbon-water contact (not to scale).

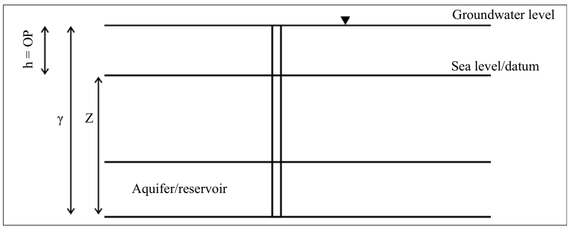

Figure 2. Graphical representation of hydraulic head (*h*), elevation head (*z*), and pressure head (γ). For conversion, *z* is negative because it is located below datum, while h is positive because it is above datum.

Each component competes to give the influence to the hydraulic head. With respect to this circumstance, if the elevation head is the most contributing factor to the hydraulic head, then it is said that there is 'classical gravity-driven hydrodynamic flow'. While if it is dominated by the pressure head, it is said that the 'lateral reservoir drainage' type is hydrodynamic.

In a realistic sedimentary basin, both types of hydrodynamic flow could be drawn as shown in Figure 3. The 'classical gravity-driven' is commonly characterized by cropping out of reservoir in higher elevation, while the 'lateral reservoir drainage' is commonly characterized by reservoir that is encased in highly overpressured mudrock.

In oil industry, it is more convenient to describe hydraulic head in terms of pressure, because the hydraulic parameters measured during drilling of an oil and gas well is the pressure. The conversion of the units is given in the following equation:

$$P = \rho_w g \gamma \quad \text{.......................................}(3)$$

where:
P = fluid pressure ($ML^{-1}T^{-2}$)
ρ_w = density of water (ML^{-3})
g = gravity acceleration (LT^{-2})

The fluid pressure is said to be hydrostatic if the increase in fluid pressure through depth is only the function of the weight of the fluid. For a fluid with the density of 1 g/cm3, the increase of fluid pressure through depth (or simply said as pressure gradient) will be 9800 pa/m or conveniently 9.8 MPa/km, or 0.433 psi/ft in imperial unit. Any pressure gradient which is significantly above that value could be said as overpressure fluid.

Dennis *et al.* (2000) further demonstrates that the overpressure is another form of hydraulic head, and therefore Eq. (1) could be written in the form of:

$$v = K\frac{dOP}{dl} \quad \text{.......................................}(4)$$

where OP = the amount of overpressure, *i.e.* pressures at any given depth subtracted by hydrostatic pressure. It is very clear in Eq. (4) that the fluid flow will be (≠) if there is overpressure gradient.

Hydrodynamically Tilted Hydrocarbon-water Contact

As demonstrated by Hubbert (1953), the active hydrodynamic flow will cause tilted hydrocarbon-water contact, on the contrary to commonly assumed flat hydrocarbon-water contact (Figure 1). The tilting magnitude is given by the equation:

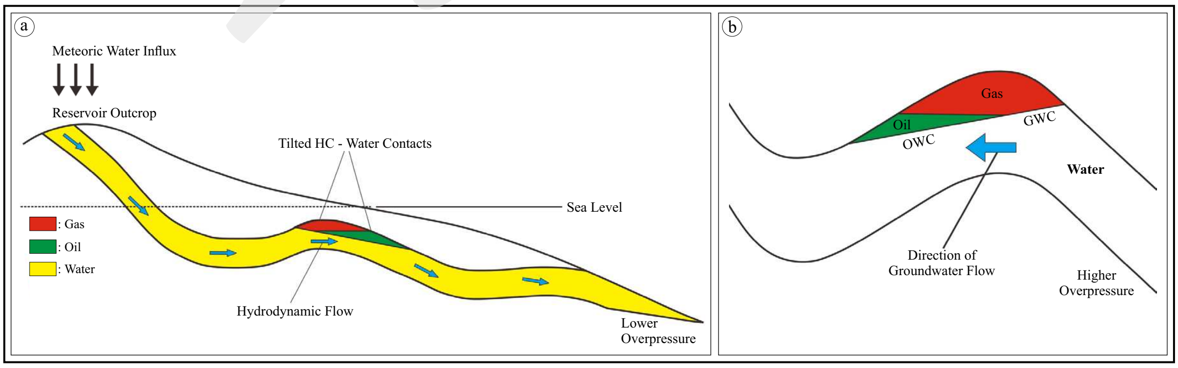

Figure 3. Cartoon of (a) the classical gravity-driven and (b) lateral reservoir drainage types of hydrodynamic (not to scale).

$$\tan\alpha = \frac{\rho_w}{\rho_w - \rho_{hc}} \frac{dh}{dl}$$, or in term of overpressure

$$\tan\alpha = \frac{\rho_w}{\rho_w - \rho_{hc}} \frac{dOP}{ds} \quad \text{.....................................} \quad (5)$$

where:
α = tilting magnitude (degree)
ρ_{HC} = density of hydrocarbon (ML^{-3})

It can be seen in Eq. (5) that the greater the density difference between water and hydrocarbon, the smaller the tilting magnitude. Therefore, gas-water contact will give smaller tilting magnitude compared to oil-water contact for a given overpressure gradient. With respect to the overpressure gradient, it is obvious in the equation that the greater the overpressure gradient, the greater the tilting magnitude. As reviewed by Dahlberg (1995), hydrocarbon will be trapped if the structural dip is greater than the expected tilting magnitude.

The hydrodynamic trap could be observed from pressure-depth plot as shown in Figure 4. The tilted hydrocarbon-water contact will be indicated by one hydrocarbon line indicating one hydrocarbon pool, accompanied by several water lines indicating a difference in overpressure. Specifically for lateral reservoir drainage, its presence can be observed from the existence of sand-mudrock pressure discrepancy and its associated shoulder effect as shown in Figure 5. The discrepancy shows that the reservoir pressure is less than mudrock pressure and, therefore permitting the water to flow from mudrock to sand. Meanwhile, the shoulder effect (the term introduced by O'Connor and Swarbrick, 2008) represents sand-mudrock pressure continuity since the mudrock is not entirely impermeable.

Lateral Drainage Leading to Hydrodynamic Trapping In Some Indonesia's Basins

This section will be started by discussing proven hydrodynamic trap in Indonesia's sedimentary basins. It is then followed by some fields with documented tilted hydrocarbon water contact but with no hydrodynamic analysis, and lastly with some opportunity of the presence of lateral reservoir drainage in other areas.

