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Fluid inclusions in quartz: Implications for hydrocarbon charge, migration and reservoir diagenetic history of the Penyu Basin and Tenggol Arch, offshore Peninsular Malaysia

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Abstract: A review of clastic sandstone reservoirs in the Penyu Basin and Tenggol Arch area, adjacent to the south-western flank of the Malay Basin revealed that most deep reservoirs are affected by diagenetic alteration of reservoir mineral components. Furthermore, fluid inclusions in quartz are seen at distinct stratigraphic reservoir levels. These inclusions occur in Oligocene reservoirs in Groups L and M and in Miocene reservoirs of Groups K and H. However, to-date no oil inclusions have been found in Groups I and J. There appear to be two distinct populations of fluid inclusions in the so-called 'oil quartzes':

(i) oil inclusions in allochthonous, detrital quartz grains. These inclusions are thought to be of the primary type, formed when oil was incorporated in growing quartz crystals, and oil is seen encapsulated in 'loose' quartz grains. There is no evidence of destructive diagenesis or cementation in these relatively shallow (Miocene) host reservoirs, and oil migration is not confirmed by other indicators such as bitumen, which is often found in deeper carrier beds together with oil quartzes. The origin of these oil quartzes is somewhat controversial, and cannot be determined with certainty. They were probably shed into the basin from eroded granitic basement horsts and ridges.

(ii) *in situ* oil inclusions in quartz cement. The occurrence of oil encapsulated in quartz cement (secondary or tertiary inclusions) indicates oil migration had preceded quartz cementation. So-far, oil-bearing inclusions attributed to fractures could not be confirmed with certainty. Assuming a relatively constant temperature gradient in the basin during the Miocene, quartz cementation will have started at a palaeo-depth of *ca.* 2000 m or at 105 ^{0}C, and porosity was mostly destroyed by a depth of *ca.* 3000 m and 130 ^{0}C. Occasionally overpressures are observed. According to this model, oil had migrated into and percolated within reservoirs during the Miocene, but became locked in closed pores as quartz cement invaded pore spaces under increasing overburden and temperature. Consequently, fluid inclusions in quartz for this model suggest that depths of greater than 3000 m below mud line (BML) are likely to encounter sandstones with deteriorating reservoir properties in the study area.

Keywords: diagenesis, inclusions, Penyu Basin, quartz cementation, Tenggol Arch

INTRODUCTION

The study of fluid inclusions in quartz as indicators of the timing of oil migration and reservoir diagenesis has important implications for assessing the optimum depth of exploration targets in the Penyu Basin, Tenggol Arch and adjacent areas of the Malay Basin. Oil quartzes are somewhat counter-intuitive, but are actually quite common in the study area. The occurrence of oil quartzes always points to an interference of hydrocarbons with the crystal growth and/or diagenetic processes that affect the crystal and cement later. Occasionally, oil can also penetrate fractures.

The prerequisite of a working petroleum system is the presence of a generative kitchen and the migration of hydrocarbons to the reservoir, also referred to as 'hydrocarbon charge'. In a rich and productive basin, migration paths may be inferred from the spatial distribution of discovered accumulations and assuming the presence of a kitchen down dip of the accumulations. Rarely is migration observed or physically demonstrated by well data. The generative source rocks are seldom penetrated by the wells, which are drilled on structural highs. In a less explored basin or frontier basin, more effort is usually invested to demonstrate the presence of hydrocarbons, and even traces of hydrocarbons may be interpreted as proof of a working petroleum system.

Direct evidence for oil migration may be provided by the presence of traces of oil/gas entrapped in the fluid inclusions contained in the sedimentary sequences. This technique has been well established in the literature (e.g., Burrus *et al*., 1983; McLimans, 1987). Critical to the determination of the timing of oil migration is the relationship between the fluid inclusions and diagenetic processes occurring in the sediments, as the entrapped oil/gas in fluid inclusions is found within diagenetic cements formed during sediment burial. Thus, an important part of the analysis of fluid inclusions relates to the diagenetic history of the host sediment itself.

In this paper, we discuss an example of fluid inclusion evidence for oil migration in the Penyu Basin and Tenggol

Arch area, and the potential implications it may have for the adjacent Malay Basin. The Penyu Basin is a relatively small, lightly explored Tertiary extensional basin located offshore Peninsular Malaysia, with the Tenggol Arch forming a stable high block separating it from the Malay Basin (Figure 1). Fluid inclusion and petrographic data were analysed to determine the timing of oil migration, and its implications for the reservoir quality and hydrocarbon prospectivity.

GEOLOGICAL SETTING

The Penyu Basin and the more well-known Malay Basin are part of a system of Cenozoic sedimentary basins developed along a major zone that stretches from the Gulf of Thailand to the Natuna region. Different geological and tectonic models have been proposed to explain the origin of the basins, as discussed recently by Tan (2009) (Figure 1). The basins are considered to have originated either in a back-arc setting (Kingston *et al*., 1983; Ismail *et al*., 1992), as a pull-apart basin developed along a major strike-slip fault (Tapponier *et al*., 1982), or through thinning of continental crust (White and Wing, 1978). Other tectonic models involve crustal extension over a hot spot (Hutchison, 1989; Ngah *et al*., 1996), extensional subsidence along a major left-lateral shear zone (Madon and Watts, 1998) and as a failed rift arm of a triple junction above a mantle hot spot (Tjia, 1999). Morley and Westaway (2006) proposed a geodynamic model of the Malay Basin, involving lower-crustal flow in response to post-rift sedimentation.

Most of these models are regional in nature and were proposed without the benefit of offshore data. However, recent years have seen widespread acquisition of 3D seismic data, as well as marine gravity data. These data show a thoroughly sheared crust with basement (granite, metamorphic rocks, and basalts) forming elongated slivers along a number of strike-slip faults, particularly at the edges of the Tenggol Arch (Figures 1 and 2; Ng, 1987). Accordingly, the present authors believe that the basins originated as pull-apart basins on top of a highly sheared continental crust, which started to subside at the end of the Eocene. According to this model, there may not have been any rifting in the sense of pure extension as such, but instead pulses of basement shear that resulted in repeated phases of subsidence.

PETROLEUM SYSTEMS

The stratigraphy of the Malay and Penyu basins are summarised in Figure 3, and seismic type sections for the basins are illustrated in Figures 4 and 5, respectively. The post-Cretaceous Malay Basin is subdivided into Groups M to A (Upper Oligocene to Quaternary), and consists of mainly depositional sequences associated with post-rift thermal subsidence (Figures 3 and 4). The Penyu Basin on the other hand, is subdivided into lithostratigraphic units such as the Penyu, Pari and the Pilong formations; with ages ranging from the Early Oligocene to the Pleistocene, and sometimes

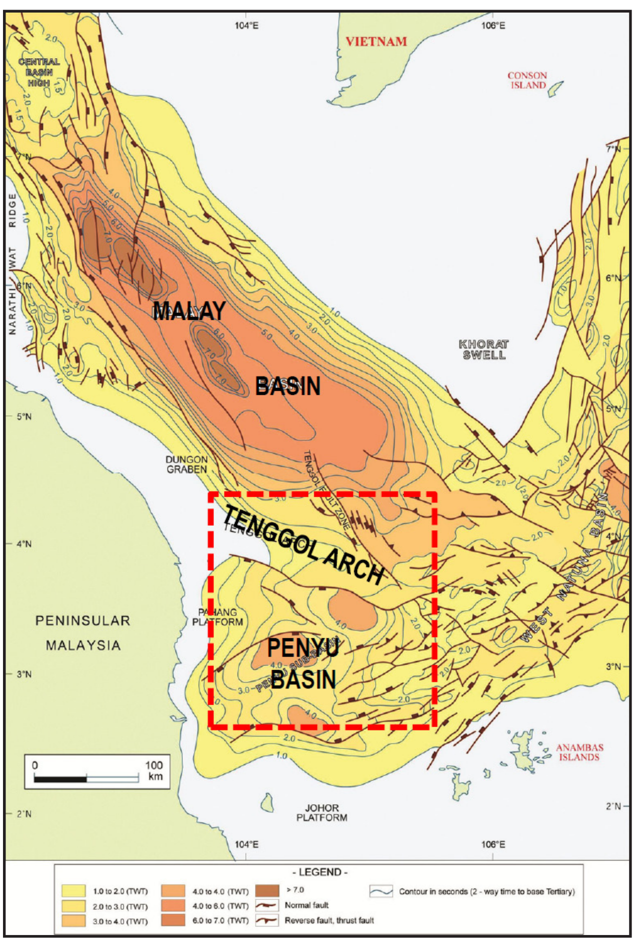

Figure 1: Structural framework map of the Malay and Penyu basins after IHS Energy in 2010, offshore Peninsular Malaysia. Quartzes with fluid inclusions are reported from the Penyu Basin, the Tenggol Arch and the adjacent area of south-western Malay Basin covered by the study area outlined by the dashed red line.

