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Integrated Approach to Investigate the Potential of Asphalt/Tar Sand on Buton Island, Indonesia

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ABSTRACT - Buton island as a potential area for conventional oil and gas, as well as asphalt/bitumen has long been the target of evaluation aimed at exploiting this potential, although to date no economic exploitation has been implemented. In this study, the potential of Buton asphalt/bitumen with mineable and in situ (non-mineable) status was studied and evaluated. In this study, qualitative and quantitative analysis have been carried out from Landsat 8 and Shuttle Radar Topography Mission (SRTM) data with the aim of identifying the presence of active faults and gravity due to orogenic processes. The lineament density pattern shows a general direction of NE-SW to NNW-SSE. The lineament process between satellite image data and gravity surveys helps efforts to identify the distribution of asphalt on Buton Island. Through combining distribution patterns of the Sampolakosa, Tondo, and Winto Formations, contain asphalt/bitumen, the study produces distribution of asphalt/bitumen accumulation in the region, both in surface/mineable and in situ categories. The 'best estimate' reserves obtained are 786.6 million barrels and 46 million barrels, respectively for asphalt/bitumen surface/mineable reserves and in situ/non-mineable reserves. It is hoped that this information regarding the potential/reserves of asphalt/bitumen on Buton Island may support efforts to exploit it.

Keywords: buton, asphalt/bitumen, reserves, lineament

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INTRODUCTION

Indonesia has an ambitious target to achieve national production of one million barrels of oil per day (MMBOPD) and 12 billion cubic feet per day (BSCFD) of natural gas by 2030 (Fitnawan et al. 2021). Efforts made to achieve this include enhanced oil recovery (EOR) (Hendraningrat et al. 2021), activating small and idle oil fields to help recover reserves (Azmalni et al. 2023), heavy oil exploration (Susantoro et al. 2022; Widarsono et al. 2021), and asphalt/bitumen extraction (Mu et al. 2023). In connection with efforts to support efforts to increase production, the asphalt/bitumen extraction approach needs to be given attention. Asphalt is define as, "A naturally occurring hydrocarbon of very viscous character. They may occur as the high boiling point residuum of an oil pool after the lighter fraction has evaporated. Bitumen is naturally occurring hydrocarbon tar-like hydrocarbon mineral of indefinite composition. It ranges in consistency from a thick liquid to a brittle solid" (Whitten and Brooks 1978).

Indonesia is one of the countries that has large resources of unconventional oil/tar sands after Canada, Venezuela, the United States, and Russia (Ma et al. 2021). One of the largest deposits is natural asphalt located in Lawele, Buton Island, Southeast Sulawesi Province (Siswosoebrotho et al. 2005). Currently, this asphalt is exploited only for road/highway pavements. This condition has resulted in studies tending to focus on matters relating to the characteristics and performance of asphalt for road asphalt purposes. An example is a scientific article with the theme on performance and modification mechanism of Buton rock asphalt (Lv et al. 2019) and mixing Buton rock asphalt with petroleum bitumen aimed at modifying the asphalt to produce a porous mixed asphalt product (Mabui et al. 2020). In fact, asphalt can also be extracted through hot water injection, steam, solvents, or combustion to produce crude oil (Tumanyan et al. 2014). There is a great abundance of scientific articles presenting and discussing over many aspects of oil sand/bitumen extractions in countries such as Canada, United States, Venezuela, and China (e.g Fan and Bai, 2015; Liu et al. 2019; Vishnumolakala, 2020; Ma et al. 2021).

Buton island has asphalt deposits that have been known and studied since the 1920s, and are the only asphalt deposits mined in Indonesia (Satyana et al. 2013). Asphalt deposits on the surface of Buton Island form an asphalt belt that runs through the Lawele and Sampolawa locations in the southeastern part of the island (Hetzel 1936 in Satyana 2011). Based on the experience of exploiting asphalt and oil/tar sand in the world - such as in Alberta (Canada) and Asphalt Ridge (Utah-USA) - a study of Buton asphalt has been carried out based on various similarities such as the physical properties of asphalt/bitumen, geological composition, heat gradient, and hydrodynamic conditions with those regions. Buton asphalt can be categorized as petroleum that has undergone degradation so that it can still be categorized as heavy petroleum with very high viscosity. The results of geochemical analysis indicate that Buton asphalt is of marine crude oil with kerogen type 2. The presence of asphalt and oil seep deposits on Buton Island indicates that the petroleum system has worked, migrated, and been trapped but afterward the trap's cap rocks of were eroded due to intensive deformation. This makes it possible to follow up in oil and gas exploration scenarios (Satyana et al. 2013). Oil and gas prospects in Buton are generally considered favorable, where Triassic bituminous shale and limestone are the main sources of petroleum, whereas potential reservoirs are Upper Cretaceous, Early to Middle Miocene, and Pliocene clastics and carbonates. Hydrocarbon migration occurs with the main migration routes of Miocene trust and Pliocene wrench related anticlines (Davidson 1991). Due to the scarcity of studies on the extraction of asphalt into oil or bitumen on Buton Island, further studies need to be carried out to better understand the use of asphalt on Buton Island and its surroundings. The aim of this study is to review and identify the unconventional hydrocarbon potential of asphalt/bitumen on Buton Island so that in the future it can be exploited further using exploitation scenarios for the benefit of petroleum production. A special approach is used by integrating satellite image data and gravity survey data to identify the heights of geological structures, and the use of laboratory test data to estimate asphalt/bitumen reserves, both of those categorized as mineable and those categorized as *in situ* (non-mineable).

METHODOLOGY

Study area and brief history

Buton island, which is the object of study, is considered a fragment that has separated from the Australia-New Guinea continent (Metcalfe, 2013) and is located to the southeast of the island of Sulawesi, as shown on Figure 1. This is based on the correlation of similarities between Mesozoic fossils and stratigraphy. pre-rift, and during the rift. Based on its tectonic history, its formation is similar to the formation of the islands of Buru, Seram, Banggai-Sula, and Timor (Satyana et al, 2013; Nainggolan et al., 2017; Audley-Charles, 1988; De Smet et al., 1989). Lithologically, the types of rocks exposed on Buton Island vary greatly, as does the age of the rocks, ranging from Mesozoic to Quaternary. The most extensive distribution of Pre-Tertiary rocks is found at the northern tip of Buton Island in the Kalisusu area and around the Mukito River, South Buton. Quaternary rocks are dominated by reef limestone units, distributed mainly in the southern and central parts of Buton Island.

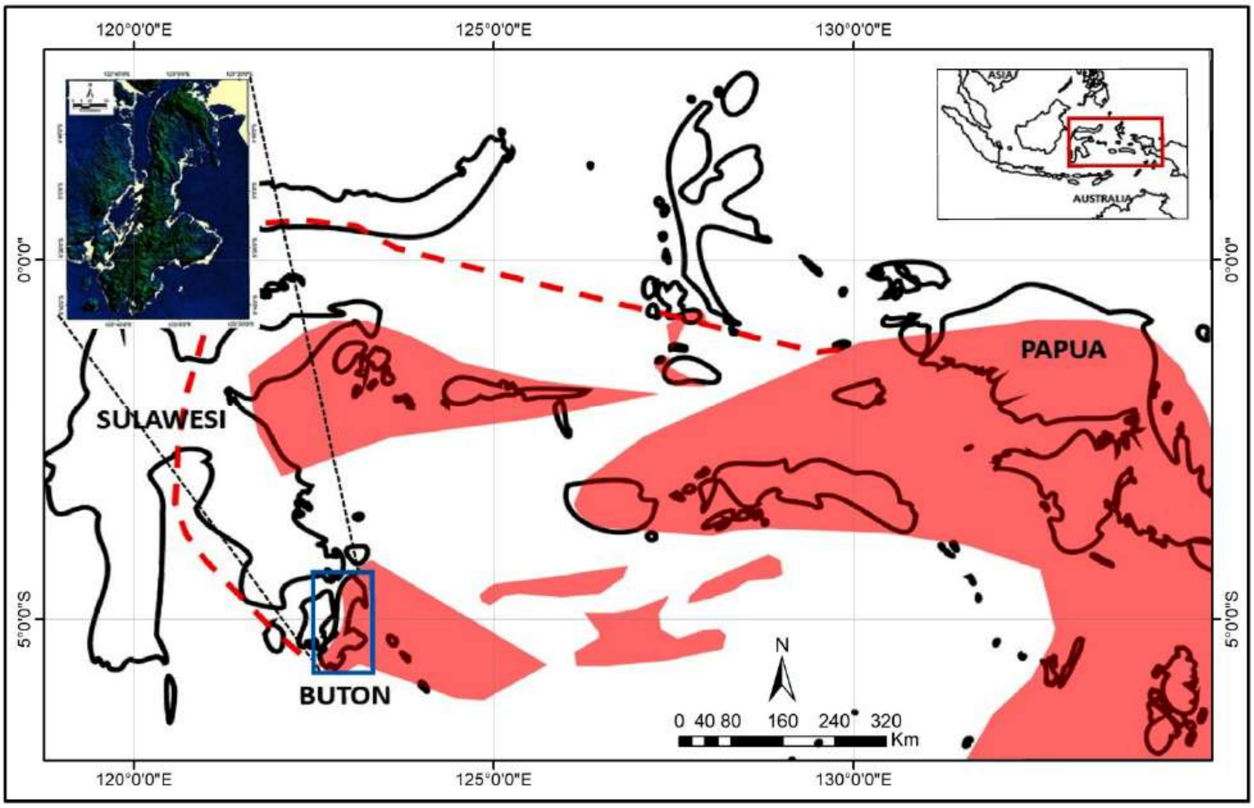

Figure 1
Buton Island is a fragment of a microcontinent whose formation is similar to the formation of Banggai Sula, Seram, and potential oil and gas areas in Eastern Indonesia (simplified from MetCalfe 2013).

