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Evaluation of shales of the Belaga Formation in Central Sarawak, Malaysia, using the Spectral Gamma Ray method

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Abstract: The Belaga Formation is a deep marine turbidite interpreted in relation to a submarine fan and therefore a prospect worth evaluating. The scope of this paper will focus on the shales from the thick sedimentary sequence of the Belaga Formation (Upper Cretaceous to Eocene) consisting of five (5) members in Central Sarawak, Malaysia, of which attention is given to the depositional environment and clay minerals as factors to consider as predictive tools for organic matter richness and gas storage capacity using the spectral gamma ray method using Thorium (Th), Potassium (K) and Uranium (U) as indices for inferences. A mineralogical chart of Th/K (ppm/%) indicates that the dominating clay minerals of the shales are mixed-layer types. The Th/U as a redox indicator is used to assert that the shales are of anoxic conditions of deep-marine environments. Despite the relatively high insoluble Th values (9.93-20.13) ppm, the presence of U in substantial amounts, which only occurs in reducing conditions where it is preserved as a lower insoluble valence (U^{4+}) explains for the low Th/U values ranging between (1.86-4.57) ppm/ppm of the fifty-eight analyzed shale samples. The overall Th/U value of the evaluated shales remain less than 7, where Th/U < 7 is suggestive of marine sediments, grey and green shales, whereas Th/U < 2 is indicative of marine black shales of reducing conditions. The 30Ma interval of sediment deposition of the Belaga Formation Eocene recorded varied climatic fluctuations influential to clay minerals contained in the shales and ascribe the paleoweathering state of the shales, which from the standard imitative ternary plot of normalized K-U-Th of shales from Northern America address the shales of the Belaga Formation as of deep weathering residuum.

Keywords: Belaga Formation, shales, spectral gamma ray, clay minerals

INTRODUCTION

Thick clastic sediments of the Belaga Formation occur between the Sibu and Tatau districts of Central Sarawak, composed basically of thick-bedded sandstone, thinly bedded heterolithic sandstone-mudstone interbeds and shale facies (Bakar *et al*., 2007). The Formation is interpreted as a major component of the Rajang Group sediments in Central Borneo which formed in one of the world's largest ancient submarine fans, characterized by turbidite and large debris flows (Galin *et al*., 2017) of deep marine sequence (Bakar *et al*., 2007).

The globally acknowledged hydrocarbon generative potential of submarine fans by way of their geometry, facies relationship and reservoir quality (Shanmugam & Moiola, 1988), coupled with the source rock potential of shales from deep-marine depositional environments as well as the syntectonic sedimentary character of turbidites, usually of great lateral continuity and thickness makes the shales of the Belaga Formation of keen interest to study especially in an era of dwindling conventional resources, as an important scope for evaluation of shale gas (unconventional resources). Buttressed with the historical knowledge of previous studies, most shale in Sarawak are prolific for hydrocarbon plays, typically those ranging between (Cretaceous - Miocene) age of which accounts for about 23% of Malaysia's total oil and 51% of natural gas reserves of which the Belaga Formation is less explored (Madon, 1999). Thus, the shales of the Belaga Formation are of focus in this study where the Spectral gamma ray method is basically used as mode of evaluation.

The advent of various instrumentation such as the Spectral Gamma Rays (SGR) detector has gained acceptance in the global energy industry as an important non-destructive, automated, rapid and inexpensive survey tool for petro-mineralogical and geophysical assessment using radio-isotropy as its mode of determination of clay content, evaluation of clay mineralogy, identification of fissure zones, organic matter quantification, reservoir characterization, source rock evaluation and depiction of sedimentary conditions and processes which proves their wide acceptance in the areas of sedimentology and stratigraphy (Ruffell *et al*., 2006; Schnyder *et al.*, 2006; Klaja & Dudek, 2016).

