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An Integrated Approach for Revisiting Basin-Scale Heavy Oil Potential of The Central Sumatera Basin

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ABSTRACT - Central Sumatra Basin is one of the most prolific hydrocarbon basins in Indonesia and has proved itself as being the largest contributor to Indonesia's national crude oil production. Heavy oil fields in the basin, such Duri field as the largest one, plays a very important role in making up the basin's whole oil production output. In general, the Central Sumatra Basin is also acknowledged for its heavy oil potential. Accordingly, a study under the auspices of the Ministry of Energy and Mineral Resources (MEMR) of the Republic of Indonesia is carried out to re-visit the potential. The study establishes and implements an integrated approach formed by a combined macro and micro analyses. In the macro analysis, a combined evaluations of regional geology, geophysics, geochemistry, remote sensing/geographic information system (GIS), regional geothermal study, and field survey/microbiology is performed to identify geological positions of the heavy oil potential. In the micro analysis, on the other hand, qualitative and quantitative well-log analyses supported by well-test and laboratory measurement data on the identified geological positions are carried out with an aim of identifying heavy oil bearing reservoirs/traps under three categories of certainty. The main result of the study is identification of 51 fields/structures - producing and non-producing – that bears heavy oil within the three categories. Findings of the study can certainly be used as a prerequisite for more intensive and expansive studies to meet the need for a more solid conclusion regarding the heavy oil potential of the Central Sumatra Basin.

Keywords: Central Sumatra Basin, heavy oil potential, study, integrated approach.

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INTRODUCTION

In its oil and natural gas industry Indonesia has been witnessing the up and down of its national oil production. Since its emergence in significant level in 1960s Indonesia's oil production has witnessed two major peaks, in 1977 and 1995. The national oil production ramped up steeply in late 1960s and early 1970s with the entrance of Minas field's production that supported the first national production peak in 1977. The ensuing production decline afterward was then lifted into the second peak in 1995 with the production apex of steamflood project in Duri field

(Figure 1). Both Minas and Duri fields are located in Central Sumatra Basin (Figure 2), and along with other fields in the region they have delivered a continuing major contribution to the national crude oil production. During the highest level of production of around 1.6 million BOPD in 1977 and 1995 the basin's contribution made up to around two third with its around one million and 850 thousand BOPD, respectively.

First oil discovery in the basin was made in 1939 (Courteney, *et al.*, 1991). Due to its significance an abundant volume of studies have been devoted to its oil fields, but apart from Duri field (discovered in 1941; Curtis et al, 2002) not much attention has been given to the basin's overall heavy oil potential. There have been sufficiently studied regional scale issues such as regional geology and source rock investigation (e.g. Mertosono & Nayoan, 1974; Eubank & Makki, 1981; Seiffert & Moldowan, 1980; Williams, *et al.*, 1985; Katz & Mertani, 1989; Carnell, *et al.*, 1998; Hartono, *et al.*, 2020) but no publications have given any hints about basin-wide heavy oil potential outside the currently producing oil fields. At field level, publications (e.g. Yi, 2008; Nugraha, *et al.*, 2019; Syahputra, 2020) usually report results of various field operational activities and studies but none enters into issues related to heavy oil potential especially in non-producing fields. General sources such as Courteney, *et al.* (1991) provide information mainly about producing heavy oil fields only. All productive reservoirs and hydrocarbon bearing zones are sandstones.

In an effort to maximize the grand image about the hydrocarbon potential of the Central Sumatra Basin a study team has been assigned by the Ministry of Energy and Mineral Resources of The Republic of Indonesia to study the potential of heavy oil accumulation in the basin. Through the study it is expected that overal image of the potential can be mapped and constructed for its distribution, not only of the known producing fields such as Duri, Batang, and Kulin, but also their upside potentials and as well as other potentials that have long been suspended and forgotten. Through the multi-disciplinary approach applied in the study the heavy oil potential in the basin has been - or at least mostly - unlocked. The overal results are reported in Lemigas (2020), and through this article the underlying approach of the study and its qualitative results are presented. It is hoped that the information presented may encourage further driving interests in the potential.

METHODOLOGY

Generation of heavy oil

Heavy oil, extra heavy oil, and its other forms such as oil/tar sands (bitumen) is a crude oil state that is characterized by its higher density - normally expressed in API gravity - than normal. There are various definitions made to describe heavy oil but in this study the upper limit of 25^{o} API gravity (McKinsey & company, 2020) is adopted. Heavy oil is normally also marked by its viscous behavior (Figure 3) with lower API gravity crude oils tend to be more viscous and may approach solid state at atmospheric condition for oil/tar sands and bitumen.

Heavy oil exists mainly as results of biodegradation and 'water washing' processes normally occur at shallow depths and at temperatures below 80^{o}C (Santos, *et al.*, 2014). At shallow depths, the originally light/medium-weight crude oils in its traps underwent microorganism activities that transform the oil into becoming heavier oils characterized by their rich contents in poly-aromatic, resin, and asphaltic components. This biodegradation process is usually coincided with 'water washing' mechanism in which the oil lost its light fractions through physical 'washing' by encroaching water into highly permeable shallow traps. The two mechanisms may strengthen each other and eventually yield oils that have only heavy components, acidic in nature, and are often highly viscous.

Katz & Mertani (1989) revealed that from various works that have been done for source rock study in Central Sumatra Basin (CSB), it is generally agreed that the source rock of most oil in the basin is the Pematang Brown shale formation. From it came out the oil that transformed into four chemically different paraffinic oil families which, among others, are characterized by API gravity values ranging between 16.5^{o} (heavy oil) and 47^{o} (light oil). The lowering of oil API gravity in the CSB cannot be else than the results of biodegradation and water washing. Even Minas field with its light oil has the potential of oil seepage into becoming shallow heavy oil accumulation (McGregor, 1995).

The integrated approach

Upon understanding the mechanism of heavy oil generation, the main thrust of the study is deliberately made through efforts to explore geological condition in the sedimentary basin that are favorable for presence of heavy oil. Figure 4 presents a flowchart

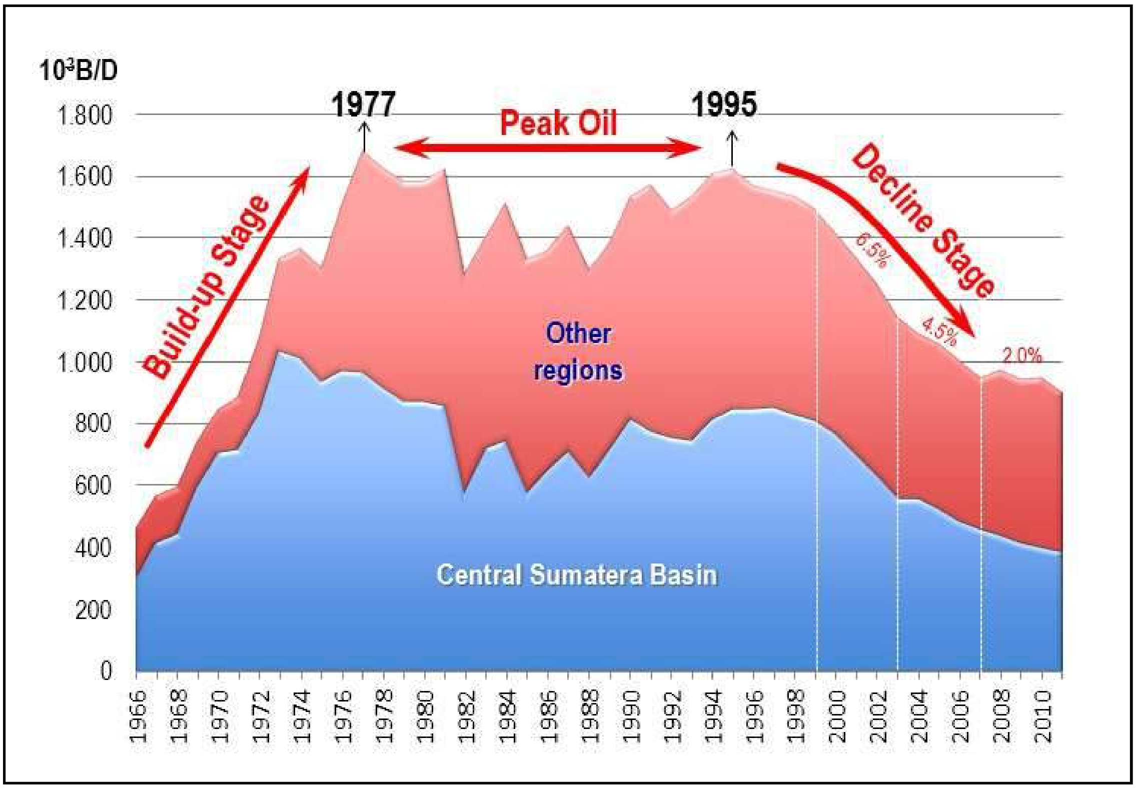

Figure 1
Indonesian national oil production (1966 - 2010) which accentuates contribution of Central Sumatra Basin and the two peaks boosted by Minas and Duri fields production, both are located in the basin. Production decline after 1995 keeps going up to present. (source: Muin, 2014).

that shows how the combined analyses work their way toward identifying fields, structures, and/or abandoned exploration wells that contain or may contain heavy oil. The integrated approach is basically formed by two parts that interact to each others; macro analysis (regional), and micro analysis (field/structure) which includes categorization of certainty over the heavy oil accumulation.

The macro analysis is basically an integrated approach to understand regional geological condition in the Central Sumatra Basin from which attention can be focused on particular area that are considered as favorable for heavy oil acumulation. The study maximizes use of data and information available that covers all working areas in the basin. Regional geology analysis is made to study the tectonic setting in the basin, and with analyses on satellite imagery anomalies and seismic cross sections geologically high locations are identified. These locations are bound by 'heavy oil window' which is created as the result of combined studies on collected microorganism and geothermal gradient mapping, whereas geochemistry analyses on existing data confirm that these locations are sufficiently charged with oil from source rocks. The macro component of the method is essentially a combined approaches that acts as spatial screening for pinpointing heavy oil locations.