The exploration survey of the Buton area, among others, was initiated by the Nederlands Indies Geological Survey (NIGS) in 1920, and then by van Haeften (1924), Zwierzycki (1925), and van Bemmelen (1949). In June 1969, on behalf of the Indonesian Government the state oil company Pertamina and Southeast Asia Oil and Gas Company signed a production sharing contract (PSC) for the offshore area of South Sulawesi, while in 1970 the Indonesian Gulf Oil Company received an operating permit in this block for carried out a survey covering 10,990 km of aeromagnetic data, 1406 km of marine seismic data, 314 km of land seismic data, approximately 440 km of surface geological data, and was equipped with drilling of three wells, namely Bale-1S, Bulu-1S, and Sampolakosa-1S.

Despite the 43-meter long column of biodegraded oil (Satyana 2011) penetrated by the Sampolakosa-1S well, and the presence of oil in the Bulu-1S well, the three wells were then plugged, abandoned, and given the status of dry wells. In December 1987, the Buton working area was awarded to Conoco and Shell. Conoco's evaluation of the work area included the acquisition of 541 km of marine seismic data, 302 km of land seismic data, 863 km of surface geological data, and the collection of 850 outcrop samples for analysis. In August 1990, a consortium of Japex Co Ltd – Premier Oil FBV - Kufpec KSC with oil and gas working areas in South Lasalimu - onshore/ offshore started activities. It is recorded that JAPEX BUTON PSC committed to the first three years of its exploration period (2009) including geological and geophysical studies, a 265 km 2D seismic survey, and one exploration drilling. Pertamina Hulu Energi (2022) carried out multi-zone 2D seismic survey activities in the Buton area. This seismic survey activity is a follow-up to the previous seismic survey in 2008. All the exploration activities above are aimed at looking for conventional oil and gas traps which are thought to be found in the Buton island area, and not particularly to assess the potential of Buton asphalt, of which some is accumulated on the surface while the others are contained *in situ* (non-mineable).

The Indonesian Geological Survey (Center for Geological Resources), in 1976, conducted an investigation into the accumulation of asphalt on

Buton Island through surface surveys, drilling, and rock/tar sand and asphalt laboratory analyses. According to Hadiwisastra (2009), Buton asphalt is mainly found in the southern part of Buton Island in several locations related to the graben shape, which extends in a southwest – northeast direction, in an area known as the Lawele Graben. However, those past studies are more directed at studying hydrocarbon potential as a whole, whereas this study focuses on the potential of asphalt/bitumen only, both categorized as mineable (exploitation/ production through open pit mining) or categorized as *in situ*/non-mineable (exploitation/ production through conventional oil production and/or enhanced oil recovery, EOR).

Research Stages

Up to present, the tectonic structure of the Eastern Indonesia region, which also includes Buton Island, is still being studied by many geoscientists. In the initial stages of this study a new approach, namely the 'rollback' theory (Spakman and Hall, 2010; Hall, 2014), was used to support understanding of the formation of geological conditions and the accumulation of asphalt deposits which were first discovered in large quantities in Indonesia. This rollback theory was proposed as a form of correction to the current tectonic theory, namely the last collision of Sulawesi with Buton-Tukang Besi and Banggai-Sula micro-continents is ongoing as confirmed by the continued uplift (Satyana and Purnamaningsih, 2011 in Satyana, 2011) and is considered more suitable for explaining regional geological conditions in eastern Indonesia (Hall 2014; Prasetyadi 2021).

Henceforth, in the study of Buton's asphalt/ tar sand potential, activity stages were carried out that include: (1) data collection from Landsat 8 OLI, and the Shuttle Radar Topography Mission (SRTM), the data of which came from the site https://earthexplorer.usgs.gov/, and gravity data from the site https://topex.ucsd.edu/cgi-bin/get_data.cgi; (2) processing of Landsat, SRTM, and gravity data in a geographic information system (GIS) format so that it can be used for lineament interpretation and determining area correction factors for estimating the volume of *in situ* (non-mineable) asphalt/ bitumen accumulations; (3) lineament density processing based on the results of surface lineament interpretation to identify the level of surface structure density; (4) plotting lineament direction to identify surface structure complexity; (5) overlay of surface and subsurface interpretation results to identify and support estimates of Buton's *in situ* (non-mineable) asphalt potential; and (6) analysis of the calculation of surface/mineable Buton asphalt reserves based on deposit and survey data originating from various sources, both published and unpublished (Bothe 1929; Hetzel 1936; Hardjono 1966; Sarana Karya 1986; and Pusjatan 2012).

Interpretation of Satellite Images and Gravity-Free Anomalies

Geological interpretation carried out on the Landsat OLI 8 image (Figure 2a), SRTM image (Figure 2b), and the gravity anomaly map was carried out regarding the direction of the rock layer plane, the direction of alignment, and the straightness of the contour pattern of the gravity anomaly. Identification of the direction of rock layers is intended to determine the presence of folds, while straightness is to determine the presence of geological structures in the form of joints or faults. This interpretation is important for initial oil and gas exploration because it can provide an understanding of geological conditions (Susantoro et al. 2022) and can be used for initial analysis of the presence of heavy oil (Suliantara et al. 2021).

In this study, to study the potential for *in situ* asphalt/bitumen accumulation, the use of the lineament approach is aimed at identifying locations of high subsurface structures that geologically have the potential to contain heavy oil and even asphalt or bitumen. As shown in Widarsono et al (2021) and Susantoro et al (2022) in their studies in the Central Sumatra Basin, the lineament approach is used to identify locations of heavy oil accumulation whose formation occurs in these high areas (Hadimuljono and Firdaus, 2021) and confirmed by Julikah et al (2021). Information from this lineament is also used to estimate geological correction factors for the area estimated to contain *in situ* asphalt/bitumen.

Buton island consists of a pre-Neogene carbonate sequence and is covered by Neogene sediments and Quaternary reef limestone. Pre-Neogene rocks underlie the Neogene basins to the north and south of Buton, imbricated by thrust faults and located above continental basement rocks which are the Doole Metamorphic Group of Paleozoic age. Pre-Neogene rocks consist of the Triassic Winto, Ogena Jura, Late Jurassic Rumu, and Late Cretaceous-Oligocene Tobelo formations. To the north of Buton, the Winto formation consists of calcareous sandstone and mudstone, while to the south of Buton it contains a mixture of clastic, bituminous limestone and shale. Stratigraphically, the Winto formation is covered above by the Ogena formation of Jurassic age, consisting of well bedded limestone with thin shale intercalations, the northern part of the Buton limestone contains chert which is a special characteristic of deep sea sediments. To the south of Buton, the Late Jurassic Rumu formation lies aligned above the Ogena formation. The Rumu Formation consists of dolomites, pink calcilutites with red chert, chert mudstones. The youngest sedimentary sequence is the Early Cretaceous - Oligocene Tobelo Formation. Consisting of massive bedded micritic limestone (calcilutites), chert lenses and nodules (Figure 3). The Neogene stratigraphy in southern Buton consists of the Tondo group and Sampolakosa formation, in the form of marls and calcarenite forams rich, Early - Late Pliocene age deposited in an outer-batial shelf environment (Figure 3). The Sampolakosa, Tondo, and Winto Formation are rock formations containing asphalt. In this study the lateral distribution of the two formations helps in estimating *in situ* asphalt/bitumen reserves.

