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Optimization of Geophysical Design Survey Priority Areas for Unconventional Oil and Gas Exploration using Topex Gravity Data Analysis

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ABSTRACT
The exploration of unconventional oil and gas resources requires efficient identification of priority areas with high hydrocarbon potential and reduced exploration risk. This study aims to optimize geophysical survey design by integrating TOPEX gravity data analysis with geological interpretation techniques. The TOPEX satellite gravity dataset was processed and filtered to delineate subsurface density anomalies that may indicate structural traps, fault zones, and basin configurations associated with hydrocarbon accumulation. Quantitative interpretation was carried out using spectral analysis and derivative filtering methods to enhance shallow and deep anomaly features. The integration of gravity anomalies with regional geological data enabled the identification of priority zones for further seismic and drilling investigations. Results show that TOPEX gravity data provides a cost-effective and reliable approach for delineating potential unconventional reservoirs, particularly in frontier or data-limited regions. The optimized geophysical survey framework proposed in this research can serve as a strategic tool for national energy exploration programs, ensuring efficient resource allocation and improved success rates in unconventional hydrocarbon exploration.

Keywords: TOPEX gravity, geophysical survey optimization, shale gas, tight sandstone

INTRODUCTION

Gravity surveying has long been recognized as a fundamental geophysical method for subsurface structural mapping in hydrocarbon exploration. The basic principle relies on measuring variations in the Earth's gravitational field caused by lateral density contrasts in subsurface geological formations (Mulet-Forteza et al., 2020; Parker et al., 2022; Telford et al., 1990). In the context of petroleum exploration, gravity anomalies can effectively delineate sedimentary basins, structural highs and lows, fault systems, and salt domes—all of which are critical elements in petroleum system analysis (Li* et al., 2019; Watts, 2014). The integration of satellite-derived gravity data, particularly TOPEX (Topography Experiment) mission data, has revolutionized regional-scale exploration by providing high-resolution, cost-effective gravity measurements over large and often inaccessible areas (Sandwell et al., 2014). This approach offers significant advantages in frontier exploration where conventional ground-based gravity surveys are economically prohibitive or logistically challenging.

The theoretical framework for using gravity anomalies as survey optimization tools is grounded in the direct relationship between subsurface density distribution and gravitational potential. Bouguer anomaly maps, derived from free-air gravity corrections and terrain compensation, reveal density variations that correspond to lithological changes, basin geometry, and structural features (Blakely, 1995). In unconventional hydrocarbon systems, where source rocks, reservoirs, and seals are often vertically stacked within the same formation (shale gas/oil plays), gravity surveys can identify structural depressions (synclines) that favor organic-rich sediment accumulation and thermal maturation (Jarvie et al., 2007). By delineating these prospective zones early in the exploration workflow, operators can strategically prioritize seismic acquisition and drilling programs, thereby reducing exploration risk and optimizing resource allocation (Sheriff & Geldart, 1995).

Currently, Indonesia is facing a rapid increase in world energy demand of 6.7% per year, most of which is supplied from fossil fuels. On the other hand, Indonesia is facing the reality that both production and exploration of oil and gas reserves have proven to continue to decline. By 2030, in the business scenario of primary energy needs, the realization of the lifting target of around 1 million barrels of oil per day is needed. This is a challenge to find new resources, develop frontier areas and produce more oil and gas from the remaining fields. Currently, the focus of oil and gas production in Indonesia is still very much dependent on conventional availability. Meanwhile, several developed countries have started to produce unconventional oil and gas to meet the needs of domestic use and export interests (Kapustin & Grushevenko, 2018). The unconventional oil and gas system is unique in that the entire system is contained directly within the parent rock which is rich in organic material (Katz et al., 2021). One of the unconventional oil and gas potentials in Indonesia is in the Northern Java Basin with a structure in the northeast-southwest direction (Jumiati et al., 2020).

The North East Java Basin has been recognized as a potential hydrocarbon-producing basin since the 19th century, and several wells have begun to be drilled by Dutch oil and gas companies (Nawawi et al., 1996). The North East Java basin itself has experienced cracking and expansion of the bedrock into anticline heights. The deformation forms highs and lows (basins) rich in oil and gas. The altitude associated with oil and gas forms two paths, namely the Rembang Zone and the Randublatung Zone. The Rembang Basin is a place for the deposition of layers of organic shale from the terrestrial environment of the Ngimbang Bajo, Kujung Bawah and Tawun Formations. The Rembang Zone is a prospective oil and gas route characterized by oil and gas seepage for future exploration with unconventional systems (San et al., 2017). Oil and gas migrate from the basin through faults supplying high-altitude areas to the upper layers of the Rembang Zone and Randublatung Zones. However, so far in oil and gas exploration of the North East Java Basin, the focus has generally been on reservoir and trap exploration compared to the parent rock (Jamaluddin & Johanes Gedo Sea, 2018; Oei et al., 2020; Y. Situmorang et al., 2017; Yazid et al., 2017).

The petroleum system of the North East Java Basin comprises several critical elements distributed across distinct stratigraphic intervals. Source rocks are primarily identified in the Middle Eocene Ngimbang Formation, consisting of organic-rich shales and coals deposited in lacustrine to marginal marine environments. Reservoir intervals include the carbonate buildups of the Kujung Formation and the fluvio-deltaic sandstones of the Ngrayong Formation, while sealing capacity is provided by overlying shales of the Tuban and Wonocolo Formations (Pertamina BPPKA, 1996). Structural and stratigraphic traps formed during multiple tectonic phases—from Eocene rifting to Miocene inversion—create complex hydrocarbon entrapment geometries (Satyana, 2005). Understanding this integrated petroleum system framework is essential for interpreting gravity anomaly patterns and linking geophysical signatures to geological features conducive to hydrocarbon accumulation (Barbosa et al., 2022; Cedeño et al., 2019; Wang et al., 2019).