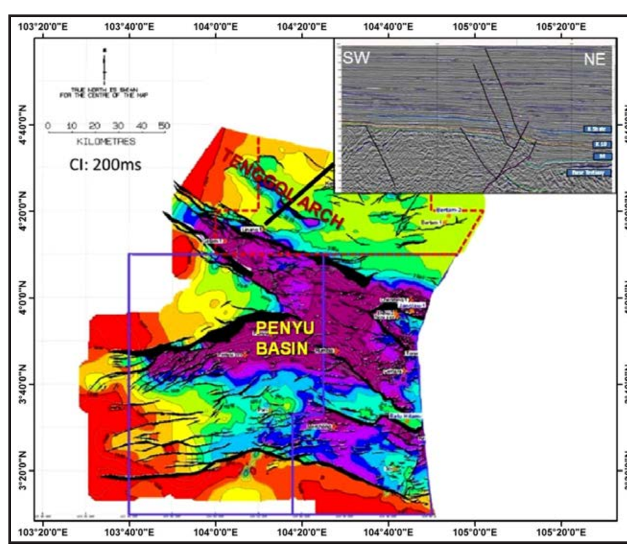

Figure 2: Base Tertiary (Top Basement) map over the Penyu Basin and Tenggol Arch showing strike-slip faulting at the southern edge of the latter. Purple zones represent half-grabens and depocentres and indicate the land-locked nature of the basin at the time. Inset is a SW-NE seismic section that illustrates the basement faulting over the Tenggol fault zone.

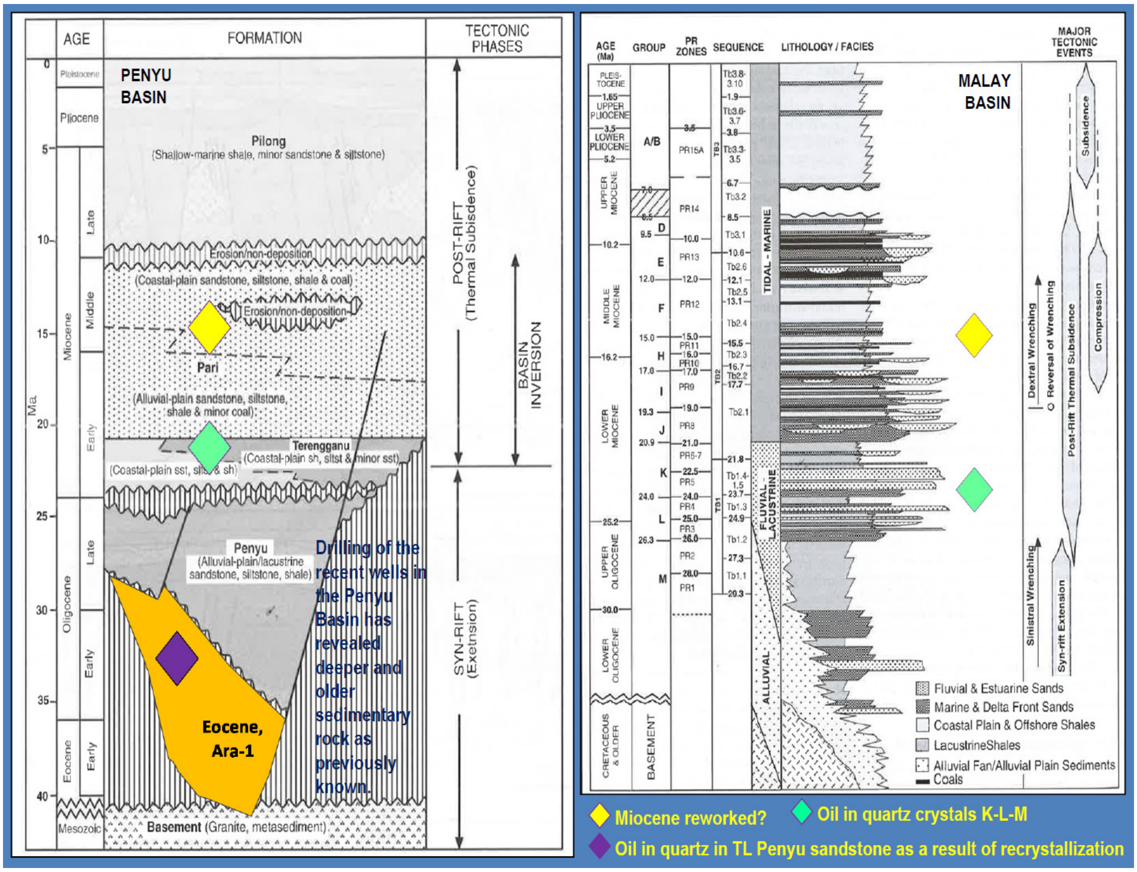

Figure 3: Comparison of Penyu and Malay basins stratigraphy modified after Tan (2009), originally from Madon and Anuar (1999, Penyu Basin) and Madon *et al*. (1999, Malay Basin). Oil inclusion quartzes are found at coeval strata levels in both basins. Most authors agree on two overlapping charge systems from Palaeogene and Neogene sources. The deeper charge originated from lacustrine source rocks and has yielded oil which, given its likely early migration, became biodegraded in places.

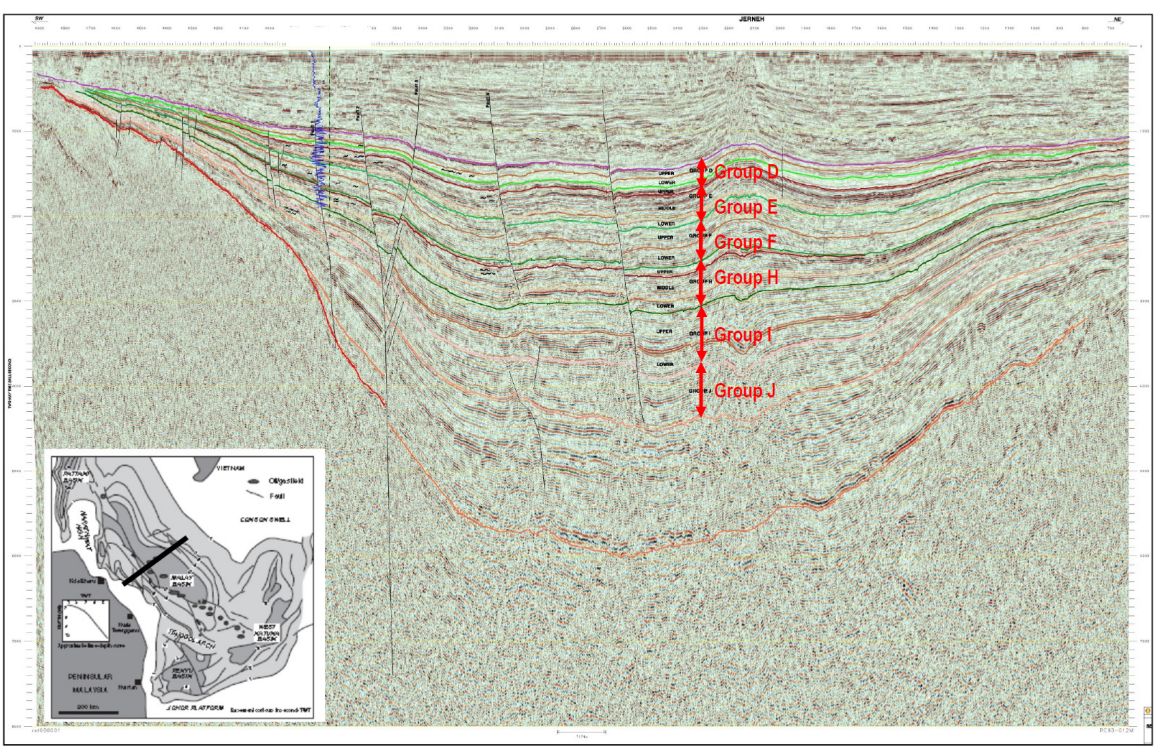

Figure 4: Malay Basin regional type seismic section illustrating the sequence intervals of Group J to Group D from Lower Miocene to the Upper Miocene. The K, L and M groups is difficult to correlate on this section.