STUDY AREA

The research area spans about 200 km wide outstretch of Central Sarawak, which is termed the Sibu Zone as shown in Figure 1 (Haile, 1974; Galin *et al.*, 2017). The

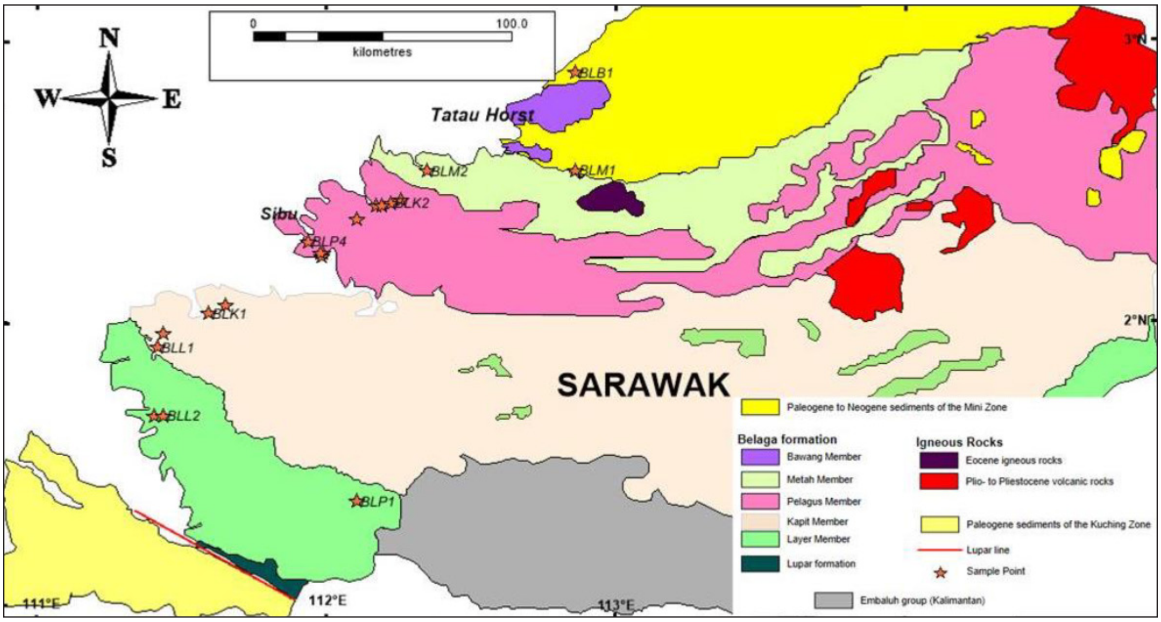

Figure 1: A Geological Map of the Belaga Formation showing its five members in Central Sarawak, Malaysia (Galin *et al.,* 2017).

Belaga Formation is divided into five members (Wolfenden, 1960) and sandwiched between the southern Lupar Valley and northern Bukit Mersing, extensively exposed by road cuttings from Sibu to Bintulu (Boyer *et al*., 2006). The members in younging order from south to north are (Figure 1): Upper Cretaceous (Cenomanian-Turonian) Layar Member, Paleocene to Lower Eocene Kapit Member, Early to Middle Eocene Pelagus Member, Middle to Late Eocene and the Bawang member of Eocene age (Hutchison, 2005).

METHODS

The Spectral gamma ray tool (Gamma Surveyor II) of GF Instruments with dimensions 24”x47”x118” (60x120x300 cm) was obliquely and securely set on the face of an outcrop for an interval of 3 minutes of which point counts of Potassium (K), Thorium (Th) and Uranium (U) were measured in addition to the total gamma rays. The counts of K were measured in %, Th and U in parts per million, and total radiation, DR (Dogit rate) was measured in nGy/h.

The records were taken at various shale outcrops using the methodology from previous studies (Slatt *et al*., 1992): a repetition of K, Th and U values to identify radiation as well as check for consistency. Therefore, the lowest and highest were discarded with the 3 results remaining averaged.

The predominant dark-grey to black shales of the Layar Member were encountered along the Jalan Sri Aman Sarikei road showing strong similarities with overlying Northeastern shales of the Kapit Member along the Jalan Kjd road. In the Sibu locality and along the Sibu - Selangau highway, dark grey to black shales of the Pelagus were seen with the Metah shales outcropping due north along the highway. The reddish to black shales of the Bawang Member outcrop in Tatau.