Estimated Buton Asphalt Reserves

In general, reserves and potential accumulations of asphalt/bitumen on Buton Island are divided into two categories, namely reserves for accumulations that are considered mineable - located at depths shallower than 75 meters (or taken as 100 meters for this study) - and accumulated resources that are *in situ* or non-mineable. The depth criteria for separating these two categories are based on the criteria presented by de Klerk et al (2014) regarding the exploitation of oil sands in Canada. Mineable accumulation can be categorized as having reserve status because the data is generally obtained from surface surveys supported by geoelectrical and drilling data, while *in situ* (non-mineable) resource accumulation is speculative because it is not

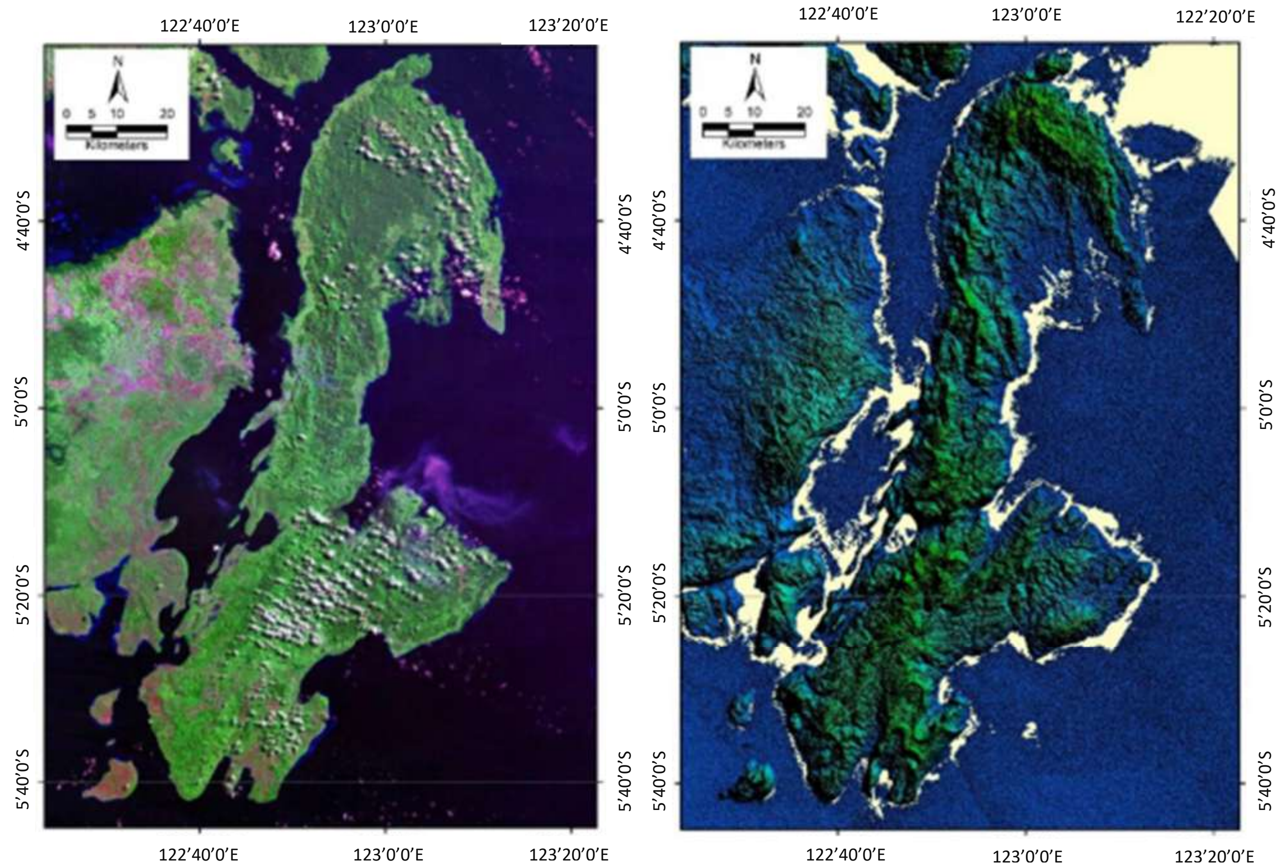

Figure 2
Appearance of the study area based on satellite data: a) Landsat, and b) Shuttle radar topography mission (SRTM). Landsat images record the condition of the earth's surface and illustrate surface geological conditions, while SRTM images are used to describe the topographic conditions of the earth's surface, in addition to supporting the depiction of geological structures such as joints, faults, and folds.

supported by direct discovery data but its occurrence is believed to exist. However, conversion was then carried out using empirical data to change it to reserve status using data adopted from Rogner (1997). For asphalt/bitumen reserves in the mineable (surface deposit) category, estimates are carried out using a simple and straightforward approach following Equations (1) and (2), where OOIP is in barrels, and 'Total deposit' is the number of mineable asphalt/bitumen deposits on Buton Island, derived from the compilation carried out in this study based on study data obtained from primary sources (unpublished reports).

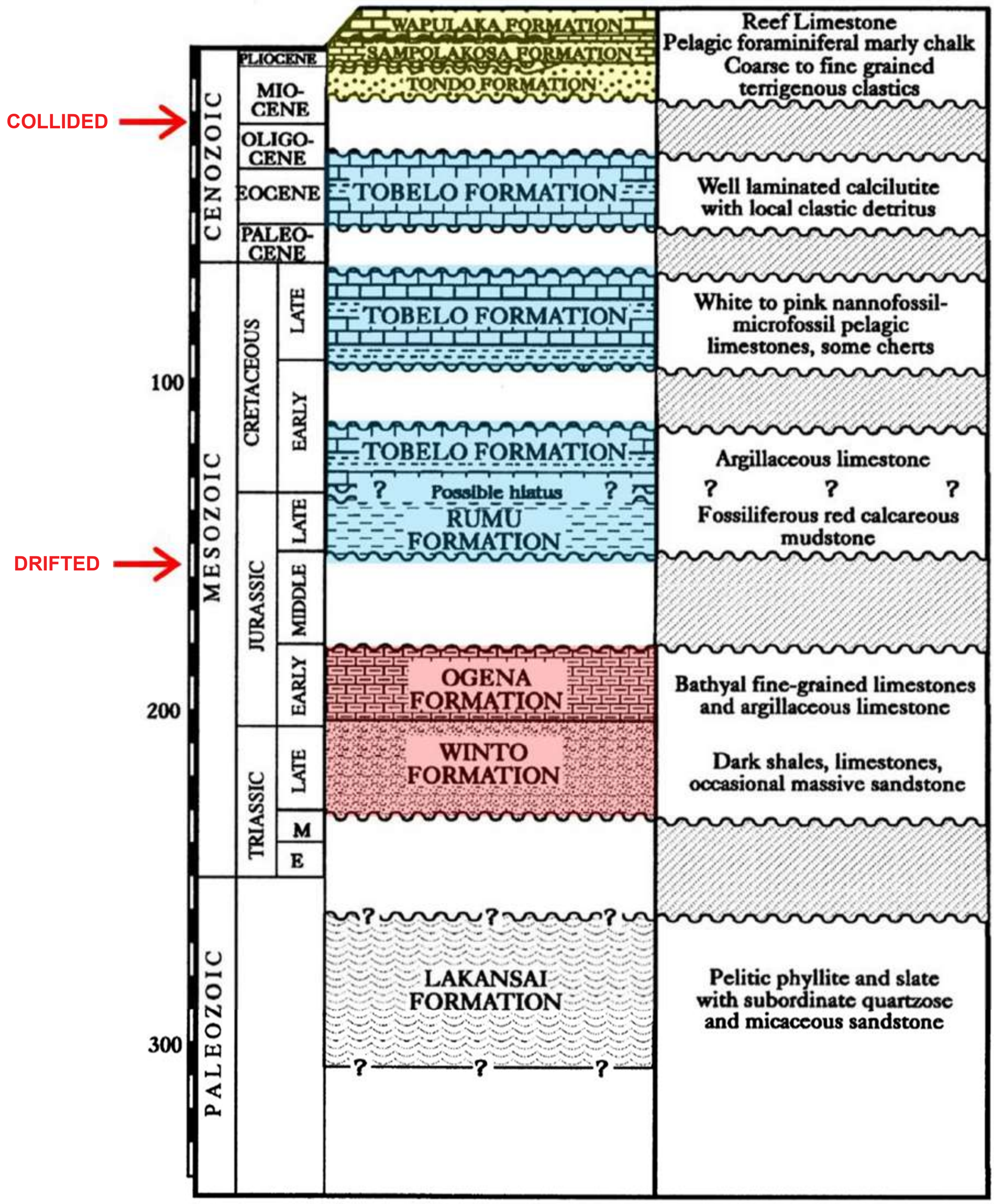

Figure 3
Regional stratigraphy of the Buton area
(Modified, Lemigas, 2005 and Satyana et al. 2022).

$$\text{Original oil in place (OOIP)} = \frac{\text{Total deposit} * 0.22 * 6.2}{\text{tar sand density}}\text{, barrel} \quad (1)$$

$$\text{Estimated ultimate reserves (EUR) = OOIP x 95\% , barrel} \quad (2)$$

$$\text{Area of } \textit{in situ} \text{ asphalt (AIA)} = \text{Area of Buton island} \times \text{correction factor, } m^2 \quad (3)$$

$$\text{Volume of } \textit{in situ} \text{ tar sands (VTS)} = \text{AIA} \times \text{h , } m^3 \quad (4)$$

$$\text{Resources of Buton asphalt (RBA)} = \text{VTS} \times 22\% \text{ , } m^3 \quad (5)$$

$$\text{Estimated ultimate resources (EUR)} = \text{RBA} \times 0.014 \text{ , } m^3 \quad (6)$$

Table 1
Asphalt/bitumen content from laboratory tests on Buton asphalt samples reported by several sources. The Rongi, Kabungka and Lawele deposits are the three largest in the South Buton area, while the North Buton block consists of small fields with low bitumen content.

