HYDROCARBON RETENTION IN CLASTIC RESERVOIRS OF NW BORNEO - EXAMPLES OF HYDROCARBON TRAP, RESERVOIR, SEAL AND IMPLICATIONS ON HYDROCARBON COLUMN LENGTH

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ABSTRACT

Several siliciclastic fault-trap settings of the NW Borneo margin, from the West Baram Delta covering offshore Sarawak and Brunei to offshore NW Sabah, are compared with each other to assess the intricate relationship between hydrocarbon retention, seal capacity and reservoir parameters. Hydrocarbon column length is found to be a derivative of several parameters potentially affecting the integrity of a hydrocarbon trap. The presence of an effective and laterally continuous top seal is perhaps the most important success parameter; though relatively thin top seal can be surprisingly efficient. Seal capacity is featured by parameters such as mineralogy, grain size, contiguity, diagenesis and lateral continuity. Contiguity of hydrocarbon reservoirs is also important as discontinuous reservoir bodies commonly lead to very short and variable columns. The overall sand-to-shale ratio governs to some extent clay gouging capacity, with hydrocarbon columns tending to be longer in overall clay-prone environments, such as those found in outer shelf and deepwater turbidite environments. In these depositional settings, P50 columns are in the order of 250 m because sand-to-clay juxtaposition is more likely in fault-controlled traps. A better fault seal is often realized due to good shale gouge. However, hydrocarbon columns tend to be short (P50 of around 30 m) in sand rich shallow marine to deltaic settings given the discontinuity of reservoirs, leaky top seal, abundant yet discontinuous reservoir sand bodies and poor fault sealing capability. It is also observed that there are patterns of parameters such as sealing, reservoir, pressure and drive that have been identified, and combinations that appear viable (probabilistic success patterns) and non-viable for hydrocarbon retention (probabilistic failure patterns). The authors thus suggest to develop plausible patterns/ scenarios and apply probabilistic simulations to each of the various combinations to assess the likely outcomes for column length predictions.

Key words: *column length, hydrocarbons, reservoir, seal, NW Borneo*

INTRODUCTION

The oil and gas accumulations found along the coastline from Miri to the Kudat Peninsula are relatively young, namely during the Neogene and Quaternary (Figure 1). The hydrocarbon habitats originated during the Late Oligocene in areas between Borneo and Vietnam. The continental crust was stretched by a failed rifting that led to the formation of several SW-NE striking grabens, of which the most prominent feature is called the NW Borneo Foredeep (Figure 1). Today's topography can be largely attributed to the original phase of crustal stretching, with a noted overprint of compression, inversion and gravity deposits (Jong et al., 2014a & 2015; Kessler and Jong, 2016).

As shown in Figure 1, the foredeep runs parallel to the Borneo coastline, and its hinterlands that are formed by folded deep marine meta-sediments and a handful of mafic intrusive bodies. Mass balancing studies by the authors carried out in Sarawak onshore suggest that the mountain ranges in Northern Sarawak as well as the Rajang/Crocker mountain belt have seen rapid uplift and subsequent erosion in the order of 6000-8000 m (Kessler and Jong, 2015a; Jong et al., 2016a), and huge quantities of sediments were delivered and led to the formation of sandy reservoirs and claystones both on the shelf and within the deepwater settings. Furthermore, volcanic activity located from the Java and Philippine arches has likely delivered ash to the evolving depocentres.

On closer inspection, however, it is realized that mechanisms other than extension were at work, too. In purely descriptive terms, the areas of Sarawak and Sabah can be described as a mosaic of tectonic blocks. These are endowed with varying degrees of rigidity, and responded in different ways

to compression. The latter originated as result of a Miocene continent-to-continent collision between the Australian Plate and Sundaland (e.g., Hutchison, 2005), of which Borneo forms the south-central part; such tectonics led to inversion, and reverse faulting/thrusting in parts of the basin (Jong et al., 2015; Kessler and Jong, 2016). Inversion features are common in both Sarawak and Sabah, and predominantly affected areas of the paleo-shelf and paleo-slope. Through the process of folding and uplift, areas of the former shelf were eroded and became sources of sediment, the latter re-accumulated in deeper portions of the basins of NW Borneo Foredeep (Figure 1, Gartrell et al., 2012).

A third and equally important process is gravity gliding. Dislocated bodies such as overthrust imbricates, as well as mass flow deposits dominate the slope and abyssal setting. Areas in the foredeep are indicative of a narrow and relatively steep slope margin, areas of which collapsed and slid basinward repeatedly (Jong et al., 2016b).

On the long journey from recognizing a potential hydrocarbon trap to discovery, development and finally commercial success, there can be room for wrong assumptions and pitfalls. Quite often it is seen that exploration approaches are too clinical in the sense that play and prospect elements are dealt with in isolation, without sufficiently acknowledging interdependence of parameters, as well as treating each prospect as a combination of parameters and not as a genuine feature. The length of a hydrocarbon column might be one of the most decisive factors for or against the economic viability of a field, yet it is one of the most elusive constituents to define and predict. Empirical analysis can help narrow uncertainty and prevent expensive faulty conclusions. Furthermore, explorers tend to consistently and significantly underestimate geological Probability of Success (POS), and overestimate the success case volumes relative to the available database information on historical exploration success rates and sizes of previously discovered fields (Mirkow, 2017). In particular, one should realize the inseparability of reservoir and seal. Geophysical approaches should take account of the most likely drive mechanism, as well as seismic signal attenuation and signal aliasing. A significant component of risk, however, is vested in the strength of both top seal and fault seal discussed in the following sections.

TOP SEAL RETENTION CAPACITY

Unfortunately, there appears to be a knowledge gap when it comes to understand sealing capacity of a top or bottom seal when a good core calibration of the sealing sequences is hardly ever realized. Although wireline or MWD tools provide useful data, these belong only to one data point and are difficult to extrapolate to the surface of an entire oilfield. Accordingly, we remain ignorant to how much column pressure it can withhold.

In absence of hard data, one may consider a few criteria that may help to establish continuity of both quality and lateral retention capacity of a top seal body, such as:

- Lateral continuity and constant clay isochore thickness: Documented extremely well in deepwater sediments in turbidite reservoirs, although mostly poor in shelfal setting. Marine shelfal sediments beneath the tidal influence can form continuous reservoirs and seal layers, hence are better suited to host contiguous hydrocarbons. Within the tidal range (Figures 2 and 3), however, we observe clay-contaminated reservoir (Figure 4), as well as sandy/silty clay layers. Reservoirs and seals can be scoured, hence limiting potential of good hydrocarbon columns both from the reservoir and seal perspective.

- Vertical anisotropy: Persistent vertical layering in anoxic deepwater clay tends to form potent pressure boundaries; on the contrary, bioturbation, scouring, etc. are common in tidal-influenced deltaic deposits and can lead to seal failure and hydrocarbon leakage.

- Mineralogy: Silt rather than clay sequences that are partly distal turbidite deposits, the beds may also contain clay that originated from volcanic dust, containing minerals such as smectite (Figure 5). Unlike most other basins in the world, NW Borneo deepwater has a siltier top seal with lower clay minerals fraction, rather than clean clay with higher clay minerals fraction (Ngu et al., 2010). This could explain why capillary seal capacity could constitute a dominant control on the hydrocarbon column length in deepwater turbidite setting than the typical four-way dip closure or mechanical top seal capacity. Figures 6 and 7 shown the intricate relationship between turbiditic sands and mass transport deposits (MTDs), the latter also provide capable sealing capacity for hydrocarbon retention (Algar et al., 2007).

- Grain size: Silty seal may hold oil, and/or gas, this being dependent on pore size, capillarity and reservoir pressure. In the capillary seal model presented in Figures 8 and 9, it can be observed that a dominant control on hydrocarbon column length in NW Borneo deepwater depositional setting is capillary seal capacity.

- Diagenesis: It has been shown in deepwater traps, that unconsolidated clay ooze cannot stand much hydrocarbon pressure, and only lithification/diagenesis will lead to a cohesive body which can withstand buoyancy pressure from both oil and gas (Figure 9).

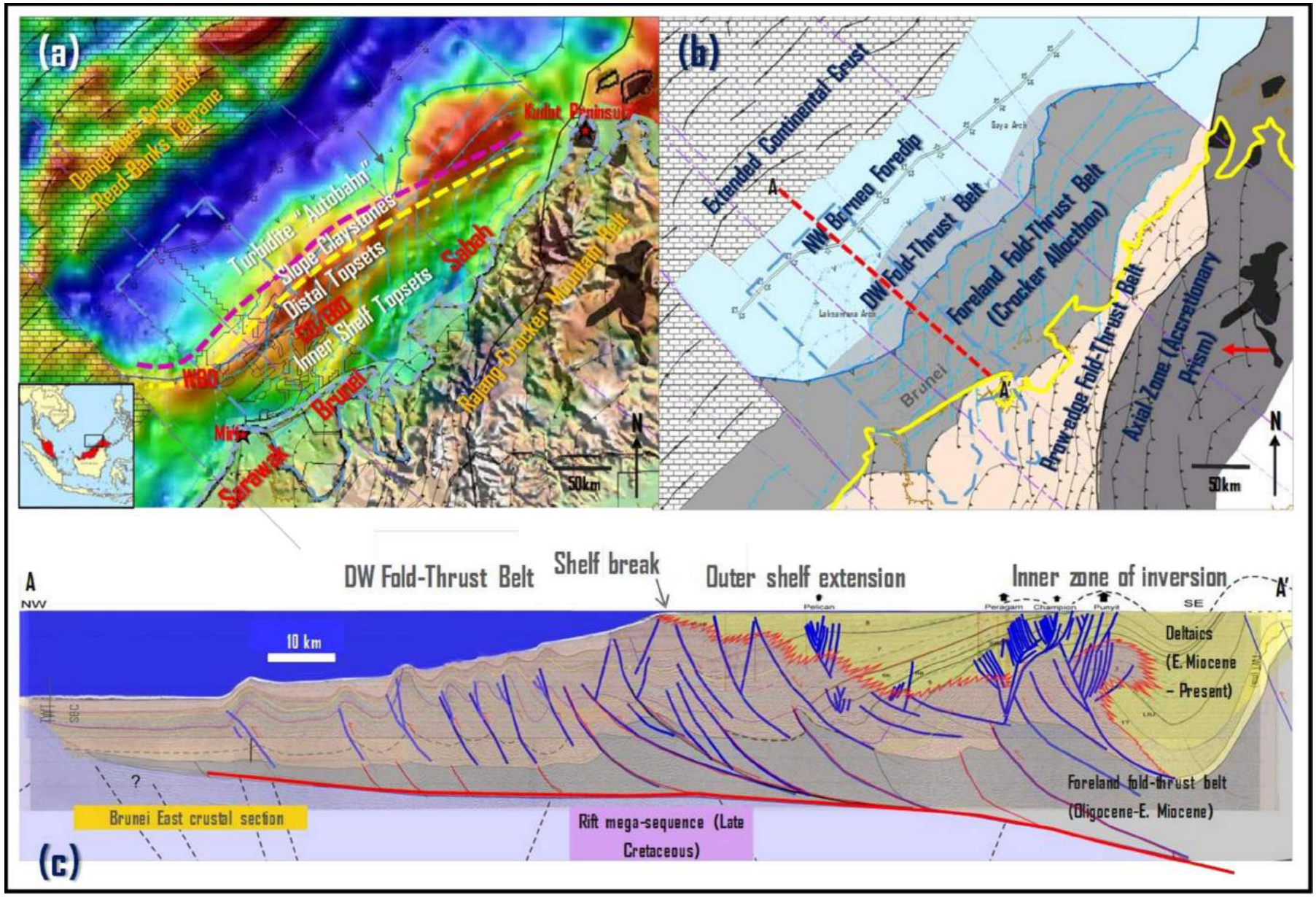


Figure 1: *Tectono-stratigraphic architecture of offshore Sarawak, Brunei and Sabah from Miri to Kudat Peninsula. WBD = West Baram Delta, CD/EBD = Champion Delta/East Baram Delta. (a) Satellite gravity with Digital Elevation Model (DEM) illustrating the zones of inner shelf to distal topset areas, the slope claystone and basinal turbidite depositional settings are approximately defined by the yellow and pink dashed lines. (b) Tectonic elements and mechanical basement map with location of structural section A-A'. (c) Structural section A-A' from inner zone of inversion to outer shelf extension, the slope setting to deepwater fold-thrust belt. Modified from Gartrell et al. (2012).*



Figure 2: *It is important to properly characterize the facies of a reservoir/seal assemblage. Marine shelfal sediments beneath the tidal influence can form continuous reservoirs and seal layers, hence are better suited to host contiguous hydrocarbons. Within the tidal range (of the Pliocene Tukau Formation) as shown in this figure, however, we observe clay-contaminated reservoirs as well as sandy/silty clay layers. Reservoirs and seals can be scoured, hence limiting potential of good hydrocarbon columns both from the reservoir and seal perspective.*



***Figure 3**: Shelfal sediments beneath the wave basis (Canada Hills, Miri) often show layered and contiguous sand and clay bodies, impacting in a positive way column length and STOIIP. Subtidal sandstones tend to have significant permeability variations leading to sub-optimal oil recovery. In Miri, highly continuous and bituminous clay layers, with a thickness of less than 10 cm, and encased within meter-banked clayey and silty rock, provide effective sealing between the reservoir bodies, such that there is no common aquifer support. In the case of the Miri field exploitation, sealing between individual reservoir sands had been largely overlooked with the result that prime quality reservoirs watered out quickly, and a lot of the virgin STOIIP was bypassed and left behind.*

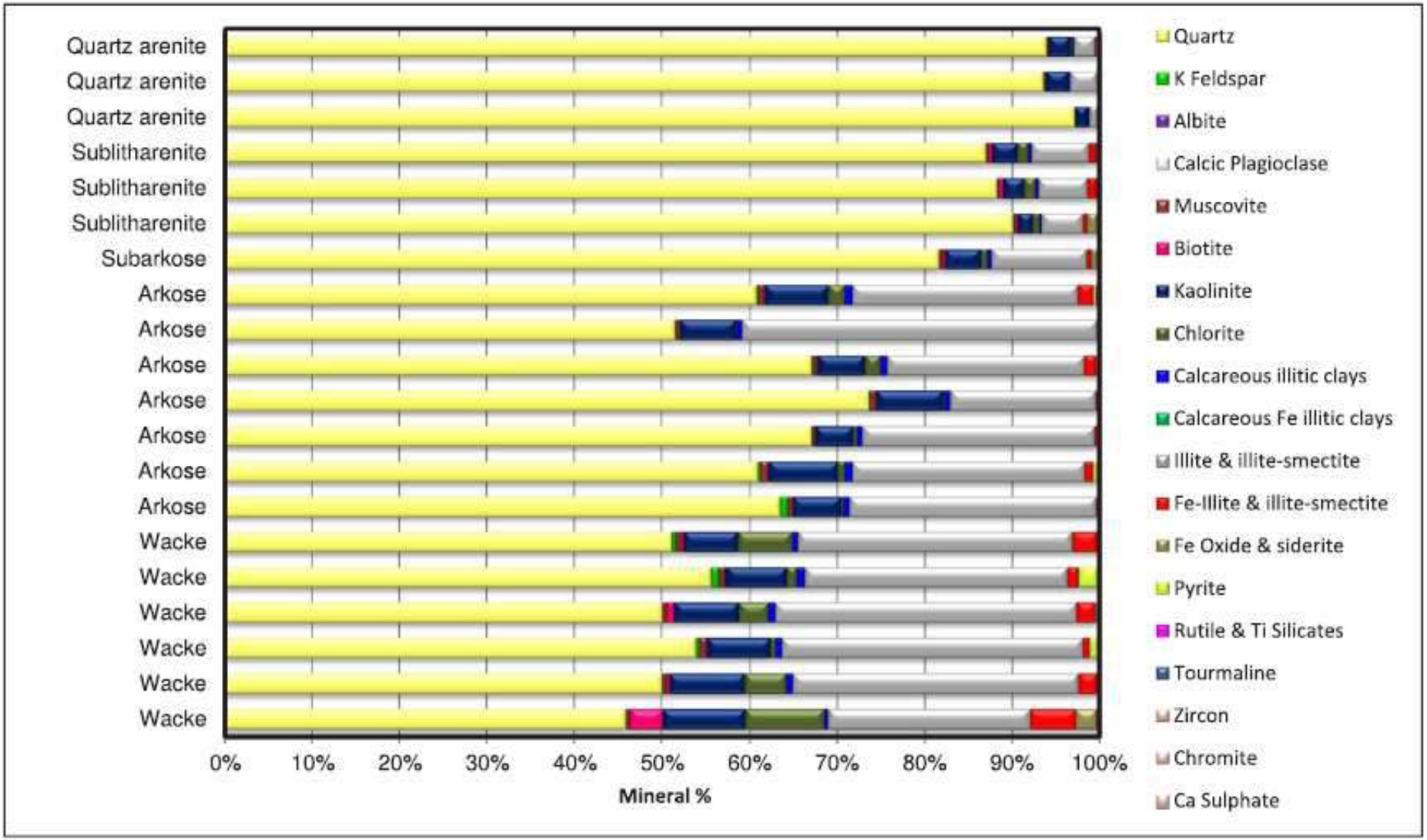


Figure 4: *Bulk mineralogy (in wt%) of sedimentary rocks from the Pliocene Tukau Formation analysed in (Quantitative Evaluation of Minerals by Scanning electron microscopy). Although quartz is the major constituent (46 - 97 wt%), clay minerals also form a significant portion of the studied samples, while K-feldspar occurs in trace amounts (< 1 wt%) and plagioclases are absent. Clay mineral assemblage acomprises illite and illite-smectite (1- 41 wt%) and minor kaolinite (1.5–9 wt%). From Nagarajan et al. (2017).*

