Subsurface Interpretation Approach Gravity Method In Hydrocarbon Exploration:

Study Subsurface Geology East Java Basin Cepu-Bojonegoro Area for reference study in Jambi Basin at South Sumatera.

Abstract
Survey of subsurface geology at Bojonegoro area has been done with gravity method. This study will contribute to obtaining a picture of the possibility of a new hydrocarbon exploration targets in the central part of East Java. This study shows that Bouguer anomalies can be divided into two groups, the first anomaly between 26 to 30 mGal as high anomaly at South-Central area. The second anomaly, is between 26 to 20.5 mGal as low anomaly at Central-Northern part. Analysis was done by spectral analysis, stage filtering to separate the residual anomaly and regional anomalies from the Complete Bouguer Anomaly. Two-dimensional modeling of the “Bojonegoro” area has a trend of the structural configuration from North-South shows the normal fault relative trending northeast-southwest, which is formed as a result of extensional forces during the Tertiary to Early Oligocene. Residual anomalies at eastern of Kasiman area shows the contour pattern of protruding to the south the possibility of hydrocarbon trap. The picture that illustrated in the 2-D subsurface model, showing bedrock in the study area is relatively shallow, so that the target of exploration for the Kujung or Ngimbang Formation is still possible. Integrated of the geological data, seismic models, suggesting that appears on the Kujung Formation assumed or suspected to be carbonate build-up results from the major transgressive at Oligo-Miocene and Ngimbang Formation as anticline.

Keywords: Bouguer anomaly, residual anomaly, 2-D Subsurface model, Carbonat Build up, hydrocarbon trap.

Preface
The Central East Java Basin has been proven to be a hydrocarbon basin-rich area, since the late 19th century began the production of petroleum at the oil fields around Cepu area (Kawengan, Ledok, Nglobo, etc.), as well as regions around Surabaya (Lidah, Kruka, etc.). The discoveries of new oil fields are still ongoing, as the discovery of new fields in the end of 1990 and early 2000; Mudi (Petrochina), Sukowati, Banyuurip, and Jambaran (Exxon), Kedungtuban and Randublatung (Pertamina). The exploration targets in Central East Java Basin including Ngimbang Formation, Kujung Formation and Tuban Formation. Considering the distribution of the oil fields, it can be inferred that the whole area of the Central East Java Basin, including the central part of the Island of Java, between the Central Java and East Java is the area of petroleum province (Fig 1.). It is also supported by the fact that a number of seismic acquisition has been conducted in almost this entire area in order to enhance the hydrocarbon exploration activity. Nonetheless, the eastern part of Cepu with an approximately 50 km square width which covered by the carbonate sediments. This can cause difficulties in conventional seismic method, either in the operational section or the interpretation. Despite of the difficulties, considering this area is a potential area for hydrocarbon prospect, it is necessary to attempt an alternative geophysical method in order to get the subsurface information i.e. gravity method. The area of Central East Java Basin is a hydrocarbon prospective area. In the Oligo-Miocene, the central part of East Java was an open marine, and the carbonates of which become nowadays exploration target grow at the high. There are several recognizable highs
i.e. West Cepu High, East Cepu High, and Kemandung Ridges. The Carbonate Reef in the Kedung Tuban Field, Banyuurip Field, Mudi Field, Sukowati Field, and Kembangbaru Field which located at the East Cepu high area the examples of that hydrocarbon generally occurred at the highs (Satyana, 2005).

Again, considering this is a hydrocarbon prospective area, it is necessary to conduct a study of subsurface geology in order to understand the subsurface structural characteristic and its relationship with the presence of hydrocarbon trap. The information about subsurface configuration is an advantageous data in order to determine the presence of hydrocarbon trap, which often exhibited by the presence of high structure in the subsurface.

II. Geology
Physiographically the studied area is included into the Rembang Zone at the central part, which is predominantly composed of carbonates, and into the Randublatung in the southern part which is mostly covered by the alluvial sediments.