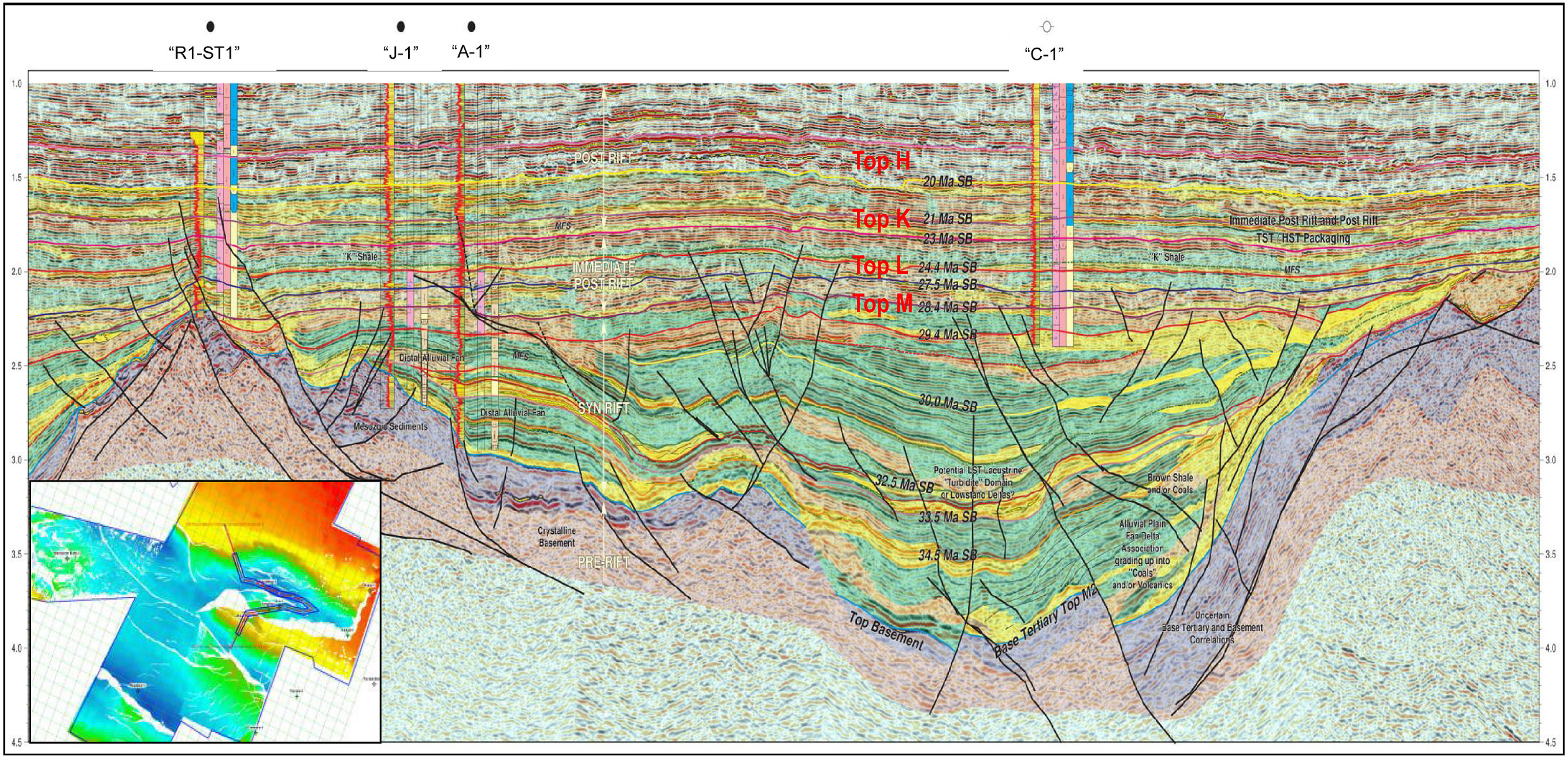

Figure 5: Penyu Basin regional seismic section illustrating mapped sequence boundaries (SB) and related depositional facies; yellow = sandy facies, green = lacustrine shales, purple = meta-sediments. The depositional system of the Penyu Basin comprises mainly restricted lacustrine facies up to Base Miocene, near Top L event and was isolated from the fluvial sedimentary pulses of the Malay Basin until this time, after Barber (2013).

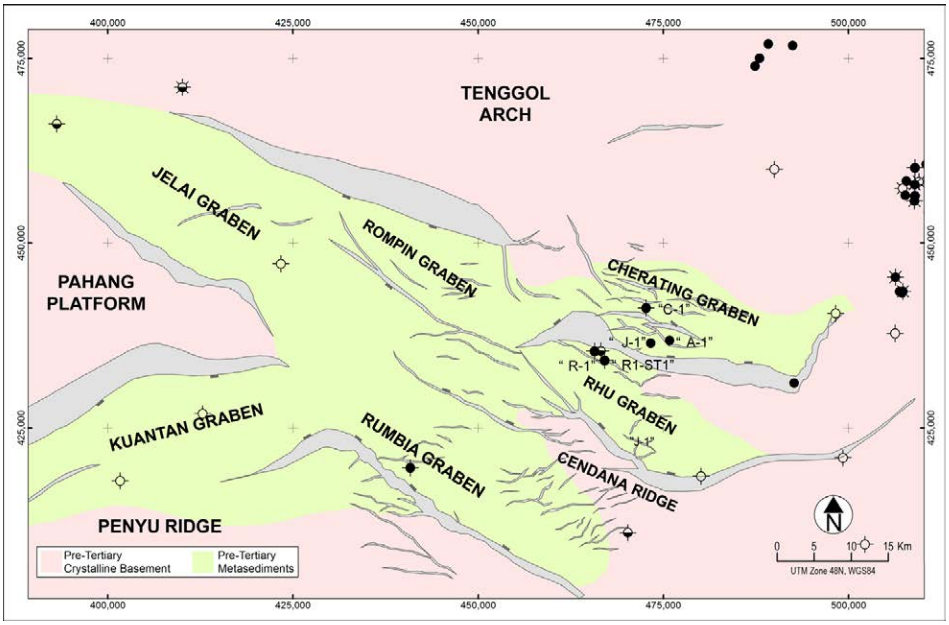

Figure 6: Exploration wells and structural elements of the Greater Penyu Basin (well status from IHS Energy).

described in terms of syn-rift to post-rift sequences separated by erosional unconformities. Nonetheless, it is possible to correlate the key seismic events defining the various group intervals of the Malay Basin into the Penyu Basin (Figure 5). It is also worth mentioning that drilling of recent wells in the Penyu Basin has revealed sedimentary rocks deeper and older than previously known, of Early Eocene age (Figure 3).

The basin-filling sediments are of terrestrial and fluvio-lacustrine origin, interrupted by occasional periods of marine ingression. A number of source rock intervals have been identified in both basins, and at least two pulses of oil migration have been observed (e.g., Tan, 2009). The main reservoirs in the Malay and Penyu basins are siliciclastic, deposited mainly in fluvio-lacustrine channels and deltas, with varying grain sizes from (rarely) coarse, middle to fine.

Penyu Basin

The Penyu Basin lies south of the Malay Basin (Figure 1) and straddles the Malaysia-Indonesia maritime boundary. The basin has been explored since 1968 (pre-PSC days) when Conoco was given a concession that covered the entire basin. To-date, there have been more than 20 exploration wells drilled, mainly on Miocene (post-rift) inversion structures. So-far exploration efforts have resulted in one oil discovery at Rhu-1 in 1991 in late syn-rift sediments in a basement-drape structure (Madon *et al*., 1999), and reasonable shows in a few other wells. Recent exploration drilling by the operator of the Penyu blocks in the Cherating Half Graben confirmed the presence of abundant live oil in the mid syn-rift section despite the apparent dearth of good reservoir rocks (Figure 6). The Rhu-1 well encountered oil in fluvial Oligocene syn-rift sandstones, tentatively correlated to Group L in the Malay Basin (Figure 3). The Rhu oil is light (API 35°), moderately waxy and of high pour point (44 °C). With Oligocene-Miocene levels (Groups L and K) only marginally mature for oil, charge is inferred to stem from isolated pods of Eocene-Oligocene age lacustrine source rocks with a potential contribution from coal and coaly shale layers.

The Penyu Basin is tectonically complex, and has seen at least two phases of major strike-slip tectonism and inversion; the older and very widespread inversion occurred intra-Oligocene, with a weaker and localized one in the Miocene. This may have had the effect that originally channelized reservoir bodies were compartmentalized even further.

Only in the case of Rhu-1, can a clear case for vertical oil migration be made. Some oils trapped in reservoirs and fluid inclusions are low-gravity, suggesting oil migrated along conduits at low temperatures implying limited rock overburden, and a likely early migration during the Early Miocene (Group I). The Rhu-type light oils probably originated during a secondary; later migration pulse, whereby the relatively high reservoir temperatures prevented biodegradation. The Rhu discovery is evidence of a functioning petroleum system (Tan, 2009).

Malay Basin

The petroleum system in the Malay Basin is relatively well-known from the hundreds of wells and studies carried out by PETRONAS and other operators since the late 1960's. Reviews have been made by Madon *et al*. (1999), Madon *et al*. (2006) and Tan (2009). There appears to be two main, spatially overlapping, petroleum systems; namely an Oligocene-Miocene lacustrine system, often characterised by low gravity with a paraffinic signature, and a Miocene system with oil and gas derived from lipid-rich coals. Madon *et al*. (1999) referred to these two main hydrocarbon charge systems as 'lacustrine' and fluvio-deltaic', respectively. They can be summarised as follows:

(i) Lacustrine system. As shown by Madon *et al*. (1999), source rocks belonging to the lacustrine system occur within lacustrine claystone sequences ('shales') of the

Late Oligocene to Early Miocene Groups L and K. The K shale acts not only as a source of hydrocarbon charge but, given its widespread deposition, homogeneity and thickness (20 – 50 m), also as a migration and, sometimes, pressure boundary. It forms the top seal in the Tenggol Arch fields of Bertam, Malong and Belida, where charge is proven to have migrated through amalgamated fluvial/shallow marine channel sands, forming a pseudo-sheet sand at K-10 sand level with regional pressure continuity.

There are indications, particularly in the south-eastern area of the Abu-Bubu and Penaga Field cluster, that there is an even older Eocene-Oligocene lacustrine system, restricted to isolated pods located in the centre of this and other individual syn-rift grabens. The Groups L and K source beds are believed to have charged reservoirs from Groups M up to H. In the northern part of the basin (overlap area with Vietnam), lacustrine source rocks have been inferred from the oil geochemistry to be present in isolated half-grabens (sub-basins) on the basin flanks to the northeast (Madon *et al*., 2006).