Proven Hydrodynamic Trap in Indonesia

The proven hydrodynamic trap in Indonesia's basins is coming from the Lower Kutai Basin

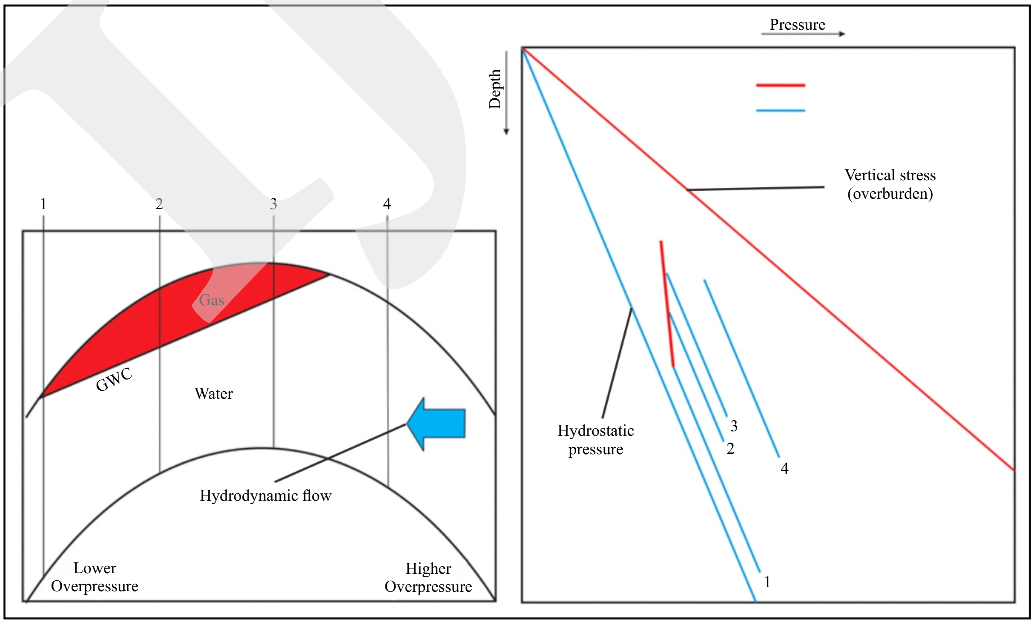

Figure 4. Cartoon of pressure *vs.* depth plot for a reservoir exhibiting tilted hydrocarbon water contact. It is characterized by one hydrocarbon line accompanied by several water lines (not to scale).

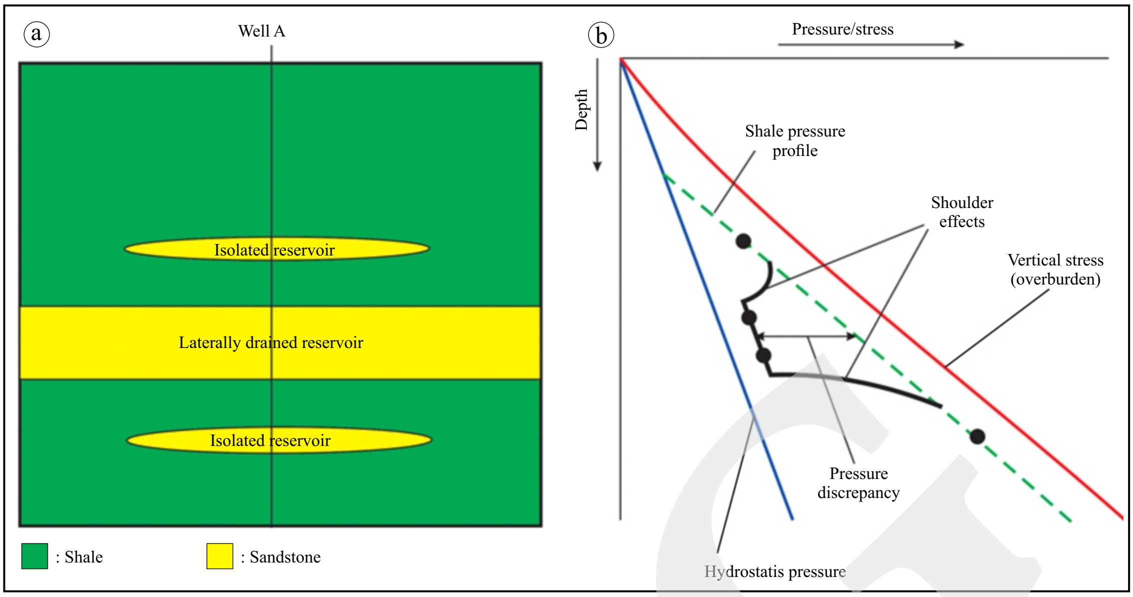

Figure 5. Cartoon of (a) sand-mudrock pressure discrepancy and (b) its associated shoulder effect as an indication of the presence of lateral reservoir drainage (not to scale).

(Figure 6). This basin is located on the eastern coast of Kalimantan, covering onshore to deep-water of the area. The main structural feature is Samarinda Anticlinorium, with the axis more or less parallel to the coastline. In the shelfal area of the basin (the area surrounding the present day

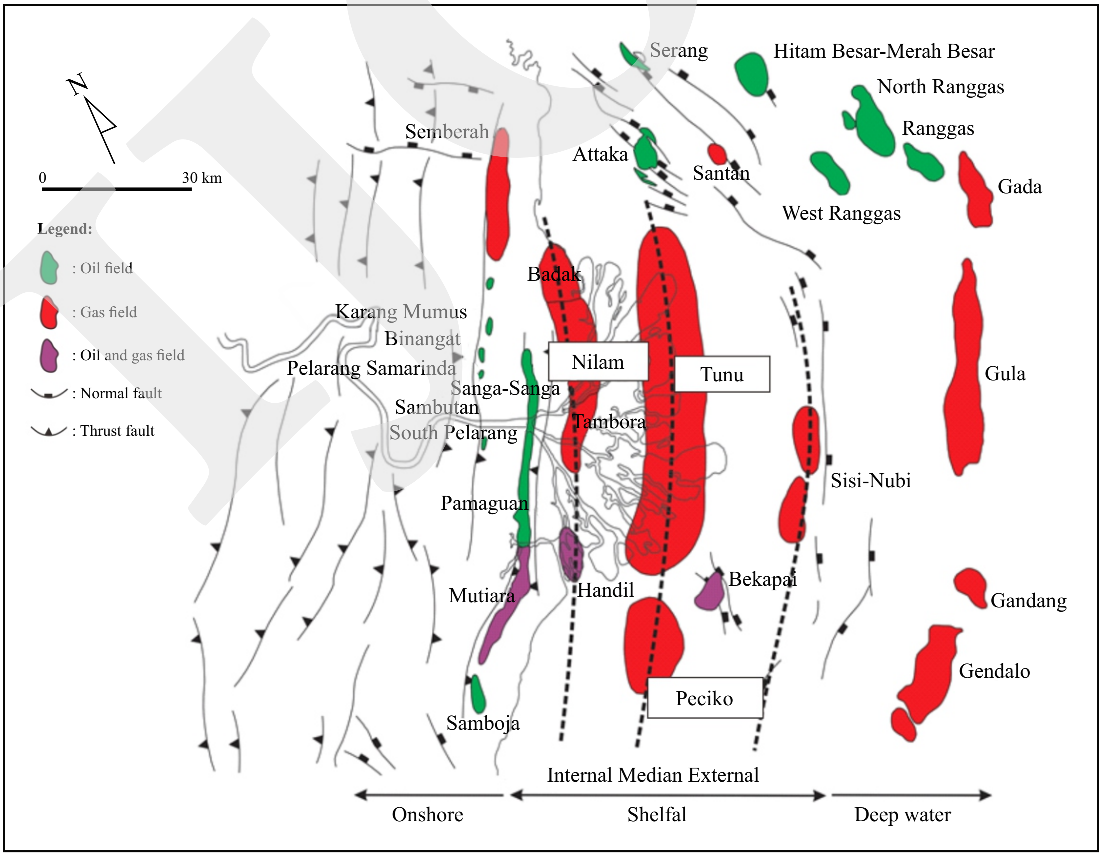

Figure 6. Oil and gas fields in the Lower Kutai Basin.

