

# **Hydrodynamic Trapping, Tilted Contacts and New opportunities in Mature Onshore Kutei Basin, East Kalimantan, Indonesia\***

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Search and Discovery Article #41060 (2012)

Posted October 29, 2012

\*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG International Conference and Exhibition, Singapore, September 16-19, AAPG©2012

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## **Abstract**

The role of hydrodynamic mechanism as a cause of tilted hydrocarbon-water contact has been discussed since the 1950's. Hydraulic gradients caused by topographic elevation differences between surface recharge in hinterland area and discharge in basinal lowland area that makes formation water flow is identified as the source of the hydrodynamic force. Another cause of the hydrodynamic force is correlated to formation fluid flow expelled from overpressure toward normal pressure sediments in the deep subsurface. However, the idea of a hydrodynamic role in tilting hydrocarbon-water contact is frequently debated. Other controls are discussed by several authors, such as lateral permeability variation. The permeability variation causes lateral height difference in transition zone which makes the hydrocarbon-water contact seen as "tilted". The onshore Kutei Basin in East-Kalimantan, in which acquisition of exploration and production data are very extensive, provides a unique opportunity for an integrated analysis to contribute solutions to the controversy related to the tilted-contact phenomena.

Gas-water contacts (GWC) are identified as tilted in the deep G reservoir series connected to overpressured shales in the Kutei Basin. The tilting of the GWC is triggered by existence of the hydraulic gradient of water legs in opposite anticline flanks. The higher pressure gradient of water legs in one flank provides the hydrodynamic force to push the GWC to a higher structural position in one flank. Thus, the center of gas accumulation becomes shifted from the crestal anticlinal structure to the flank area. At the same time, shallow E reservoirs unconnected to overpressured shales have a flat GWC. Water legs in the opposite anticlinal flank of the shallow reservoirs are identified as having normal hydrostatic conditions. The hydrostatic condition in the opposite water legs does not provide energy to tilt the GWC as in the overpressured-influenced reservoirs. Understanding of hydrodynamic roles in the tilted GWC has opened new opportunities for further development in flank areas.

## Introduction

A key role of the hydrodynamic trapping mechanism in generation of tilted hydrocarbon-water contacts was initially introduced in the 1950's by King Hubbert (Hubbert, 1953; Hubbert, 1967). Since then, other works have been published discussing the topic with examples from several fields around the world (Thomassen and Jacobsen, 1984; Wells, P.R.A., 1988; Elsenberg et al., 1994; Grosjean et al., 1994; Lies and Letourneau, 1995; Lambert et al., 2003; Zawisza et al., 2005; Grosjean et al., 2009; Zawisza, 2006). The hydrodynamic theory is triggered by the fact that water in many hydrocarbon bearing formations is in regional motion or flow conditions. Under this hydrodynamic condition, hydrocarbon trapping may behave markedly both in position and in attitude (i.e. tilted) from those under hydrostatic conditions (Hubbert, 1967). The force of the hydrodynamics that cause the formation water to flow regionally is generated by the potential energy difference of the water, known as the regional hydraulic gradient due to topographic relief. The water flows from recharge areas in high elevation hinterland to low elevation areas. Such hydrodynamic gradients are capable of tilting hydrocarbon accumulations (Hubbert, 1967; Lies and Letourneau, 1995). Another cause of hydrodynamic force is deep formation water flow expelled from very thick overpressured shale-dominated sediments which are drained laterally toward lower pressure, higher permeability deltaic strata (Grosjean et al., 1994; Lambert et al., 2003; Grosjean et al., 2009). In spite of much documentation in the role of a hydrodynamic mechanism controlling tilted hydrocarbon-water contact, the idea is still debatable in that other scenarios may play key roles in the tilting, such as permeability and porosity, tectonics, fluid density, and thermal convection (Yuster, 1953; Stenger, 1999; Stenger, 2001; Carlos and Cesar, 2000).

The onshore Kutei Basin in East Kalimantan is a hydrocarbon prolific basin in Indonesia ([Figure 1](#)). The basin had been explored for oil and gas since the early 1960's. Nevertheless, aggressive exploration and production were started only in the late 1990's. The basin is currently in a mature stage, but exploration and production activities are still at their peak. The intensive oil and gas exploration and production activities in the basin provide a complete set of data packages that can be used to contribute solutions to the controversy related to causes of tilted hydrocarbon-water contact phenomena. The objectives of this article are to demonstrate: (1) how tilted gas-water contacts are identified in deep G reservoir series, (2) how the hydrodynamic trapping mechanism plays a major control in generation of the tilted contact, (3) how a new model of the tilted gas-water contact leads for opportunity identification in a field's development.

