

# “Fractured basement” play in the Sabah Basin? – the Crocker and Kudat formations as hydrocarbon reservoirs and their risk factors

MAZLAN MADON<sup>1,\*</sup>, FRANZ L. KESSLER<sup>2</sup>, JOHN JONG<sup>3</sup>, MOHD KHAIRIL AZRAFY AMIN<sup>4</sup>

<sup>1</sup> Advisor, Malaysian Continental Shelf Project, National Security Council, Malaysia

<sup>2</sup> Goldbach Geoconsultants O&G and Lithium Exploration, Germany

<sup>3</sup> A26-05, One Residences, 6 Jalan Satu, Chan Sow Lin, KL, Malaysia

<sup>4</sup> Malaysia Petroleum Management, PETRONAS, Malaysia

\* Corresponding author email address: [mazlan.madon@gmail.com](mailto:mazlan.madon@gmail.com)

**Abstract:** Exploration activities in the Sabah Basin, offshore western Sabah, had increased tremendously since the discovery of oil and gas fields in the deepwater area during the early 2000s. However, the discovery rates in the shelfal area have decreased over the years, indicating that the Inboard Belt of the Sabah Basin may be approaching exploration maturity. Thus, investigation of new play concepts is needed to spur new exploration activity on the Sabah shelf. The sedimentary formations below the Deep Regional Unconformity in the Sabah Basin are generally considered part of the economic basement which is seismically opaque in seismic sections. Stratigraphically, they are assigned to the offshore Sabah “Stages” I, II, and III which are believed to be the lateral equivalents of the pre-Middle Miocene clastic formations outcropping in western Sabah, such as the Crocker and Kudat formations and some surface hydrocarbon seeps have been reported from Klias and Kudat peninsulas. A number of wells in the inboard area have found hydrocarbons, indicating that these rocks are viable drilling targets if the charge and trapping mechanisms are properly understood. This study assesses the potential and risks of a conceptual “basement” hydrocarbon play in the Crocker and equivalent formations in the Sabah Basin.

**Keywords:** Crocker Formation, Kudat Formation, fractured basement play, hydrocarbon exploration, Sabah Basin

## INTRODUCTION

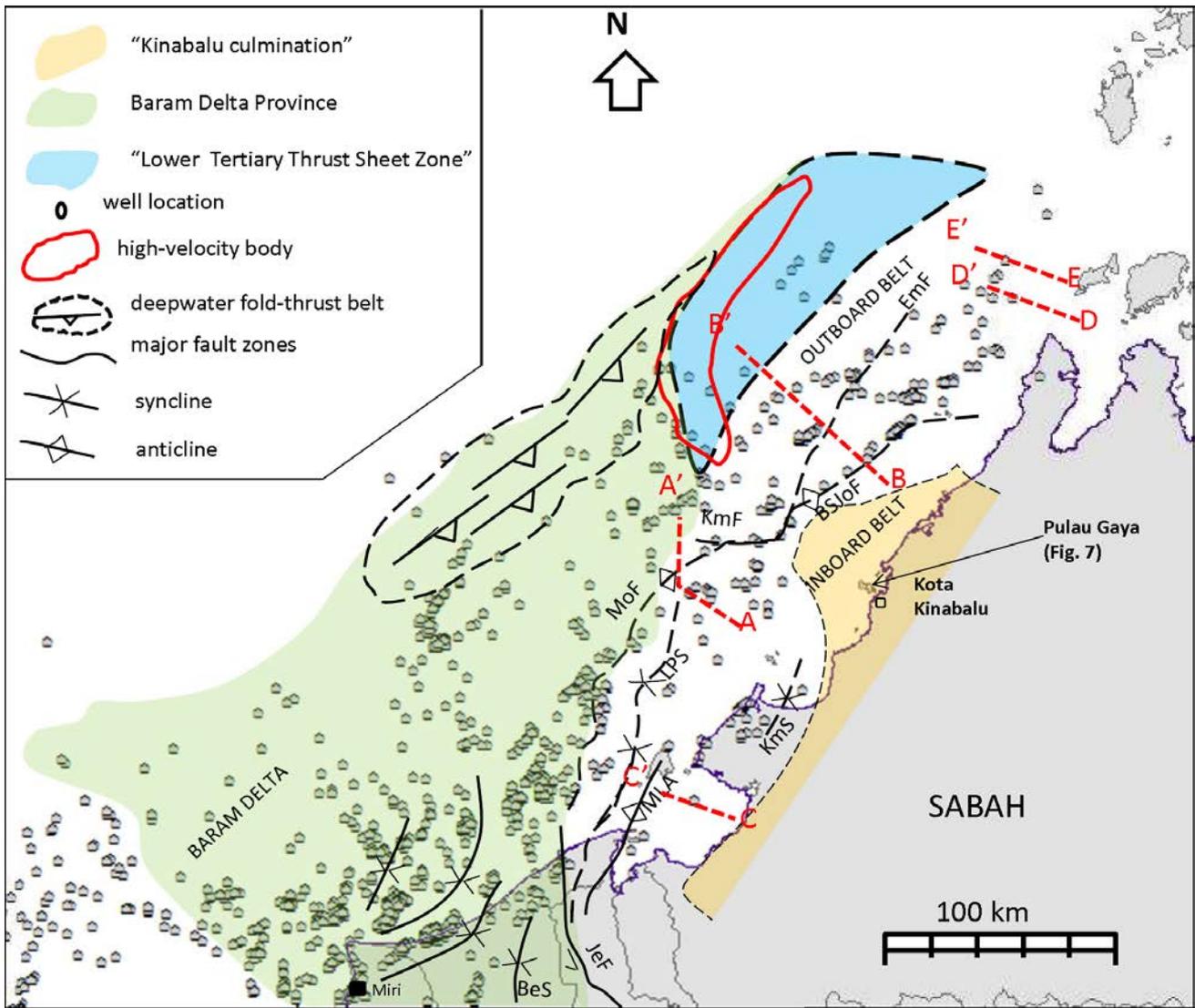
Traditionally, “basement” is often thought of as crystalline rocks in continental cratonic regions and may include granitic igneous and metamorphic rocks (cf. Landes *et al.*, 1960) or in the oceans, mafic igneous rocks beneath the sedimentary basins and sea floor (hence, the term “oceanic basement”). In sedimentary geology, the term “basement” is often used to refer to rocks that underlie a sedimentary basin with great unconformity, regardless of age, composition or origin (cf. Sircar, 2004). That unconformity represents a significant hiatus in the rock record and therefore marks the end of a previous tectonic-sedimentary cycle. In such a usage, “basement” does not necessarily imply that the rocks beneath that unconformity are crystalline rocks but could also include sedimentary rocks that had been deformed, uplifted, and partly eroded by the tectonic event that resulted in the unconformity.

In the offshore area of western Sabah (Figure 1), between Brunei Bay and Kudat Peninsula, “basement” has been used in a similar context by Levell (1987) and Tan & Lamy (1990) to refer to rocks that lie beneath the “Deep Regional Unconformity” (DRU), a major regional unconformity that separates highly deformed pre-Middle

Miocene deep marine deposits (which are stratigraphically subdivided into “Stages” I, II, and III) from less-deformed Middle Miocene and later sequences of sediments deposited by northwestward-progradation of shelf-slope sequences (“Stage” IV). This basement to the Sabah Basin<sup>1</sup> extends onshore as the outcropping turbidites and melanges of the Crocker Formation and roughly age-equivalent rock units in western Sabah, including the Trusmadi, Setap Shale, Wariu, Chert-Spilite, Temburong, and Kudat formations. The Crocker Formation has been studied most extensively in the western and northern parts of Sabah, where it is known as the “West Crocker Formation”. Due to poorly constrained ages, this designation appears to be arbitrary and geographic in nature and has no stratigraphic significance (Hutchison, 2005). For brevity, the term “Crocker Formation” is used throughout this paper.

Tan & Lamy (1990) considered these rock units collectively as the Crocker Accretionary Prism, which forms the “mechanical basement” beneath a major part of the offshore Middle Miocene basin. Rocks beneath the DRU have been penetrated in many wells in the near offshore and in coastal areas of western Sabah. However, the seaward extent of these “basement” rock formations, especially the

<sup>1</sup> “Sabah Basin” is used here to refer to the Middle Miocene sedimentary basin above the Deep Regional Unconformity (DRU), following the usage in PETRONAS book (1999). In the literature it is sometimes referred to as the “NW Sabah Basin”.