The micro analysis, on the other hand, consists of analyses that are aimed at determining the zones - within the heavy oil/biodegradation window - that contain or are suspected as containing heavy oil. The analyses are mainly performed through qualitative well log analysis supported by results of well test analysis, production test, and laboratory fluid analyses (including API gravity data). This micro component of the integrated method is not applied on fields that are known to have been producing heavy oil, but instead it may help in pinpointing upside potential in those fields. On the other hand, however, combined with all sort of information this approach is certainly the tool for finding heavy oil potentials in non-producing fields/structures notably through re-evaluation of *plugged & abandoned* (P&A) exploration wells and other well 'suspects'.

As heavy oil zones within the heavy oil window are determined, it is important to assess certainty level of the very existence of theheavy oil accumulation. This categorization - as part of the micro analysis - of certainty levels will help in concluding the study and the follow-ups that need to be taken afterwards. Albeit simpler, similarly to reserves categorization (e.g PRMS, 2011), categorization of certainty level for heavy oil presence is established as follows:

- A heavy oil zone that has been producing and/or well-tested for proving its heavy oil content is categorized within Category #1 for its high certainty (above 90%) of heavy oil existence. Untested/ unproduced oil-bearing zones within the heavy oil window and above the heavy oil producing/tested zones, as well as connected structures with strong resemblance in log reading are also put within this category.
- An oil-bearing zone that has well log data with strong similarity with well log data of a heavy oil zone of Category #1 but in separate field/ structure, without heavy oil evidence

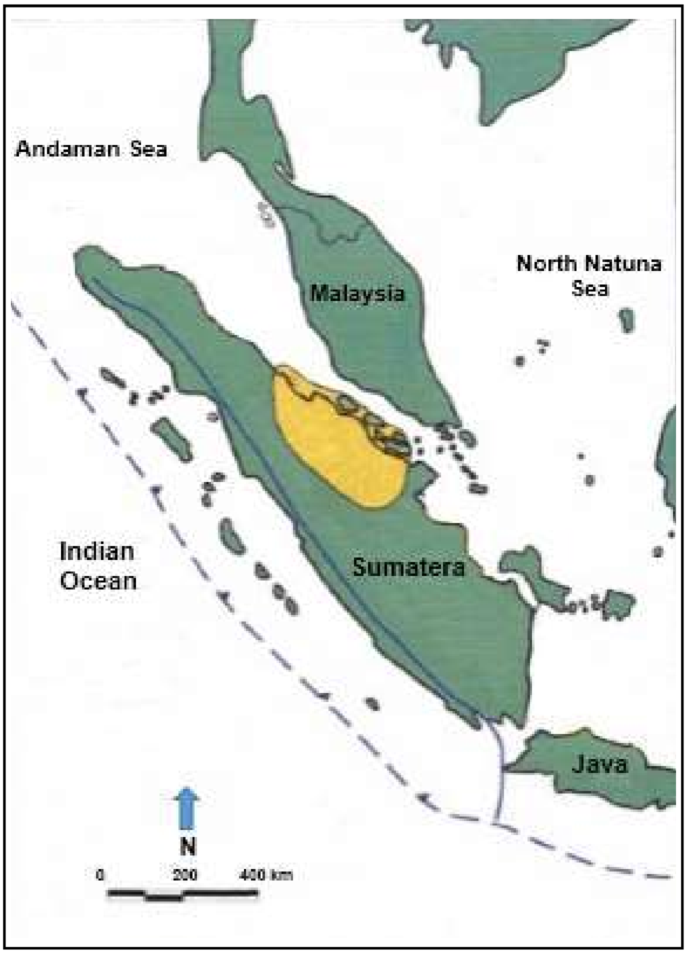

Figure 2
Location of Central Sumatra Basin (yellow area)
(modified from Science & Technology, 2019).

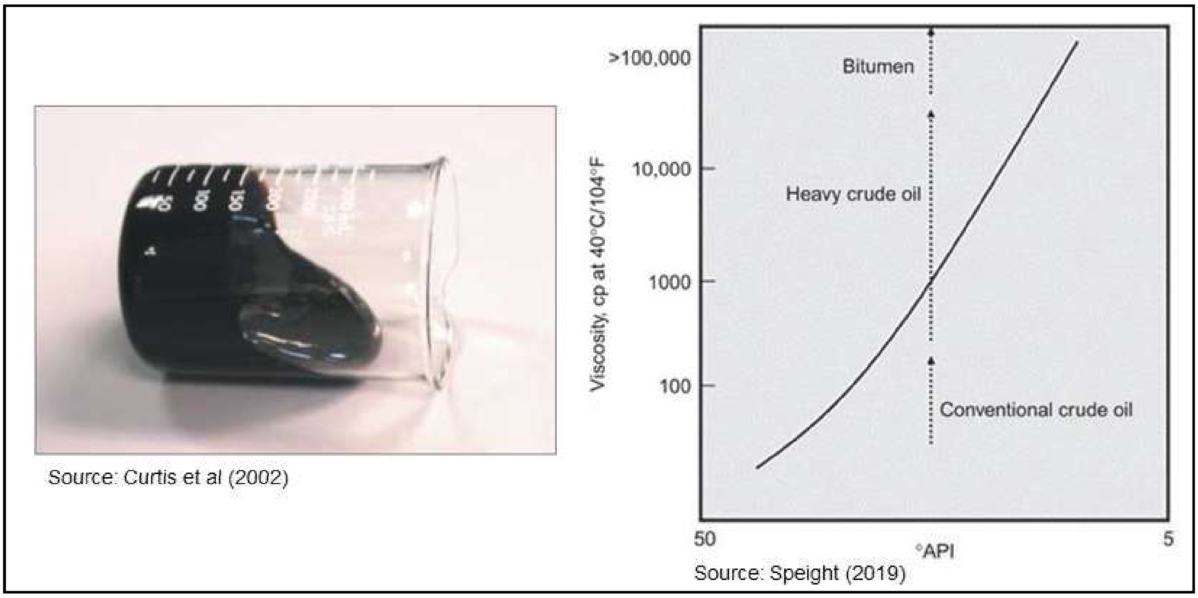

Figure 3
(a) Viscous heavy crude oil, and (b) general relation between crude oil API gravity and viscosity.

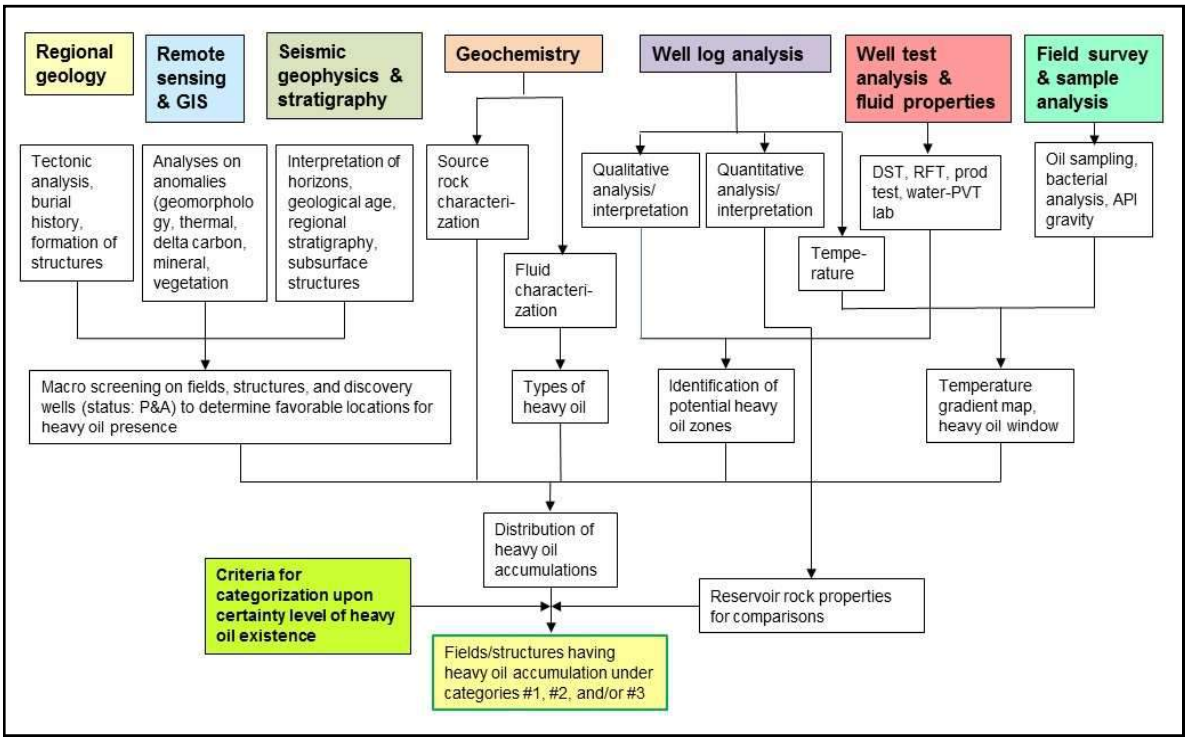

Figure 4
Methodology adopted in the study. (source: Lemigas, 2020).

from well test, and also without evidence from well test proofing otherwise, is regarded as within Category #2. This category represents heavy oil presence with less certainty (termed ‘medium to high certainty’) compared to Category #1 (> 90%). Proximity to Category #1 zones may support inclusion into this category including shallow oil-bearing zones (within heavy oil/ biodegradation window) that overlie zones with tested medium-heavy oils (i.e 25° - 30° API gravity).

- A supposed oil-bearing zone from well log qualitative/quantitative analysis within the heavy oil window, has no similarity to well log of Category #1 zones, has no evidence of heavy oil presence, and has no evidence to proof otherwise is regarded included within Category #3 (termed ‘low to medium certainty’). This category for zones with the highest uncertainty suits to secluded exploration wells with shallow oil bearing zones.