Block	**Bothe (1929)**	**Hetzel (1936)**	**Hardjono (1966)**	**Sarana Karya (1986)**	**Pusjatan (2011)**
	(%/ton)	(%/ton)	(%/ton)	(%/ton)	(%/ton)
Rongi	-	-	-	-	4.2 – 35.4
Kabungka	13 – 25	4 – 33	6.4 – 46.2	15 – 35	7.1 – 34.2
Lawele	15 – 30	13 – 29.6	-	15 – 30	4.3 – 27.5
North Buton	-	-	-	-	4.2 – 4.4

The figure of 22% (or 0.22 in fraction) is the percent weight of asphalt content per ton of tar sand in mineable deposits for fields in South Buton. Table 1 presents the ranges of asphalt content per ton of tar sand in the Kabungka and Lawele pools, which are the largest asphalt/bitumen pools on Buton Island. The figure of 22% is a figure that is considered the average or generally representative for the Kabungka and Lawele blocks in South Buton, while for the North Buton block the figure of 4.3% is used. Value of 6.2 in Equation (1) is the conversion value of one ton of bitumen into volume in barrels, while the 95% figure in Equation (2) is the recovery factor figure which itself is a conservative choice compared to the 99% figure stated by Ralston (2021) from close-cycle solvent-extraction applications in Asphalt Ridge, Utah-USA. For tar sand density, the figure taken is 1.06 tons/m^3 (Hadisi and Tjitjik, 2011). Thus, Equation (2) produces estimated ultimate reserves (EUR) of mineable asphalt/bitumen on Buton Island.

To estimate the accumulation of *in situ* (non-mineable) asphalt/bitumen, a different approach is taken because it is speculative in nature without any discovery or other evidence from drilling. The category of *in situ* asphalt resources is speculative resources, based on the belief that in accordance with the principles of petroleum migration and the occurrence of biodegradation processes due to contacts with meteoric water. While still referring to the local geological setting, the volume of speculative resources is estimated using a simple volumetric approach following Equation (3) through Equation (6) where h is the average thickness or which can be considered as representing the general thickness of the in situ tar sand accumulation. What is meant by the correction factor in Equation (3) is a multiplier factor that represents the portion of the total area of Buton Island estimated to contain tar sand. The estimate of this correction factor in this study is obtained from the lineament process between satellite image data and gravity data. The 22% figure in Equation (5) is the average asphalt/bitumen content per ton of tar sand, as discussed earlier in relation to Equation (1) above. For simplicity, the North Buton block also continues to use the value of 22% because the effect is not significant on the overall asphalt volume. For the factor 0.014 in Equation (6), this figure is adopted from Rogner (1997) who empirically linked the amount of calculated speculative resources with observed reserves - reserves to resources ratio - for several tar sand accumulations in the world.

RESULT AND DISCUSSION

Interpretation of Satellite Images and Gravity-Free Anomalies.

The results of the interpretation of the pattern and direction of the rock layers in Buton show that there are differences between South Buton and North Buton. The direction of the layer plane in South Buton appears to be in a NE-SW direction and there is an elliptical pattern of the rock layer plane which is the tip of the subduction of the fold axis, so the reconstruction of the fold axis is in a NE-SW direction. Meanwhile, in Central Buton and North Buton, the layer plane is observed in an N-S direction and an elliptical pattern is observed representing the tip of the fold axis, so this appearance indicates presence of folds in the N-S direction.

The main directions of the Buton lineaments can be divided into three, namely South Buton with a NE-SW direction, in Central Buton with a NNE-SSW and N-S direction, and in North Buton with a N-S direction. The lineament density pattern shows a NE-SW direction in South Buton, NNW-SSW in Central Buton and NNE-SSW, and in North Buton a N-S and NNW-SSE direction. Based on the direction of the fold axis and the direction of the lineaments in Buton which shows differences between South, Central, and North Buton, it is interpreted that there are differences in the direction of the main forces forming the geological structure of Buton's surface. In the South Buton area the main force is in NW-SE direction, while in Central Buton and North Buton it is in relatively E-W direction.

Interpretation of lineament on the gravity (bouguer) anomaly map shows that there are differences in the direction of lineament developing in South Buton, Central Buton, and North Buton. Lineaments of gravity anomaly values in South Buton are in NE-SW direction, in Central Buton are in NNE-SSW direction, and in North Buton are in N-S and NW-SE direction. It can be interpreted therefore that the main force forming the geological structure in the Buton bedrock during movement from the east and hitting Southeast Sulawesi has different directions between South Buton, Central Buton, and North Buton. It can also be interpreted, however, that impacts of forces had affected Buton Island in more than one occasion. It is very possible that Buton experienced rotation which resulted in differences in the structural direction of South Buton and Central Buton-North Buton. Overlay interpretation of gravity anomaly map lineament, SRTM imagery, and Landsat imagery shows the same orientation between bedrock lineament data and the earth's surface. In South Buton the dominant structure is trending NE-SW, NNE-SSW in Central Buton, and N-S and NW-SE in North Buton (Figure 4).

Plotting the population in the direction of the Buton lineament is separated into a rose diagram of South Buton, Central Buton, North Buton and a consolidation of the lineament direction throughout Buton. The South Buton lineament population develops predominantly in NE-SW direction, even though there are also several N-S and E-W direction lineaments (Figure 5a) present. In Central Buton, lineament population points in rather arbitrary directions even though in general the N-S direction is dominant (Figure 5b), while in North Buton lineament population is dominantly developed in N-S direction, in spite of islands founds in other directions (Figure 5c). For the consolidated data on the lineament directions throughout Buton – which is the sum of total lineament populations of South Buton, Central Buton, and North Buton – overall result shows a predominantly N-S and NE-SW directions (Figure 5d).

Lineaments are generally closely related to the level of complexity of the surface geological structure and the distribution of rocks affected by the geological structure. In Buton, the level of lineament density related to the complexity of the surface geological structure is separated into five levels, namely very dense, dense, medium, rare, and very rare. In South Buton the density level is very dense to very sparse in the NE-SW direction, very dense to sparse in the N-S direction in Central Buton, while in North Buton the lineament density level of dense to sparse in the NNW-SSE and N-S directions is observed (Figure 6a).

Processing the gravity anomaly data produces a gravity map, interpretation of the lineament on the map shows several directions; NE-SW and N-S in South Buton, less observable in Central Buton, and N-S and NW-SW in North Buton (Figure 6b). The gravity anomaly values for South Buton ranges within 60 - 120 mgals, 40 - 100 mgals for Central Buton, and 60 – 160 mgals for North Buton. Small anomaly values occur in the eastern part of Buton with values as low as -140 mgals, and become higher toward the western part of Buton to reach 20 mgals.

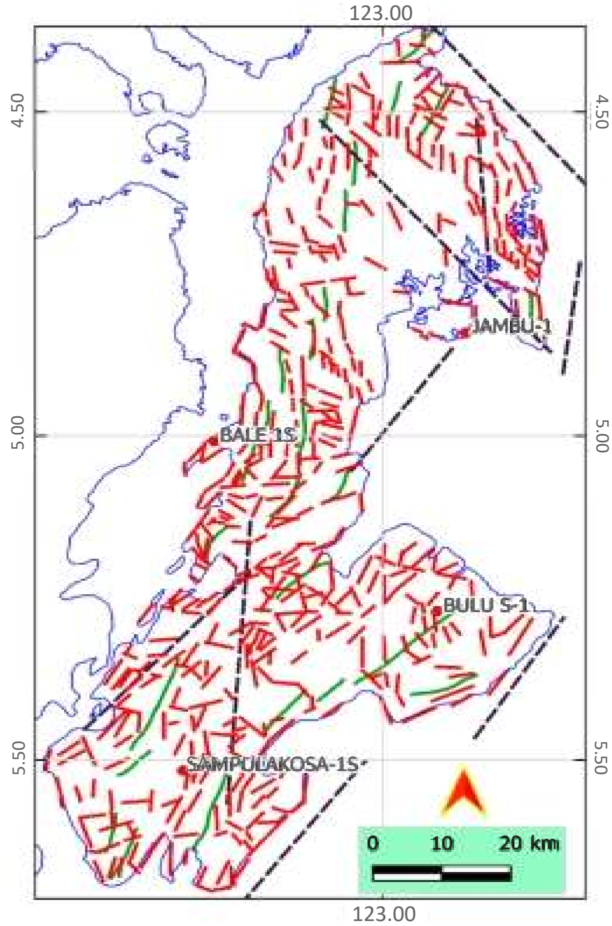

Figure 4
Overlay of the gravity anomaly map lineament (black), SRTM image lineament (red), and the direction of the fold axis (green).