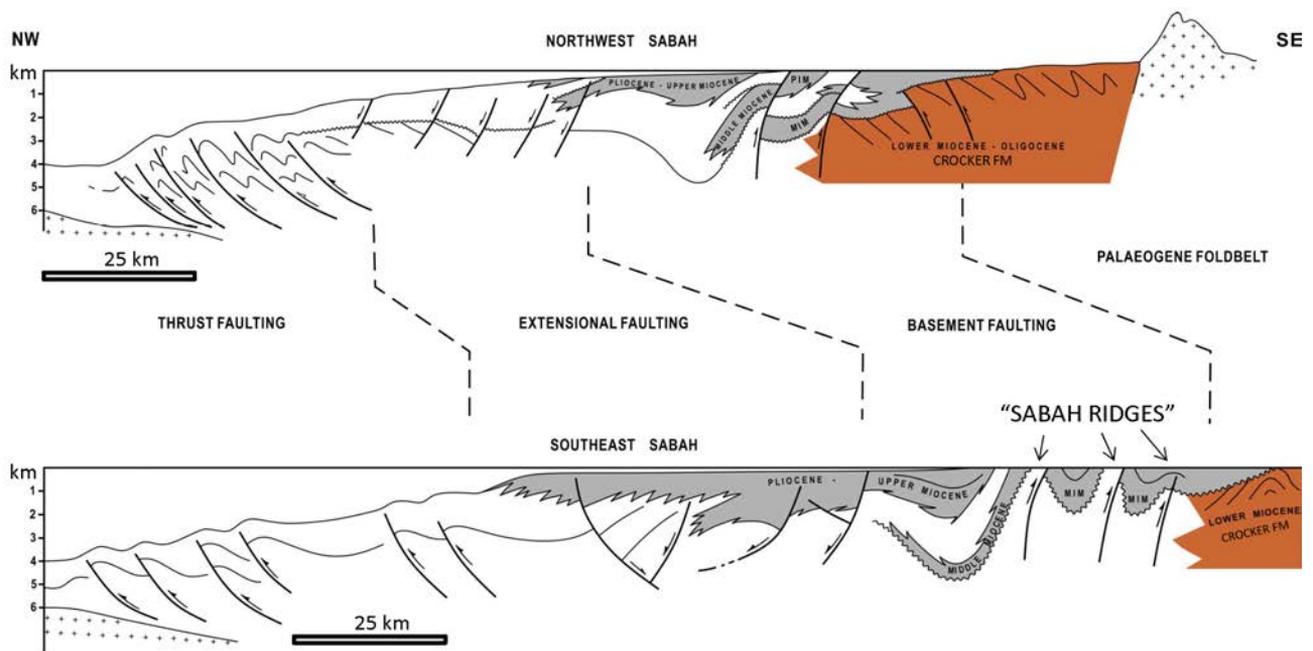
**Figure 1:** Location map of study area in offshore western Sabah, with the main structural features mentioned in the text. Red dash Lines A, B, C, D and E are the locations of cross sections shown in Figures 5, 6, 8 and 9, respectively. Abbreviations: BeS – Belait Syncline, JeF – Jerudong Fault, MLA – Muara-Labuan Anticline, KmS – Kimanis Syncline, LPS – Labuan-Paisley Syncline, MoF – Morris Fault, KmF – Kimanis Fault, EmF – Emerald Fault, BSJoF – Bunbury-St. Joseph Fault. Map compiled from Madon *et al.* (1999), Hazebroek & Tan (1993), and Franke *et al.* (2008). Well locations are from IHS Markit database (2018).

Crocker Formation is uncertain. Some of those wells have encountered hydrocarbons, making them potential targets for exploration (Figure 2). This study assesses the potential of Crocker and equivalent formations as future targets for hydrocarbon reservoirs in the offshore Sabah Basin. The discussion also includes the Kudat Formation, outcropping on Kudat Peninsula (Tongkul, 2006), and is generally believed to be slightly younger than the Crocker Formation but has been dated by foraminifera as Late Oligocene to Early Miocene (e.g., Hafzan *et al.*, 2017). The stratigraphic relationship between the Crocker and Kudat formations, which are in thrust/melange contact, is still unresolved due to the wide age-dating results (Ahmad Ridhwan *et al.*, 2017). Nevertheless, seismic data clearly show that the Kudat

Formation also forms part of the acoustic basement to the Neogene Sabah Basin as it continues offshore underneath the northern Sabah Basin.

### GEOLOGICAL SETTING

The study area in western Sabah is shown in Figure 1. The Sabah Basin is regarded as a post-orogenic foreland basin that developed as a result of the subduction-related uplift of Sabah following its Early Miocene collision with the Dangerous Grounds continental terrane. This collisional event was referred to as the “Sabah Orogeny” by Hutchison (1996), which is often considered as the time of cessation of sea-floor spreading in the South China Sea marginal basin (e.g., Barckhausen *et al.*, 2014).



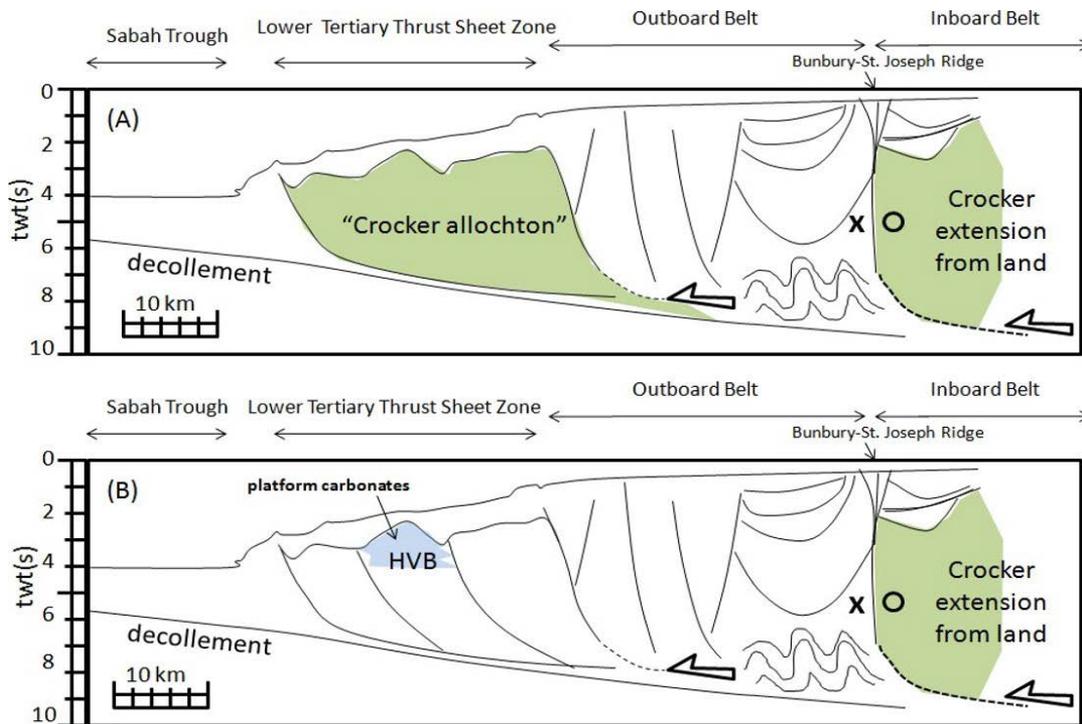
**Figure 2:** An early construction of the regional cross sections of offshore western Sabah by Bol & van Hoorn (1981) shows the Sabah Basin developed above a major regional unconformity that truncates folded and uplifted “Paleogene foldbelt”, shown on the left of the cross-sections as ?Oligocene to Lower Miocene rocks (shaded brown). These deformed rocks of the Crocker Formation and its equivalents crop out onshore. They also form the core of some of the upthrusted anticlines in the inboard areas, termed the “Sabah ridges” by Bol & van Hoorn (1980), but how far the “Paleogene foldbelt” continues seaward is not known for certain.

The Crocker Formation (of Eocene-Lower Miocene age) crops out extensively in western Sabah and, especially in the Kota Kinabalu area, has been subject to many field studies (Figure 2). The formation is made up of thick- and thin-bedded turbiditic sandstones and shales and is highly deformed, as indicated by its characteristically steep, almost vertical bedding which is widely observed in the field. Previous workers have described these flysch-like deep-sea sediments as being deformed into imbricate thrust slices due to convergent margin tectonics associated with that Early Miocene collision of Dangerous Grounds with Sabah (e.g., Tongkul, 1990).

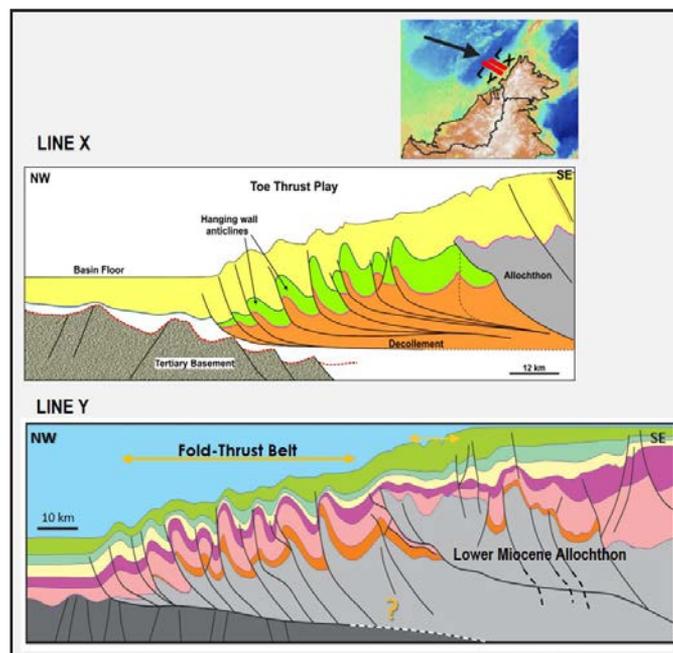
Some of these imbricate thrust slices seem to have been translated for long distances offshore underneath the present-day shelf of western Sabah. Seismic data from the northern part of the basin and in the adjacent Palawan margin have shown the presence of an allochthonous dense body of rock beneath Middle Miocene and younger sediments as far as 90 km from shore (Figure 3). Since its identification by Hinz *et al.* (1989) of a “Lower Tertiary thrust sheet” (LTTS) zone beneath the northern headwall of the Sabah Trough and the Inboard Belt, subsequent authors have recognized its presence based on more extensive oil industry seismic data and included them in their tectonic maps and structural cross-sections (Hazebroek & Tan, 1993). Seismic interpretations in that region of offshore Sabah showed the presence of a wedge of allochthonous material intruded into younger Neogene sequences (Grant, 2005;

Ingram *et al.*, 2004). Geoseismic profiles of Hazebroek & Tan (1993) (Figure 3) suggest that the “Crocker allochthon” is limited to within a 40 km-wide LTTS zone and seems to be absent landward of this zone until near until the Inboard Belt, coincident with Bunbury-St. Joseph Fault (“BSJoF” in Figure 1), a fault line that runs approximately through Ketam, Erb West, Tembungo to SW Emerald oil and gas fields. The outcropping Crocker Formation is shown by Hazebroek & Tan (1993) to extend offshore and terminate abruptly at this fault line, which seems to be a major wrench fault zone that joins up with the Morris Fault and further south-westwards into Brunei as the Jerudong Fault (Figure 1). Accordingly, this fault line (BSJoF) effectively separates the Sabah shelf into the Inboard and Outboard belts.