A total of fifty-eight (58) gamma ray points were taken about 30-50 meters apart. The instrumentation of the SGR is quick and automated which did not require invasion or destruction of the outcrops. The operational limitations and error margins are 5% for total counts, K and U, and 10% for Th (Slatt *et al.,* 1992).

RESULTS AND DISCUSSION

Averaged data of shales from Upper Cretaceous Layar Member, Paleocene to Lower Eocene Kapit Member, Early to Middle Eocene Pelagus Member, Middle to Late Eocene and the Bawang Member of Eocene age was recorded (Table 1).

Overall, the total count of gamma radiation follows a consistent pattern for all shales, where the highest radioactivity is Th counts with intermediate U and lower K counts relatively. The response indicates that the decay of isotopes of these shales are of common shales (Fertl, 1979). Comparatively, the shales from the Layar and Kapit members show close range of Th, U and K decay. Pelagus and Metah shales also show similar radioactive emission, with the Bawang shales generating generally higher radiation.

THORIUM AND POTASSIUM RATIO FOR CLAY TYPE

Th/K ratio was computed using Fertl (1979) clay type procedure as diagnostic for determination of the dominant clay minerals (Table 2). The averaged Th/K of all shales are predictive of mixed layer clays (Th/K > 3.5 but < 10).

Layar, Kapit and Bawang shales show high K values as compared to lower K of the Pelagus and Metah shales. The Pelagus and Metah shales thus tend to have higher Th/K values and skew towards the smectite region of mixed layer clays whilst the Layar, Kapit and Bawang shales skew into

Table 1: Average of Spectral Gamma Ray data from the shales of the Belaga Formation using Th/K as predictive of clay minerals.

Member	Kmin (%)	Kmax (%)	Umin (ppm)	Umax (ppm)	Thmin (ppm)	Thmax (ppm)	Th/K (ppm/%)	Th/U
Layar	2.19	2.84	3.5	8.02	13.36	20.13	5.80-8.47	2.0-5.75
Kapit	2.16	2.9	4.53	5.98	13.6	18.67	5.14-7.21	2.27-3.7
Pelagus	1.48	2.91	3.04	7.29	11.26	17.11	4.58-8.47	1.87-5.20
Metah	1.36	2.81	3.65	6.56	9.93	18.25	4.72-8.47	1.86-4.58
Bawang	1.9	3.95	3.06	8.37	11.79	24.23	5.17-7.79	2.63-4.64

Table 2: A table of clay minerals based on Th/K (ppm/%) (Fertl, 1979).

No.	Th/K (ppm/%)	Minerals
1	<0.5	Feldspars
2	0.6-1.5	Glauconite
3	1.5-2.0	Micas
4	2.0-3.5	Illite
5	>3.5	mixed-layer clays
6	10 and above	kaolinite & chlorite

the illitic region of the mixed layer clays. Predominance of clay minerals shown by the mineralogical plot (Figure 2) by Quirein *et al*. (1982) validate Fertl (1979) as mixed layer clays. However, the mineralogical plot shows minor smectite of the Pelagus and Kapit shales which Fertl (1979) estimates do not infer.

IMPORTANCE OF CLAY MINERALS TO GAS GENERATION

The Belaga shales are seen to be principally mixed-layer clays using Th/K as an index of assessment. Clay minerals are helpful in studying the hydrocarbon generation of the shales because a common coincidence exists between their temperatures for oil and gas generation. Convincing evidence and research have proven that, mixed-layer clays are not a continuous solid solution, but mixtures of dioctehedral phases with very little compositional variations (Aagaard & Helgeson, 1983). The spectral gamma ray technique is unable to differentiate the evolution of mixed-layer I/S clays, although estimate projections are made from the mineralogical plot of Th/K (ppm/%) (Figure 2), Layar, Kapit and Bawang shales may be considered as showing dominance illite in mixed-layer I/S clays whilst Pelagus and Metah shales are considered as dominant in smectite in mixed-layer I/S clays.

