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Relationship Between Tectonic Evolutions and Presence of Heavy Oil in The Central Sumatra Basin

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ABSTRACT - Heavy oil is formed through biodegradation process of hydrocarbons, as well as water washing, in which light hydrocarbon fraction disappears and leaves the heavy fraction. Heavy oil is essentially an asphaltic, dense (low API gravity), and viscous that is chemically characterized by its high content of asphaltenes in the oil. Although variously defined, 25^o API is set the upper limit for heavy oil. Heavy oil in the Central Sumatra Basin is evidently formed as a result of biodegradation and water washing (a hydrodynamic process within oil reservoir) mechanisms. These processes occur as result of tectonic uplift of the reservoir after it has been filled with hydrocarbons. Heavy oil reservoir depths in the Central Sumatra Basin are generally shallower than 1,000 feet (300-400 meters), at which surface water may may be associated with the reservoir hence enabling the heavy oil transformation. A combined geology, remote sensing/geographic information system (GIS), geophysics, stratigraphy, and well-based analyses is utilized to serve the study. It has been observed that within the northern part of the basin, heavy oil is mainly found in fields located within uphill fault blocks such as the up-thrown part of the Sebanga thrust fault with its Duri, Sebanga North, Kulin, Rantau Bais, Batang, Akar, and Genting fields. In the western part of the basin there are the Kumis, Kotalama and Pendalian heavy oil fields associated with Dalu-Dalu thrust fault and Gadang Island uplift. In total 51 fields/structures containing or suspected to contain heavy oil are associated with uplifted geological positions, hence showing the strong relations between tectonic evolutions and present day presence of heavy oil within the basin.

Keywords: Heavy oil, tectonic evolution, Central Sumatera Basin.

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INTRODUCTION

The Central Sumatra Basin is a poly history sedimentary basin that has been proven by its history to produce massive quantity of hydrocarbons. This Tertiary basin is covered by pre-tertiary Metamorphic Rocks which began to form and filled with sediment since the Paleogene (Eocene) Period. In the Paleogene period this basin can be classified as a rift basin and in the Neogene period it turned into a back arc basin. Packham (1996) divides tectonic movements in the Southeast Asia region into three phases: (1) Eocene to Oligocene, (2) Oligocene to Middle Miocene and, (3) Middle Miocene to present. The structures associated with the extensional tectonic regime dominate the structures formed in the Paleogene period. Meanwhile, the structures associated with the strike slip tectonic regime and the compressional tectonic regime dominate the structure of the Neogene period.

The Central Sumatra Basin is also a hydrocarbon producing basin with its two giant fields of Minas and Duri fields, both were discovered in early 1940s and are still producing today (Barber, *et al.*, 2005). In addition to the two massive fields, there are dozens of other oil fields in the Central Sumatra basin. In this paper, description and regional geological analysis over the Central Sumatra Basin is intended to evaluate presence of heavy oil in the basin. Several productive oil fields in the Central Sumatra Basin such as Duri, Kulin, and Batang have been proven to produce heavy oil (often defined as oil having density lower than 25^{o} API), whereas several lower profile oil fields are also known to have heavy oil potential. This evidence has indicated that processes of heavy oil generation through biodegradation and water washing occured in the basin. As pointed out by Santos, *et al.* (2014) biodegradation is a process that separate heavy and lighter fraction of oil through microorganism activities, whereas in water washing a similar occurence takes place through forceful 'oil washing' by encroaching surface water into the oil trap.

The transformation of light or medium oil into becoming heavy oil is nevertheless achieved if the geological setting permits. Evidently, this geological setting includes uplift of oil-bearing traps hence enabling the heavy oil generation to take place. Some of the oil traps uplifts are caused by major thrust faults activities within the basin, which occurence are tightly related to the tectonic evolutions in the region. The study which results are presented in this paper is to show that there is a coherent relationship between the tectonic mechanism that causes the formation of thrust faults in Central Sumatra and the processes required to form heavy oil.

METHODOLOGY

In studying relationship between tectonic evolution and the presence of heavy oil in the Central Sumatra Basin, an integrated approach has been established and implemented. The integrated approach is essentially a combination of multy-disciplinary approaches of regional geology, remote sensing and geographic information system (GIS), and geophysics (Figure 1). This integrated approach is to ensure use of multi-angle analysis in viewing and confirming geological phenomenons within the sedimentary basin in order to achieve the objective of the study.

In the methodology, regional geological studies is made to determine general geological order and setting that prevails in the Central Sumatra basin through the use of data obtained from past studies covering analyses of tectonics, sedimentation history, and generation of structures that can be observed today. Through this combined study information such as general depositional environment and the distribution of rock facies are produced. Using this information preliminary view over the petroleum system within the basin is understood, from which information such as destination of oil migration toward traps in which heavy oil generation occurs are known.

In understanding subsurface morphology such as Basement highs and lows, combined lineament interpretation between subsurface morphology and surface morphology is made. Subsurface lineament interpretation is made using geophysics data (seismic and gravity) whereas the surface lineament interpretation on surface objects - such as vegetation and lithology - is carried on satellite images (remote sensing) supported by geographic information system (GIS) data. Interpreted lineaments of the two analyses are to be compared for their agreement, using which confirmation over the subsurface features (i.e substructure map) is made. As confirmation of the subsurface features of the basin has been reached, the results are to be used as a reference in finding the most suitable geological features (i.e uplifted oil-bearing traps) that may serve as location of heavy oil acumulations. These locations are then receive confirmation through the use of all available proof of heavy oil presence from oil fields and discovery wells. Upon this confirmation, understanding between tectonic setting and heavy oil presence in the Central Sumatra basin is obtained.

RESULTS AND DISCUSSION

General Geology, Tectonic Evolution, and Stratigraphy

The Central Sumatra Basin extends for about 103,500 km sq., mostly consisting of an area of land (Figure 2). Geographically, this basin is located between 90^{o} - 103^{o} East and 1^{o} South - 4^{o} North. In the northern part, the Central Sumatra Basin is separated from the North Sumatra Basin by Asahan High, while in the southern part it is separated from the South Sumatra Basin by the Tigapuluh Mountains.

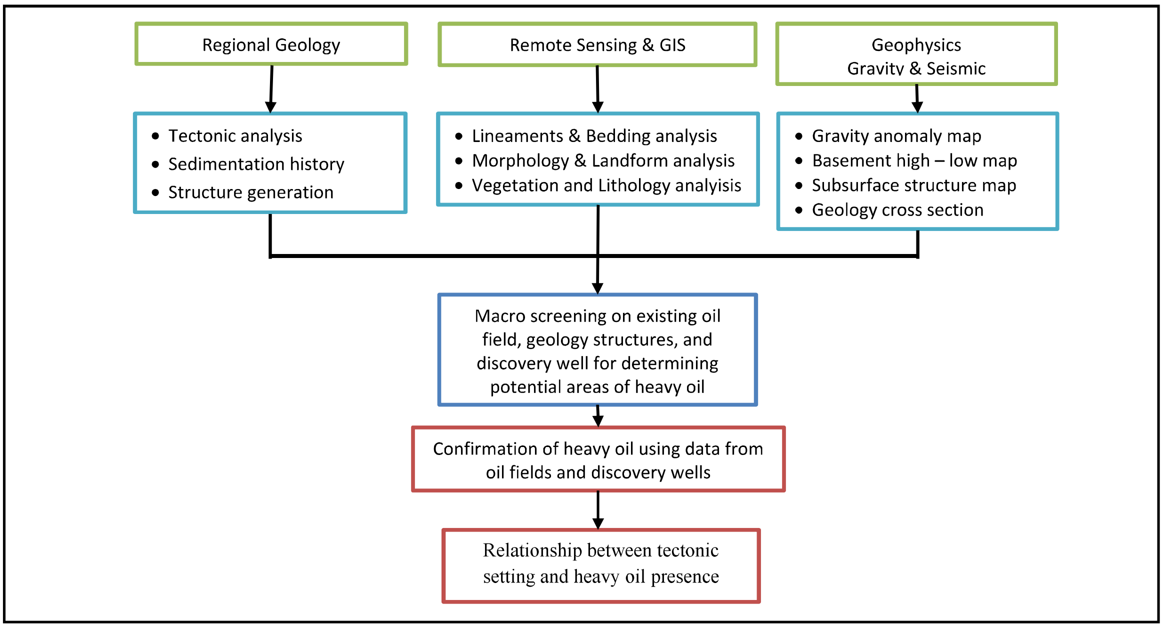

Figure 1
Work flow of study for understanding relation between tectonic setting and heavy oil presence.