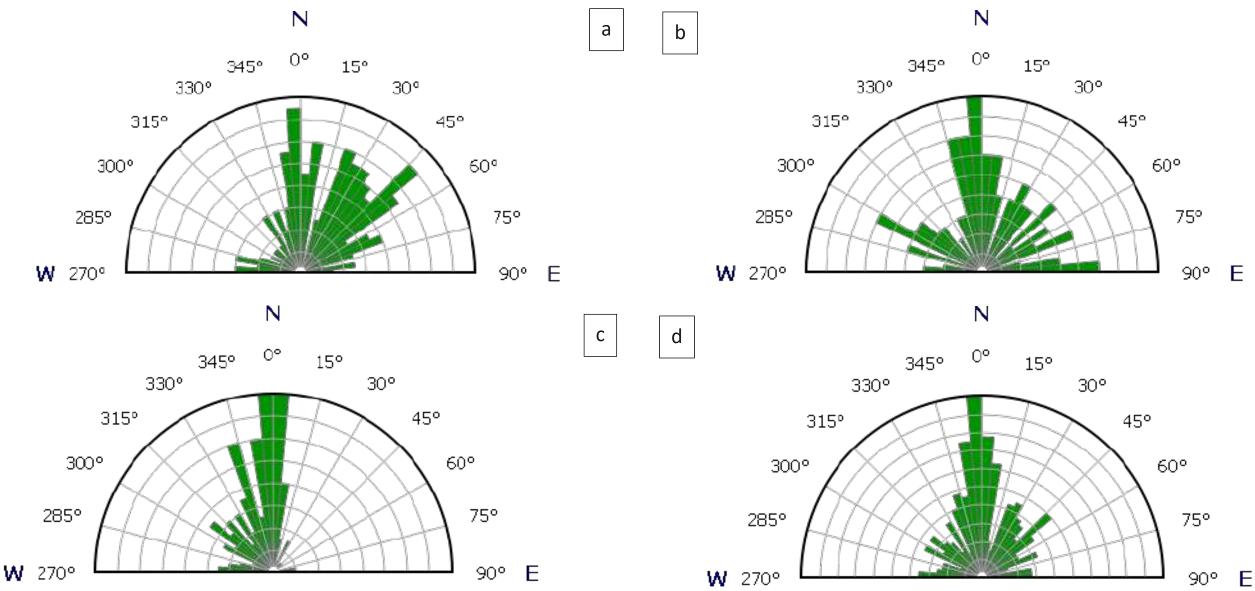

Figure 5
(a). South Buton lineament population plot, (b). Central Buton lineament population plot, (c). population plot of North Buton lineaments, and (d). lineament population plot throughout Buton.

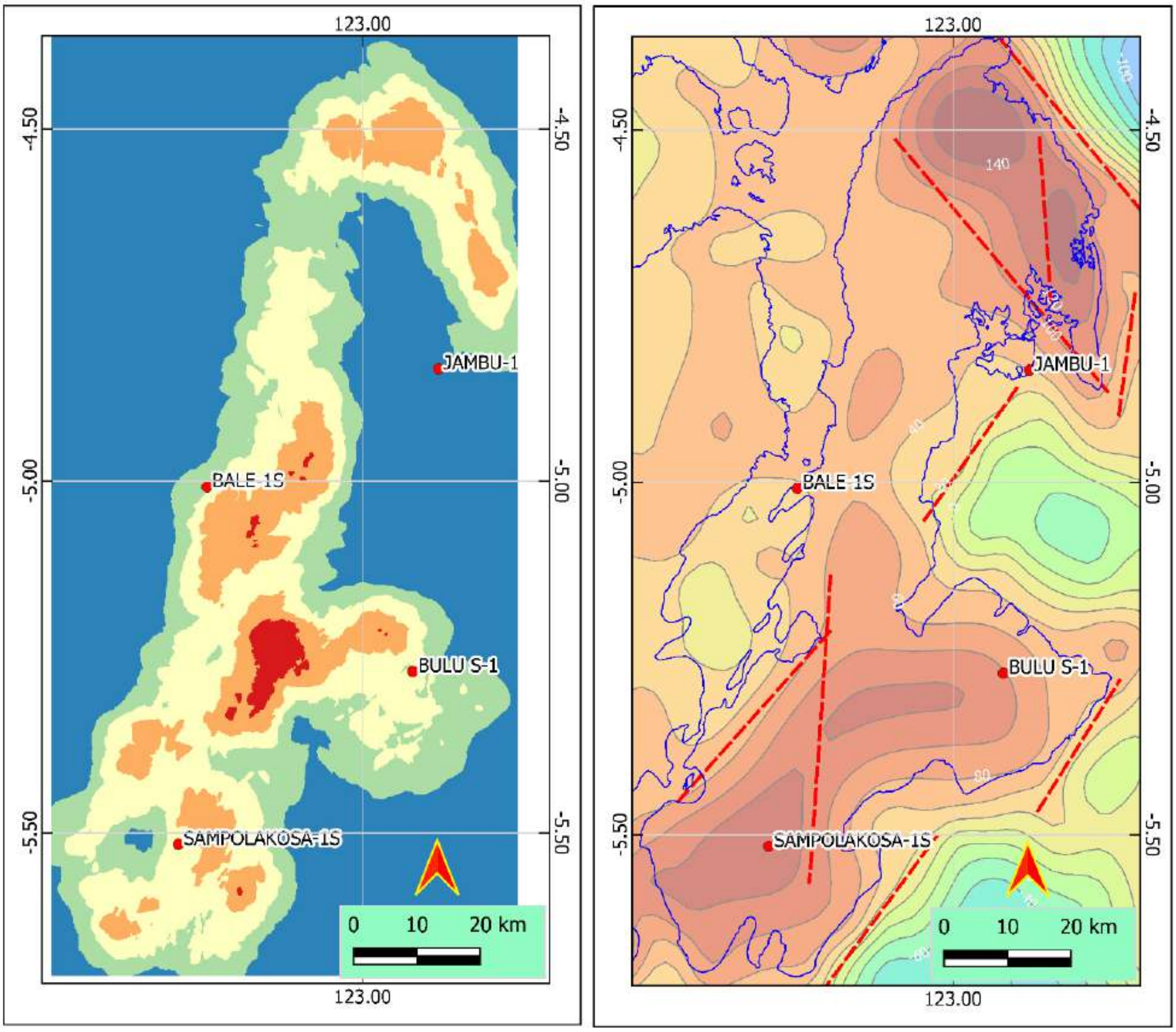

Figure 6
(a) Lineament density levels are very dense (dark brown), dense (light brown), medium (beige), rare (green), and very rare (blue). (b) The gravity anomaly map with lineament interpretation at the northwest area shows positive anomalies and is limited by faults (red dotted line).

Based on the analysis of gravity anomaly values which reflect the thickness of the sediment, it appears that there is an internal area to the east of Buton, this internal area has the potential to be the origin of the source rock. It is worth noting that presence of bedrock lineaments presents an opportunity to act as a migration route for oil and gas from the source rock to the trap(s). Taking into account the existence of fold structures which are expected to function as traps with medium to low lineament in density maps, it is hoped that this area acts as barrier to oil and gas migration to the earth's surface. Accordingly, three oil and gas prospect areas are proposed as sources of asphalt formation, namely on the east side of Buton geographically along the east coast of Buton (Figure 7). Meanwhile, the level of lineament density related to asphalt-bearing rock formations shows the consistency of lineament density in the distribution of the Sampolakosa Formation, Tondo and Winto Formation. For this reason, distribution of the two rock formations are quantified and is compared to the area of Buton island derived from satellite image data and MapInfo.

Figure 8 depicts results of the comparison. The ratio resulted from the comparison is used to determine the correction factor needed in the use of Equation (3) for calculation of Buton's *in situ* asphalt reserves.

