An overview of 20 years' hydrocarbon exploration studies and findings in the Late Cretaceous-to-Tertiary onshore Central Sarawak, NW Borneo: 1997–2017 in retrospect

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Abstract

An overview and integration of key petroleum exploration findings in the onshore Central Sarawak Basin, NW Borneo in the last 2 decades is presented. Findings revealed that critical moments for the generation and preservation of hydrocarbon may be found in the Early Oligocene, Early Miocene, and Late Miocene times. Geochemical data of ninety-five (95) source rocks suggest TOC values of 1.54 wt% (Miri Formation) to 70.00 wt% (Nyalau Formation) with promising S_2 and S_2/S_3 ratios. T_{Max} fell below the 435 °C maturation threshold. Reservoir facies of the Nyalau, Belait, and Lambir formations and their subsurface equivalents have moderate-to-poor poro-perm properties. Reservoir plays in the area are the Oligocene–Miocene clastics and limestones of Cycles I, II, III, and IV. Significant diagenetic modification is evident in analogue reservoir sandstones, and could constitute major poro-perm control in subsurface reservoir units. Observed predominance of structural related traps gleaned from seismic data is a reflection of the paleotectonic (Sarawak orogenic) event (*ca.* 40 – 36 Ma) associated with the region. Shale rocks overlying possible reservoirs and observed juxtaposition of reservoir units against impermeable beds provide seal integrity. Deeply seated faults are potential conduits, in addition to buoyancy. Concentration of future research efforts on petroleum/basin modeling and subsurface reservoir assessment was to further improve current understanding of the under-explored onshore Central Sarawak.

Keywords Onshore Sarawak Basin · Balingian Province · Tinjar Province · Petroleum system · Source rocks · Reservoir rocks · Hydrocarbon play · Malaysia

Introduction

The Sarawak Basin is an integral part of the NW Borneo Island that lies within the complex geological crustal mass of the SE Asia. Hitherto, the onshore segment of the Sarawak Basin, is relatively “unproductive” in terms of hydrocarbon except for the onshore Baram Delta Province with three discoveries and two producing fields. The relatively unproductive nature of the onshore provinces vis-à-vis the oil flowing offshore region had diverted major exploration attention

to the latter for over 50 years now. However, the intricate geological landscape of the Onshore Sarawak has become a natural laboratory for researchers over the years. The last 20 years have specifically witnessed substantial research attention in the central and northern Sarawak from geoscientists both within Malaysia and overseas. Different workers have looked at various aspects of its geology in relation to oil and gas generative potential, preservation of generated hydrocarbons, and production possibilities (see Tate 1991; Madon 1999a; Mat-Zin and Tucker 1999; Abdullah 1997a, b; Abdullah 2001; Ibrahim et al. 2005; Baker et al. 2007; Sia and Abdullah 2011; Wilson et al. 2013; Ben-awuah and Padmanabhan 2014; Mathew et al. 2014; Rahman 2014; Togunwa et al. 2015; Ali et al. 2016; Kessler and Jong 2016a, b; Jong et al. 2017a, b; Hakimi et al. 2013b among others).

The high cost required for exploration and production of hydrocarbons necessitates commensurate efforts to reduce risks and uncertainties. One way to achieve this is

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by integrating previously executed studies on the subject of petroleum geoscience to provide a holistic view of petroleum system elements. This is particularly needful in frontier areas, where knowledge of the subsurface geology and the hydrocarbon system elements is relatively limited. Geologically, the availability and correct interplay of hydrocarbon source rock, reservoir rock, seal, traps, and timing must create a geological chance that allows for the generation, migration, and entrapment of petroleum. This is because the geological chance of discovery is hinged on the probability of occurrences and effectiveness of these aforementioned elements. It, therefore, becomes imperative to assess these parameters in a sedimentary basin, to ascertain the possibility of hydrocarbon occurrence.

Chronicles of previously executed studies showed that most were independently carried out by individuals and university's research groups. It is not uncommon to have a proliferation of publications with possible overlap and/or duplication of research efforts in settings like this. In addition, since these studies were executed by various individuals, it is difficult for interested stakeholders and academia to integrate their findings for a better understanding that could possibly aid future exploration work. The current study is warranted to provide an integrated view of key-documented research findings in the study area, thereby providing a clearer view

of duodecadal exploration milestones covered. This article provides readers with a concise but holistic detail of known facts as it concerns hydrocarbon exploration in the onshore Central Sarawak Basin, East Malaysia based on research executed between the years 1997 and 2017. No study known to us has conducted a similar review on the subject matter within this time frame, and hence, its originality. The term “onshore Central Sarawak Basin” as used in this study connotes the non-producing onshore provinces; hence, the onshore Baram Delta is not inclusive in the study.

Geologic setting and stratigraphic framework

Cullen (2010) subgrouped the entire NW Borneo crustal mass into five geological provinces; the Interior Highlands, South China Sea Rift, NW Borneo Trough, Luconia, and the Baram–Balabac Basin (Fig. 1). The last two provinces occupy the coastal lowland and offshore areas. These duos mark the Pan-Borneo change from deep-marine to shallow-marine conditions following the Sarawak Orogeny (Cullen 2010). Evolution of the Cenozoic Sarawak Basin is believed to be connected with the Late Eocene collision of the Luconia Block with the West Borneo Basement, and the closure

Fig. 1 Overview of the geo-provinces of the NW Borneo displayed on bathymetric map and Shuttle Radar Topography Mission Digital Elevation Model. *BB* Brunei Bay, *D* Dulit Plateau, *FTB* fold and thrust belt, *K* Mt. Kinabalu Pluton, *M* Mulu, *T* Telupid ophiolite, *WBL* West Baram line, *TL* Tinjar line, *BAL* Balabac line, *U* Usun Apau volcanic plateau (adapted from Cullen 2010)

of the Rajang Sea (Dickinson 1974). Tectonic deformation and uplift of the Rajang Group accretionary prism to form the Rajang Fold-Thrust Belt provided sediment input into the Sarawak Basin (Hutchinson 2005; Kessler and Jong 2015). The basin is of Late Eocene-to-Holocene age and sits unconformably on the deformed Rajang Group (Figs. 2, 3). On the basis of tectonostratigraphic zonation, the entire Sarawak Basin is segmented into seven (7) geological provinces, namely the West Baram, Balingian, Central Luconia, Tinjar, Tatau, West and SW Luconia, and SW Sarawak provinces (Fig. 2). The Luconia Block constitutes the northern segment of the Sarawak Basin (Fig. 2). The collision of this block with Borneo along the Lupar Line occasioned the formation of two wrench fault systems: a dextral system associated with the West Balingian Line, and a sinistral system associated with strike-slip basement tectonics in East Balingian (Madon 1999b; Madon and Abolins 1999). However, main mechanisms in recent time demonstrated sinistral movement on the West Balingian Line (Simons et al. 2007).