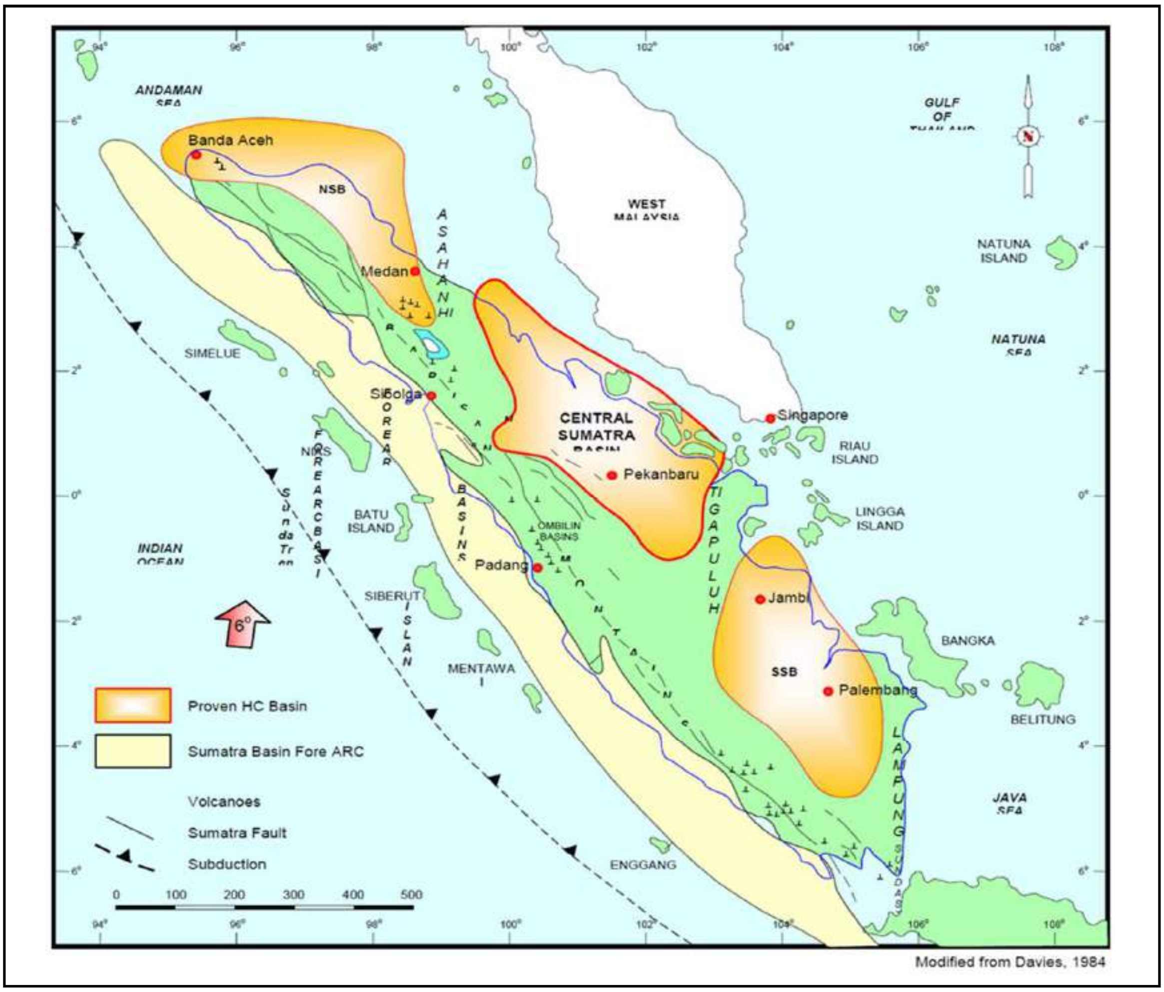

Figure 2
Central Sumatera Basin location map (modified from Yarmanto, 2010).

The Central Sumatra Basin is on the edge of the Sunda Microcontinent which is part of the Eurasian Plate and is one of a series of Tertiary basins. The Central Sumatra Basin is relatively long in the north-west - southeast (N- S) direction (Hamilton, 1979; Pulunggono & Cameron, 1984, Yarmanto, *et al.,* 2010).

The Central Sumatra Basin is dominated by two structural patterns with trends in north-south (N-S) and northwest-southeast directions (Heidrick & Aulia, 1993). The N - S trends structure is relatively older and is formed in the Paleogene (Mertosono & Nayoan, 1974; De Coster, 1974 in Heidrick & Aulia, 1993). According to Eubank & Makki (1981) the two structural patterns are active during the Tertiary. Heidrick & Aulia (1993), which was then followed by Heidrick & Turlington (1994), had divided the tectonic phase of the Central Sumatra Basin into four main tectonic stages (Multiple tectonic episodes) which were named the deformation phases of F0, F1, F2, and F3 (Figure 3).

Deformation Phase F-0 (Pre-Tertiary)

This phase took place between the Late Paleozoic - Mesozoic (Pre-Tertiary). The tectonostratigraphy

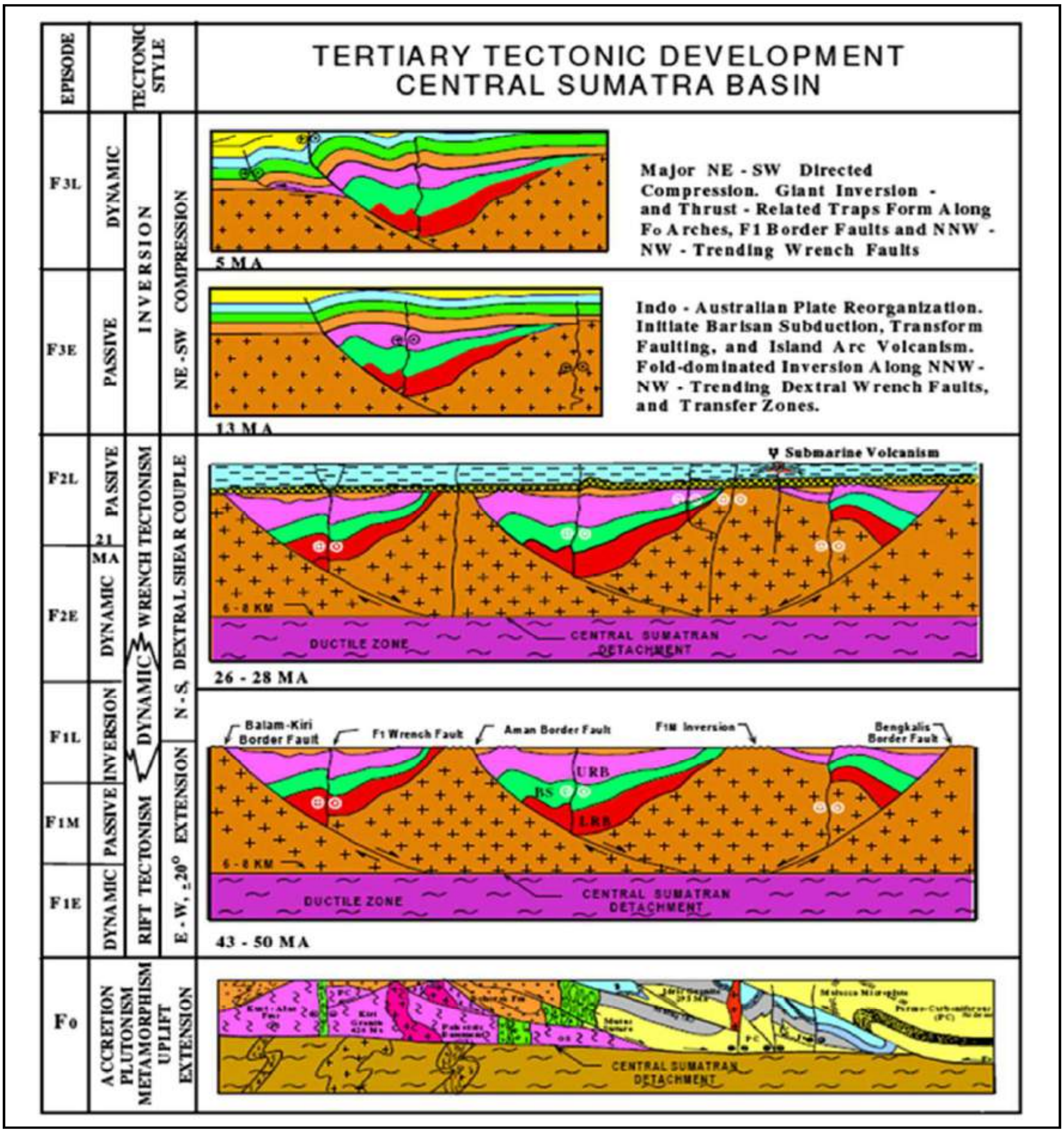

Figure 3
Tertiary tectonic evolution of Central Sumatera Basin.
(source: Heidrick & Turlington, 1994., *Vide Pertamina BPKKA, 1996).*

of this phase includes the basement of the Central Sumatra Basin, which Eubank & Makki (1981) divided into four rock units, namely the Mutus terrane group, Mergui terrane, Malacca terrane, and Kluet terrane. In this phase the sub-basins in the form of the rift graben have not yet been formed, so this phase is also known as the pre-rift phase.