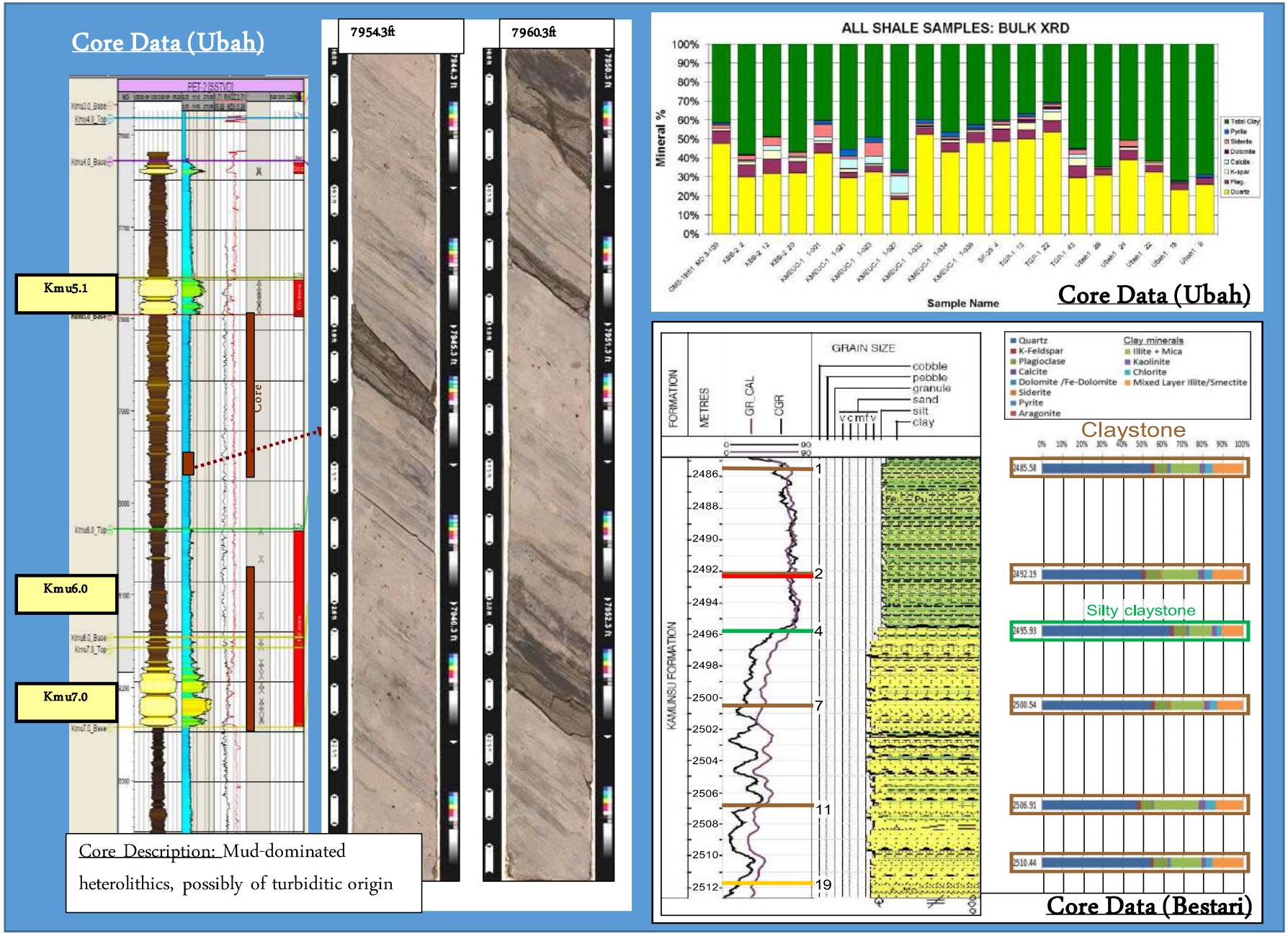


Figure 5: *Mineralogical composition of thin clay intervals in an amalgamated turbidite sequence. Average NW Borneo deepwater shale contains 51% clay minerals (range from 30 – 70%), while average tertiary GOM shale contains 67% clay minerals (modified from Ngu et al., 2010, Bestari data from J. Jong).*

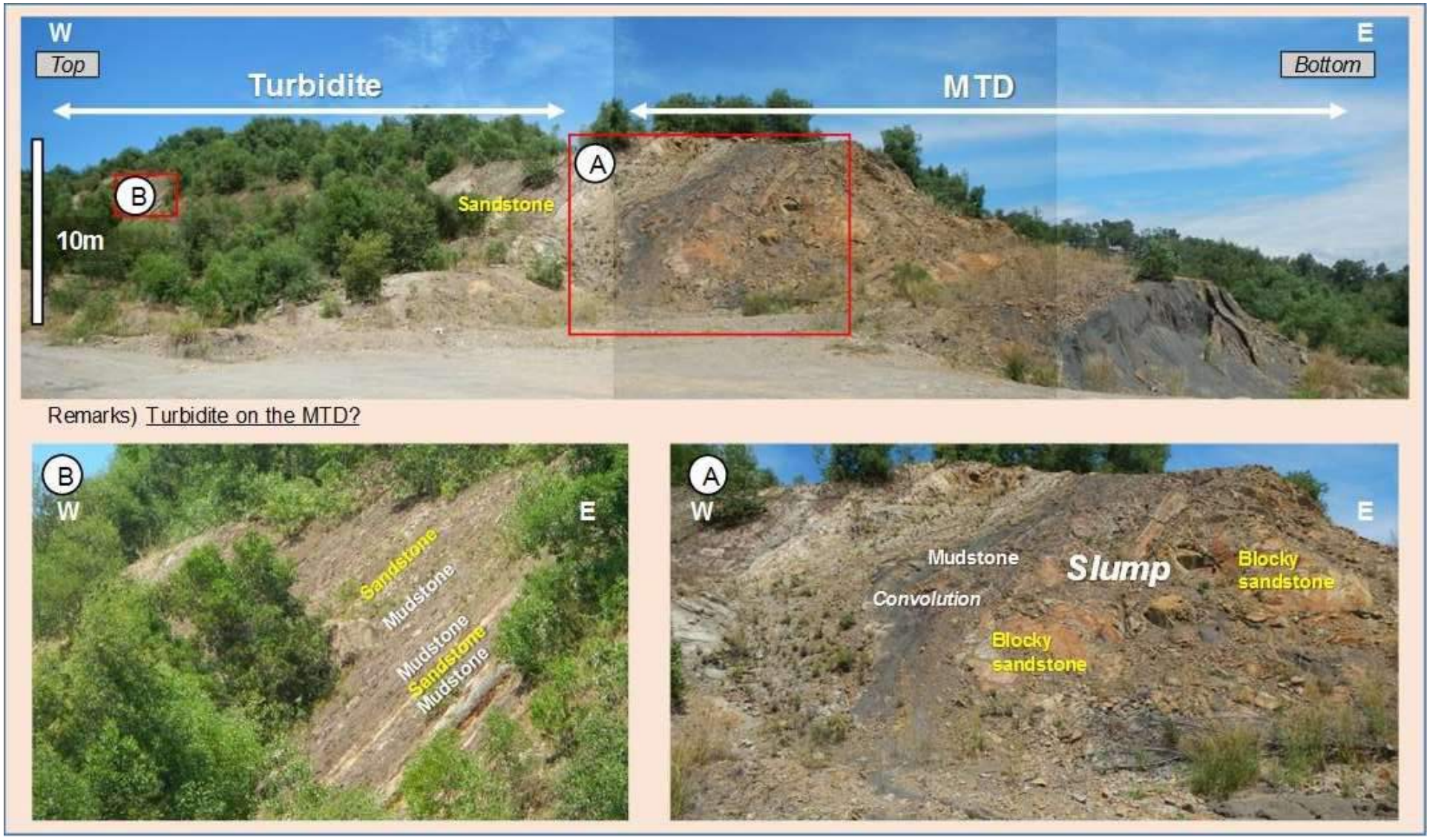


Figure 6: *An outcrop located near Kota Kinabalu of deepwater turbidite deposited on top of the mass transport deposits (MTD). (A) An MTD section of slump deposits consisting of block sandstones and convolved mudstones, and (B) A turbidite section of layered mudstones and sandstones.*

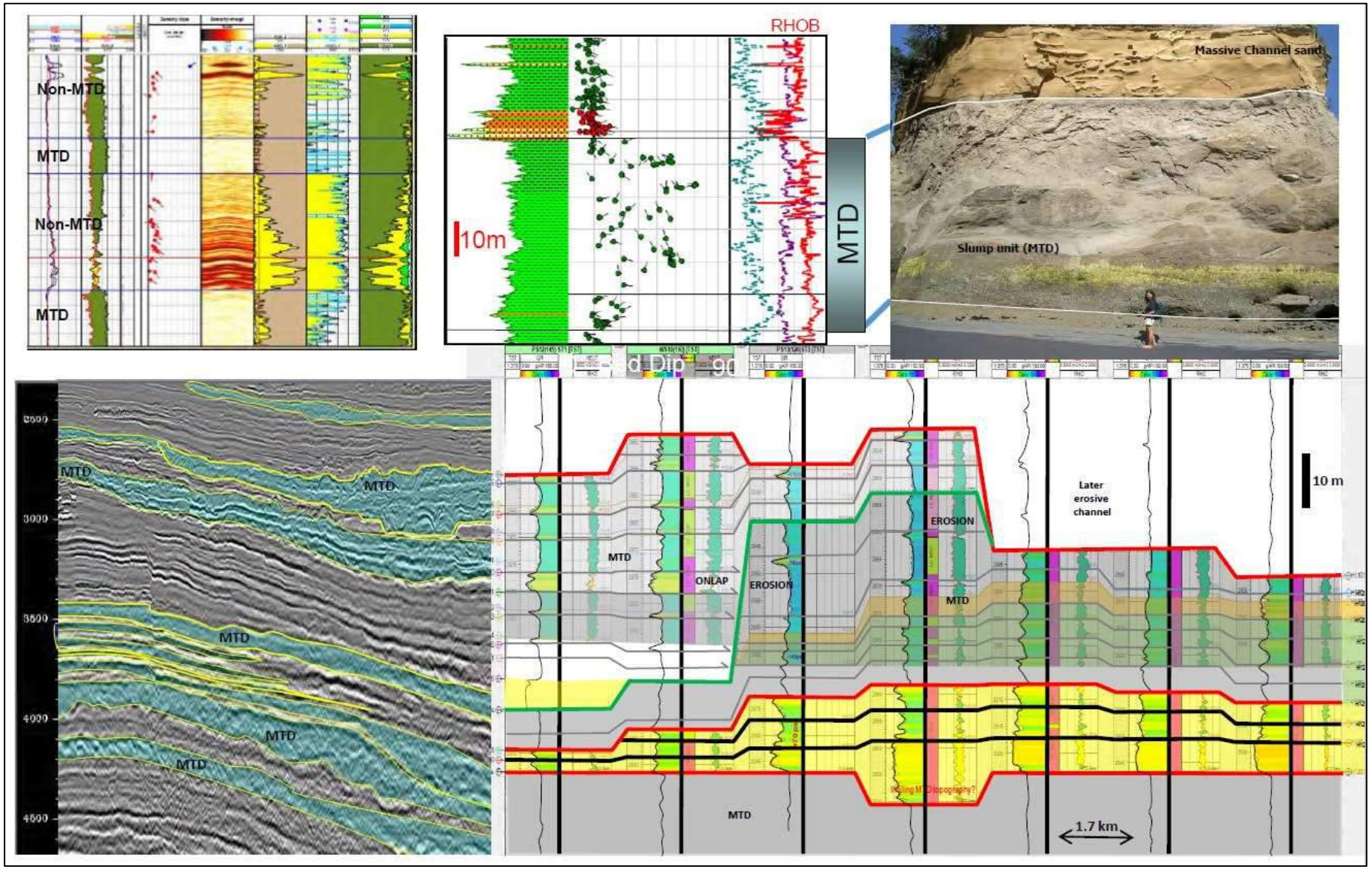


Figure 7: *Relationship between reservoir sandstones and mass transport deposits (MTDs) as shown on image and dip meter logs, outcrop and seismic-to-well correlation. From Jones et al. (2016).*

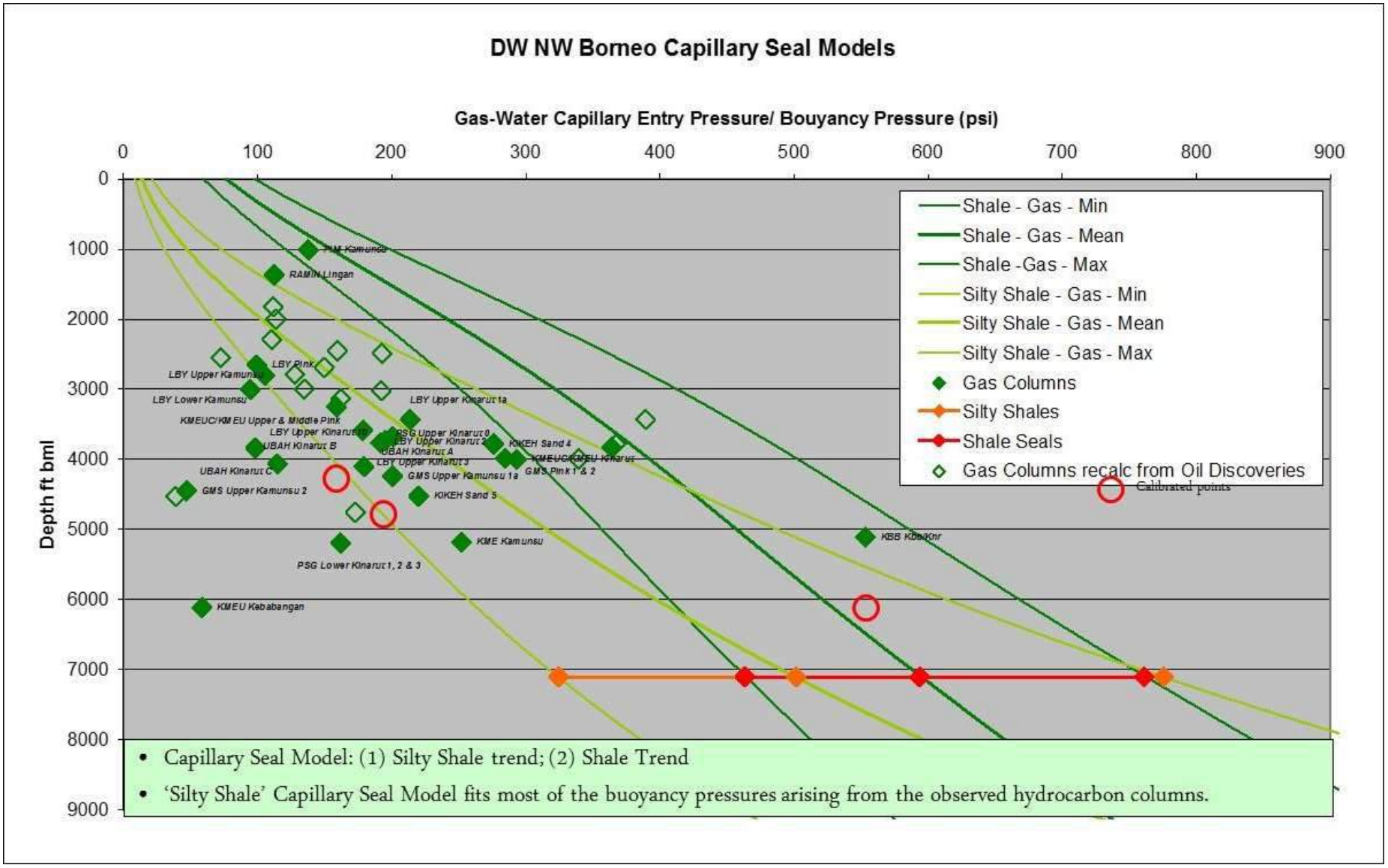


Figure 8: *Capillary seal models of Sabah deepwater where the 'Silty Shale' model fits most of the buoyancy pressures arising from the observed hydrocarbon columns, The data suggests that a dominant control on hydrocarbon column length in NW Borneo deepwater is capillary seal capacity and retention of overpressured liquids and gasses is not common in less than 300m (1000 ft) below mudline (from Ngu et al., 2010).*

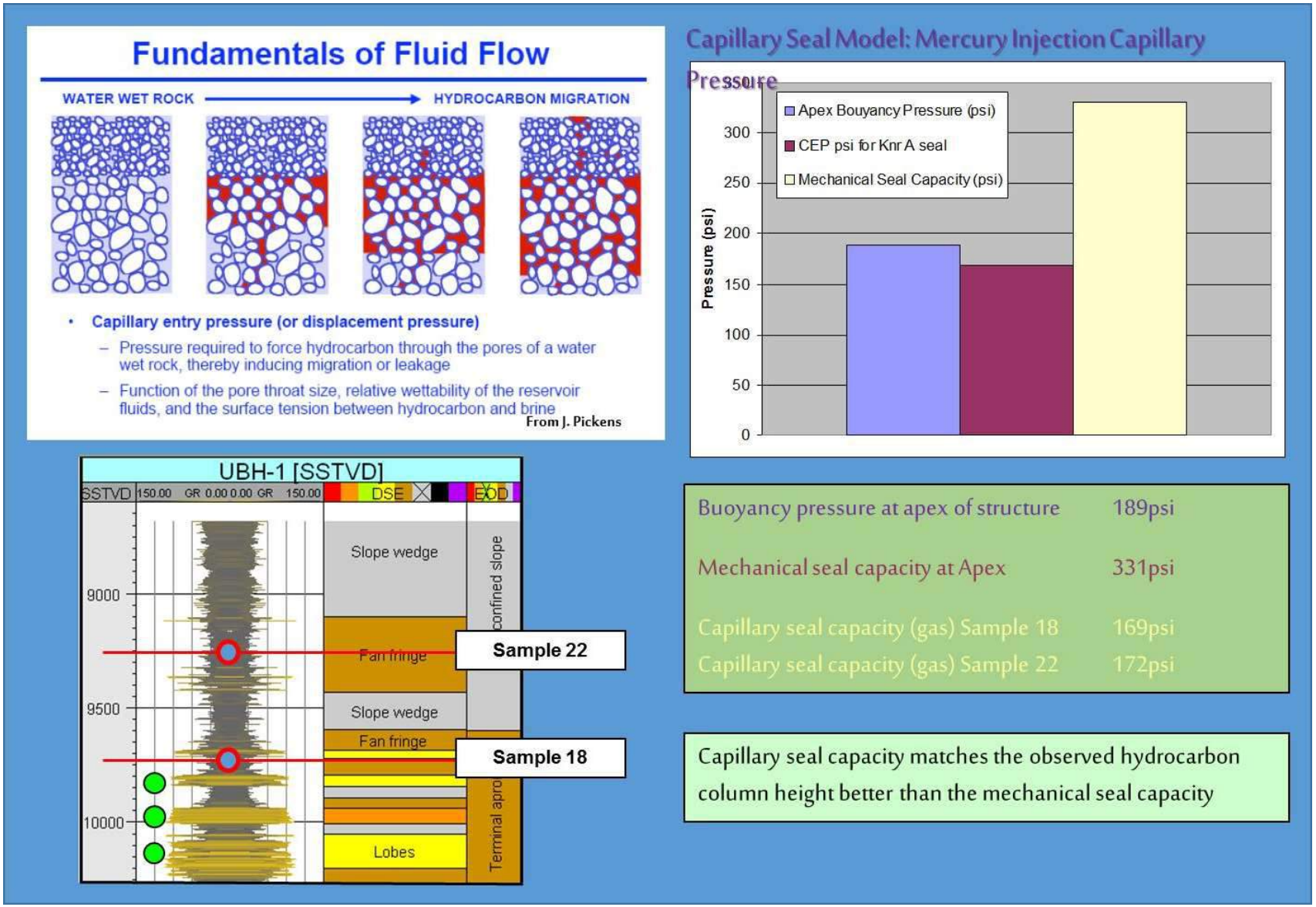


Figure 9: *In the case of a studied Sabah deepwater Ubah-1 well, the best fit between measured reservoir pressure and seal retention is best realized by using a capillary seal model (from Ngu et al., 2010).*