The Central Luconia province is dominantly characterized by Oligocene-to-Early Miocene, shallow-marine clastic rocks with isolated carbonate buildups, while the Middle-to-Late Miocene witnessed the development of more carbonate

buildups (Madon 1999b; Hutchinson 2014). As at the year 1980, some 200 carbonate structures have been reportedly mapped on seismic by Sarawak Shell Berhad (Epting 1980). According to Ali and Abolins (1999), northeastern migration of clastic deposition environment into the neighbouring Sabah Basin accounted for the increased carbonate deposition in Mid-Miocene, and the continuous elevation of the Crocker-Rajang Accretionary Complex favoured influx of siliciclastic sediments at the close of the Miocene to Holocene. The only observable structures in the Central Luconia province are normal faults at the borders of the carbonate bodies, suggesting that the block has been relatively calm since its convergence with the NW Borneo in Eocene–Early Miocene (Ali and Abolins 1999).

The Neogene Baram Delta occupies the northeastern segment of the Sarawak geological province. A thick succession of sand-shale sequences alongside minimal carbonates rocks estimated to be 9–10 km thick and sourced mainly from the neighbourhood of the present day Baram river have been documented (Tan et al. 1999; Ibrahim and Light 2012). The West Baram Line (WBL) separates this basin from the contiguous, southwesterly, and relatively stable Luconia and Balingian provinces (Figs. 1, 2). The nature, extent, and

Fig. 2 Petroleum provinces of the Sarawak Basin and the contiguous NW Sabah Basin. *NWST* Northwest Sabah Trough, *OB* outboard belt, *IB* inboard belt, *TJP* Tinjar Province, *CTOS* Crocker-Trusmi overthrust sheet (modified after Tjia 2000)

Fig. 3 Simplified geological map of the Sarawak Basin (Modified after Mineral and Geoscience Department of Malaysia 2012)

significance of the WBL have generated a number of publications with diverse views (e.g., Swinburn 1994; Hutchison 2010; Cullen 2014, 2016; Kessler and Jong 2016a, b; Zheng et al. 2016). Arguably, the WBL is thought to be a regional transform system in the Luconia deep waters (Hutchison 2010; Kessler and Jong 2016a, b). Possible onshore extension of this “line” has been proposed to be the “Tinjar Line” (Zheng et al. 2016), although Cullen (2014) had earlier dismissed the notion of the Tinjar Line being the onshore extension of the WBL and also concluded that rather than a major strike-slip boundary between Luconia and the Dangerous Grounds, the WBL marks the border between areas of continental crust that underwent differential extension in the Eocene (Fig. 1). The dominance of carbonate sedimentation in the Luconia Block and the conspicuously different siliciclastic prevalence in the Baram Delta province buttressed the interpretation by Cullen (2014).

The southern Balingian Province is structurally more complex (Almond et al. 1990). The north–south-oriented Acis and Balingian subbasins segmented the Balingian province into two main areas; the older East Balingian and the younger West Balingian provinces (Madon 1999b; Madon and Abolins 1999). During the Late Oligocene-to-Early Miocene, an active WNW–ESE trending dextral wrench

system associated with the NNW–SSE striking west Balingian Line led to the formation of NW–SE trending folds and faults in the Balingian subbasin (Madon and Abolins 1999). The eastern Balingian province was reported to be tectonically stable all through Middle-to-Late Miocene until the Early Pliocene when an insignificant tectonic event occurred. According to Madon (1999b), an ENE–WSW sinistral wrench system occasioned by the strike-slip basement reactivation and was active in the Late Miocene-to-Pliocene forming NE–SW-oriented folds. Sediment deposition in the Balingian area was almost continuous from the Oligocene to Holocene, with siliciclastic sediments that grades from fluvial to marine in the Early Miocene (Madon and Abolins 1999). Unlike the Baram Delta and Balingian provinces, the Tinjar province lies onshore essentially (Fig. 2), flanking the petroliferous Balingian province. The stratigraphic successions in the province are generally older than the northern provinces (Figs. 3, 4). The province underwent two tectonic events in the Miocene epoch; the Early Miocene deformation, which is evident by WNW–SSE strike-slip offset and a later wrench along the NE–SW with a lateral pattern (Ismail et al. 1997).

The rocks in the onshore Sarawak were grouped by Heng (1992) into six (6) major litho-units; the tectonic mélange

Fig. 4 Overview of onshore Sarawak stratigraphy. Alphabets used in logs represent formation names, which are displayed adjacent to each formation. Note the upward younging from the Kerait Schist in

the Kuching zone (NNW) to the Liang Formation in the Miri zone (NNE) Modified after Mineral and Geoscience Department of Malaysia (2012)

rocks, volcanic and plutonic rocks, Carboniferous–Cretaceous rocks, Late Cretaceous–Eocene rocks, Eocene–Pliocene, and the Quaternary rocks. Liechti et al. (1960) had earlier subdivided the sedimentary successions in the onshore Sarawak Basin into seven (7) lithostratigraphic units and also grouped the basin's stratigraphy records into three zones: the Kuching, Sibui, and Miri zones. Fui (1978) identified eight sedimentary cycles in the Sarawak offshore and correlated the onshore stratigraphic formations to their equivalent offshore cycles. These Sarawak cycles have been regionally extended and correlated to the sedimentary stages in the contiguous Sabah Basin recently (Lunt and Madon 2017).

Based on the updated geological map of the Sarawak Basin (Mineral and Geoscience Department of Malaysia 2012), the Kuching zone hosts the oldest rocks of the basin: The Upper Paleozoic metasediments alongside some Cretaceous–Quaternary intrusive and extrusive rocks. These are sandwiched between younger Triassic and Holocene sedimentary materials. Litho-units in this zone range from Kerait Schist (Pre-Late Carboniferous) to the unconformity-bounded Kayan Sandstone of Maastrichtian? to Late Miocene age (Fig. 4). Five lithologic formations ranging from the Mid Cretaceous Lupar Formation to the Mid-Late Miocene continentally deposited Plateau Sandstones typified the

Silantek–Engkilili–Lupar Valley area (Sibu Zone). The Miri Zone comprises the central and northern Sarawak. Stratigraphy of this area has been reviewed in parts by numerous publications (e.g., Peng et al. 2004; Madon and Rahman 2007; Jia and Rahman 2009; Sia and Abdullah 2012a, b; Hakimi et al. 2013b; Madon et al. 2013; Ali et al. 2014; Nagarajan et al. 2014, 2015, 2017; Simon et al. 2014; Jong et al. 2015; Siddiqui et al. 2017 among others). Detailed stratigraphic order of the onshore Sarawak had been documented alongside other Malaysia basins in the “Stratigraphic Lexicon of Malaysia” (Peng et al. 2004). Readers are referred to pages 83–115 of this book for details on Onshore Sarawak stratigraphy. Known formations in the “Miri Zone” are summarized below, based on Fig. 4 and the quoted references.