## Geological Setting

[Figure 1](#) shows the location of the study area. It is located in the hydrocarbon prolific mature Kutei Basin in East Kalimantan Indonesia. Major oil and gas fields in this basin are SW-NE trending, parallel to regional structure of the area. The study area is an anticlinal structure trending SW-NE. The anticline is a simple structure popping-up from eastward dipping regional stratigraphy. No major faults are identified crossing productive intervals. Stratigraphy in this area is characterized by multi-layered sandstone interbedded with shale and coal. The lithologies are deposited by a complex fluvio-deltaic environment of the Mahakam River which has been active since Early Miocene to Recent time.

## Hydrostatic Trapping Model

Common reservoir modeling in the area uses a flat gas-water contact to picture gas distribution in a reservoir. As shown in [Figure 2](#), initial gas-water contact in one of the E reservoirs is identified at a depth of -9718' subsea. The contact is defined by fluid sampling during logging, water-saturation analysis and supported by gas readings in the mudlog. Development wells drilled above the contact are proven as gas producers. Pressure data acquired during logging in intervals below GWC on wells drilled on opposite flanks (east and west flank) show that water legs in the east and west flanks have similar pressures (8.3 ppg). The water legs of this reservoir are at hydrostatic conditions. The concept of a flat gas-water contact works well in the E reservoir. Nevertheless, when the concept is applied to deep G reservoir series, it rises several uncertainties.

The anomaly to the concept of a flat GWC is observed in most reservoirs in the deep G sandstone series. In [Figure 2](#) a flat GWC is used to model gas distribution in one of the deep G reservoir series. The deepest gas leg at -13,489' subsea is penetrated by well N56 drilled in 1981 at west flank structure. The reservoir in this well was tested and produced an initial gas rate of 6 MMSCFD at 1750 psi FTHP. However, development wells (i.e. N32, N34 and N46) drilled prior to production of this zone and located at higher structural levels in the east flank structure were identified as wet. N32, penetrating the reservoir at -12,556' SS (859' updip of N56) resulted in water in tubing after perforation. N34, penetrating this reservoir at -12,812 SS (603' updip of N56) resulted in no flow after perforation; swabbing conducted after perforation recovered 8.2 ppg formation water with no indication of gas. A similar situation is observed in well N46 which penetrates the sandstone at -13,048' subsea (367' updip of N56). Fluid sampling acquired during logging of the N46 well from this reservoir recovered 45 liters of 5227 ppm formation water. The data show that wells drilled in the east flank area have water legs at higher structural positions than the wells drilled in the west flank area. The GWC in this reservoir is structurally shallower in the east flank than in the west flank. This situation leads to a hypothesis that GWCs in the deep G reservoir series are not flat as observed in the shallow E reservoir.

## Hydrodynamic Trapping Analysis

A hydrodynamic analysis approach is carried out to find solutions for the hypothesis of whether GWCs in the deep G reservoir series are flat or not. For the analysis, remodeling to a geological model, especially reservoir connectivity analysis, was carried out first. After the geological model achieved a high confidence level, all data that can lead to understanding of pore pressure distribution in the study area were collected and thoroughly analyzed.

An example of the geological remodeling results is shown in [Figure 3](#). One of the G reservoir series is a giant meandering channel with abnormal aspect ratio of the valley system (3 km wide and 40 m thick). The giant meandering channel is interpreted as an Incised Valley Fill (IVF) deposited as a back-stepping sequence during a relative sea level rise, based on the integrated interpretation of all available core, well and 3D seismic data (Butterworth et al., 2002). It consists of multistory channel sandstones which amalgamated into a single thick reservoir. Pressure data acquired in wells penetrating this reservoir prove good connectivity within the reservoir. The pressure data in wells drilled in different years follow a single depletion trend during production.

[Figure 4](#) shows analysis results of all data that can lead to understanding of pore pressure distribution in the study area. Seismic velocity section in a west-east direction shows that the top of overpressure is crossing, or non-parallel to, regional stratigraphic markers. Top of overpressure is characterized by a reversal in velocity versus depth in the seismic velocity section. The reversal characteristic of velocity at top of overpressure is also observed in one deep well (N109). The seismic velocity section shows that the top of overpressure is tilted to the west which is shallower at the east flank and becomes deeper toward the west flank. The top of overpressure is regionally tilted to the west. In addition to the seismic velocity section, pressure data acquired in water sands and mud weight used during drilling also support the phenomena of the westward-tilted top of overpressure. Pressure and mud weight data acquired in wells drilled in the east flank area show that overpressure starts at a depth of -12,000' subsea. Meanwhile, wells drilled to TD at -14,000' subsea in the west flank area had not reached the top of overpressure. There is a more than 2000' depth difference in the onset of overpressure between east and west flanks.