(ii) Fluvio-deltaic system. The younger (Miocene) coaly system, yielding often high-gravity oil, relies on thermally mature oil and gas strata in the central parts of the basin. These strata, which are currently in the oil/gas window, are found mainly in Groups H and I. They tend to be overmature in the basin centre but are at peak oil-to-gas maturation at the basin flanks (Madon *et al*., 2006). Abdullah (2014) has shown that some coals that are thermally labile can yield significant amounts of oil at lower vitrinite reflectivity (maturity) than commonly expected. However, there remain questions as to how much these coal-derived hydrocarbons may have migrated laterally, given the likely channelized nature of the conduits, and equally likely 'imperfect' clay seal frequently incised by meandering channel systems. Deep-seated faults appear to have acted as major conduits for vertical migration of gases from the Group I and older source rocks in the central parts of the basin (Madon *et al*., 2006).

According to Bishop (2002), more than half of the total estimated oil reserves (68 %), 45 % of the gas reserves and 43 % of condensate reserves in the Malay Basin are derived from the older, lacustrine beds (of Groups K, L, M). The Miocene system (mainly Groups H I, and J) are believed to have delivered the remainder. For comparison, a more updated view on the discovered hydrocarbon distributions in the Malay Basin according to stratigraphic units and depositional environments is provided in Figure 7, suggesting oil provenance from deltaic-to-shallow marine depositional environments are marginally more dominant than those that originated from the fluvio-lacustrine setting.

KEY RESERVOIRS

Hydrocarbon-bearing reservoirs in the Penyu Basin are (with the exception of Rhu) of mostly poor quality, and are located in the Oligocene and pre-Oligocene sections. A recent sequence stratigraphic study by Barber (2013) suggests that the depositional system of the Penyu Basin is mainly composed of restricted fluvio-lacustrine facies up to Base Miocene level (near Top Group L), and was isolated from the fluviatile sedimentary pulses of the Malay Basin to the north by the imposing Tenggol Arch until Early Miocene time (Figure 3). After post-Early Miocene, the Penyu and the Malay basins practically formed a fused sedimentary system of mainly fluvio-terrestrial and shallow marine deposits sourced from the north, which culminated in a major inversion episode in the study area.

In the Malay Basin, hydrocarbons are trapped in several Tertiary stratigraphic units from Groups M to B and also in the pre-Tertiary basement in the south-eastern part of the basin (Figure 7). Good quality sands are often associated with fluvio-lacustrine, deltaic and shallow marine environments. Shoreline sands include tidal channels, tidal flats and estuary tidal bar deposits. On the western flank of the Malay Basin, hydrocarbon-bearing reservoirs are found in Groups M up to I. All of the reservoirs are channelized. Group K and J reservoirs were deposited in a marginal marine setting, and may have a semi-sheet like character.

RESERVOIR PETROGRAPHY AND DIAGENESIS

There have been few studies on the diagenetic histories of sediments in the Malay and Penyu basins. Most studies were conducted in the Malay Basin (e.g., Nik Ramli, 1987, 1988; Ibrahim and Madon, 1990; Chu, 1992; Madon, 1994), with little published information available on the diagenetic history of the Penyu Basin. Chu (1992) carried out a comprehensive basin-wide petrographic study of sandstones in the Malay Basin, using 241 samples and established the main porosity reduction mechanism to be mechanical compaction down to a depth of about 1200 m (see also Madon, 1994). Beyond this depth, chemical processes took over, including cementation by quartz or, more rarely, calcite, siderite, pyrite and clay minerals (Figure 8).

Uplift and erosion in some parts of the basin (especially in the south) resulted in secondary porosity by dissolution of framework grains, including feldspar. These are recognised from the presence of oversized pores left by dissolution of framework grains, and are developed particularly in Group J and K sandstones (Nik Ramli, 1987; Ibrahim and Madon, 1990). Hence, more secondary porosity is expected to occur in sandstones with moderate percentages of lithic/felspathic grains compared to 'clean' quartzose sandstones. This is ultimately tied to the provenance and depositional environments of the sandstones (Ibrahim and Madon, 1990).

Madon (1994) studied the Groups D and E sandstones in Jerneh Field, northern Malay Basin, and observed increases in quartz overgrowths with depth, from an average of 1% at 1270 m to 7% at 1940 m. Quartz overgrowths begin at about 90 – 100 ^{0}C. The amount of quartz cementation appears to increase with age and depth of burial (Chu, 1992) (2-10% in Groups D and E sandstones, Madon, 1994), and also appear more prevalent in 'clean' sandstones. At shallow levels (< 1200-1500 m) authigenic clays are mainly

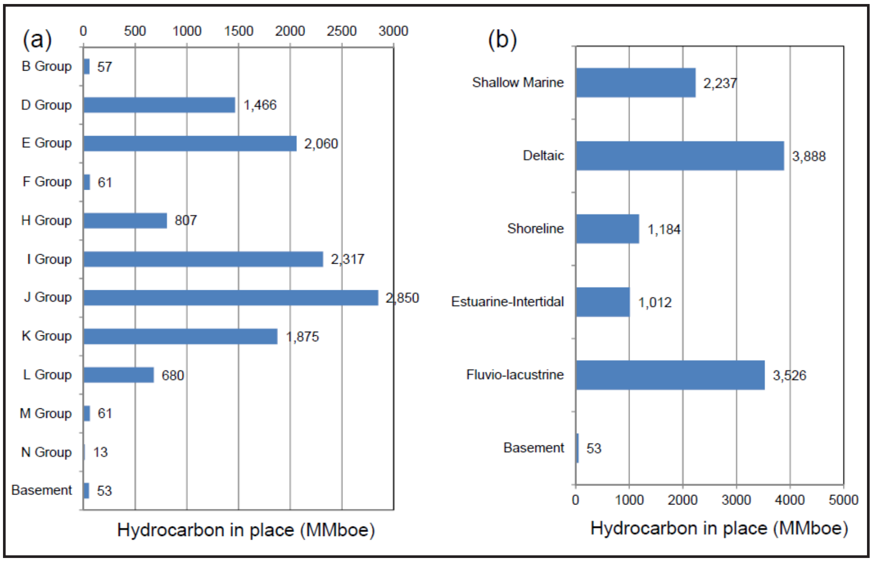

Figure 7: Statistical summary of discovered hydrocarbon distribution in the Malay Basin (a) by stratigraphic units, (b) by depositional environments of the reservoirs. Data compiled from IHS database (2014).

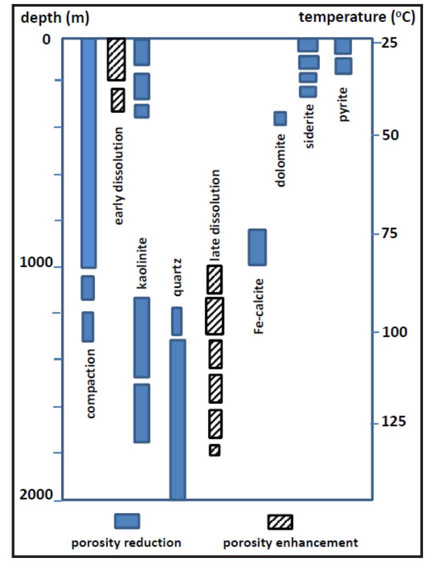

Figure 8: Diagenetic sequence in the Malay Basin, based on Madon (1994).

kaolinite derived from the alteration of feldspars, but illite may occur in sandstones that have been subjected to deeper burial (higher temperatures). Study of samples from the Tinggi Field had shown that mixed-layer illite/smectite is dominant over kaolinite at depth.

The pattern of diagenesis as described above can occur in parallel with oil migration. It is possible or even likely, that pulses of hot water brines flushed carrier beds together with oil, or alternated with the latter. In this way oil could have been trapped in the diagenetic pore spaces.

FLUID INCLUSIONS

Fluid inclusions result from microscopic defects in crystal growth, which lead to the entrapment of fluid within the growing crystal. Three types of fluid inclusions are normally observed:

(i) Primary (Figure 9): These are fluid inclusions formed during the growth of the enclosing crystal, i.e., from a mixture of inorganic and organic brines. The inclusions tend to be solitary or isolated, and are identified by being trapped in discrete trails that are parallel to the growth zones or crystal faces. When analyzed, these inclusions yield information on the subsurface conditions of formation or crystallization of the host mineral.

(ii) Secondary (Figures 10-12): These inclusions occur along 'healed fractures', i.e., cement rims. Oil can be trapped as residual liquid phase in pore space that is increasingly cemented. Secondary inclusions can be recognized by forming trails or clusters that often cut across grain boundaries or crystal growth zones.

(iii) Tertiary: These inclusions form during crystallization of the host mineral during fracturing, whereby fluids are trapped in inclusions along the fractures. These inclusions will therefore occur along fracture trails. In practice, Tertiary inclusions are very difficult to distinguish from the secondary ones, given that natural fractures are often difficult to distinguish from fractures induced by drilling/coring activities. In the latter case, oil-based mud could possibly act as a contaminant, however there is no indication that this has happened in the study area.