Deformation Phase F-1 (45 - 28 Ma)

This phase takes place between Eocene - Oligocene, and is also called the rifting phase or rifting infill. In some publications it is also known as the intra-cratonic rifting phase. The tectonic rifting activity that occurs in the basement is characterized by the formation of N - S trending grabens and half grabens which are then filled with sediment deposits from the Pematang group. Subduction activity is oblique between the India - Australia plate with a gentle slope under the Sundaland causing the activation of the Sumatra dextral fault movement with a relatively northwest-southeast orientation. During this tectonic period, normal faults were formed in a NNE - SSW

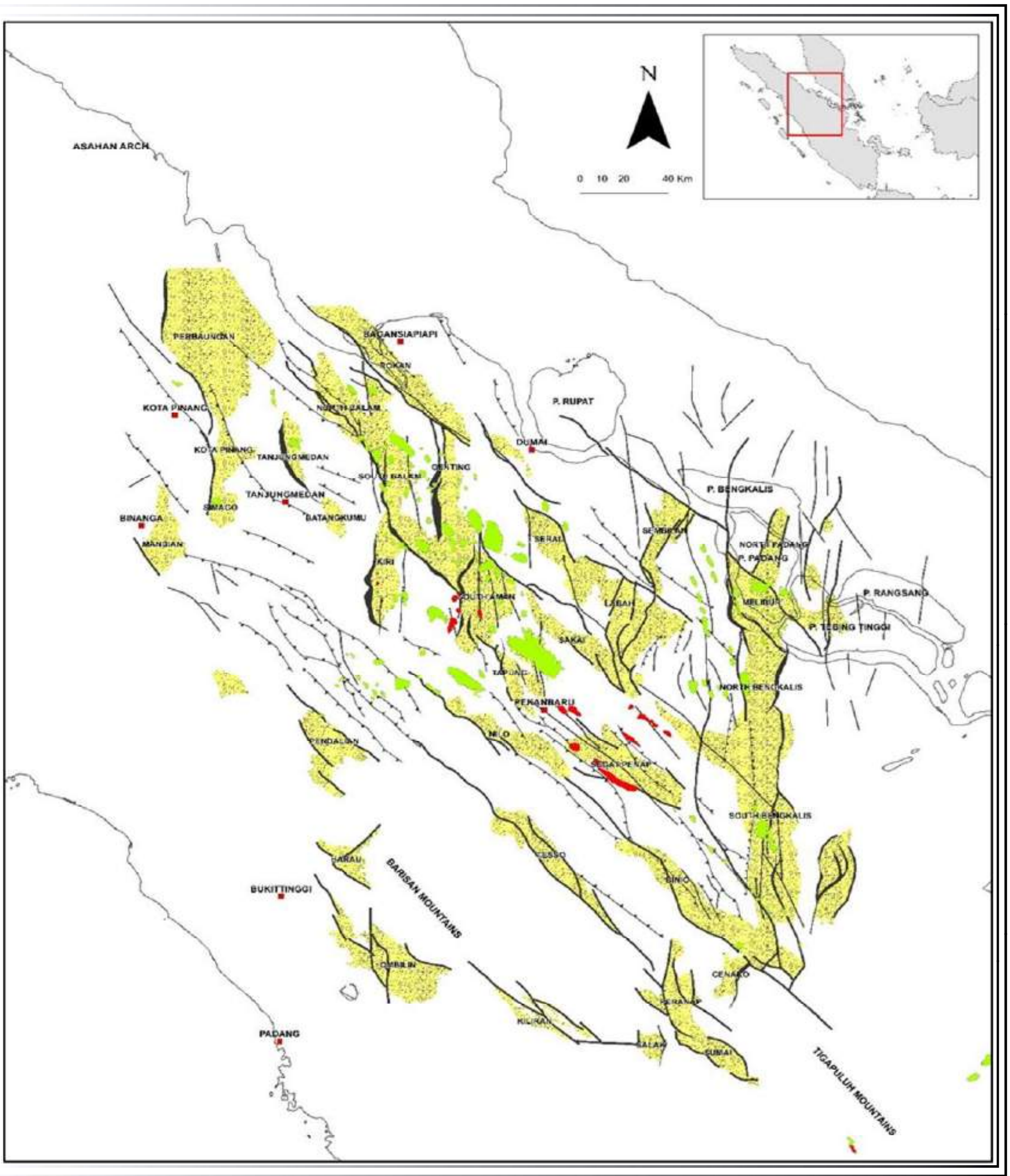

Figure 4
Paleogene Low structural configuration of Central Sumatera Basin
and associated oil and gas fields (Heidrick 1993, vide Lemigas 2020).

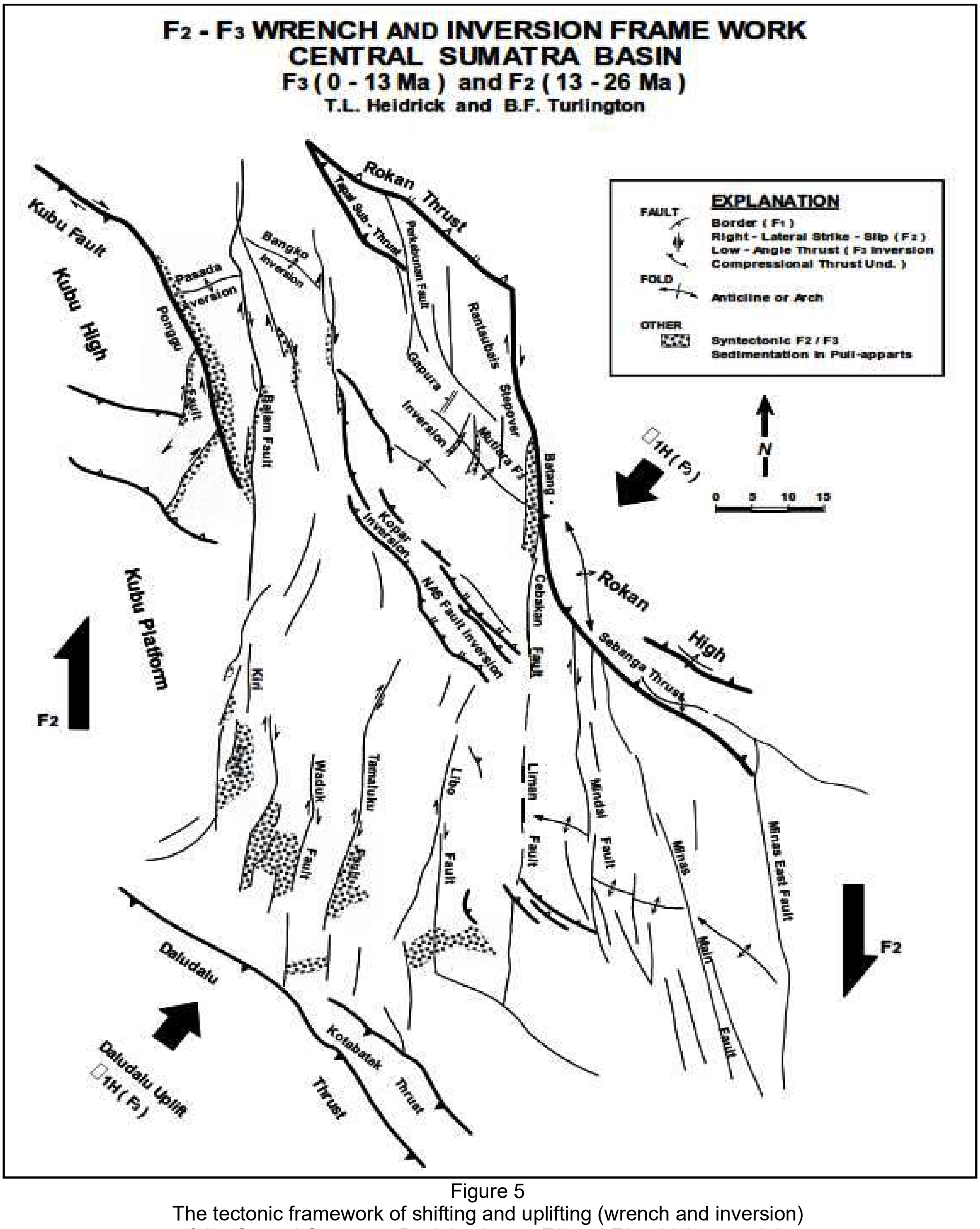

Figure 5
The tectonic framework of shifting and uplifting (wrench and inversion)
of the Central Sumatera Basin's phases F2 and F3, which control the
final uplift of this basin (Hendrick & Turlington, 1994., Vide Pertamina BPKKA, 1996).

straight line pattern, and caused the activation of old pre-Tertiary structures, resulting in a Paleogene deep pattern in the Central Sumatra Basin (Figure 4), which developed continuously into the Central Sumatra Basin. Heidrick & Aulia (1993) divided three structural patterns that developed at the F1 stage, namely N - S,NNE -SSW and NW - SE, with the N - S pattern as the predominant pattern. Minimum horizontal stress that developed in this period is in west - east direction.