The basal Belaga Formation is of Upper Cretaceous–Upper Eocene. It is lithologically characterized by thick shale unit with thin sandstone intercalations. Liechti et al. (1960) estimated its thickness to range from *ca.* 5000–8000 m. It is believed to be deposited in a deep-marine environment, owing to the presence of well-developed shale rock (Peng et al. 2004; Bakar et al. 2007). Sia and Abdullah (2012a) described the sandstone intercalations present within the Belaga Formation as deepwater turbidites, thereby justifying its marine environment of deposition (EOD). Five distinctive end members of the Belaga Formation; the Layar, Kapit, Pelagus, Metah, and Bawang members have been identified and mapped (Fig. 4).

The Eocene–Oligocene Tatau Formation is believed to be deposited after the Sarawak Orogeny and thus sits unconformably on the Belaga Formation. It is a thick succession of sandstone, siltstone, and shale with the presence of minor intercalated conglomerate and limestone. It is reported to be of 600–700 m thick and deposited in a submarine fan or slope environment. The Buan, Nyalau, and Setap formations overlaid the Tatau Formation. Buan Formation was reported to be 500–700 m thick, shallow marine and essentially shale sequence with minor silts and sandstones. Early Oligocene age was assigned to the formation by Liechti et al. (1960).

In central Sarawak, facies of the Tubau, Nyalau and Setap shale graded into the Balingian Tangap and Belait formations, respectively. The Balingian, and Late Oligocene to Early Miocene Nyalau Formations are believed to be deposited in coastal plain and/or shallow-marine environment. They range from 3500 to 4000 m and 5200 to 6000 m thick, respectively. Lithologically, the former is composed of sandstone and shale with abundant lignite, while the latter is an alternation sequence of sandstones and shale with occasional coal beds. Comparable lithologic characteristics suggest similar depositional environments and the equivalency of their ages as Oligocene–Early Miocene. The Sibuti, Lambir and Belait formations represent lateral equivalents to different sections of the Balingian Formation (Fig. 4). The Mid-Miocene coastal plain Begrih Formation

is unconformity-bounded. It sits on the Balingian and Belait formations, and it is composed of 600–700 m successions of clays and pebbly sandstone. Stratigraphic order of the northern Sarawak varies considerably from the Central Sarawak with new formational names (owing to facies differences?). The Late Cretaceous-to-Mid–Late Eocene Kelalan and Mulu formations sit at the stratigraphic base. The Melinau Limestone, West Crocker, Kelabit, and Meligan formations are also distinctive stratigraphic units’ peculiar to the northern Sarawak. The Late Miocene–Pliocene Liang Formation (Amir Hassan et al. 2013) capped the successions across the central and northern segment of the Miri Zone. It comprises *ca.* 520 m-thick alternation of shale, sandstone, conglomerate, and abundant lignite. These stratigraphic units make up the elements of the petroleum system in the basin’s onshore segment.

Methodology

Adopted methodology for this study was based on sourcing and reinterpretation of published data sets on the subject matter. Our understanding of field geology in the study area and interpretation of available 2D seismic line were also integrated with data gleaned from the previous studies. Articles published earlier than 1997 and those focused essentially on offshore hydrocarbon exploration were discarded even when such articles were published in the last 2 decades, except in situations where they have been used to establish generic facts on the geology of the basin. The chronicle of literature used for this study are summarized in Fig. 5. Selected articles were grouped based on their research foci (e.g., source rocks assessment, reservoirs quality etc.). Where possible, integration of research findings was done

Fig. 5 Summary of cited bibliography. CAP conference abstracts and proceedings (11.96%), CIB chapters in books (7.61). Approximately 70.65% of cited works were peer-reviewed journal articles, 7.61% were textbooks, and 2.17% are maps

to give a regional picture of the measured parameters. The advantage of the adopted approach is that it gives wider and better view of exploration work done on the basin, owing to the availability of larger data set. Although differences in laboratory conditions and possibly methodologies adopted by the cited researchers may not be the same, our understanding, that measured parameters have standard scientific measurements in addition to the fact that most of the references (> 70%) were published in highly rated peer-reviewed journals allayed our fears (Fig. 5).

Overview of industry-based exploration in onshore Sarawak

The onshore Sarawak has received fair share of exploration efforts, though relatively small when set in comparison with the basin's offshore reaches. Between the years 1975 and 2014, acquired 2D seismic lines were put at of 11,754 km, while 310 wells have been drilled as at 2013 (Fig. 6). Most

of these seismic data and drilled wells were in the onshore Baram Delta. The onshore sections of the SW (13 wells) and East (2 wells) Balingian subprovince had also been penetrated by a total of 15 wells (Fig. 6; Table 1). Only ten (10) and two (2) wells have been drilled in the Tinjar Province and Half Graben subprovince, respectively. Six of the wells drilled in Tinjar are concentrated in the segment flanking the East Balingian subprovince (Tinjar subprovince 4), while subprovince 5, which is contiguous to the onshore Baram Delta, had been penetrated by four exploration wells. Much of the acquired 2D seismic lines in the Tinjar also fall within the subprovince 4 and 5, although a few seismic lines have also been acquired in the subprovinces 1 and 3. Based on the available information, no well has penetrated the subprovinces 1, 2, and 3 of the Tinjar Provinces as at the year 2014. The least explored segments in the Onshore Sarawak are the SW Sarawak Basin and the Tinjar subprovinces 2; as no evidence of drilled wells nor seismic acquisition have yet been documented in these areas based on the available evidences. It is noteworthy to say that this research is starved

Fig. 6 Overview of seismic lines and well locations in Sarawak onshore. Observe the high density of drilled wells and acquired seismic sections in the Onshore Baram Delta

Table 1 Overview of hydrocarbon wells drilled in onshore Central Sarawak (modified from Madon and Abolins 1999; Mahmud et al. 2001)