The presence of hydrocarbons in fluid inclusions in a reservoir rock provides strong evidence for the migration of hydrocarbons through that rock. Inclusions trapped in authigenic quartz overgrowths around detrital quartz grains have been used extensively to determine the temperatures of overgrowth formation and the geochemical and physical characteristics of the hydrocarbons trapped therein (e.g., Walderhaug, 1990). Oil inclusions in quartz crystals are common phenomena in hydrocarbon-bearing basins, but can only be detected in thin sections of drill cuttings and cores, by careful examination under the microscope with the help of ultraviolet light. Under UV light, bright blue inclusion colours are typical for light oil, whilst low gravity oils (genuine low gravity expelled oil, or biodegraded oil) tend to yield dull bluish, whitish or yellowish fluorescence colours.

Previous research on quartz cements and fluid inclusions suggests that there is a relatively wide range of temperatures under which oil inclusions in quartz may form. Lander and Walderhaug (1999) established kinetic models of quartz cementation in which quartz cementation starts at an effective threshold temperature of around 70 – 80 °C. Oelkers *et al.* (2000) suggested that cementation is a continuous process, with cement developing as a function of both temperature and quartz surface area, and with most cement precipitating between 100 - 120 °C.

Suchýa *et al*. (2010) investigated the petroleum charge history of the Barrandian Basin in Bohemia (Czech Republic), by analysing quartz and calcite and organic phases that occur in veins and fractures cutting dolerite

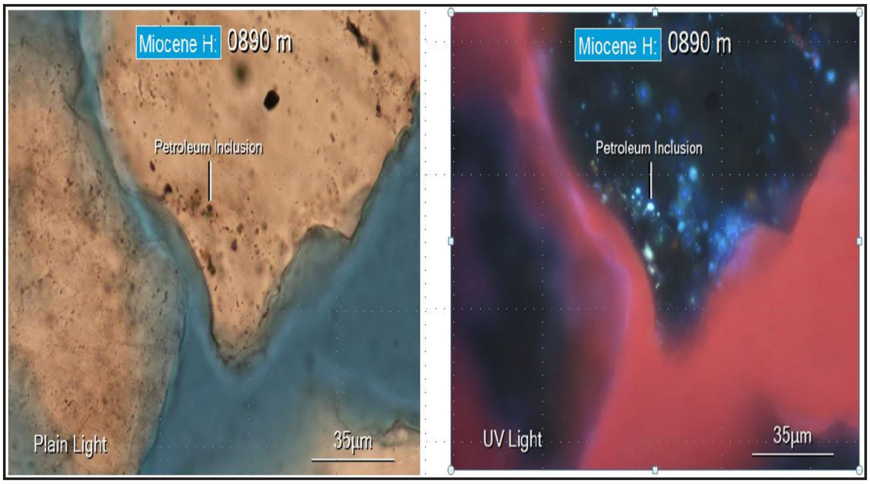

Figure 9: Light petroleum oil inclusions in a loose (non-cemented) sand grain of Miocene Group H sand. Such inclusions are scattered throughout the grain in a transparent matrix of a quartz crystal, and appear to fit best the primary type of fluid inclusion.

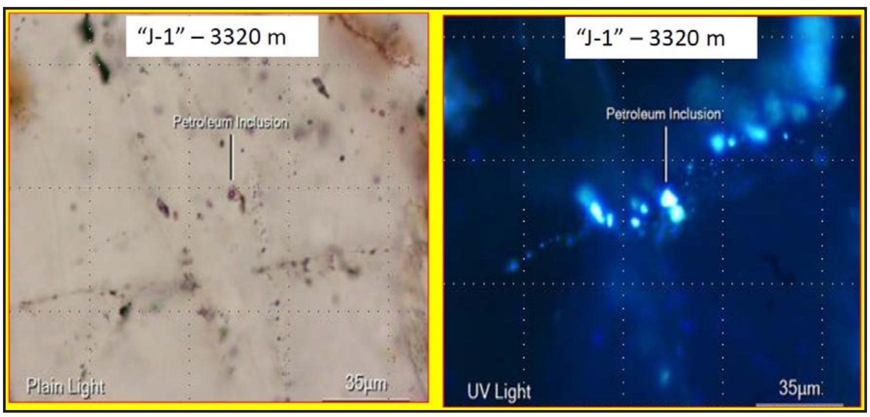

Figure 10: Composite grain with annealed cementation rims. High gravity oil droplets are seen to follow one particular direction, and it can be argued that these became encapsulated when the rock recrystallized, and quartz cement plugged all remaining pore space. The example shown appears to best fit with the secondary type of fluid inclusion.

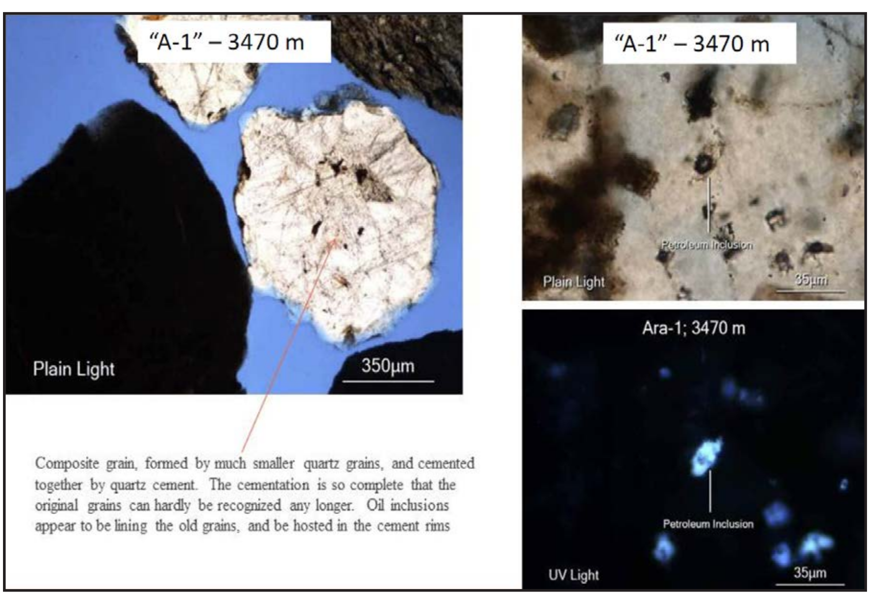

Figure 11: Top left - picture shows a strongly compacted and recrystallized quartz grain. Bottom left - example of secondary oil inclusion, probably high gravity oil. The old cement boundaries are almost entirely annealed and oil occurs as isolated droplets in residual pore space. Secondary to tertiary oil inclusions.

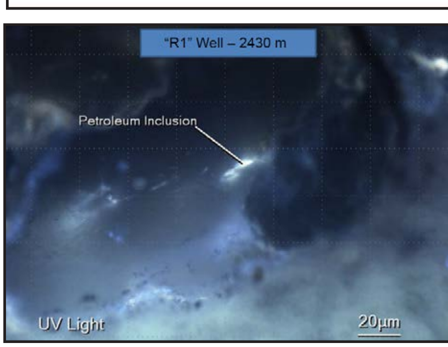

Figure 12: Group 'L-K' equivalent in the Penyu Basin 'R-1' well contains pale blue–white fluorescence inclusions. These are often equated with low gravity oil; secondary to third order inclusions.

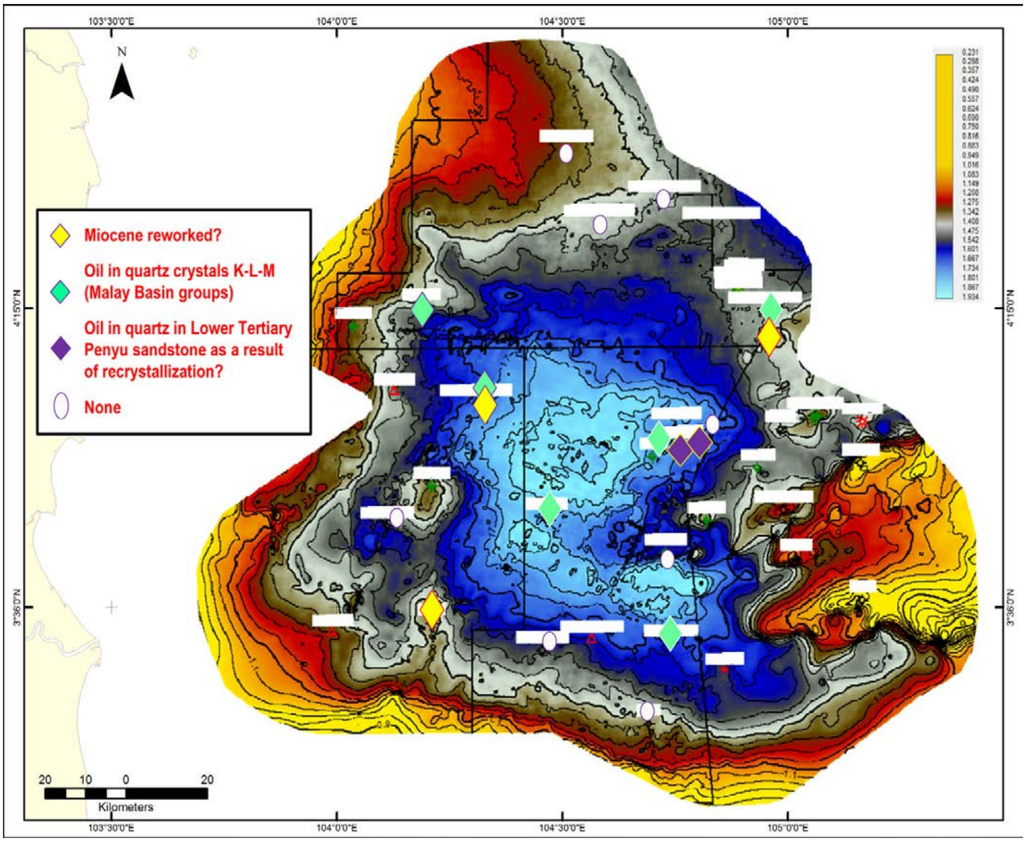

Figure 13: Locations of investigated wells and occurrence of types of inclusions. Blue areas denote depocentres.