Deformation Phase F-2 (28 - 13 Ma)

This phase occured during Late Oligocene - Middle Miocene, and is also called the interior sag basin phase. The tectonic process that occurs in this phase is crustal sagging and dextral wrenching which causes the formation of a transtensional fracture zone with N0°E - N20°E strikes and tranpressional lifting with N0°W - N20°W strikes.

In general, during this period there was a complete decrease in the basin and the trangesive sediment deposits of the Sihapas group were deposited. The structural patterns that develop during the deformation phase F2 vary widely, being a combination of the pull-apart graben, half-graben, negative and positive flower structures, normal and reverse faults. The fold patterns formed in this phase have N and NNE trends, are short, discontinuous, and are often dragged into local flanking negative sag troughs. These structures are the result of the dextral lateral strike-slip fault, which can be divided into three types of geometry; transtension type, transpression type, and pure strike slip type.

Deformation Phase F-3 (13 Ma - Recent)

This phase occured in the Late Miocene - Resen. This phase is also called the compression phase. F3 tectonic activities include sea floor spreading of the Andaman Sea, regional uplift, formation of volcanic mountain belts, and right lateral strike slip along Bukit Barisan in the direction of N35°W + 10° which causes compression/upthrusting along the North Sumatera and Central Sumatra Basin in the direction of the NE - SW force (Figure 5). In this phase, regional unconformity was formed and the Petani and Minas Formations were deposited on an unconformity above the Sihapas Group.

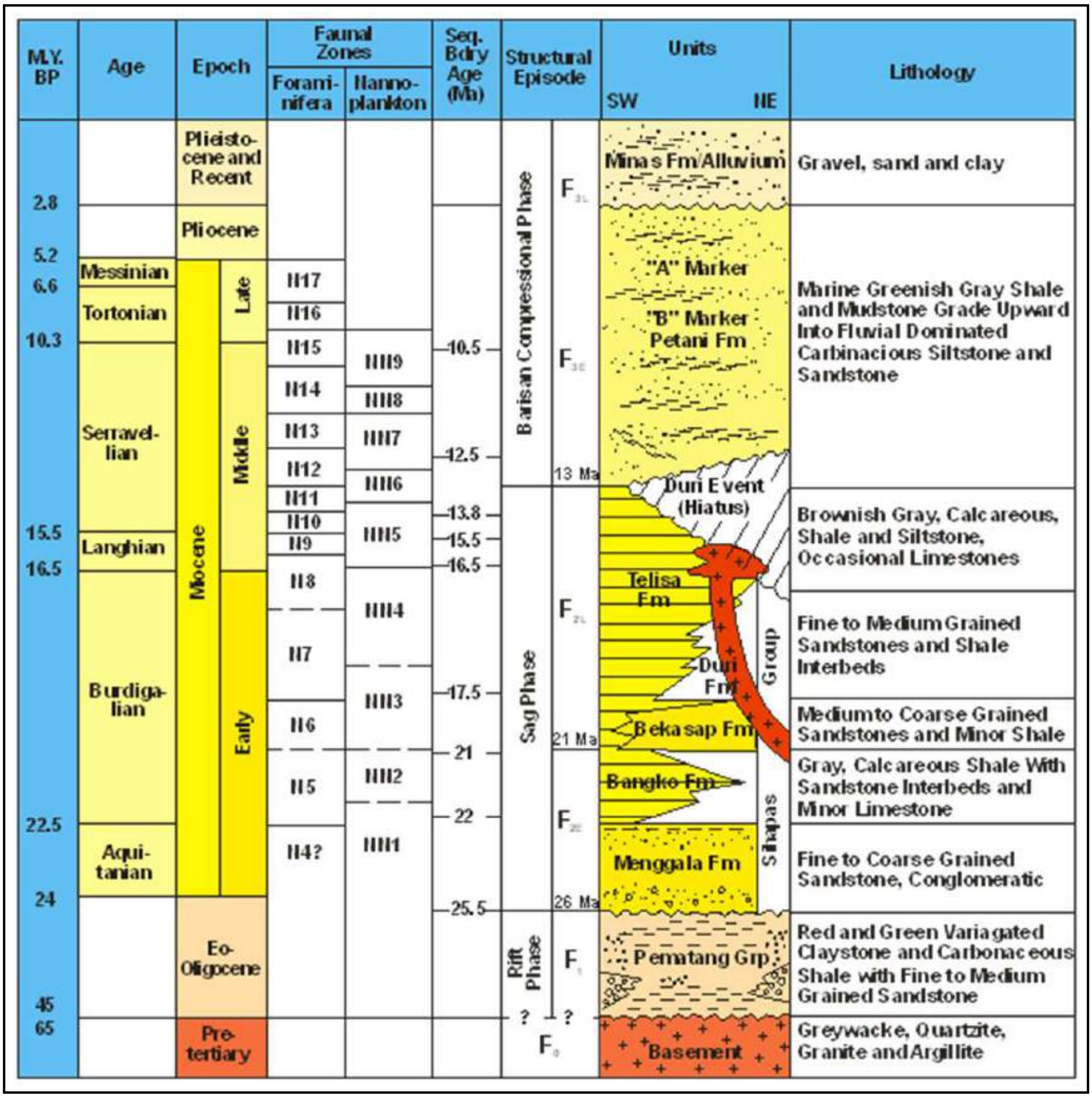

Figure 6
General stratigraphy of Central Sumatera Basin (modified from Heidrick & Aulia, 1993).

Stratigraphy and Sedimentation

Eubank & Makki (1981), Cameron, 1983, Yarmanto & Aulia (1988), and Heidrick & Aulia (1993) divided the regional stratigraphic units of the Central Sumatra Basin from Paleogene - Pliocene and Quaternary into five groups / formations, namely Pematang Formation, Sihapas Group, Telisa Formation, Petani Formation, and the Minas Formation (alluvium); as shown on Figure 6. Heidrick & Aulia (1993) divides the regional stratigraphy of the Central Sumatra Basin into Pre-Tertiary bedrock, Paleogene sedimentary rocks, Neogene sedimentary rocks, and Plistocene deposits.

The Tertiary sedimentary stratigraphic succession in the Central Sumatra Basin has proven to contain hydrocarbons and produce large oil reserves. Oil accumulations generally found in the sandstone reservoirs of the Sihapas Group which are supported by the lacustrine shale source rock of the Brown Shale Formation which has the potential to produce oil volumes of up to 60 billion barrels (Cameron, 1983). The Tertiary Sedimentary Rocks that fill the Central Sumatra Basin have been shown to produce hydrocarbon accumulation with the main kitchen area coming from the Aman, Bengkalis, Balam, Tanjung Medan and Kiri/Rangau grabben (Figure 7).

