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Radioactive apatite-rich "Hot Sands" of the Tenggol Arch: Stratigraphic curiosity or sub-seismic reservoir correlation tool?

John Jong[1,*], Franz L. Kessler[2], Mazlan Madon[3], Hamdan Mohamad[4]

[1] JX Nippon and Gas Exploration (Malaysia) Limited, Malaysia
[2] Goldbach Geoconsultants O&G and Lithium Exploration, Germany
[3] Advisor, Malaysian Continental Shelf Project, National Security Council, Malaysia
[4] Custodian Petroleum Geoscience, Malaysia Petroleum Management, PETRONAS, Malaysia
*Corresponding author email address: jjong2005@gmail.com

Abstract: A review of Late Oligocene to Early Miocene reservoir sandstones in the Tenggol Arch area has identified a number of intervals with anomalous radioactive levels within the K, J, and I Tertiary sequences. A correlation between spikes on the spectral gamma ray logs and petrographic analysis of cores and cutting samples points to Thorium-bearing, apatite-rich sandstones and siltstones as the main source of radioactivity. The elevated radioactivity levels occur within meandering channel sequences with sediment derived from the Malay Peninsula, the Johor Platform and perhaps some local cuesta ridges nearby on the Tenggol Arch. Commonly, the anomalous radioactive intervals are represented by flaser-sand/silt and clay associations. Given the relatively thin radioactive intervals, measuring at most a few metres, these sandy intervals cannot be imaged on seismic data, but could be used as a tool for correlating reservoir units at reservoir or field scale. Furthermore, the high radioactivity due to Thorium (Th) and Uranium (U) could lead to wrong estimates of clay and sand percentages, unless they are corrected with the help of spectral gamma ray logging.

Keywords: apatite, correlation, radioactivity, Thorium, Uranium, Tenggol Arch

INTRODUCTION AND DATABASE

The Tenggol Arch is located offshore east of Peninsular Malaysia in the South China Sea. It encompasses an area of relatively shallow pre-Tertiary basement on the south-west flank of the Malay Basin and north of the Penyu Basin. It straddles the Malaysia-Indonesia maritime border (Figure 1). The geologic knowledge of the study area is based on the results of decades of oil and gas exploration efforts, including those from published literature of the neighbouring Indonesian fields integrating all seismic, gravity, magnetics and, most importantly, well outcomes. Hydrocarbon reservoirs in the area are located mainly within the Oligocene (L, M) and Lower Miocene (I, J, K) sequences (Figure 2).

To-date, the following oil and gas resources have been discovered in the study area:

- **Anding/Anding Utara and Basement cluster** – a producing oil and gas/oil field. The Anding wells are located in the Malay Basin, close to the Tenggol Fault, the main basin-bounding normal fault that separates the Tenggol Arch from the Malay Basin. The wells found oil-bearing fractured reservoirs in the Mesozoic basement phyllites, long distance charged from the adjacent deep half-grabens in the Malay Basin.
- **Malong** – a producing oil field, on the eastern flank of the Tenggol Arch, is characterised by channelised reservoirs of the K (Late Oligocene to Lower Miocene) and J (Lower Miocene) groups of reservoirs (Ibrahim & Madon, 1990).
- **Sotong** – a producing oil and gas field. The field, located across the Tenggol Fault from Malong field, is very close to the fault, and is also formed by a number of channelised reservoirs. The K Group reservoirs consist