The nature of the allochthon in the LTTS zone, although presumed to be of Crocker Formation, is still unknown, for no wells have been drilled into it. Support for its existence, however, has been provided by Franke *et al.* (2008) who identified a high-velocity rock-body at that location, but with a narrower extent (20 km wide) than previously thought (70 km wide) (Figure 1). These authors, however, proposed an alternative explanation: that this high velocity body may be platform carbonates, similar to Kudat platform (a little-known carbonate province in the northern Sabah Basin, briefly described by Madon *et al.*, 1999), instead of an overthrust slice of Crocker Formation. The question as to which of these two interpretations are more likely (Figure 3) is yet to be resolved, and a matter for a follow-up research.



**Figure 3:** According to Hazebroek & Tan (1993), the Lower Tertiary thrust sheet (LTTS) zone, interpreted as an allochthon derived by overthrust from the Crocker Range (see A), is separated from the main offshore continuation of the Crocker Formation in the Inboard Belt. The “gap” in the Outboard Belt between these domains does not appear to be underlain by such extraneous rock masses. A common interpretation is that the LTTS represent imbricates of Crocker Formation that had been overthrust onto the decollement surface (e.g., Hinz *et al.*, 1989; Hazebroek & Tan, 1993). Alternatively, based on the interpretation of new data by Franke *et al.* (2008), a high-velocity body (HVB) at the supposed location of the allochthon represent platform carbonates in the Neogene clastic sequence instead of an allochthon. X and O represent the sense of strike slip movement along the Bunbury-St. Joseph Fault (X towards, O away from viewer).



**Figure 3b:** Structural-stratigraphic cross sections across the northern Sabah Basin and its deepwater fold-thrust belt. Note the interpreted presence of allochthonous overthrust material emplaced into the Middle Miocene-Recent sequences (labelled “allochthon”) believed to be the subcropping continuation of the Crocker Formation in the Inboard area and onshore Sabah. Line X modified after Ingram (2004) and Line Y modified by Jong *et al.* (2015) after Grant (2005).

Regardless of the model preferred, the presence or absence of Crocker or equivalent formations beyond the BSJoF line is pertinent to determining the possible lateral extent of Crocker Formation as a “basement” hydrocarbon play. The question is how far does the Crocker Formation extend seawards? According to the interpretation of Hazebroek & Tan (1993) (Figure 3), it is likely that the western limit of the subcropping Crocker Formation beneath the Sabah Basin is marked by the BSJoF (see Figure 1). This major fault line could represent the boundary or “suture” between the petroliferous foreland basin and the Sabah hinterland where the Crocker basement is expected to occur at relatively shallow depths. It is interesting to note that none of the exploration wells in this part of the basin lie landward of this fault zone (as shown in Figure 1), probably due to the shallow Crocker subcrop and therefore thin overburden of Middle Miocene and younger sediments. The occurrence of oil and gas shows in the Crocker basement (Stage III and older) in other places, however, requires further investigation.

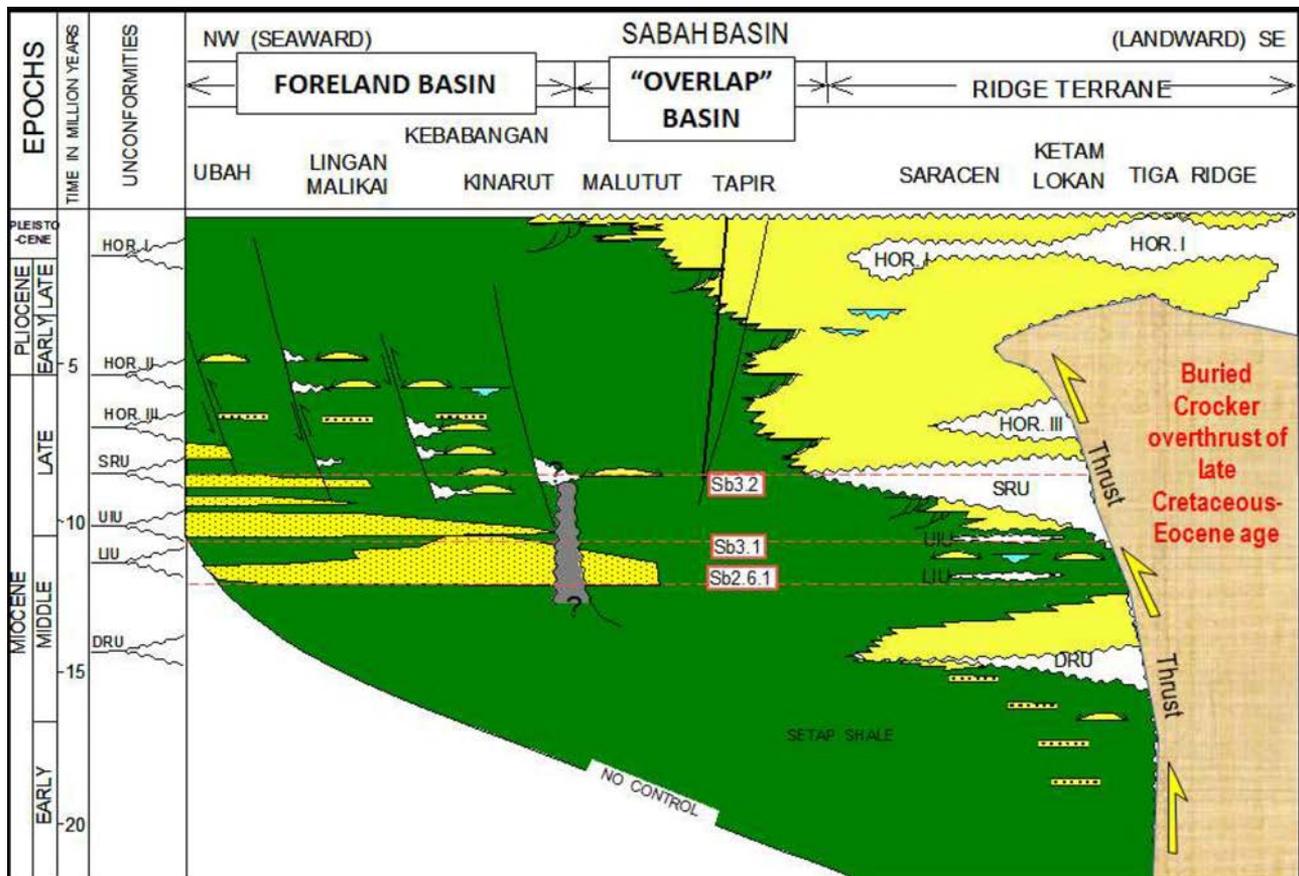
### STRUCTURAL DOMAINS

In published stratigraphic charts of the Sabah Basin, Crocker Formation is usually shown as Eocene basement

beneath the petroliferous foreland basin. Arguably, as a result of the tectonic events discussed above, allochthonous thrust sheets of Crocker Formation may be “intruded” into the Neogene foreland basin sequences, as shown schematically in Figure 4.

