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**ASSESSMENT OF THE CO₂ STORAGE POTENTIAL OF THE
SUNDA STRAIT AREA, INDONESIA**

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**ASSESSMENT OF THE CO₂ STORAGE POTENTIAL OF THE
SUNDA STRAIT AREA, INDONESIA**

by

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Dedication

I dedicate this thesis to my beloved parents, Banu and Sumarmi, as well as my only sister, Ayu. I also dedicate this thesis to whom who will read it in the future, hoping that what I have created here can be a guide to solve any geological and CCS problem anywhere in the world. Last but not least, this thesis is for everyone who are still trying to make their dreams come true because I used to be in that exact position.

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I am nobody without all of you.

Once again, thank you to everyone and here I present you my work below

Statement on the Use of AI

This thesis was entirely formulated, written and edited by humans (the aforementioned author). However, Artificial Intelligent (ChatGPT) involvement was utilized for the following matters:

- Literature summarization and synthesis (but not for thesis writing)
- Grammatical and spelling corrections
- Petrel troubleshooting
- Illustration making (Figure 5.1, 5.2, and 6.1) based on the author's Petrel figures

Abstract

ASSESSMENT OF THE CO₂ STORAGE POTENTIAL OF THE SUNDA STRAIT AREA, INDONESIA

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The University of Texas at Austin, 2026

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Indonesia has great potential of Carbon, Capture, and Storage (CCS), especially in saline aquifers in sedimentary basins that have been characterized for hydrocarbon exploration. The study aims to assess the CO₂ storage potential of the Sunda Strait Area, offshore Southeast Sumatra, focusing on the Late Oligocene Upper–Middle Zelda Group of the Talang Akar Formation (TAF). The subsurface characterization combines ~1,050 line-km of 2D seismic data, 600 km² of 3D seismic data and well logs from six wells. Based on well correlation, the Upper–Middle Zelda interval (1,500–2,600 m) is indicated as the main storage reservoir, and the overlying Miocene Gumai Formation is a laterally continuous regional seal. Seismic interpretation identifies an extensional half-graben system where reservoir thickness and sandstone development is focused towards the central depocenter. The presence of relatively sand-prone facies is also supported by RMS seismic attributes.

A three-dimensional geocellular model was developed to capture the reservoir heterogeneity, based on lithofacies and effective-porosity distributions. The 45 geological realizations were made by combining 9 facies realizations with 40%, 60%, and 80% sand and silty-sand proportions of combined sandstone and silty-sandstone with 5 effective-porosity realizations each.

The storage-resource estimates from the static volumetric assessment were between about 180 and 1,928 Mt CO₂, depending on the inclusion of CO₂ density and saline-storage efficiency (ESaline). Comparable EASiTool conditions were applied to the conservative 40% reservoir scenario to provide average static estimates of 201, 602 and 1,003 Mt CO₂ for ESaline values of 1%, 3% and 5%, respectively, for comparison with the dynamic analytical modeling. Permeability values of 200 and 610 mD were used in the Dynamic EASiTool simulations under both closed and open-boundary conditions. Resulting storage-resource estimates range from 336 to 616 Mt CO₂ at 200 mD permeability and 391 to 1,433 Mt CO₂ at 610 mD permeability. A comparison of the static and dynamic approaches shows that an ESaline range of about 3–5% is most representative for the Upper Zelda reservoir, with 3% being the central estimate and higher values being related to more favorable permeability and pressure-dissipation conditions

Keywords: Carbon Capture and Storage (CCS), Saline Aquifer, Talang Akar Formation, 3D Geocellular Modeling, EASiTool, ESaline, Storage Resources

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CHAPTER 1: INTRODUCTION

1.1. CARBON, CAPTURE, AND STORAGE BACKGROUND

Carbon Capture and Storage (CCS) is one of the technologies for mitigating climate change by capturing large quantities of carbon dioxide (CO₂). CCS encompasses a set of processes that capture CO₂ emissions from major industrial and energy-related sources such as natural gas processing, coal-fired power plants, cement manufacturing, and other heavy industries before permanently storing them in the subsurface (IEA, 2023). After capturing CO₂, it is compressed, transported, and injected into suitable geological formations for long-term containment (See Figure 1.1).