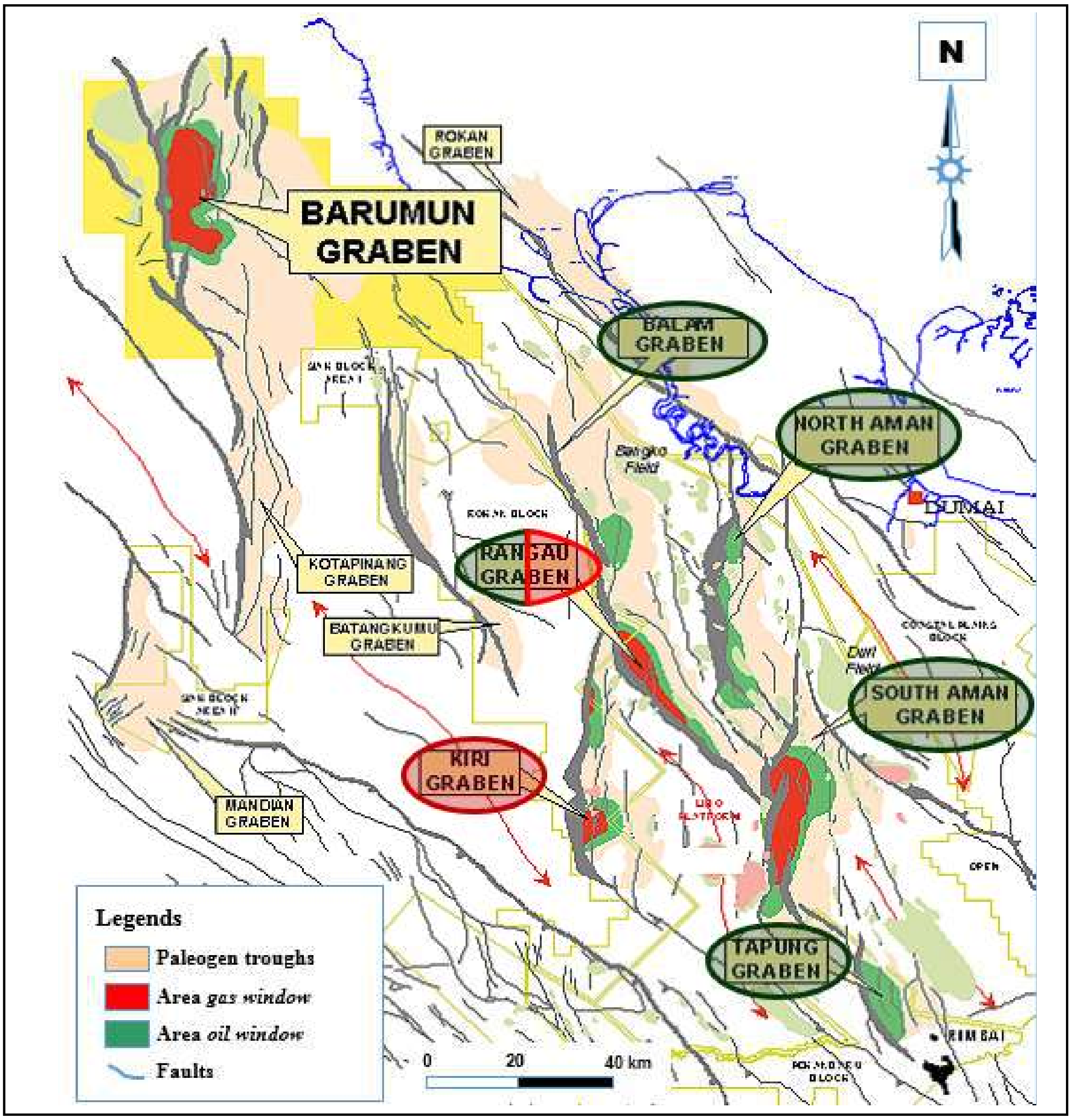

Figure 7
Paleogene low structural arragement
in Central Sumatera Basin (modified from Heidrick & Aulia, 1993).

The upper of the Sihapas succession is composed of Telisa Formation deposits which are dominated by marine shale lithology with intercalation of sandstones, siltstone, and limestone. The Telisa Formation extends regionally and has thick sediments that have the potential to act as cap rock. The accumulation of hydrocarbons in this basin results from the completeness and quality of the elements of the petroleum system, especially source rock, reservoir rock, and cap rock as well as petroleum system processes such as generation, migration, accumulation and preservation that are running well.

Geology Setting and Heavy Oil Occurence

Heavy oil in this study is defined as crude oil having specific gravity values of below 25° API. In Central Sumatra Basin, oil fields that have been proven to produce heavy oil are Duri, Kulin, North Kulin, Batang, Rantau Bais, and North Sebanga fields. As shown in Lemigas (2020), heavy oil generally accumulates within zones at depths of 400 to 800 meters below sea level. In accordance with the basin's geological setting, presence of heavy oil is generally identified as residing at the Basement highs (Figure 8 and Figure 9). The approach to identify and delineate surface geological arrangements is also carried out through the use of the remote sensing support (Figure 10). The spread of highs and lineaments of the structure can be interpreted from remote sensing data. Furthermore, all geological information that has been obtained is integrated with the geographic information system (GIS) technology.

Several structural highs are found in the Central Sumatra Basin. One of them is the Rokan High, at which the Duri field - a massive trap of huge heavy oil accumulation - is located (Figure 9 and Figure 10). It lies on the northeast side of the Center deep (Aman Deep) which is basically the main grabben in the Central Sumatra Basin, being so this area is in paleogen depositors and the presence of this large heavy oil reservoir is therefore relatively close to its source rock (Pertamina & Beicip, 1992; Pertamina BPKKA, 1996).

In regional section B (Lemigas, 2020), the current mapped F1 (Paleogene) structure is interpreted as a border fault and the ones that can be observed in this section include Kiri Trough, Rangau Trough, and Serai Trough. Several border faults that experienced

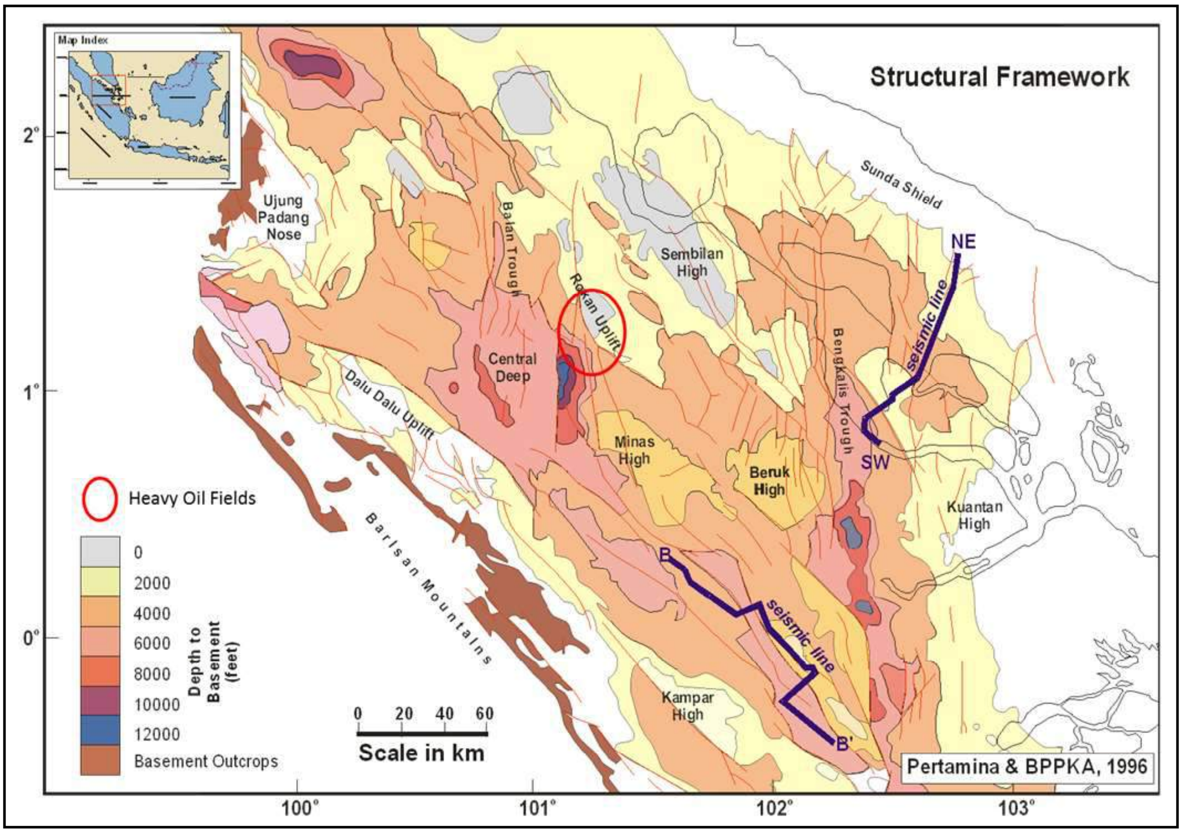

Figure 8
Basement map of Central Sumatera Basin (source: Pertamina BPKKA, 1996).