Mahakam Delta), the anticlinorium is divided into three trends, namely Internal, Median, and External trends. In this basin, hydrodynamic trap has been proven to occur in Peciko, Tunu, and Nilam Fields.

The most intensive study of hydrodynamic trap in this basin is in the Peciko Field. This field is a gas field located in the Median Trend (Figure 6). The field contains around 6 tcf gas (Lambert *et al*., 2003), and it is classified as a giant field (Halboulty, 2003). The gas accumulation in this field is in the deeper part, which is in overpressure condition, and located in the flank instead of in the crest of the structure (Figure 7). The cross-section illustrating tilted hydrocarbon water contact in this field is shown in Figure 8.

The pressure-depth plot of gas accumulation in a stratigraphic unit in this field is shown in Figure 9. It can be seen that there is one gas line accompanied by several water lines indicating tilted gas water contact. This plot is very indicative for tilted gas-water contact as illustrated in Figure 9. This plot cannot be attributed to compartmentalization since we only have one hydrocarbon line.

The pressure-depth plot of gas accumulation in a stratigraphic unit in this field is shown in Figure 9. It can be seen that there is one gas line accompanied by several water lines indicating tilted gas water contact. This plot is very indicative for tilted gas-water contact as illustrated in Figure 9. This plot cannot be attributed to compartmentalization since we only have one hydrocarbon line.

As can be seen in Figures 7 and 8, the tilting direction is towards the northern direction of the field. The overpressure cross section given in Figure 10 shows the decrease in overpressure magnitude in the same stratigraphic unit is also towards the northern direction, in accordance with the observed tilted water contact. Therefore, it is very conclusive to say that gas in this field is trapped hydrodynamically by overpressure gradient, or it can be said that the reservoirs in this field is experiencing active lateral reservoir drainage.

Another field that has been proven to tilt hydrodynamically in the Lower Kutai Basin is the Tunu Field. This is the largest gas field in the

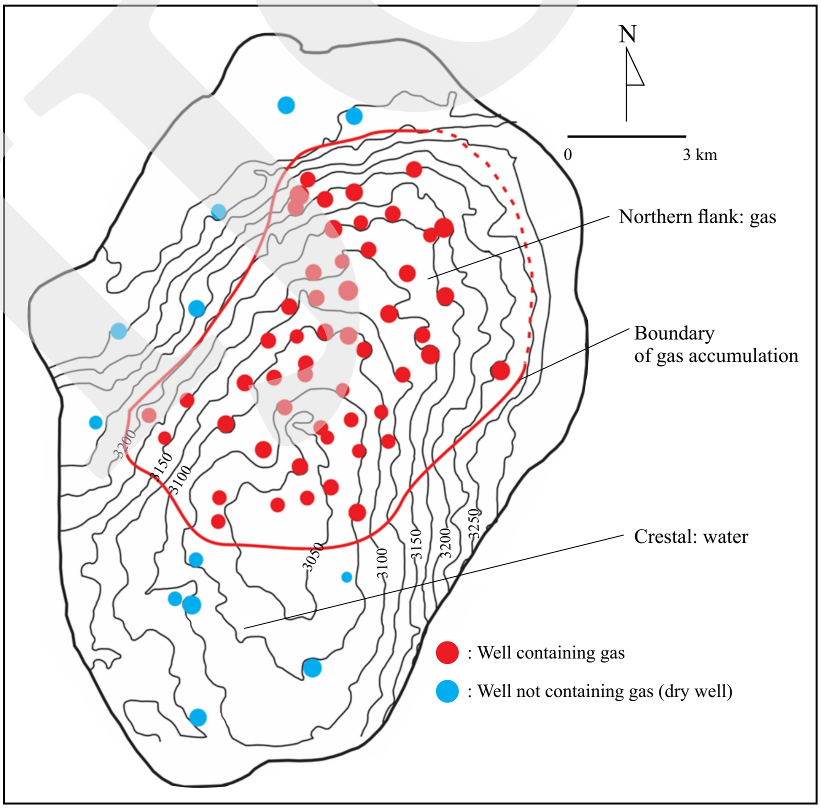

Figure 7. Gas accumulated in the flank of the structure in overpressured section in the Peciko Field.

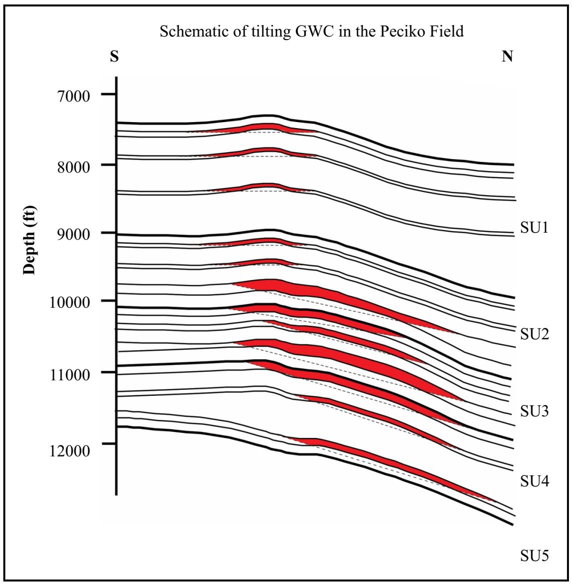

Figure 8. A schematic tilted gas-water contact in the Peciko Field. Red colour indicates gas accumulation and SU is stratigraphic unit (lateral extend not to scale) (simplified from Ramdhan and Goulty, 2010).

basin with the initial gas in place is about 16 tcf (Lambert *et al.*, 2003). According to Halboulty (2003), this field is categorized also as a giant gas field.

Lambert *et al.* (2003) analyzed that the gas in the deeper overpressure part in this field is accumulated at the western flank of the field (Figure 11). The overpressure map in a stratigraphic unit in this field is shown in Figure 12. From the overpressure map, it can be seen that the overpressure magnitude decreases towards the western part of the field, in accordance with the observed gas accumulation, *i.e.* in the western flank. Therefore, it can also be concluded that the gas in the deeper part in this field, in overpressured section, tilts hydrodynamically due to lateral reservoir drainage.