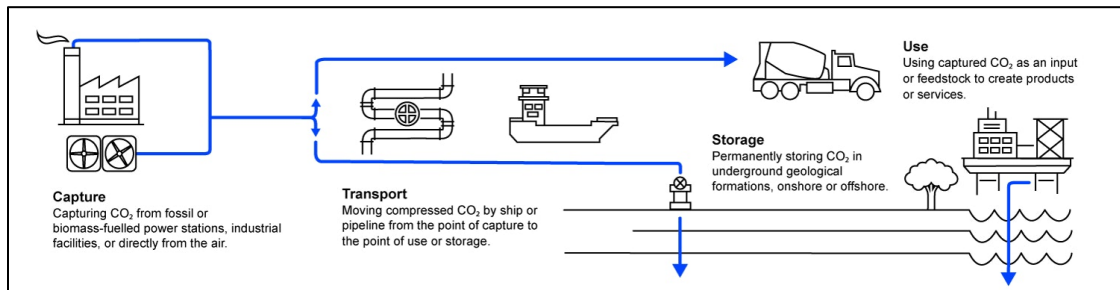


Figure 1.1. A visual overview of each step in the CCS process (IEA, 2023)

Geoscience explores potential storage areas and assesses the CO₂ storage resources of such areas and to identify capability of the geological formation(s) to securely store CO₂ over long timescales. This process includes interpretation of seismic data, well-log correlation, structural and sand mapping, facies analysis, geomechanics analysis, and 3D reservoir modeling, in order to evaluate key parameters such as depth of the storage section, porosity, permeability, caprock integrity, reservoir presence, and lateral continuity (Bachu, 2015). High-resolution 2D and 3D seismic data are useful to model the geometry of reservoir and identify faults that could trigger CO₂ leakage. Petrophysical and

geomechanical analyses estimate injectivity and storage resources (Tarkowski, 2019). Additionally, exploration is done with regional stress assessment, pressure conditions, and hydrogeologic settings to ensure long-term containment and minimize leakage risk (IPCC, 2005). This multi-disciplinary approach is the technical basis for pre-development and pre-injection assessment of CO₂ storage sites.

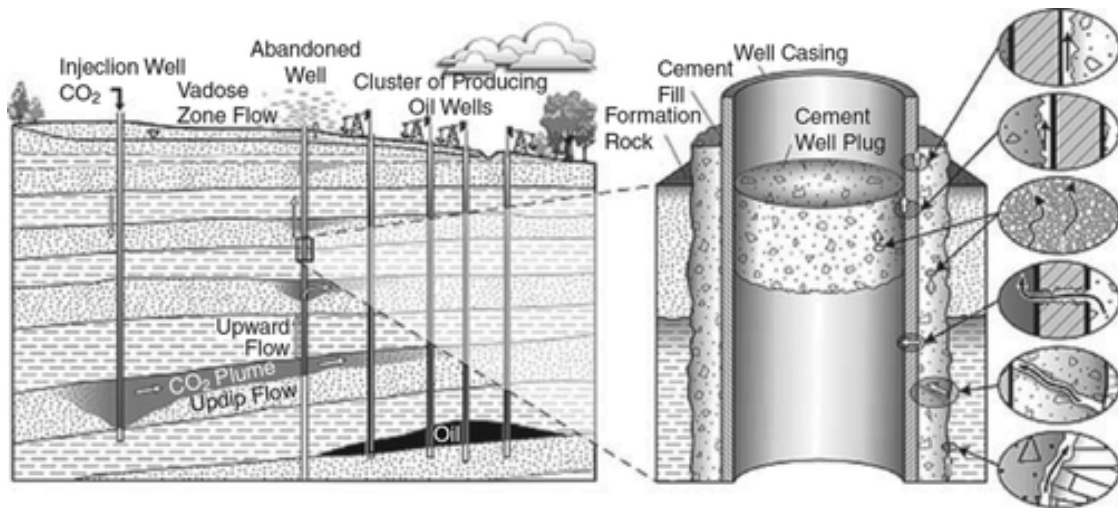


Figure 1.2. Schematic of how CO₂ is injected into a formation that includes a number of old oil and gas wells (Nordbotten and Celia, 2012)

A variety of subsurface settings can be utilized as CO₂ storage sites, including depleted oil and gas reservoirs, deep saline aquifers, and unmineable coal seams (De Silva & Ranjith, 2012). These formations have to be porous, permeable, and have sufficient trapping mechanisms to store and trap CO₂ over geologic timescales (Ringrose & Meckel, 2019). Of these, deep saline aquifers typically hold the greatest theoretical storage resources potential globally and are considered essential for large-scale deployment of CCS.