Mixed layer clays exist here as a geothermometer and indicator of thermal maturity based on the concept first applied in detailed studies of the Gulf Coast (Hoffman & Hower, 1979). The transformation of clay minerals during diagenesis is from montmorillonite to mixed –layer smectite/illite to illite (Jiang, 2012). During early diagenesis, maturity of the source rock is relatively low and smectite favors the percentage of illite–smectite mixed layer clays. With time and thermogenic conditions, clay minerals lose water and at this point become oil generative until smectite are converted to more illites percentages of the mixed layer in order to favor the expulsion of dry gas (Jiang, 2012). The progression of this activity produces a series of smaller hydrocarbon molecules of higher volatility and hydrogen content, thus favoring the culmination of methane gas. With evolving kerogen by thermal maturation, the chemical composition of the shale changes progressively with increasing carbonaceous content and reverse of hydrogen content (McCarthy *et al*., 2011).

The Pelagus and Metah shales may thus be considered less diagenetically and geothermometrically mature (less gas prone) as relative to the Layar, Kapit and Bawang shales of more progressive evolution (K rich). The illite favored mixed-layer clays are less expandable in contrast to the smectite favored mixed-layer clays. Smectite has a large sorption capacity relative to illite, but the presence of moisture in its expandable structure can greatly reduce gas-sorption capacity. A high maturity gas window usually exists in shales which have most of the smectite content converted to illite (Gasparik *et al*., 2013). The shales of the Layar, Kapit and Bawang members are considered more gas viable with respect to clay mineral type inference of Th/K.

DEPOSITIONAL ENVIRONMENT

Th/U is instrumental in evaluation of depositional environment as it functions as a redox indicator. U is geochemically mobile and more soluble than Th thus prone to mobilization during leaching and clay mineral diagenesis. Therefore, under reducing conditions U^{6+} takes on the lower valence as U^{4+} and becomes insoluble producing low Th/U. On the contrary, oxidizing conditions are indicated by high Th/U (Schnyder *et al*., 2006; Klaja & Dudek, 2016).

Basically as recorded (Table 1), Th/U < 7 for shales from all members is indicative of reducing conditions as discussed by (Klaja & Dudek, 2016) where Th/U < 7 is generally affiliated to marine depositional environments. Although further distribution of Th/U shows that, Th/U < 2 is of deep marine depositional environments, and typical of black shales. Th/U from radioactive decay in this paper

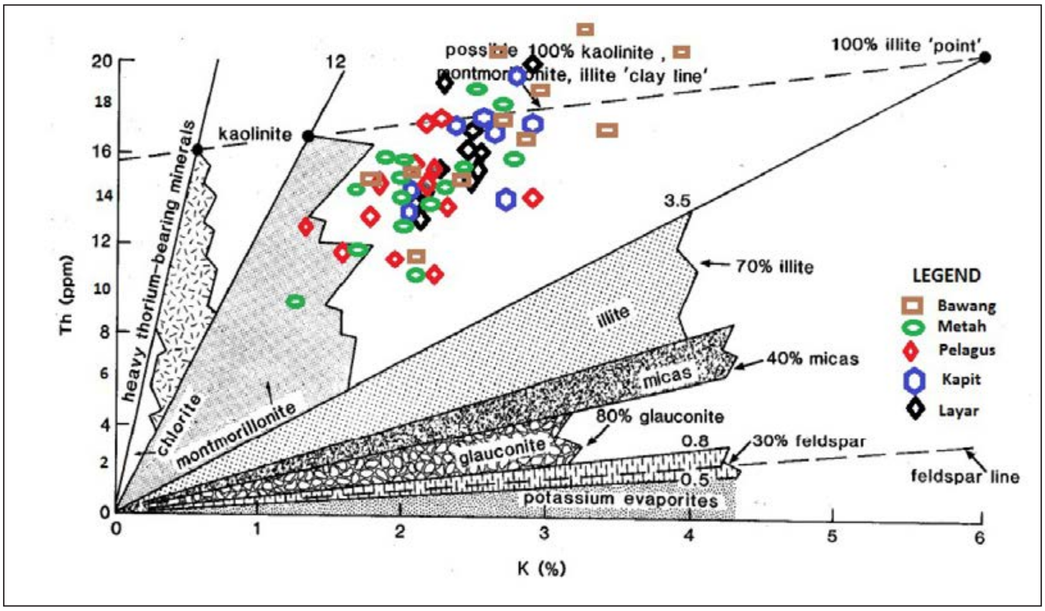

Figure 2: A mineralogical chart of Th/K ratio chart for dominant minerals (Quirein *et al.,* 1982).

shows an estimate of 78% of (Th/U: < 7 and > 2) which is proposed by Adams & Weaver (1958) as of transitional environment, grey and green shales of shallow marine (Klaja & Dudek, 2016) and 22% of (Th/U < 2) indicative of black shales. An overall assertion infers a marine depositional environment of the shales from the Belaga Formation.