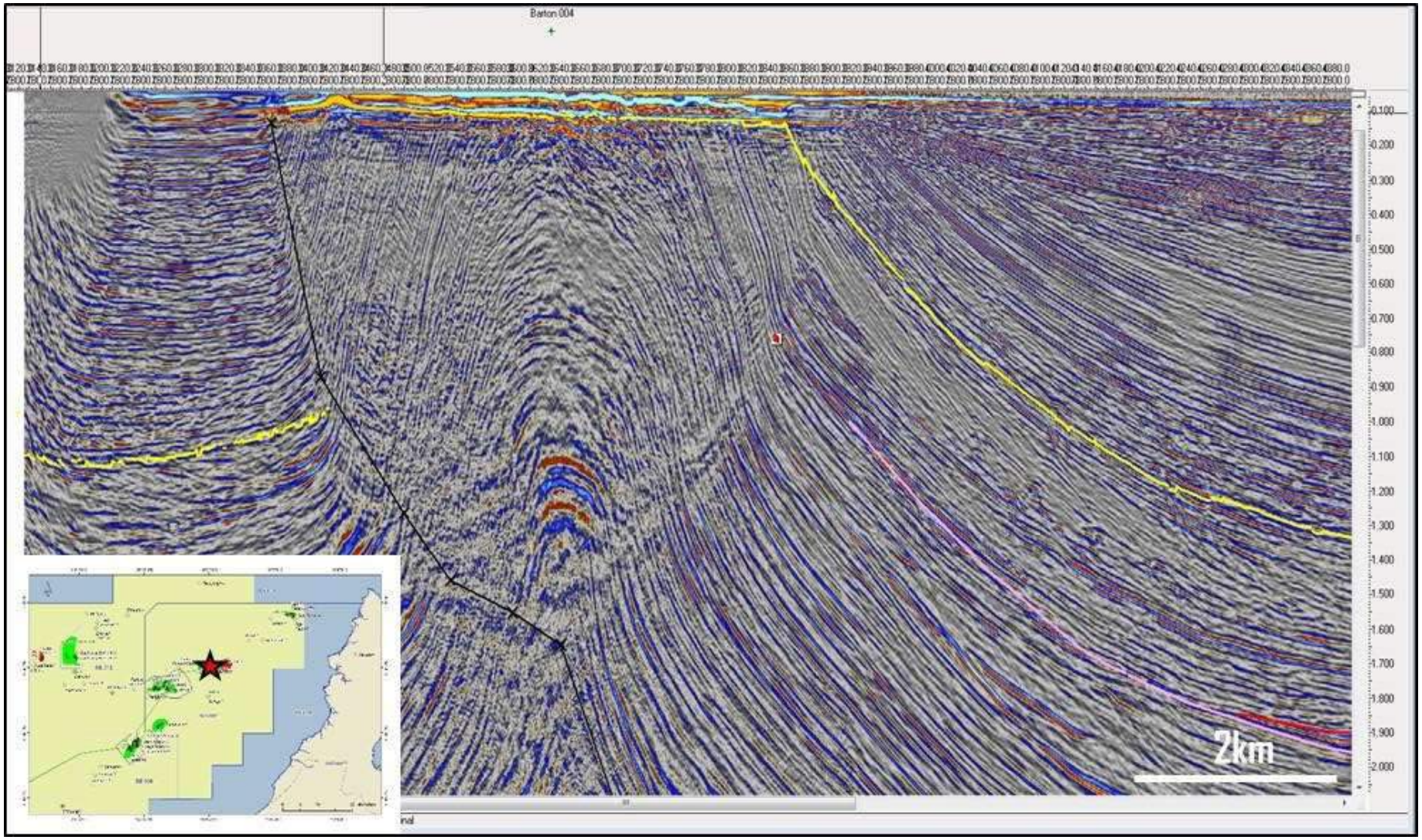


Figure 10: *Overthrust structure in offshore Sabah with a diapiric clay core. The structure contains an oil field constituted by up to a hundred of outer shelf reservoir/seal pairs. The strong and very young tectonic (folding, uplift) had a detrimental impact on the pre-tectonic oil and gas accumulations (super-steep anticline in the centre of the above picture). A secondary post-tectonic migration occurred and erratically re-arranged both hydrocarbon, and water fill. The field had a seemingly very large STOIIP but only a very low (marginally commercial) production. Later attempts to increase production by water flooding did not see a benign outcome.*

- Tectonic history: It is known that many Sarawak onshore traps with shallow marine reservoirs and seals originally contained hydrocarbons but leaked later. This was caused by a Pliocene phase of compression combined with significant uplift (of some 600 m since the onset of Pliocene, and 20 m since the beginning of the Holocene) (Kessler and Jong, 2014a & 2014b; Jong et al., 2016a). It is believed that reactivation of older faults and the formation of joints may have broken both top and fault seals. There are only four accumulations which have, despite tectonism, survived, namely Seria, Miri, Asam Paya and, discovered more recently, Adong Kecil (Jong et al., 2017a). Figure 10 shows an overthrust structure in offshore Sabah, with a diapiric clay core. The structure contains an oilfield comprising up to a hundred outer shelfal reservoir/seal pairs. The strong and very young tectonics (folding, uplift) had a detrimental impact on the pre-tectonic oil and gas accumulation. A secondary post-tectonic migration occurred and erratically re-arranged both hydrocarbon, and water fill. The field had a seemingly very large STOIIP but only a very low (marginally commercial) production. Later attempts to increase production by water flooding failed.

EFFICIENCY OF DEEPWATER TOP SEAL CAPACITY – AN EXAMPLE FROM DEEPWATER SABAH TURBIDITE PLAY

The top seals in deepwater depositional environments are commonly formed by intercalated mudstone and shale layers both within and above the gross reservoir sequence. In the Bestari well and other developed fields elsewhere in the basin, units of thick MTDs constitute the most effective seals (Jong et al., 2016b). Hydrocarbon columns in the order of several hundred metres in the discovered fields are evidence that these top seals can be very competent (Figures 11 and 12). However, the fact that many Sabah deepwater fields (e.g., Gumusut-Kakap; Kikeh, Figure 13) have extensive overburden gas clouds and shallow gas traps shows that the top seal capacity is relatively constrained, thus leakage is common. Having said that, the existence of hydrocarbon accumulation at the Pink Fan level in Bestari-1 at some 700 m bml (below mudline) depth suggests a similar overburden thickness would be the minimum requirement to hold an effective column in deepwater Sabah. It appears that lithification of clay ooze to contiguous clay, and clay stone layers may start at a depth of some 500 m bml. Whether time, pressure and/or temperature, or again a combination of these parameters could be responsible for the formation of seal, remains poorly understood.

Top seal leakage due to later stage faulting can be another geological risk, but numerous major fields in the area do have extensive faulting over the structure (and extensive shallow gas clouds), while nevertheless trapping hydrocarbons. It has been noted that differential top seal leakage might have allowed gas to escape from accumulations in the area resulting in the loss of light-end hydrocarbons from the reservoir, thus enriching them to give more oil-rich deposits (Algar, 2012; Jong et al., 2014b; Jones et al., 2016). Some crestal faults are seen to extend up from the reservoir formations to the seafloor, providing potential vertical leakage pathways, which may open and reseal as a function of pressure. While the large thrust displacements may juxtapose reservoir sections against unconsolidated younger sediments, evidence from the fields is that the pressure differentials across the main thrust-bounding faults tend to be very high and that lateral seal failure is an unlikely risk factor. With an overall clay-dominated system in a deepwater setting, both normal and thrust faults are thought to have excellent shale gouge ratios (SGRs). As shown in Figure 14, prominent hydrocarbon columns located in faulted traps appear to require a minimum SGR of 0.4. Fault seal analysis conducted by JX Nippon suggests that fault-dependent traps in deepwater Sabah have SGR ratios of greater than 0.5.

UNLIKELY UPSIDE CASES RECORDED IN SHALLOW MARINE AND SHELFAL SETTINGS

Although discoveries in shallow marine and shelf settings such as those made in the West Baram Delta offshore Sarawak and Brunei contain mostly short columns, there are a couple of exceptions:

1. Adong Kecil (Figure 15), a recent discovery by JX Nippon is located on the Miri-Seria anticlinal trend, which is partly developed as a wrench fault system, and partly as an overthrust that also shaped the Miri field. Both reservoirs and seals consist of semi-continuous Neogene shelfal deposits. Faults in the prospect area showed only little throw, which gave little hope for efficient clay gouging and hence preservation of significant hydrocarbons. Surprisingly, however, the discovery well encountered several stacked hydrocarbon-bearing zones of some 350 m of net hydrocarbon column allocated in six sandstone horizons trapped by the lower part of the fault, where its throw was minimal (Figure 15; Uchimura et al., 2014). Since the fault throw is smaller than the sandstone thickness, extensive sand-to-sand juxtaposition can be expected unless there is a continuous clay smear. It is not well-understood why some equally minor faults sealed, while other similar faults leaked and it could be that the sealing capacity of faults could have been reinforced with additional lateral and/or vertical clay injection into the fault plane. Lateral clay injection into normal faults in the greater Miri area based on outcrop

observation and model experiments has been described by van der Zee et al. (2003) and van der Zee and Urai (2005). This may be one of the effective mechanisms for trapping potentially longer hydrocarbon columns in the West Baram Delta. Pro-delta shale is widely distributed in the delta as muddy distal facies and is widely known to be overpressured with mud diapirs and clay ridges, both well-known in the greater Miri area (Kessler and Jong, 2014a). However, it is noted that the oilfields: Miri, Adong Kecil, Asam Paya and Seria are aligned on the same late inversion and wrench fault system. It is therefore possible that the events leading to inversion and wrenching may have had some positive, yet poorly understood, effect on the plumbing of oil reservoirs.

2. A limnic silty claystone seal from the Malay Basin, which we would like to add as a somewhat uncanny example from a recent gas discovery. Although located outside the study area, it is found in a similar shallow marine setting. The trap is fault-bounded and sealed by clay gouging. In that well both reservoir and seal were cored, and it was found that 74 cm of banded clay retained some 14 m of gas column over a surface of 30 km2 (Figure 16). This example shows that one cannot exclude extreme cases. In the shown example, a gas-bearing and highly porous reservoir, connected to the regional aquifer, indicated a convincing amplitude effect on seismic, thus making a good case for exploration.

In summary we conclude that seal continuity, and seal quality, are the most important factors for seal and trap integrity.

CALIBRATION AND SIMULATION OF CLAY SMEAR

In two recent papers by Kessler and Jong (2017a & 2017b), the authors discussed merits and pitfalls of near-surface clay gouge calibration. Among the studied faults, smeared faults were reviewed to identify the sealing capacity and seal-failure envelope. The smeared faults were then further broken down into two groups to differentiate between shear- and abrasion-type smears for simplifying calculation on SGR (Fristad et al., 1997; Yielding, 2002), shale smear factor (SSF) (Lindsay et al., 1992), and clay smear potential (CSP) (Bouvier et al., 1989). Smear properties in the region were then identified with calculated across-fault pressure difference (AFPD) (Bretan et al., 2003), and hydrocarbon column length. By calculating amount of clay with surrounding distance, the probabilities of faults were determined. A calibration constant, C, is added into the formula only when discontinuous shear-type smear is present (Vrolijk et al., 2016; after Bouvier et al., 1989). The calibration constant C is depending on the rheology and competency of a rock at a certain depth and it varies in depth, while the SSF formula determines the likelihood of continuous smearing by measuring the slip of fault and surrounding mud layer thickness (Lindsay et al., 1992).

The more recent study (Kessler and Jong, 2017b) summarized the field work conducted by Curtin University Malaysia (2017) found that Lambir Formation located in the greater Miri area has a seal-failure envelope at SGR as low as 0.14, even though siliciclastic sequences were determined to have common seal-failure envelopes for SGRs ranging from 0.15 to 0.2, or higher. Overall, there was no sound correlation between fault throw and clay gouging thickness. However, in an earlier study, Kessler and Jong (2017a) provided data which suggest that such a correlation might exist (Figure 17). Nonetheless, the two studies suffer from the fact that small faults are more common and large faults are more rarely found in outcrops. In a nutshell, although outcrop studies as carried out can provide insight into important processes that shape traps and retention parameters alike, it is not clear whether such measurements can be applied for simulation of subsurface fault seal retention – the jury is still out.

There are several modelling packages for seal modeling available on the market such as FaultRisk by Faultseal, TrapTester by Badley Geoscience and Structural and Fault Analysis module in Petrel. However other than using calculations, there is a good rule of thumb supported by basin-wide data and working experience:

- Clay content in distinct layers being greater than sand thickness in gross sequence: chances for clay smear are very good, and possibility for decent hydrocarbon columns;

- Sand content is greater than layered clay content: commonly minor hydrocarbon columns only. Obviously, one should reconcile this with other viewpoints such as reservoir quality and contiguity, drive and aquifer, and the expected pressure regime, as discussed in the following sections.

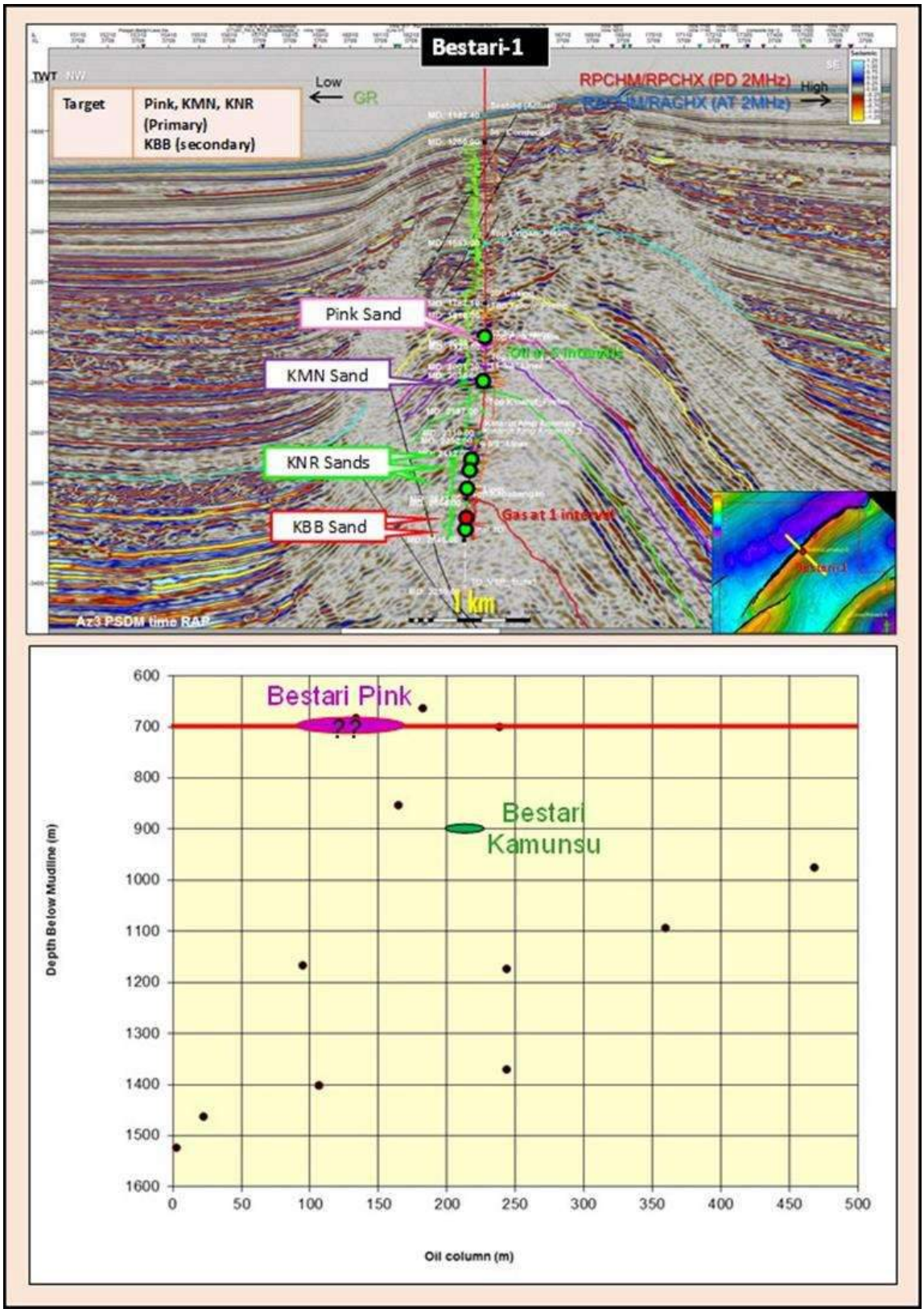


Figure 11: *Top - Bestari oil discovery in deepwater Sabah found multiple stacked oil accumulations in Miocene turbiditic reservoirs (from Ogawa and Jong, 2016). Bottom - Depth below mud line in Bestari versus oil column length data from nearby fields. Note that at Bestari-1 some 700m bml at Pink level, the existence of an oil column is present based on resistivity log and FLAIR (real-time fluid logging and analysis service) results with uncertainties on the actual column length. The well is significant in the sense it highlights the possibility of a relatively shallow but still effective sealing capacity.*

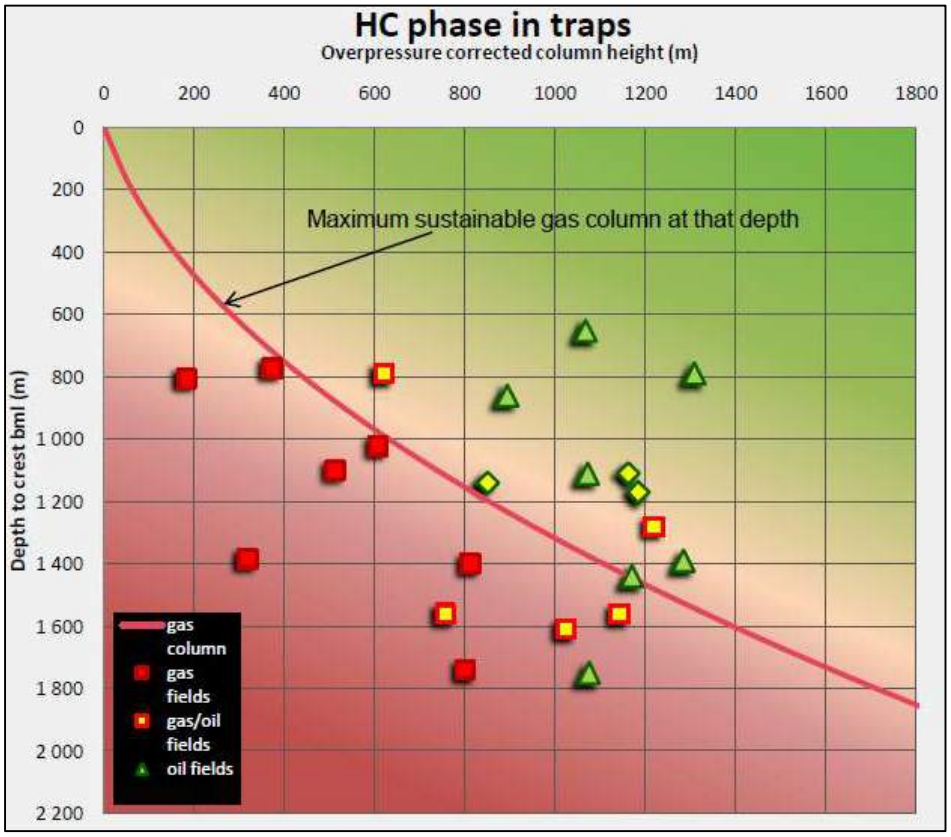


Figure 12: *Hydrocarbon phase in traps. Fluid types and proportions in hydrocarbon columns are controlled by burial depth, column length and overpressure and a leaky trap would be required for a significant oil accumulation (Algar, 2012).*