1.2. CARBON, CAPTURE, AND STORAGE IN INDONESIA

Indonesia has set an ambitious target to produce 1 million barrels of oil per day (BOPD) and 12 billion standard cubic feet per day (BSCFD) of natural gas by 2030 (SKK Migas, 2021). However, achieving such a high level of energy production is expected to result in a huge number of emissions. Currently, Indonesia is embracing an energy transition to produce less carbon-intensive energy in the future with zero emissions called Net Zero Emissions (NZE). Carbon Capture and Storage, better known as CCS, is a key strategy Indonesian energy experts would perform to achieve the goal of increased hydrocarbon production. As Indonesia produces considerable amount of CO₂, Carbon Capture and Storage is important for meeting national goals. Indonesia has significant CO₂ storage resources at competitive costs to start doing CCS. According to the Indonesian Ministry of Energy and Mineral Resources (2023), Indonesia already plans to implement CCS in at least 15 areas across the country and is predicted to commence the projects as soon as 2026 (Figure 1.3).

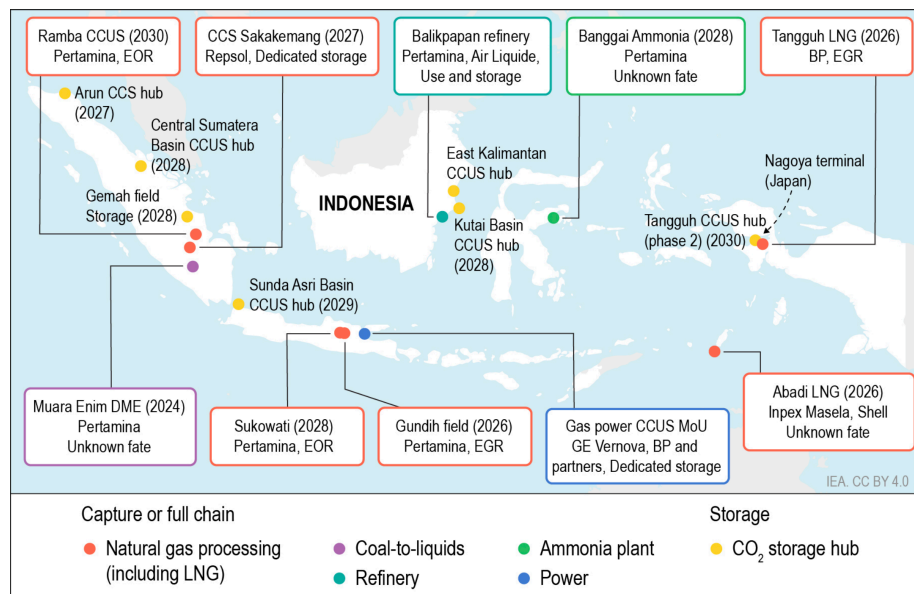


Figure 1.3. CCUS Projects in Indonesia as reported by IEA (2023)

Their initial CCS study in Indonesia at Gundih Field in 2019 concentrated on transforming a depleted well at the field called Jepon-1 into an injector well (Marbun et al., 2019). However, the project encountered a palpable leakage at depths of 440 m and 881 m despite the cementing process. It resulted in the postponement of the project. Several years later, in 2022, Indonesia succeeded in a different pilot study at the mature field of Jatibarang, located in Indramayu, West Java.

1.3. GEOLOGIC SETTING

One of the most prominent projects and subsurface studies in Indonesia is located in The Sunda Strait Area, where ExxonMobil conducts a CCS hub evaluation in the offshore basin. The Sunda Strait Area is part of several basins situated in Sunda Shelf (11,046 km²). Historically this region was thought to have a lower maturity source rock, which seems less interesting for hydrocarbon exploration (Ralanarko et al., 2021), but it might be suitable for CCS. The Sunda Strait Area's tectonic setting was influenced by the northward movement of the Australian Plate, which generated the half-graben system in the southern margin of the Sunda Shelf (Sumatra and Java) during the Eocene and Oligocene (Longley, 1997). According to Bishop (2000), the basin's boundaries are defined by the fault trend of the N-S faulting system and faulted plateaus included in the offshore structure as the manifestation of the tectonic activity mentioned before.