Detailed analysis of pressure data acquired in the above example of G sandstone also strongly supports that the top of overpressure in this sandstone is tilted to the west ([Figure 5](#)). Pressure data acquired from water sand in east flank wells show 8.65 ppg which is higher than normal hydrostatic pressure, meanwhile those acquired from water sand in west flank wells are 8.2 ppg, which are at normal hydrostatic pressure. The pressure difference proves that there is a hydraulic pressure gradient westward in the water legs. The westward hydraulic pressure gradient generates hydrodynamic forces in the G reservoir which then tilts and shifts the center of gas accumulation to the west flank area. The hydrodynamic forces make the GWC position shallower in the east flank than the west flank. A plot of depth versus pressure acquired in wells penetrating this reservoir prior to production also supports the tilted of GWC ([Figure 5](#)). As seen in the pressure plot, the gas trend line of wells located in the east flank intersects the water line of east flank at a depth of -12,600' subsea. Meanwhile, the gas trend line of wells drilled on the west flank intersects the water line of the west flank area at a depth of -13,600' subsea. This pressure plot shows that the G reservoir has a GWC about 1000' shallower on the east flank than on the west flank.

### **New Hydrodynamic Trapping Model and Impact to Field Development**

Phenomenon of a tilted GWC is not observed in one G reservoir, but is identified in most G reservoir series in the area. However, the shallow E reservoir series does not show the tilted GWC phenomenon. The seismic velocity section and pressure data plot ([Figure 4](#)) show that the G reservoir series structurally cross the overpressure interval in the east flank, meanwhile these series remain above top of overpressure in the west flank. In other words, the G reservoir series enters the overpressure interval shallower in east flank than in the west flank. The different depth in onset of overpressure triggers hydrodynamic forces due to existence of hydraulic gradients in water sands between the east and west flanks. The hydrodynamic mechanism creates an equilibrium condition of what is now observed as a tilted GWC or shifted gas accumulation centered to the west flank in the G reservoir series.

On the other side, all pressures taken on the shallow E reservoir series have the same magnitude of hydrostatic condition (~8.3 ppg) and have a flat GWC across east and west flank areas. There is no evidence of hydraulic gradient forces that can create a tilted GWC.

The new hydrodynamic model ([Figure 6](#)) leads to significant changes in field development strategy. Since oil and gas has been produced mostly from shallow E reservoirs, major remaining reserves are retained in the deep G reservoir series. Considering the tilted GWC, or shifted gas

accumulation center to the west flank in the G series, the future development strategy of G series needs to be expanded to the west flank rather than the east flank.

### **Conclusions**

Pore pressure distribution analysis, after combined with robust geological models in the study area, reveals a key role of a hydrodynamic trapping mechanism in generation of tilted GWC or shifted gas accumulation center to the west flank in the deep G reservoir series. The hydrodynamic trapping is triggered by existence of a hydraulic pressure gradient in water legs of the reservoir. The hydraulic pressure gradient is caused by differential onset depth of overpressure between the east flank and west flank areas. The phenomena of tilted GWC are not observed in the shallow E reservoir series. Water legs of the E reservoirs are at hydrostatic conditions, having the same pressure gradient. The same pressure gradient in the water legs does not provide any hydrodynamic forces in the reservoirs. This zero hydraulic pressure gradient makes the GWC in the shallow E reservoirs flat. A new hydrodynamic model of tilted GWC or shifted gas accumulation center to west flank area in the G reservoir series has significantly changed development strategy in the area. The west flank has now become the target location for future development to produced reserves retained in the G reservoir series.

### **Acknowledgement**

We would like to acknowledge VICO Indonesia for permission to publish this paper. We would also like to thank co-workers in VICO Indonesia who have contributed to development of the idea discussed in this article.