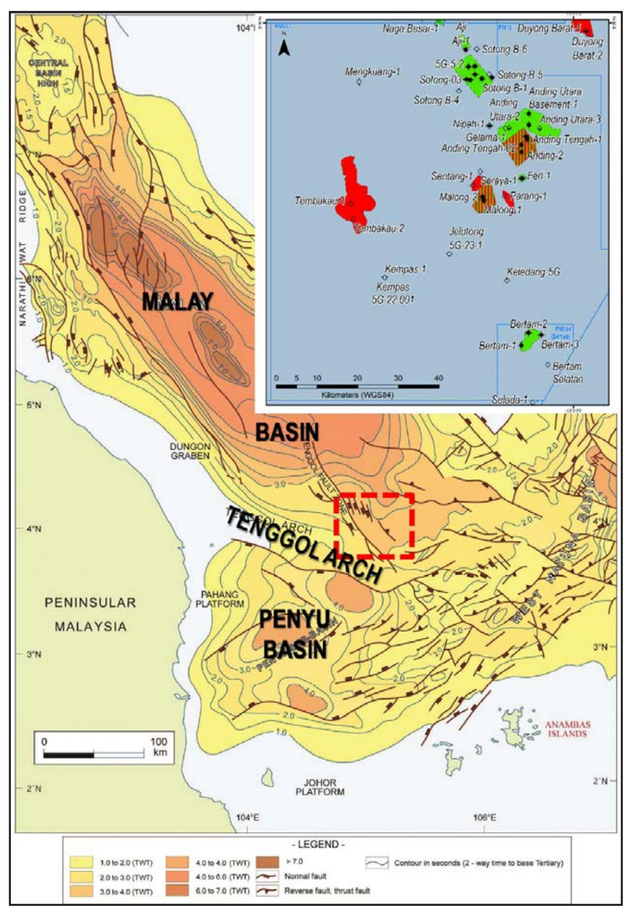

Figure 1: Structural framework map of the Malay, Penyu basins and Tenggol Arch, offshore Peninsular Malaysia. The study area located in the Tenggol Arch is outlined by a dashed red line. The inset map shows locations of the main fields in the study area (maps from IHS Markit).

mainly of fluvial channels, with individual thicknesses of 5 to 6 m, stacked into channel complexes of 6 to 15 m thickness deposited in flood plain, tidal flat and lower shoreface environments (Madon *et al*., 1999; Tan, 2009).

- **The "B" field** – a producing oil field from the K Group reservoirs formed by fluvial channels, tidal and delta front sequences. Given that the source rocks on the Tenggol Arch are immature, both oil and gas must have been originated from either the Malay, Penyu or West Natuna basins.
- **Tembakau** – a small gas field, located in the centre of the Tenggol Arch. Gas was found in two separate channelised reservoirs in I Group.
- **Tembikai** – a marginal oil and gas field.
- **Belida** – a mature oil field on the southern Tenggol Arch in neighbouring Indonesian waters, with reservoirs similar to those in the Tembakau and B fields (Maynard *et al*., 2003).

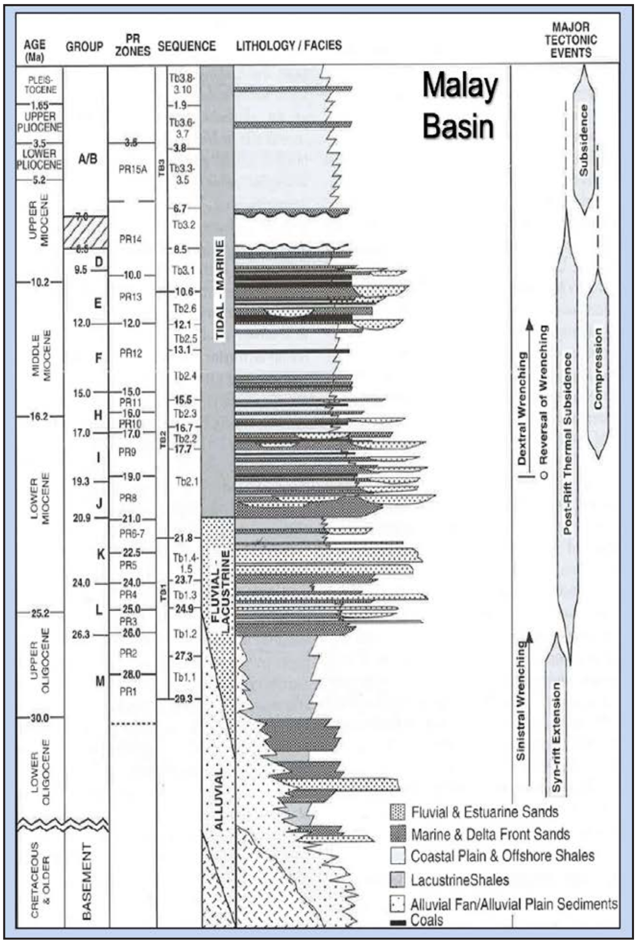

Figure 2: Generalised stratigraphy and major tectonic events of the Malay Basin and Tenggol Arch (from Tan, 2009, and modified after Madon *et al*.,1999).

The study area covers mainly the exploration blocks in the Tenggol Arch region (Figure 1), previously operated by PETRONAS Carigali, Conoco, Texaco and more recently by Lundin Petroleum (now called International Petroleum Corporation). The database of the study consists of a number of selected exploration and development wells, where wireline logs, cuttings evaluation, fluid inclusion stratigraphy (FIS), and thin-section petrographic analyses are available. Detailed FIS and petrographic analyses were provided by Fluid Inclusion Technologies, Inc. (Tulsa) and Corelab (Kuala Lumpur), respectively. Rock composition data were generated by AnaMin using infrared spectrometer analysis. The available core data are shown in Table 1.

In our studies we refer here mainly to reservoir data from the Tembakau and adjacent fields, all located on (or on the edge of) the Tenggol Arch, where core and spectral gamma ray log data are available. Within these fields, the Late Oligocene to Early Miocene sedimentary sequence (K, J, I) is constituted by mostly fining-upwards reservoir cycles, of which some are radioactive. Spectral gamma logs in the Tembakau wells and the B fields, show Thorium- and Uranium-related radioactivity anomalies. This paper deals with the composition of sediments, their mineralogy, the source of the radiation, and last but not least, the potential use of radioactivity anomalies as a tool for reservoir correlation on a sub-seismic scale.