sills within the Liteň Formation (Silurian). The geochemical characteristics of fluid inclusions trapped in vein quartz and calcite, vein bitumens and adjacent potential source rocks when combined with burial and thermal history data reflect the presence of at least three separate episodes of hydrocarbon charge. The liquid oil preserved within the fluid inclusions in vein quartz and calcite cements represents a second hydrocarbon charge that migrated after the cooling of the sill, at temperatures between 73 and 150 °C. This migration event probably occurred during the peak burial of the strata. The inclusion oil is moderately mature and non-biodegraded. Bright yellow-fluorescing, low-reflectivity (VR = 0.25 %) wax, forming thin coatings on vein minerals, represent the third and most recent pulse of hydrocarbon migration after the peak heating of the strata. Accordingly, fluorescence and wax content, as well as other associated parameters can give hints on the origins, maturity and expulsion timing of the migrating oils.

Harwood *et al*. (2013) performed isotope analyses on sandstone from the Jurassic Ness Formation from the North Sea to reveal the growth history of single quartz overgrowths to a resolution of 2 µm. Measured $\delta^{18}O$ (cement) range from +28 to +20‰ V-SMOW in early to late cement and are consistent with quartz cementation models that propose the bulk of quartz precipitates as a continuous process beginning at 60-70 °C.

Data from above mentioned studies help to establish a temperature window for quartz cementation, and in the context of oil quartzes, the temperature environment in which oil inclusions can form.

Methodology

Fluid inclusions in authigenic cements can be measured directly from thin sections. Unfortunately, none of the oil companies that have operated in the study area carried out micro-thermometry on any sample. Alternatively, an indirect method is used whereby the depth of occurrence of both quartz cements and fluid inclusions is recorded and compared with borehole temperature and vitrinite reflectance data. Vitrinite reflectance is correlated with temperature using the formula by Barker and Pawlewicz (1995). If there is no significant difference between the measured borehole temperature (which is derived from various sources, in the order of descending quality: DST, MDT, wireline log headers) and vitrinite-derived maximum temperature, it can be assumed that the heat flow history of the area had been stable over time. This can be shown by the comparison of temperature-converted Vitrinite Reflectivity Measurement (VRM) data, and the measured borehole temperature (Figure14). Accordingly, the present-day borehole temperatures appear to represent the fluid temperatures at the time of cementation, which is somewhat puzzling in the context of the strike-slip/inversion tectonics the study area has witnessed.

Database

The study area covers the main part of the Penyu Basin and the Tenggol Arch area adjacent to the south-western Malay Basin (Figure 1). The area was previously explored by PETRONAS Carigali, Conoco, Texaco and more recently by Lundin Petroleum. The database for this study consists of 12 exploration wells (Figure 13), and includes wireline logs, cuttings evaluation, fluid inclusion stratigraphy (FIS), and thin-section petrographic analyses. The latter two studies were provided mostly by Fluid Inclusion Technologies, Inc. (Tulsa) and Corelab (Kuala Lumpur), respectively.

Penyu Basin - Well Temperature and Vitrinite Reflectance

The stratigraphy of the Penyu Basin (Figure 3), as well as of the south-western edge of the Malay Basin, is characterized by a varying thickness of pre-Oligocene strata, and a mighty Oligocene section (> 3 km in the centre of the Penyu Basin) covered by an isopachous Neogene section in the order of some 1200 m thickness. There was mild tectonism during the Miocene, with a locally rather strong Serravallian tectonic inversion along a number of fault lines. In the Rhu area, the well data indicates a temperature gradient of between 3.3 and 4.0 °C/100m (Figure 14). The temperature gradient is fairly uniform throughout the borehole, but increases in the bottom (Oligocene and deeper) section of the wells; most likely as a result of higher formation density and increased thermal conductivity. Note that the correlation between vitrinite-derived temperature and borehole temperature measurements is fairly good.

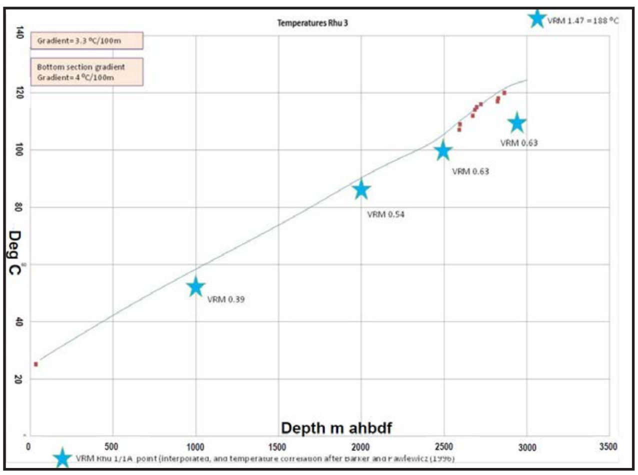

Figure 14: Borehole temperatures and vitrinite reflectivity data, converted to °C using the Barker and Pawlewicz formula (1995) are well aligned, with the exception of one very high VRM data point on the bottom of the well, which belongs arguably to a much older (? Mesozoic) stratum. If the latter value is real, it would point to a significant stratigraphic gap of some 1000 - 2000 m missing sediment.

Depth and Temperature Dependent Diagenetic Overprint

In the Penyu Basin, as well as in the Malay Basin, there are two important diagenesis boundaries:

(i) Beyond the porosity-reducing mechanism of mechanical compaction, the onset of destructive diagenesis starts with mineral cementation, in particular quartz cement/overgrowth. This boundary is found in the western Malay Basin at around 1200 m (Chu, 1992; Madon, 1994) and in the Penyu Basin between 1800 and 2000 m. Depending on the temperature gradients in these basins, these depths correspond to temperatures ranging from 105 – 130 ^{0}C in the Penyu Basin and 90 - 100 ^{0}C in the Malay Basin (Figure 15). Below this depth, diagenetic processes appear to have affected permeability more than porosity, as the pore throats and smaller pores are occluded by quartz and clay cements. In larger pores, fluids (occasionally oil) may be preserved but are no longer mobile. A similar pattern of diagenesis is observed in the study area as summarised in Figure 16.

(ii) The depth at which permeability destruction is deemed complete is at around 2800-3000 m. At this depth, authigenic cements have occluded the pore spaces and only some isolated porosity remains. In clean sandstones, most of the permeability is destroyed by quartz cementation, and clay minerals such as kaolinite, especially in clay- or feldspar- rich intervals (Figure 17).

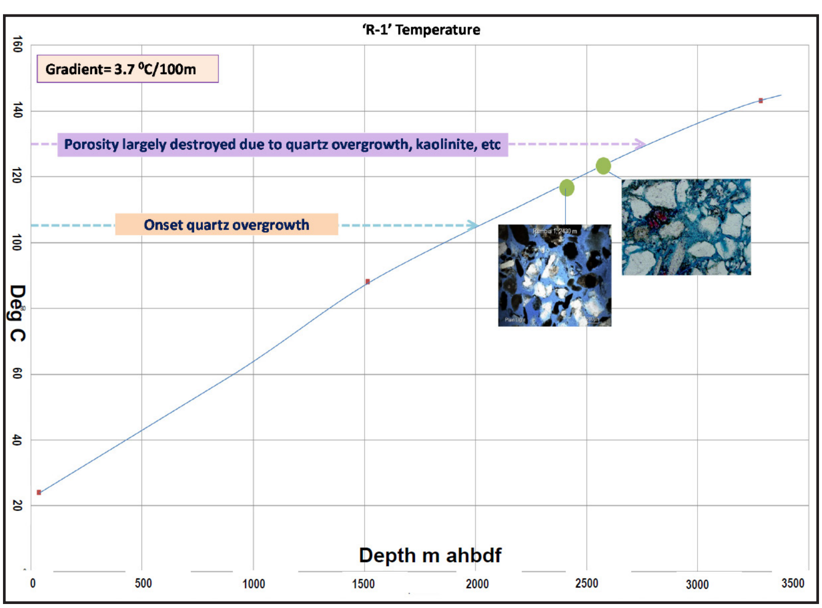

Figure 15: In the study area, quartz overgrowth starts at a depth > 1800- 2000 m, depending on the respective temperature gradient rather than on stratigraphic unit.