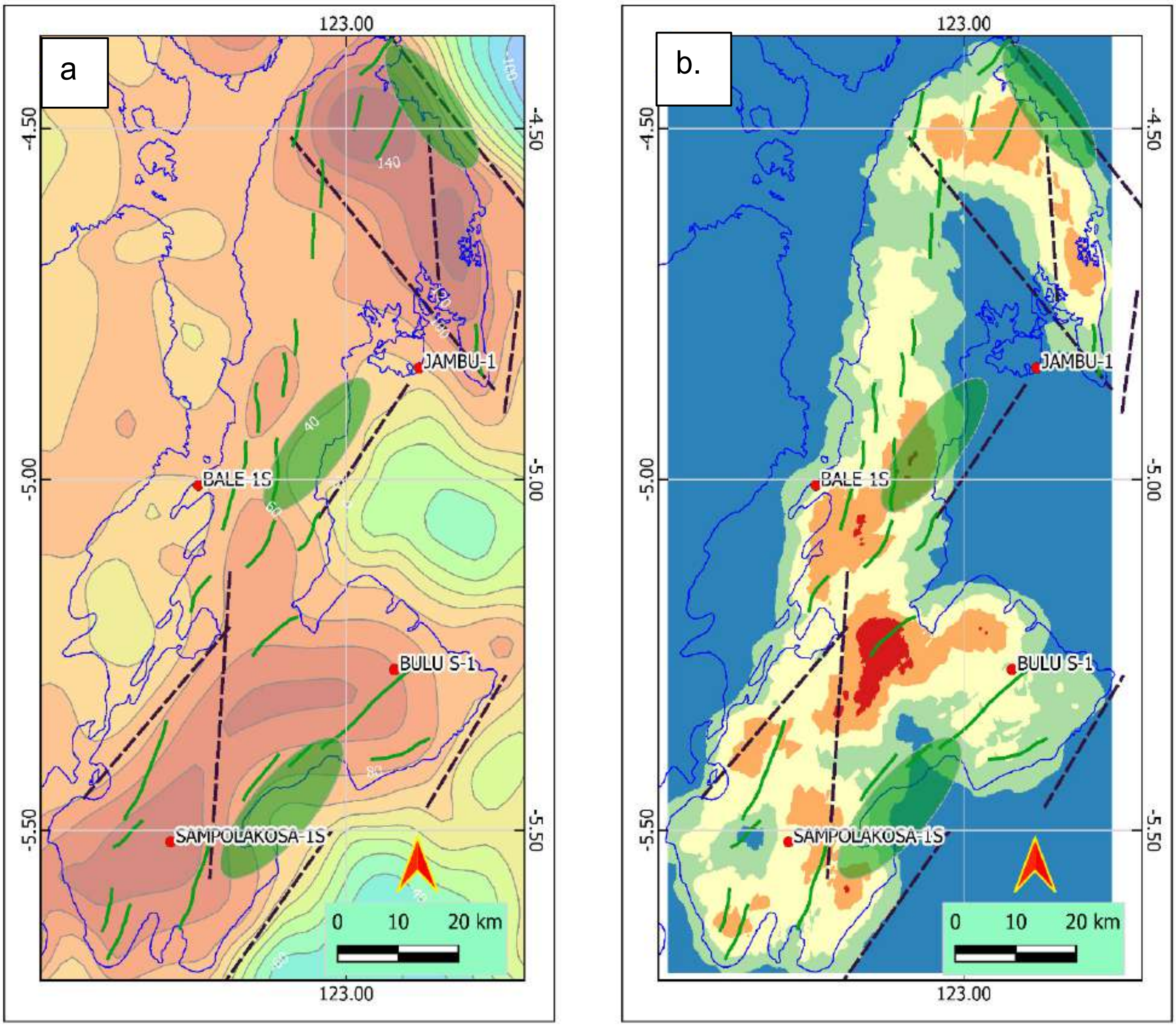

Figure 7
(a). Overlay of the prospective area (green ellipse), lineaments of gravity anomaly values on the gravity map; (b). overlay prospective area (green ellipse), lineament gravity anomaly values, direction of the fold axis on the lineament density map of the earth's surface.

South Buton has a dominant structure trending NE-SW and North Buton trending N-S and NW-SE influencing the distribution pattern of rock formations on Buton Island, as well as the distribution pattern of asphalt on the surface and subsurface. The existence of Buton asphalt is closely related to rock formations and the folded geological structure that controls it, as well as fault structures as asphalt migration routes (Harun Said 1976).

Based on outcrop data, it shows that the existence of uplifted fold structures that cause the Tondo and Sampolakosa formations to be exposed, which is closely related to the presence of asphalt. Interpretation and calculation of structural alignment from satellite images shows that there is a close connection with the fold structure. The level of density and lineament density indicates the location of uplifted fold structures and is therefore related to the presence of asphalt.

To fulfill data for the area of Buton Island as required in Equation (3), an estimate of the area of Buton Island has been made, and a correction factor – the ratio between the geologically high areas where asphalt/bitumen occured and the total area of Buton Island – is produced. Estimation of Buton Island's total area produce an area of 4,496 km2. In accordance with the understanding presented above regarding the formation of asphalt on Buton Island, Buton asphalt accumulates in the Sampolakosa and Tondo Formations. Evaluation over the area of these highlands – as a result of lineament – resulted in estimates of the Sampolakosa Formation with a distribution area of 1,182 km2 and the Tondo and Winto Formation with a distribution area of 1,087 km2 that make up a total area of 2,269 km2. A correction factor of 0.5046 is obtained and used in Equation (3). Compiled map estimates of the Sampolakosa Formation and the Tondo and Winto Formation see Figure 9.

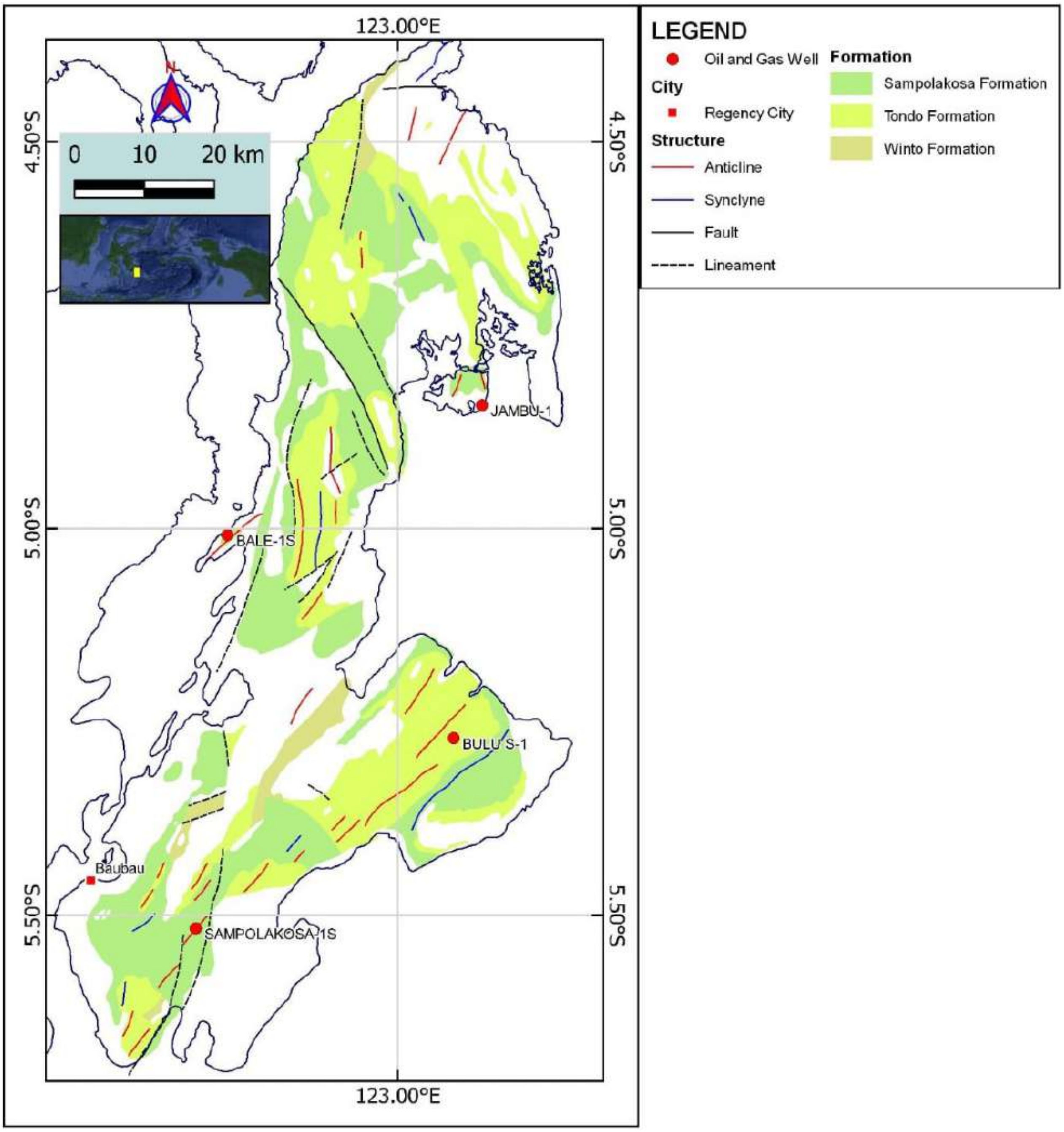

Figure 8
Calculation of Ratio Sampolakosa - Tondo - Winto Formation and Buton Area.