Elongated ridges occupy the northern part of the area which characterized by the appearance of rough morphology, whereas in the southern part which occupied by the lowland morphology, a number of swampy and wet area can be found (Bemmelen, 1949).

According to the map (Fig. 2), the stratigraphic unit order found in the studied area in ascending order (oldest — youngest) are as follows: the oldest rock unit is the Kujung Formation (Oligo-Miocene in age) which consist of four member i.e. Marl member (Tomkm), Prupuh limestone member (Tomp), Claystone member (Tomkc), and the Siltstone member (Tomks). The Kujung Formation conformably overlain by Early-Middle Miocene Tuban Formation (Tmtl), which is consist of siltstone with intercalated sandy marly limestone. The Mundu Formation and the Paciran Formation unconformably overlies the Tuban Formation, with the age of Pliocene. Mundu Formation (Tpm) consist of sandy marl and chalky limestone, whereas the Paciran Formation consist of limestone which composed by a number of fragments, such as algae, corals, large forams and molluscs, dolomitic limestone and dolostone.

On the top of this formation lies conformably the Pleistocene of Lidah Formation (Qtl) and Kabuh Formation (Qpk). The youngest stratigraphic unit is the alluvium which consist of pebbles, gravels, sand, silt, and mud which form in the fluvial and swamp environment (figure 4).

East Java Basin, including those in the land part there is microcontinent (East Java microcontinent) of which dynamics considerably affects the formation of East Java Basin configuration. There are two different trend of basin configuration in the East Java Basin, i.e. Luk Ulo – Meratus trending configuration (SW-NE) and West – East trending configuration which is a pull apart basin, where the Eocene Ngimbang Formation was found in the EJ-1 well, and now become the exploration target in the East Java Basin. The West – East trending structures are the microcontinent basement structure which reactivated into transform fault along the Sakala Fault (Sribudiyani, et al., 2003). The Sakala Fault Zone develops to the West through the Kangean, Madura, as far as Rembang area (RMKS fault zone) this fault zone form at the age of Upper Early Miocene-Middle Miocene, marked by the presence of flower structure, indicating a very strong inversion deformation (Satyana, A. H., 2004).

III. Methodology Study
The contribution of the earth crust mass density in the surface only as much as 0,3% of the earth gravitational field and the mass density as below as 5 km or in the places where geological phenomenon contribute about 0,5% of the earth gravitational field. This small amount of contribution holds an important role because the variation of the gravitational field can be mapped. The variation of the gravitational field is basically a variation of mass density, then by knowing the variation of mass density in the subsurface as measured by the gravity method, the subsurface setting can be interpreted (Grant & West, 1965). (figure 5).

The principle of the gravity method is to obtain the anomaly value which caused by the difference of mass density of the objects that causing the anomaly. The calculation of complete Bouguer Anomaly (gB) done by using the equation (Telford et al, 1990)
\[ gB = gobs - gn + dgFA - dgB + dgT \]  
…………………………………….(1)

where \( gB \) is the Bouguer gravity anomaly, \( gobs \) is measurement result after tidal and drift correction, \( gn \) is the normal force at the measuring point, \( dgFA \) is the free air correction, 0.3086 mGal/meter, \( dgB \) is The Bouguer correction and \( dgT \) is the terrain correction.

Residual anomaly map derived from the separation of Bouguer Anomaly and Regional Anomaly by using Moving Average, while 2D subsurface modeling is done by using Grav 2D software.

Using quantitative and qualitative analysis of gravity data and assumes that a hydrocarbon trap occurred somewhere in the highs, then the possibility of the trap position can be expected based on its lithological orientation. Field studies conducted are the measurement of gravity and rock sampling. Laboratory analysis is done in order to determine the the mass density of the rock which represent the rock in the gravity measurement point. The gravity data processing includes: Workstation study activity includes data processing, the construction of Bouguer anomaly map, residual anomaly map, and study of 2D subsurface model approach.