Meanwhile, the parent rock in the North East Java Basin is identified as effective parent rock derived from Middle Eocene deposits in the form of shale and carbonate rocks originating from the marine marginal environment, delta, and lakustrin. One of them is found in the shale layer of the Ngimbang Formation (Aprilana et al., 2018). Based on the above, the target of this research is in the Ngimbang Formation with a depth of 2500 - 4000 m below the earth's surface which has a porosity value small, mature, and ensured to meet the characteristics of shale gas. Satellite gravity data will be used to determine the basin area as seen from the mGal value as well as a combination of seismic record historical data, drill coordinate data, and surface geological data.

Physiographically, the East Java Basin can be divided into three main configurations, namely the North Basin, the Rembang-Madura-Kangean Zone (RMK Zone), and the South Uplift (Satyana, 2005). The northern bassoon consists of sub-basins that head northeast-southwest as an implication of the basin being segmented into several horsts and graben. The formation of rifting in a northeast-southwest direction is controlled by the Suture Meratus trend (Hall, 2012) and the constituent components of the microcontinent itself. Meanwhile, according to Lunt (Lunt, 2019), the trend of rifting in the southwest-northeast direction in the Northern East Java Basin is influenced by the expansion that occurs in the Makassar Strait. The RMK zone is characterized by the existence of uplifts in the Tuban and Madura Island areas because of the developing horizontal fault system. Meanwhile, the southern uplift is marked by its northernmost boundary by the Kendeng Fault Belt.

Central Deep itself is part of North Basham, with a structure that is oriented northeast-southwest. Sediment filling in the Northern East Java Basin, especially the Central East Java Basin, is closely related to its tectonic development. Expansion occurred in the Eocene-Oligocene at the same time as alluvial clastic deposition. clay, and lacistrin flakes. These shales are rich in organic matter and are the source rock of hydrocarbons in this area. This was followed by a period of tectonic calm in the Early Miocene, which was characterized by the development of carbonate rocks, and generally became reservoir rocks in the Northern East Java Basin. Based on the tectonostratigraphy that developed in the area investigated, there are two oil systems, namely the early post-rift marine petroleum system and the late post-rift transgressive delta petroleum system. In the early post-rift phase, shale from the Tuban Formation, sandstone from the Ngrayong Formation, and shale from the Wonocolo Formation were deposited due to the change in subduction from northeast to southwest in the Late Cretaceous to west – east at the beginning of the Neogen. Meanwhile, the late post-rift phase that developed included marine clay deposits, volcaniclastics, carbonate deposits and sandstone deposited in a variety of shallow to deeper water environments.

According to Pringgoprawiro (1983), the oldest stratigraphic order of the North East Java Basin is metasedimentary bedrock and volcanic rocks of Late Cretaceous age. Then it continued with the deposition of the Pre-Ngimbang Formation (Early Eocene) which was composed of sandstone inserted shale, coal, and coal. Furthermore, the Ngimbang Formation was deposited in an inconsistent manner in the Middle Eocene – Early Oligocene. The upper part of the Ngimbang Formation consists of shale with interspersed limestone and sandstone, while the lower part consists of sandstone, shale, and silt with thin inserts of coal. (Source Rock) derived from the shale and coal of the Ngimbang Formation and the Kujung Formation; Rocks that have the potential to be reservoirs are sandstone and limestone of the Ngimbang Formation, Kujung Formation, Ngrayong Formation, and Paciran Formation; Seal rocks which are shale and carbonate rocks of the Ngimbang Formation, Kujung Formation, Tuban Formation, and Tongue Formation. The traps of the North East Java Basin include carbonate build-up and compressive/inversion structures (Pertamina BPPKA, 1996).

The quantity of the parent rock is obtained by looking at the TOC and S2 values as shown (Figure 3a) Based on Peters & Cassa (1994), the richness of organic matter is seen from the TOC value. A TOC score of 4 is excellent. The potential of hydrocarbons that can be produced can be seen through the S2 value where the S2 value is 0 – 2.5 including poor, 2.5 – 5 including fair, 5 – 10 including good, 10 – 20 including very good and >20 including excellent. In the weighing formation around the research area, analysis has been carried out in the Late Oligocene – Basement. The results of the analysis of TOC and S2 values show that the quality has a poor – excellent range as shown (Figure 3b). The average TOC value ranges from 0.09 – 4.68 wt% (Poor – Excellent). The deposits that have the highest quantity are in the Middle Eocene deposits due to the influence of the existence of coal lithology formed by the accumulation of woody plants so that organic materials show high values. The S2 value shows an average of 0.23 – 10.72 so that the potential for poor – very good to produce hydrocarbons is known.