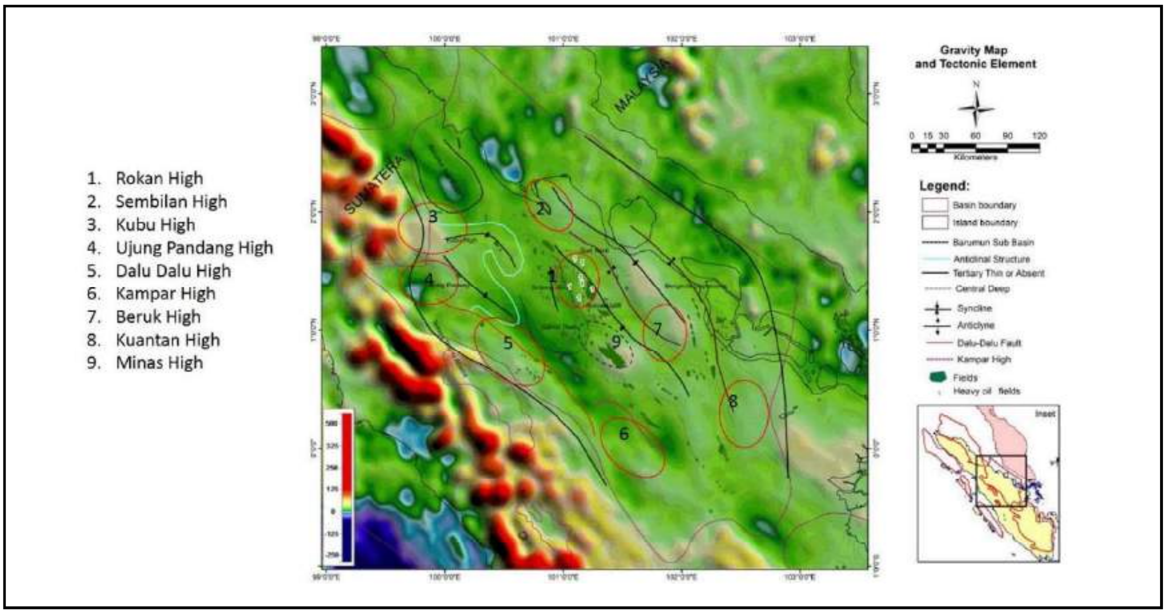

Figure 9
Gravity anomaly map showing structurally
high positions in the Central Sumatra Basin (source: Lemigas, 2020).

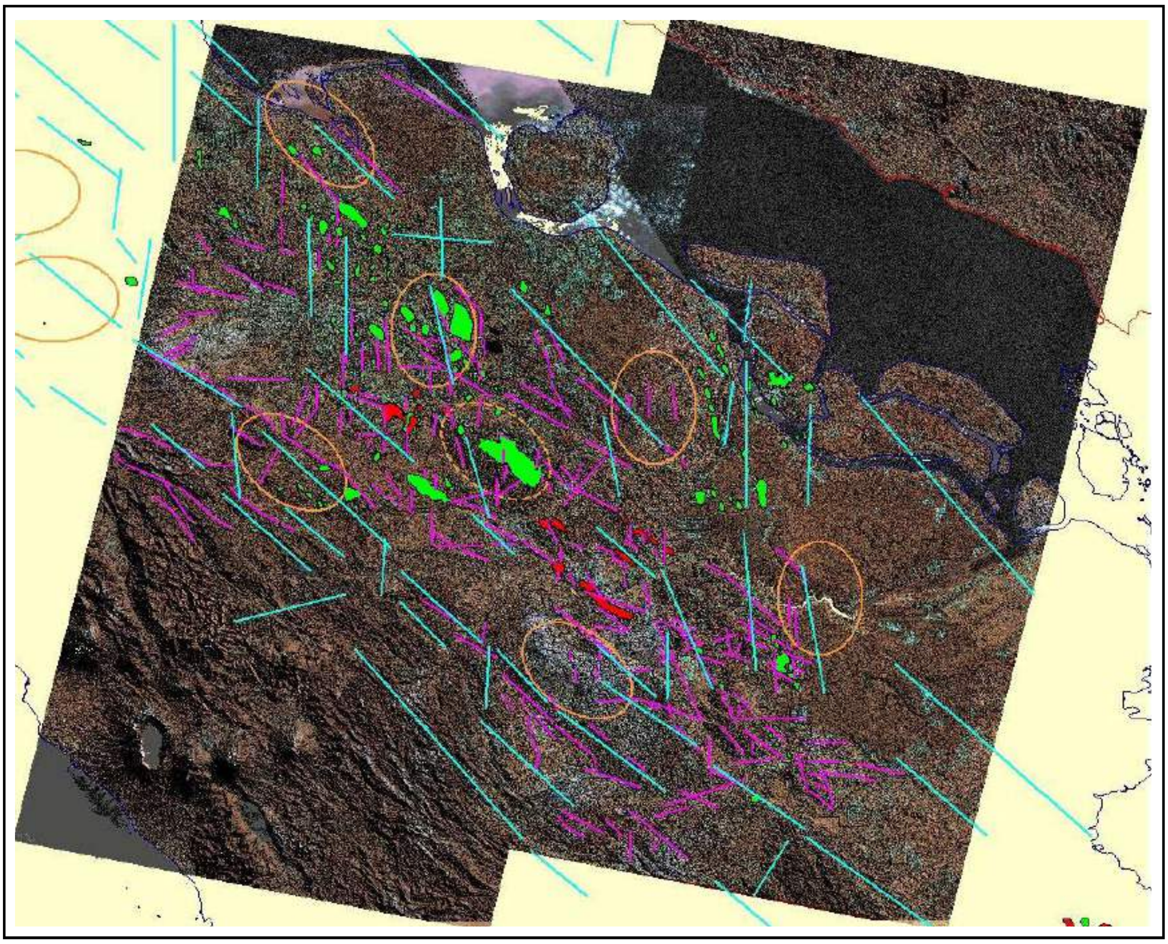

Figure 10
Lineament overlay of the gravity anomaly (cyan), lineament of
the Landsat imagery (purple), structural highs (orange circles), oil fields (green),
and gas fields (red) on the Fuzed Landsat - SRTM Imagery (source: Lemigas, 2020).

reactivation in the tectonic events were the youngest observed in the North Aman Trough (Figure 11). Oil fields that contain heavy oil are located in this cross-section, with a blue circle that marks boundary of the high edge on which the Duri field is located. Some of these highs in the Central Sumatra Basin can be identified on gravity maps. These structurally high positions include Rokan, Sembilan, Kubu, Ujung Pandang, Dalu Dalu, Kampar, Beruk, and Kuantan Highs. The blue circle on the map on the regional geological section B Structure F3 (Late Miocene - Recent) marks the position or presence of heavy oil fields of Duri and Kulin.

Analysis of the Presence of Heavy Oil and its Relationship with Tectonics

Heavy oil in the Central Sumatra Basin was formed due to the process of biodegradation and water washing, which occurred due to the tectonic lifting of the reservoirs after migration of oil from kitchen/source rock to the them had completed. The reservoirs that contain heavy oil are at present condition generally at depths shallower than 1,000 feet (300-400 meters), shallow depths that may easily be associated with encroaching surface water into the reservoirs. In this kind of geological setting, data has shown that heavy oil acumulations are mainly found in fields located in uplifted/uphill fault blocks. The high locations associated with the up-thrown part of the great Sebanga thrust fault are where Duri, Sebanga North, Kulin, Rantau Bais, Batang, Akar, and Genting fields are found; whereas in the western part of the basin high positions associated with Dalu-dalu thrust fault and the uplift of Gadang Island are locations of Kumis, Kotalama, Pendalian, and Langgai heavy oil fields (Figure 12).

Based on the understanding that biodegradation and water washing mechanisms occur on uplifted medium or light oil bearing reservoirs, examinations on fields and discovery wells in these uplifted positions were carried out (Lemigas, 2020). In general, this lifting process usually occurred in the tectonic