Jauhari *et al.* (2012) found the presence of tilted gas water contact in the Nilam Field. As in the Tunu Field, the hydrodynamic in this field

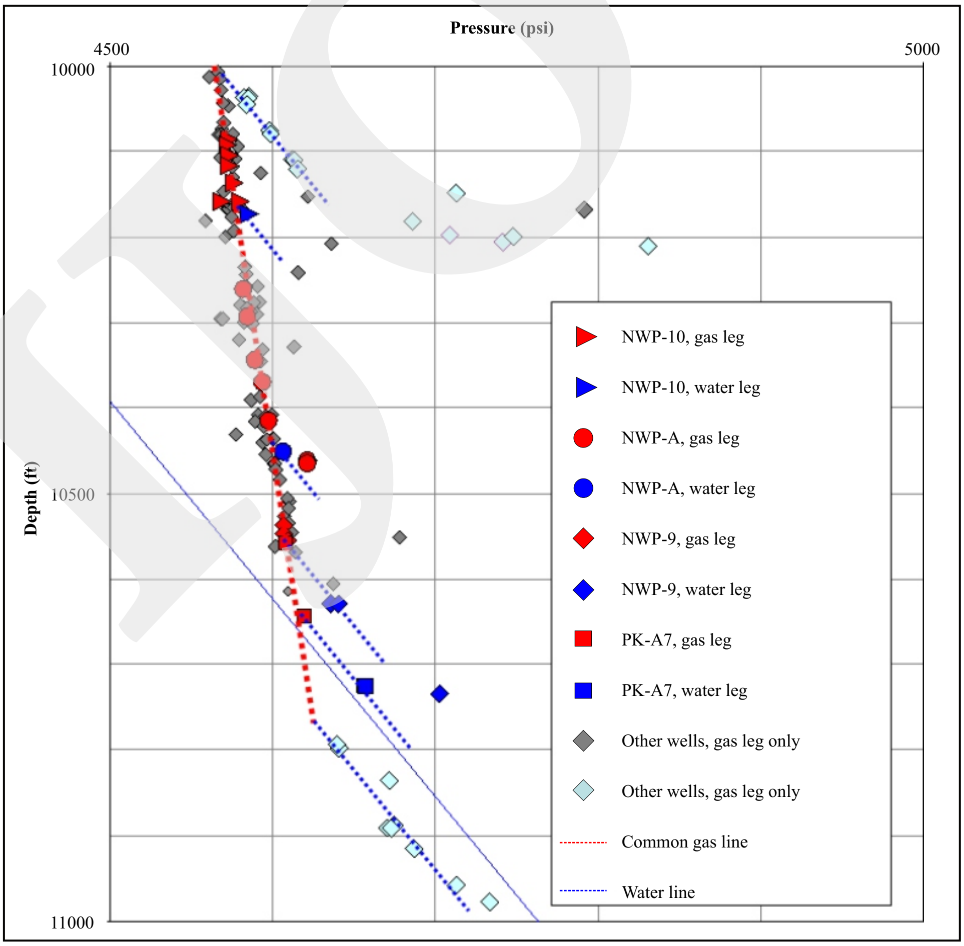

Figure 9. Pressure against depth plot in the Peciko Field showing one gas line accompanied by several water lines indicating hydrodynamically tilted gas-water contact.

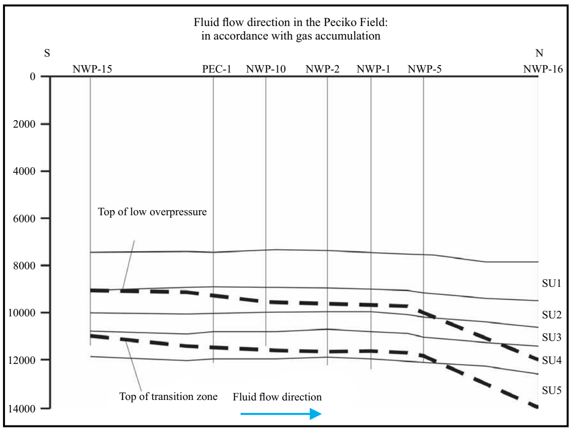

Figure 10. Overpressure cross section in the Peciko Field showing overpressure decrease towards the northern part of the field in the same stratigraphic unit, in accordance with observed gas accumulation in the northern flank.

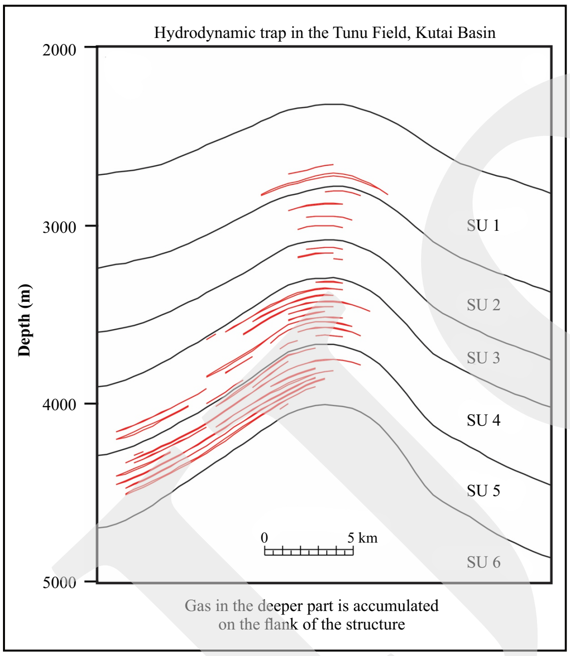

Figure 11. Gas accumulated in the flank of the structure in overpressured section in the Tunu Field. Red lines indicate gas accumulation and black lines indicate boundary of stratigraphic unit (redrawn from Lambert *et al.*, 2003).

has shifted gas accumulation to the western flank of the structure. The gas accumulation in relation with variations of top of overpressure was analyzed as shown in Figure 13. It can be seen that top of overpressure is deeper towards the western flank, and it also crosses stratigraphic unit, causing pressure difference in the same stratigraphic unit. This circumstance leads to active hydrodynamic flow, caused by lateral reservoir drainage.

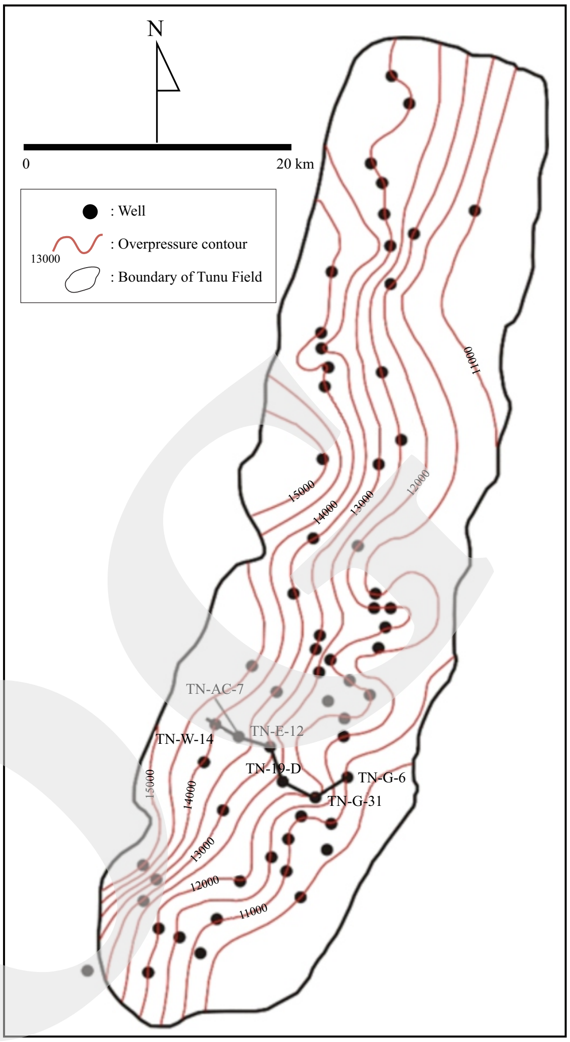

Figure 12. Overpressure map in a stratigraphic unit in the Tunu Field showing overpressure decrease towards the western part of the field, in accordance with observed gas accumulation in the western flank (see for field location).