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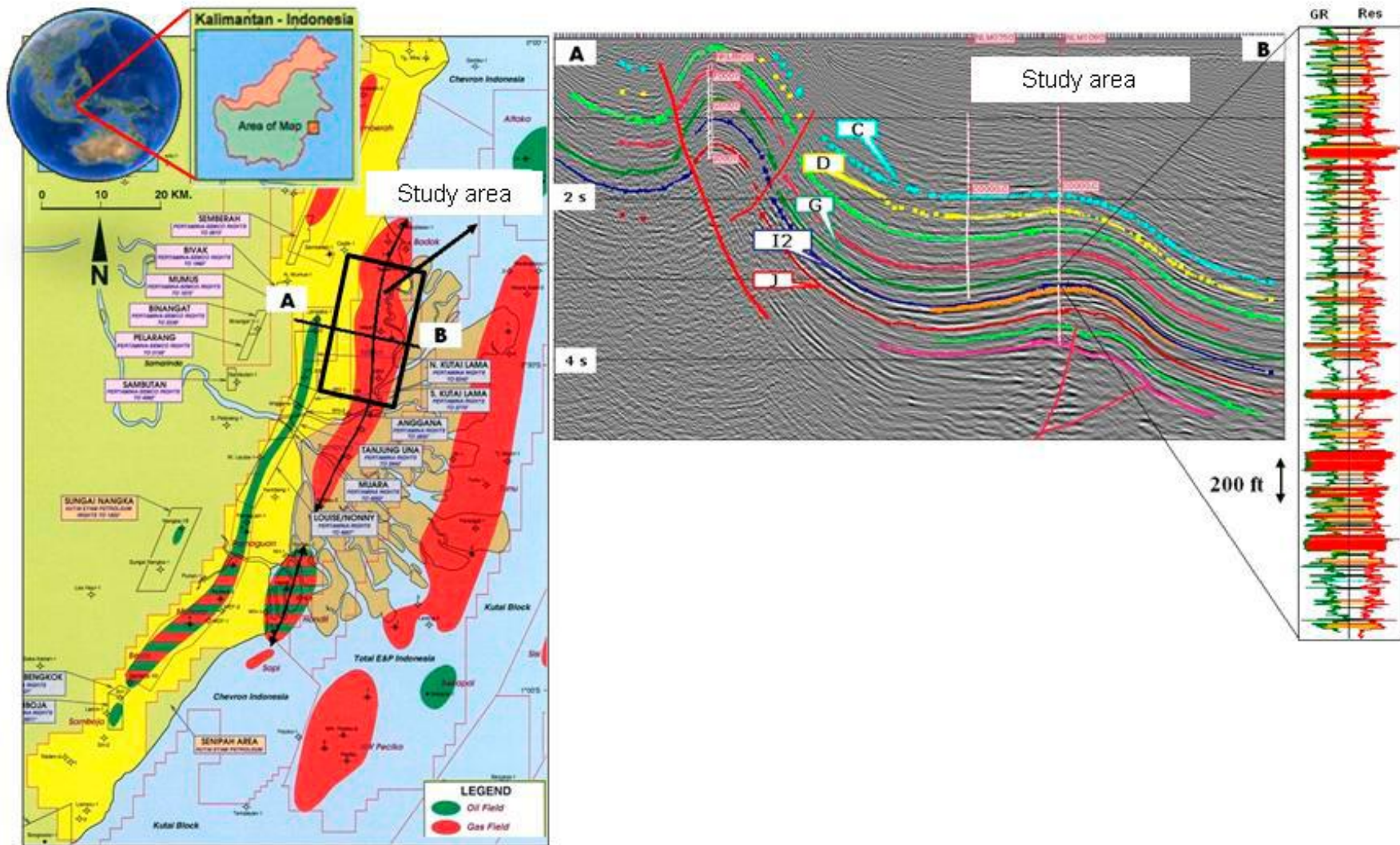


Figure 1. The study area is located onshore East Kalimantan Indonesia and is in part of the mature, prolific Kutei Basin. The study area is a simple anticlinal structure trending SW-NE. Stratigraphy in this area is dominated by interbeds of multi-layer sandstones, coals and shales deposited by the Mahakam River which has been active since Early Miocene to Recent time.