The Sunda Strait Area developed as a half-graben geological setting (Figure 1.4). In terms of the depositional stratigraphy, the half-graben was filled by the material from its vicinity (mainly from highland Sumatera), with various depositional environments from fresh lake to lacustrine (Bishop, 2000). During the Oligocene, The Sunda Strait Area experienced syn-rift depositional event forming a thick section of sandstones as the accommodation was filled by eroded sediments from the northern Sunda Shelf. During

Miocene times, major transgression occurred forming a shallow marine carbonate platform. Eventually, the Sunda Shelf was exposed during Pleistocene resulting in deposition of clastic and volcanic material. Today, the majority of Sunda Shelf is submerged (beside Sumatra and Java) and The Sunda Strait Area represents one of the offshore parts of the Sunda Shelf. The Sunda Strait Area is considered a pull-apart (extensional) basin (Ralanarko et al, 2020).

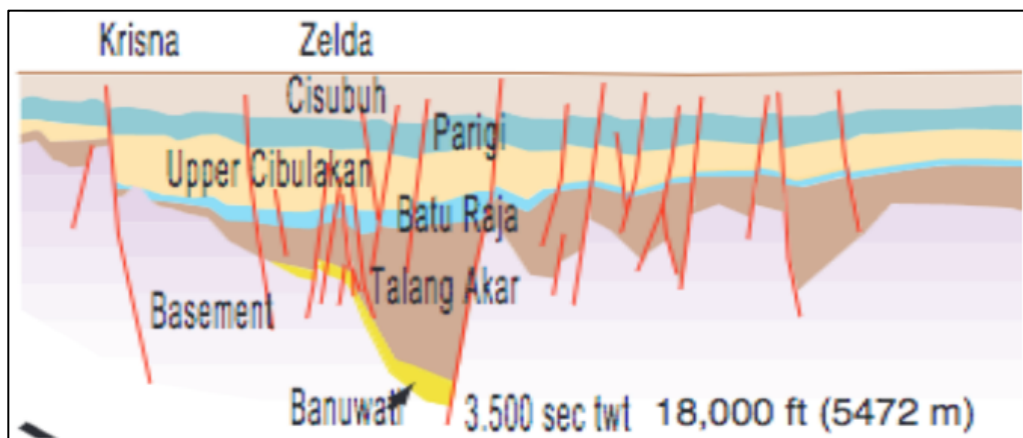


Figure 1.4. Schematic Cross Section of Sunda Strait Area (Noble et. al, 1997)

Stratigraphically, the Sunda Strait Area contains formations resulting from its tectonic activity (Figure 1.5). Lacustrine rocks were deposited in Eocene – Oligocene times and includes the Banuwati Formation consisting of thick dark brown shale which is an oil-prone shale (Prayitno et al., 1992). Overlaying the Banuwati Formation, The Talang Akar Formation (TAF) is dated Oligocene age, and it is characterized by a thick sandstone section with some fine-grained lithologies that divide it into Zelda Member (Oligocene) and Gita group (Miocene). Both groups feature distributary channel deposits, represented by the Zelda Member deposited in a fluvial environment while Gita deposited in a mixed environment of fluvial and marine transgressive deposits (Bishop, 2000). The Baturaja

1.4.PREVIOUS WORK

In the Sunda Strait area is considered partially productive and unproductive, in terms of hydrocarbons. The Sunda Strait area has been explored for hydrocarbons for a long time with many large prospects identified. From 1971 - 1995, the exploration in the Sunda Strait Area was considered light with only 12 exploration wells with no discoveries. The previous exploration activity before CCS was initiated merely focused on the adjacent productive area, located to the southwest. Since 1995, Indonesian oil and gas companies broadened their focus of their exploration, resulting in having both CCS and hydrocarbon exploration given the TAF has significant reservoir potential. In addition to having good reservoir geology for oil and gas, the TAF also contains saline aquifers which could be prospects for storage of carbon dioxide. To provide a technical perspective on these storage resources, a CCS analog to the TAF could be other Tertiary intervals associated with saline aquifers, like for instance, the Utsira Formation in the Sleipner CCS Project, Norway.

Several previous geological studies in the area have established a strong foundation for understanding its structural evolution and petroleum prospectivity that ultimately will be helpful for CCS characterization. Basin-scale research by Sukanto et al. (1998) defines the Sunda Strait Area's petroleum systems, highlighting its development as a back-arc rift system with multiple tectonic phases. Starting from early sag-style extension to later half-graben subsidence, this study highlights the stratigraphic framework which serves as the key to define the source and reservoir intervals, (Sukanto, 1998).

The syn-rift tectonic event was the most important in shaping the TAF. This explains the significant thickness of the TAF especially within the depocenter in the middle of the basin (Figure 1.6). The results of this study will be the final parameters used to assess the integrity of the geology and suitability of the reservoir for the CCS project in the basin.