Ramdhan (2002) analyzed hydrocarbon-water contact in the Semberah Field (see Figure 6 for field location), and he found that in a stratigraphic horizon in this field, the contact between oil and water was tilted. He further analyzed that the tilting was due to an active lateral reservoir drainage, driven by difference in overpressure in the same stratigraphic unit.

Documented Tilted Hydrocarbon Water Contact

In several fields in Indonesia's sedimentary basins, the tilted hydrocarbon water contact has also been documented, but thorough hydrodynamic analysis has not been yet performed.

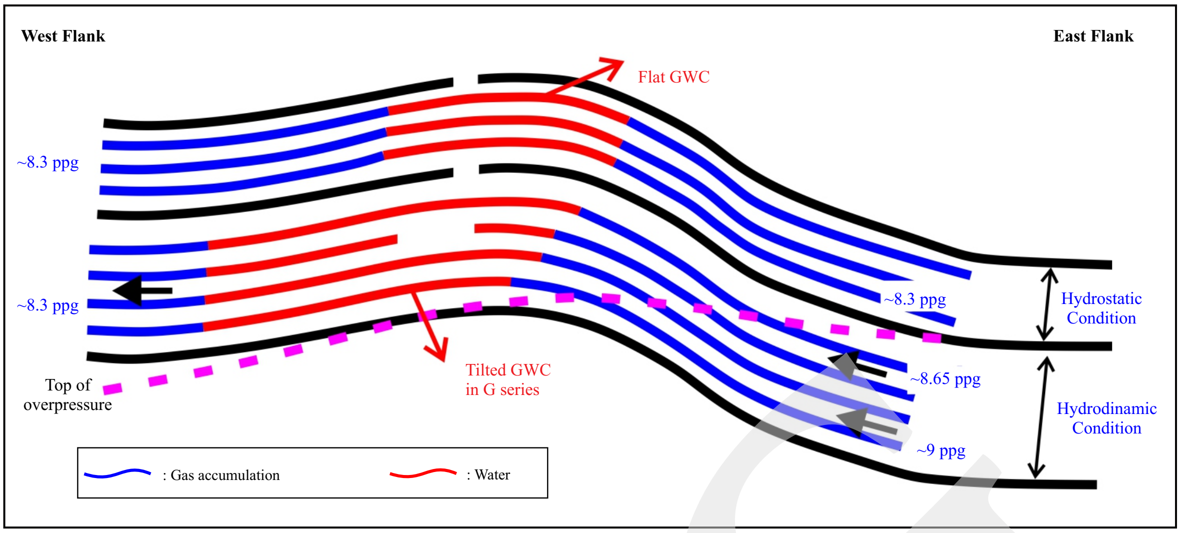

Figure 13. Variation in top of overpressure in the Nilam Field; Overpressure is deeper toward the western part of the field, in accordance with observed gas accumulation in the western flank of the field in overpressured section (red lines indicate gas accumulation; blue lines indicate water) (redrawn and slightly modified from Jauhari *et al*., 2012).

Among the fields there are Badak, Tambora, and Semberah in the Lower Kutai Basin (see Figure 6 for field location), Arun in the North Sumatra Basin (Figure 14), and Tangguh in the Bintuni Basin - Papua (Figure 15).

The schematic showing tilted hydrocarbon water contact in Badak Field is shown in Figure 16 (Cockroft *et al*., 1987). The reservoir with the tilted hydrocarbon water contact is observed at the depth around 5,350 - 5,500 ft. below surface. The tilting direction is towards the north - northeastern part of the field, with the tilting magnitude for oil water contact is about 20. The reservoir where the tilting occurs is located at the overpressured section. Therefore, it is hypothesized that the active hydrodynamic flow is due to lateral reservoir drainage.

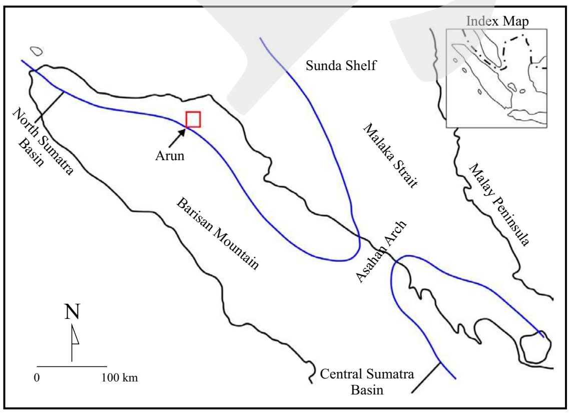

Figure 14. Location of the Arun Field, North Sumatra Basin (simplified from Aziz and Bolt, 1984).

In Tambora Field, tilted oil water contact is found at the depth of 9,350 - 10,000 ft., while tilted gas water contact at the depth of 12,630 - 13,125 ft. below surface (Pertamina BPPKA, 1996). The tilting direction is to the southeastern and western parts of the field, for oil and gas, respectively. The tilting magnitude for the oil water contact is about 20, and for the gas water contact is about 40. The reservoirs where the tilted are present occur in the overpressure section, and they are out of reach of meteoric water recharge (Duval *et al*., 1992; Paterson *et al*., 1997).

Ramdhan *et al.* (2012) analyzed the presence of tilted hydrocarbon water contact in the Arun Field in relation with lateral reservoir drainage in the Arun Field, North Sumatra Basin (Figure 17). The tilting in this field was first observed by Budiono (1988). As shown in Figure 17, the tilting is toward the southern part of the field, located in a reef limestone complex of Lower and Middle Miocene. Ramdhan *et al.* (2012) concluded that the tilting is a hydrodynamic one, opposite the possibility of capillary tilting as proposed by Budiono (1988). Further, the presence of 'shoulder effect' as illustrated in Figure 18 leads to the interpreta-