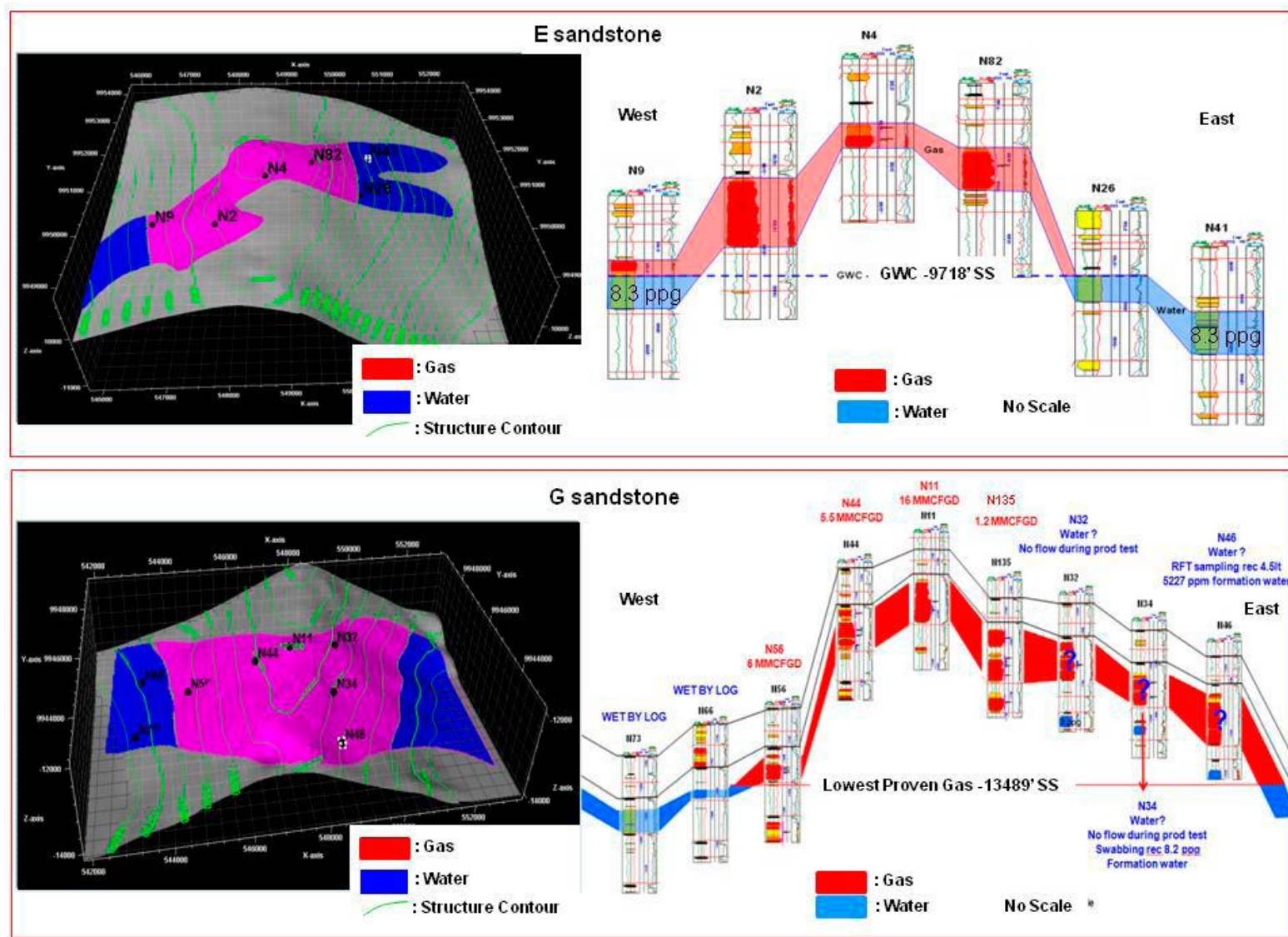


Figure 2. Gas distribution model using assumption of hydrostatic condition or flat GWC. A shallow E reservoir has a flat GWC at depth of -9718' subsea. Nevertheless, the model of flat GWC rises questions when applied in the deep G reservoir series. N32, N34 and N46, which are located in the east flank at shallower structural positions than modeled flat GWC position, tested wet during production and RFT sampling.