The bedrock is seen through the HI value. Through these values, the products produced by the parent rock can be known. Peters & Cassa (1994) divided the types of kerogen based on HI values, namely type I kerogen with an HI value of >600 (oil-prone), type II with an HI value of 300 – 600 (oil prone), type II/III with an HI value of 200 – 300 (oil-gas prone), type III with an HI value of 50 – 200 (gas prone) and type IV with an HI value of <50 (inert). The results of the analysis of HI values and crossplots carried out in the Middle Eocene deposits, especially the Ngimbang formation, show that the type of kerogen is dominated by type II/III as shown in (Figure 3c). From the type of kerogen, it is known that the products that will be produced when it has reached the mature phase are a mixture of oil-gas and gas. The level of maturity of the parent rock can be determined based on the Tmax value resulting from Rock Eval Pyrolysis as shown (Figure 3d). Peters

& Cassa classify the level of maturity into immature, mature and postmature. Immature maturity has a Tmax value of < 435 oC and a Ro value of 0.2 – 0.6%. Early maturity has a Tmax value of 435 – 445 oC and a Ro value of 0.6 – 0.65%. Peak maturity has a Tmax value of 445 – 450 oC and a Ro value of 0.65 – 0.9%. Late maturity has a Tmax value of 450 – 470 oC and a Ro value of 0.9 – 1.35%. Postmature maturity has a Tmax value of > 470 oC and a Ro value of > 1.35% (Peters & Cassa, 1994). Based on the Tmax value, the oil window in one of the wells in the study area shows the early maturation phase in the Ngimbang Formation deposit.

1D modeling of sedimentation history shows the speed of sediment accumulation in the Mandu-Ngimbang Formation. In the Tuban Formation – The end of the speed of sediment accumulation increases followed by tectonic inversion events that cause uplift and sediment on it to erode. When the sedimentation speed is fast, the thickness of the sediment is relatively thick and vice versa. Based on the modeling results, the Ngimbang Formation around the research area which has an early maturity level in the Middle Eocene deposits is at a depth of 4500 meters.

Despite extensive exploration history in the North East Java Basin, significant knowledge gaps remain regarding the spatial distribution of mature source rocks in under-explored sub-basins. Previous studies have primarily focused on conventional structural traps in anticlinal closures, with limited attention to unconventional shale gas/oil potential in synclinal depocenters where organic-rich sediments are thickest and most thermally mature (Jumiati et al., 2020). Furthermore, seismic coverage remains sparse in several frontier areas, and drilling data are concentrated in known productive trends, leaving vast regions without subsurface calibration. This creates an urgent need for cost-effective reconnaissance tools that can guide strategic exploration decisions before committing to expensive seismic and drilling programs.

Therefore, this study aims to: (1) integrate TOPEX satellite gravity data with existing geological, seismic, and well data to delineate subsurface structural features and basin geometry; (2) identify priority exploration zones characterized by synclinal configurations, adequate source rock depth (2500-4000 m), and minimal previous exploration activity; and (3) develop an optimized geophysical survey design framework that maximizes exploration efficiency by targeting high-potential, low-risk areas. The expected benefits of this research include: (a) reducing exploration costs through strategic targeting of geophysical surveys; (b) enhancing national energy security by unlocking unconventional hydrocarbon resources; and (c) providing a replicable methodological framework applicable to other frontier basins in Indonesia and similar geological settings globally. The implications extend beyond immediate exploration gains, potentially informing national energy policy and investment strategies for unconventional resource development, thereby contributing to Indonesia's transition toward energy self-sufficiency in the face of declining conventional reserves.

RESEARCH METHOD

This study employed an integrated geophysical-geological approach to optimize survey design for unconventional hydrocarbon exploration in the North East Java Basin. The methodology comprised several sequential stages, from data acquisition and processing to interpretation and integration, culminating in the delineation of priority exploration zones.

The research process began with a comprehensive literature review encompassing the geology, tectonics, stratigraphy, petroleum system elements, and exploration history of the study area. Published geological maps, basin analysis reports, and petroleum system studies were synthesized to establish a conceptual framework for interpretation (Satyana, 2005; Pertamina BPPKA, 1996). Emphasis was placed on understanding the depositional environment, thermal maturation history, and structural evolution of the Ngimbang Formation—the primary unconventional target interval.

TOPEX satellite altimetry-derived gravity data were acquired from publicly available databases, providing regional coverage of the North East Java Basin at a spatial resolution suitable for basin-scale structural interpretation. The raw gravity dataset consists of free-air gravity anomalies measured at satellite altitude, which require several processing steps to derive geologically meaningful Bouguer anomalies at the Earth's surface.

The data processing workflow involved the following steps:

1. Free-Air Correction: Elevation effects were removed by applying the free-air correction, which accounts for the decrease in gravitational acceleration with increasing altitude above the reference ellipsoid. The free-air anomaly (FAA) was calculated using the formula: $FAA = g_{obs} - g_{theoretical} + 0.3086h$ where g_{obs} is the observed gravity, $g_{theoretical}$ is the theoretical gravity at the ellipsoid, and h is the elevation in meters.
2. Bouguer Correction: To account for the gravitational attraction of rock mass between the observation point and the reference datum, a Bouguer slab correction was applied using an assumed crustal density of 2.67 g/cm^3. This correction removes the effect of topographic mass, yielding the Simple Bouguer Anomaly (SBA).
3. Terrain Correction: Given the variable topography of Java, terrain corrections were applied to compensate for the gravitational effects of nearby topographic irregularities (valleys and hills). This process utilized digital elevation model (DEM) data and resulted in the Complete Bouguer Anomaly (CBA), which reflects subsurface density variations more accurately.
4. Gridding and Filtering: The processed CBA data were interpolated onto a regular grid using minimum curvature algorithms to facilitate spatial visualization and interpretation. Regional-residual separation techniques were applied to isolate shallow crustal features (residual anomalies) from deeper structural trends (regional anomalies). Band-pass filtering enhanced anomalies associated with basin-scale structures at depths corresponding to the target Ngimbang Formation (2500-4000 m).