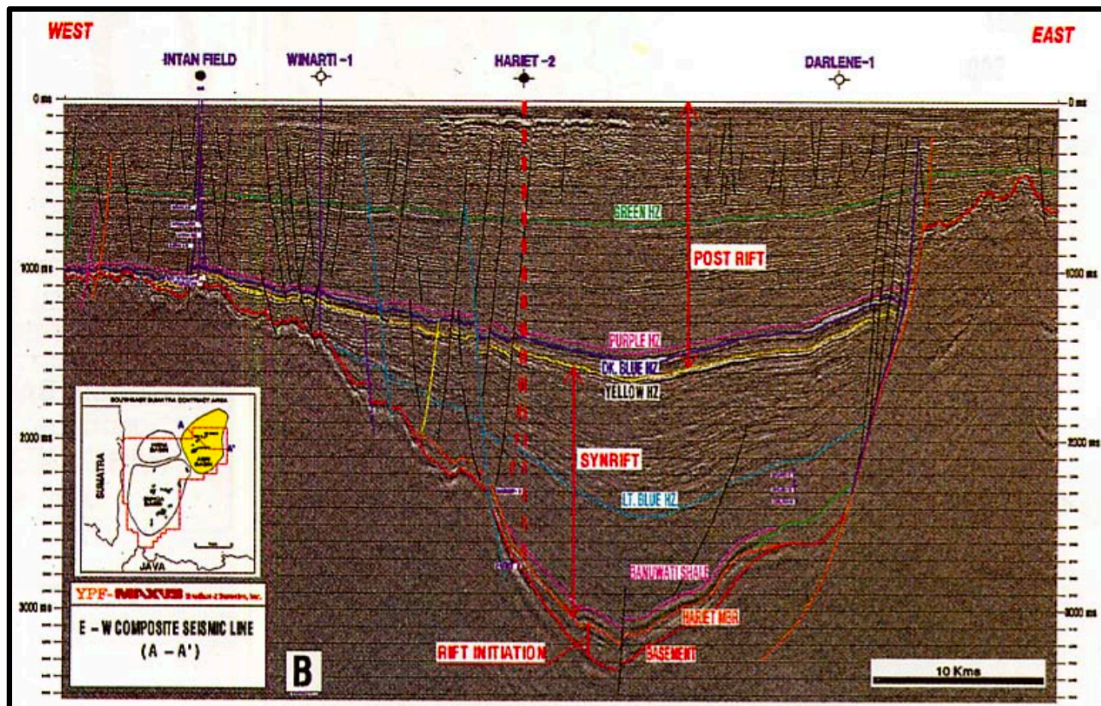


Figure 1.6. The E-W seismic composite line (A-A') shows the major structural components of the Sunda Strait Area (Sukanto, 1998)

1.5.PROJECT GOALS

This research focuses on the integrated subsurface evaluation of the Sunda Strait Area to define its carbon sequestration potential. This area represents a very prospective storage option to progress the CCS industry in Indonesia. It contains many geological targets with saline storage potential, such as the sandy Talang Akar Formation (TAF). Also, the Sunda Strait Area is located in a half-graben setting with fault trapping and impermeable shales capping the stratigraphic section, which can be considered as the cap rock. The objectives of this research are:

1. To generate a detailed stratigraphic framework to understand the distribution of the sandstone reservoirs in the study area, especially for CCS purposed. Well-log correlation is an important step in this process, and electric logs from six of wells are available for this analysis.

2. To interpret available seismic data to generate structural maps of key reservoirs of the study area to identify some potential storage prospects.
3. To assess the CO₂ storage resources of the most prospective storage opportunities. Dynamic volumetric capacity will be conducted using simplified dynamic analytical EASiTool (GCCC-BEG software) calculations.

1.6. STUDY AREA AND DATASETS

PT. Pertamina (LLC) is the most active oil and gas company in CCS development in Indonesia with 11 projects identified, one of them in the Sunda Strait Area (Figure 1.7). This thesis will feature one of PT. Pertamina upstream subholders' data in the Sunda Strait Area called PT. Pertamina Hulu Energi Offshore Southeast Sumatra (PHE OSES). They started conducting research in CCS recently and this thesis will be a valuable insight for PHE OSES to continue further CCS assessment in the Sunda Strait Area.