Data for study

Practically, all data available to the study and relevant to the methodology established for achieving the objectives of this study. Results of gravity and seismic studies, satellite imagery, reports of regional geology studies, field development study reports, drilling reports, well log suites, well test results, and laboratory fluid test reports are among data types used in this study. Large quantity and volumes of data from database of Special Task Force for Upstream Oil and Natural Gas Business Activities (SKK Migas) - Ministry of Energy and Mineral Resources of The Republic of Indonesia (MEMR-RI), database of Center of Data and Information (Pusdatin) - MEMR-RI, Lemigas archives, and publications are available to the team to use effectively and selectively.

RESULTS AND DISCUSSIONS

Central Sumatra Basin (CSB) roughly covers an area of 119,000 sq km. As described in Inameta (2006) the basin’s reservoirs are in the Sihapas Group (Menggala, Bangko, Bekasap, Duri, and Telisa Formations), Pematang Formation, and Petani/ minas Formation. Main reservoirs are the lower parts of the Sihapas Group which are thick and generally are characterized by medium to very good in storage and hydraulic capacities, whereas other reservoirs of Pematang and Petani/Minas Formations are of lower quality in nature. The main hydrocarbon source rock is the lacustrine brown shale of the Pematang/Kelesa Formation.

Macro Analysis

In the macro analysis, the first step made was to fully understand the regional geology and tectonic setting of the CSB, to understand why producing heavy oil fields such as Duri, Batang, Kulin, and Rantau Bais had come to their existence. In conjunction with the undertanding over the prevailing theory of heavy oil generation through biodegradation and water washing, it was with relative ease to find that heavy oil reservoirs in those fields are shallow, permeable, connected to hydrodinamic system, and are located in basement highs within the basin. The shallow depths of the reservoirs (mostly around 300 - 400 meters below sea level) took place due to tectonic uplift after oil entrapment within the reservoirs, often due to thrust faulting within the region. The large Sebanga and Dalu-dalu thrust faults that caused some of the uplifts - with their associated discontinuities (i.e fractures) - may also serve as water conduits for the water washing processes.

From gravity surveys in CSB at least nine Basement highs are identified: Rokan, Sembilan, Kubu, Ujung Pandang, Dalu Dalu, Kampar, Beruk, Kuantan, and Minas (Figure 5). The Rokan, Sembilan, Beruk, Kuantan, and Minas Highs are associated with the Sebanga thrust fault's uplift (northeast) whereas the Kubu, Ujung Pandang, Dalu Dalu, and Kampar Highs are related to the Dalu Dalu and Pulau Gadang thrust faults (southwest). A good example is that the prominent Duri heavy oil field is located in Rokan High.

In order to further delineate the potential positions of the heavy oil accumulation interpretation over lineaments on the surface of the CSB was carried out using combined satellite imagery data of Landsat 8 OLI and digital elevation model (DEM). This interpretation was made in conjunction with subsurface lineament interpretation using gravity survey data. In the interpretation information was extracted both qualitatively and quantitatively through image reading (i.e pattern, texture, color, shadow, form, and other related features), image

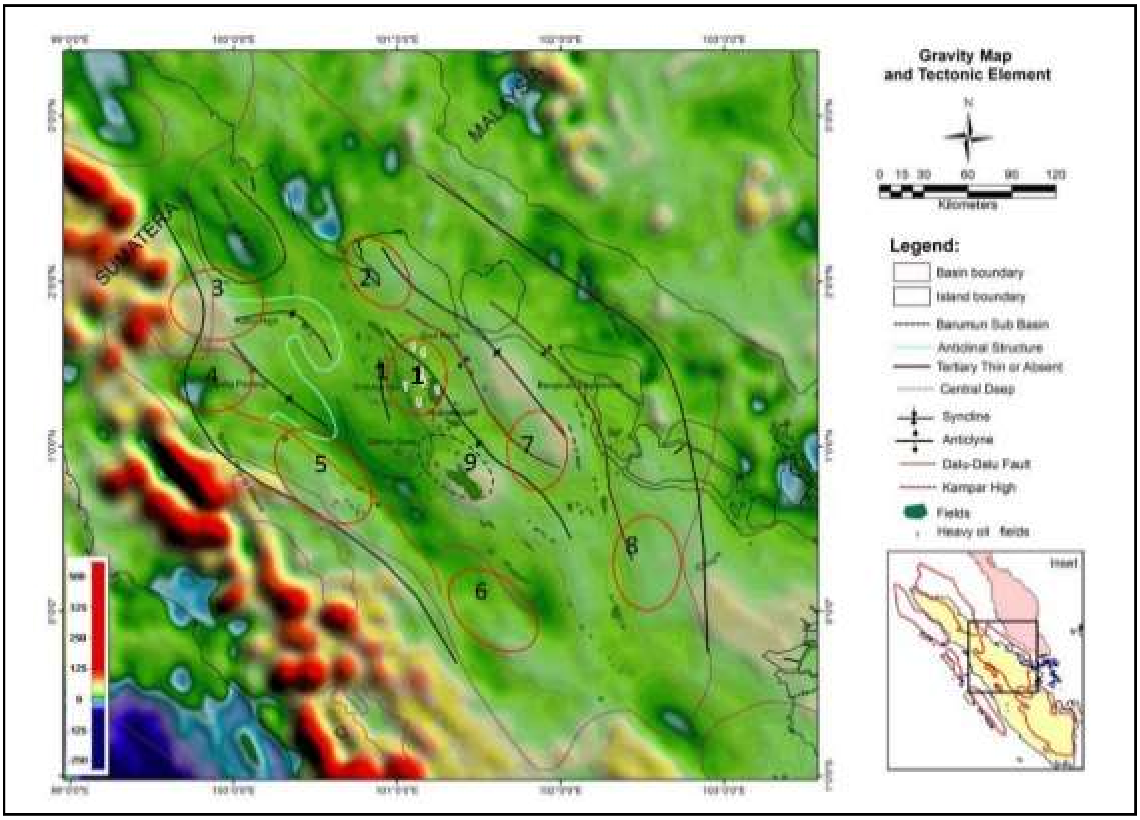

Figure 5
Gravity map of Central Sumatra Basin depicting rough locations of 9 basement highs of (1) Rokan, (2) Sembilan, (3) Kubu, (4) Ujung Pandang, (5) Dalu-Dalu, (6) Kampar, (7) Beruk, and (8) Kuantan. Dotted circle of no. 9 marks location of Minas field, which is located at the edge of Minas High. The Sebanga great thrust fault is on the northeast-east whereas the Dalu Dalu and Pulau Gadang thrust faults are on the southwest-west. (source: Lemigas, 2020).

visual measurement (i.e length, height, density, etc), and image analysis (i.e relations between extracted information and actual objects). The overal surface lineament interpretation was then overlain with the subsurface lineament interpretation (Figure 6). The overal results show a general consistency between the two lineament interpretations. Based on this lineament interpretation it is shown that the heavy oil fields - Duri and others are used as reference - are usually located at the edge of the Basement highs.

With an understanding that heavy oil bearing traps are usually situated at edges of Basement highs, it is suggested that the heavy oil potentials are mainly located - apart from the Rokan Basement High that contains the producing large heavy oil fields - in Dalu Dalu and Kampar Highs in the southwest and Beruk, Kuantan, and Sembilan Highs in the northeast-north of the basin. In Rokan/Minas/ Sembilan Highs axis there are Duri, Kulin, Batang, Sebanga, and Rantau Bais producing heavy oil fields, while in Dalu Dalu High there are heavy oil tested fields of Kotalama, Kumis, Kasikan, and Langgak. In Dalu Dalu High there are also some exploration/ discovery wells (status P&A) such as Batu Kecil-1, Ngaso #1, Kepanasan #1, Bacang #1, Ladang #1, and Paitan #1 that need further investigation for its heavy oil potential in micro analysis. Other cases are also true for the other Basement highs, whether in the form of P&A wells or in the shallow depths of non-heavy oil producing fields.

Evaluation of subsurface geology was also carried out in order to describe further the subsurface structures and stratigraphy of the Basement Highs that have been identified. The evaluation was mostly made using 2D seismic data wth support of any well log data available. The evaluation covers sequence stratigraphy analysis based on well data, seismic interpretation, and subsurface description regarding structural characteristics and rough structural subsurface mapping. The evaluation was heavily hindranced by some lacks of seismic line data and the various vintages that characterizes the available data. Nevertheless, findings have been made that most of the structures containing or indicated to contain heavy oil are mostly of anticlinal type and strongly uplifted adjacent to the main