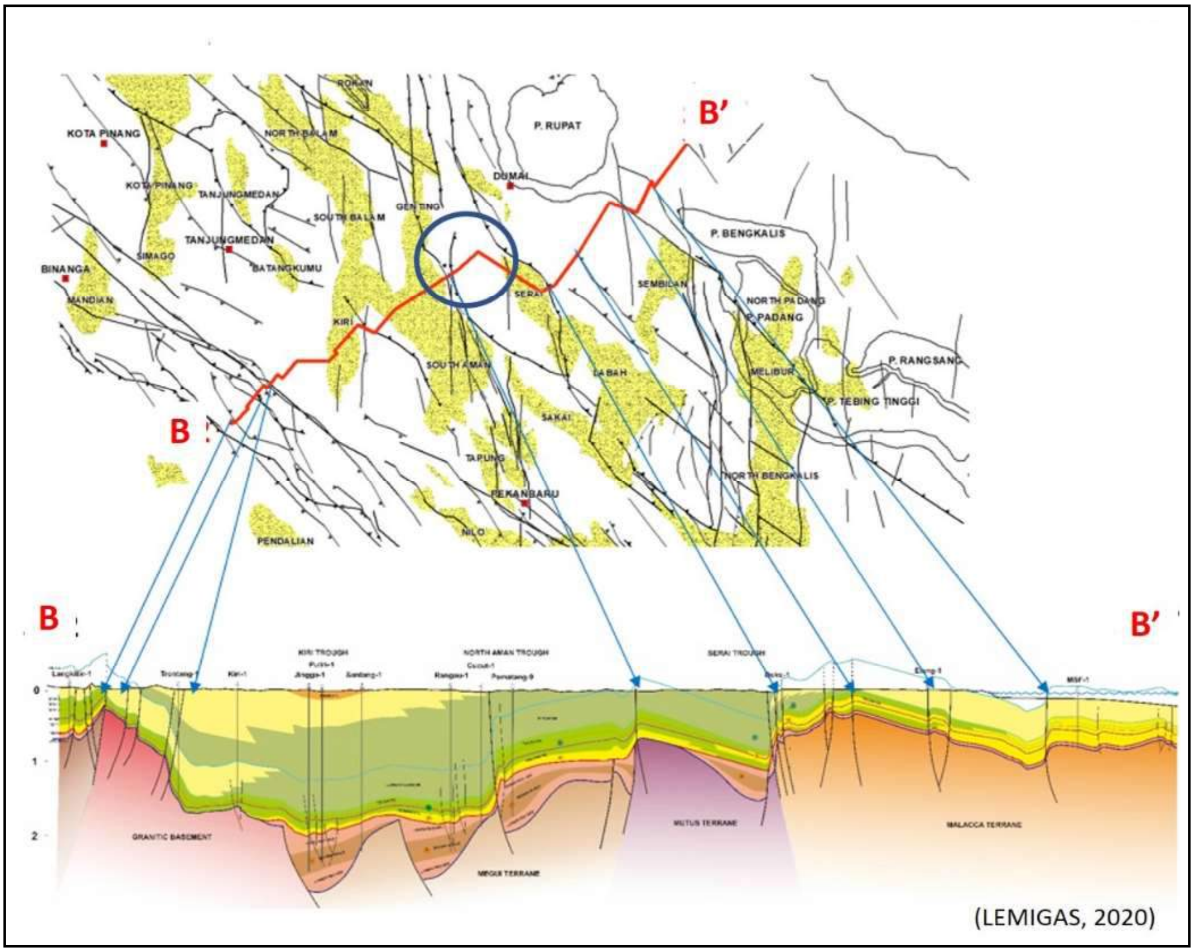

Figure 11
Regional geology cross section showing the position of the
Duri heavy oil field, which is proven as heavy oil producing
(Tectonic F3, compression phase that causes the lifting process) (source: Lemigas, 2020).

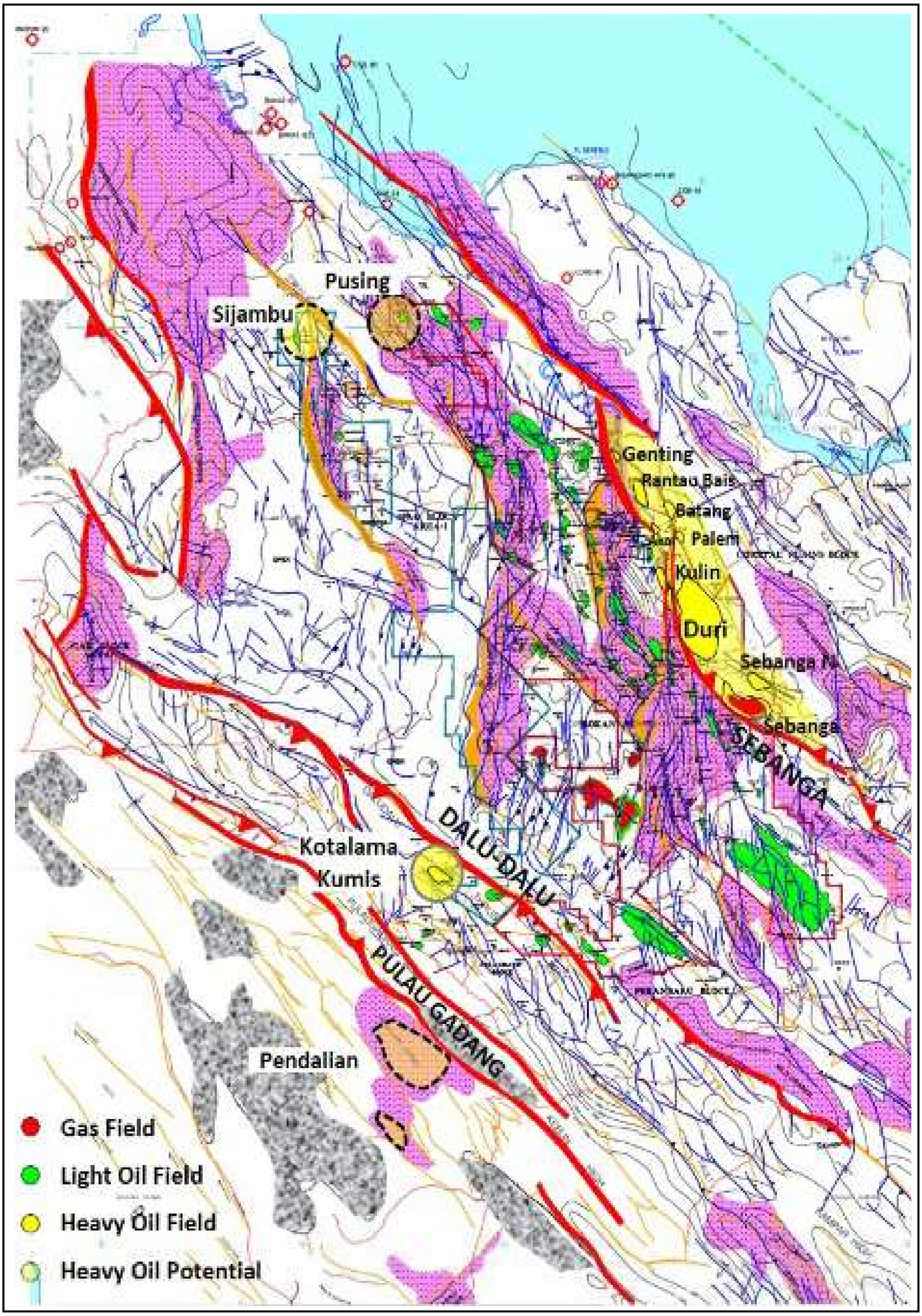

Figure 12
Thrust faults (Sebanga and Dalu Dalu) are believed to have caused the biodegradation process and water washing which resulted in the formation of heavy oil in the Central Sumatra Basin (modified from Hendrick & Aulia, 1993).

phase of compression taking place in the Plio-Pleistocene with compression trend in west - east direction. The areas that are proven to have accumulation and production of heavy oil are those associated with the Sebanga thrust fault, the Rokan uplift, the Dalu-Dalu thrust fault, and the Pulau Gadang uplift. Therefore, thrust faults are believed to be the main control that triggered both biodegradation and water washing processes to take place. Accordingly, with reference to faulting patterns throughout the basin, oil fields and discovery wells - apart from the six producing heavy oil fields - associated with the tectonic phase are examined, mainly using qualitative well-log analysis with an understanding that bio-degradation process normally takes place at sub-surface temperature of less than 60-80°C (Santos, *et al*., 2014). Figure 13 presents distribution of oil fields and discovery wells that have proven containing and/or are strongly suspected to contain heavy oil.