Based on the foregoing, we can subdivide the Sabah Basin into three structural domains, from NW to the SE:

- i) The foreland basin (including Outboard Belt, seaward to the Sabah Trough), in which clastic sediments derived from the uplifted hinterland of Crocker Formation and equivalents accumulated during Neogene times. There is no Crocker Formation in the basement in the offshore foreland basin but, instead, clay-rich sediments deposited in deep marine environment that existed prior to the Sabah Orogeny. This seems to be in line with the alternative model proposed by Franke *et al.* (2008).
- ii) An “overlap” basin, including parts of the Inboard and Outboard belts of Hazebroek & Tan (1993) underlying the geomorphological shelf, in which the Crocker Formation may exist as overthrust slices or “outliers” (the term used by Hutchison, 2005). In such cases, the contact between the “allochthons” with the underlying and overlying sediments is structural (thrusts) rather than

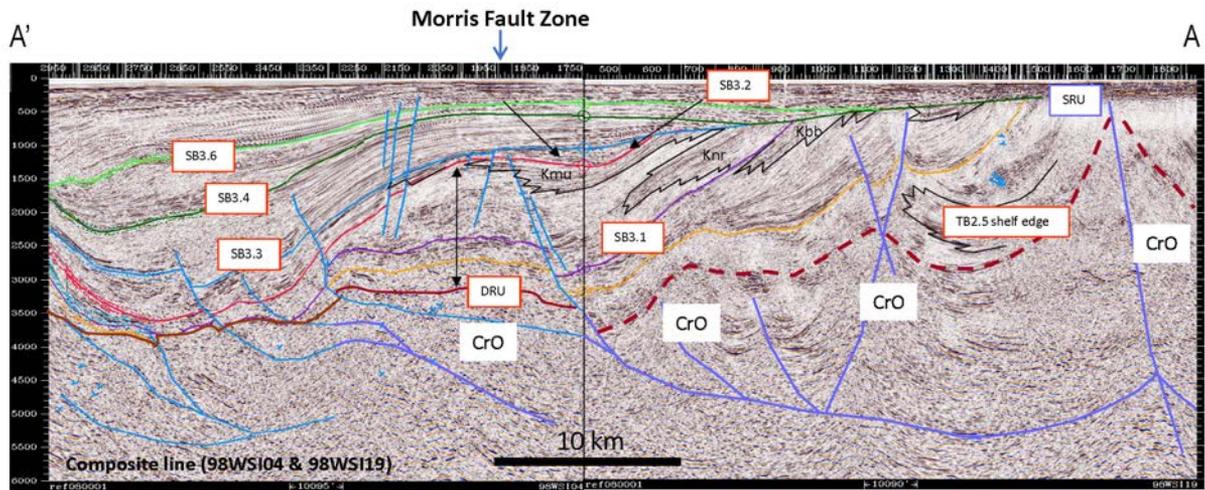


**Figure 4:** Lithostratigraphic scheme of Sabah Basin. In the so-called Ridge Terrane, in the Inboard Belt of Sabah Basin, outliers of Crocker Formation may appear as coeval sequences within the Neogene succession, but more likely with structural (thrust) contacts. This Sabah Basin chart has been modified from that of Grant (2005).

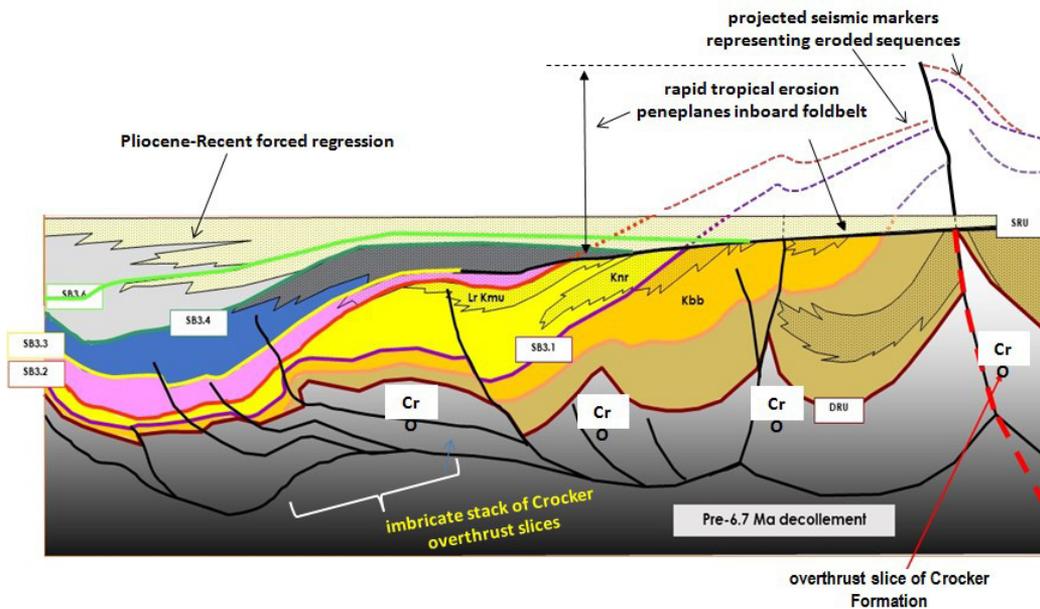
a stratigraphic one (unconformity). This domain is also called Ridge Terrane (Figure 4), based on Bol & van Hoon (1980) who referred to the characteristically tight anticlinal structures, many of which host hydrocarbons in the Neogene (Stage IV), as the “Sabah Ridges”. The geomorphology of this domain is such that Neogene sand-rich sequences occur in broad synclinal sub-basins (e.g., Labuan-Paisley Syncline, LPS in Figure 1) between the relatively narrow ridges that are usually cored by Crocker Formation and its clay-rich equivalents

(Figure 5). These allochthonous or diapiric rock masses, often referred to as “clay plugs”, generally do not contain generative source rocks, as their oil generation capacity may have been already spent, but according to maturity studies (Abolins, 2007; Sorkhabi & Tongkul, 2012) may still be in the wet or dry gas generation window (vitrinite reflectance,  $R_o = 1.3-2.0\%$ ).

iii) The domain of uplifted and deeply eroded Crocker Formation in onshore and nearshore areas, which provided the source of sand supply to all the Neogene



**Figure 5a:** Seismic Profile A (location in Figure 1) showing the influence of old early Middle Miocene structuration on the palaeogeography of the Late Miocene. Overthrust slices of Crocker Formation (labelled as “CrO”) appear seismically as a poorly imaged and mostly non-characteristic section below the DRU. The Crocker-cored thrust anticlines acted as intra-basinal highs that were by-passed by younger (TB2.6-3.2) sediments that were being transported from the shelf to the Sabah Trough. From Kessler & Jong (2015).



**Figure 5b:** A geosection drawn based on Figure 5a with reconstructed initial topography of the Crocker thrust slices (CrO) of deep marine sequences, which was later uplifted and subsequently eroded, particularly during the timing of SRU (Shallow Regional Unconformity). Modified from Grant (2005).

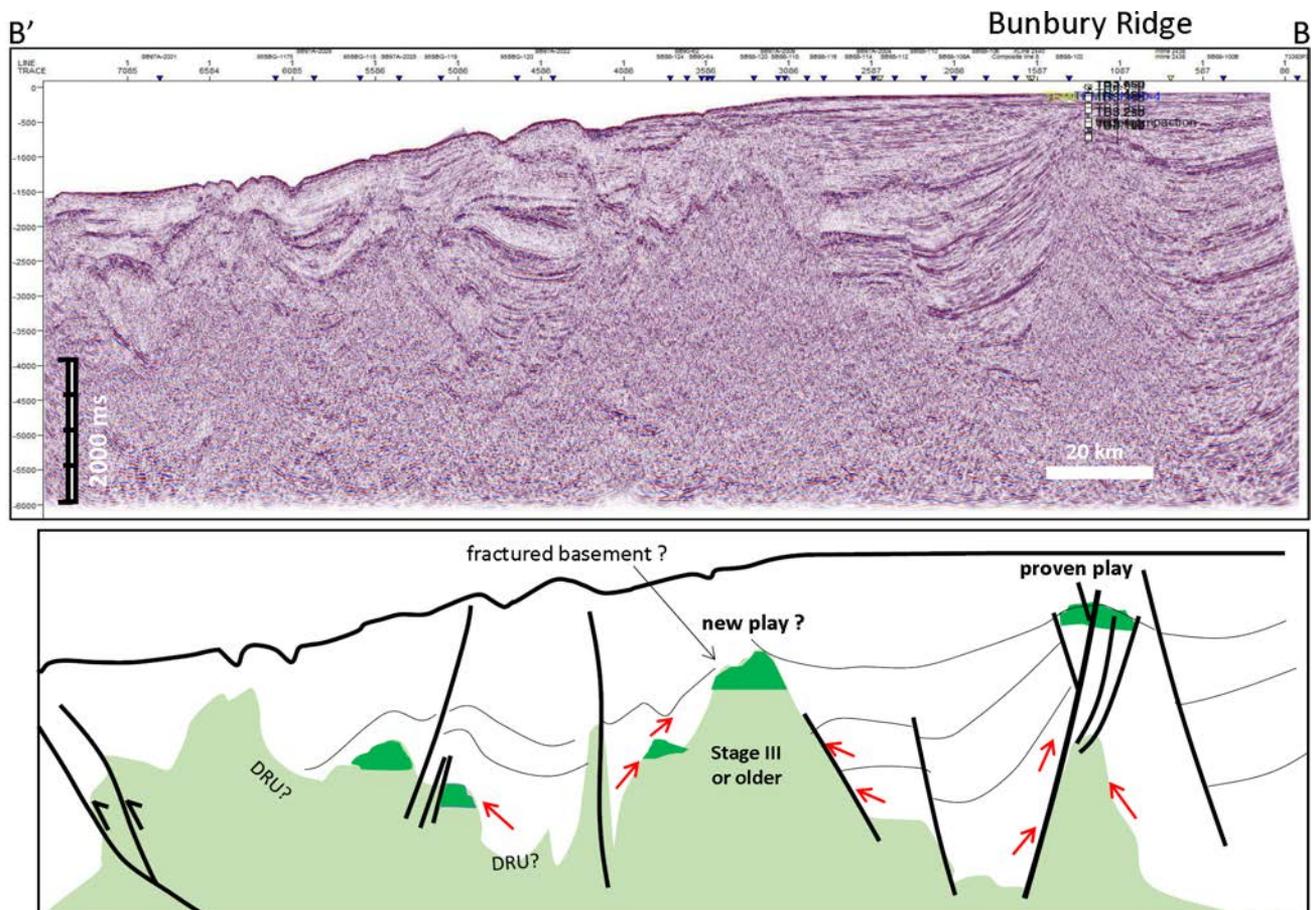
foreland basin reservoirs. The Crocker Formation, interpreted by many as an accretionary wedge complex, may be regarded as an older deep marine basin that had undergone several pulses of deformation and uplift (Kessler & Jong, 2015), and therefore represents a tectonic-sedimentary unit in its own right.