GEOLOGICAL SETTING

In respect of the formation of both the Malay and Penyu basins, there is a wide variety of opinions. The basins are considered to have originated either in a back-arc setting (Kingston *et al*., 1983; Mohd Tahir *et al*., 1994), or as a pull-apart basin developed along a major strike-slip fault (Tapponier *et al*., 1982), or through thinning of continental

Table 1: Availability of core and sidewall core materials in the study area.

Well	Sq. I-10	Sq. I-20	Sq. I-80 channel A	Sq. J	Sq. K10 +	Sq. L-M	Basement
Bertam-1	no	no	no	no	no	no	no
Bertam-2 (log)	Thin 'I'	Thin 'I'	Thin 'I'	Not assessed	Y	Y	Y
Bertam-2 (core)	No core	No core	No core	No core	Y	No core	No core
Bertam Selatan-1 (log)	n.a	n.a	n.a	Not assessed	Y	Y	?
Tembakau-1	Y	Y	Y	Y	Y	Y	Y
Tembakau-2 (log)	Y	Y	Y	Y	Not drilled	Not drilled	Not drilled
Tembakau-2 (core)	Y	Y	Not present	No core	No core	No core	No core

crust (White & Wing, 1978). Other tectonic models involve crustal extension over a hot spot (which is close to thinning of continental crust) (Hutchison, 1989; Khalid Ngah *et al*., 1996), extensional subsidence along a major left-lateral shear zone (Madon & Watts, 1998; Md Yazid *et al*., 2014; Maga *et al*., 2015; Kessler & Jong, 2018) and as a failed rift arm of a triple junction above a mantle hot spot (Tjia, 1999). Morley & Westaway (2006) proposed a geodynamic model of the Malay Basin, involving lower-crustal flow in response to post-rift sedimentation.

The Tenggol Arch was mainly a peneplain during Early Oligocene times and is formed by basement rocks such as granitoids, volcanics, phyllites, argillites, slates and limestones (Tan, 2009). Structuration within the arch is highly complex and may represent a Palaeozoic fault and thrust belt (Figure 3). This ridge formed a barrier to sediments advancing basin-wards from the Malay Peninsula until the very late Oligocene. Subsequently, during the Neogene, clastic sediments overwhelmed the ridge and were draped over this peneplained, heavily folded ancient mountain belt. In Early Miocene, subsidence in both adjacent basins slowed, and sediments derived from uplifted mountain belts on the Malay Peninsula eventually reached the Malay Basin. During the Miocene, the area was subjected to compression and lateral strike-slip movements (dextral wrenching), which resulted in inversion.

STRATIGRAPHY AND LITHOFACIES

The Tenggol Arch stratigraphy shows an almost layered sequence, which consists of channelised sands, claystone and coals (Figure 3). The groups K, J, and I within the Malong sections show an age range from the Early Oligocene to the Middle Miocene (Figure 4). Given that the biostratigraphy of the section lacks good marine marker fossils, the precise location of the Base Miocene is difficult to establish. The sediments are of fluvio-lacustrine and intertidal origin, often cyclic and characterised by the occasional periods of marine transgression. An immature source rock interval has been identified (K Shale), however, it is noted that the sediment thickness on the Tenggol Arch is less than ~2 km, so it is unlikely to have generated significant amount of hydrocarbons due to low maturity of source rock, even at relatively high geothermal gradients (*ca.* 4.5 ^{0}C/100m). Nonetheless, there have been at least two pulses of oil migration observed (e.g., Tan, 2009). With no oil generated on the arch, both oil and gas must originate from either the Malay or the Penyu basins.

The reservoirs are siliciclastic, deposited mainly in fluvial-lacustrine channels and deltas, with varying grain sizes from (rarely) coarse, middle to fine sands (Figure 5). Sediments were deposited, initially, in a low-relief playa environment characterised by stacked meandering channels. As summarised in Ibrahim & Madon (1990), these basal sediments pass up to the prograding shoreface sequences in Malong, consists of upward coarsening units in which heterolithic sandstone-mudstone are overlain by ripple cross-laminated and parallel-laminated sandstone. The inner-shelf

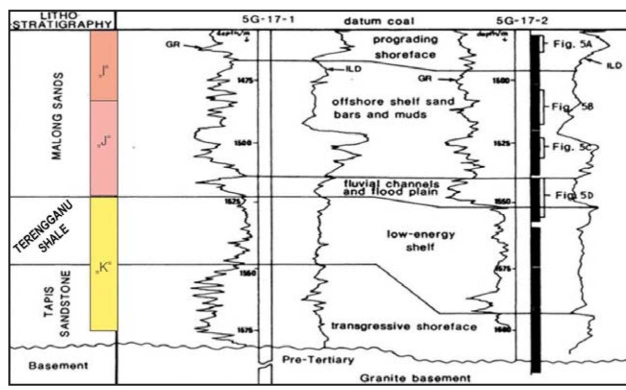

Figure 4: Log correlation of 2 Malong wells and facies. Several high gamma ray peaks might represent hot sands, but this remains speculative in absence of spectral gamma ray logging (from Madon, 1990 and modified after Ibrahim & Madon, 1990).