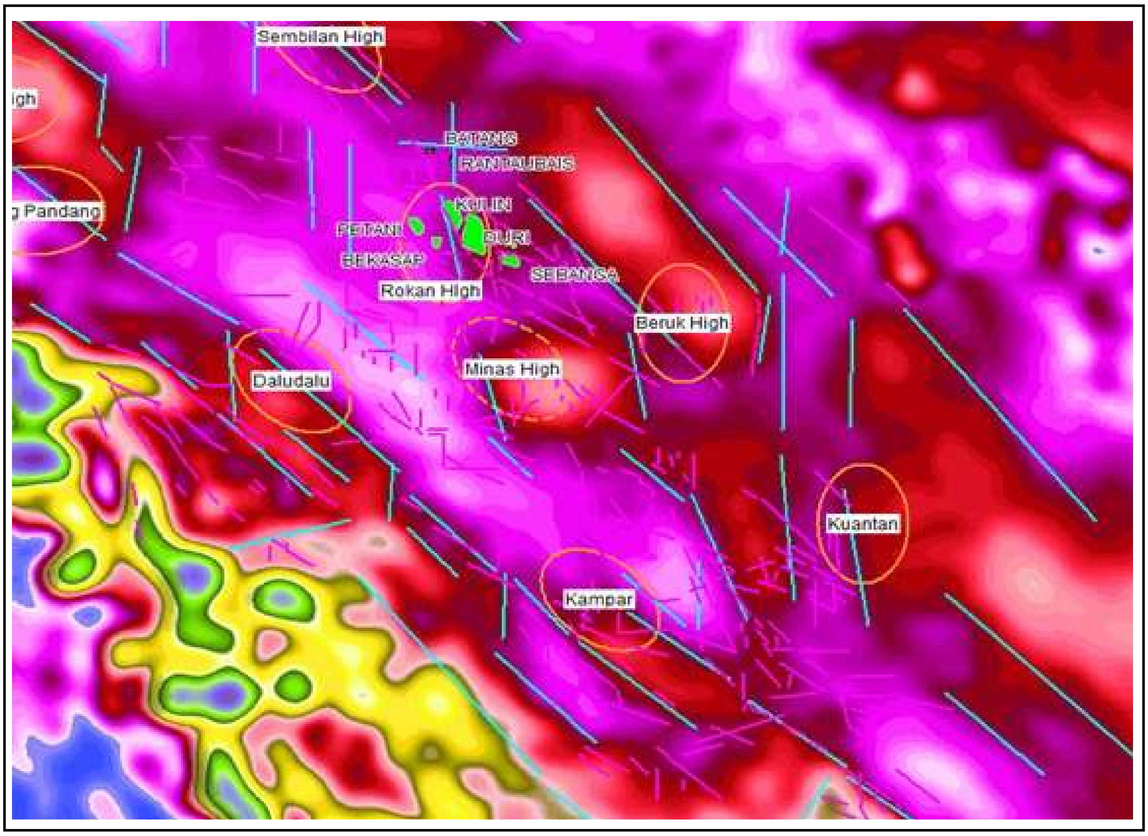

Figure 6
Surface lineament interpretation (purple lines) and subsurface lineament using gravity map (light blue lines) showing general agreement in trends. Red circles represent potential areas for heavy oil generation (edge of basement highs). (source: Lemigas, 2020).

thrust faults. Lesser faults have also been identified around the identified heavy oil bearing structures with a thought that water associated with biodegradation and water washing processes often enters traps through these faults. Figure 7 presents an example showing the anticlinal nature of structure in Pendalian field in Dalu Dalu High.

For establishing the heavy oil/biodegradation window required for limiting the scope of investigation vertically, two activities are performed; field sampling to sample the heavy oil and examining microorganism that has been generating it, and establishing geothermal gradient map that leads to the spatial temperature distribution within the CSB. Heavy oil sampling was carried out on seepage (or oil spill?) locations in Minas area (Lemigas, 2020). Laboratory analysis and measurements on the samples results in oil density of 11° API and identified microorganism of *Burkholderia multivorans* ATCC BAA-247 and *Moraxella osloensis* strain NCTC 10465. The *Burkholderia multivorans* ATCC BAA-247 is known to thrive in atmospheric condition but can withstand temperature of up to 60°C (Akita, *et al.*, 2017) Figure 8. This temperature value is taken as the lower limit of the biodegradation interval.

Geothermal gradient of the Central Sumatra Basin was firstly published by Kenyon, *et al.* (1976) in the form of Geothermal Gradient Map of Indonesia. Other publications are byAadland & Phoa (1981) (Geothermal Gradient Map of Indonesia) and Eubank & Makki (1981). Data from thethree sources was then combined, verified using several well log and report data, and then was used for a new geothermal gradient map (Figure 9). From the newly established map, it was found that lower depth of the heavy oil biodegradation window - based on *Burkholderia multivorans* ATCC BAA-247 characteristics - varies throughout the CSB, but in general within depths range of 500 - 600 meters below sea level.

Apart from the effort to identify reservoirs containing or suspected to contain heavy oil through the integrated macro analysis, efforts have also been made to clusterize heavy oils in the CSB through geochemistry approach in relation with density (API gravity) and geological locations. Information was obtained from various reports, which often verified using correlation between degree of biodegradation with API gravity established by Head, *et al.* (2013). In general there have been recognized four (4) heavy oil types in CSB (not to be confused with the four chemically different oils in CSB as presented in Katz & Mertani, 1989), which are: 1) Type-1, in shallow reservoir and fully biodegraded/water washed; 2) Type-2, in shallow reservoir and partially biodegraded, with meteoric water; 3) Type-3, in deep reservoir usually in form of tar/oil sands, which is probably generated through vertical segregation between the original oil's light and

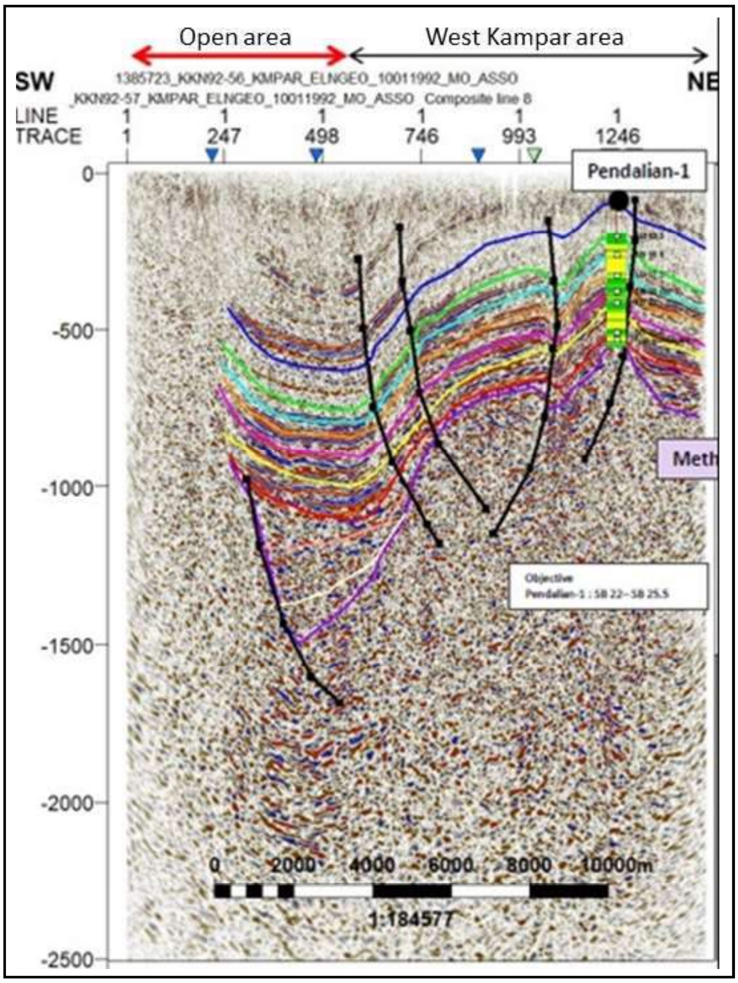

Figure 7
Anticlinal structure of Pendalian field in Dalu Dalu High.
(source: Lemigas, 2020).

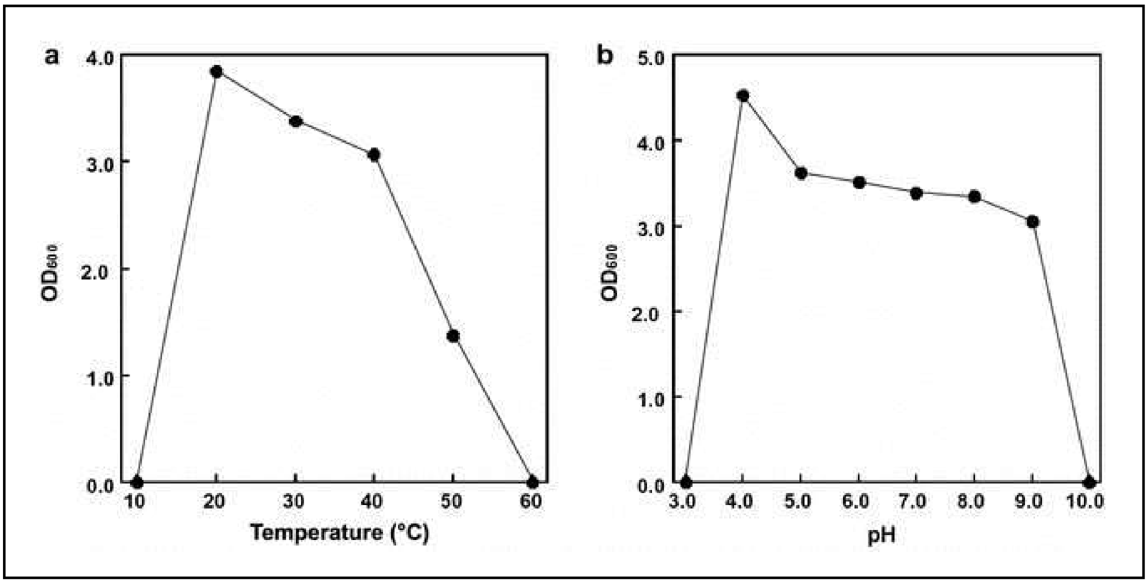

Figure 8
Effect of temperature and pH on ***Burkholderia multivorans*** ATCC BAA-247 growth (Akita, ***et al.,*** 2017).

heavy fractions; and 4) Type-4, medium-heavy (25^o - 27^o API) oil in deep reservoir, which generation mechanism is still unknown. Figure 10 depicts chromatograms of the four heavy/medium-heavy oil types.

The Type-3 and Type-4 oils may still be included into heavy oils being studied even though their presence are not in line with the concept adopted in this study. The Type-3 tar/oil sands is found in Kotabatak and Kotagaro deep zones (not in Basement highs), whereas the Type-4 medium-heavy oil is found in Sijambu and Pusing fields in the northern part of CSB. The overall results of the macro analysis - including the four heavy/medium-heavy oil types - are presented in the regional geological map (Figure 11). This map is essentially a guidance for locations to be further studied in micro analysis.