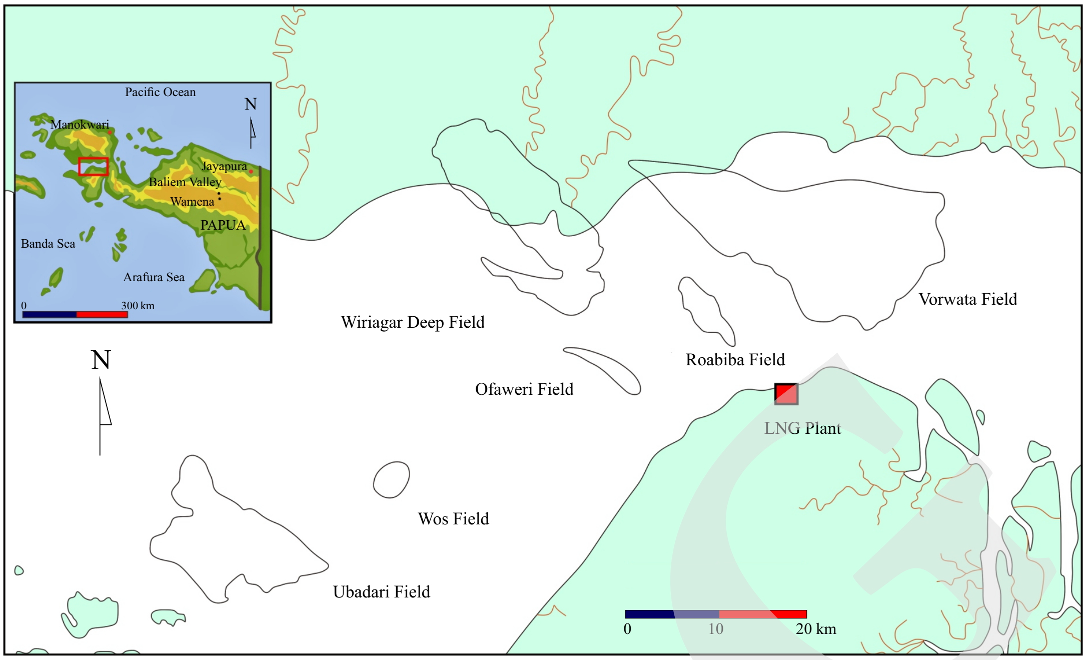

Figure 15. Location of Tangguh Area, Bintuni Basin, Papua (simplified from Marcou *et al.*, 2004).

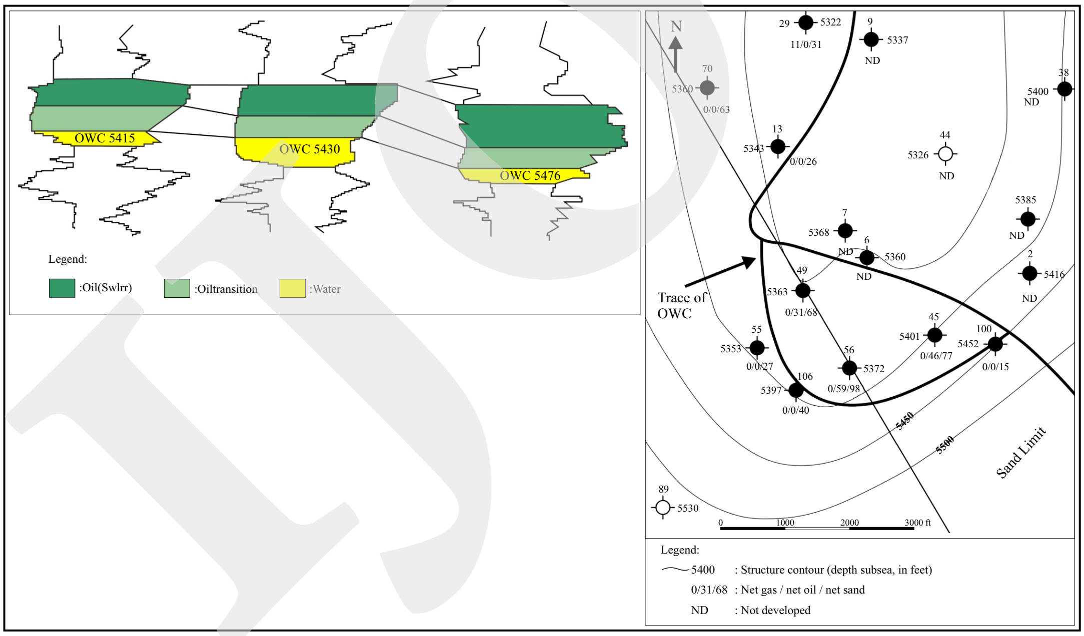

Figure 16. A schematic showing tilted hydrocarbon water contact in Badak Field (cross section not to scale) (redrawn and slightly modified from Cockroft, 1987).

tion that an active lateral drainage is present in this field. The active drainage is caused by Baong mudrock dewatering as indicated in the figure.

Ramdhan *et al.* (2012) challenged the interpretation of the presence of perched water to explain variable gas water contact in the Vorwata Field, Tangguharea, Bintuni Basin, Papua (Figure 19), as proposed by Marcou *et al.* (2004). Instead, they proposed that hydrodynamics is the cause of the variable gas water contact, thus hydrodynamically tilted hydrocarbon water contact. Their argument was mainly based on the presence of water at the highest structural point that cannot sufficiently be explained by the perched water concept.

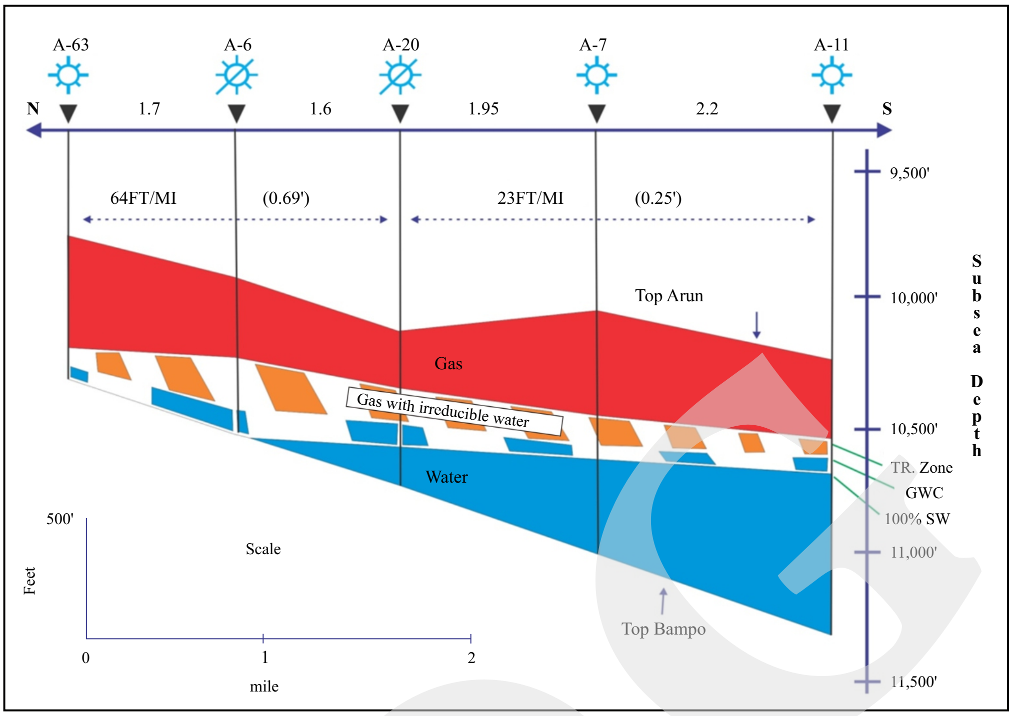

Figure 17. Tilted gas-water contact in the Arun Field (redrawn from Budiono, 1988).