IV. Field Work and Data Processing

1. Mass Density

To determine the mass density of the rock from the study area the Nettleton method is applied, by minimize the correlation between topography and gravity anomaly.

2. Gravity Anomaly

The data used to construct the Bouguer Anomaly map is the complete Bouguer anomaly. From the CBA map (Fig10) author derives appearances as follows:

In this study, author conducted a spectral analysis to ascertain the approximate depth of the Regional Anomaly and Residual Anomaly, and estimate the width of the window used for data filtering process. Filtering process is done by using Moving Average method, which separate the regional anomaly and the residual anomaly, where the residual anomaly is derived from Bouguer anomaly minus regional anomaly.

The next step, author conducted a modeling process based on the geological information or data (lithological distribution and stratigraphy). From the Nettleton profile the mass density value obtained around 2.5 gr/cm³.

Wavenumbers (k) and gravity anomaly amplitude (ln A) relationship chart:

3. Anomalies Depth Estimation and Filter Window

By calculating the average of window from the anomaly separation above resulting filter window as much as 19 or 19 x 19 km² with the grid spacing 250 (Figure 7,8,9), (Table 1). Filter window 19 will be used to separate the regional and residual anomaly which later used in 2D modeling.

The result of spectral analysis used to estimated the depth of the anomaly and the filter window calculation:

**Table 1**  The Result of Spectral Analysis calculation
V. Mapping and The Separation of Bouguer, Regional and Residual Anomaly

High frequency wave anomaly can be removed using the Moving Average method. This technique is basically done by averaging the gravity anomaly data (CBA) where the result of this method is the value of regional anomaly. The residual anomaly is calculated by lessen the value of CBA with the regional anomaly (Figure 10).

VI. Result / Discussion

Quantitative interpretation

The interpretation is done quantitatively, aim to recognize the geological model of subsurface which comprises dimension of the model, the type of the composer lithology which made based on the physical parameter of rock density on the model. From this quantitative interpretation, it is expected to obtained the subsurface geological structure. To perform such quantitative interpretation a 2D Talwani forward modeling is conducted using the Grav2 DC software.

1. Bouguer, Regional and Residual Anomaly Map

Based on the spectrum analysis result from the three track line, it is shown that the average depth of the regional anomaly source in the study area located at the depth of approximately 3.2 km. Regional anomaly map derived from the filtering process shown in figure 6.

Overall, the value of the Bouguer anomaly in the regional anomaly map ranges between 21-28 mgal (purple – red color index) where it becomes more deep to northeast.

Bouguer Anomaly is a total amount of Regional Anomaly and Residual Anomaly, so the residual anomaly value is derived by the subtraction between Bouguer Anomaly value and the Regional Anomaly.

- Lower anomaly occupied the northern part of the study area map, with an open contour pattern and higher anomaly occupied the southern part with a small, closed contour pattern (short wavelength) in the center part, and slightly spread in the southern part.

- In the center part of the map, with the anticlinal pattern and yellow-red color index (1-3.2 mgal) indicates that the area is a high which expectedly contained carbonate buildup structure. Therefore it is necessary to perform a 2D Talwani modeling.

- From the South-Southwest towards North-Northeast is towards the deeper area with dominant green color index (-0.2 to -0.8 mgal) up to blue color index (-0.8 to -1 mgal)

VII. Forward Modeling

2-Dimension modeling in gravity, one of its direction is defined as infinite. The modeling method that used is forward modeling, where the model is determined along with its density value, which then its gravity field is calculated using the Grav2-DC software.