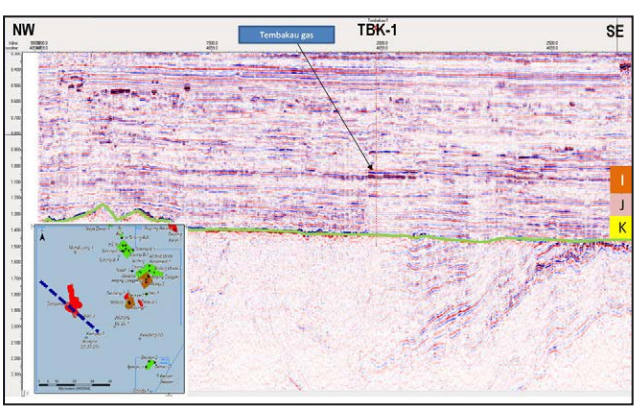

Figure 3: A seismic section of *ca.* 50 km length running NW-SE on the Tenggol Arch with approximate line location shown on the inset map. The geology can be divided into (bottom) a strongly deformed basement section, with an isopachous Neogene drape above. The Basement unconformity is highlighted in green. A marked amplitude anomaly in the centre of the picture indicates the presence of gas. The stratigraphic group intervals, I, J, K are annotated.

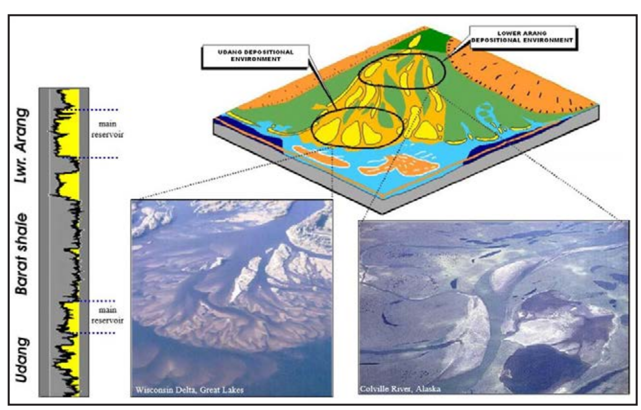

Figure 5: Reservoir depositional model with type sections of the Belida field offshore Indonesia, in close vicinity to the B field. Udang corresponds to K Group, Lower Arang to J Group. Udang reservoir sands in Belida field are pressure-connected to the K reservoirs in the B field (from Maynard *et al*., 2003). In the figure, Belida is compared to examples from the Wisconsin Delta and the Colville River.

sequence is made up of upward-coarsening offshore bar sandstones encased in shelf muds. The shelf sand bodies show evidence for deposition by storm-generated currents, and are characterised by the association of distal, low-energy heterolithic facies overlain by proximal, amalgamated high-energy sandstone units. The fluvial channel sequence consists mainly of trough cross-bedded sandstone, intercalated with minor floodplain mudstone.

A brackish environment is more strongly expressed in the eastern portion of the Tenggol Arch, such as in the Malong field area. The position of the coastline within the lowermost sequence (Terengganu Shale) is in places marked by oolithic ironstone beds (Madon, 1992). Palynological evidence further suggests that deposition of the Terengganu Shale (older term for K Shale) took place during a dry climatic phase, which might have caused the reduction of terrigenous influx into the basin and promoted ironstone accumulations. There is, however, no mention of "hot sands" in the Malong well, as spectral gamma ray log data were not acquired.

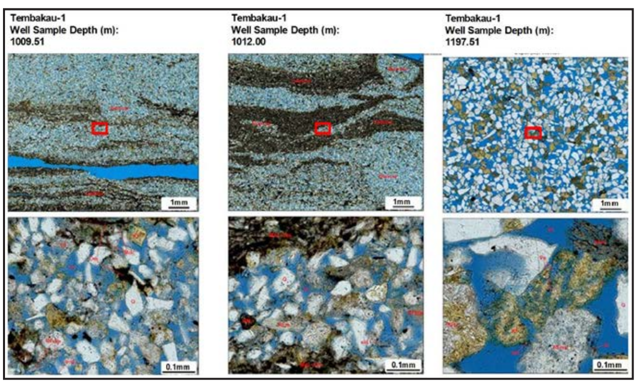

Figure 6: Heterolithic clastic hot sand samples as shown above from I-10 interval, Tembakau-1, are very well-sorted, and mostly fine sands. Surprisingly, most grains are sub-angular suggesting deposition relatively close to the provenance. Likely the sediment did not form solely in an aqueous environment. Wind transport may also have played a role. The highlighted areas in the upper photos are the location of the magnified pictures immediately below.