To complement the gravity analysis, ancillary datasets were compiled from the Indonesian Ministry of Energy and Mineral Resources (ESDM) Geoportal:

1. 2D Seismic Line Distribution: Historical seismic survey trajectories were mapped to identify areas with sparse seismic coverage, which represent opportunities for new seismic acquisition.
2. Well Location Data: Coordinates and classifications (wildcat, exploration, development) of existing wells were compiled to assess drilling density and avoid redundant exploration efforts.
3. Structural Geology Maps: Regional fault systems, fold axes, and tectonic zones were integrated to constrain the structural interpretation of gravity anomalies.

The interpretation phase focused on correlating gravity anomaly patterns with geological structures and petroleum system elements. Low gravity anomalies (15-40 mGal) were interpreted as synclinal basins filled with low-density sedimentary rocks, particularly organic-rich shales of the Ngimbang Formation. Conversely, high gravity anomalies (40-60 mGal) corresponded to anticlinal highs or basement uplifts with higher-density rocks (Priyono et al., 2024; Dr. B. Situmorang, 2022). The gravity interpretation was calibrated using available well data (e.g., JAVA-1 well) that penetrate the Ngimbang Formation, confirming the depth and thickness of target intervals in synclinal settings.

All geospatial datasets—CBA map, seismic line distribution, well locations, and structural geology—were integrated in a Geographic Information System (GIS) environment. Overlay analysis identified regions that simultaneously satisfied multiple criteria for unconventional exploration potential:

1. Low gravity anomalies indicating synclinal basins
2. Target depth range (2500-4000 m) for thermally mature Ngimbang Formation
3. Sparse or absent seismic coverage
4. No existing well penetrations
5. Favorable structural position relative to known petroleum system elements

Priority exploration zones meeting these criteria were delineated and ranked based on the degree of confluence of favorable indicators. These zones represent optimal targets for subsequent detailed geophysical surveys (high-resolution seismic) and exploratory drilling, thereby maximizing exploration efficiency and resource allocation.

The methodology developed in this study is conceptually illustrated in the research flowchart (Figure 5), which outlines the systematic progression from data acquisition through processing, interpretation, integration, and finally to the identification of priority exploration areas. This framework is replicable and can be adapted to other sedimentary basins with similar data availability and geological settings.

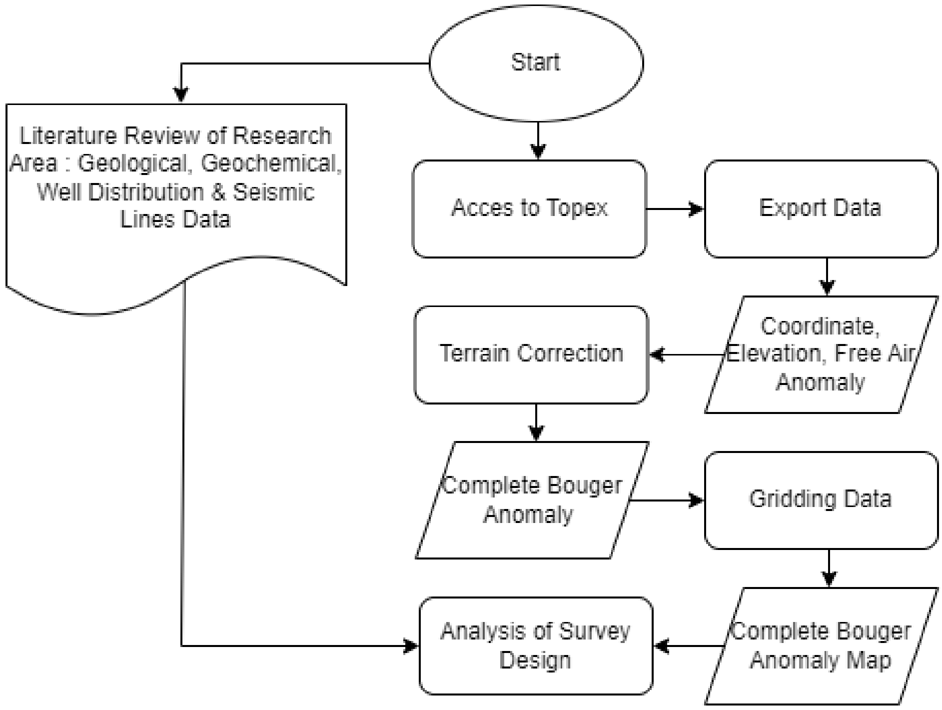

Figure 1. Flowchart of research

RESULTS AND DISCUSSION

Gravity Anomaly Interpretation and Basin Delineation

The Complete Bouguer Anomaly (CBA) map derived from TOPEX gravity data reveals distinct spatial patterns across the North East Java Basin, reflecting subsurface density variations associated with basin geometry, lithological contrasts, and structural features (Figure 2). The gravity field exhibits a bimodal distribution, with anomaly values ranging from approximately 15 to 60 mGal. This range is characteristic of sedimentary basins where low-density sedimentary fill contrasts with higher-density basement rocks and volcanic intrusions.