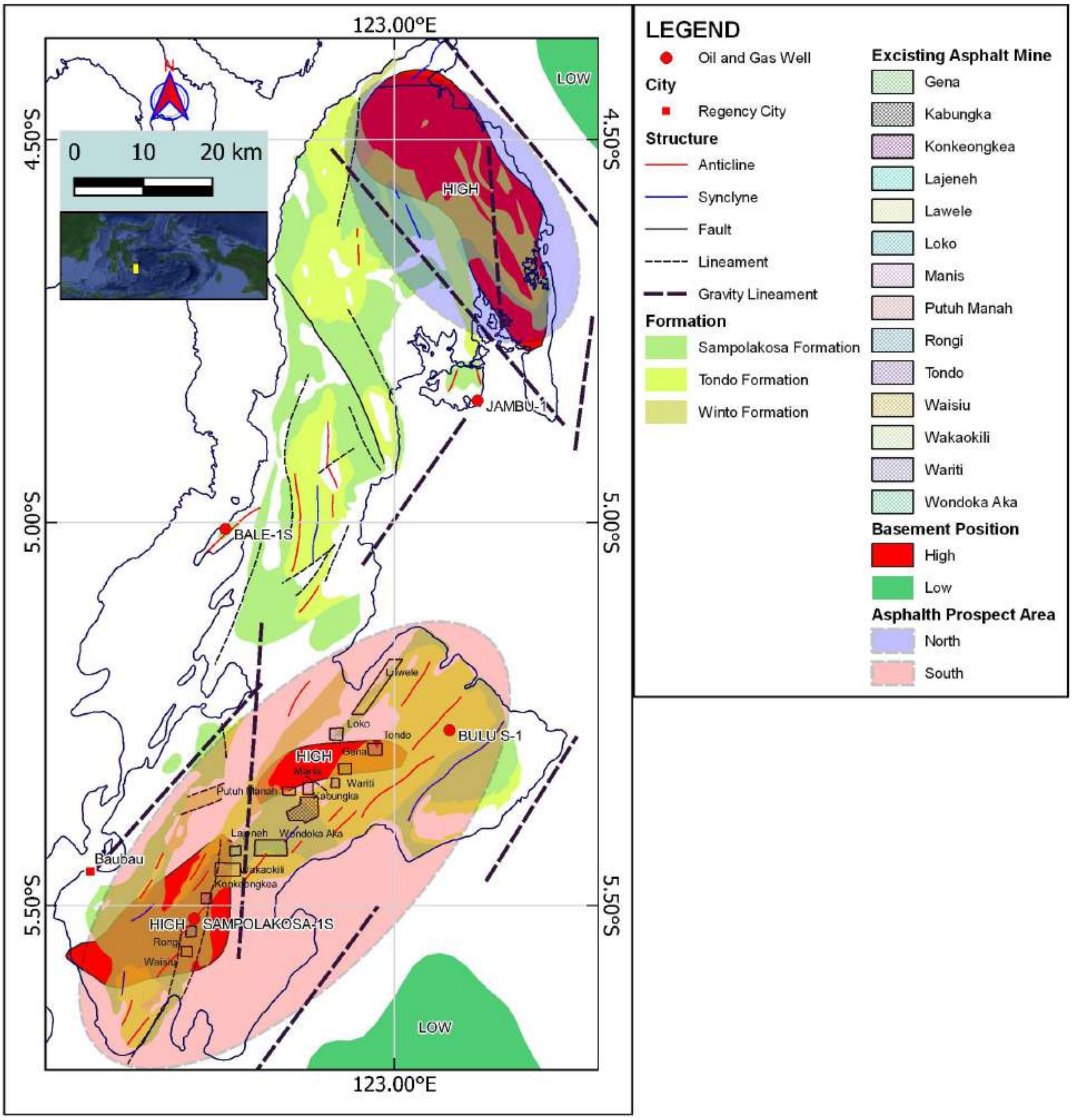

Figure 9
Buton asphalt potential map (compiled from existing data)

Resources and Asphalt Reserves

The results of the identification and megascopic description of Buton asphalt based on locations of discovery are divided into two, the Lawele and the Kabungka. Lawele asphalt-containing rocks, has physical characteristics of shiny black, conglomeratic, very hard, compact, granular (sandstone-granule), massive, brittle, idiocromatic, and associated with limestone. On the otherhand, Kabungka asphalt-containing rocks is characterized by being brownish black, coated, hard, compact, clay-sized grain, not shiny, hackly/shard pointed tip, allocromatic, and associated with marl. Figure 10 presents the physical appearance of both types of asphalt-containing rocks on Buton island.

The calculation of Buton asphalt deposits is based on data from the Research and Development Centre for Roads and Bridges (Pusjatan, 2012), where on the island of Buton there are estimated 662,960,267 tons of asphalt located in Rongi, Kabungka, Lawele,

Figure 10
Appearances of (a) Lawele, and (b) Kabungka asphalt-containing rocks (collection of Research Center of Process Manufacturing Industry Technology)

and Buton North. In the overall of Buton Island there are a total of 19 (nineteen) asphalt fields (pools) that have been identified and exploited for road asphalts, such as Waisiu, Kaongkeoka, and Mana (Hetzel, 1936 in Satyana, 2011). The 19 fields are simplified and grouped into four blocks as shown in Table 2.

EUR quantity is a reserve that can theoretically be obtained by using 95% as a recovery factor for open pit mining with closed cycle closed cycle extraction, which refers to Ralston (2021). As explained above, the asphalt/bitumen content of 22% is the average value as presented in Table 1.

Table 2
Buton asphalt deposits are mineable in three blocks in the South Buton area, plus the entire deposit in the North Buton area (Pusjatan 2012)

Block	Areal spread (m^2)	Deposit of tar sand (ton)
Rongi	57,755,000	226,165,670
Kabungka	181,004,200	312,718,460
Lawele	130,906,500	99,786,080
Buton North	6,870,000	24,290,057
Total	376,535,700	662,960,267

Information from initial studies on Buton's asphalt contents, such as one given by Hetzel (1936) gave a range of asphalt content numbers within 10 - 40% by weight. Hardjono (1966) conducted a survey and sampling of 20 samples from several shallow wells and reported bitumen contents in the range of 6 – 46% by weight, and density of bitumen-containing rocks in the range of 1.38 – 2.30 gr/cc (ton/m^3). The next information is from the Coal and Geothermal Mineral Resource Centre (1976) and Pusjatan (2011) which conducted survey drilling and laboratory analyses on samples obtained from 19 fields resulting in the asphalt/bitumen contents range of 4 - 40% by weight. The largest deposit is the Kabungka block that has asphalt contents within 15-25%, while the Lawele block has a corresponding range of 17-30 %, and Rongi with its asphalt contents range of 10-35%. All data was then compiled on Arisona (2022) in the book "Recognizing The Potential of Local Wisdom of Natural Asphalt Rocks in the Buton Island Basin Eastern Indonesia" (Recognize The Potential of Local Wisdom of Natural Asphalt Rocks in the Buton Island Basin Eastern Indonesia). Analysis of all existing data indicates that the average asphalt content value of 22% is considered representative, especially in the South Buton area. Accordingly, this value is used as the basis for reserves estimation. For the North Buton block, the average asphalt content value of 4.3% is still used. Table 3 presents the results of calculating surface/mineable reserves based on gross tar sand tonnage data in the South Buton and North Buton areas adopted from Widhiyatna et al (2007) and Pusjatan (2011). Using all the parameters described above, use of Equation (1) and Equation (2) results in an estimated ultimate reserves (EUR) of siurface/mineable asphalt of 786,595, 165 barrel, rounded to 786.6 million barrels. This obtained quantity can be considered as a reserve with the status of 'best estimate'.

For reserves estimation of the *in situ* Buton asphalt, deeper than 100 metres calculated from the surface (Hardjono, 1966), the calculation is carried out with several assumptions, namely: 1) The accumulation of asphalt on Buton island is deposited on a graben that extends in the southwest - northeast direction through the Rongi-Kabungka-Lawele area (Hadiwisastra, 2009) so that it is estimated that the surface area of the deposit is approximately 1/2 of Buton island area, according to the correction factor 0.5046 that has been obtained; 2) The slope of the layer (dip) of the rock in the asphalt deposit area is less than 5° so that it can be assumed to be flat laterally flat (Suharni, et al., 2022); 3) Average thickness (h) of 20 feet or about 6,096 metres (Resnick et al, 1981); and 4) The density of tar sand used is 1.06 tons/m^3 (Hadisi and Tjitjik, 2011). By using a conversion factor of 6.2 bbl/m^3 for asphalt/bitumen, the EUR volume in barrels can be determined. In order to provide a sense of uncertainty a slightly different approach is taken in the estimation of the *in situ* asphalt/bitumen EUR. In addition to the use of asphalt/bitumen levels of 22% which produce EUR volume with the status of 'best estimate', calculations have also been carried out using lower and higher asphalt/bitumen levels of 10% and 35%, respectively to produce EUR estimates with 'low estimate' and 'high estimate' status. Table 4 presents the calculation’s results. Rogner's reserves-to-resources ratio of 0.014 is also used to convert the volume of calculated speculative resources into EUR values. Nevertheless, the EUR 'best estimate' value obtained is 46,009,853 barrels or rounded to 46 million barrels.

A striking comparison between mineable and *insitu* asphalt/bitumen reserves of 786.6 million barrels and 46 million barrels, respectively, shows conservatism in estimating the *in situ* (non-mineable) reserves. This can be understood from the point of view of the absence of primary data – in the form of discovery and sampling – which can support a more optimistic estimation approach. Speculatively it can be argued that the actual accumulated value could be much larger, given the enormous amount of mineable reserves that can be estimated quite well with a high degree of certainty. However, only drilling can prove the truth of the argument with respect to the in situ reserves.

Table 3
Estimation of the amount of estimated ultimate reserves (EUR) from asphalt/bitumen deposits in the mineable category.