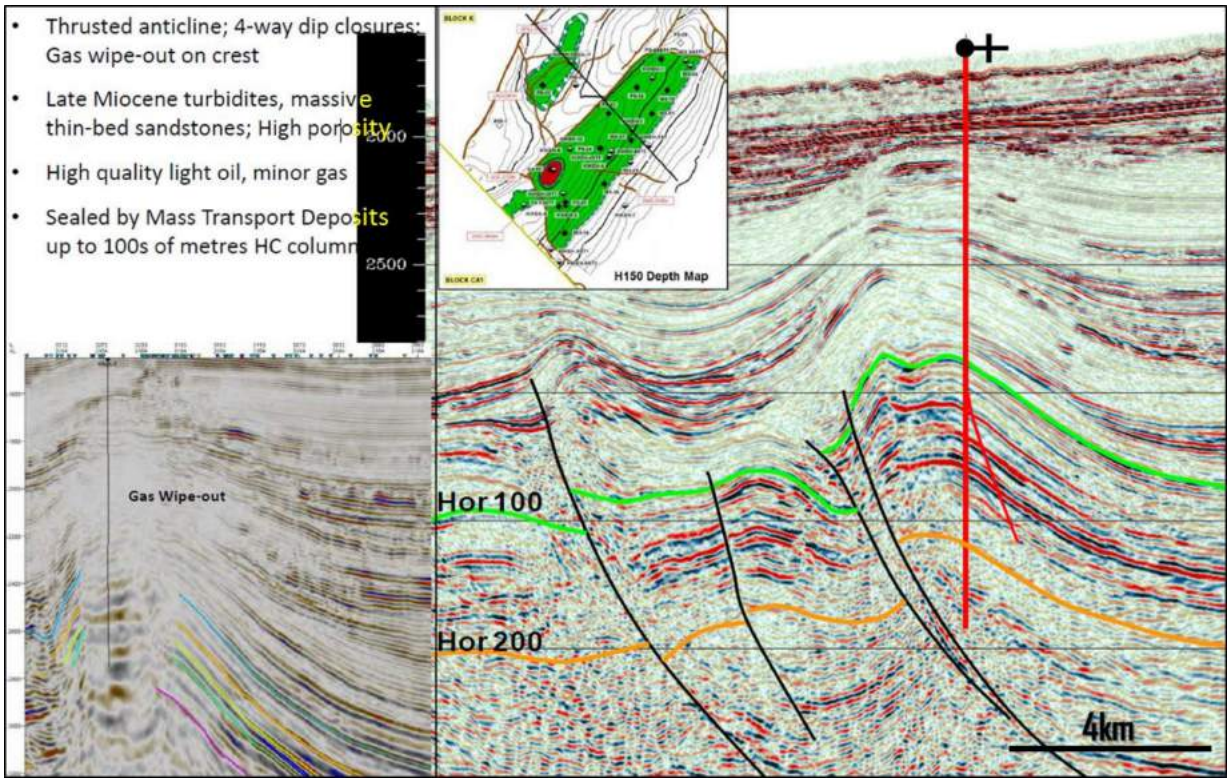


Figure 13: *Kikeh field discovery made by Murphy Oil in 2002 dominated by crestal gas clouds. From Jones et al. (2016)*

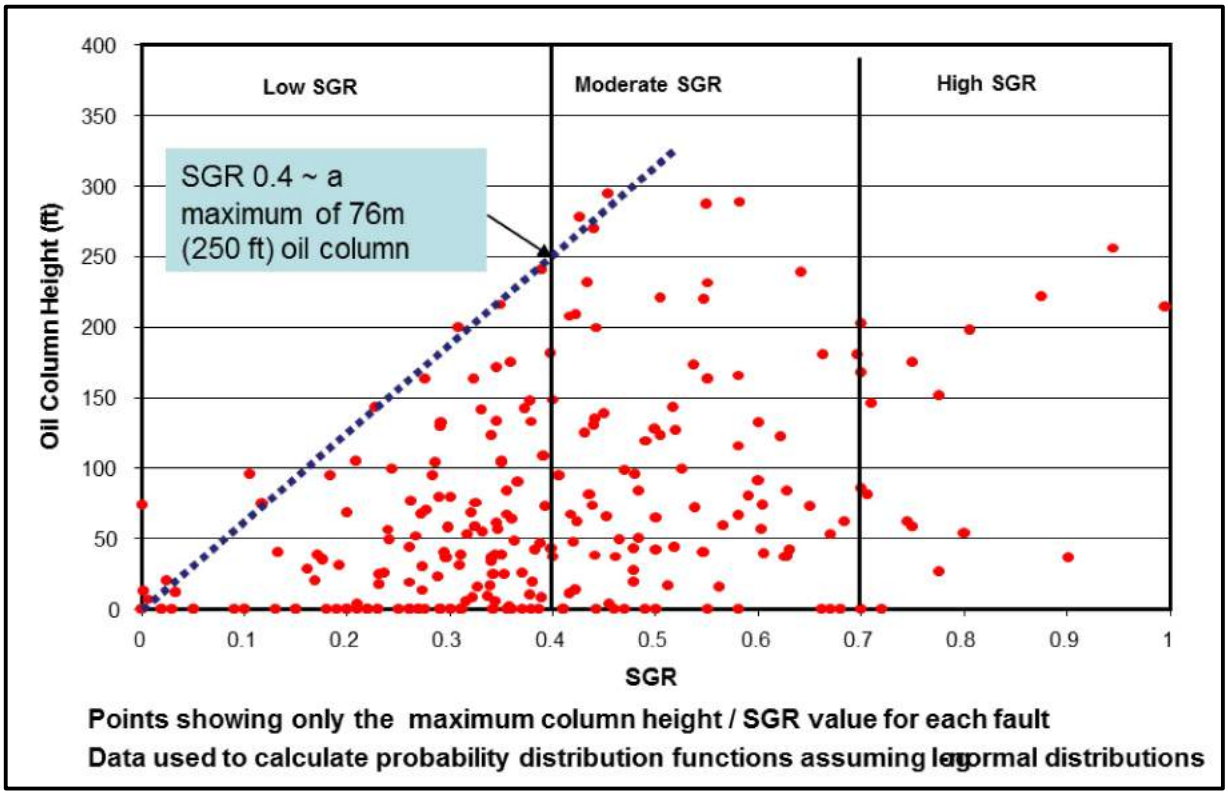


Figure 14: *Oil column length (note in feet) versus SGR based on data compiled by Shell. The above cross-plot shows that column length in faulted traps could be related to the SGR. The data suggest that hydrocarbon columns of above 75 m (250 ft) require a SGR of at least 0.4.*

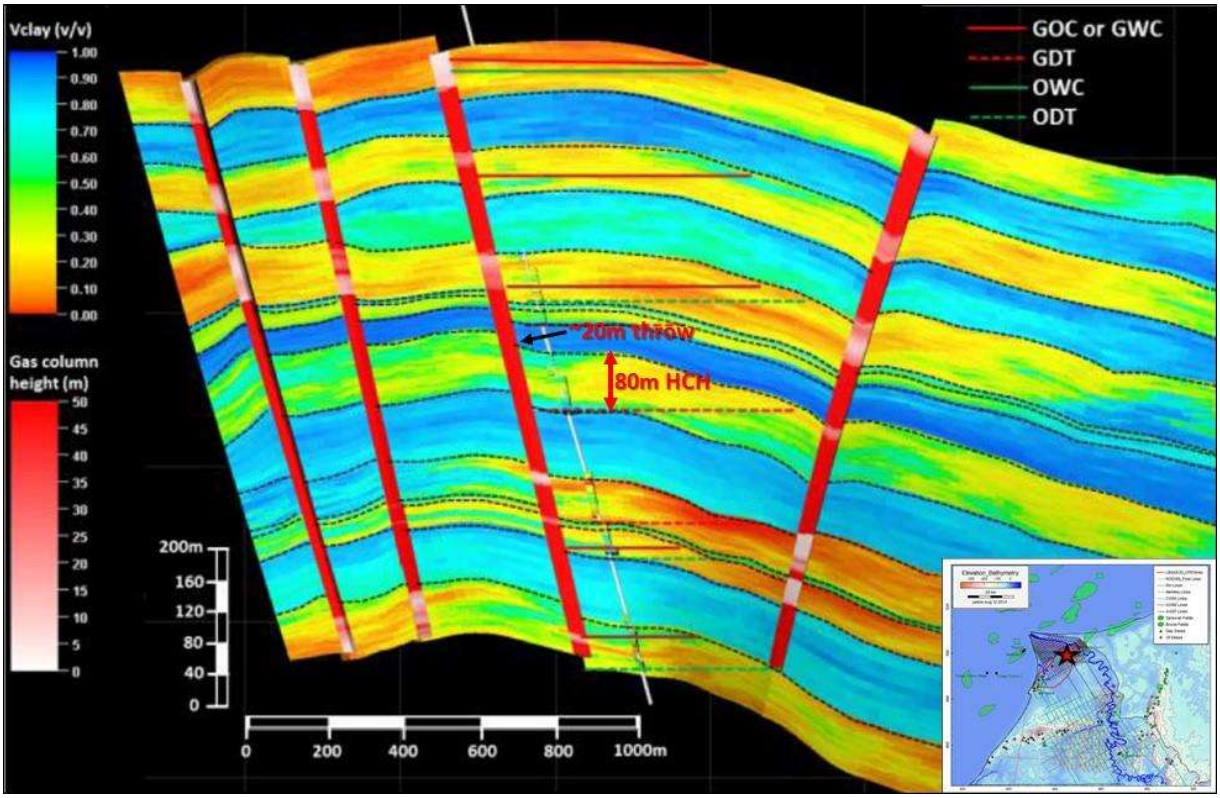
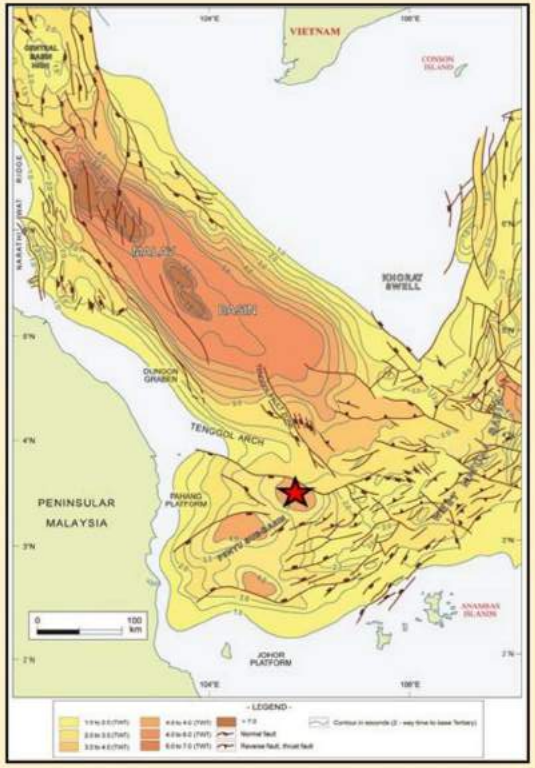


Figure 15: *Adong Kecil is a recent discovery by JX Nippon, and located in a shallow marine sandstone and clay deposits. The cross section shows a Vsh model and faults with potential HCH (hydrocarbon column length, gas case) in comparison with the actual fluid contacts observed by the well (from Uchimura et al., 2014).*

Short Reservoir description	Net sand (m)	Facies A-D	Est. % core/facies	core gamma ray hotsand > 30ppm
	0		0	
5 cm hardground, burrows	0		0	
74 cm banded clay/slit	0		0	30 ppm Th
38 cm banded silt	0,03	D	12	
46 cm bioturb/ and laminated clay	0,15	D	12	
16 cm fractured coal	0,02	D	12	
21 cm fract. coal	0,03	D	12	
78 cm homog. fine sand	0,78	C	20	
56 cm dtto	0,56	C	20	
14 cm banded fine sand, clay	0,04	C	20	
30 cm lam clay/slt	0,02	D	12	
14 cm dtto	0,02	D	12	
85 cm laminated fine sand	0,85	B	25	
64 cm fine sand, breccia, fine sand	0,62	C	20	34 ppm Th
19 cm lam siltst/ clay/ fine sst	0,1	D	10	
17 cm coal, then fine sand	0,11	C	16	
40 cm fine sand/ laminated with slt, clay	0,39	C	18	
60 cm lam clay/slts/sst	0,2	D	12	
100 cm fine sand/ lam./slt/clay/flasers	0,45	C	20	
dtto	0,8	C	20	
dtto	0,85	C	20	
dtto	0,75	C	20	31 ppm Th
dtto with flasers	0,7	C	20	
32 cm dtto	0,3	C	20	
68cm mid-coarse sand	0,63	B	25	
100 cm dtto	0,96	B	25	
50 cm (partly not recov)	0,5	B	25	
50 cm medium sand, flasers, lam.	0,4	B	25	
100 cm dtto	0,96	A	30	
32 cm dtto	0,3	A	30	
68 cm thin beds/ lam., fine sand, flasers	0,15	C	20	31 ppm Th
54 cm dtto	0,2	C	20	
46 cm sand/slt, laminated clay	0,3	C	20	
68 cm thin beds/ lam., fine sand, flasers	0,29	C	18	
11 cm lam cly, little sand	0,05	D	15	
21 cm lam med sand, clay, coal	0,17	B	25	
100 cm dtto	0,98	B	25	
	13. 66 Gas			



Structural framework map of the Malay and Penyu basins (from HIS). The star symbol annotates the approximate location of the mentioned well.

Figure 16: *Core evaluation of a reservoir/seal assemblage in a gas well from the Malay Basin, located outside of the study area in a shallow marine setting. Four beds contain levels of Apatite-group minerals which form significant radioactive anomalies. There are five facies types in the reservoir section: A = massive, loose medium to coarse sand; B = mainly coarse to medium grained sand, unconsolidated, with flaser beds; C = mostly fine grained and laminated sand; D = marginal reservoir, mostly silt with little sand; Blue = clay/silt. The net top seal is formed by only 74 cm of dark clay and silt. It sounds uncanny, but this rather thin bed is sealing the ca. 14 m gas column cover an area of almost 30 km², and the trap is fault-bounded and sealed by clay gouging.*

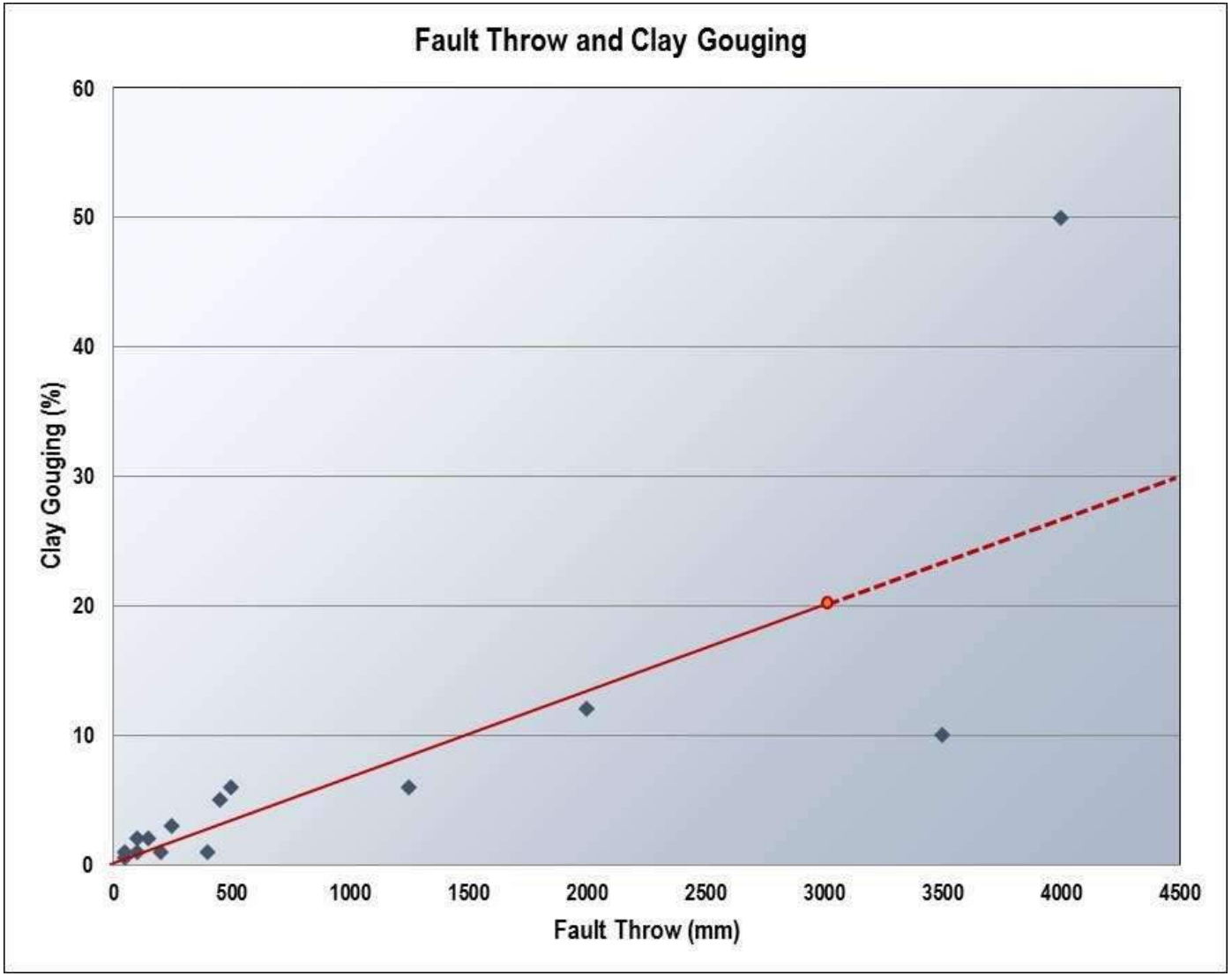


Figure 17: *Measurements of clay gouging and fault throw taken from the shallow marine Neogene sedimentary outcrops located in Miri. Small fault throws result in thin layers of clay gouging, whereas large fault throws offer thicker layers of clay smear. Note the lack of data points for fault throws of more than 2000 mm resulted in an unreliable trend line for throw values of more than 3000 mm. However, this trend may be substantiated with more data, and may be useful to predict potential hydrocarbon columns in fault-traps. From Kessler and Jong (2017a & 2017b).*

THE ROLE OF RESERVOIR

Trap integrity is not only defined by seal parameters, but perhaps equally by reservoir characteristics. Reservoir connectivity and permeability distribution are playing an important role. There are several depositional settings to be discussed here, starting with shallow marine settings leading to the neritic, bathyal settings.

A. Shallow Marine Shelfal Reservoir and Seal Setting

Shallow marine, inner shelf topset reservoirs, of Late Miocene, Pliocene and Pleistocene ages are found within some 40 km counting from the respective Sarawak, Brunei and Sabah shorelines (Figure 1). The youngest and deepest depocentre is situated offshore Brunei.

Geophysical Aspects

Layered, and often thin-bedded reservoir causes tuning effects that are difficult to interpret. Given the nature of relatively thin-layered sand and clay sequences, we encounter aliasing of reservoir and seal reflections, with the effect of causing complex tuning effects. Amplitude versus offset (AVO) analysis and flat spot detection do not work well.

Facies Model and Reservoir Parameters

A layered reservoir with mostly laterally discontinuous porosity and permeability parameters; sands are deposited in ribbons, point bars, lobes and tidal-influenced thin-bedded sequences. The reservoir bodies are often poorly sealed by shallow marine claystone sequences with higher overall sand content and resulted in shorter column in comparison to those fields discovered in deepwater settings (Figure 18).

Drive Mechanism and Pressures

The common case for near-to-mudline reservoirs is a link to a regional aquifer given its recharge areas on the mountainous and high precipitation Borneo mainland; it produces a healthy water drive. Gas depletion drive is characteristic for deeper reservoirs, that are disconnected from the regional aquifer. Overpressures abruptly rise at the interface from sand-dominated to clay-dominated stratigraphy. Within the latter (and particularly within the distal top set play, see below), overpressures tend to be high or even extreme up to 12000 psi, such as seen in several fields at the Sabah/Brunei border area.

Trapping and Column Constraints

Within faulted traps, it appears that trap integrity aspects are mainly driven by reservoir-to-reservoir, reservoir-to-clay juxtaposition and clay gouging particular for deepwater depositional setting, where a number of fault-dependent discoveries in the fold-thrust belt have recorded hydrocarbon columns longer than the four-way closures vertical heights (e.g., Bestari and Pisagan). Column length in the shallow marine sand prone interval is likely confined by the strength of the fault seal. Normally the sand/clay ratio is 60:40, with the result that sand-to-sand contact across the trap defining fault is common.