Wells	Year Drilled	TD (m)	Targets	Availability of				Hydrocarbon Indications/ Remarks
				Reservoir	Trap	Seal	Conduit	
Balingian-1	1929	166	Cycle V/VI	V-VI				Slight indication in core 52-162m
Balingian-2	1929	249	Cycle V/VI	V-VI				Common gas pockets below 77m
Balingian-3	1956	1982	Pre-Cycle III; Cycle VI	I-II, VI				Fluorescence in cuttings @ several horizons. Stratigraphic test of Pre-Liang Fm. in east Balingian
Bawan-1	1991	1820	Cycle I/II	I-II				Fluorescence in swc @ 1598 – 1720m. Residual oil
Mukah-1	1938	2049	Cycle I/III	I-III				Oil traces 1432m and 1440m. Oil smell and stains between 224-2028m. Gas produced @ 448m, blow out at 1948m
Mukah-2	1938	1805	Cycle I/III	I-III				Oil show and free oil between 407-410m. Gas show between 406-421m. Oil and gas indications and smell @352-1396m. Gas blowout at 177m
Mukah-3	1938	1938	Cycle I/III	I-III				Oil indication @ 480-640m
Mukah-4	1938	850	Cycle I/III	I-III				Oil show at 633m
Penian-1	1939	617	Cycle I/II	I-II				Nil
Tatau-1	1928	159	Cycle I/II	I-II				Minor gas show @ 16.7m; gas blow out at 19m
Tatau-2	1956	1526	Cycle I/II	I-II				Faint fluorescence @1402m
Teres-1	1934	139	Cycle I/II	I-II				Minor oil and gas shows
Teres-2	1934	206	Cycle I/II	I-II				Minor oil and gas shows @ 178m
Teres-3	1937	627	Cycle I/III	I-III				Nil
Teres-4	1936	555	Cycle I/II	I-II				Slight gas traces
Teres-5	1938	2129	Cycle I/II	I-II				Free oil in sandstones @ 1076-1398.4 m; gas shows @ 1161-1176.5m
Teres-6	1991	2474	Cycle I/II	I-II				Traces of oil from a DST @ 1222-1232m/ 1267-1275m. Very good fluorescence in swc at 963-1420m and 1704-1754m
Bulak Setap-1	1914	438	Cycle I	I				Oil and gas shows
Bulak Setap-2	1915	586	Cycle I/II	I-II				Gas shows
Bulak Setap-3	1951	3543	Cycle I/II/III	I-III				Oil shows
Subis-1	1939	305	Cycle I/II	I-II				Nil? (Suspended due to war)
Subis-2	1953	3264	Cycle I/II	I-II				Gas shows
Suai-1	1952	1168	Cycle II	I-II?				Fluorescence
Suai-2	1953	1087	Cycle II	I-II?				Fluorescence
Suai-3	1953	392	Cycle II	I-II?				Tested 30 BOPD between 840'-890'
Suai-4	1955	680	Cycle II	I-II				Gas shows
Suai-5	1955	1659	Cycle I/II	I-II				Gas shows
Suai-6	1955	603	Cycle I/II, LST	I-II				Residual oil
Selungun-1	1956	2248	Cycle I/II, LST	I-II				Fluorescence

*TD is total depth. Approximately 90% of the wells targeted Pre-Cycle IV sequences with over 50% having relatively shallow depth (< 1000m). Indicators of hydrocarbon were observed in a good number of them.

Unsure Present Balingian Province Tinjar Province

of subsurface data, as virtually all available studies were outcrop focused. We observed huge paucity of published subsurface exploration research and had no access to the well logs of drilled wells (Table 3). Obtained 2D seismic sections from Petroliaam Nasional Berhad (PETRONAS), Malaysia were incorporated with due permission.

The onshore Sarawak petroleum systems

The hub of basin-scale hydrocarbon exploration and production is dependent on the identification of an active petroleum system. The hydrocarbon system involves the relationship between all the elements and processes required for petroleum accumulation to occur. An active source rock, reservoir rock, seal (cap) rock, and overburden rock form the basic hydrocarbon system elements (HSE), the essential processes refers to trap formation, generation, migration, and accumulation of oil and gas (Magoon and Dow 1994). To date, the hydrocarbon system of the onshore Sarawak Basin is poorly understood even in the onshore Baram Delta where two successful fields have been developed (Togunwa et al.

2015; Jong et al. 2017a, b). This is probably connected with the difficulty in identifying subtle source rock intervals in the province (Rijks 1981).

Basin-scale hydrocarbon exploration is focused on using available information to understand the possibility of hydrocarbon occurrence. One of the tools that can be of invaluable help in this regard is the petroleum system event chart (PS event chart). According to Magoon and Dow (1994), the PS event chart showcases relationships between important petroleum system's elements and processes. Data presented on this chart are usually gathered from stratigraphic, lithologic, and basic petroleum geology data. The term critical moment refers to the time with the best chance for the accumulation (in the trap) and preservation of possibly generated oil and gas in a defined petroleum system. It usually corresponds to the stratigraphic times in which all elements required to generate and preserve hydrocarbons (i.e., source rocks, reservoir rocks, trap formation, seal rocks, overburden, generation, maturation, accumulation, and preservation) are present in their correct order. Constructed PS event chart for the basin under review is suggestive of at least three "critical moments" (Fig. 7), that spread across the late Early

Fig. 7 Constructed petroleum systems event chart for the Sarawak onshore. Identification critical moments was based on chronological ordering of key petroleum system's elements that is suitable for hydrocarbon occurrence

Oligocene, Early Miocene, and Late Miocene. It does follow that the Tertiary sequences in the area under review could possibly yield positive results in terms of hydrocarbon discovery, depending on the certainty of the elements of the petroleum systems, as detailed below.

Source rock availability in onshore Sarawak

Mean organic geochemical data of 95 potential source rock samples obtained across seven known geologic formations by previous scholars (Hakimi and Abdullah 2013; Hakimi et al. 2013a, b; Togunwa et al. 2015) in the onshore Sarawak provinces are tabulated in Table 2, while Table 3a–c showcases set geochemical parameter thresholds for classifying source rocks (Bacon et al. 2000). Careful comparison of the data sets in the tables revealed mean organic richness that range from 1.54 wt% in Miri Formation to 70.00 wt% in the Nyalau Formation (Fig. 8), epitomizing good-to-excellent total organic carbon (TOC) contents based on the classification of Peters and Cassa (1994) and Bacon et al. (2000).

The high TOC recorded in the analysed source rocks obtained from the Tanjong (68.10 wt%), Nyalau (70 wt%), Balingian (40.34wt%), and Liang (34.83 wt%) is connected with the high concentration of organic matter known to be present in coals. This notwithstanding, coals have been variously reported as functional hydrocarbon source rocks in different basins of the world (Carter and Naish 1998; Petersen and Brekke 2001; Wilkins and George 2002; Petersen et al. 2004, 2008a, b; Abdullah and Abolins 2006; Petersen 2006; Petersen and Nytoft 2006; Cardott

et al. 2015; Carvajal-Ortiz and Gentzis 2015; Daher et al. 2015; Uguna et al. 2015; Wang et al. 2015; Xuanjun et al. 2015; Pan et al. 2016; Zou 2017), although an additional care should be put into consideration in assessing coals as a petroleum source rock (Sykes and Snowdon 2002). The onshore Sarawak coals have been reported to be rich in nitrogen, sulfur, and oxygen (NSO) compounds (Sia and Abdullah 2011, 2012a, b; Sia et al. 2014) and other potentially hazardous metallic materials that may not only influence the quality (API rating) of generated oil and gas but also pose possible dangers on the environment during production. Data from previously executed studies suggest good hydrocarbon generation potential of these coals (Abdullah 1999, 2001; Sia and Abdullah 2012b; Sia et al. 2014).