Based on the appearance on the TOPEX gravitational anomaly map in Figure 2, it is known that there is a transition zone between high and low anomalies. Bouguer anomalies can be systematically classified into two primary domains based on their geological significance. Low anomalies, ranging from 15 to 40 mGal, are interpreted as synclinal depocenters filled with thick sequences of low-density sedimentary rocks, including organic-rich shales, sandstones, and carbonates. These synclinal basins represent sites of maximum sediment accumulation during the Eocene-Oligocene rifting and post-rift thermal subsidence phases. The low density values are consistent with the presence of porous sedimentary rocks, particularly when saturated with hydrocarbons or formation water, and with organic-rich shales that have inherently low bulk densities due to high organic content (Jarvie et al., 2007).

Conversely, high anomalies in the range of 40-60 mGal correspond to anticlinal highs, horst blocks, or areas where basement rocks are structurally elevated closer to the surface. These features are typically composed of higher-density metamorphic or igneous basement rocks and are less favorable for unconventional shale gas/oil accumulation due to shallower burial depths and reduced thermal maturity. However, these structural highs play a critical role in the petroleum system by forming migration pathways and structural traps for conventional reservoirs in overlying formations (Satyana, 2005).

Based on JAVA-1 Well data, the Ngimbang Shale Formation is in a syncline with a depth ranging from 3000-4000 m. This depth range is particularly significant for unconventional resource potential, as it places the organic-rich shales within the thermal maturity window for oil and gas generation (Tmax 435-450°C, Ro 0.6-0.9%) as confirmed by geochemical analyses (Peters & Cassa, 1994; Pradono & Rakasiwi, 2018). The synclinal geometry not only facilitates greater sediment thickness and organic matter concentration but also provides favorable pressure-temperature conditions for hydrocarbon generation and retention in low-permeability shale matrices. Therefore, the area delineated with a white dashed line on the gravity map (Figure 2) is interpreted as a priority basin with significant accumulation of source rock in the Ngimbang Formation, making it optimal for further detailed surveys.

This interpretation is further supported by comparing the gravity anomaly patterns with established petroleum system concepts. In unconventional plays, unlike conventional systems, the source rock also serves as the reservoir and often the seal (self-sourced and self-sealed system). Therefore, identifying areas of maximum source rock thickness and optimal thermal maturity is paramount (Jarvie et al., 2007). The low gravity anomalies effectively map these synclinal kitchens, providing a first-order screening tool for unconventional exploration targets.

Internationally, similar gravity-based exploration strategies have been successfully applied in other rift basins hosting unconventional resources. For example, in the Karoo Basin of South Africa, regional gravity surveys were instrumental in delineating the extent and depth of organic-rich shales in the Whitehill Formation, guiding subsequent shale gas exploration efforts (Cole et al., 2016). Similarly, in the Neuquén Basin of Argentina—one of the most prolific unconventional plays in South America—gravity data integration helped identify structural compartments and basin depocenters that were later confirmed as productive Vaca Muerta shale oil/gas zones (Spacapan et al., 2018). These international case studies validate the methodological approach employed in this study and underscore the global applicability of satellite gravity data for unconventional resource assessment in frontier rift basins.