B. Fault-Dependent Traps in Distal Topset Settings

Distal top set traps are a particularity of deep young depocentres such as areas of the West Baram Delta, Champion Delta and the Sabah/Brunei border area (Figure 1). They are sand bodies that are single point sourced and recycled shelfal sands, hence in some way bear similarity to turbidite deposits. In some respect these deposits are unique, given their raison d´etre lies in a sudden uplift and erosion of the Miocene shelf. The reservoirs are relatively thin and fully encased in neritic clay, isolated from any regional aquifer, and mostly dominated by gas depletion drive.

Geophysical Aspects

Given the nature of relatively thin-layered sand and clay sequences, we observe an aliasing of reservoir and seal reflections; leading to complex tuning effects, which means that AVO and flatspot detection do not work well.

Facies Model and Reservoir Parameters

One deals with layered reservoir units with mostly laterally homogeneous porosity and permeability parameters; sands are point-sourced from eroded areas near to the outer shelf break, and the recycled sands are mostly very fine and may contain silt or clay in the matrix and lowering porosity values below 18 % and permeability below 50 mD. The reservoir bodies are encased by neritic or deep marine claystone sequences, the latter providing excellent sealing.

Drive Mechanism and Pressures

We observe typically a gas depletion drive, or gas depletion supported by weak aquifer support; the layered reservoirs are indicated by an increase of overpressure with increasing depth, and a shift from oil (shallow) to wet gas (intermediate) and finally to dry gas (deep reservoirs). It is noted that this play is only viable in deep, young (Plio-Pleistocene) depocentres. Only there is the transition from hydrostatic to hard overpressures benign. On the other hand, when the change from sandy to clayey facies is abrupt, the transition from hydrostatic to hard overpressure is short and sharp – most time too abrupt to be manageable at reasonable cost. The sketch in Figure 19 shows an

east-west section from outer deepwater Sabah to the inner shelf, indicating, in simplified terms, the context of reservoir sands (yellow and orange brown), clay barriers (green) and overpressure (red). The inboard shelf deposits are stronger lithified, older, geopressured and hotter compared to younger and colder sediments in the west. An expansion of sediments in the western, younger and cooler depocentres is responsible for a benign pressure transition ('inclined pressure ramp') from normally pressured oil in shallow reservoirs to mildly overpressured wet gas and finally strongly pressurized dry gas reservoirs (Figure 20). In the inboard area of Sabah and Sarawak, however, we observe a rapid transition ('flat pressure ramp') from hydrostatic pressure to high overpressure once a regional pressure boundary is transgressed. This scenario has been found prohibitive for drilling safety and gas developments.

Trapping and Column Constraints

Both reservoirs and seals, which are more commonly found to be continuous over many kilometers in coast-parallel direction (SW-NE), but less continuous in SE-NW direction. At the locations of the paleo-shelf edges, reservoirs shale out. Therefore, the only trap uncertainty is largely fault-related. Fault seal failure is rarely observed when reservoir is offset against reservoir, and retention depends on clay smear along fault planes. An example of pressure-layered reservoirs and fault pressure sealing is shown in Figures 21 and 22. In the deeply buried and predominantly gas-bearing, overpressured reservoirs, columns are constrained only by the structural spillpoint. The sand/clay ratio here is typically 30:70 leading to mainly reservoir to clay juxtaposition at the trap-defining faults. Column length can be significant, in company of high but manageable overpressures. Figure 23 shows column length statistics for the mentioned area. The short columns belong to shallow and hydrostatic oil reservoirs, while the long columns are found in deep, overpressured gas- and condensate-bearing reservoirs. The division between gas- and oil-prone settings is also shown in Figure 24.

C. The Outboard Turbidite Reservoir/ Seal Setting

Turbidite reservoirs, both as meandering talweg or basin floor fans, are often near-to-ideal reservoirs, from the standpoint of quantitative seismic amplitude studies, pressure maintenance as well as hydrocarbon recovery.

Geophysical Aspects

We observe good to excellent seismic imaging of both reservoir and seal (Figure 25); geophysical reservoir fluid analysis (AVO, flatspot detection) gives good results. Figure 26 shows a straightforward correlation from PSG-1A to amplitude anomaly due to clear markers above and below, and relatively constant thickness of the section and the clear reflections in the interval of interest, while Figures 27 and 28 illustrate nice flatspot detections at the Kebabangan field, and Rotan discovery of turbidite reservoirs, respectively.

Facies Model and Reservoir Parameters

A layered reservoir with laterally near-to-constant porosity (20-25 %) and permeability parameters (< 1 D); sands are derived from the shelf, channeled into the deepwater from major outlets stemming from Sarawak from proto-Baram and Brunei's East Baram/Champion deltas, and one to the north-east confined by the Gaya Arch and the uplifting inboard area, with probably a third outlet in Sabah feeding the Bestari, Limbayong, and outboard Gumusut, Kikeh (Figure 29). In more detailed investigation, it appears that basement lineaments have configured long-lived sediment conduits that delivered further into outboard settings, with strike of these depositional systems running axial along the intervening synclines. On the other hand, line-sourced channel systems provide limited reservoir potential into outboard settings (Figure 30). Sands can be immature at times; reservoir bodies being encased by neritic or deep marine claystone sequences, providing excellent sealing. It is noted that hydrocarbon traps not far below mudline may not be properly sealed given poor consolidation and lacking mechanical strength.

Drive Mechanism, Pressures, Columns and Trap Constraints

Gas depletion drive, or gas depletion supported by weak aquifer support is more common, active water drive is rarer. Reservoirs are at hydrostatic pressure or moderately overpressured. Hydrocarbon column statistics for the deepwater area are shown in Figures 31 to 33. The shown column realizations suggest an almost linear trend, indicating that with sufficient charge, most traps could be filled to structural spillpoint and beyond for fault-dependent traps and that sealing mechanism is unlikely a limiting factor. In faulted traps this means trap integrity aspects are mainly driven by reservoir-to-reservoir (clay-gouged faults, estimated pressure retention up to 250 psi), while reservoir-to-massive clay juxtaposition can hold massive overpressure (up to 8000 psi).

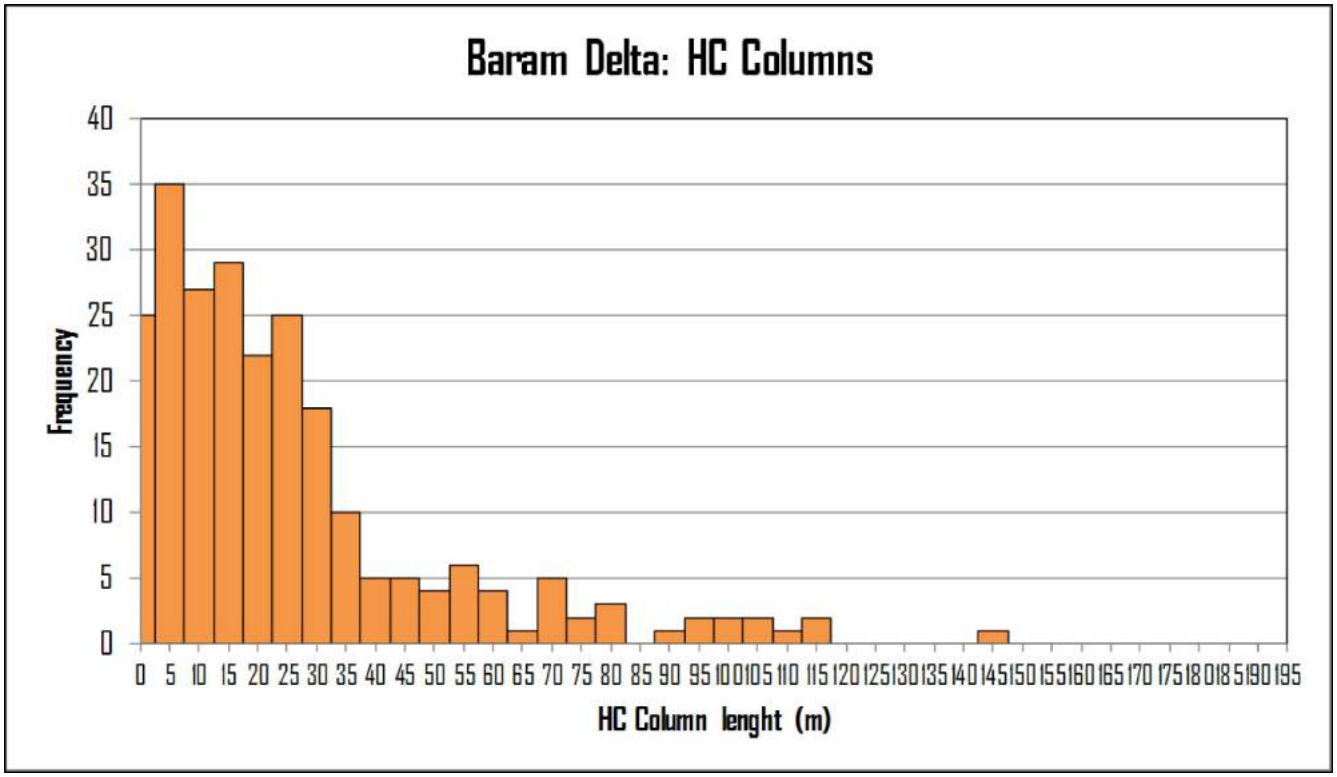


Figure 18: *Hydrocarbon columns from the West Baram Delta fields. The combination of discontinuous reservoir and clay is not favourable to the preservation of long hydrocarbon columns. In the above figure, P50 is around 30 m and hydrocarbon column length significantly beyond 100 m may be a smaller than P10 probability only. From Jong and Shimada (2009).*

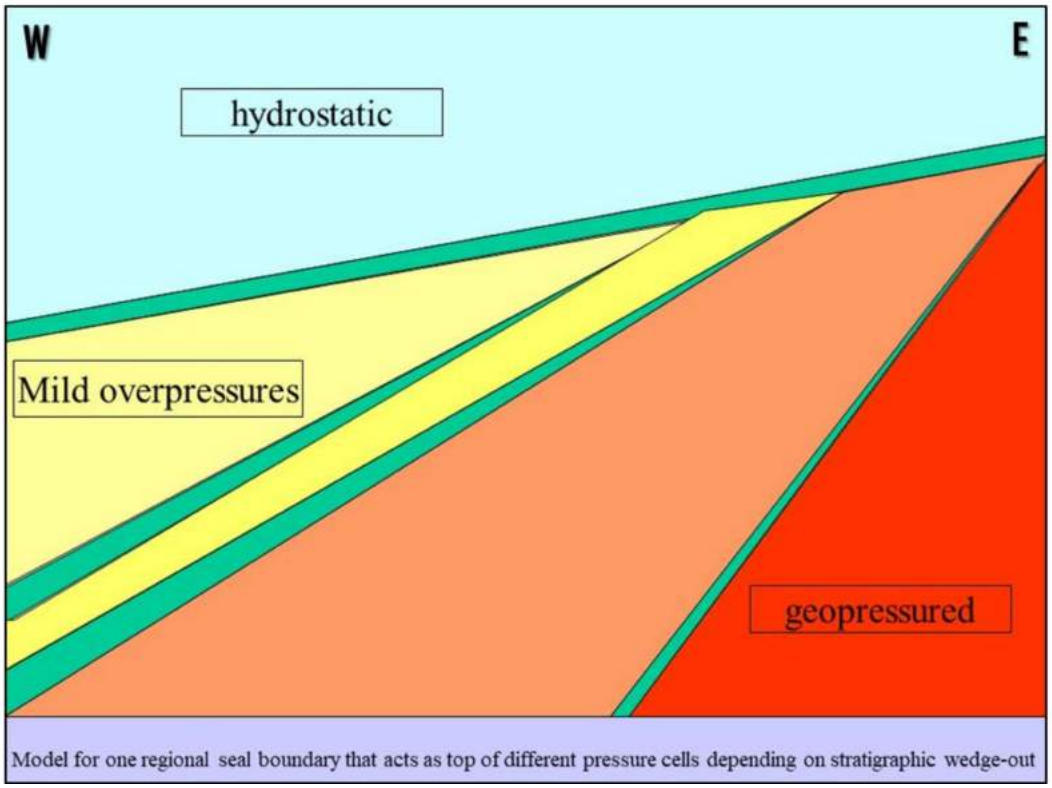


Figure 19: *A sketch showing a E-W section from outer deepwater Sabah to the inner shelf, indicating, in simplified terms, the context of reservoir sands (yellow and orange brown), clay barriers (green) and overpressure (red). See text for further explanation*

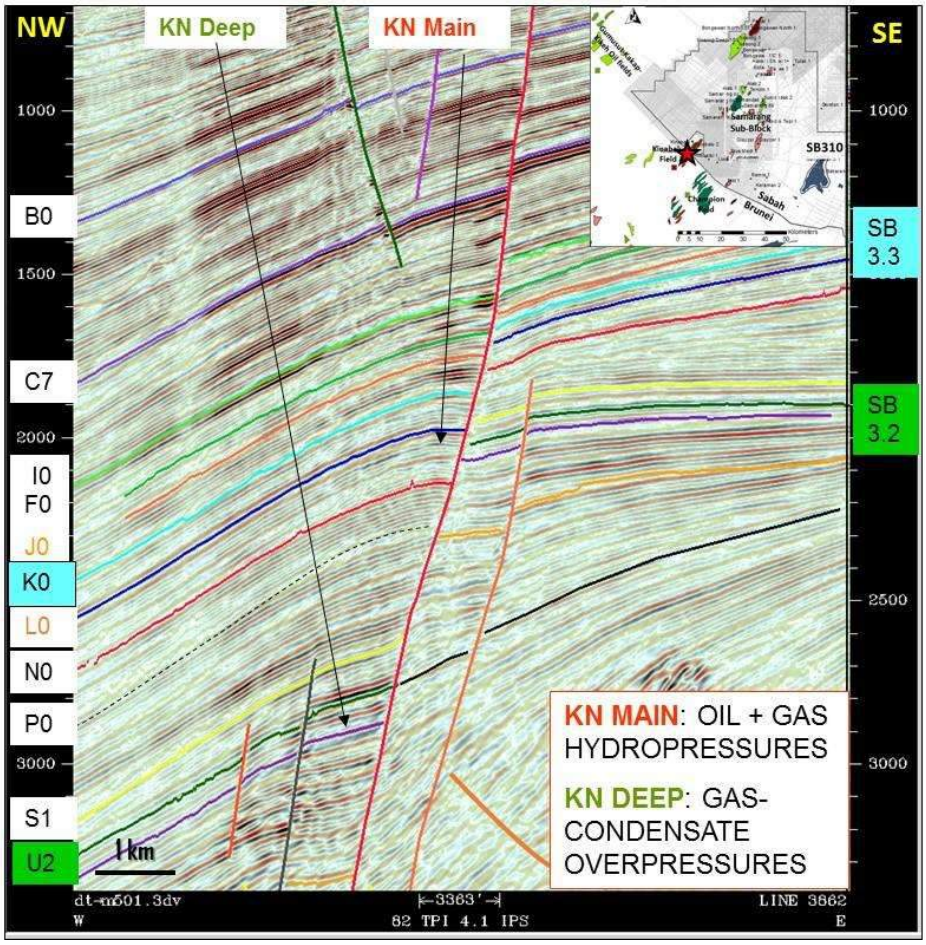


Figure 20: *NW-SE seismic section across the Kinabalu field, offshore Sabah. The main Kinabalu field found both oil and gas and hydropressures, while Kinabalu Deep gas-condensate and overpressures*

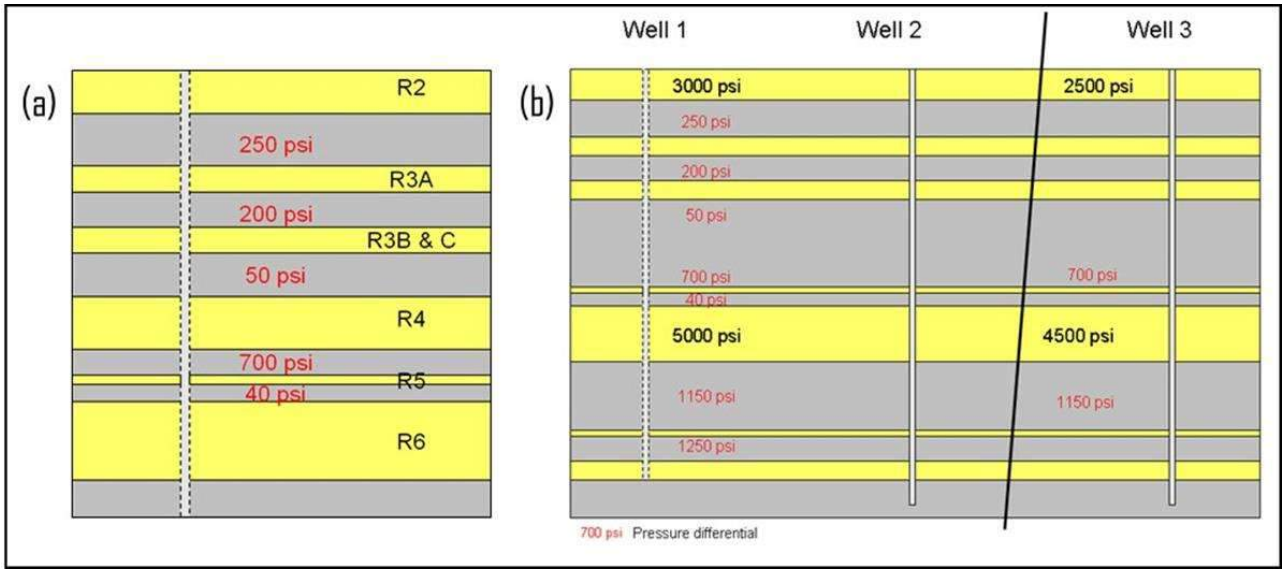


Figure 21: *(a) An example of proven minimum pressure retention by seals; Brunei/Sabah border area. (b) A Sabah example of fault seal and pressure retention where pressure layering is a common feature in stratigraphic outer shelf topset reservoirs, as well as in deepwater turbidite reservoirs. Similar to sediments in a stratigraphic table, the pressures occur in stratified layers of common pressure and gradients. In this example, a minor normal fault divides the pressure-layered reservoir and seal assemblage. The block of Well 3 shows constantly lower pressures in reservoirs, which indicates clay gouging and a pressure barrier of 500 psi.*