Gravity value from the calculation result (calculated gravity) is compared with the one derived from the field measurement. The modeling is done by varying the parameter (trial and error), such as its density, its depth, and the shape of the structure to obtain the similarity of gravity observed and gravity calculated value in the profile. This way shows that the result of field measurements gravity is used as a comparator in interpreting the subsurface structure geometry. This method allows the obtainment of similar gravity responses. The result earned by inserting the geological interpretation inside. Forward modeling of residual anomaly with 19x19 km² filter used to model what is expected to be a carbonate buildup. The modeling process needs the information about geological condition in that area and other supporting data that is references from seismic data, along with the interpretation (source: Pertamina, 2007). Density background that is
applied in the construction of the model is as much 2.67 gr/cc, while the amount of density is expected by comparing the lithology and laboratory result with the density table from Telford et al. 1976 (Table 2). The amount of estimated density can be seen as follows:

**Table 2.** Rocks Mass Density (Telford et al., 1976), Lab Analysis

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Range gr/cc</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>1.61-2.76</td>
<td>2.35</td>
</tr>
<tr>
<td>Shales</td>
<td>1.77-3.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Limestones</td>
<td>1.92-2.9</td>
<td>2.55</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2.28-2.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>2.4-2.8</td>
<td>2.6</td>
</tr>
</tbody>
</table>

3 cross section are made (A, B, and C) from the residual map for the 2D subsurface structure modeling, by using the **Grav 2-DC** software (figure 10). This 3 cross sections is selected based on the variation of density contrast fluctuation which is very prominent, perpendicular to the strike, and assumed to be at different types of lithology.

The cross section B modeling is chosen and considered as the best model and can be used to represent the subsurface structural and lithological condition in this study, because its center part exhibits the anticlinal pattern with yellow – red color index (1 – 3.2 mgal), indicates that the area constitutes a high area, which expected to be a carbonate buildup structure. Another modeling process also carried on in this study which can be used as one means to validate that model by creating a comparison where there is another assumption to be considered that the structure can be expected as a carbonate build up, horst, magma intrusion, or shale diapir.

**The Modeling of Subsurface Structure for Studied Area.**

1 Section B Interpretation

<table>
<thead>
<tr>
<th>Model</th>
<th>Mineralogy</th>
<th>Horizon</th>
<th>Type of model</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>Anhydrite</td>
<td>Shall</td>
<td>Carbonate buildup</td>
</tr>
<tr>
<td>b.</td>
<td>Anhydrite</td>
<td>Shall</td>
<td>Carbonate buildup</td>
</tr>
<tr>
<td>c.</td>
<td>Anhydrite</td>
<td>Shall</td>
<td>Carbonate buildup</td>
</tr>
</tbody>
</table>

**Carbonate buildup assumptions**

1. This model is formed by the distribution of density (using gravity method and geological survey) which develops the subsurface geological structures. The G-calculated value corresponds well with the G-observed value at 2.06 % of error point. (Figure 11).

In this model, all gravity anomalies happen because of the anomalous things contribution at ± 3400 m depth up until the surface. The deepest bed that resides at depth of 3400 m is a Pre-Tertiary basement which become the base of all sedimentary basins in Java, that later on, was filled by density distribution from Ngimbang Formation (2.30 gr/cc) that is dominated by sandstone which is relatively thin-distributed. On top of that was distributed a density value of 2.49 gr/cc or so called Kujung Formation which is dominated by limestone, where selectively thickening to form an undulation structures with a thickness of 1000-1250 meters. This thickening of the Kujung Formation is assumed as carbonate buildup which geologically grew and distributed very well at basement high. This thing happened because of the basement’s own configuration from tectonics activities (basement which is dominated by both Late Cretaceous metamorphic rocks {such as Slate and Phylite} and igneous rocks) and a relatively major transgressive environment at Oligo-Miocene. On top of that was distributed a density value from Tuban Formation, Ngrayong Formation and a thinner and younger Wonocolo Formation.
2. Based on 2-D Seismic Model Interpretation, it is seen that the pattern of the seismic data intensively varies; therefore a proper distinguishing technique between data and its noises is vital. In this case such problem can surely be solved by well data to predict the response of the lithologies or the fluid contents. Below is a figure that shows a 2-D seismic model from the PT. Pertamina final report, 2007.