Micro Analysis

In macro analysis, the main objective is to delineate geographical and spatial scope of investigation, even though attention was still spent

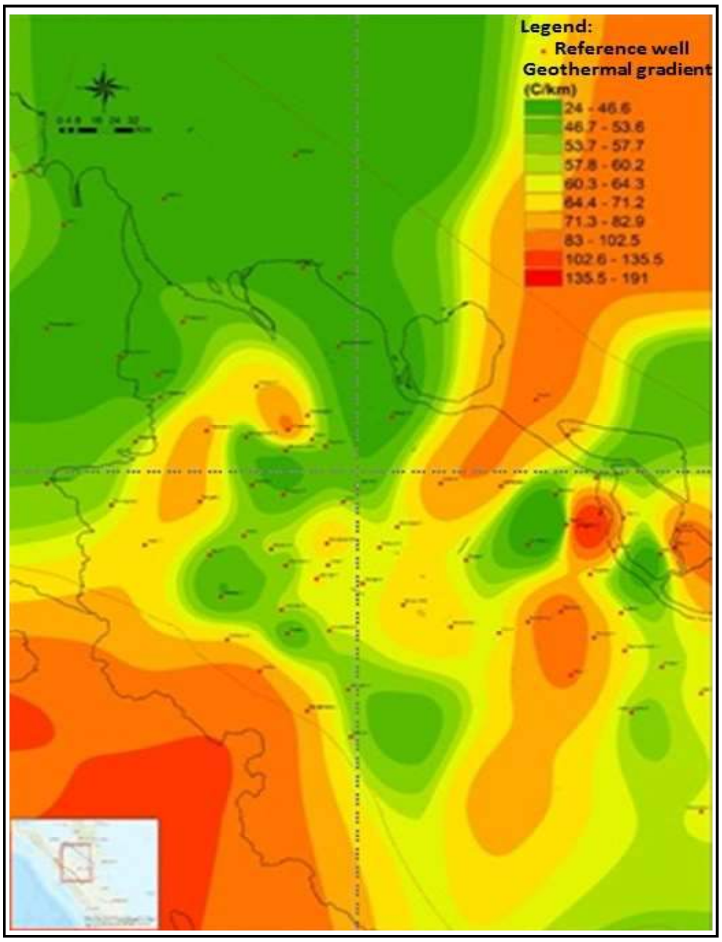

Figure 9
Geothermal gradient (^{o}C/km) map of Central Sumatra Basin.
The map is substantially based on compiled data from Kenyon *et al.,* (1976); Aadland & Phoa (1981); and Eubank & Makki (1981).
(source: Lemigas, 2020).

to information regarding presence of heavy oil beyond the Basement high areas. On the other hand, in micro analysis the main objective is to identify and determine over the exact whereabouts of the heavy oil presence. Different state of development and different level of data availability lead to the need to enclose status of certainty of presence to the identified heavy oil accumulation.

The micro analysis is essentially carried out through qualitative and quantitative well log analysis supported by all relevant data available from well test and laboratory measurement reports. Standard open hole log interpretation/analysis was performed on standard log suite covering electric and radioactive logs. Following the categorization of heavy oil presence described previously, heavy oil producing fields like Duri, Batang, Kulin, and rantaubais are within Category #1. Despite Category #1, analysis was nonetheless performed to find the upside potentials within the fields.

Duri field in the Rokan High, for instance, is producing heavy oil under Duri Steamflood (DSF) project from its main reservoirs of Baji/Jaga, Dalam, P-K, and Rindu. Analysis for upside potential in the field reveal shallower heavy oil bearing sands around depths of 100 - 200 meters below sea level. Another example is analysis on Kotabatak field, a field that produces medium/light oil. From the analysis it was discovered the field has unproduced deep tar/oil sands (Figure 12), of which drilling and laboratory testing reports indicate presence of the extra heavy oil in the deep interval. The Duri's shallow sands contains Type-1 oil while the deep Kotabatak intervals contain Type-3 oil. Both accumulations are within Category #1 (high certainty).

Another example is the Sebanga field - located in Rokan High - which production comes from the deeper sands with their medium/light oil. Analysis on Sebanga #11 (representative) well identified permeable intervals at depth interval of 295-393 meters below sea level (Figure 13),which is well within the biodegradation window. Combined deep/shallow resistivity logs and neutron-density logs interpretation indicates strong indication of oil accumulation within the permeable interval. Fluid samples and well test data for the interval is not available, including from shallow intervals in other Sebanga wells, that can be used for confirmation on contents. The only source of information is from the nearby

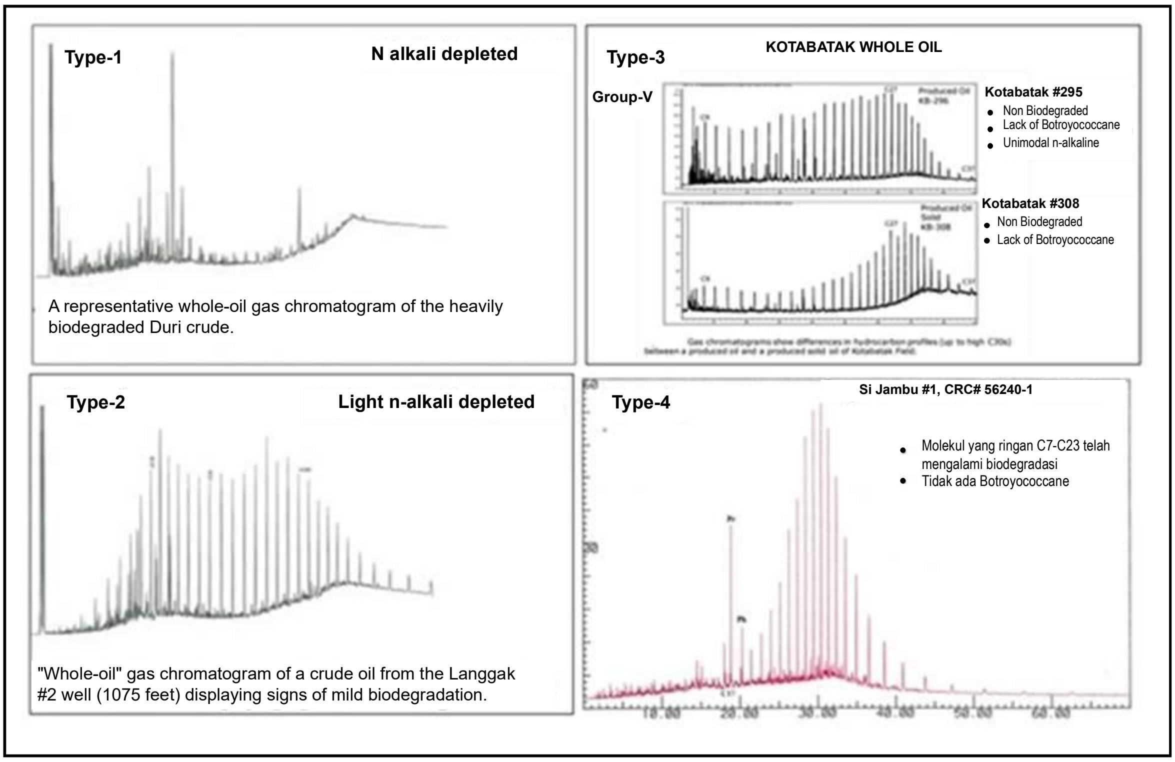

Figure 10
Chromatograms from gas chromatographic measurements for
the four heavy/medium-heavy oil types in Central Sumatra Basin. (source: Lemigas, 2020).

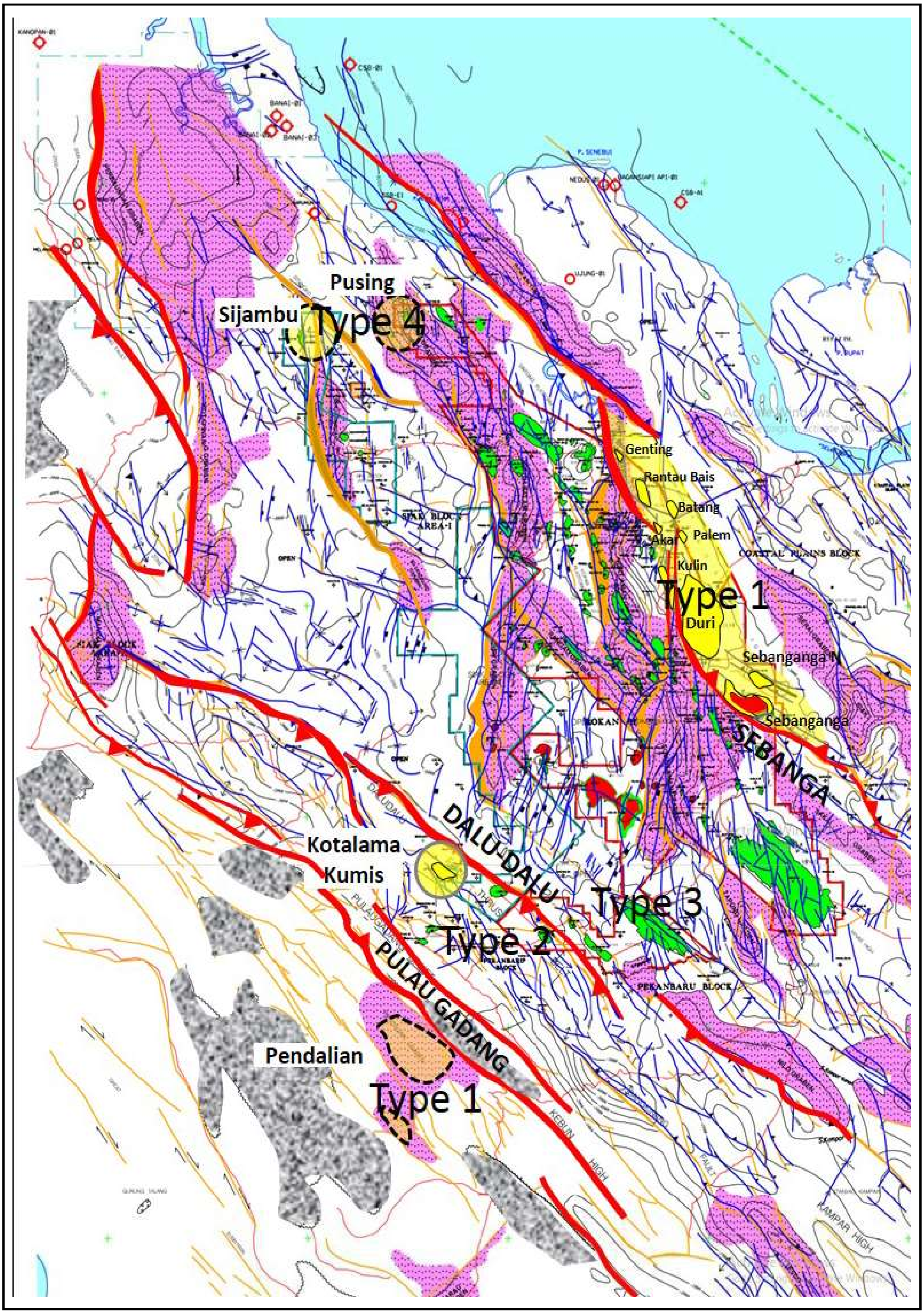

Figure 11
Structural map of Central Sumatra Basin with clusters of the four heavy/medium-heavy oils.
This map is the guidance for deeper evaluation in reservoirs within the clusters. (source: Lemigas, 2020).