### CROCKER FORMATION AND EQUIVALENTS AS POTENTIAL RESERVOIRS

The Eocene-Lower Miocene Crocker and Kudat formations, which form the offshore basement in Domain (iii) mentioned above, crop out extensively in western Sabah. They are made up predominantly of thick- and thin-bedded turbiditic sandstones and shales and related debris flow deposits (e.g., Tongkul, 2006; Abdullah Adli Zakaria *et al.*, 2013). The succession is highly deformed, as indicated by the invariably steep, almost vertical bedding. Measurements of outcrop samples collected from Kota Kinabalu area (Teoh, 2007) show high densities (2.3-2.8 g/cc) and high velocities (4500-7500 m/s). This is not unexpected since, due to the intense deformation, the Crocker Formation and its lateral equivalents are typically highly indurated

although not yet attaining metamorphic grade (Hutchison, 1989). These characteristics of the Crocker Formation mean that on seismic they would mostly appear as acoustically opaque, devoid of coherent reflections and therefore often recognized in seismic as the "acoustic basement". Figure 6 shows some examples of the seismic characteristics and strata relationships of the Neogene sequences, source rock kitchens and the Crocker basement reservoirs/traps as a play concept.

The reservoir properties of the Crocker Formation in the Kota Kinabalu area have also been studied in detail by Teoh (2007). Due to higher degree of compaction and cementation the Crocker sandstones recorded low porosities and permeabilities ( $\Phi$ : < 10 %;  $k$ : < 1 mD). The low poro-perm values, high densities and high velocities of the Crocker sandstones suggest that they generally have non-reservoir quality for oil but could still be targeted as tight gas reservoirs. The porosity and permeability may be enhanced, however, by natural fracturing in the subsurface and this may increase the likelihood of oil accumulation in the Crocker basement. Intense fracturing of the Crocker sandstones is commonly observed in the field. Figure 7



**Figure 6:** Regional Seismic Profile (Line B in Figure 1) across the western Sabah margin showing the configuration of the basement (Stage III) beneath the interpreted Deep Regional Unconformity (DRU), where there may be potential for "Crocker basement play" within reach of the drilling range (central area). Seismic line courtesy of PETRONAS.

shows some examples of highly fractured sandstones of the Crocker Formation on the islands of Gaya and Sapi, just off Kota Kinabalu.

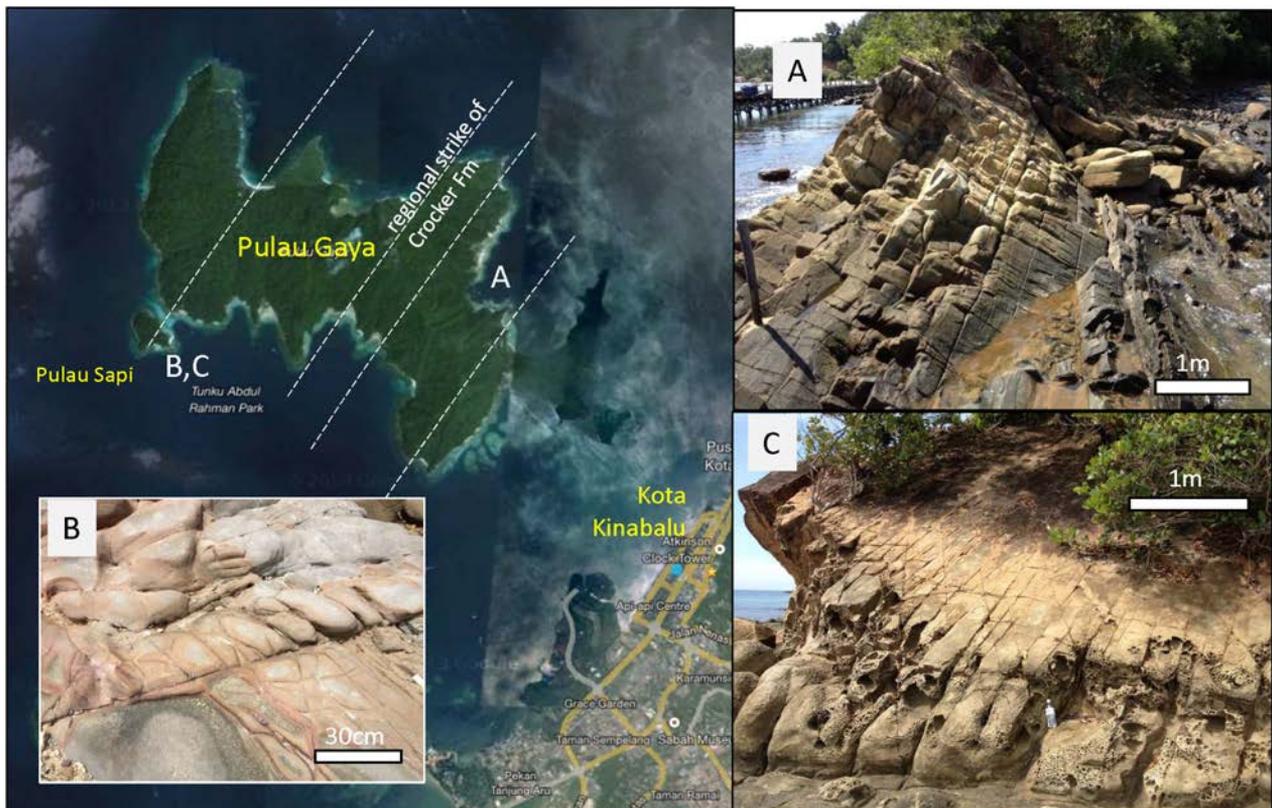
### PLAY CONCEPT

The task of the petroleum explorationist then is to find areas where the Crocker/Kudat formations may subcrop and where the pre-requisite elements of a petroleum system (source, trap, migration, and timing) may be satisfied. The structural architecture of the Sabah Basin, characterized by the tight anticlinal ridges and wide synclines (Bol & van Hoon, 1980), is such that oil and gas have so far been discovered almost exclusively in the Stage IVA-F sequences which form traps on structural highs (those “ridges”) separating large synclinal “sub-basins”. Hydrocarbons are thought to have been generated by the Stage IV sediments, which are in the hydrocarbon generating window within the synclines.

As mentioned above, geological and geochemical studies have so far indicated the low possibility of source rocks occurring in the Crocker Formation due to low organic carbon content and over-maturity. A basement play in the offshore areas, therefore, requires structural highs formed by Crocker Formation to be in juxtaposition and in communication with effective source rocks in the fine-grained, “distal” equivalents of the Stage IV prograding shelf sequences (Figure 6).

Since the porosity of the Crocker Formation sandstones are generally poor, reservoir properties may be enhanced where the formation may have been subjected to intense faulting and fracturing. Intense fracturing of the Crocker Formation such as that observed on the islands offshore Kota Kinabalu (Figure 7) could be studied as analogues for the subsurface fractured reservoir. Further evaluation of this play concept will include characterization of the nature and extent of the fractures and the reservoir properties of the sandstones. The timing of tectonism and fracturing would be another important component of play assessment. Some tectonic movements leading to the exhumation of Crocker thrust slices may have post-dated the hydrocarbon migration (see risk factors below), and hence may not result in a viable exploration target.

Despite the potential risk factors mentioned, well records show that the Crocker/Kudat basement have been penetrated in many wells within the Inboard Belt and some have even encountered hydrocarbons (Figure 8). Based on this distribution of “basement hydrocarbon” occurrences, it may be inferred that the potential areas for basement play are areas where the fractured Crocker Formation subcrops beneath the DRU. This is likely to occur in the Inboard Belt stretching from Brunei Bay to Kudat Peninsula where the DRU tends to be shallower and within normal drilling range. In addition, in the offshore area off Kudat Peninsula sub-



**Figure 7:** Field photos of outcrops of fractured Crocker Formation on (A) Pulau Gaya and (B,C) Pulau Sapi, offshore Kota Kinabalu, could be studied to understand the fractured basement characteristics and distribution. Location map from GoogleEarth™.

basins (Profiles D and E in Figures 1 & 8, shown in Figure 9) the Crocker basement appears to be highly deformed and fractured and therefore are also potential areas for further investigation into this play.