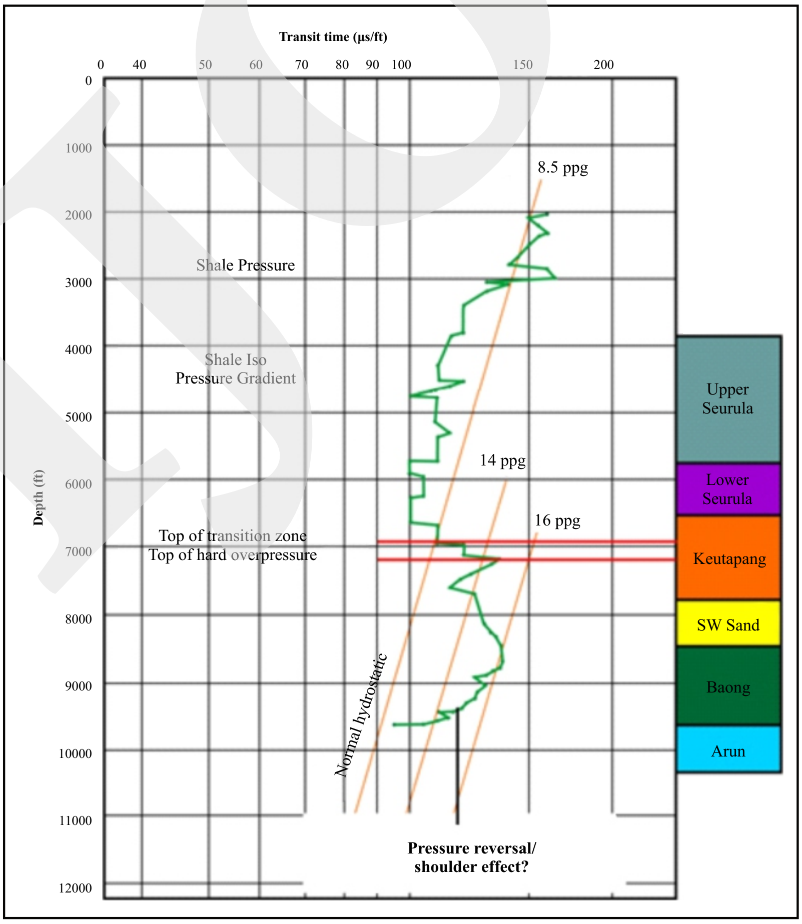

Figure 18. Shoulder effect indicating active lateral drainage in the North Sumatra Basin (redrawn from Aziz and Bolt, 1984).

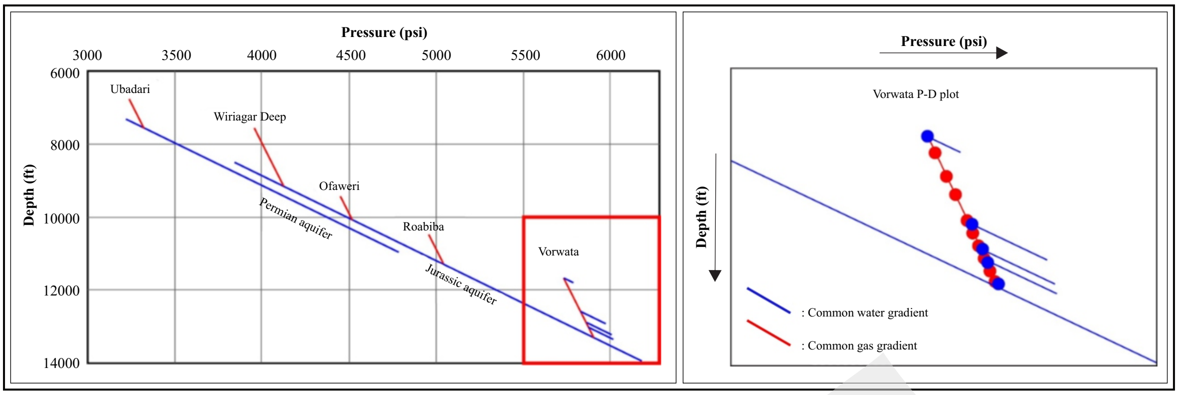

Figure 19. Variable gas-water contact in the Vorwata Field, Bintuni Basin (redrawn and slightly modified from Marcou *et al*., 2004).

Hutasoit *et al*. (2013) proposed the opportunity of the presence of lateral reservoir drainage in Mid Baong sandstone in the North Sumatra Basin. The Mid Baong Sand is turbiditic sand encased in thick overpressured Baong Mudrock (Figure 20). Further, they investigated the presence of shoulder effect in Baong Mudrock that is in contact with Mid Baong Sand indicating an

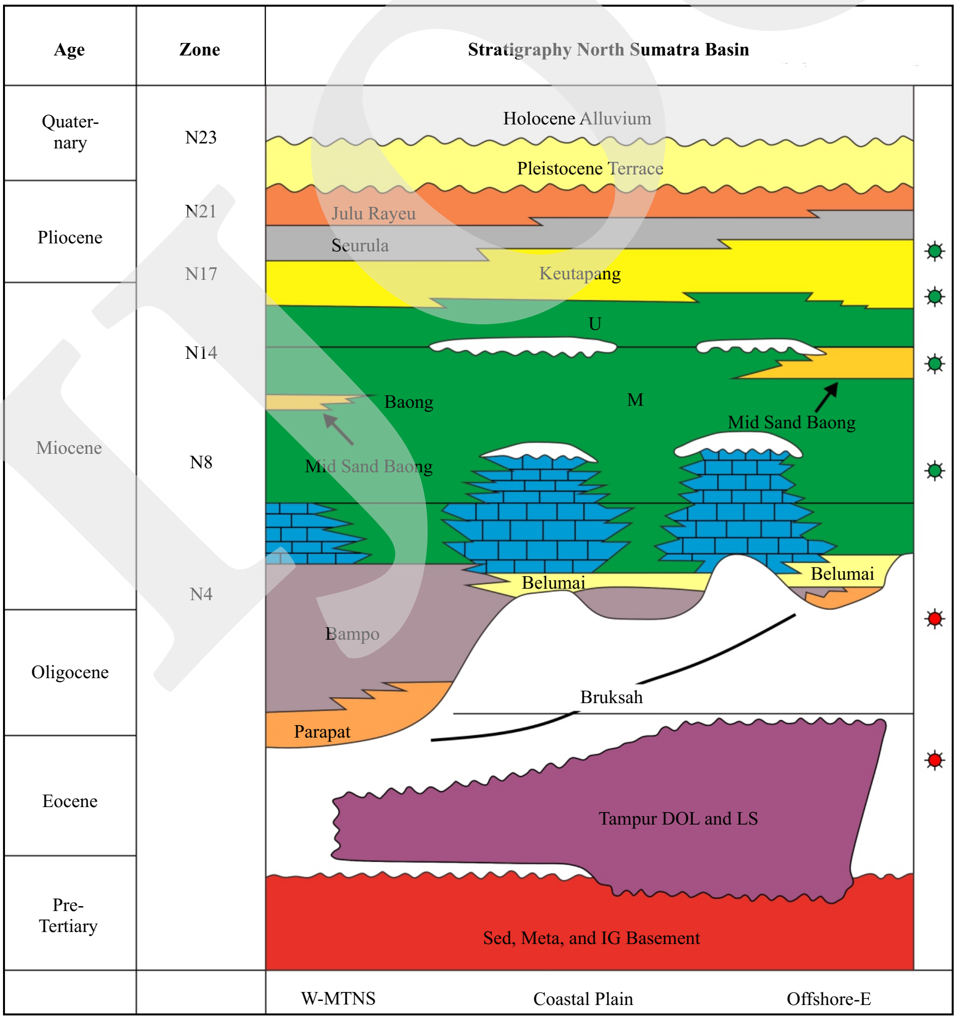

Figure 20. Mid-Baong Turbiditic Sand encased in the overpressured Baong Mudrock (modified from Pertamina BPPKA, 1996).

active dewatering, thus active fluid flow, from Baong Mudrock to Mid-Baong Sand. Since the Mid-Baong Sand crops out, for example to the west in the Barisan Mountain area, it is conceivable to hypothesize that lateral reservoir drainage is present in the Mid Baong Sand, and it may lead to the presence of hydrodynamic trap in this sand.