Figure 7: Thin section from a Tenggol Arch field core at depth 1634.37 m (K sequence). Typical heterolithic facies formed by sub-angular, yet in general well-sorted quartz and dark and greenish components, likely minerals of the apatite family as well as chlorite and possibly glauconite.

INVESTIGATION METHODOLOGY – PETROGRAPHY, RADIOACTIVE SIGNATURES AND RESULTS

The first step in the investigation was to review existing rock descriptions from the published Malong and Belida field data, with the objective to compare them with samples (sidewall cores, cores) from Tembakau-1 and other wells (Table 1). The petrology of reservoir sands in Belida, Malong, Tembakau and B fields suggests a common sedimentary source and transport direction (Figures 6 to 9). Thorium radioactivity levels from Tembakau-2 are quoted in Table 2.

As a next step, core sample composition data obtained by Infrared Spectrometry (Figure 10) were plotted against the spectral gamma ray curves consisting of the Thorium, Uranium and Potassium-40 (K40) tracks. K40 is a radioactive isotope of potassium, which has a half-life of 1.251×10^9 years. As shown in Figure 11, Thorium is the dominant

Figure 8: Raw core picture from Tembakau-2, Core 1. The thin, 1-5 mm (with a key for scale) grey gas-bearing sand intervals are flasers, and are intercalated between soft clay beds. The sands however, are very clean and do not contain any significant amount of clay.

Figure 9: Raw core picture from a fresh Tembakau-2 core showing heterolithic (left) and relatively clean massive facies (right).

Table 2: Radioactive levels in a cored (I-sequence) interval of Tembakau-2.

Tembakau-2 core analysis: I sequence - high Thorium levels and radioactive layer thicknesses					
Core	Measured Depth (m)	Box	Highest Value	Range	Thickness of Layer (cm), near/above 30ppm
1	1038.87	1	30.4	1038.67 - 1039.16	49
	1042.96	5,6	34.05	1042.86 - 1043.01	15
	1047.44	10	31.35	1047.34 - 1047.82	48
	1048.88	11,12	33.65	1048.69 - 1049.03	34
2	1082.45	18	33.65	1082.25 - 1082.45	20
3	1103.71	12	29.3	1103.71 - 1103.80	9
4	1109.32	2	32.82	1109.22 - 1109.56	34
	1111.17	4	30.82	1111.02 - 1111.37	35
	1113.37	6	35.98	1113.32 - 1113.51	19
	1119.32	12	33.4	1119.12 - 1119.41	29
	1120.63	13	32.62	1120.59 - 1120.68	9
	1122.44	15	37.71	1120.10 - 1122.63	53
	1127.27	19,20	33.95	1126.88 - 1127.37	49
5	1128.88	1	32.54	1128.83 - 1128.93	10
	1147.12	20	34.61	1146.78 - 1147.22	44
	1148.63	21	36.45	1148.53 - 1148.72	19
	1154.84	27	31.1	1154.74 - 1155.18	44
6	1166.53	11	30.55	1166.43 - 1166.67	24
	1181.15	26	31.28	1181.05 - 1181.25	20

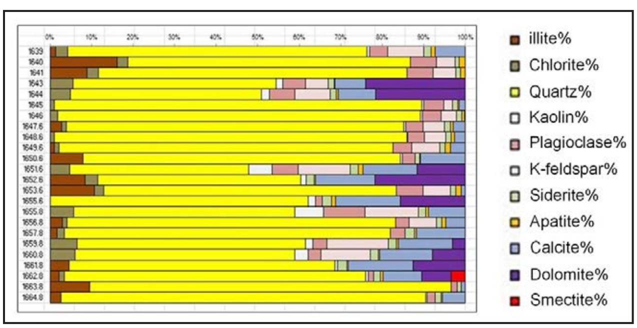

Figure 10: Mineralogical compositions of core plugs in a Tenggol Arch field (analysis by AnaMin). Note the relatively high Apatite percentages at 1640 m, 1641 m, 1649.6 m and 1653.6 m.