Based on that reference, it is concluded that there is an undulation structure (red box area, Figure 16) which is indicating a carbonate buildup.

From Figure 16, it can be seen that the structures pattern in the studied area are thrust faults, with a relatively reside at southwest – northeast and southeast – northwest. From the oldest to youngest formations are Kujung, Tuban, Ngrayong, Wonocolo and Ledok Formation. In Kujung Formation there is an undulation structure as seen at

b. Horst assumptions
1. Based on gravity method, the curves matching method shows a model that holds a 2.38 % value of error, which is bigger than the carbonate buildup. This result convinces that the horst assumption is not well-matched in approaching the subsurface of geological conditions in section B.

2. Based on geological survey, there was tectonic activities in the first phase (Tertiary – early Oligocene) of the studied area, basement is at Pre – Tertiary which shows accretion pattern in northeast – southwest, that is clearly shown by the fault orientations in the basement and horst or graben in control of the extensional force.

3. Based on Seismic model shows a negative value.

c. Intrusion assumptions
1. Based on gravity method, the intrusion assumptions model can’t show a more representative result in approaching the subsurface geological condition, because of its error count which is 2.89 %, even bigger than the previous assumptions. (figure 13)

2. Based on geological survey, the model that show an undulation structure as intrusion is not possible because there are no such intrusions in the regional geology of studied studied area.

d. Shale diapir assumptions
1. Based on gravity value, the model from this assumptions has an error value of 3.14 % which is the highest of all previous assumptions.(figure 14)

**Cross section A and C interpretation model**

Based on the cross section A and C modeling it appears that there is an undulation / mound structure which relatively similar to the one in cross section B, where the structure is assumed to be a carbonate buildup. Formasi Kujung Formation was precipitated on the highs (basement highs). This is because there are basement configuration effects as a consequence of tectonic activity (the basement is dominated by Late Cretaceous Metamorphic rock, such as slate, and phyllite, and also igneous rocks) and the sea level setting was tend to be transgressive relatively in that time.

This cross section modeling (A and C) is shown to emphasize assumption about the presence of carbonate buildup. Kujung Formation in the study area Kasiman which has been shown in the cross section B modeling ( Figure 17, 18)

**Cross Section A, B, and C Model and Interpretation**

Gravity model interpretation in the form of lithological distribution, the structure that formed in the study area Kasiman which is the manifestation of the quantitative interpretation which is done by constructing the 2D model, in this case the cross section A, B, and C.

Modeling result of the cross section A, B, and C exhibits a similarity, that is the presence of mounded structure which appears in the Kujung Formation assumed as carbonate buildup which occupied the depth of ± 2.5 km with the density value of ± 2.49 gr/cc and is
the result of major transgressive during Oligo-Miocene, and distribute very well at the high area (basement high)

By the presence of carbonate buildup it is stated that at the North East Java Offshore, especially at the west Madura working area the hydrocarbon found in the carbonate reefs (carbonate buildup) of Kujung Formation, this reefs are relatively small, but intensely productive and contain hydrocarbon almost entirely. At the same reef complex at the region of Cepu (including the study area Kasiman), a huge amount of hydrocarbon has been found. This evidence reinforce the assumption of the presence of the Kujung Formation carbonate reef (carbonate buildup) in the study area yang distributes from the NW – SE at the center part of the map.