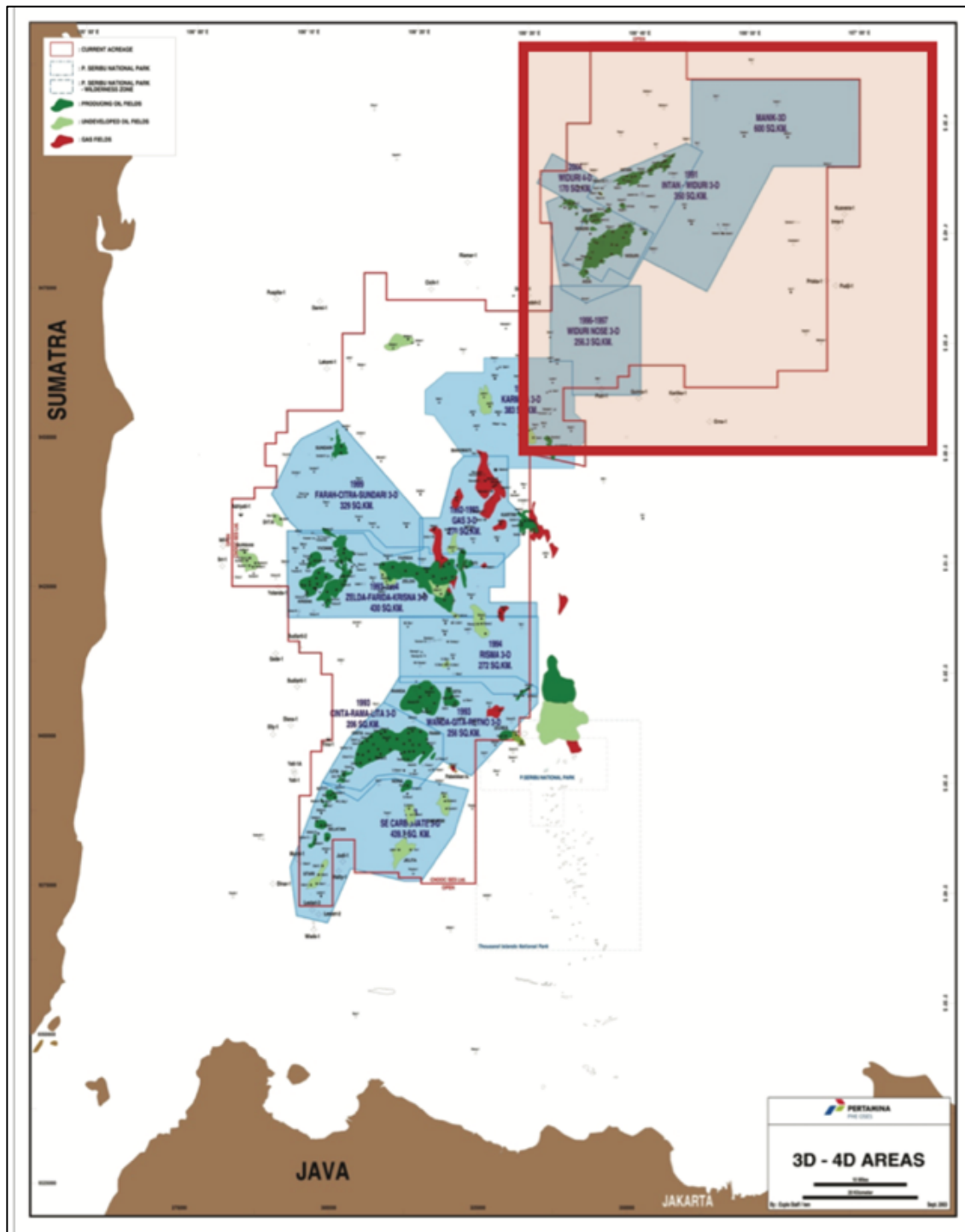
In order to conduct the research, there are several datasets needed to reach the goals of this research:

1. Seismic 2D and 3D

This seismic data provides insight into the structural framework and distribution of the reservoir units both vertically and aerially. Seismic interpretation is performed to generate structure maps of the reservoir of interest. Other structural elements like faults were interpreted for definition of the structural compartments.

2. Well-log data

Wells logs from six of wells are available for this study. Log curves include gamma-ray for lithology, sonic for pore-pressure estimation, resistivity for fluid identification, density (RHOB) and neutron (NPHI) for the porosity estimation. This data is crucial for characterizing the reservoir properties.



1.7. PROJECT WORKFLOW

The research employed several methods in order to achieve the stated objectives.