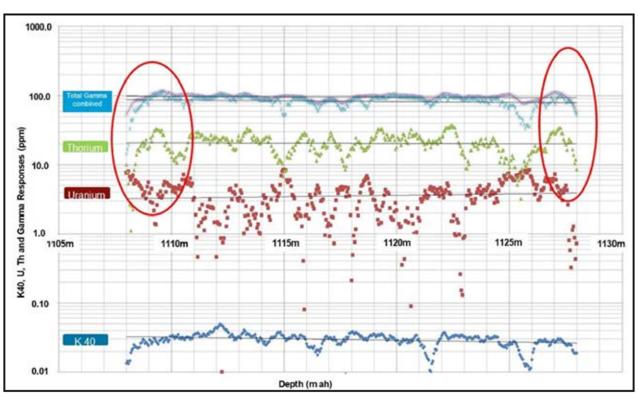

Figure 11: Hot sands, I sequence in Tembakau 2. Total gamma (upper greenish blue) is influenced by Thorium (green), causing peaks that are not related to K40 (lower blue curve as shown). Uranium content (red-brown) being low, has no influence on the composite signal.

source of radioactivity among the three measured, followed by Uranium and K40. Accordingly, the composite gamma ray signal is dominated by Thorium content. This observation is

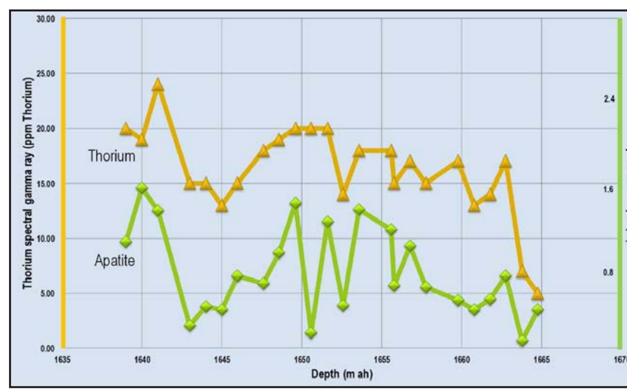

Figure 12: Correlation between apatite content (green curve, in sample percentage), and Thorium on spectral gamma ray log (golden curve, converted to ppm Thorium) from a Tenggol Arch field, both plotted against depth in meters along hole. Apatite (present as isolated heavy mineral grains, as well as in rock fragments) is inferred to be the host of observed anomalous radioactivity.

confirmed when plotting apatite mineral percentage (grains and/or apatite in igneous rock fragments within sands) with the Thorium gamma ray curve, and we obtained a very a good correlation (Figure 12).

The apatite family components reach several percent within the hot sands. The cut-off for Thorium sands was set arbitrarily at 20 ppm Th, a value chosen as the entire K, J and I sequence showed a strong Thorium background signature. However, we found a number of samples with elevated Th radioactive levels, and those peaks were chosen for reservoir correlation in Tembakau and adjacent areas. In addition, our studies showed that there is a weak correlation between grain size (and therefore porosity in well-sorted sand and silt) and Thorium content (Figure 13). However, there is no convincing rock-to-curve correlation

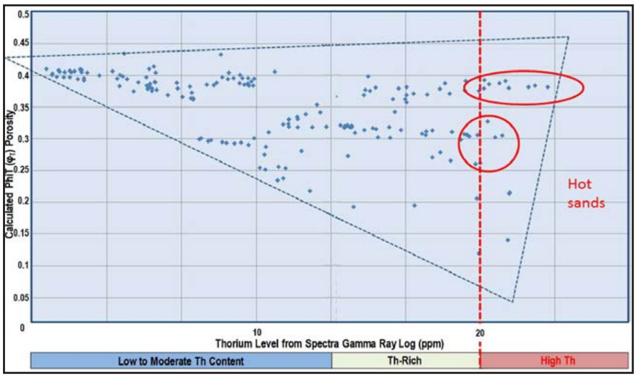

Figure 13: Calculated porosity and Thorium radioactivity. The dashed red line corresponds to 20 ppm Th, and gamma radiation levels are shown on the x-axis. The hot sands in the right corner are found within the I-10 sequence of Tembakau-1 exploration well, and in different porosity classes.

for Uranium and sediment composition; hence its source mineral remains unknown.

RESEARCH APPLICATIONS

The presence of hot sands in the investigated wells has two practical applications:

1. Petrophysical log analysis. Without correcting for the effect of Thorium, and also Uranium in sands, bulk gamma ray may lead to erroneous clay percentage computations, and hence to elevated "shaliness" estimates and possibly leading to an underestimation of net reservoir.
2. Precise correlation of reservoir beds at sub-seismic scale; this could be of value in fields such as Malong, Tembakau and others, where reservoir sand-to-sand correlation in wells might pose significant challenges due to the presence of thin beds and sometimes sub-seismic faults (Figures 14 -15).