The S_1 and S_2 are complimentary parameters that enable the organic geochemist/petroleum geologist to understand the generative potential or possible quantity of hydrocarbon that a source rock can yield given the right temperature condition. Using the Peters and Cassa (1994) and Bacon et al. (2000) classifications as yardsticks, the tabulated mean S_1 and S_2 data for the Sarawak source rocks suggest the Miri ($S_1 = 0.14$, $S_2 = 1.33$), Lambir ($S_1 = 0.08$, $S_2 = 2.78$), and Tuka ($S_1 = 1.39$, $S_2 = 0.42$) formations to generally be of poor source quality. Conversely, the Tanjong (TJF), Nyalau (NYF), Balingian (BLG), and Liang (LNG) formations all have S_1 and S_2 values that complement their TOC data; as S_1 value ranges from 4.09 mg/g (LNG) to 11.10 mg/g (TJF). Similarly, recorded mean S_2 values for these formations are

Table 2 Organic geochemical parameters of possible source rocks in the Sarawak onshore

Formation	Geologic age	SF	TOC (wt%)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	S_2/S_3 (mg/g)	T_{MAX} (°C)	HI	OI	PI	PY	HC (PPM)	R_o (%)
Miri (MRF) ^a	Middle-Late Miocene	N=10	1.54	0.14	1.33	0.46	3.02	425.00	89.00	30.00	0.09	1.47	0.88	0.44
Lambir (LBF) ^a	Middle Miocene	N=10	3.25	0.08	2.78	0.96	3.09	416.00	82.00	27.00	0.05	2.86	0.86	0.42
Tukau (TKF) ^a	Late Miocene	N=10	1.68	0.09	1.39	0.42	3.33	424.00	84.00	26.00	0.07	1.50	0.85	0.43
Tanjong (TJF) ^b	Oligocene – Early Miocene	N=10	68.10	11.10	268.60	241.00	226.20	430.00	393.00	4.00	0.03	ND	ND	0.54
Nyalau (NYF) ^{c,b}	Early to middle Miocene	N=10	70.00	6.20	289.40	216.00	175.90	432.00	401.00	3.00	0.03	ND	ND	0.55
Balingian (BLG) ^d	Upper Miocene	N=25	40.34	9.01	73.54	10.66	7.11	407.76	182.60	26.97	82.55	0.11	6526.14	ND
Liang (LNG) ^d	Upper Pliocene	N=20	34.83	4.09	73.94	8.00	9.60	418.40	210.32	23.56	0.05	78.03	7335.5	ND

ND connotes data that were not available, SF sample frequency (i.e., the number of samples, which average is shown), TOC total organic carbon (wt%), S_1 volatile hydrocarbon content (mg HC/g rock), S_2 remaining hydrocarbon generative potential (mg HC/g rock), S_3 carbon dioxide yield (mg CO₂/g rock), HI Hydrogen Index = $S_2/100/TOC$ (mg HC/g TOC), OI Oxygen Index = $S_3/100/TOC$ (mg CO₂/g TOC), PI Production Index = $S_1/(S_1 + S_2)$, PY production yield = $S_1 + S_2$, T_{Max} temperature at maximum generation, R_o vitrinite reflectance. The MRF and TJF are from the onshore Baram Delta and the Sabah Basin respectively

Tabulated data are averages estimated from the works of:

^aTogunwa et al. (2015)

^bHakimi et al. (2013a)

^cHakimi and Abdullah (2013)

^dHakimi et al. (2013b)

≥ 73.54 mg/g. These data are suggestive of excellent hydrocarbon potential in these quadruple set.

Qualitative kerogen assessment deals with the type of kerogen present in an analysed source rock materials. Parameters such as hydrogen index (HI), oxygen index (OI), atomic H/C, and the ratio S_2/S_3 are diagnosis of kerogen types, which, in turn, reveals the hydrocarbon types that an analysed petroleum source materials can generate. Computed values of these parameters for seven formations in the basin are shown in Table 1. Powell and Boreham (1994) stressed that the hydrogen concentration (HC) of candidate source rocks is the most important parameter as it relates to the potential of such rocks to generate hydrocarbons. Although HC values for the Nyalau and Tanjong formation could not be found in any of the recently published articles on the study area, comparison of the onshore Sarawak HC data (Table 2) and the set thresholds in Table 3 showed that only the coals of the Balingian and Liang Formations meet up the thresholds for good and very good source potential.

According to Bacon et al. (2000), measurements from reflected-light petrography (microscopy) is a dependable tool that could be used to determine hydrogen content, and as well dependent on a classification of rock organic matter based on their maceral types. Macerals are thought of as recognizable disseminated organic fragments that make up kerogen. These essential kerogen building blocks are basically grouped into four; Alginite (Liptinite), Exinite, Vitrinite, and Inertinite. The predominant maceral group(s) on an analysed kerogen samples foretells possibility of hydrocarbon generation in a source materials and the hydrocarbon types generated by the same (Peters and Cassa 1994). This is because the hydrogen contents of the various maceral types vary, with alginite/liptinite having the highest potential and inertinite being the least. Maceral data composition for seventy potential hydrocarbon source rocks gleaned from the published works (Hakimi and Abdullah 2013; Hakimi et al. 2013a, b; Togunwa et al. 2015) and re-plotted on a ternary diagram (Fig. 9) revealed the dominance of vitrinite over liptinite and inertinite macerals. Vitrinite generally exceeded 70% composition of all the macerals present. Conversely, liptinite and inertinite compositions in these samples are less than 30% and 20%, respectively.

The diverse annotated plots of geochemical data commonly utilize by geoscientist to display source organic geochemical parameters were utilized to characterize the bulk kerogen and the types of kerogen present in the onshore Central Sarawak based on the amalgamated ninety-five (95), shales, shaly rocks, and coals samples (Hakimi and Abdullah 2013; Hakimi et al. 2013a, b; Togunwa et al. 2015). The plots of HI against OI as proposed by Tissot et al. (1974) to modify earlier published van Krevelen diagram (van Krevelen 1961), and S_2/TOC against T_{Max} plot (e.g., Abdullah 1999; Adegoke et al. 2014), produced slightly different

Table 3 Established geochemical thresholds for qualitative and quantitative assessments of petroleum source rocks

a: Geochemical thresholds for interpreting source rock potential (Bacon et al. 2000)

TOC (wt%)	S_2 (mg HC /g Rock)	EOM (wt%)	HC (PPM)	Potential
< 0.50	< 2.50	< 0.05	< 200.00	Poor
0.50–1.00	2.50–5.00	0.05–0.10	200.00–500.00	Fair
1.00–2.00	5.00–10.00	0.10–0.20	500.00–1200.00	Good
> 2.00	> 10.00	> 0.20	> 1200.00	Very good

b: Geochemical thresholds for predicting hydrocarbon types (Bacon et al. 2000)

HI (mg HC/g TOC)	Rock Eval. S_2/S_3	Extract yield (mg HC/g TOC)	Hydrocarbon types
< 50.00	< 1.00	< 20.00	Gas
200.00–300.00	5.00–10.00	20.00–50.00	Gas and oil
> 300.00	> 10.00	50.00–300.00	Oil

c: Thermal maturation thresholds for possible source rocks (Bacon et al. 2000)

Production Index	Rock Eval pyrolysis T_{Max}			Maturation level
	Type I	Type II	Type III	
0.15	445.00	435.00	< 440.00	Immature
0.15–0.40	445.00–455	435.00–460.00	440.00–470.00	Mature
> 0.40	> 455.00	> 460.00	> 470.00	Over mature