Figure 18 is a compilation of the temperature gradients calculated from the borehole temperature measurements in the Penyu Basin. The gradients range from 2.7 to 4.4 ^{0}C/100m. Recent drilling deep wells (> 4000 m) in the Cherating Half-Graben, however, recorded anomalously high bottom-section gradients of 5 - 6 °C/100 m. The cause of these high gradients is unknown but may be the consequence of the wells being in a 'hotspot' area. Based on the temperature/geothermal gradient data, and our understanding of quartz cementation and its relationship with temperature gradient, a spatial distribution of porosity destruction by quartz overgrowths is shown in Figure 19. Ultimately, these maps are indicative of the exploration risk that oil companies are facing when exploring deep reservoir targets. Discoveries in oil-bearing but tight reservoirs are regarded as technical successes, but economic success depends to a large extent on reservoir permeability, as well as on reservoir continuity.

DISCUSSION

There appears to be a good evidence for entrapment of oil in Penyu Basin (cement-rim) quartz, as oil percolated together with hot brines through reservoir rocks. Several wells at the south-western edge of the Malay Basin (Anding area) point to oil-bearing, but strongly cemented reservoir in Groups L and M, such that no pressure sampling (MDT) has been successful. FIS studies from the Penyu Basin wells show both high-gravity, as well as low-gravity oil inclusions. Some low-gravity oil inclusions (dull blue-white fluorescence, Figure 12) are suggestive for a limited amount of biodegradation prior to entrapment in the quartz cement.

Studies in several eastern Malay Basin wells suggest biodegradation occurred at temperatures below 85 °C in a recent study carried out by the operator of the held acreage. This might indicate that oil migrated in carrier beds such as the K-10 during Middle - Late Miocene times, when there was only some 1000-1500 m of overburden (Figure 20) present at that time. This observation suggests the existence of deeper-buried source rocks that had generated the oil, followed by expulsion and lateral migration. High-gravity (bright blue fluorescence) inclusions, however, indicate that the migrating oil was not affected by biodegradation and had occurred at a higher temperature, and possibly later.

More enigmatic are the primary inclusions that occur in the Miocene Group H reservoirs. There are no other corroborating signs of oil migration in the study area. The quartz grains also appear to have grown as crystals, and oil became entrapped in them as the crystals grew in the hot, possibly basement rocks. We suggest that the inclusions might have formed in granitic basement, as oil migrated towards the edge of the basins. This would imply that at least some carrier beds delivered oil towards the edges of the Penyu and Malay basins; or alternatively, oil had migrated from isolated and deep source rock pods into the neighbouring basement rocks and became entrapped. At a later stage according to this model, in Middle - Late Miocene time, granitic basement was eroded and quartzes with primary inclusions were deposited together with the regular quartz and other minerals.

The schematic models explaining the evolution of fluid in quartzes from Middle Oligocene (28 Ma) to Middle Miocene (14 Ma) are summarised in Figure 21. The

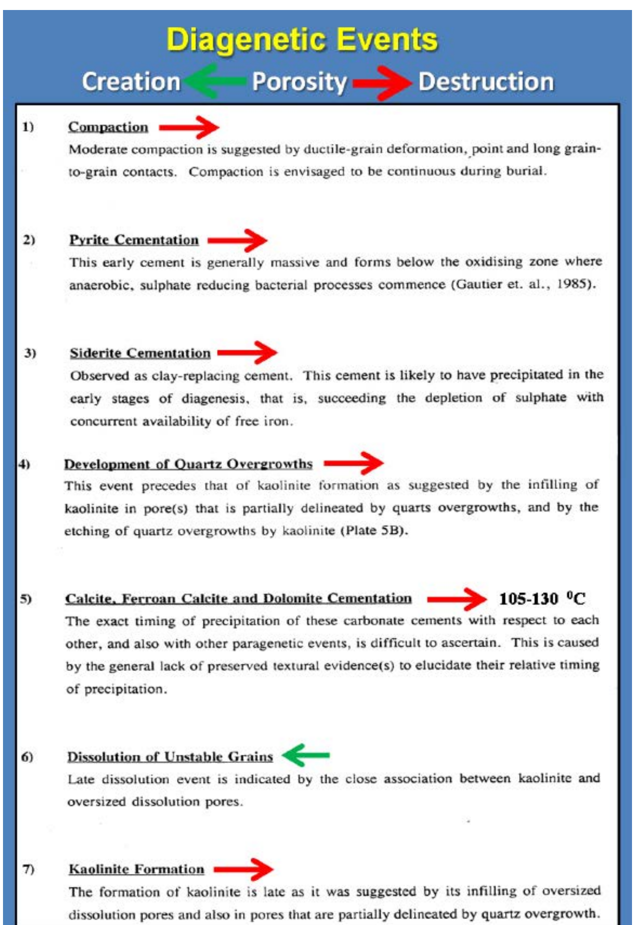

Figure 16: Common patterns of diagenesis affecting reservoir rock at increasing depth, temperature, and pressure. Mobilized quartz builds up layers of cement, with the outcome that permeability in sandstone reservoirs is destroyed gradually.

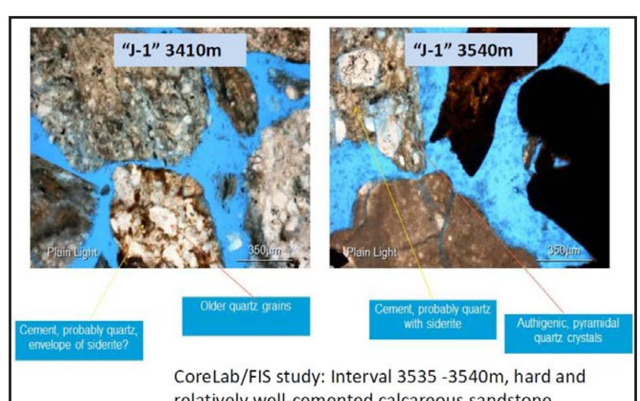

Figure 17: Miscellaneous cuttings from well J.1, show a strong recrystallization, leading to the occasional growth of authigenic quartz crystals. There is little or no reservoir potential present in these samples.

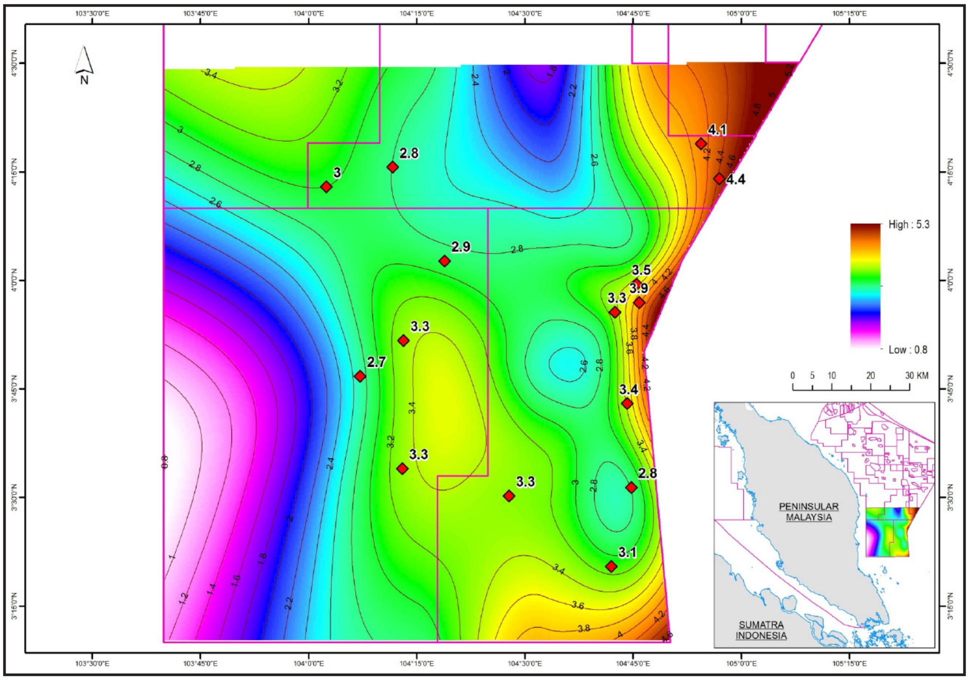

Figure 18: Penyu Basin and Tenggol Arch - temperature gradients (°C/100m) calculated from borehole measurements.

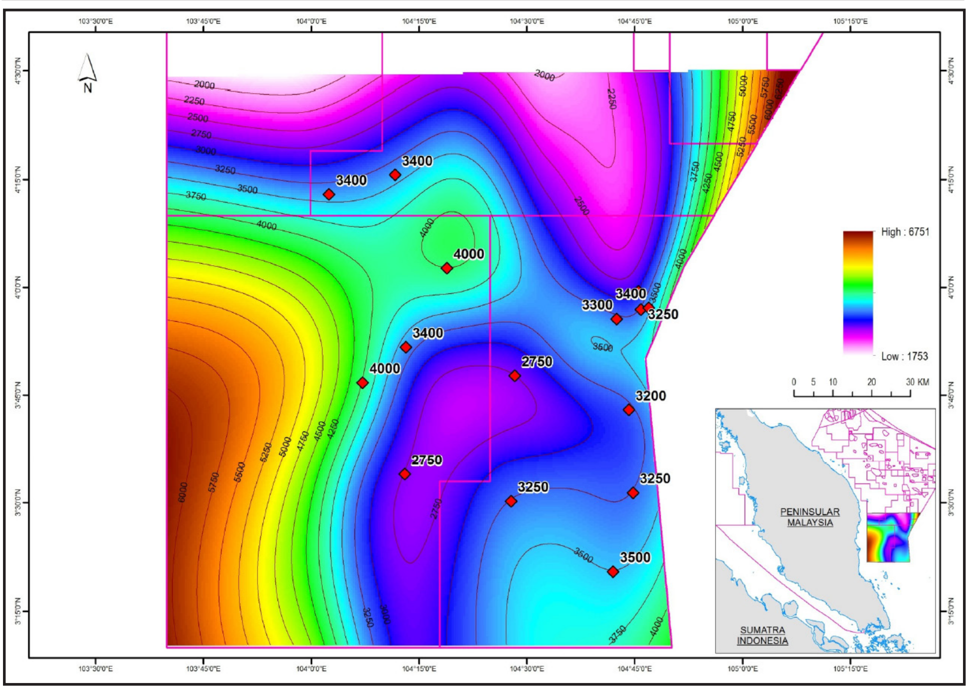

Figure 19: Penyu Basin and Tenggol Arch - porosity is largely annihilated by quartz overgrowth, below indicated depth levels (m), @ 130 °C.