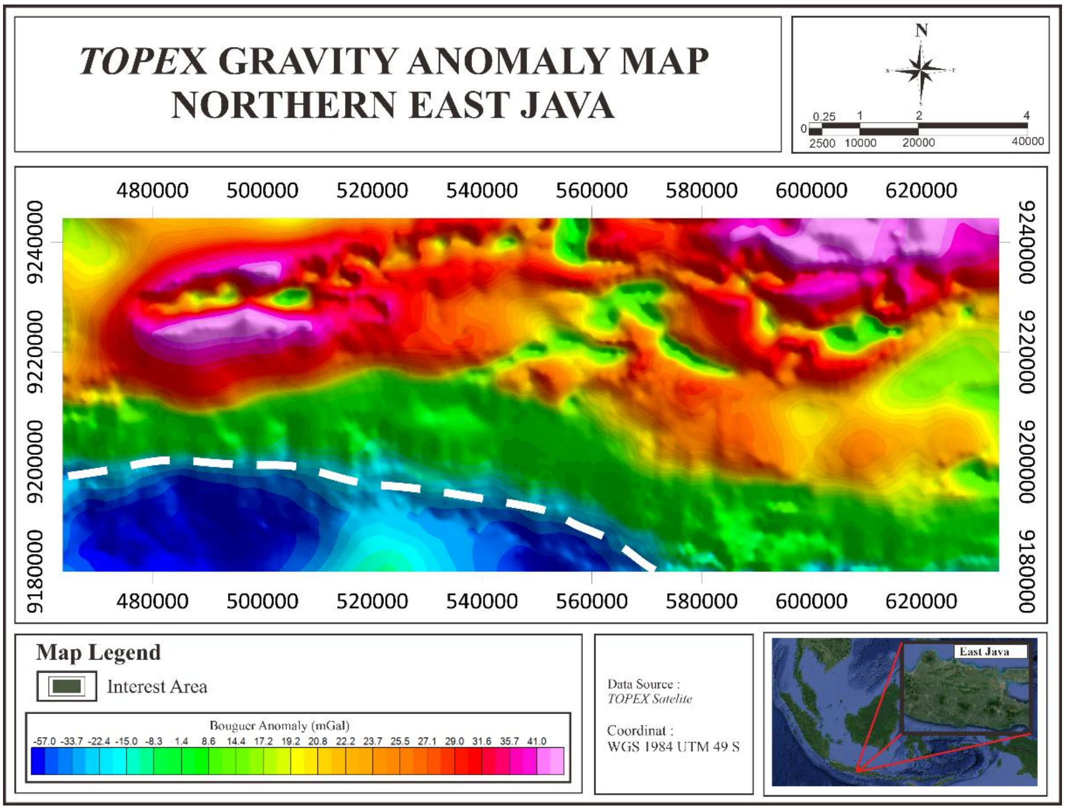

Figure 2. Topex gravity anomaly map of Northern East Java

Integration with Seismic and Well Data

The seismic trajectory distribution data that has been recorded is obtained from the ESDM Map Geoportal Website as shown in Figure 3. Seismic trajectories are marked with red lines that can be seen on the map. The spatial distribution of existing 2D seismic lines reveals significant gaps in subsurface imaging, particularly in the southern portion of the study area. These data-sparse regions coincide with zones of low gravity anomalies identified as prospective synclinal basins. The absence of seismic coverage in these areas presents both a challenge and an opportunity: while subsurface uncertainty is higher, the potential for new discoveries remains largely untested.

By overlaying the gravity anomaly map with the seismic line distribution, we can strategically identify areas where new seismic acquisition would yield maximum value—specifically, zones exhibiting favorable gravity signatures but lacking seismic characterization (Sheriff & Geldart, 1995). This seismic trajectory data is useful for determining new seismic trajectories, so that there are no seismic trajectories that overlap each other. The design of the seismic survey is better adjusted to the location or area that has not been covered by previous measurements. The seismic line that has been acquired is depicted with a solid red line on the map, while the area with a broken white line is the boundary of the area of interest or a designated area where seismic trajectories are still rare so that it is optimal for exploration, especially seismic.

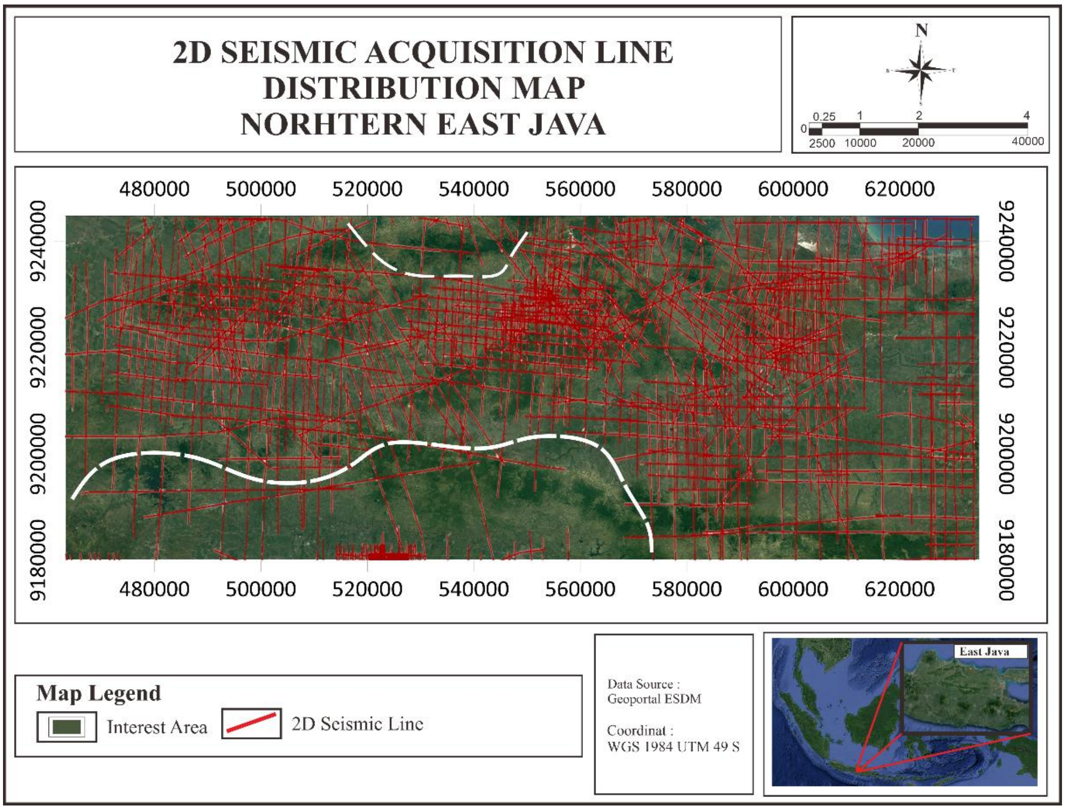

Figure 3. 2D Seismic acquisition line distribution map of Northern East Java

The data on the distribution of wells that have been recorded are obtained from the ESDM Map Geoportal Website as shown in Figure 4. Wells are interpreted with small dots or circles. On the plot, there are a total of 272 wells, including the JAVA-1 and KARANGANYAR-1 wells which are literature studies. 13 Wild-Cat Wells with orange circle markings, 41 Exploration Wells with yellow circle markings, 198 Development Wells with green circle marks, and 18 Combinasui Wells with yellow circle marks. Well density analysis reveals a strong concentration of drilling activity in the northern and central portions of the basin, corresponding to known productive trends in conventional reservoirs. However, in the priority area delineated by the white dotted line—which coincides with low gravity anomalies and sparse seismic coverage—no wells have been drilled. This undrilled, underexplored zone represents a frontier opportunity for unconventional exploration. The absence of well control introduces higher geological risk but also eliminates the bias toward previously developed plays, potentially opening new resource fairways (Katz et al., 2021). Therefore, it is optimal to carry out further drilling or exploration to complete the subsurface database of the North East Java Basin and test the unconventional hydrocarbon potential in these synclinal depocenters.