vy oil from its shallow sands. Comparison in depth intervals and log-derived petrophysical properties between the two fields' shallow sands show strong similarity. This leads to decision to include the shallow zones in Sebanga field within Category #2 (medium to high certainty) with heavy oil of Type-1.

The last example is an analysis on Bolo #1 exploration/discovery well (status: P&A) in Dalu Dalu High. Analysis on log suites indicates a hydrocarbon bearing permeable interval at 350 - 375 meters below sea level, and probably another one at 312 - 330 meters (Figure 14). At such shallow depths the permeable intervals overlie the Basement. Signs of shallow gas pocket or fresh water-bearing sands are absent, which is further confirmed from undocumented sources of information. Supporting data from well tests and/or fluid sampling for the intervals - and for the well - is not available. The only factor that may be used to determine them as heavy oil bearing intervals are the fact that they are within the biodegradation window. This heavy oil accumulation is therefore included as within Category #3 (low to medium certainty).

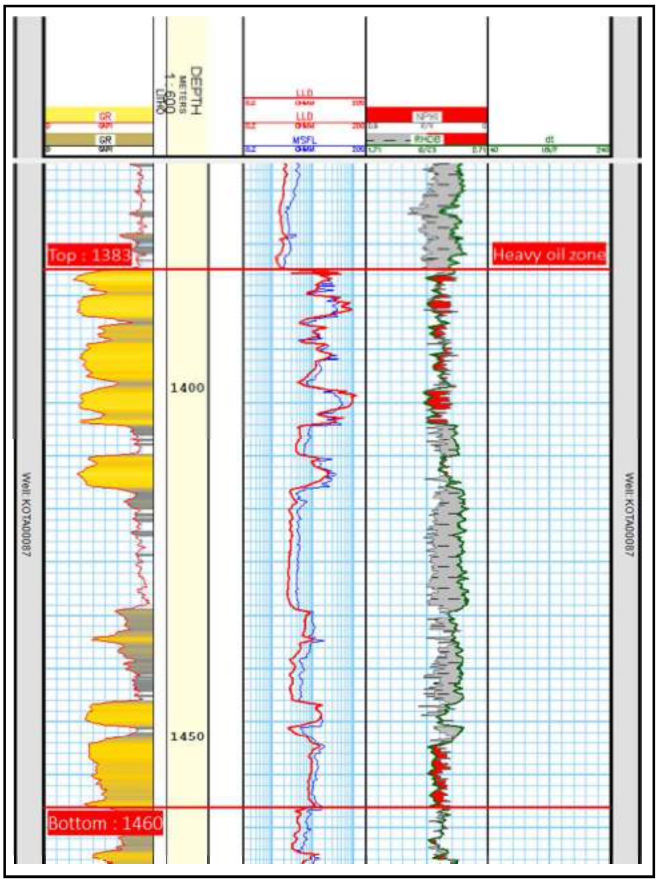

Figure 12
Analysis on Kotabatak #87 well log suite that identifies deep tar/oil sands interval at depths of 1383 – 1460 meters below sea level, which is far below the biodegradation window of 600 meters. Accordingly, the bitumen in the oil sand is of Type-3 heavy oil. The accumulation is nevertheless within Category #1 (high certainty). (source: Lemigas, 2020).

As many as 45 fields containing - or suspected to contain - heavy oils and 103 exploration wells (status: P&A with no other wells in the structure) in the nine Basement highs were put into the micro analysis (Table 1). The analysis was performed following the methodology and found situations in a way similar to what have been described for the three exemplary cases. Data and information available to each case varies significantly, but in general the approach adopted in the analysis apply to all cases. Tables 2 through Table 4 present the overall results in form of fields/structures having heavy oil accumulation in Category #1, Category #2, and Category #3, respectively. Graphically, Figure 15 presents the basin's structural map with distribution of fields/wells along with their categories of certainty.

C. Further discussion

Since the objective of the study is to re-visit and identify the potential of heavy oil, the overall results of the micro analysis and categorization of the accumulations are best presented in the form of number of fields and trap within the three categories of certainty. As many as 22 fields/traps are within Category #1 (high certainty), 6 within Category #2 (medium to high certainty), and 23 within Category #3 (low to medium certainty). One of the most important point from the figures is that out of 51 fields/traps only 6 - Duri, Kulin, Batang, Rantau Bais, Sebanga North, and Pendalian - are in the status of producing their heavy oil. Other fields in the Category #1 are mostly in the status of production, but not for their heavy oil potential and instead for their medium-lighter density oils from their lower reservoirs. Some within the Category #1 are not in status of production at all, but availability of information confirming presence of heavy oil - and oil/tar sands - put them within this category.

Another important point that can be observed is that the large number of fields/traps within Category #2 and Category #3. Although the few producing fields of Duri, Kulin, Batang, and Rantau Bais hold most of the heavy oil original oil in place up to present (Lemigas, 2020),but the considerable number of identified potential field/traps also means considerable opportunities for winning more heavy oil reserves in CSB. Micro analysis have identified some examples of substantial heavy oil-bearing gross thickness in the analyzed wells. Gross thicknesses of 235 m and 300 m have been identified for Akar (Category #1) and Pala (Category #3) fields, respectively. In geological sense, such large reservoir thicknesses are likely to spread widely leading to substantially large heavy oil accumulation. Expansive and deeper studies - with more data - are needed to further examine such cases. Furthermore, more data hence more evaluations may lead to elevation of category of certainty for the oil accumulation.

Concept of biodegradation and water washing mechanisms in Basement highs appears to apply well in Central Sumatra Basin. Fields or traps have been identified in the three categories of certainty through this concept. However, the micro analysis also reveal that some fields/traps in the Basement highs contain medium/light oils instead of heavy oil. The large Minas field is the primary example (Figure 16). The most plausible explanation for this is there must have been some factors that have denied the required condition for the two heavy oil generation mechanisms to work. Absence of sufficiently permeable water conduit that connects the trap to the surface and absence of links to any active hydrodynamic system are two likely factors. This condition may occur if the sealing cap rock to the traps are thick enough for the factors to prevail. As put by Fitris (2020), Telissa shale formation that acts as cap rocks for most CSB reservoirs is not homogeneous in thickness and sealing quality. Under thin and weak cap rock connection to the surface the mechanisms work easier leading to heavy oil transformation; and the reverse is true for thick and good quality sealing cap rock. Absence and presence of faulting also seem to be determining factors since fault planes may act as fluid conduit, for oil to migrate upward and for microorganism-containing water to encroach downward.

From the nine basement highs within the CSB two of them, Rokan (in one axis with Minas and Sembilan Highs) and Dalu Dalu, appear to bear most of the heavy oil potentials found. The Rokan (RMS) High is undoubtedly prolific in any type of crude oil. Duri, Kulin, Rantau Bais, and Batang heavy oil fields - as well as Minas medium/light oil fields - are located in this Basement highs axis. On the other hand, the Dalu-Dalu High has so far only limited number of relatively small fields, but appears to be the placefor a large number of P&A exploration wells which some of them prove to have shallow heavy oil potential (Table 1). This is not to take into account data of twenty or so P&A exploration wells that is still unavailable to

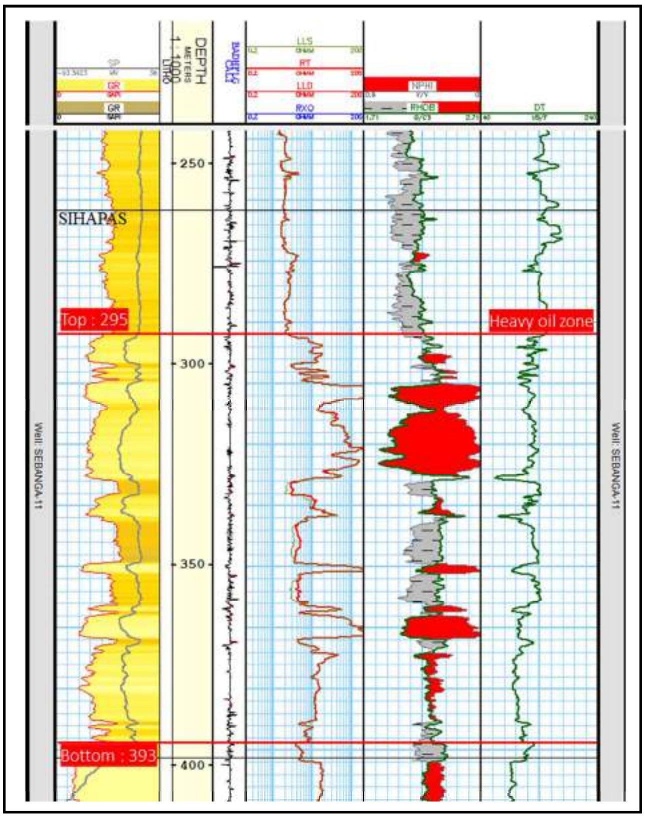

Figure 13
Analysis on Sebanga #11 well log suite that identifies deep heavy oil interval at depths of 295-393 meters below sea level. Information available to analysis led to it being included in Category #2 (medium to high certainty) accumulation with Type-1 heavy oil. (source: Lemigas, 2020).

the Sebanga North field that is producing hea study team until the end of study. Therefore, a more detailed and focused study specifically devoted to the area is suggested to be conducted for more accurate and comprehensive results.