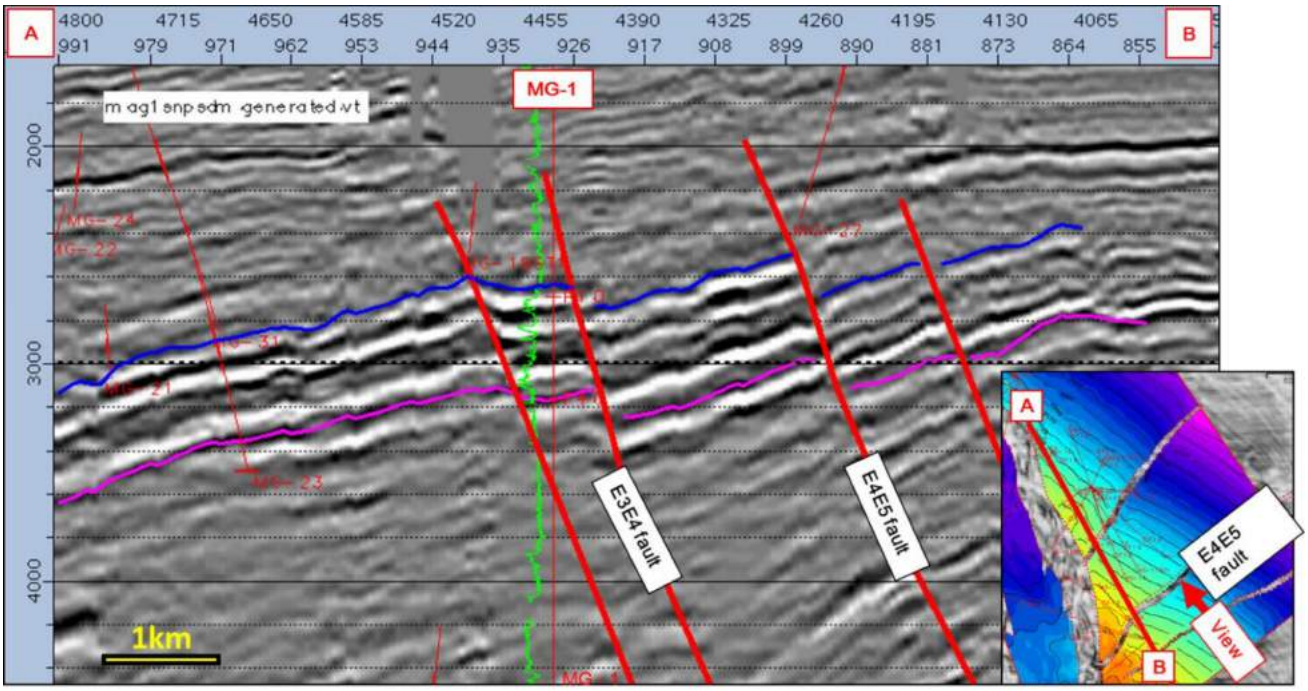


Figure 22: *Magpie field, offshore Brunei seismic-horizon-well log ties and fault-horizon network. The trap is fault-dependent and relies on fault seal for trapping hydrocarbon.*

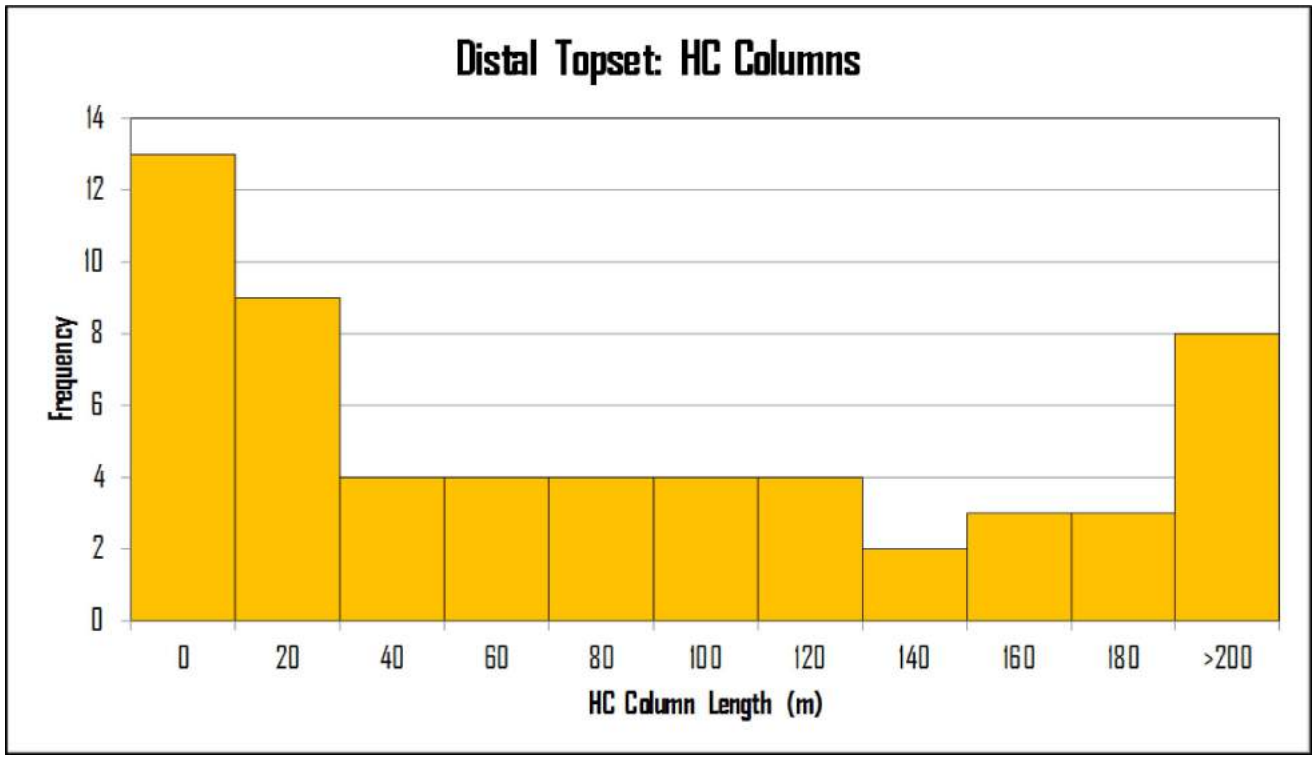


Figure 23: *Hydrocarbon columns in distal topset facies. The distribution is bimodal and shows a predominance of shelfal topset short columns (0-40m) in the shallow section and again very long columns (>200 m) pertinent to the deeper overpressured reservoir/seal associations. The short columns maximum refers mainly to oil-bearing hydrostatically pressured pay, the long columns are wet to dry gas reservoirs with overpressures.*

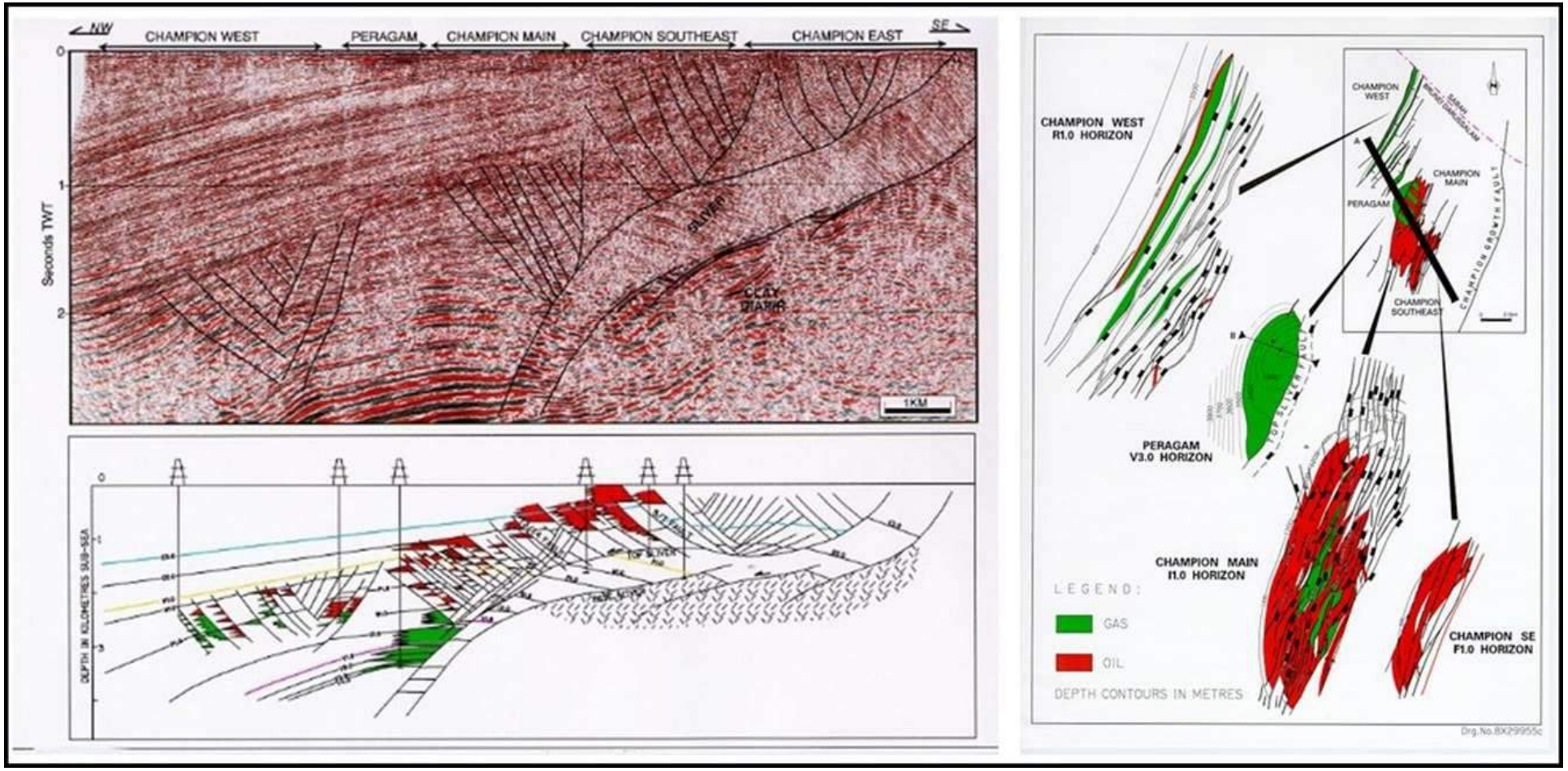


Figure 24: *Traps in shallow-marine deposits on the Brunei Shelf (from Sandal, 1996). The picture to the left shows a shallow, hydrostatic oil-dominated setting, and a deep, overpressured gas setting.*

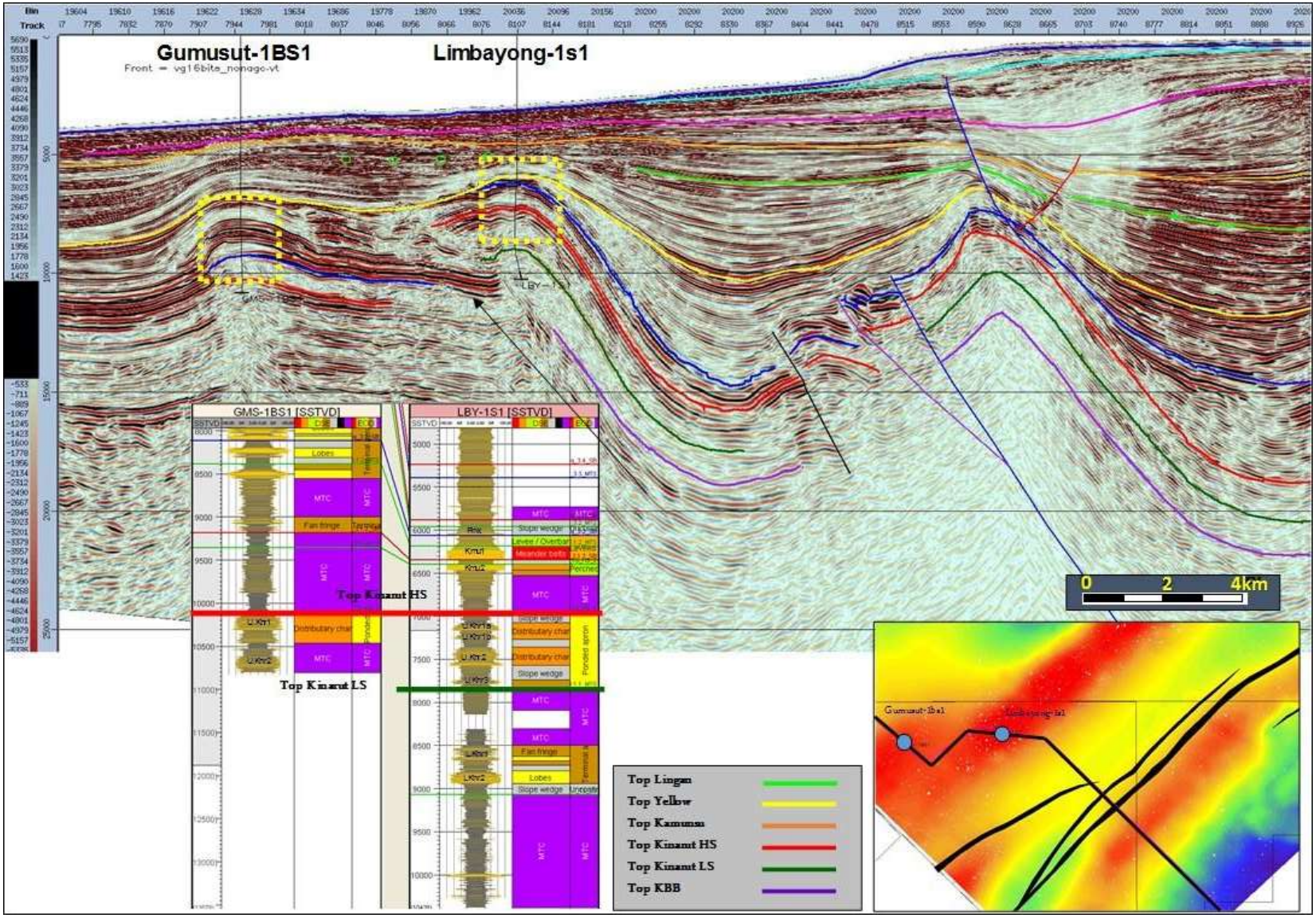


Figure 25: *An example of seismic interpretation and seismic-to-well ties interpreted by Shell in Sabah deepwater fold-thrust belt. The yellow dashed-boxes indicate the main reservoir (bright amplitudes) and seal (blank shaly section) intervals of the two wells shown. Between the reservoir sections, mass transport complexes (MTCs) are also noted forming potential permeable barriers.*

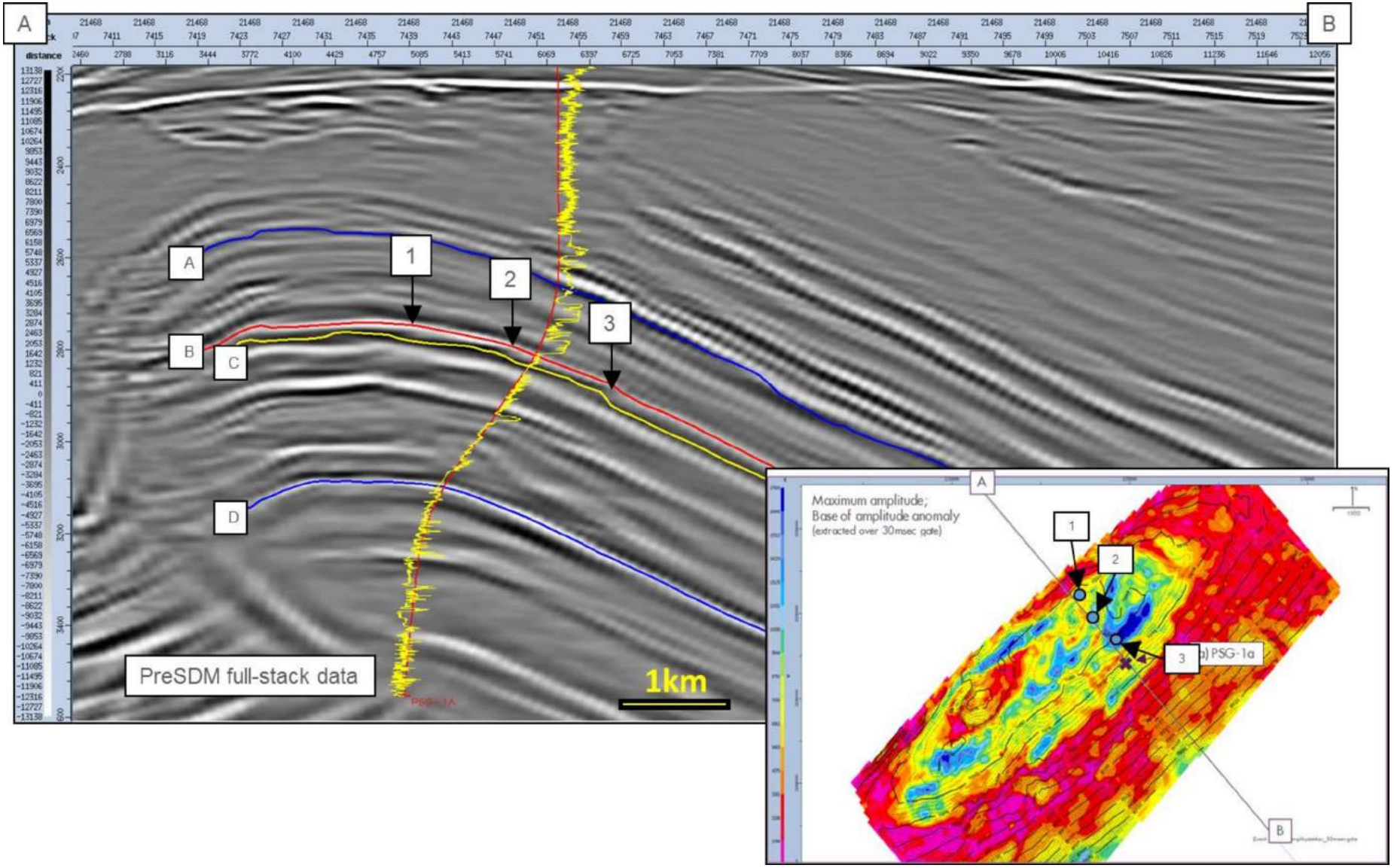


Figure 26: *Structural dip-section from Pisagan-1A to amplitude anomaly. A = second hard of shallow 'triplet', B = top amplitude anomaly, C = base amplitude anomaly, and D = hard below base KMU MTC. Correlation from PSG-1a to amplitude anomaly is relatively straightforward due to clear markers above and below, relatively constant thickness of the section and the clear reflections in the interval of interest. From Sabah Shell Petroleum Company Ltd. (2006).*

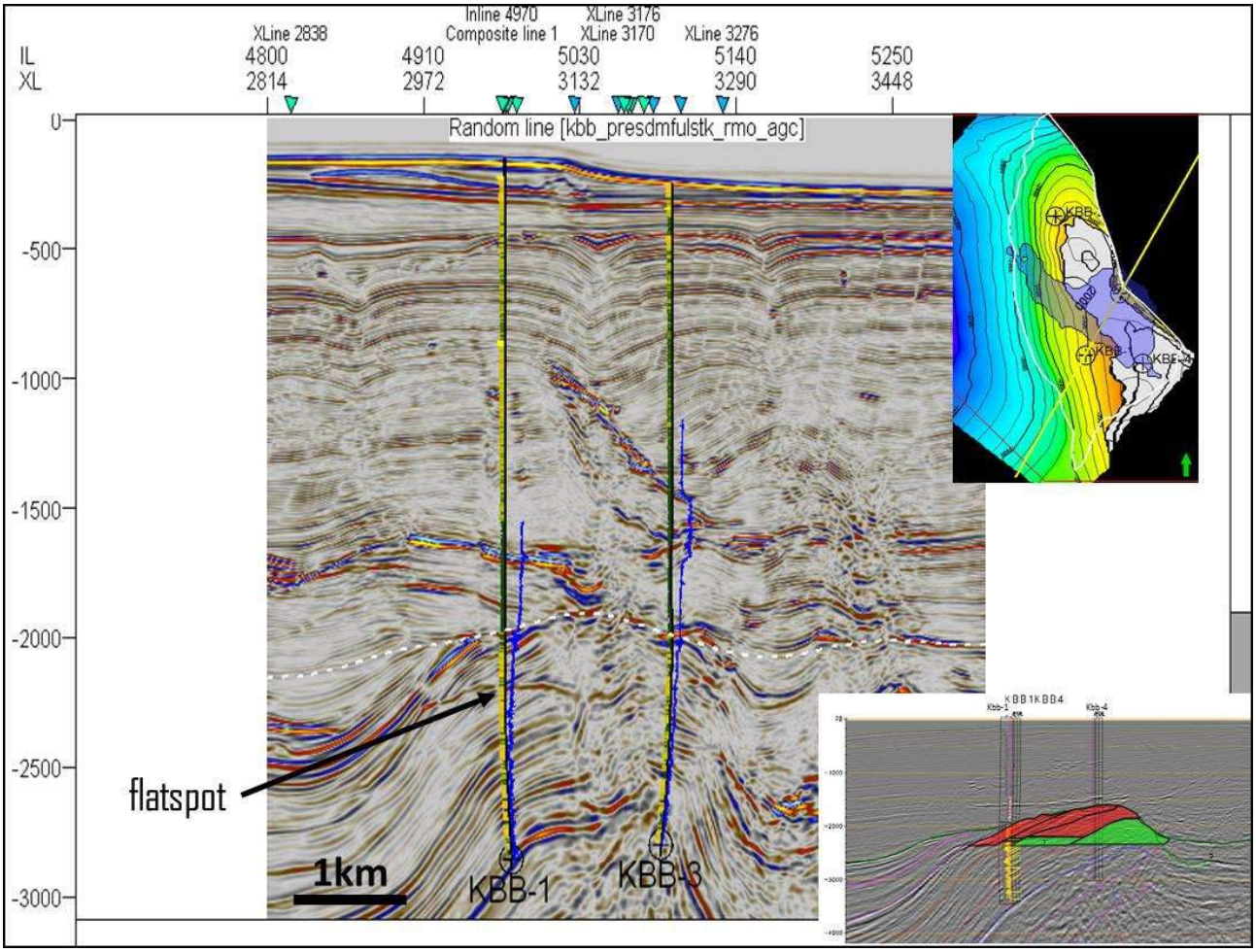


Figure 27: *Kebabangan field flatspot as observed on seismic, inset section shows potential contacts of the field*