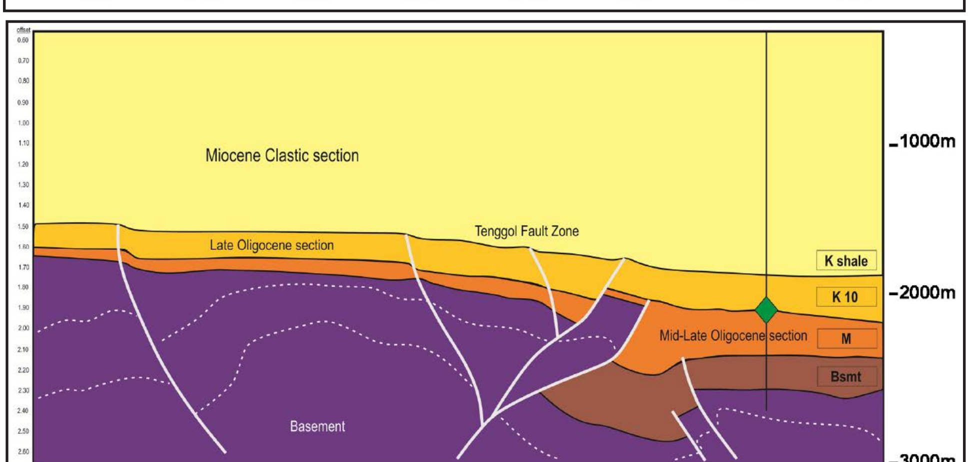

Figure 20: A geological section through the Tenggol Fault Zone, near to the Malaysia/Indonesia border, separating the Tenggol Arch (left) from the Malay Basin (right). The Tenggol Fault Zone originated as a rift-boundary fault with an overprint of wrenching and thrusting during the ? Late Oligocene – Early Miocene time. Low gravity oil inclusions in quartz are seen at the K-10 level indicate oil migration and entrapment in quartz cement within this important carrier bed.

Tenggol Arch had been a pronounced structural feature in the study area since the Middle Oligocene, as a result of block faulting and uplift of the granitic dome. Quartz dykes were formed in the roof zone with oil inclusions entrapped with the growing quartz crystals. In the Early Oligocene, the rising dome was eroded and peneplained, resulted in the re-deposition of quartz crystals with entrapped oil inclusions in the Lower to Middle Miocene sequences, which continued into Middle Miocene.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

The economic viability of deep oil and gas reservoirs depends on the presence of porosity and permeability. The latter is of particular importance, as it controls the amount of oil and gas to be produced. This case study demonstrates that reservoir porosity and permeability prognosis cannot rely on sedimentary facies patterns and compaction criteria alone, and that an understanding of diagenesis is equally, if not more, important. Fluid inclusions in quartz are important indicators of oil migration, as well as the diagenetic processes taking place during burial. The range of oil gravity in quartz inclusions provides valuable information. Some oils are of low gravity, which points to either early expulsion or biodegradation which occurred as the oils migrated at a relatively low migration-path temperature (and shallow overburden).

The co-occurrence of different oils could be used to determine the relative timing between cementation and pulses of oil migration/charge in areas such as the Penyu Basin and Tenggol Arch and the adjacent area of south-western Malay Basin. The results of this study could be used to assist in the assessment of the optimum depth for exploration targets in the study area, and have potential significance for exploration prospectivity of the greater Malay Basin area, which suggest that at depths of greater than 3000 m sandstones are likely to have poor reservoir properties. Where there have been overpressures, pore spaces in the reservoir rocks may be preserved before destruction by burial diagenesis. Having said this, the available data seem to suggest that such overpressure-driven porosity preservation did not occur in the studied tight and oil-bearing reservoirs.

In this study, at least two types of fluid inclusions have been identified in the Penyu Basin and Tenggol Arch area:

(i) Primary fluid inclusions are found in quartz grains of detrital origin. This suggests significant long-distance migration of oil from the Malay Basin, or perhaps more likely, short distance migration from isolated grabens such as the Kuantan Graben in the Penyu Basin.

(ii) Secondary inclusions in quartz overgrowths are found in the Oligocene to Early Miocene sequences of the Penyu Basin, and at the border between the Tenggol Arch and the south-western Malay Basin. The presence of both high- and low-gravity oil (identified based on fluorescence color) indicates at least two pulses of oil migration. The oils became entrapped in quartz and other cements, as brines percolated in a presumed temperature range of 105 - 130 °C. The liquids reacted with framework grains such as quartz and feldspar, and destroyed reservoir permeability, which resulted in oil droplets being isolated and trapped in the intergranular cements.

Future fluid inclusion and maturity studies should aim at obtaining pressure and temperature data from fluid inclusions. In the absence of these data, some of our conclusions are inferred indirectly from heatflows/temperature gradients and also derived from a modelled temperature gradient history. Nevertheless, a few good fluid inclusion temperature measurements (which could be obtained at a relatively low cost) would have strengthened the interpretation.

With the current study covering mainly the Penyu Basin and Tenggol Arch with implications for the adjacent

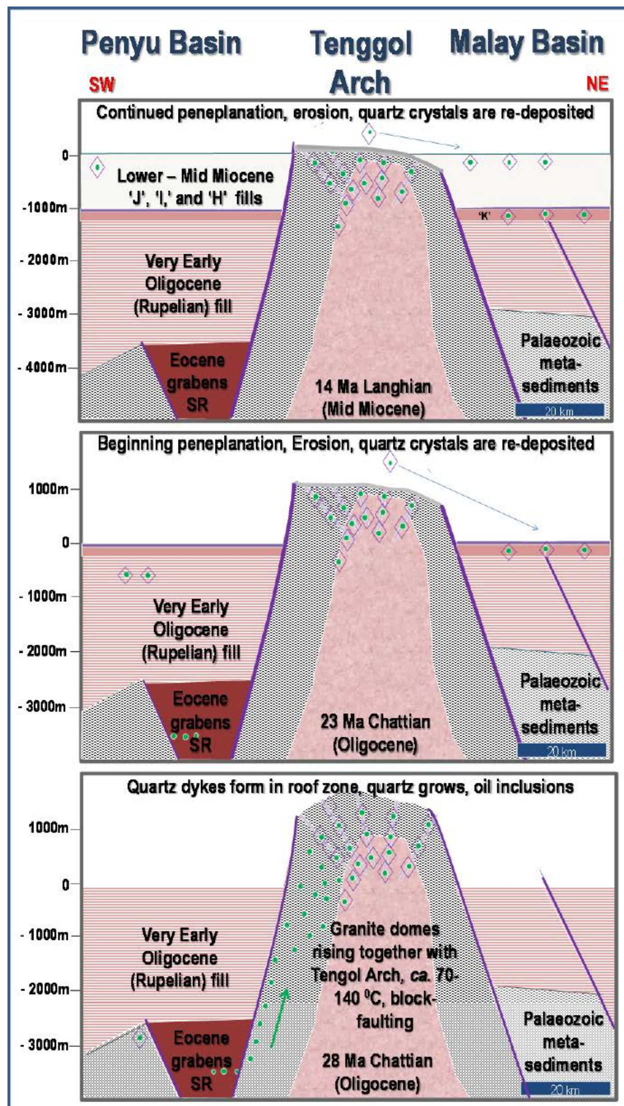

Figure 21: Schematic models explaining evolution of petroleum in quartzes observed in the study area. Bottom – 28 Ma Chattian (Oligocene), Middle - 23 Ma Chattian (Oligocene), Top – 14 Ma Langhian (Mid Miocene). Note the diamond shaped features represent inclusions with oil traces.

south-western Malay Basin area, future work should aim to expand the study to the greater Malay Basin area. Given the density of oil wells in the Malay Basin, it may be possible to align chemical fluid inclusion properties with liquids data from migrated oils in reservoirs, as these two relatively independent sources of data seem to portray various aspects of oil expulsion and migration.

Another aspect for further research should be directed at the origin of oil inclusions in quartz in water-bearing zones. The occurrence of both oil and water bubbles suggest that oil and water were both trapped as primary inclusions during the growth of diagenetic quartz. It is likely that oil and hot brine migrated together, or in alternating pulses, but to-date we noted the lack of a good description and explanation of these processes.

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