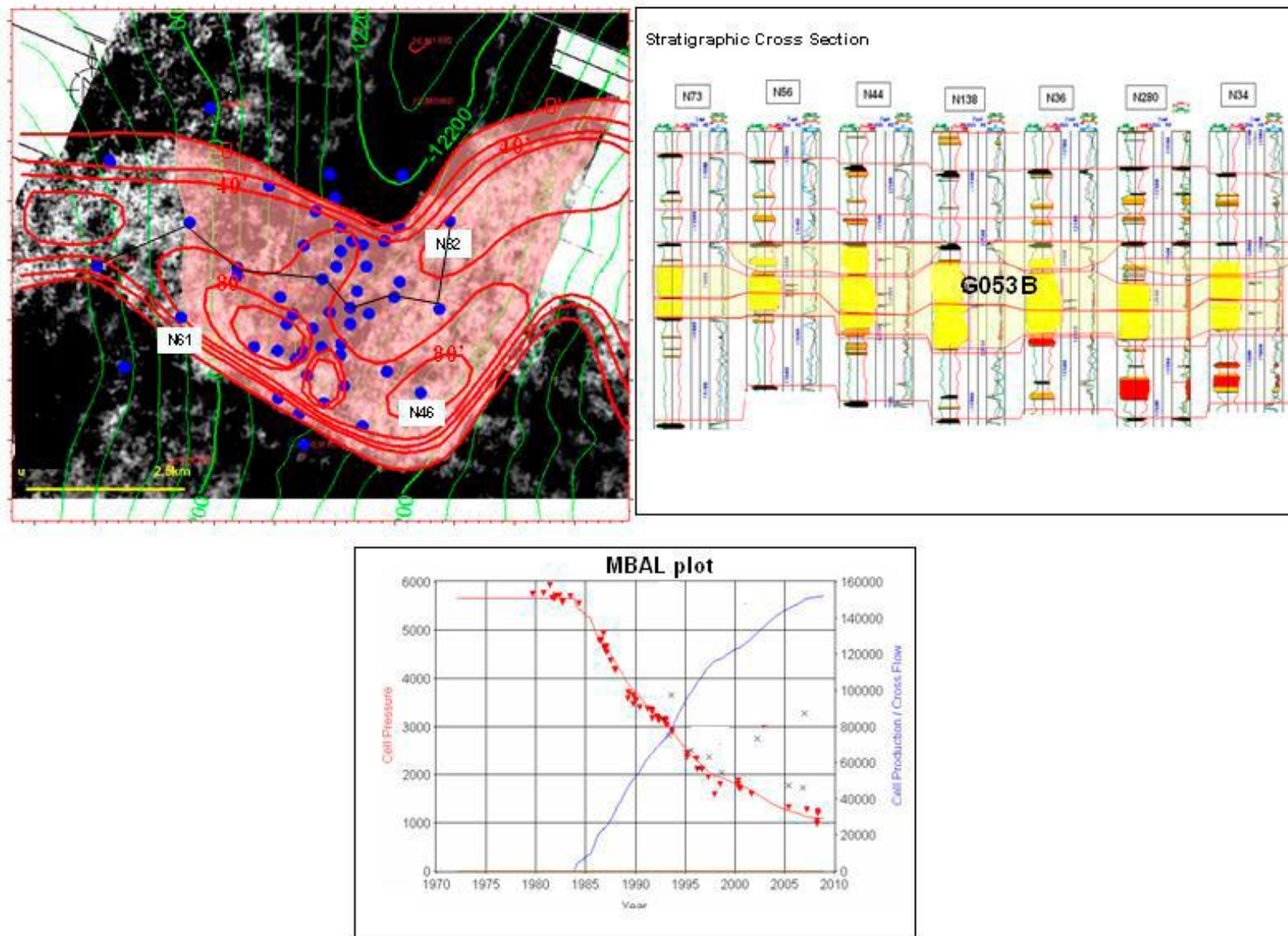


Figure 3. An example of geological remodeling on one of the G sandstones prior to hydrodynamic trapping analysis. Distribution of the sandstone is mapped using