Meanwhile, the Pre-Tertiary basement showing NE-SW trending accretional pattern, which is shown by the orientation of the faults in the basement, horst or thrust faults and graben or step fault. This evidence match with the order of regional structure of the North East Java Basin at the first tectonic phase which occurred during the Early Tertiary until Early Oligocene when the organic-rich Ngimbang Formation and Kujung Formation precipitated on the basement (syn rift – post rift) with the dominant force that occurred is extensional force. The diapir itself is an intrusion caused by the difference of pressure and buoyancy (gases that trapped inside the shale). The term diapir is used more often at the sedimentary rock, although in some occasion used in igneous rock. It is called shale diapir if the material that intrude is shale. During the intrusion process, the intrusion will cause the formation of folds (anticline) or dome at the top. This Diapir gives affect to the formation of a number of reservoir trap at its top or its side. Because of its massive nature and it incapability to pass through fluids, it acts as the seal. The diapir formation can be caused by the tectonic process or rapid deposition, or both

CONCLUSION

Based on the discussion above, there are several conclusion as follows;

1. Low anomaly Complete Bouguer Analysis map distributed in the northern part of the study with an open contour pattern and the high anomaly distributed along the southern part with a small, closed contour pattern (short wave length), in the center part and slightly spread in the southern part. Gravity anomaly in the cross section A, B, and C indicates a sloping anomaly from the south towards the north, with an anticlinal pattern in the center part.

2. Spectral Analysis results in the depth of the anomaly zone and the wavenumbers (k) which derived by Fourier-transforming the gravity anomaly using the Numeri software which generates 19 filter with spacing of 250 m. This 19 filter window is used to split the regional and residual anomaly. Based on the filtering result it is known that the regional anomaly located at the depth of ± 3.2 km and residual anomaly located at the depth of ± 183 m.

3. Residual anomaly map in the center part with the anticlinal pattern and (1 mgal – 32 mgal) indicates the area as a high area.

4. Normal fault structure with NE-SW relative trending which formed as the result of extensional force during the Tertiary until the Late Oligocene, is the pathway of hydrocarbon migration from the Ngimbang Formation below.

5. Integration of geological data, seismic model assumes that the mound that appear in the Kujung Formation was a carbonate buildup (Kujung Reef) as a result of major transgressive during the Oligo-Miocene, at the depth ± 2.5 km, which is a good reservoir.

References


Hall, R., 2005, Cenozoic Tectonics of Indonesia Problem and Models, Short Course Indonesian Petroleum Association.


Figure 1 The Location of Study Area and The Tectonic Zone of North East Java (Van Bammelen, 1949).

Figure 2 The Physiography of Java and Madura (Bemmelen, V., 1949 modified by Satyana, A. H., 2005)

Figure 3 Geological Map of study area (Hartono dan Suharsono, 1997)

Figure 4 Stratigraphic column of Northeast Java. (Pertamina 2005)

Figure 5 Regional gravity of studied area (Eko.W. 2005)

Figure 6 Flow Chart Gravity Analysis
Figure 7 The determination of wavenumber (k) value in section A

Figure 8 The determination of wavenumber (k) value in section B

Figure 9 The determination of wavenumber (k) value in section C

Figure 10 a. Bouguer, b. regional and c. residual anomaly window 19x19 km², Tracks measurement L5, L7, and L9 Residual Anomaly map with the contour intervals of 0.2 mgal along with the cross sections A, B, and C

Figure 11 Forward modeling of cross section B, assumed to be a carbonate build up

Figure 12 Forward modeling of cross section B, assumed to be a Horst and Graben
Figure 13 Forward modeling of cross section B, assumed to be an intrusion.

Figure 14 Forward modeling of cross section B, assumed to be a shale diapir.

Note:

1. Early Miocene Carbonate buildups of the Kujung and Tuban Formation
2. Middle Miocene to Pleistocene clastic reservoirs within late Miocene to Pleistocene inversion anticlines
3. Eocene Lower Ngimbang Formation sandstone drape and pinchout onto basement highs/horst blocks
4. Eocene to Early Oligocene Ngimbang Carbonate buildups

Figure 15 Subsurface geological model from East Java exploration (Pertamina 1998).

Figure 16 Section B model interpretation based on gravity and seismic data.

Figure 17 Forward modeling of cross section A.

Figure 18 Forward modeling of cross section C.
Figure 19  Cross Section A, B, and C Model Interpretation