In the interest area with a white dotted line, no wells were found so it is optimal to carry out further drilling or exploration to complete the data of the North East Java Basin. Figure 4 is a combination of data in the research area where the exploration optimization zone is at the bottom of the map or in the southern area with a white dotted line. The area is said to be optimal because it is 4 parameters that meet the petroleum system, especially in basin or non-conventional areas. The prospect areas are in the Grobogan, Boyolali, Sragen, Ngawi, and Madiun areas.

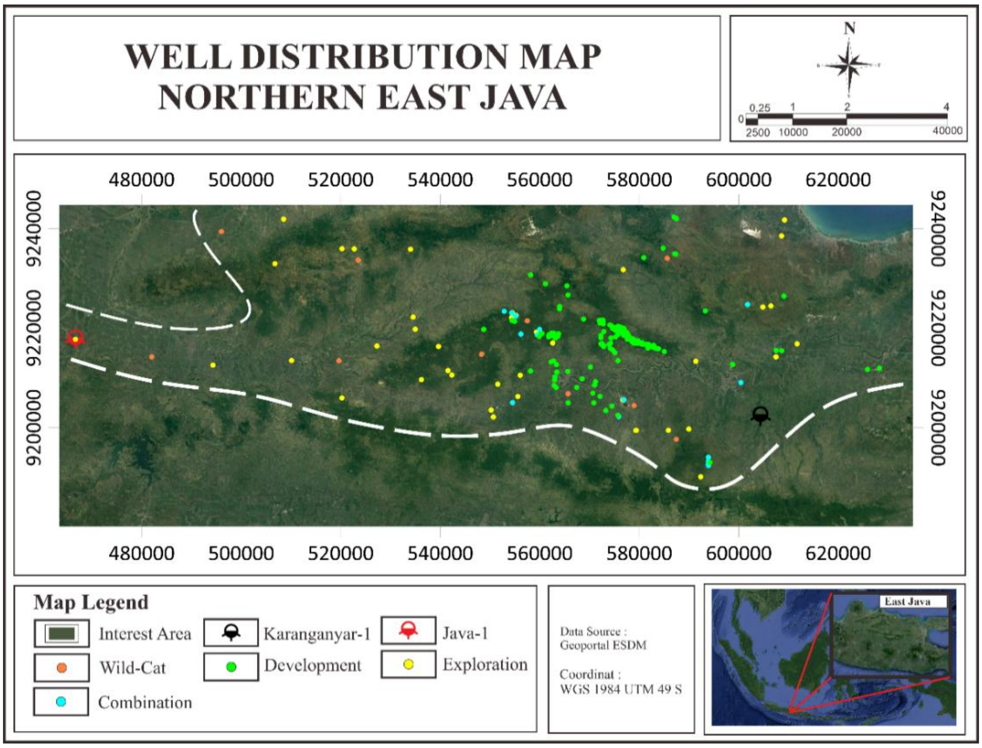

Figure 4. Well distribution map of Northern East Java

Delineation of Priority Exploration Zones

Figure 5 presents an integrated overlay map combining gravity anomalies, well distribution, seismic line coverage, and structural geology. This synthesis map represents the culmination of the multi-dataset integration approach, enabling the identification of priority exploration zones through spatial confluence analysis. The exploration optimization zone, delineated at the bottom (southern portion) of the map with a white dotted line, satisfies four critical criteria that collectively define prospective unconventional hydrocarbon fairways:

1. Low gravity anomalies (15-40 mGal): Indicating synclinal basin geometry with thick sedimentary fill, particularly organic-rich Ngimbang Formation shales at appropriate burial depths (2500-4000 m) for thermal maturation.
2. Sparse seismic coverage: Representing areas where new seismic acquisition can provide high-value subsurface imaging without redundancy, thereby optimizing survey investment.
3. Absence of well penetrations: Ensuring that the exploration targets remain untested, preserving the potential for new discoveries and avoiding areas where drilling has already established production or exhausted reserves.

4. Favorable structural position: Alignment with regional fault systems and tectonic trends that facilitated organic-rich sediment deposition during the Eocene rifting phase and subsequent thermal maturation during burial.

The confluence of these four parameters in a single geographic zone provides a robust, multi-disciplinary justification for prioritizing exploration efforts. This integrated approach reduces exploration risk by ensuring that multiple independent lines of evidence converge on the same target area, a best practice in modern petroleum exploration.

The prospect areas are specifically located in the Grobogan, Boyolali, Sragen, Ngawi, and Madiun regencies. These administrative regions, situated in the southern part of the North East Java Basin, have historically received limited exploration attention compared to the northern offshore areas. However, the gravity data analysis reveals that these onshore-to-transitional zones host significant synclinal basins with potential for unconventional shale gas/oil resources. The proximity to existing infrastructure, including roads and population centers, offers logistical advantages for future exploration and development activities, further enhancing the attractiveness of these priority zones (Jumiati et al., 2020).