seismic, well-log and pressure-production history data. The data provide a high confidence of sand distribution and connectivity.

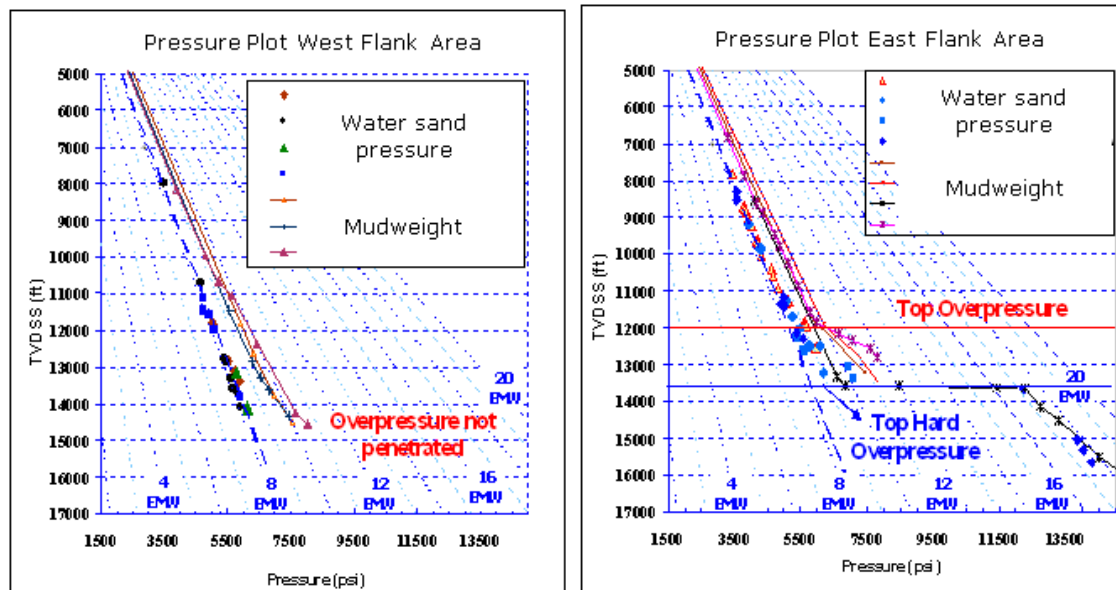
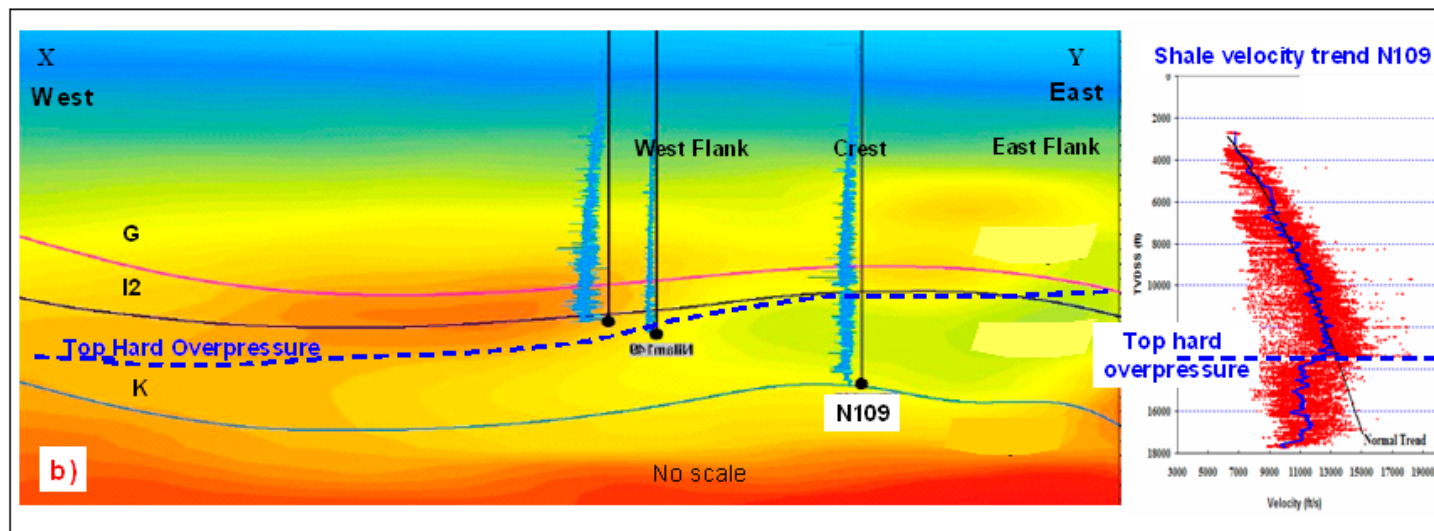