They are:

1. The initial step involves picking the top and bottom seismic horizon of the targeted sections within the CO₂ storage window. The TAF is the main target for carbon sequestration, particularly the Upper-Middle Zelda Member. Also, the seal (Gumai Formation) is considered in the seismic horizon picking. Petrel 2023 is the main software utilized for this task.
2. Analyzing the well-log data from multiple wells in the research area to understand lithology distribution thru the vertical stratigraphic section, and the presence of sealing units above the CO₂ storage targets. The well-logs are correlated for key stratigraphic horizons and integrated with seismic data to see the relation between time data from seismic and depth from the well logs. Software used in this step is Petrel 2023.
3. Picking all possible faults in the area of interest helped to identify structural compartments and define any structural trapping mechanism, as well as to identify some potential CO₂ leakage scenarios to be avoided.
4. CCS prospect identification was done after well-log and seismic interpretation were conducted. Building a geocellular 3D model and populate the model with Vshale and porosity with the trend of RMS. Prospects are defined based on the subsurface characterization: distribution of sand-prone and mud-prone intervals as reservoirs and seals respectively, porosity, permeability, overpressure, structural and stratigraphic trapping mechanism, and potential leakage risk.
5. Storage resources assessment are conducted to estimate how much CO₂ can be injected in selected storage sites. Calculations of the dynamic storage resources of

injected CO₂ in EASiTool were determined by using geological factors, such as area, reservoir thickness, porosity, permeability, and reservoir pressure.

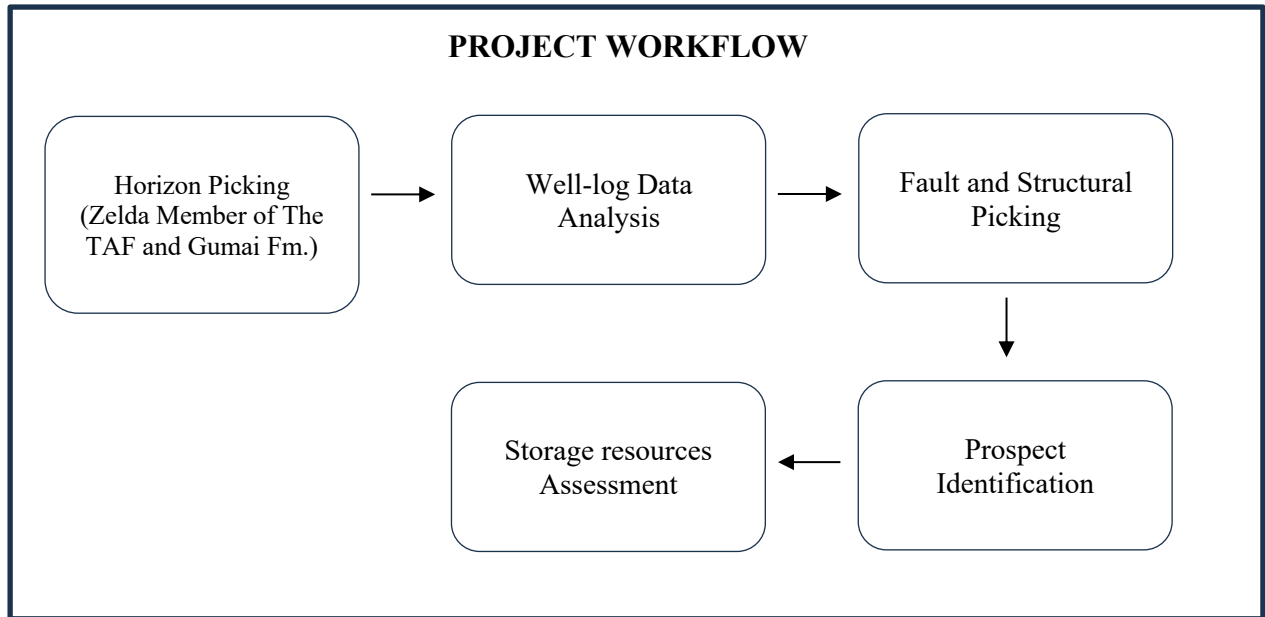


Figure 1.8. Research Workflow

CHAPTER 2: GEOLOGICAL CHARACTERIZATION OF THE SUNDA STRAIT AREA

2.1. INTRODUCTION

This study assesses the Sunda Strait Area's carbon storage resources as a CCS/CCUS Hub. CCS studies in Indonesia are still very limited despite its substantial storage potential across the country. Additionally, there are only a small number of experts in CCS, making it more difficult to develop intense studies locally. In addition, the CCS study of this research is not conducted in a depleted oil and gas field, which makes this area more challenging since saline aquifer storage is less understood in the country.