Recently, Surdaudaja (2017) investigated the presence of reefal limestone-mudrock pressure difference in BD Field, offshore portion of the East Java Basin, in Madura Strait. The limestone is located just below highly overpressured mudrock. He interpreted that the so-called 'thief zone' is responsible for the pressure difference. It is a sandstone layer attached to the reefal limestone and connected over relatively wide area (Figure 21). Some fluid from the reefal limestone dissipates through the sand, and therefore, it causes active hydrodynamic flow to be occurring in both reefal limestone and the sandstone. This circumstance makes hydrodynamic trap due to lateral reservoir drainage is plausible to occur in this basin. Moreover, it is known that the basin contains highly overpressure mudrock (*e.g.* Ramdhan *et al.*, 2013), which is required to maintain active lateral reservoir drainage.

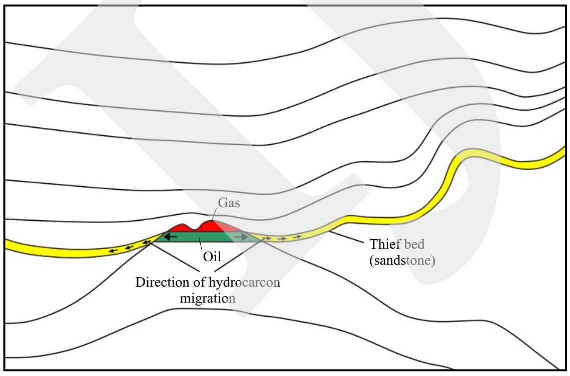

Figure 21. Cross section conceptual model of the 'thief zone' (not to scale).

Discussion

Lateral reservoir drainage leading to hydrodynamic trap of oil and gas has been proven to be present at Tunu, Peciko, and Nilam Fields in the Lower Kutai Basin. In this basin, several indications of hydrodynamic trap in forms of tilted hydrocarbon water contact have also been observed. Based on these circumstances, it is interpreted that the lateral reservoir drainage is a basin-wide phenomenon in the Lower Kutai Basin. The direction of the lateral drainage is more to the onshore, or in sedimentological terms of the deltaic environment, it is more to the proximal area, where the sand is abundant compared with the medial or distal area. Moreover, most of the reservoirs crops out on the onshore area, providing pressure difference between overpressure reservoirs at more distal compared with more proximal area. A schematics showing the direction of the lateral drainage in the Lower Kutai Basin is given in Figure 22.

Ramdhan and Goulty (2011) discussed the cause of overpressure in the Lower Kutai Basin. They came up with the conclusion that the dominant factors causing overpressure in this basin are clay diagenesis and gas generation, and they are still active until the present time. Therefore, it can be inferred that active lateral drainage in the Lower Kutai Basin is maintained by fluid resulted from the above processes.

As discussed by Hutasoit and Ramdhan (2014), the western Indonesia's Tertiary basins have a similarity in terms of overpressuring and their associated basin development. Overpressure in those basins is mainly located in thick marine mudrock of sag deposit. One of the most productive reservoirs in those basins is reefal limestone located just below highly overpressured mudrock (*e.g.* Arun Limestone in the North Sumatra Basin and Kujung Limestone in the East Java Basin both onshore and offshore) (see Figure 20). Therefore, the possibility of the presence of lateral reservoir drainage in other basins which share the similarity is plausible.

Moreover, turbiditic sandstone located within the thick marine mudrock deposit is also quite common in the western Indonesia's Tertiary basins, as observed in the North Sumatra Basin (Mid-Baong Sand). The last regional tectonic event, *i.e.* Plio-Pleistocene uplift, causes the sandstone to be uplifted and

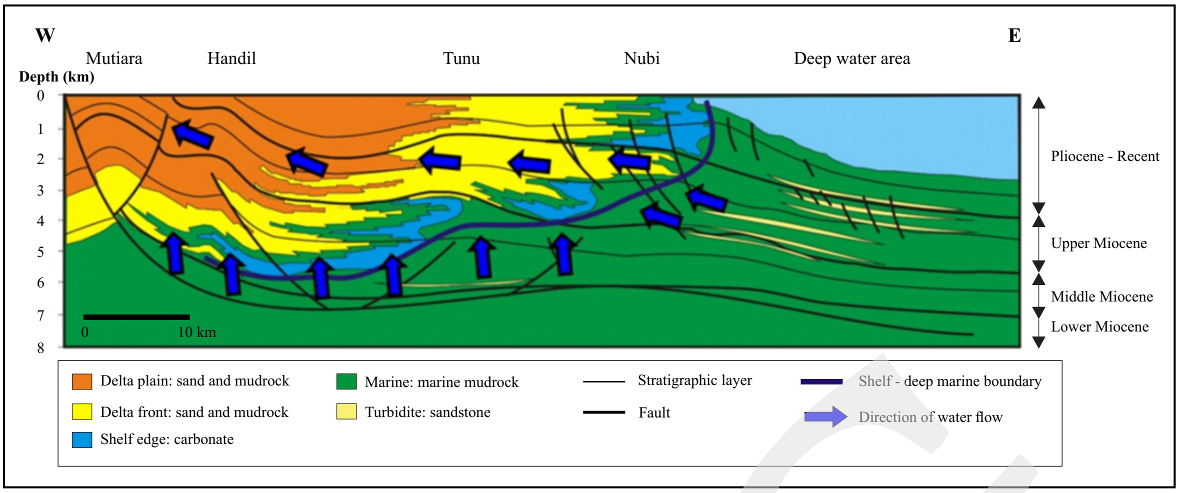

Figure 22. A schematic of lateral drainage (blue arrow) in the Lower Kutai Basin (modified from Total E&P Indonesie, 2003).

exposed. This circumstance is very plausible for lateral reservoir drainage within the sandstone to occur, and it may lead to the presence of hydrodynamic trap.

The success story in the Lower Kutai Basin (Peciko and Total) is driven by abundant pressure data. For example, in the Peciko Field, a well could have around 100 direct pressure measurements obtained from repeat formation test (RFT). As discussed in section Theoretical Overview, the main data source for hydrodynamic analysis is pressure data. Without this data, the suggestion of the presence of hydrodynamic trap will never be conclusive.

Conclusions

From the above discussion, it can be concluded that hydrodynamic trap caused by lateral reservoir drainage has been proven to be present in the Lower Kutai Basin. Based on the abundant indications of tilted hydrocarbon-water contact in this basin, it is also concluded that a lateral reservoir drainage is present in basinal scale in the Lower Kutai Basin. The tilted hydrocarbon-water contact is also observable in several basins in Indonesia, in overpressured section. This type of trap is still under-explored in Indonesia, and therefore there is still a big opportunity to find hydrodynamic traps in Indonesia's sedimentary basins.

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