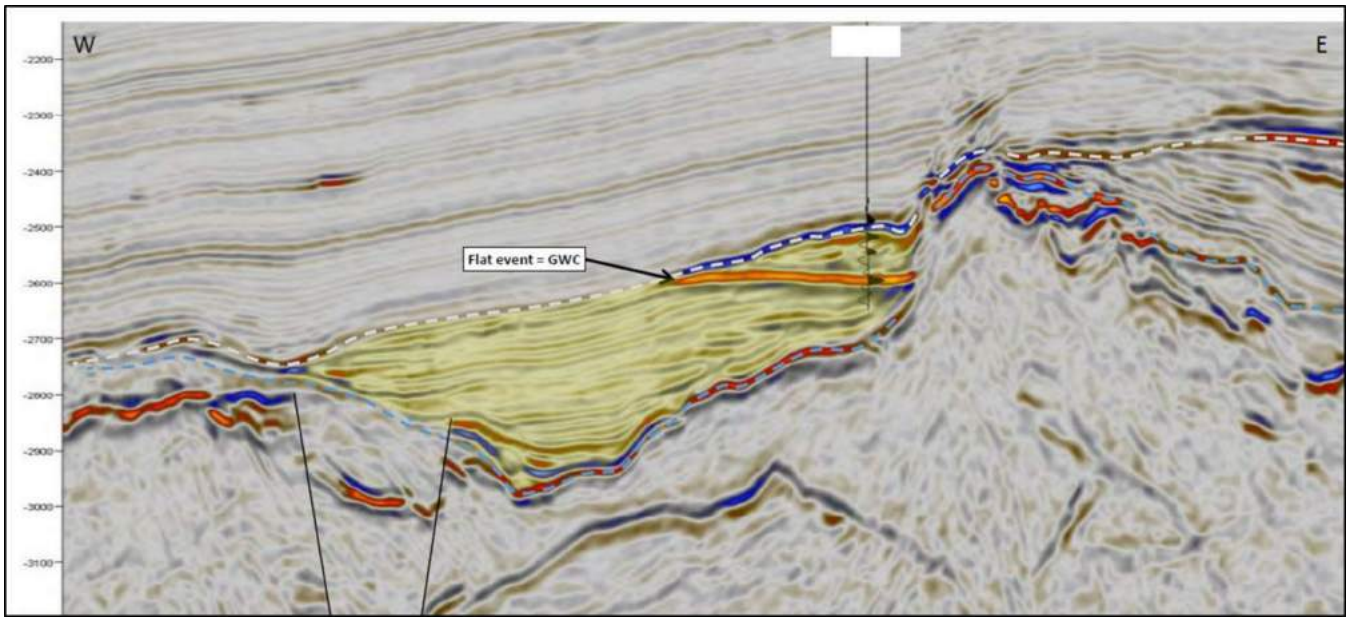


Figure 28: *Rotan discovery made by Murphy Oil (2007), with a striking flat event signifying the gas-water contact (GWC). Rotan reservoir sands were deposited in one of a series of structurally controlled mini-basins that were developed beyond the shelf-edge break. Horizontal scale not provided. From Jones et al., (2016).*

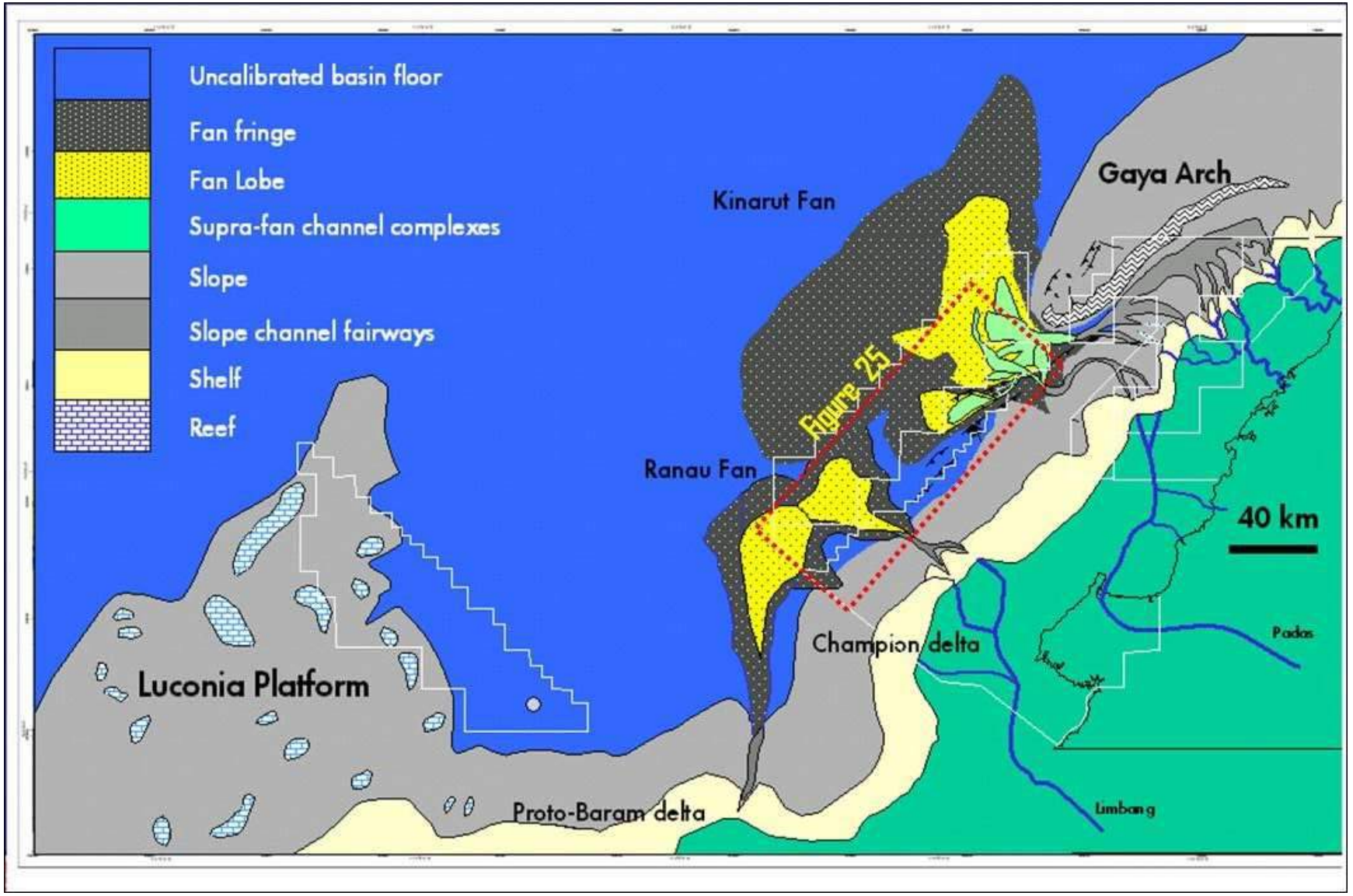


Figure 29: *Palageography of NW Borneo margin during the Lower Kinarut deposition (TB3.1), which show three main sources of sedimentary input in the study area from the proto-Baram and Champion deltas to the south, and the outlet between Gaya Arch and the inboard high areas to the north (from Grant, 2005). Details of red dashed-box is shown in Figure 25.*

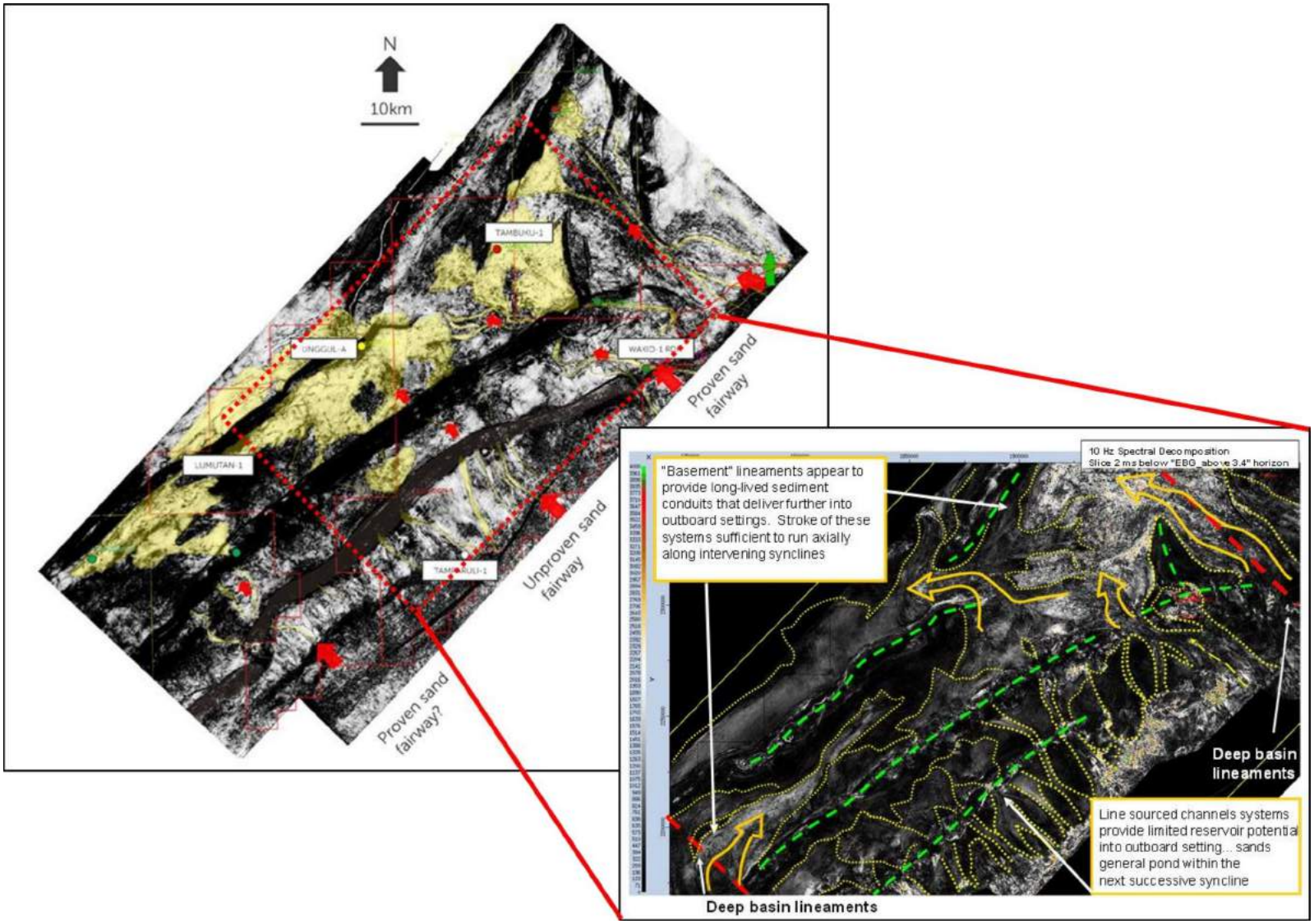


Figure 30: *Spectra-decomposition slicing at Kamunsu level showing the sedimentation pattern of deepwater Sabah. In more details, it is noted that basement lineaments appear to provide long-lived sediment conduits that deliver further into outboard setting, with strike of these depositional systems run axially along the intervening synclines. On the other hand, line-sourced channel systems provide limited reservoir potential into outboard setting.*

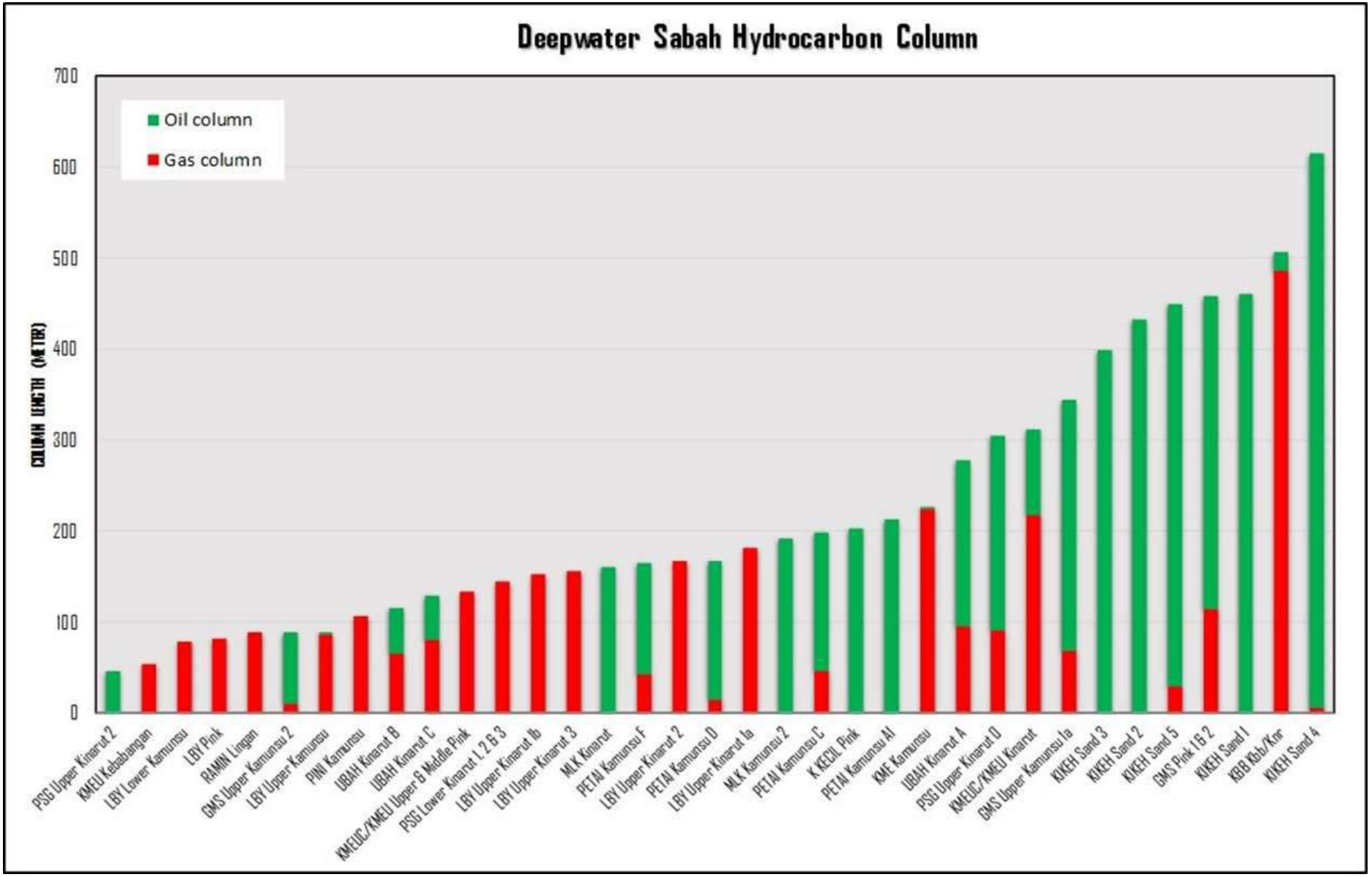


Figure 31: *A record of discovered deepwater hydrocarbon columns. The length (or length) of the columns appears to be largely independent from the nature of the fill, and or pressure. This points to a very strong and reliable retention setting. Data compiled by J. Jong.*

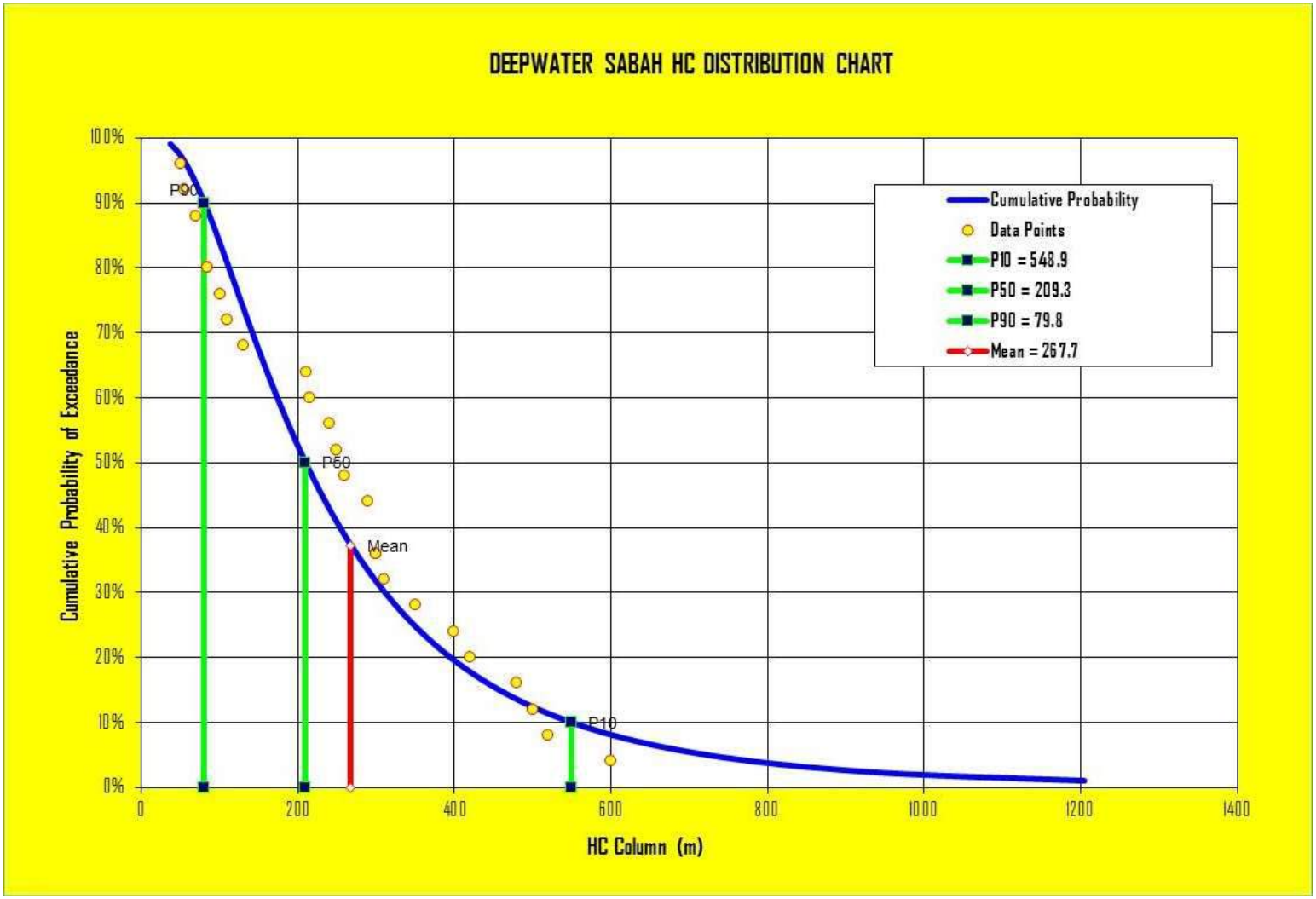


Figure 32: *Hydrocarbon column expectation curve calibrated on existing deepwater discoveries. P90 equals a length of ca. 80 m, P50 ca. 210 m. P10 stands at ca. 550 m. So far P1 has not been found yet, but the question remains if it can exist or does exist. Data compiled by J. Jong.*