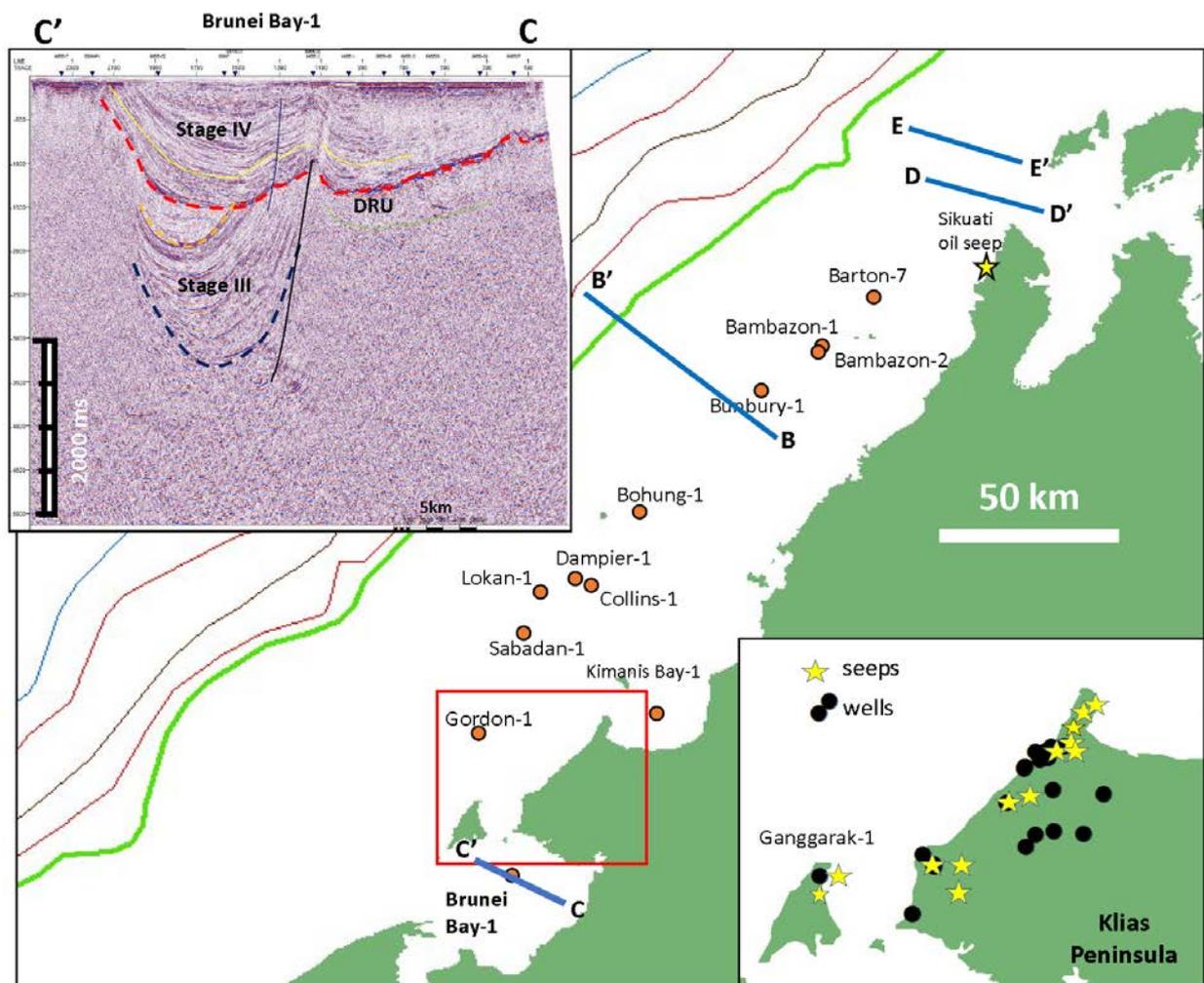
Hence, as the pre-requisite of a working petroleum system, the conceptual basement play for the fractured Crocker basement is that traps are formed by Crocker basement highs that are in juxtaposition or connected to a thermally mature and generative Stage IV source kitchen. The reservoir properties in the Crocker basement are enhanced by natural fracturing along zones of intense deformation (fault or shear zones).

There are many analogues for basement play in the region to draw from, including the fractured granite traps in the Cuu Long Basin, offshore Vietnam, and in the Anding metamorphic basement in the Malay Basin. In Sarawak, the Nuang discovery in the shallow western shelf area (Jabbar *et al.*, 2015), oil was discovered in fractured meta-sediments believed to be

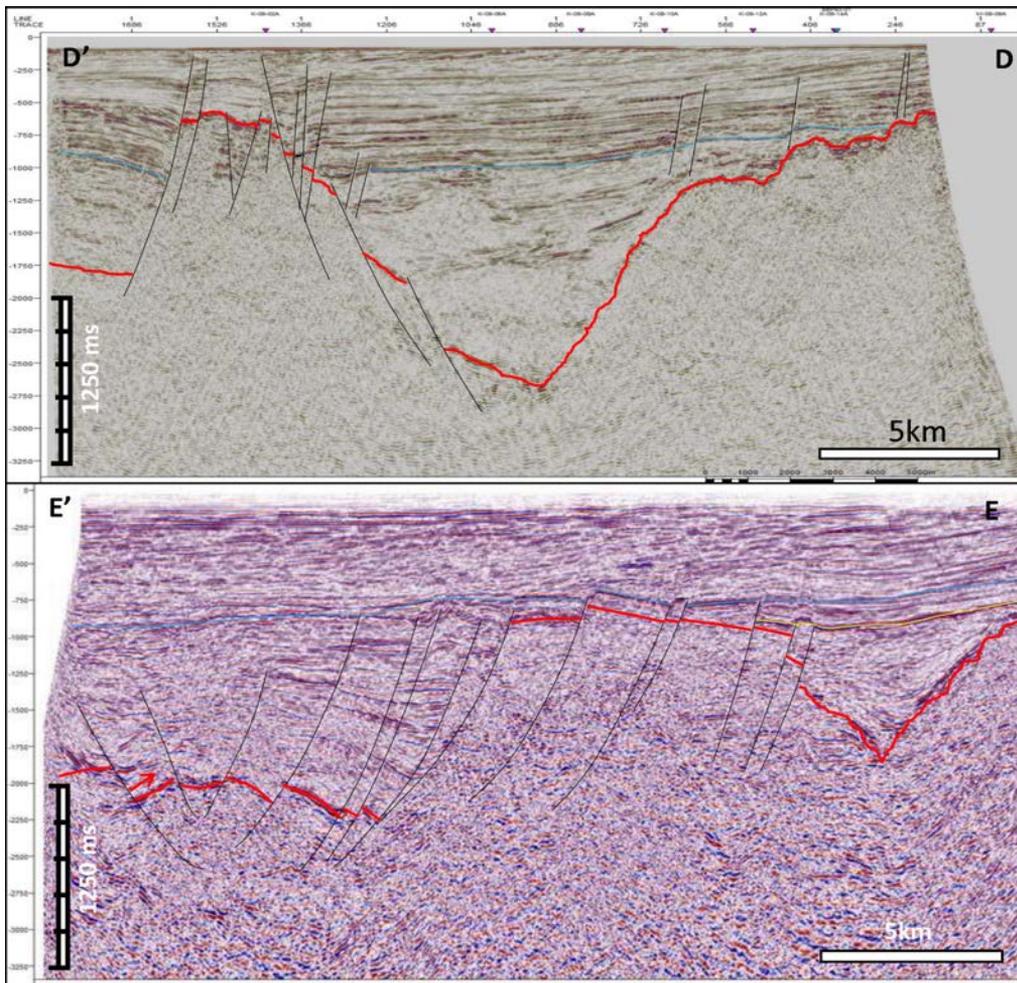
the offshore continuation of the Belaga Formation, which is of similar age and tectonic/sedimentary setting as the Crocker Formation. Analogous to the Anding example, the basement trap at Nuang is formed on the crest of a tilted fault block in an extensional province (Tatau Half Graben Province) (Figure 10). Similar situations may occur in the Sabah Basin.

### ONSHORE HYDROCARBON SEEPS

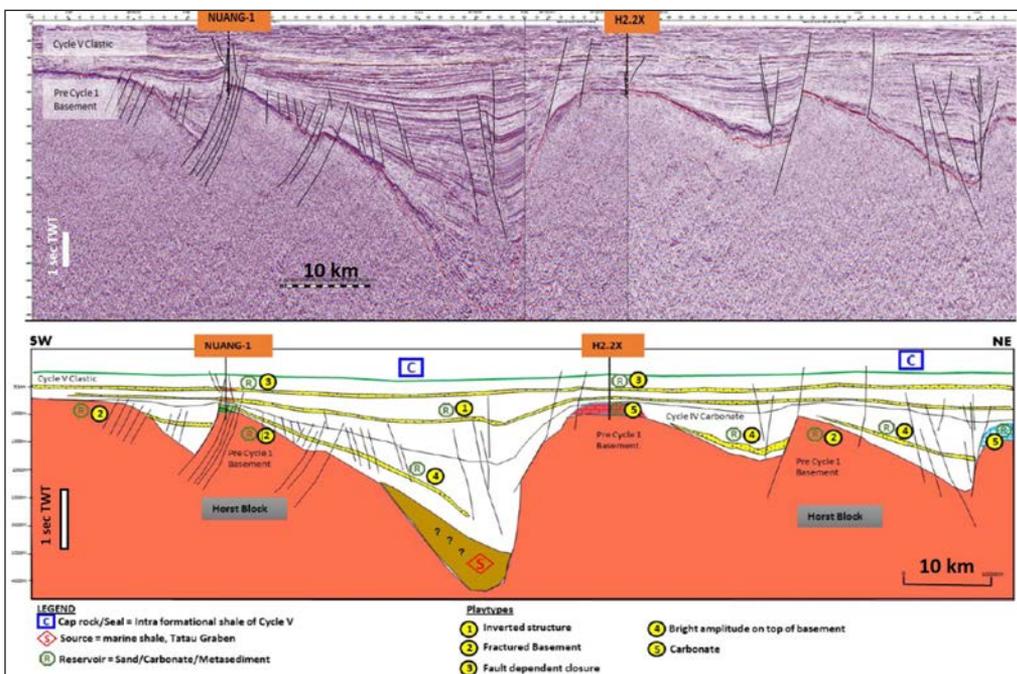
The occurrence of oil or gas seeps on structural highs (ridges, islands, and coastal areas) is not unusual, for such seeps were reported in Labuan, Klias and Kudat since the early days of exploration (Stephens, 1956; Liechti *et al.*, 1960; Wilson, 1964). The island of Labuan is a classic example of a “Sabah ridge” in the sense of Bol & van Hoorn (1980) that is emergent above sea level. Studies of source rocks at these seep localities (Labuan, Klias, and Kudat) have indicated that the coeval post-DRU shales (Stage IV) as the potential source rocks are in the immature to early