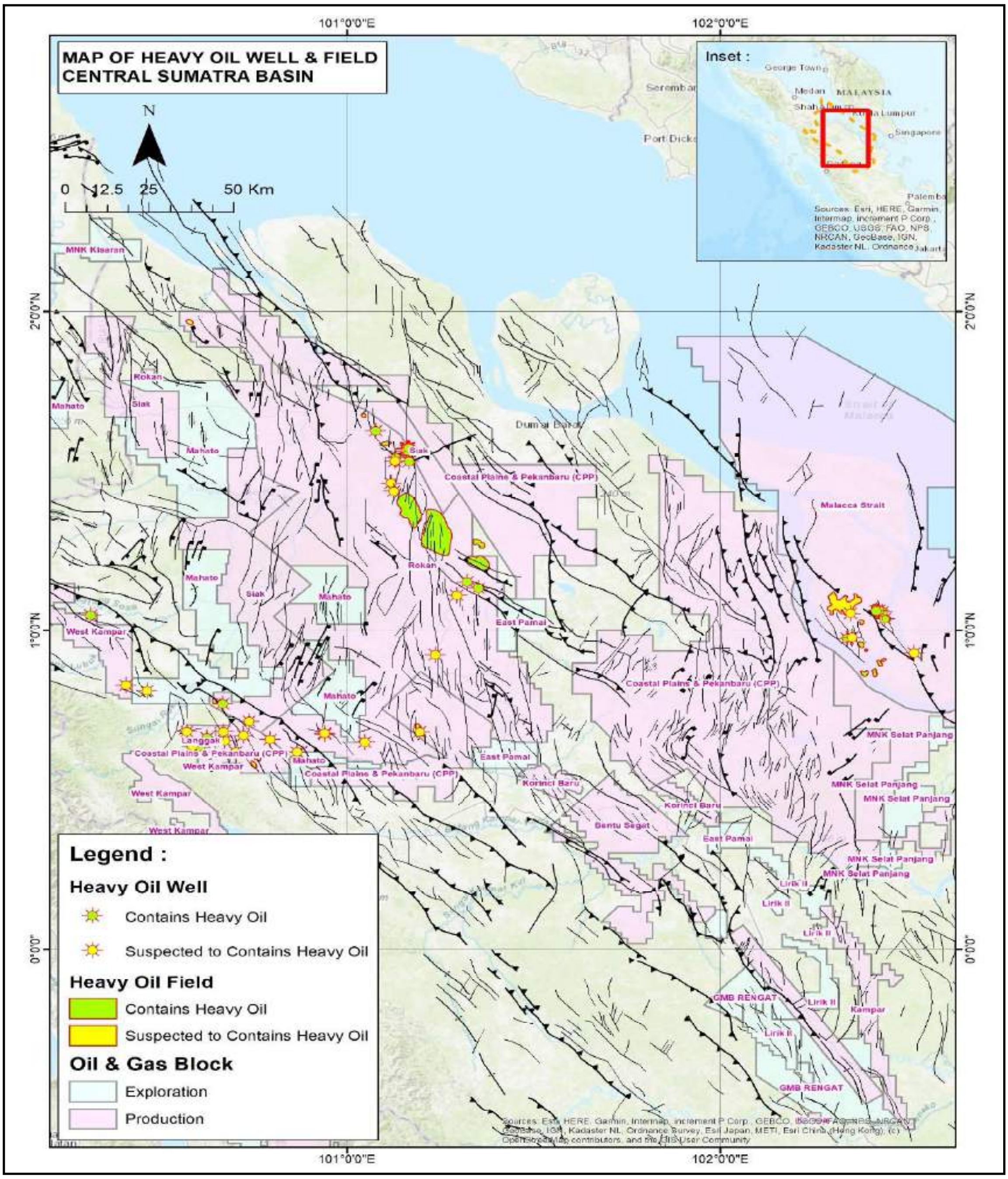

Figure 13
Distribution of oil fields and wells that are proven containing
heavy oil and are estimated to contain heavy oil (source: Lemigas, 2020).

Although it is now understood that presence of heavy oil is strongly related on its tectonic setting, and therefore heavy oil is associated with shallow depth, biodegradation process in fields and wells in the tectonic position does not always occur with uniform intensity and scale. This leads to heavy oils that show variation in density, even though those that have proven containing oil fields are all having oil density below 25°API. From 45 oil fields and 103 exploration/discovery wells (usually in status of plugged and abandonned, P&A) that have been examined, as many as 22 fields/structures are 'proven' to contain heavy oil, while 29 others are 'suspected to contain heavy oil' or equivalent to categories of 'probable' and 'possible'. All but two - heavy oil bearing zones in Kotabatak and Kotagaro fields - are located in tectonically uplifted positions hence shallow in depth. Figure 13 depicts the fields/structures while Table 1 and Table 2 contain lists of the fields/structures.

It is true that not all of fields or structures located at the tectonically uplifted positions - the nine Basement highs - in the Central Sumatra Basin have proved as containing, or at least suspected to contain, heavy oil but nevertheless it is also a fact that those uplifted subsurface positions had facilitated bio-degradation and water washing mechanisms to operate. Facts that not all sedimentary traps in those location

Table 1
List of fields and structures that are proven containing heavy oil. Kotabatak field's deep tar sands is an exception to the concept of shallowheavy oil acumulation (source: Lemigas, 2020).

No.	Field/Structure	Basement High	Depth (meters)(*)
1	Batang (Rokan)	Rokan (RMS) (**)	150-300
2	Batang (Siak)	Rokan-Sembilan	155-190
3	Duri (Steamflood)	Rokan (RMS)	300-400
4	Duri (D240;D140)	Rokan (RMS)	50-250
5	Duri North	Rokan (RMS)	300-318
6	Genting	Rokan (RMS)	210-345
7	Kotalama	Dalu Dalu	100-175
8	Kulin	Rokan (RMS)	287-396
9	Kulin North	Rokan (RMS)	285-415
10	Langgak	Dalu Dalu	355-425
11	Melibur (MSJ)	Beruk	305-365
12	Rantau Bais	Rokan	190-300
13	Selatan (MSBH)	Beruk	50-200
14	Sebanga	Rokan (RMS)	355-372
15	Sebanga North	Rokan (RMS)	300-700
16	Kumis	Dalu Dalu	172-210
17	Pendalian	Dalu Dalu	
18	Akar	Rokan (RMS)	165-400
19	Kotabatak (tar sands)	Non Bsmt high	1385-1410
20	Wilis (tar sands)	Dalu Dalu	360-405
21	Dalu Dalu	Dalu Dalu	213-244
22	Gatam	Beruk	684-700

(*) below sea level

(**) RMS: Rokan-Minas-Sembilan

Table 2
List of fields and structures that are suspected to contain heavy oil.
In a way similar to Kotabatak field, Kotagaro field's deep tar sands
is an exception to the concept of shallow heavy oil acumulation (source: Lemigas, 2020).

No.	Field/Structure	Basement High	Depth (meters)(*)
1	Kasikan	Dalu Dalu	155-225
2	Paitan	Dalu Dalu	450-460
3	Kotagaro (tar sands)	Non Bsmt high	1707-1835
4	Kurau	Rokan (RMS)(**)	112-155
5	Lindai	Dalu Dalu	100-200
6	Pemburu	Rokan (RMS)	360-492
7	Pusing	Sembilan	1209-1227
8	Puncak	Rokan (RMS)	382-390
9	Palem	Rokan (RMS)	215-340
10	Topi	Rokan (RMS)	150-175
11	Lincak	Rokan (RMS)	382-500
12	Topaz	Non Bsmt high	538-600
13	Pemula	Dalu Dalu	570-590
14	Balai	Sembilan	150-255
15	Ladang	Dalu Dalu	484-600
16	Bolo	Dalu Dalu	350-375
17	Kuala	Rokan (RMS)	175-250
18	Pala	Non Bsmt high	275-575
19	Ujung Tanjung	Rokan (RMS)	586-610
20	Kukun	Dalu Dalu	438-611
21	Batukecil	Dalu Dalu	377-490
22	Ngaso	Dalu Dalu	451-582
23	Kepanasan	Dalu Dalu	505-556
24	Jingga	Dalu Dalu	25-600
25	Bacang	Dalu Dalu	475-525
26	Intan	Rokan-Beruk	425-500
27	Waduk	Dalu Dalu	475-600
28	Langkitin	Dalu Dalu	397-517
29	Napal	Dalu Dalu	155-475

(*) below sea level
(**) RMS: Rokan-Minas-Sembilan

are heavy oil bearing are caused also by a fact that not all of the traps are oil bearing in the first place. There are also cases where shallow reservoirs in the Basement highs are medium oil bearing (density > 25^o API) in nature due to inadequate water conduit (e.g faults or leaked cap rocks) that enables surface water encroachment into the traps hence activating the biodegradation and water washing processes to take place. Nonetheless, the role of tectonic evolution in uplifting oil bearing traps are quite obvious and primal, without which generation of heavy oil through the two known mechanisms are impossible to prevail.

CONCLUSION

The concept of heavy oil formation in shallow depth geological settings through the process of biodegradation and water washing have been considered proven and generally valid in the Central Sumatra Basin, although with the exception of the accumulation of tar sands at deep depths in the Kotabatak and Kotagaro fields. These two exceptions are most probably caused by any other mechanism else than biodegradation and water washing, and this fact should motivate for further studying the potential of heavy oil in the Central Sumatra basin in a more intensive manner.

Potential of heavy oil accumulation in the Central Sumatra basin appears in general to have associated with high subsurface structures resulted from tectonic evolution that uplifted oil bearing traps upto shallow depths hence allowing the generation of heavy oil to occur. Exceptions to this rule are likely to be caused by possible factors such as absence of the oil itself in the first place (i.e water bearing) and lack of surface water conduit into the shallow oil-bearing traps. This however underlines the primary role of tectonic uplifting in the generating process of heavy oil.

Use of combined/integrated regional geology, remote sensing, geophysics, and stratigraphy has proved effective in both identification of geologically high subsurface structures as the results of tectonic uplifting and in combination with well-based analyses identification of shallow heavy oil traps. Although fine refinements in the methodology could be further pursued but this integrated approach may serve as an example for similar applications in other sedimentary basins.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
API	American Petroleum Institute for Oil Gravity	API Gravity is related to density (degree/°API)
GIS	Geographic Information System	
F1	Fase-1/Phase-1, Tectonic Evolution	
F2	Fase-2/Phase-2, Tectonic Evolution	
F3	Fase-3/Phase-3, Tectonic Evolution	

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