Field/block	Area (m^2)	Gross tar sand (ton)	Asphalt contents (%)	Asphalt tonnage (ton)	Asphalt density (ton/m^3)	Asphalt volume (bbl)	EUR Bitumen (bbl)
Epe	1,720,000	2,011,157	4.3	87,184	1.06	509,942	484,445
Rota-Mandula	5,150,000	22,278,900	4.3	965,790	1.06	5,648,962	5,366,514
Sub-total Buton North							5,850,959
Rongi	57,755,000	226,165,670	22.0	49,756,447	1.06	291,028,277	276,476,864
Kubangka	181,001,200	312,718,460	22.0	68,798,061	1.06	402,403,754	382,283,566
Lawele	130,906,500	99,786,080	22.0	21,952,938	1.06	128,403,975	121,983,776
Sub-total Buton South							780,744,206
Total EUR							**786,595,165**

Oil and Gas as the original material of Buton Asphalt

Buton asphalt is known and is stated to be the result of oil seepage that is under the surface of Buton and its surroundings. For this reason, the estimates of Buton's subsurface oil and gas reserves can also be made in principle. Calculation of the analysis results of BP MIGAS (Regulatory Task Force for Upstream Oil and Gas Business Republic of Indonesia) and PT Putindo Bintech (2010) which estimates oil and gas reserves (EUR on the status of 'best estimate, P50) of 10.93 million barrel of oil (MMBO) and 61.14 billion cubic feet (BCF) of natural gas, respectively. Indications of oil and gas are indicated by the presence of oil seepage to the north of the Lawele block. In addition, seepage is also found in several places on Buton Island. The kitchen area indication is estimated to be east of Buton island with a horizontal distance of about 15 km. Results of the seismic interpretation indicate a kitchen area close to the seepage location north of Lawele. Based on the petroleum system, the source rock on Buton Island comes from shale and coal. The Tondo Formation contains oleananes (wood fossil indicators), while other source rocks of the Triassic-aged Winto Formation, deposited in anoxid conditions during the period of transgression, consist of flakes, fine grains of limestone, carbonate flakes and contain large amounts of organic matter. It is estimated that many examples of Winto Formation rocks contain high concentrations producing petroleum (oil prone) and are rich in sulphur with total organic carbon (TOC) from <1% to above 16%. Reservoirs that develop on the island of Buton and its surroundings are in the form of coarse clastic rocks from the Tondo Formation, having thickness of between 90-140 m with an average porosity value of 19% or in the range of 8% to above 25%. In addition, there are limestone originating from the Tobelo Formation which also developed as reservoir rocks. The blocking rock on Buton Island is estimated to be clay from the Sampolakosa Formation. In addition, there are other fine clastic fasies, claystone and Tondo Formation rock, which also act as good insulation.

Anticline structural traps and a combination of anticline and faults are the main hydrocarbon traps of the Buton area. Given the active tectonics in Buton and its surroundings, the fold and fault structural traps are more dominant. The sandstone and conglomerate alternating hoses with clay-stones in the Tondo Formation indicate the existence of stratigraphic traps in this area. Traps in the form of intraformation folds found in the Tondo sequence in the southern part of Buton. Faults are the main hydrocarbon migration pathways, occurring along the ascending fault to the reservoir rock and trapped in younger rock layers. Likewise, shear faults have the potential to be a migration path for hydrocarbons. Removal during the Pleistocene in the southern part of the Buton occurred on sliding fault blocks causing bio-degradation from oil to asphalt. Shear faults located in the north of Buton as the main cause of upward oil and gas seepage, include Nunu oil seep, and Bubu/Kioko gas seeps. The combination of structure and stratigraphy such as carbonate reefs in form of anticline is a trap found in other plays. Hydrocarbon replenishment is thought to come from the low-lying areas where Winto Formation flakes have matured to produce hydrocarbons.

Table 4
Results of EUR estimates for *in situ* (non-mineable) asphalt/bitumen of Buton. 'Low estimate', 'best estimate', and 'high estimate' are represented by the use of asphalt contents of 10%, 22%, and 35%, respectively. Note that, the tar sand gross tonnage is obtained through the use of Equations (3) and (4). Focus remains on the 'best estimate' result.

Tar sand tonnage (ton)	Asphalt contents (%)	Asphalt tonnage (ton)	Asphalt density (ton/m^3)	Asphalt volume (m^3)	Reserves-resources ratio	EUR (bbl)
2,553,961,241	10	255,396,124	1.06	240,939,740	0.014	20,913,569
2,553,961,241	22	561,871,473	1.06	530,067,427	0.014	46,009,853
2,553,961,241	35	893,886,434	1.06	843,289,089	0.014	73,197,493

Further Discussion

Interpretation of the landsat image in Buton by considering the pattern and direction of the rock layer plane has succeeded in identifying the direction of the axis of the fold that develops in Buton, among others, showing the existence of different lineament in South, Central, and North Buton. However, there is a similarity in the lineament pattern in bedrock which is based on the interpretation of the lineament of the weight force anomalous map, so it is suspected that this surface structure is controlled by structures that have developed in bedrocks. Weight anomaly value is closely related to the thickness of sedimentary rocks in a basin, the smaller the weight anomaly value thicker sedimentary rocks. Several areas located in the eastern part of Buton reveal chances of being source rocks, and presence of lineament indicates oil and gas migration from source rocks to the traps. It is expected that in the western part of the island there are presence of oil and gas traps. Nevertheless, removal of cap rocks in the southern part of the Buton occurring through sliding of fault blocks had caused bio-degradation of the migrating oil to be turned into asphalt in shallower depths.

Sulawesi island’s tectonic and orogenesa activities, including within the Buton-Muna area, is one of the world's ideal case to follow the rollback theory. In the theory, Neotectonic activities cause changes in the bathymetry where sinking land and raised seabed occured. This is best marked by the disclosure of high-level metamorphs on the hills of Mount Lambohago in the north of Buton that has reached 1,000 metres above sea level (satellit data on Figure 2) indicating the occurrence of strong orogenesis. In contrast, sediments and carbonate reefs formed on the coast, are at present found at depths of more than 1,000 metres below sea level (See Buton stratigraphy presented on Figure 3). Reconstruction and re-modeling over geological setting of the Button region can provide insight into the geological history of this unique regions, and is therefore related to the Eastern Indonesia's potential of oil and gas.

One underlined issue of the analysis of this study’s finding is the existence of consistency and relationship between the phenomenon of lineament pattern and gravity of Buton island with rollback theory. Application of rollback theory (Resnick et al, 1981; Hall, 2014 and Cassel et al, 2018) supports the concept of oil/gas presence and Buton asphalt being in co-existence or being adjacent to each other in one region. This is true since it is clear that Buton's tectonic strength is known to had come along the east-west axis, plus the strength of the orogenesa coming from above and below. Orogenesis or rollback lifting has been drawn from European continental plate concept, which consistently relates present surface conditions to the subsurface events. Forces arise as results of gravity explain well the orogenesis and formation of topography in obvious absence of strong collisions between two continental plates (Kissling and Schlunegger, 2018). This results in a combination of horizontal forces and gravity that makes Buton - Muna becoming more complex geologically.

CONCLUSION

Based on landsat image data, shuttle radar topography mission (SRTM) images, and density anomaly maps, three prospect areas are indicated on the eastern side of Buton for further oil and gas and asphalt exploration activities. Interpretation of satellite data, has enabled to show impacts of active fault and gravity activities due to orogenesis. The lineament density pattern shows general direction of NE-SW to NNW-SSE, in accordance to the growing regional structure in Buton. Interpretation of satellite data and lineament has supported consistency of Buton asphalt’s presence in Lawele graben, hence leading to ratio between area of asphalt distribution on the surface to the overall area of Buton Island being at around 0.50. This ratio is very important and can be considered as a reference for determining *in situ* asphalt/bitumen reserves on the island of Buton.

Based on reported tar sand presence, it is estimated that surface asphalt/bitumen reserves (mineable) on Buton island under the category of estimated ultimate reserves (EUR) is 786.6 million barrels. This obtained value can be considered as a 'best estimate' category reserve since estimations are based on information provided by drilling, surface geological survey maps, and laboratory data. On the other hand, *in situ* (non-mineable) reserves estimate obtained from the lineament approach, application of analogy to asphalt exploitation cases in other countries, and the use of the most representative parameters result in a 'best estimate' reserves of 46 million barrels. The relatively small quantity of *in situ* (non-mineable) reserves compared to the surface reserves/mineable shows conservatism in estimating reserves for the *in situ* (non-mineable) reserves figure. With further acquisition of data and more in-depth surveys, it can be safely predicted that the reserves will grow significantly.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
AIA	Area of *in situ* asphalt	
BSCFD	Billion Cubic Feet per Day	
EOR	Enhanced oil recovery	
EUR	Estimated ultimate reserves	
E-W	East – West	
Landsat	Land satelite	
MMBOPD	Millions barrel oil per day	
NE-SW	Northeast - Southwest	
NIGS	Nederlands Indies Geological Survey	
NNE-SSW,	North Northeast - South Southwest	
NNW-SSE	North Northwest - South Southeast	
NNW-SSW	North Northwest - South Southwest	
N-S	North – South	
NW-SE	North West - South East	
NW-SW	North West - South West	
OOIP	Original oil in place	
PSC	Production Sharing Company	
RBA	Resources of Buton asphalt	
R&D	Research and development	
SRTM	Shuttle Radar Topography Mission	
TOC	Total organic carbon	
VTS	Volume of *in situ* tar sands	

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