**Figure 8:** Crocker/Kudat/Stage III penetrations by exploration wells in West Sabah Basin. Top inset: seismic Line C across the Brunei Bay-1 well. Seismic Lines B, D and E are shown in Figures 6 and 9. Coloured circles represent exploration wells. Bottom right inset: reported hydrocarbon seeps and location of wells that penetrate basement on Klias Peninsula and Labuan. Seismic line courtesy of PETRONAS, and well locations are from IHS Markit database (2018).



**Figure 9:** Possible trap configurations in basement play, north-western Sabah identified in seismic lines, location shown in Figure 1. (Top, Profile DD') extensional fault block with flanking deep grabens that may contain potential kitchen. On the eastern flank of the deep graben there are also possible basement knolls that may be fractured and form traps. (Bottom, Profile EE') normal-faulted extensional systems with possible basement structure within deep kitchen area (left), as well as basement high (centre). Seismic lines courtesy of PETRONAS.



**Figure 10:** Fractured basement-reservoir discovery in the Sarawak Basin Half Graben Province, offshore Sarawak, where intra-basinal highs formed by tilted fault blocks provide the trapping mechanisms for fractured metasediments to be charged from adjacent younger source rocks. The Pre-Cycle I basement rocks encountered at Nuang-1 (NNG-1) are equivalent to Belaga Formation, which together with Crocker Formation in Sabah forms the Crocker-Rajang Group fold-thrust belt of Borneo (figure from Jabbar *et al.*, 2015).

mature stage at outcrop level and therefore could not have generated the seep hydrocarbons (Liaw, 2000; Ahmad Ridhwan *et al.*, 2017), but the possibility of migration from their lateral equivalents offshore being in generative phase cannot be ruled out.

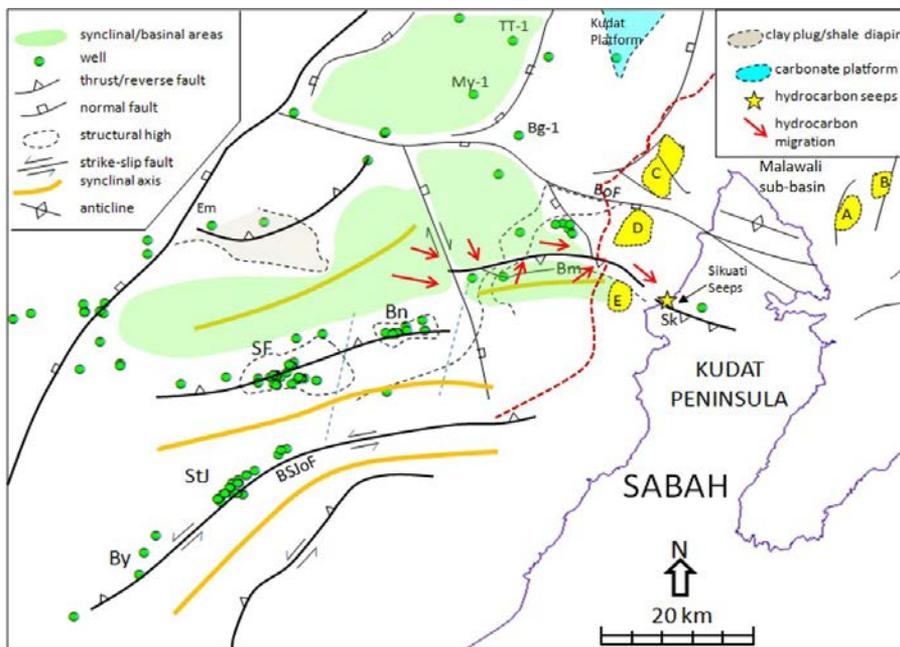
It is also likely that the seeps at Sikuati, on Kudat Peninsula, were hydrocarbons that migrated from the kitchen areas in the Sabah Basin to the west. The structures in the basin are such that the migration may be focused through conduits created by both stratigraphic (sandy channels) and structural (faults) that transmit the hydrocarbons updip to end up on the structural highs, such as in the Kudat area. Figure 11 shows the possible migration route for the Kudat hydrocarbon seeps which may serve as an analogue for a Crocker/Kudat basement play. Between the main hydrocarbon-bearing ridges there are deep synclinal sub-basins that could have provided the hydrocarbon charge to these structures and some of the hydrocarbons may have migrated along faults and carrier beds up-dip towards Kudat Peninsula to end up as surface seeps. Some leads identified in seismic are located in the migration path and possible targets to be tested (Figure 12).

### GEOLOGICAL RISK FACTORS

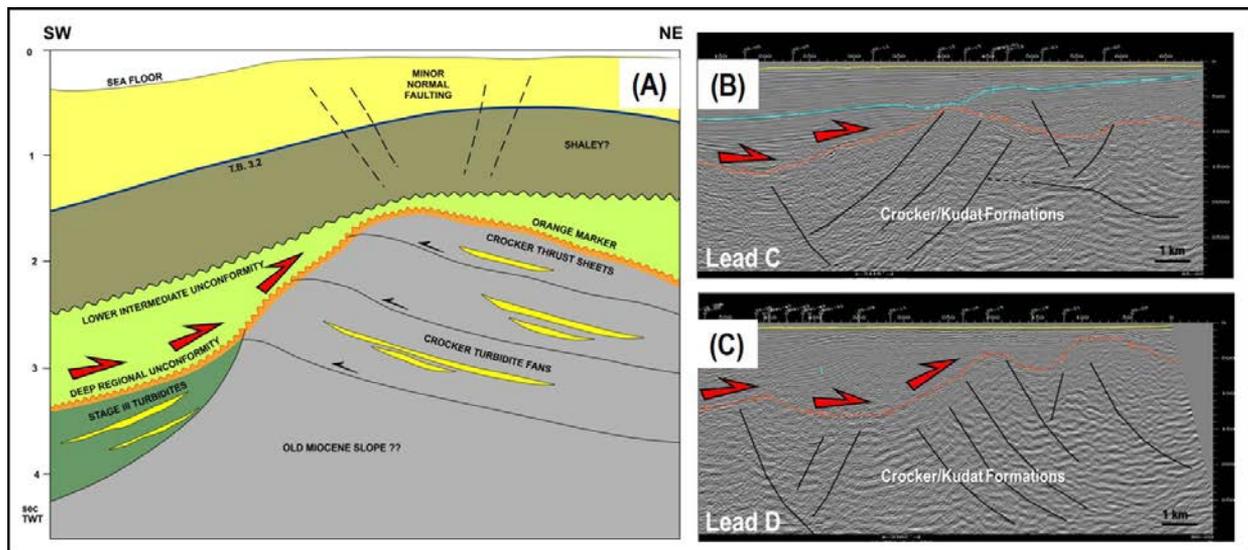
Globally, basement plays have long been developed and successfully produced (e.g., Schutter, 2003; Gutmanis, 2009; Trice *et al.*, 2019), and there are currently 126 fields producing from basement reservoirs in 24 countries (McKechnie, 2017; Trice *et al.*, 2019), with known viable basement plays include the Zeit Bay (Egypt), Bach Ho (Vietnam), La Paz (South America) and Dongshengpu (China) fields, among others. Nonetheless, each field inherently has its own specific risk factors and production challenges that need to be addressed individually for commercial hydrocarbon production.