SGR PALEOCLIMATE

Th/K can be used as a proxy for paleoclimate analysis (Ruffell & Worden, 2000; Ruffell *et al*., 2006). Most likely, the 30Ma interval of sediment deposition of the Belaga Formation recorded varied climatic conditions of which clay minerals of the shales are instrumental proxies as directly relational to Th/K.

Relatively low K values of Pelagus and Metah shales result in higher Th/K affiliated with smectite / smectite rich mixed-layer I/S clays. Therefore, the Pelagus and Metah shales thus may have been formed under warm conditions which favor the formation of smectite and smectite rich mixed-layer I/S clays. Cooler, wetter and more arid conditions may have prevailed during sedimentation of the Layar, Kapit and Bawang shales resulting in preferential rapid denudation and preservation of K, resulting in higher K values and lower Th/K, favoring illite. On the contrary volcanic sediments influx, K-adsorption and illitization of smectite may also be considered.

The paleoweathering (Figure 3) may be discussed as mechanical since mixed-layer I/S clays are regarded as primary marine sediments generated in temperate zones as opposed to kaolinite formation under tropical chemical weathering conditions (Schnyder *et al*., 2006), where kaolinite is absent in clay mineral evaluation of the shales from the Belaga Formation.

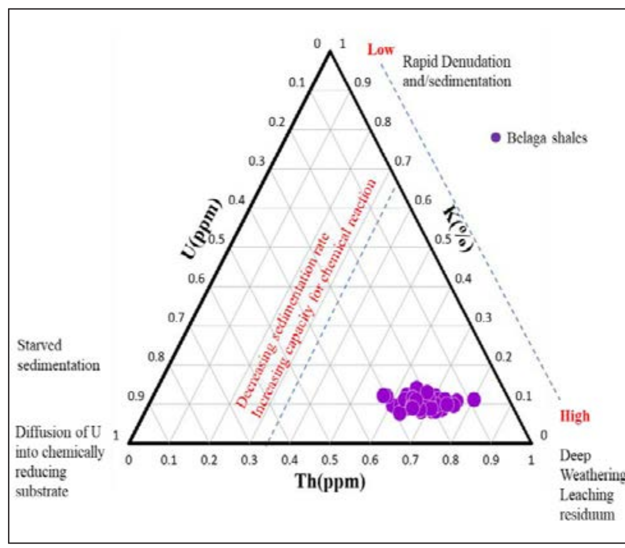

Figure 3: A normalized ternary plot of the SGR showing results of K, U, Th gamma ray emission of the shales from the Belaga Formation adopted from the evaluation of Oklahoma shales (Paxton *et al*., 2008).

CONCLUSIONS

The shales of the Belaga Formation are of marine depositional environments and typically range from grey to black shales and are interpreted as dominant in mixed-layer illite-smectite from Th/K evaluation. Perhaps, the more diagenetically mature Layar, Kapit and Bawang shales from clay mineralogy perspective are more conducive to gas generation relative to the shales of the Pelagus and Metah shales. However, this method needs conjunctive mineralogical laboratory analyses to undoubtedly consider diagenesis as well as decipher if clays are detrital or authigenic.

Organic matter is preserved under reducing conditions where U is concentrated. This relationship makes U a good indicator of organic matter. From previous studies, (U > 5) is usually considered as cut-off for black shale. Generally higher U values than K of the all shales in this study may require a follow-up TOC and Rock-Eval pyrolysis to support organic matter richness and maturity for gas generation.

Overall, shales may have undergone weathering in provenance that have resulted in leached micas and feldspars whilst Th remained insoluble, accounting for high emissions of Th and low K.

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