Fig. 8 Plot of S_2 against TOC (wt%) for the onshore Sarawak source rock ($n = 95$) representing *LBF* Lambir, *MRF* Miri, *TKF* Tunku, *TJF* Tanjong, *NYF* Nyalau, *BLG* Balingian, and *LNG* Liang formations. Note that the dominance of NYF and TJF samples plotted between Type II and Type II–III. Also note a few samples of the NYF, TJF, MRF and TKF in/around the oil window. Plotted data were sourced from Hakimi and Abdullah (2013), Hakimi et al. (2013a, b), and Togunwa et al. (2015)

Fig. 9 Ternary Plot showing the maceral types in candidate source rocks ($n=70$) of the onshore Sarawak. Sample points are colour coded based on geologic formation: *LBF* Lambir, *MRF* Miri, *TKF* Tuka, *TJF* Tanjong, *NYF* Nyalau, *BLG* Balingian and *LNG* Liang

output; as the former classified the source rocks of the area to be dominantly composed of Types II and III, with minor contribution from Type I (Fig. 10), while the latter revealed the dominance of Types II–III and III kerogen (Fig. 11). This disparity notwithstanding, the onshore Sarawak based on this data set can be interpreted to have the potential of generating hydrocarbon.

Although Type III kerogens are generally said to be of dominant gas potential, the fact that some renowned basins dominated by Types II–III and Type III kerogens have been known to yield giant liquid petroleum fields makes the onshore Central Sarawak be worthy of further exploratory investigations. This assertion is particularly true for the Cenozoic Niger Delta Basin of Nigeria, which is a world-class petroleum province with diverse giant oil fields discoveries. Several workers had reported dominance of Types II–III and III kerogens from the Agbada and Akata Shales, which are the two proven contributors of organic matter in the basin (Nwachukwu and Chukwura 1986; Bustin 1988; Haack et al. 2000; Eneogwe and Ekundayo 2003; Akinlua

et al. 2005). The geothermal gradient plays a pivotal role in ensuring that organic matter present in source rock are well cooked when in the oil window, the pyrolysis T_{Max} mimics this natural factor. Careful consideration of the plotted values in Fig. 10 and the tabulated averages in Table 1 reveals that only the source materials of the Miri, Nyalau, and Tanjong formations have partly entered into the oil window. Unavailability of subsurface geochemical data from cuttings or cores in all available publications consulted for this research did not permit us to have a vertical variation of these geochemical parameters. Nonetheless, the validity of the uniformitarianism principle strongly suggests that parameters from the surface outcrop do represent their subsurface counterparts reasonably.

Reservoir rock availability in onshore Sarawak

Although the evolving concept of producing petroleum from source rocks is gradually gaining ground and becoming relevant, the reservoir rocks still remain the focus of most

Fig. 10 Plot of hydrogen index against oxygen index for possible source rocks samples ($n=95$) representing *LBF* Lambir, *MRF* Miri, *TKF* Tunku, *TJF* Tanjong, *NYF* Nyalau, *BLG* Balingian and *LNG* Liang formations. Note the concentration of *TJF* and *NYF* points around Types I and II kerogen curves. The *MRF*, *TKF*, and *LBF* points sandwiched between Type III and IV. Plotted data were sourced from Hakimi and Abdullah (2013), Hakimi et al. (2013a, b); Togunwa et al. (2015)

exploration teams. Reservoirs are porous and permeable rocks with the capacity to absorb and retain hydrocarbons in its pore spaces, and as well release the same when penetrated by wells. The orderliness of possible reservoirs with source rock is essential to enhance the easy migration of generated hydrocarbon from source to the reservoirs; where it will be trapped. Based on our current understanding of the Sarawak stratigraphy, sandstones of varying thicknesses are sandwiched in between the Belaga Formation, Tatau Formation, Buan Formation, Balingian Formation, Begrih Formation, and the Liang Formation of the onshore environment. Recently, the sandstones of the Nyalau Formation (Siddiqui et al. 2016), Belait Formation, and Lambir Formation (Ali et al. 2016) were assessed with respect to their suitability as hydrocarbon reservoirs.

Sedimentologically, the Oligocene-to-Early Miocene Nyalau Formation is composed of alternating sandstone and shale lithologies, with a thickness that ranges from 5.2 to 6.0 km and it had been interpreted to be of coastal to a shallow-marine depositional environment (Liechti et al. 1960). Amir Hassan et al. (2013) reported the influence of different depositional energy, ranging from wave, tide, and

fluvial in the Nyalau coastal deposits. Four facies successions were identified by these authors, i.e., the wave-dominated shoreface facies successions, the fluvio-tidal channel facies successions, estuarine bay facies successions, and tide-dominated delta facies successions. In a similar disposition, five major sandstones facies of the Nyalau Formation were identified and characterized based on paleocurrent, poro-perm qualities, and bioturbation occurrence (Siddiqui et al. 2016). These units are (1) the hummocky cross stratified sandstone facies, with porosity (ϕ) of 0.32 v/v (32%) and permeability (K) of 20.78 md, (2) herringbone cross-bedded sandstone facies typified by average ϕ of 0.33 (33%) v/v and K of 17.7 md, (3) trough cross-bedded sandstone facies characterized to have ϕ of 0.36 v/v (36%) and K of 5.97 md, (4) wavy- to flaser-bedded sandstone facies, with ϕ estimated to be 0.20 v/v (20%) and K of 2.31 md, and (5) the bioturbated sandstone facies with ϕ assessed to be 0.08 v/v (8%) and K of 3.46 md.

The Belait Formation is essentially a neritic–deltaic deposit, marked with conspicuous imprints of wave-dominated features (Ali and Padmanabhan 2014). On the basis of paleoenvironment of deposition, sandstones of the Belait Formation had been classified into two broad groups, namely, the fluvial sandstone lithofacies and the shallow-marine sandstone lithofacies (Ali et al. 2016). Each of the aforementioned was also subgrouped into two strictly based on lithology and petrographic parameters. The fluvial sandstone lithofacies consist of the well-consolidated/quartz-cemented quartz arenite subfacies (mean $\phi = 5.4\%$) and the ferruginous siliciclastic conglomeratic clast subfacies (mean $\phi = 1.0\%$). The former is characterized with euhedral angular-to-subangular quartz materials with polygonal texture and well-outlined faces, whereas the latter lack the evidences of chemical dissolution justified by smooth undulating quartz surface, angular quartz face, distinctively sharp crystal edges, and minute size of the notches. The reported authigenic chlorite in the ferruginous siliciclastic conglomeratic clast facies could significantly affect its reservoir producibility when charged with hydrocarbon. The two subgroups of the shallow-marine sandstone lithofacies of the Belait Formation as identified by Ali et al. (2016) are the indurated ferruginous sandstone (mean $\phi = 4.8\%$) and indurated clayey sandstone (mean $\phi = 13.7\%$). Although the extent of the clay and iron contents in these sandstone units has not been detailed, it is plausible to infer that reported induration, clay content, ferruginisation, and authigenic chlorite are strongly suggestive of strong diagenetic influence, which may diversely affect pore throat by coating, filling, and possibly bridging the same, thereby capable on reducing or inhibiting fluid flow into and out of the pores. The occurrence of angular-to-subangular quartz in reservoir grains, however, suggests good reservoir materials. Though this review is starved