From a petroleum systems perspective, the priority zones align with the syn-rift to early post-rift depositional phases when organic-rich lacustrine and marginal marine shales of the Ngimbang Formation were deposited in rapidly subsiding grabens. Subsequent burial during the Oligocene-Miocene placed these source rocks within the oil and gas generation windows, as evidenced by geochemical data from nearby wells (Pradono & Rakasiwi, 2018). The synclinal configuration preserved in the gravity anomalies suggests that these depocenters have experienced minimal erosion or uplift, maintaining the necessary burial depth for continued thermal maturity and hydrocarbon retention.

It is instructive to compare the North East Java Basin priority zones with analogous unconventional plays in other rift basins globally. The Vaca Muerta Formation in the Neuquén Basin of Argentina, for instance, is hosted in similar syn-rift to post-rift lacustrine shales deposited during Jurassic extension (Spacapan et al., 2018). Like the Ngimbang Formation, the Vaca Muerta exhibits high TOC values (3-8%), mixed Type II/III kerogen, and is currently producing significant volumes of shale oil and gas from synclinal depocenters (Schieber & Lazar, 2021). Similarly, the Eagle Ford Shale in the Gulf Coast Basin of the United States—a major unconventional play—is also associated with syn-rift to passive margin deposits where organic-rich shales accumulated in structural lows (Cruz & Aguilera, 2017; McGarity et al., 2016; Ogiesoba & Klokov, 2017). The geological and geophysical similarities between these international analogs and the North East Java Basin priority zones provide additional confidence in the exploration potential identified through TOPEX gravity analysis.

Furthermore, the methodological framework developed here—integrating satellite gravity data with seismic, well, and geological information—mirrors best practices in frontier exploration worldwide. In the East African Rift System, gravity and magnetic surveys have been pivotal in identifying hydrocarbon-prospective sub-basins prior to costly seismic acquisition (Macgregor, 2015). In offshore Brazil, regional gravity-magnetic surveys guided the discovery of the prolacific pre-salt plays by delineating salt structures and rift basin geometries. These case studies underscore the strategic value of satellite-derived potential field data in reducing exploration uncertainty and optimizing survey design, particularly in underexplored or frontier settings.

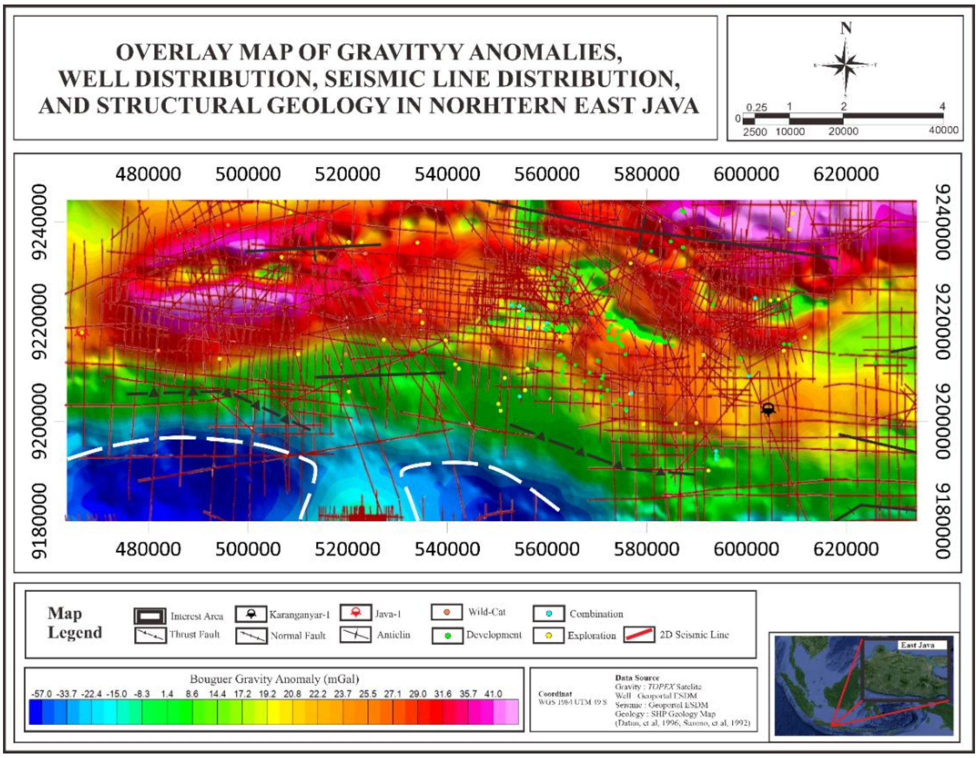

Figure 5. Overlay map of gravity anomalies, well distribution, line distribution, and structural geology in Northern East Java

CONCLUSION

Analysis of the TOPEX gravitational anomaly map, seismic data, and well distribution from the ESDM Geoportal identified the optimal exploration area in the North East Java Basin within the southern region outlined by a dotted white line, covering Grobogan, Boyolali, Sragen, Ngawi, and Madiun. This zone demonstrates high potential, meeting four key petroleum system parameters, featuring synclinal accumulations of parent rocks in the Ngimbang Formation at depths suitable for source rocks. Notably, this area lacks seismic coverage and well data, presenting a prime opportunity for targeted, efficient exploration efforts. Future research should focus on acquiring detailed seismic and drilling data to validate these findings and refine the understanding of the basin's unconventional hydrocarbon potential, ultimately improving exploration success and resource development strategies.

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