Figure 4. Data generating a better understanding of pore-pressure distribution in the study area. Seismic velocity section shows a tilted top of overpressure westward crossing or non-parallel to regional stratigraphic markers. The top of overpressure is identified by reversal in the velocity versus depth. Plot of virgin water-sand pressures and mud weight used during drilling versus depth also support the tilted top of overpressure. Overpressure starts at a shallower depth in the east flank than the west flank area.



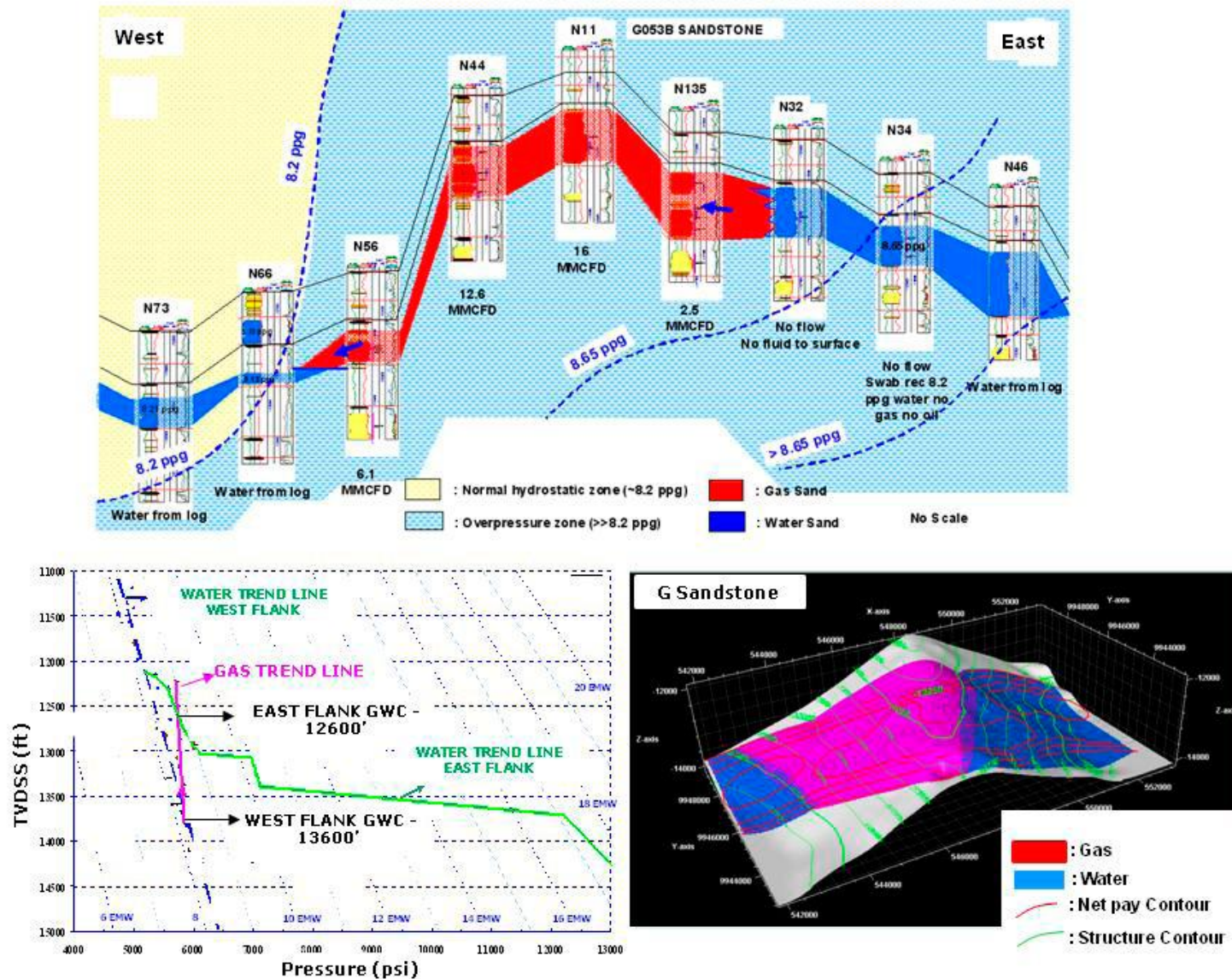


Figure 5. A new gas distribution model in one of the G sandstones. The G sandstone has a tilted GWC toward the west flank. The tilting of the GWC is caused by a pressure difference between the east and flanks. Pressure plot of gas trend line and water trend line on both flanks shows a 1000' shallower GWC in the east flank area than the west flank.

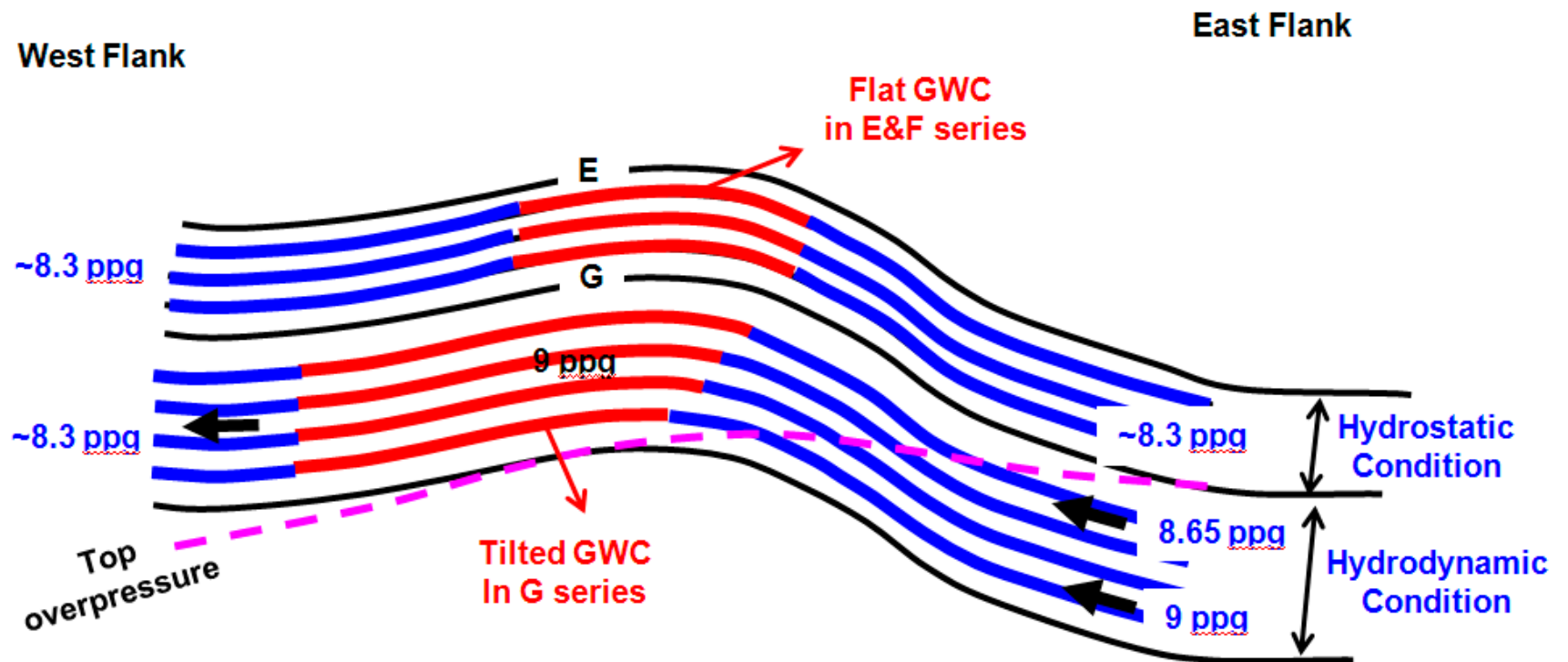


Figure 6. New model of GWC in the study area. The shallow E reservoir series has water legs at hydrostatic conditions with a flat GWC and gas accumulation centered at the crest of the structure. Meanwhile, hydrodynamic forces triggered by differential pressure gradient in the water legs of the deep G reservoir series has tilted the GWC, shifting the gas accumulation center toward the west flank.