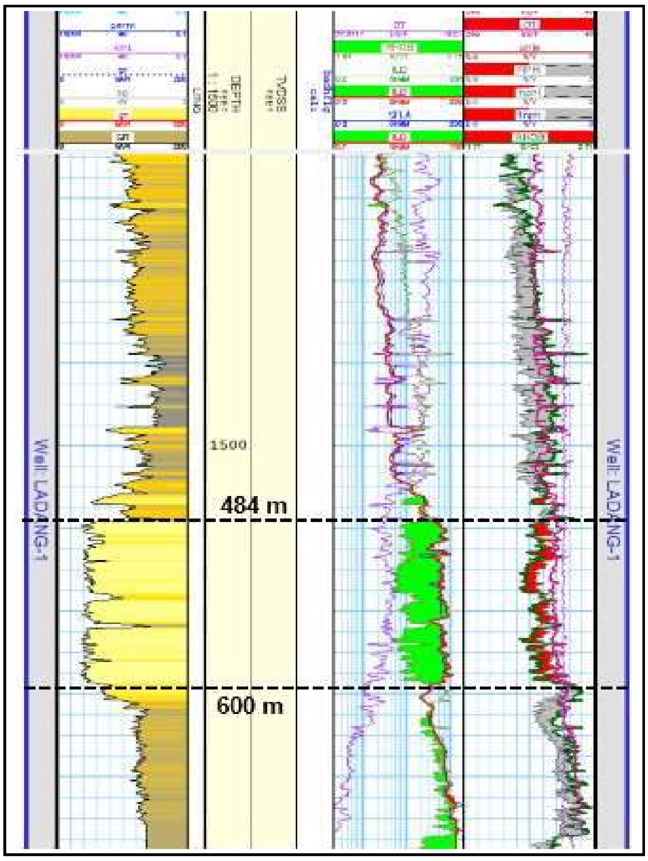

Figure 14
Analysis on Bolo #1 well log suite that identifies deep heavy oil interval at depths of 350 - 375 meters below sea level, and probably another at 312 - 330 meters. Absence of data for confirmation, apart from it being within biodegradation window, has led to it being included within Category #3 (low to medium certainty) accumulation with Type-1 heavy oil. (source: Lemigas, 2020).

CONCLUSIONS

A study to revisit and identify heavy oil potential in Central Sumatra Basin has been conducted with all available data to the study team, based on a sound integrated approach, and carried out in accordance with the team's best interpretation skills. Some conclusions have been drawn from the results:

The study has established 22 heavy oil fields/traps - six of which are in the status of producing - within Category #1 (high certainty), six (6) within Category #2 (medium to high certainty), and 23 within Category #3 (low to medium certainty). The sufficiently large number of combined Category #2 and Category #3 fields/traps indicates that there is still considerable heavy oil potential in the Central Sumatra Basin. This underlines the need to study further and deeper for a better picture of the basin's heavy oil potential.

Within the Category #1 heavy oil fields/traps only six are in status of producing, while the rest of them (16 fields/traps) are either non-producing fields with sufficient evidence of heavy oil accumulation or up-side potential in producing heavy oil/non-heavy oil fields. This has certainly been realized by the operators of the fields, but probably due to certain technical and economical considerations this potential is not exploited. However, this piecemeal individual field heavy oil potential may make up a substantially large quantity, especially when this upside potential is combined with the heavy oil potential in Category #2 and Category #3 fields/traps. The large combined basin-scale potential is worth considering for exploitation in the future, provided condition permits.

The integrated approach adopted in this study proves itself working properly for geographycal/lateral focusing in effort to identify locations of the heavy oil bearing reservoirs. All nine Basement highs have been identified and most of them are proved to have heavy oil presence, confirmed by the micro analysis

Table 1
Number of producing fields and individual exploration/discovery wells (P&A) that underwent micro analysis.

No.	Basement High	Field	Well (P&A)
1	Kuantan	-	8
2	Kampar	-	4
3	Dalu Dalu	8	37
4	Ujungpandang	-	5
5	Sembilan	4	12
6	Rokan (RMS)(*)	26	18
7	Beruk	3	11
8	Kubu	-	-
9	NBH (**)	4	8
Total		45	103

(*) RMS: Rokan-Minas-Sembilan axis

(**) non Basement high, locations between Basement highs

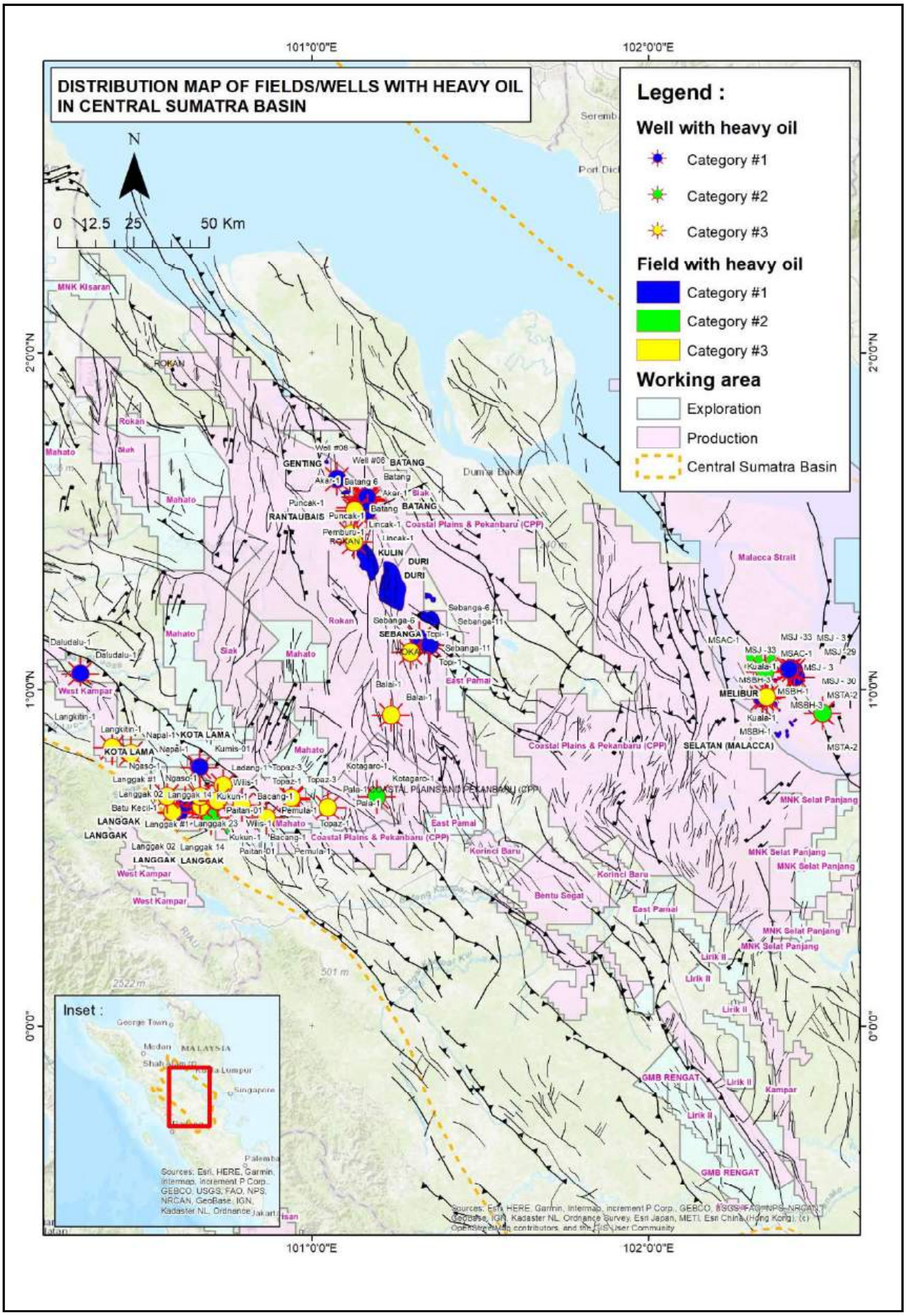

Figure 15
Central Sumatra Basin's structural map with distribution
of fields and wells having heavy oil of the three categories. (source: Lemigas, 2020).