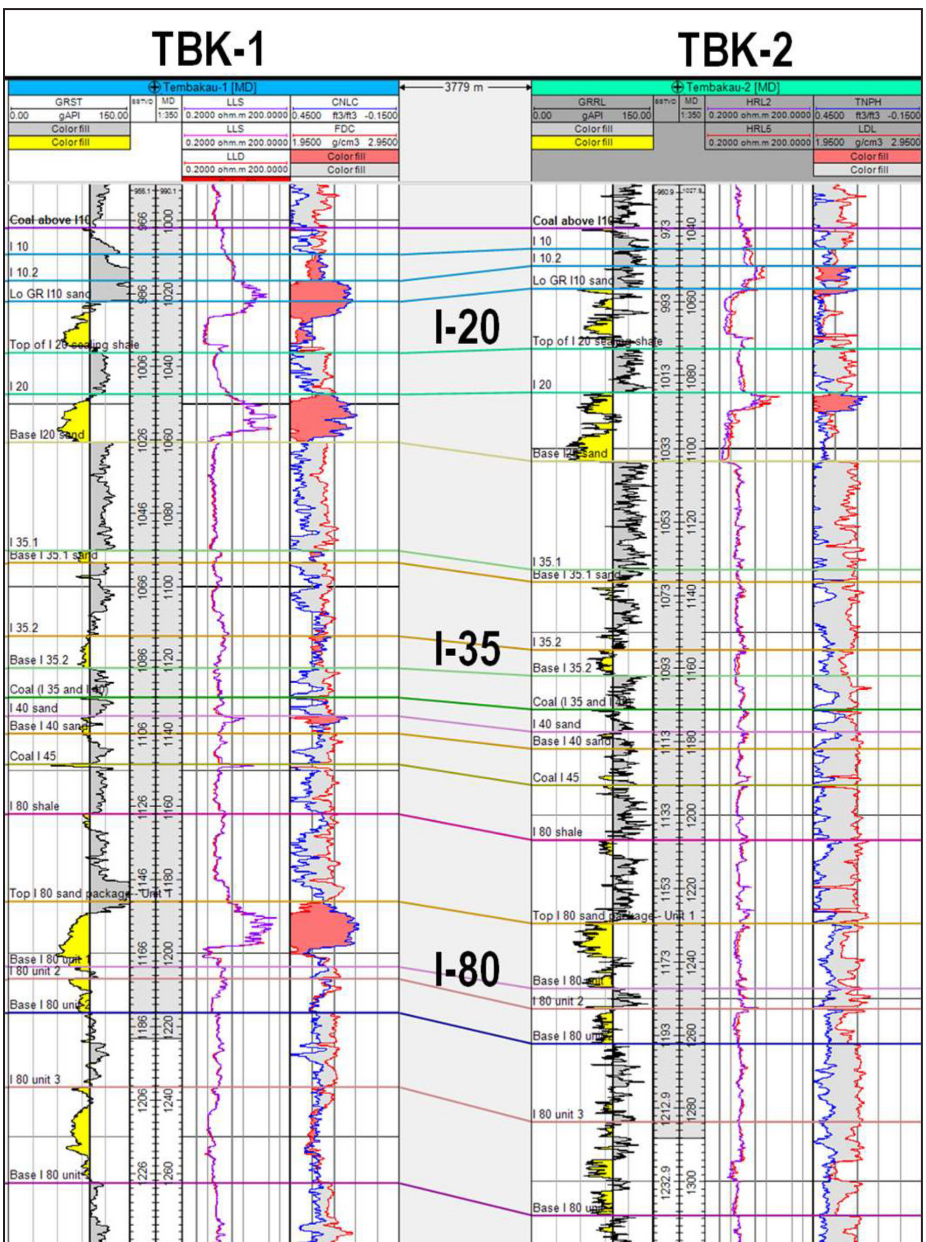

Figure 14: Correlation between neighbouring wells (Tembakau-1, Tembakau-2) using Thorium gamma ray responses. It could help refine reservoir modeling and sub-seismic wireline log correlation.

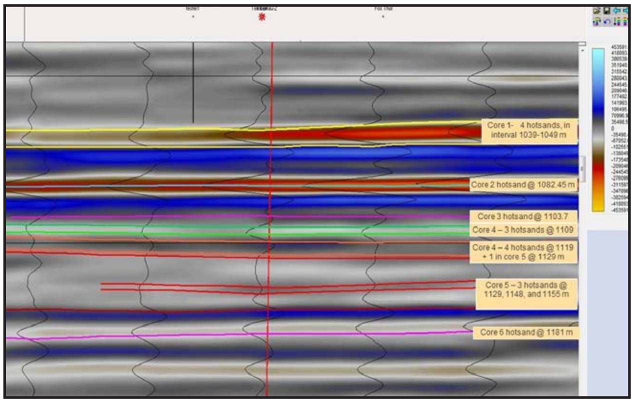

Figure 15: An example of hot sand well-to-well correlation in Tembakau area.