Fig. 11 Plot of hydrogen index against pyrolysis T_{Max} for samples ($n=95$) representing *LBF* Lambir, *MRF* Miri, *TKF* Tukai, *TJF* Tanjong, *NYF* Nyalau, *BLG* Balingian and *LNG* Liang formations. Note the dominance of NYF and TJF samples plotted between Type II and Types II–III. Also note few samples of the NYF, TJF, MRF, and TKF in/around the oil window. Plotted data were sourced from Hakimi and Abdullah (2013), Hakimi et al. (2013a, b), and Togunwa et al. (2015)

with the unavailability of subsurface data, the previous correlation of the offshore cycles to onshore lithological sequences in the Sarawak Basin by Fui (1978) correlates the Belait Formation to the subsurface Cycles IV and V, which is known to be producing in the offshore reaches.

The Lambir Formation correlates to offshore Cycles II, III and IV (Fui 1978). Unlike the Belait Formation, which is composed of continental and marine deposits, the Lambir Formation is essentially characterized as part of the shallow-marine siliciclastics of onshore Sarawak (Fig. 4). No quantitative petrophysical data were found for this formation from our literature search; nevertheless, substantial qualitative reservoir details can be gleaned from the work of Ali et al. (2016). Authors grouped the entire sandstones of the Lambir Formation into one facies association nomenclature as the shallow-marine sandstone lithofacies, which was in turn subdivided into a quadruple set of lithofacies. These sub facies units are (1) the friable ferruginous sandstones (mean $\phi = 9.9\%$), (2) indurated laminated ferruginous sandstone (mean $\phi = 17.1\%$), (3) pyritic sandstones (mean $\phi = 27.9\%$), and (4) indurated calcareous sandstones (mean $\phi = 1.3\%$). Data from scanning electron petrography suggested pore clay coating and bridging in the friable ferruginous sandstones and the indurated laminated ferruginous sandstone. Strong evidence of iron oxide

materials coating reservoir pores was documented and this could significantly affect poro-perm quality. In addition to pore coating, bridging of quartz grain was also documented in the pyritic sandstones facies (Ali et al. 2016).

With regards to the fluid-flow parameters (ϕ and K) in the three formations, the reservoir facies of the Nyalau Formation appear to be of better quality than those of the Belait and Lambir formations. Differences in the laboratory analytical methods adopted for the determination of porosity and permeability in the threesome, however, hinders empathic conclusion in this regard. Estimated 20%, 75%, and 50% of the reservoir facies in the Nyalau, Belait, and Lambir formations yielded low poro-perm values ($\phi < 10\%$; $K < 0.1\text{md}$) that justify their classifications as tight reservoir (Zou et al. 2012; Gao and Li 2016). Tight reservoirs are characterized by intricate pore structure and strong heterogeneity owing to the far-reaching influence of diagenetic alterations since their deposition (Lai et al. 2016; Wang et al. 2015; Ma et al. 2018). Complete reliance of all available poro-perm data on outcrop samples strongly suggests that relatively high porosity and permeability values observed in the Nyalau Formation may have been influenced by weathering. This is further substantiated by the presence of hematitic cementation (Fig. 12c). Hence, notable variation in subsurface porosity and

Fig. 12 Thin-section and SEM images showing diagenetic signatures in representative reservoir sandstones of the central onshore Sarawak: **a** long grain contact indicated by red arrows, **b** broken quartz grains shown by red arrow and quartz overgrowth indicated by white arrows, **c** brown-to-dark reddish hematitic cement in fine grained reservoir, **d**

broken quartz grains (red arrows) in angular and poorly sorted sandstone framework, **e** authigenic quartz grains (red arrows) and quartz cementation (white arrows), and **f** dissolved feldspar shown by white arrows (Adepehin et al. 2019)

permeability is anticipated, owing to the effects of compaction created by overburden loads. Compaction significantly decreases the initial porosity (Paxton et al. 2002). It typically involves two stages; the mechanical compaction and chemical compaction/ pressure dissolution. The former involves grain rearrangement, breakdown of micaeous minerals and soft fragments, as well as evolution

of pseudomatrix (Freiburg et al. 2016). The petrographic images in Fig. 12 showcase the evidences of mechanical compaction such as occurrences of long grain contacts (Fig. 12a, f), grain fracturing (Fig. 12b, d), development of authigenic minerals (Fig. 12e), quartz overgrowth (Fig. 12b, e), and quartz cementation (Fig. 12e) in the reservoirs sandstone of the onshore central Sarawak.

Though with limited coverage, these diagenetic evidences (Fig. 12) are dominantly potential contributors to porosity and permeability loss. Broken grains and feldspar dissolution (Fig. 12f) may, however, be potential poro-perm enhancers.

Trapping styles, seals, and migration pathways

The intercalated nature of the lithologies in the Onshore Sarawak naturally favours the possibility of oil generation and preservation, as most of the probable reservoir materials are sandwiched in between lithologies of finer grains that are capable of impeding upward hydrocarbon flow. The complexity of deeply seated structural features, such as the West Balingian Line, West Baram Line, Anau-Nyalau fault, Tatau Mersing Line, and half graben (Swinburn 1994; Tjia 2000; Mathew et al. 2014) in the area under review is suggestive of possible structural traps. van der Zee and Urai (2005) identified normal faults, collapsed crest structure within the Miri Formation. Trapping styles in the West Balingian Subprovince are dominantly anticlinal-fault structures (Fig. 13). These are associated with the multiphase wrench deformation convergence and divergence, while reservoirs of target within these structures are fluvial deposited stacked clastics of Cycles I, II, and III. As reported by Ibrahim et al. (2005) large anticlinal trap and wrench-related faults were identified from 2D—seismic data acquired in the onshore Tinjar province (Fig. 14). Identified structural closures were believed to be connected with the NW–SE-oriented dextral faults and NNE–SSW-oriented sinistral faults (Fig. 14). Over 40 of these NW–SE-oriented structures have been reportedly mapped in subprovinces 3 and 4 of the Tinjar Province, while subprovinces 1 and 2 are considered less productive owing to structural complexity and erosion of reservoirs (Fig. 14).

In the onshore Baram Delta, where two fields have so been developed targeted traps are the growth faults and anticlinal traps within Cycles III, IV, and V sandstones (Tan and Lamy 1990; Jong et al. 2017a, b). These cycles are equivalent to the Miri and Lambir formations (Fui 1978). The juxtaposition of reservoir rocks against impermeable rocks often orchestrated by the development of faults favours lateral sealing of the traps, while overlying impermeable rocks such as the shale units in the Buan, Setup, Nyalau, and Liang hold the potential to serve as roof or cap rocks. The effect of buoyancy and the density of overlying beds aid primary migration of hydrocarbon from source to traps. Deeply seated faults are possible conduits for the migration of hydrocarbons from source to traps.