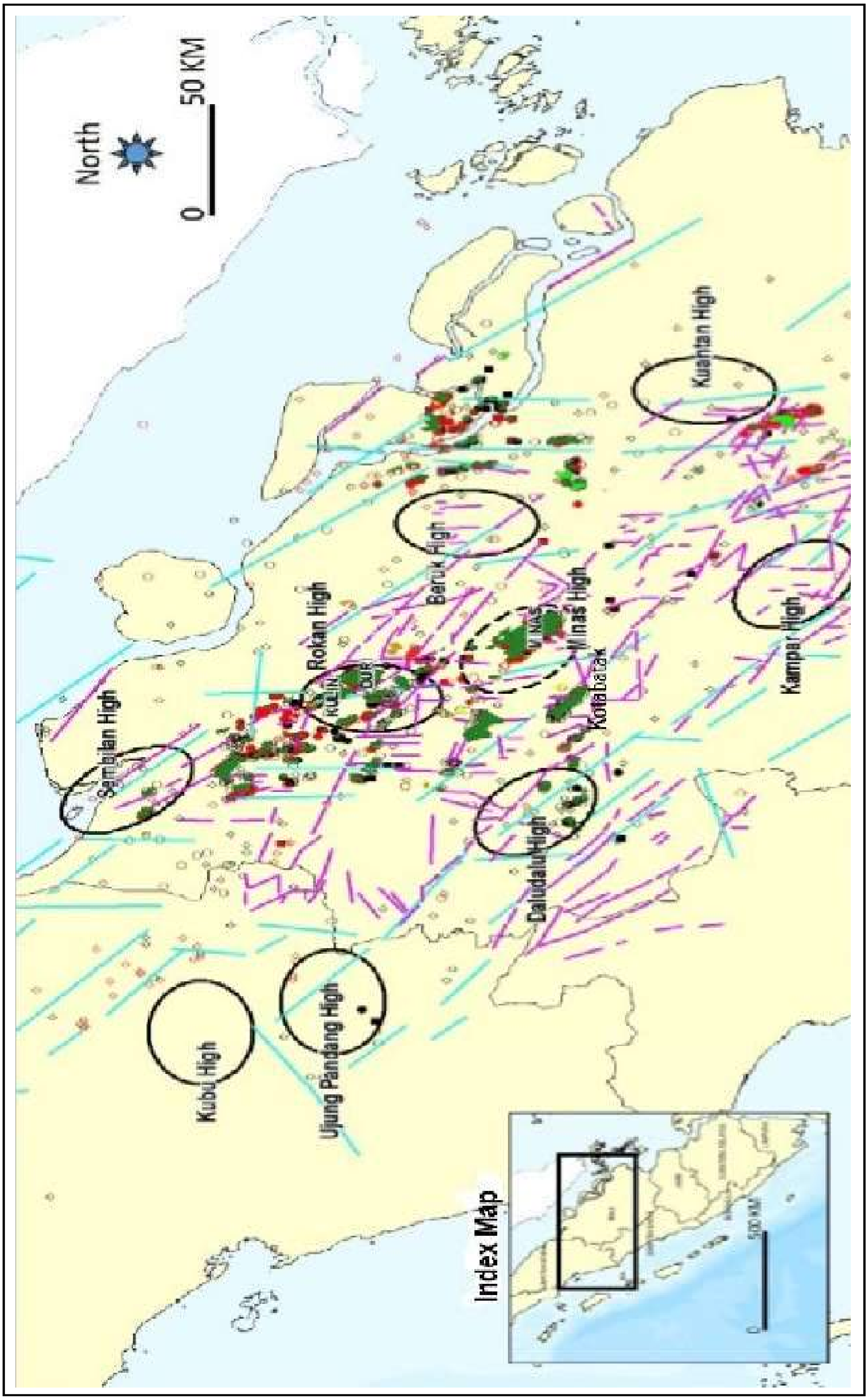

Figure 16
Duri, Kulin, Kotabatak, and Minas fields with circles marking approximate locations of the nine Basement highs.

Table 2
Fields/trap of heavy oil within Category #1 (high certainty). (source: Lemigas, 2020)

No.	Field/Trap	Basement High	Depth(*) (meters)(**)	Heavy oil type	Status
1	Batang (Rokan)	Rokan (RMS) (***)	150-300	Type-1	Producing
2	Batang (Siak)	Rokan-Sembilan	155-190	Type-1	Non-producing
			1015-1100	Type-3	Non-producing
3	Duri (Steamflood)	Rokan (RMS)	300-400	Type-1	Producing
4	Duri (D240;D140)	Rokan (RMS)	50-250	Type-1	Non-producing
5	Duri North	Rokan (RMS)	300-318	Type-1	Non-producing
6	Genting	Rokan (RMS)	210-345	Type-1	Non-producing
7	Kotalama	Dalu Dalu	100-175	Type-2	Non-producing
8	Kulin	Rokan (RMS)	287-396	Type-1	Producing
9	Kulin North	Rokan (RMS)	285-415	Type-1	Non-producing
10	Langgak	Dalu Dalu	355-425	Type-2	Non-producing
11	Melibur (MSJ)	Beruk	305-365	Type-1	Non-producing
12	Rantau Bais	Rokan	190-300	Type-1	Producing
13	Selatan (MSBH)	Beruk	50-200	Type-1	Non-producing
14	Sebanga	Rokan (RMS)	355-372	Type-1	Non-producing
15	Sebanga North	Rokan (RMS)	300-700	Type-1	Producing
16	Kumis	Dalu Dalu	172-210	Type-2	Non-producing
17	Pendalian	Dalu Dalu		Type-1	Producing
18	Akar	Rokan (RMS)	165-400	Type-1	Non-producing
19	Kotabatak (tar sands)	Non Bsmt high	1385-1410	Type-3	Non-producing
20	Wilis (tar sands)	Dalu Dalu	360-405	Type-2	Non-producing
21	Dalu Dalu	Dalu Dalu	213-244	Type-2	Non-producing
			1510-1565	Type-3	Non-producing
22	Gatam	Beruk	684-700	Type-1	Non-producing

(*) depth recorded in representative well
(**) below sea level
(***) RMS: Rokan-Minas-Sembilan axis

Table 3
Fields/trap of heavy oil within Category #2 (medium to high certainty). (source: Lemigas, 2020)

No.	Field/Trap	Basement High	Depth(*) (meters)(**)	Heavy oil type
1	Kasikan	Dalu Dalu	155-225	Type-2
2	Paitan	Dalu Dalu	450-460	Type-2
3	Kotagaro (tar sands)	Non Bsmt high	1707-1835	Type-3
4	Kurau	Rokan (RMS)(***)	112-155	Type-1
5	Lindai	Dalu Dalu	100-200	Type-2
6	Pemburu	Rokan (RMS)	360-492	Type-1

(*) depth recorded in representative well
(**) below sea level
(***) RMS: Rokan-Minas-Sembilan axis

Table 4
Fields/trap of heavy oil within Category #3 (low to medium certainty).(source: Lemigas, 2020)

No.	Field/Trap	Basement High	Depth(*) (meters)(**)	Heavy oil type	Status
1	Pusing	Sembilan	1209-1227	Type-4	Non-producing
2	Puncak	Rokan (RMS)(***)	382-390	Type-1	Non-producing
3	Palem	Rokan (RMS)	215-340	Type-1	Non-producing
4	Topi	Rokan (RMS)	150-175	Type-1	Non-producing
5	Lincak	Rokan (RMS)	382-500	Type-1	Non-producing
6	Topaz	Non Bsmt high	538-600	Type-3	Non-producing
7	Pemula	Dalu Dalu	570-590	Type-2	Non-producing
8	Balai	Sembilan	150-255	Type-4	Non-producing
9	Ladang	Dalu Dalu	484-600	Type-2	Non-producing
10	Bolo	Dalu Dalu	350-375	Type-2	Non-producing
11	Kuala	Rokan (RMS)	175-250	Type-1	Non-producing
12	Pala	Non Bsmt high	275-575	Type-3	Non-producing
13	Ujung Tanjung	Rokan (RMS)	586-610	Type-1	Non-producing
14	Kukun	Dalu Dalu	438-611	Type-2	Non-producing
15	Batukecil	Dalu Dalu	377-490	Type-2	Non-producing
16	Ngaso	Dalu Dalu	451-582	Type-2	Non-producing
17	Kepanasan	Dalu Dalu	505-556	Type-2	Non-producing
18	Jingga	Dalu Dalu	25-600	Type-2	Non-producing
19	Bacang	Dalu Dalu	475-525	Type-2	Non-producing
20	Intan	Rokan-Beruk	425-500	Type-1	Non-producing
21	Waduk	Dalu Dalu	475-600	Type-2	Non-producing
22	Langkitin	Dalu Dalu	397-517	Type-2	Non-producing
23	Napal	Dalu Dalu	155-475	Type-2	Non-producing

(*) depth interval recorded in representative well
(**) below sea level
(***) RMS: Rokan-Minas-Sembilan axis

carried out to pinpoint the depth intervals containing the heavy oil. Establishment of a biodegradation window through combined microorganism study and generation of updated geothermal gradient map for the basin proves very useful in limiting further the study's spatial scope of investigation. This also proves that mechanisms of biodegradation and water washing have worked well in Central Sumatra Basin.

Presence of oil/tar sands in Kotabatak and Kotagaro fields' deep reservoirs have opened a new insight over presence of another type of heavy oil in Central Sumatra Basin. This deep oil/tar sands - unlike in other examples such as in Athabasca region in Canada – is not accompanied by heavy oil accumulation in shallower zones. Segregation between heavy and lighter components due to gravity forces is probably the cause, but the exact factor(s) that triggers the gravity-driven segregation is virtually unknown. A more thorough study has to be performed to yield a more convincing answer.

From the nine Basement highs identified by the study, the Rokan (Rokan-Minas-Sembilan) Basement High can certainly be considered as the most prolific place for heavy oil accumulation in Central Sumatra Basin. The Dalu Dalu High, however, has shown itself as the Basement high with the most numerous exploration wells (status: P&A) with shallow oil bearing zones (mostly of Category #3). Serious attention has to be given to investigate further Basement high's heavy oil potential in order to improve its category of certainty.

The presence of very shallow heavy oil bearing zones - D240/D140 sands in Duri field (Rokan, Category #1) and very shallow zones in Jingga trap (Dalu Dalu, Category #3) - has led to possibility of heavy oil open pit mining scenario in Central Sumatra Basin. This exploitation option certainly requires more extensive and intensive studies over its feasibility. Nonetheless, this option should not be omitted as one possible exploitation mode, provided favorable condition is met.

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GLOSSARY AND TERMS

Symbol	Definition	Unit
API	American Petroleum Institute for Oil Gravity	
BOPD	Barrel oil per day	
CSB	Central Sumatra Basin	
DEM	Digital elevation model	
GIS	Geographic information system	
OLI	Operational land imager (type of satellite image)	
P&A	Plugged and abandonned (well)	
PRMS	Petroleum Resources Management System	

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