In summary, this research work has led to the following observations and discussion points:

- Hot sands are present within the I, J, and K sequences in Tembakau field and the K interval in the adjacent B field. These sands belong to the so-called heterolithic facies type. The hot sand layers (defined by a cut-off at 20 ppm Th) are relatively thin (9-53 cm thick, average 30 cm), and are found mostly in the fine sand to silt grain size bracket, and occasionally also in medium-grained sand. The quartz sand grains are angular to sub-angular, which likely point to relative proximity to the source area.
- The relatively high radioactivity in the hot sands stems from Thorium in minerals of the apatite family. The Thorium radiation dominates other radioactive sources (U, K40). There is a moderate correlation between Thorium content and Phit [Φt] (total) porosity (Figure 13). Thorium-Phit plots yield characteristic data distribution patterns, which may be used to finger-print individual channel sequences. Possibly, there is a grain size and sorting influence such that apatite is predominantly found in the fine sand to silt fraction.
- Hot sands can potentially be used as a sub-seismic correlation tool at field scale (e.g., Tembakau and adjacent areas), using spectral gamma ray log-to-log correlations (Figures 14 -15). However, when it comes to regional correlation, one should proceed with caution. Most likely regional scale correlation will be difficult to perform given the narrow linear nature of channel sands perpendicular to the flow direction. Within a field, channels may be correlated in time but probably not their reservoir sands. This means that events are being correlated but not necessary reservoirs. This could lead to a strong overestimation of net to gross parameter, since in between those channels sand reservoir quality may be low or even very poor. Regional correlation using the hot sands approach should therefore be accompanied and checked by additional correlation features for consistency such as maximum flooding events.

DISCUSSION

Thorium-bearing minerals occur in granites and pegmatites, albeit Thorium does not occur in the nature in metallic form. These are concentrated in richly mineralised but small accumulations. Furthermore, Thorium may be distributed throughout granite as apatite. Secondary deposits of Thorium-rich sediments occur at the mouths of rivers draining granitic mountain regions. In these deposits, Thorium is enriched along with other heavy minerals (Stoll, 2005). Initial concentration varies with the types of deposit. In the studied case, the Thorium radiation can be traced to heavy minerals of the apatite family. The latter consists of phosphate minerals of complex composition: (Ca, Ba, Pb, Sr, Th)5 (F, Cl, Oh) [(P04, CO3)3]. Both, apatite and its cousin monazite (Ce, Lu, Nd, Th) [P04] contain Thorium. Apatite is relatively heavy, with a specific density of 3.1-3.7 g/cm^3 compared to quartz 2.65 g/cm^3. Most quartz grains (in particular the fine fraction) are angular to sub-angular and appear incompatible with long distance aqueous transport. Apatite grains appear to be in phase with the size of quartz grains but are usually smaller (silt-size), suggesting quartz and apatite were transported together. Possibly, the apatite containing quartz sands might be aeolian/fluvial placer deposits derived from igneous and perhaps also metamorphic rocks.

The origin of the radioactive sands remains somewhat speculative. A fission track analysis carried out by Krähenbuhl (1991) suggests that some Peninsular Malaysia granites (Central and Eastern Belts) were uplifted during the Paleogene, and hence could have provided a source for the Oligo-Miocene clastics deposited on the Tenggol Arch, including the hot sands. Malaya granites of the Central and Eastern Belts contain up to 900 ppm Thorium (Azman A Ghani, 2009), which could explain the Thorium anomaly in the investigated sediments. Additional material might be derived from Tioman Island and perhaps also cuestas on the Pahang Platform, and the Tenggol Arch.

CONCLUSIONS

A review of Late Oligocene to Early Miocene reservoir sandstone intervals of the Tenggol Arch area has identified a number of high radioactivity levels within the K, J, and I sequences. The "hot sands" signatures represent more than a mere scientific curiosity. A correlation between spikes on the spectral gamma ray log and petrographic analysis of core and cutting samples suggests Thorium-bearing apatite and perhaps also monazite as the main source of radioactivity. The radioactive sands occur within meandering channel sequences formed by sediments derived from the Malay Peninsula, the Johor Platform and perhaps also some local cuesta sources nearby on the Tenggol Arch. Commonly, the hot sands are found in flaser-type thin-bedded sand and clay associations. Given the relatively thin radioactive intervals, measuring at most a few meters, these sandy intervals are below seismic resolution and could be used as a tool for correlating reservoir units at the reservoir unit /field scale. However, it is noted that channel correlation is extremely difficult and may result in event correlation and not in sand/reservoir correlation. Channels are linear features sometimes straight, sometimes meandering, depending on the terrain and slope, and hence the "hot sands" technique may not be suitable for regional scale correlation.

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