Overview of possible plays in onshore Sarawak

Establishing hydrocarbon plays in a basin involves ascertaining the presence and functionality of play requirements. These include an active charge system (source rocks and migration pathways), porous and permeable reservoir rocks, and regional top seal and trapping system. These faults are also possible conduits for the passage of generated hydrocarbons into the traps. Potential plays in the onshore West Baram Delta are believed to essentially be the Lower-to-Upper Miocene Cycles III and V top set sands and low fan deposits in possibly combination (structural and stratigraphic) traps or stratigraphic traps alone (Tan and Lamy 1990; Jong et al. 2017a, b). Principal hydrocarbon plays in the Tinjar Province include the Oligo–Miocene (Cycles I/II) clastic plays, Oligo–Miocene limestone plays in the northern hemisphere and the easterly oriented Lambir Formation (Ismail and Abu Hassan 1999). The Oligocene–Lower Miocene Cycles I/II clastic (the Nyalau Formation) of the essentially onshore Tinjar province are believed to be important hydrocarbon reservoir plays in the province, while the Cycles III/IV clastics of Lambir are secondary reservoir plays. The intercalated shales within these clastic materials hold potential for dual roles, first as source rocks to charge overlying reservoir sands, and also as reservoir seal. Apart from the onshore Baram Delta, the Balingian onshore is the most explored province in the onshore Sarawak Basin. At least 18 boreholes (dominantly concentrated in the SW Balingian subprovince) have penetrated its subprovinces to test possible hydrocarbon plays (Table 1). Although several discoveries in form of shows were made, the interplay of economics and estimated STOIP seem to have hampered their development, as Madon and Abolins (1999) had reliably reported that none of the discoveries was developed.

As discussed in “Geologic setting and stratigraphic framework”, several carbonate buildups have been mapped as gas play in the offshore Central Luconia Province. Limestone outcrops in the Onshore Sarawak (see Fig. 15 for their distribution) includes the Bekuyat (Bintulu area) and Subis (Batu Niah area) limestones; both of which are time equivalents of Cycles 1, 2, and 3. The Rupelian-to-Lattorian Sayang Limestone (Bintulu area) seats on the Tatau Formation and correlates to upper Pre-1 and lower Cycle 1 in the subsurface. The Batu Gading and Melinau limestones are of Priabonian-to-Aquitania age. They are essentially upper Pre-1 to Cycle 1 equivalents. Jong et al. (2015) had reasoned based on gravity and magnetic data sets from south of Miri the possible occurrences of undrilled carbonate anomalies in the Tinjar Block. Although no record of drilled carbonate play is known to authors in the Balingian Province, a number of onshore wells in northeastern Tinjar Province, e.g., Suai-4, Suai-5,

Fig. 13 Structural trapping styles identified in the Balingian Province (Madon and Abolins 1999; OXY 1989; Shell 1994)

Fig. 14 Overview of trapping models in Tinjar Province Modified after Ismail and Abu Hassan (1999)

Fig. 15 Distribution of on onshore carbonate rocks in NW Sarawak. The WBL partitions the stable Tinjar/Luconia Block from the subsiding Baram Delta to the north. Note the occurrence of limestone in the

Suai area, where wells Suai 1, 2, 3, 4, 5, and 6 wells (Table 3) were drilled Adapted from Kessler and Jong (2017)

Suai-6, Selungun-1, and Subis-1 (Table 1), have penetrated some Oligocene–Miocene limestone bodies (Ismail and Abu Hassan 1999; Mahmud et al. 2001; Dedeche et al. 2013; Kessler and Jong 2017).

Play risks and future exploration considerations

A careful appraisal of hydrocarbon exploration focused studies published on onshore Central Sarawak revealed a number of exploration enigma that needs to be resolved. Although

exploration risks and uncertainties have become frequent terms among petroleum explorers and investors, some risk requires a lot of research efforts to bring them down to the barest minimum. There is need for further studies that will utilize fingerprinting technology and possibly kerogen correlation to define the petroleum system(s) of the onshore Sarawak provinces, thereby providing better insights on play identification. Since high content of total organic matter and the right kerogen types alone are insufficient for the generation of petroleum, and hence, conducting an extensive and regional petroleum systems and basin modeling studies in the area under review will enhance future exploration work, by resolving the ambiguity of whether the kerogens in this area have entered the oil window or not. Hitherto, virtually all available studies consulted for this manuscript were conducted on basin scale and utilized surface data sets, there is a strong need for higher resolution studies targeted at identifying and defining the hydrocarbon plays in the provinces and subprovinces of onshore Sarawak. This can be greatly enhanced if 3D seismic data and other useful subsurface data are integrated with known outcrop deductions. Reservoir thickness, lateral extent of reservoirs, as well as pore-scale reservoir quality require improved insights. Characterization of fluid-flow parameters and possible reservoir heterogeneities are also recommended in the Central Sarawak. Indications of hydrocarbons in the onshore Balingian and Tinjar wells (Table 1), strongly upholds the presence of petroleum systems in the subbasins, as such the duo should be revisited for thorough investigations using the recent innovations and technology in the field of geosciences, as most of these wells were drilled over 50 years ago.

Conclusions

The following statements can be concluded based on the findings of this study.

1. The onshore Central Sarawak has witnessed more of petroleum “source rocks evaluation” studies in the period under review than all the other elements of the petroleum systems. The amount of organic matter and the quality of the kerogen types in the Tunku, Tanjong, Nyalau, Balingian, and Liang formations of the study area are suitable for the generation of hydrocarbons based on obtained geochemical parameters (TOC, S_2 , and S_2/S_3 ratio). The maturity level of the organic matter is, however, still too low as shown by the T_{Max} values.
2. Analogous reservoir facies within the Nyalau, Belait, and Lambir formations, as well as their subsurface equivalents, have moderate-to-poor poro-perm qualities (tight reservoirs). Reservoir facies of the Nyalau

Formation have higher fluid-flow propensity than the Lambir and Belait formations. The reservoir sandstone has experienced low-to-moderate diagenetic influence ranging from weathering, compaction, feldspar dissolution, and evolution of authigenic mineral. Thus, subsurface reservoir would have been significantly modified

3. The dominance of fault-assisted traps, and minor folding on seismic section suggest more of structural traps ahead of their stratigraphic counterparts.
4. Main petroleum systems/petroleum play risks in the area which are the maturity of the organic matter in the source rocks and the quality (thickness) of available reservoirs. Further studies on petroleum systems and basin modeling of possible source rocks sequences, as well as high-resolution seismic stratigraphy and structural mapping for better insights into subsurface trapping styles and reservoir behaviours, are strongly recommended.

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Compliance with ethical standards

Conflict of interest The authors declared that they have no conflict of interest.

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