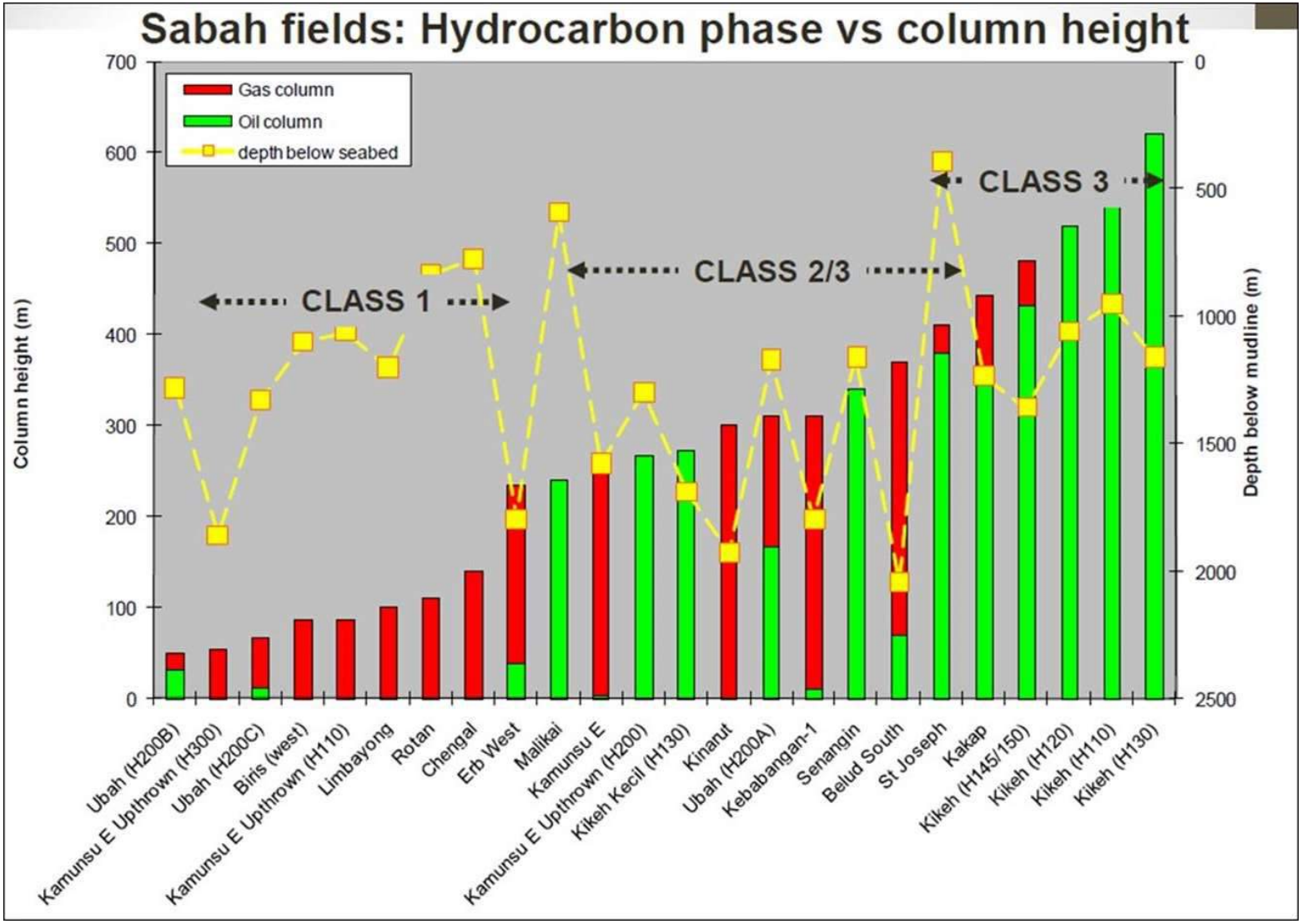


Figure 33: *Hydrocarbon phase versus column length from the Sabah fields. Data compiled by Murphy Oil. Class 1 = predominantly gas examples with columns generally less than 200m, Class 2/3 = mixed oil and gas fields with columns ranging from 200m to 400m, Class 3 = predominantly oil examples from Kikeh with columns ranging from 400m to 600m. Data compiled by Murphy Oil.*

FLUID REGIME, TEMPERATURE AND PRESSURE

We observe a full spectrum of oils (low API to condensate), and very dry to wet gas. Regional work by various researchers is leading to the rationale that all oil and gasses found trapped in reservoirs around Borneo stem from a mixed plant-derived and coaly source rocks, with a high wax content derived from mangrove detritus (e.g., Algar, 2012; Jong et al., 2014b & 2017a). Consequently, the variety of observed hydrocarbons is explained by osmotic processes, in which hydrocarbons are separated (or retained) according to capillary pore size in reservoir and thief zones (Figures 8 and 9). Generally speaking, light to heavy oil appears to have percolated through leaky formations, while well plumbed reservoir has retained its well-sealed gas content.

The heat flow in NW Borneo is elevated, and significantly higher compared to many other passive margin settings (Figure 34). Analytical work by Jong et al. (2014a) and Nagarajan et al. (2017) suggests that the NW Borneo margin is not a pure passive margin, but also shows signs of compression. Reasons for this are: (i) Sundaland being a continent that has formed relatively late in Earth's history (Late Paleozoic to Mesozoic), with the result that continental crust is thinner (in the order of 30 km, see below), hence hotter compared to other continents. Furthermore, the NW Borneo crust has been stretched to the point of rifting, leading to crustal thinning, again with higher heat flow characteristics. In Figure 34 well temperatures were projected to a 3300 m (10000 ft) depth basin-wide, then gridded and contoured. We see that as we move from east to west, and increasingly through younger formations, formation temperatures generally decrease, with the exception of a few unusually hot areas.

Like in many other young hydrocarbon basins in the world, Brunei and Sabah offshore oil and gas accumulations are found in both hydrostatic and overpressured reservoirs. Some fields offer both regimes, with a tendency of overpressured gas/condensate reservoirs to be found at deeper structural levels, and with low-GOR (gas-oil ratios) oils typically found at shallower levels.

Temperature and pressure affect the physical strength, electronic properties, sealing technology and chemical reaction of a technology or process. This imposes very real limitations on much of the technology currently available to help develop these reservoirs. High temperatures and/or high pressures are often found in these uncharted territories, presenting complex challenges including casing buckling, accelerated drilling fluid chemical reactions and rock collapse. For well planning, it is therefore necessary to assess the existence and lateral extent of overpressured reservoirs. Overpressure data can be obtained by empirically assessing overpressures in a basin (such as this study); other measures include the use of seismic methods such as 3D velocity cube analysis and seismic inversion.

To show the pressure regime at 3300 m (10000 ft) (Figure 35), well pressures were sampled and projected to the 3300 m below sea level. The pressure data indicate lower pressures in the cooler and younger off-shelf sub-basins. However, it must be noted that the temperature and overpressure pictures, confined to the dataset compiled by and made available to the authors are much more complex than shown in the simplified regional overview, but instead are constraint by faults, structural evolution and the extent of reservoir and aquifer presence. It is noted that a number of operators exploring the NW Borneo basins have conducted detailed in-house studies of temperature and pressure implications for hydrocarbon exploration and it would be useful for further regional investigations if they can be made publicly available.

COMBINATIONS OF WORKING (PROBABILISTIC SUCCESS PATTERNS) AND COMBINATIONS OF NON-VIABLE PARAMETERS (PROBABILISTIC FAILURE PATTERNS)

In summary, it seems important to crystallize patterns of parameters that allow for reasonable hydrocarbon columns to be retained, and exclude those combinations (and the related Monte Carlo loops) that lead to scenarios that are not viable.

Combinations of probabilistic success patterns appear to be:

1. Deepwater claystone seal + deepwater turbidite reservoir + gas + overpressure
In this scenario there is little or no retention risk in relation to top seal, as long as seals are sufficiently lithified to withstand buoyancy pressure (e.g., Figure 20).

2. Deepwater claystone seal + deepwater turbidite reservoir + oil + hydrostatic
In this case oil is preferentially retained, while gas is removed via a regional aquifer possibly leading to small gas accumulations in the updip direction (e.g., Figure 11).

3. Shallow marine clay + topset reservoir + hydrostatic + oil (gas more rarely)
In shelfal, but essentially subtidal settings, relatively thin and often bituminous clay sequences can potentially hold back significant oil and gas columns. This setting, however, is also characterized by frequent reservoir discontinuity, such that hydrocarbons are located in (at least on production scale) isolated lenses (e.g., Figure 24).

Combinations of non-viable parameters or failure patterns appear to be:

1. Deep marine clay seal (< 500 m bml) + shallow deepwater reservoir + overpressure
Given the poor consolidation and lithification of the top seal, it cannot withstand the buoyancy pressure from hydrocarbons in the reservoir beneath, and only columns in the order of several meters can be retained, before seal failure occurs.

2. Deepwater claystone seal + deepwater reservoir + oil + hard overpressure
The authors do not recall any case of significantly overpressured oil. Although the latter may exist for a short while (for geological time), it is likely that overpressured oil may fracture seals and escaped.

3. Intertidal clay seal + intertidal reservoir + overpressure + oil/gas
This scenario applies to shelfal areas, where both reservoir and seal may have been deposited in the intertidal realm. Characterized by both discontinuous reservoir and seal, it appears highly unlikely that overpressure develops over a larger area (prospect) area. Possibly overpressured gas could be seen in isolated lenses only, but neither leading to significant columns nor economic success volumes. However, when present these overpressured gas columns could constitute a shallow but significant drilling hazard.

How then can we translate this parameter combination approach into a meaningful probabilistic evaluation exercise? We advise that one should first, with a very open mind, define all possible patterns and, in particular, include negative outcomes. The individual patterns are then run as Monte Carlo simulations, yielding pattern-specific P50 column length models data for a specific prospect. The individual pattern outcomes can also possibly be merged for economic ranking purposes, etc.

DISCUSSION AND CONCLUSIONS

Data shown in this paper demonstrate a marked difference between shallow marine shelfal reservoir/seal and deep marine reservoir/seal combinations. Both success volumes and POS for long hydrocarbon columns appear to be far more favorable in deep marine settings than in the shallow depositional realms. This said, an atypical strike such as Adong Kecil shows that hydrocarbons can still be found in relatively intensively explored areas, even onshore. However, to probe which faults are sealing and have retained hydrocarbons, appears to be a daunting task.

This paper, essentially written describing hydrocarbon column parameters, falls short of a number of issues, which need further research. These include:

Sub-seismic discontinuity of lenticular reservoir bodies such as those seen in tidally-influenced shallow marine shelfal reservoirs and seals. Many accumulations are known possessing large STOIIP values, however are associated with poor recoverable volumes, and low amplitudes. How realistic are STOIIP values in such a case? Conventionally, we imply hydrocarbon and water form layers of liquids and gases within layers of rock. In reality however, the layering of rock is less than perfect, and liquids may be connected in various ways. To obtain a better economic grip one might try to replace a STOIIP and recovery-based model by a permeability/fluid mobility model.

Hydrocarbon fractioning by osmotic processes in reservoirs is certainly happening, but how reservoir and marginal seal interact physically and chemically may be poorly understood and could form an attractive avenue of research.

In conclusion, column length is a derivative of several factors affecting the integrity of a hydrocarbon trap. The presence of an effective and laterally continuous top seal is perhaps the most important, although in rarer cases relatively thin top seal can be surprisingly efficient. Contiguity of hydrocarbon reservoirs, with isotropic reservoir characteristics can be a positive factor for the development of longer hydrocarbon columns. Moreover, the overall sand-to-shale ratio is critical. Hydrocarbon columns tend to be longer in clay prone environments (sand to clay juxtaposition is here more likely; and a better fault seal due to good SGRs). On the other hand, hydrocarbon columns tend to be short in shallow marine to deltaic settings given discontinuity of reservoirs, abundance of sand and poor fault sealing capacity. Therefore, both POS of volume and POS of long columns is far higher than in turbidite reservoir/seal associations compared to shallow marine shelfal settings. This observation applies at least to proximal turbidite settings, although it has been shown that very distal turbidite settings are not synonymous with good reservoir development, which has a great impact on economic success volume (e.g., Jong et al., 2017b).

Last but not least, we believe that the datasets compiled and presented in this paper are sufficient to generate meaningful hydrocarbon column outcomes for the discussion of trapping mechanisms of various depositional settings of NW Borneo clastic systems. Nevertheless, we welcome further data contributions in terms of field hydrocarbon columns, temperature and pressure data from the readers so that all possible scenarios can be properly captured, evaluated and presented to generate more complete hydrocarbon distribution patterns of the study area.

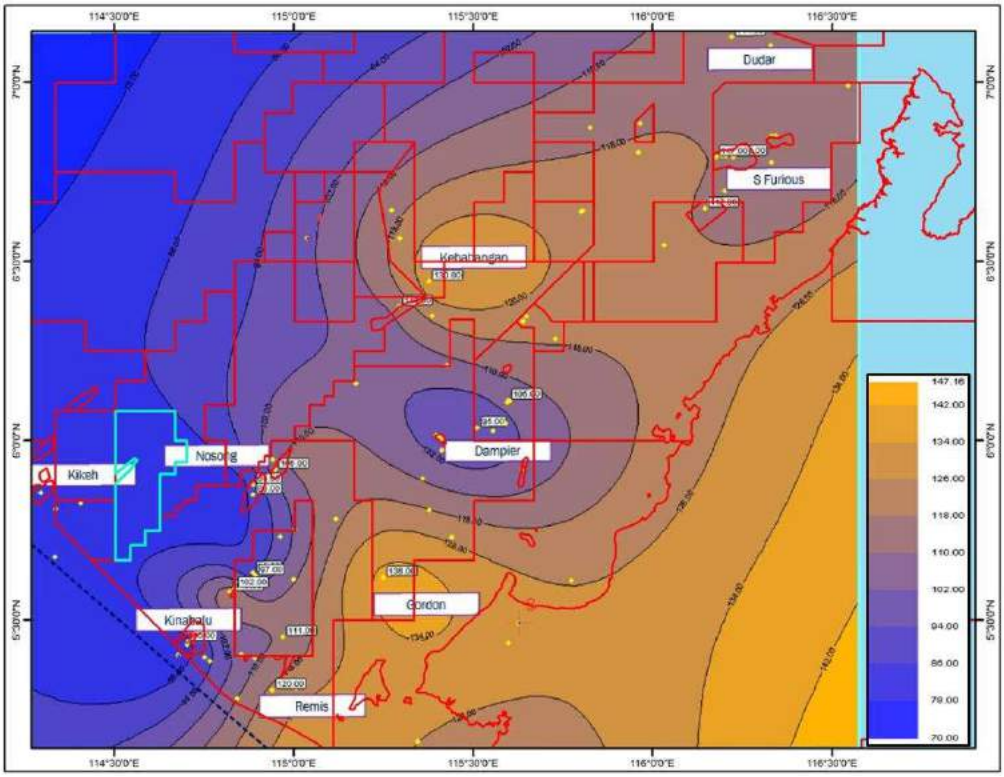


Figure 34: *A 3300 m (10,000 ft) depth slide showing prevailing temperatures of offshore Brunei and Sabah. The temperature slice at 3300 m shows a moderately hot shelf, and hot deepwater areas, with temperatures above 110 ^{0}C and several clusters of elevated heat (130 ^{0}C). The south-west corner however, is comparatively cool with temperatures below 100 ^{0}C.*

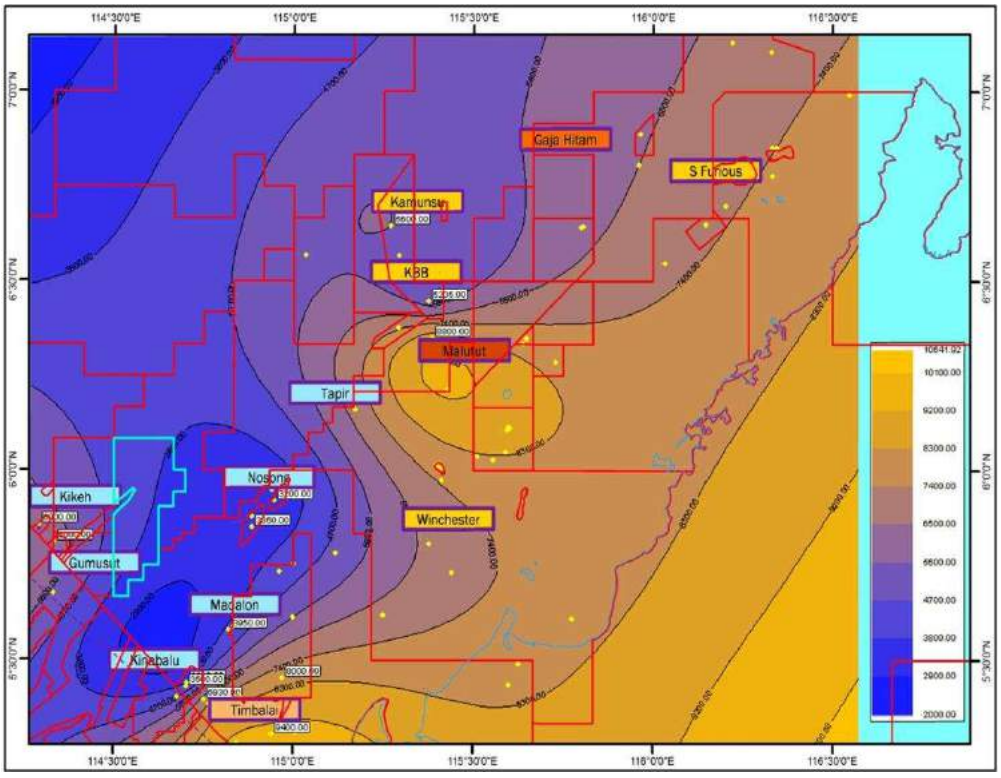


Figure 35: *A 3300 m (10,000 ft) depth slide showing prevailing pressures of offshore Brunei and Sabah. The pressure slice at 3300 m shows comparatively lower pressure in the outer, and younger depocentres compared to pressures seen in the inboard and significantly older sequences.*

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