Unlike the above-mentioned basement fields in which the reservoir is commonly fractured crystalline (igneous) rocks, the Crocker fractured basement play concept comprises tight sandstones that depend on the occurrence of intense faulting and fracturing. Hence, a number of geological risk factors should be considered, including:

- i) **Fracture networks and reservoir risk.** Understanding regional and local stress regimes, faulting and fracture development is important to predict the likelihood of trap and reservoir in the basement. For example, what processes control fracture distribution and networks in the Crocker Formation? Are deep processes such as tectonic compression, faulting and hydrothermal activity more important near-surface diagenetic processes, including fragmentation, corrosion and dissolution? Near-surface tectonic fissuring processes due to tensile fracture, associated hydrothermal mineralization and weathering are key controls on the porosity and permeability development of basement reservoirs (Trice *et al.*, 2019). In this regard, the use of outcrop fault and fracture statistics to constrain fracture frequency and fracture aperture distributions, and by comparing such outcrop information with subsurface data can provide confidence in fracture properties and yields important insights into the geological processes that result in subsurface fracture distribution (e.g., Franklin, 2013; Pless *et al.*, 2015).
- ii) **Migration risk – access to charge via lateral migration.** The buried Crocker Formation forming the “basement highs” must have direct connectivity with and favourable migration pathways from the source



**Figure 11:** Conceptual hydrocarbon migration model to explain the occurrence of hydrocarbon seeps at Sikuati, Kudat Peninsula. Migration may start from the sub-basins, where source rocks are mature (green shaded areas) through sandy channel/canyon fills and some of the major faults (red arrows) to the domain of uplifted and deeply eroded Crocker Formation (with its edge defined roughly by the brown-dashed line) and potential Leads A-E as indicated. According to Frank (1981), the Sikuati beds of the Kudat Formation on Kudat Peninsula may extend offshore into the Batumandi anticline (Bm) but at deeper structural levels. Bm seems to be in same trend as South Furious (SF) and Barton (Bn) structures, but displaced by several N-S faults (LLR strike-slip faults). Well locations are from IHS Markit database (2018).



**Figure 12:** (A) Schematic basement play concept of Crocker overthrust slices in Sabah Basin inboard area. The orange marker is mapped as the time-equivalent of the DRU, overlain by the Stage IV and younger sequences. Red arrows represent possible migration from a mature kitchen to the SW. On the right are seismic profiles through two leads in the basement made up of Crocker or Kudat formations in northern Sabah Basin, offshore Kudat Peninsula: (B) Lead “C”, and (C) Lead “D” identified on the map in Figure 11. Seismic lines courtesy of PETRONAS.

rock kitchens located downdip in the synclines or deep sub-basins, wherein hydrocarbons migration can occur *via* fault conduits as well as carrier beds in the sandy canyon and channel systems (Figure 11). With such favourable conditions, hydrocarbons from the mature kitchen in the synclinal “sub-basins” may reach as far as the onshore areas, as indicated by the presence of oil seeps at Sikuati, Kudat Peninsula (Figure 13). Migration risk may be higher in some near-coastal half-grabens or sub-basins, being shallower and devoid of mature source rocks at the bottom, intra-basinal highs may form barriers to lateral hydrocarbon migration. In addition, some basement highs may lie in the migration shadows and be bypassed.

iii) **Seal risk – presence of sealing and non-sealing lithologies.** At the basin edge in contact with the Crocker sandstones. As long as hydrocarbons can migrate up-dip *via* the Neogene topset carrier beds, they may reach the edge of the basin or beyond, as illustrated in Figure 11. However, in the St. Joseph field area offshore West Sabah, we observe the upwelling of clays (“clay plugs”) which can form effective barriers that prevent lateral migration.

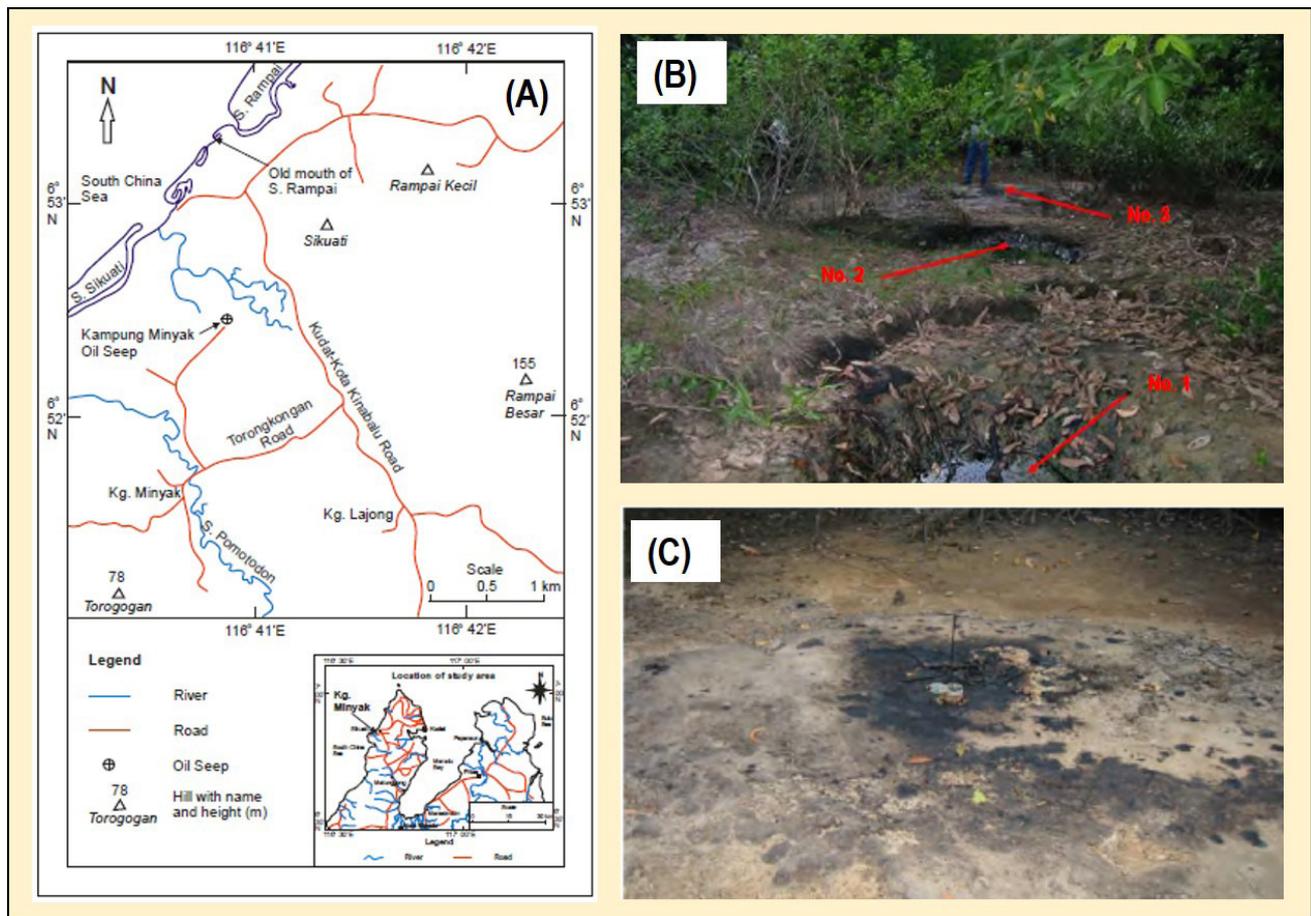
iv) **Timing of migration and trap preservation.** The timing of uplift and deformation event relative to that of hydrocarbon migration will have a significant impact on hydrocarbon trapping. Recent uplift event will likely breach the relatively thin top seals of Crocker basement traps, so that trap efficiency may be higher in areas with sufficient overburden. Hydrocarbon migration

during Pleistocene and Recent would likely to charge the fractured basement in marginal areas, as earlier traps could have been breached by later deformation.

v) **Drilling and operational risks.** Exploration of Crocker basement play requires more than just drilling a basement high. It will involve a carefully considered drilling plan and execution to optimise the intersection of tight sandstones and associated fracture sets, which in turn required a high resolution and deep imaging seismic dataset. More importantly, a prudent drilling plan to establish subsurface reservoir characteristics and sustainable production profile is critical to ensure commercial success, while force fitting of conventional analytical techniques to the basement play may result in gross miss-statement of resources (e.g., Guttormsen, 2010). Therefore, it is paramount to compare this risk factor with other analogue fields in the region such as Anding before attempting to exploit the Crocker basement reservoirs.

## CONCLUSIONS

A new play type is conceptualized in the offshore Sabah Basin, wherein the “basement” to the petroliferous Middle Miocene foreland basin, formed by the Crocker Formation and equivalents lying beneath the DRU, could form fractured reservoirs and traps if the right conditions for a working petroleum system exist. The most critical factors are the presence of enhanced porosity and permeability of the rocks due to intense fracturing, probably along fault or shear zones, coupled with the juxtaposition of these rocks against carrier beds with direct access to a thermally mature Stage IV source kitchen. The seal is provided by the shale units in the



**Figure 13:** The complex migration route in Figure 11 may reach as far up as to the onshore area, manifested by the presence of oil seeps at Kampung Minyak (Muda, 2010) and Sikuati (Nurul Izzati Azman & Siti Nur Fathiyah Jamaludin, 2017). (A) Location of Kampung Minyak oil seepages at Kudat Peninsula, Sabah. (B) three outlets of the oil seepages at Kampung Minyak aligned in straight line indicating a fault-controlled structure. (C) A layer of hard bitumen formed at Oil Seepage No.3 which has dried up. Modified from Muda, 2010.

overlying younger formations; a thicker overburden is likely to retain the migrated hydrocarbons. The area most conducive for such conditions is deemed to be in the shallow inboard areas. However, further investigations into the extent and distribution of fractured Crocker and Kudat formations are necessary. The possibility of lateral hydrocarbon migration from the deep kitchens in the outboard areas should be considered (as indicated by the Kudat seeps), taking into account the geological risk factors such as basin tectonics, lateral migration, lithological controls, and the reservoir/production characteristics of basement rocks. This play concept is being investigated as a future exploration target in offshore Sabah Basin.

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