The Sunda Strait Area is well known as a productive oil and gas production area but contains an overlooked region to the northeast that it is nonproductive. This region to the northeast of the Sunda Strait Area contains significant potential for carbon storage. The prospective tor age interval is in the sandy Talang Akar Formation (TAF), which needs further characterization and evaluation before recommending any carbon sequestration projects. Therefore, it is expected that the northeast area will be one of the most pivotal areas for carbon storage in Indonesia. This thesis will provide a regional geologic characterization of the storage potential of the Sunda Asri Basin and will provide the Indonesia CCS community with a case study demonstrating the feasibility of developing a CCS industry in the country.

2.2. WELL LOG INTERPRETATION AND CORRELATION

In this area, we have six wells available for subsurface interpretation, named S, H, D, B, A, and Y. All the wells are concentrated in the middle of the depocenter (See Figure 2.1), the targeted CO₂ storage interval expected to have sufficient reservoir quality and thickness. Each well contains their own respective log measurements (Table 2.1).

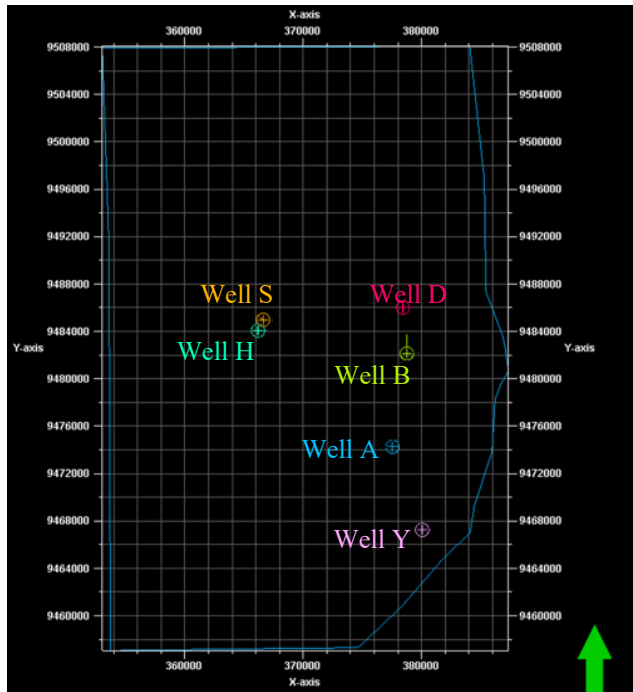


Figure 2.1. Well locations

Correlation using shown configuration and sequence of wells were conducted to establish the lateral correlation and vertical lithology. The primary log used was Gamma-Ray (GR) which distinguishes sand-dominated (low GR) from shale-dominated (high GR) intervals and helps identify major stratigraphic boundaries. Other logs included were Caliper (CALI), Spontaneous Potential (SP), Shallow and Deep Laterologs (LLS and LLD), Density

(RHOB), and Neutron Porosity (NPHI). They provided a more detailed lithology interpretation and eventually reservoir properties:

- Caliper detecting borehole enlargements or washouts that may affect log quality.
- Spontaneous Potential to identify more permeable formations and correlate sand–shale contacts.
- LLD and LLS provide deep and shallow resistivity measurements
- Neutron Porosity & RHOB estimating porosity, especially when integrated with resistivity data and lithology indicators. These two wells combined can identify Porosity Total (Φ_T) & Effective (Φ_E) that will be discussed later in the next chapter.

Table 2.1. below shows every availability of logs mentioned above in all wells across the research area.

Log	Well S	Well H	Well D	Well B	Well A	Well Y
GR	v	v	v	v	v	v
CALI	v	v	v	x	v	v
SP	x	v	v	x	v	v
LLD	x	v	v	x	x	x
LLS	x	v	v	x	x	x
NPHI	x	x	v	x	v	v
RHOB	v	v	v	v	x	v
PEF	v	v	v	v	x	v
DT	x	v	v	x	v	v

Table 2.1. Logs available component in all wells

Well-log correlation across the six wells allows investigation of the lateral and vertical continuity of the reservoir units that are relevant for CO₂ storage. Gamma ray (GR) log was the main log to do this correlation (explained in Sub Chapter 3.2). The shallowest formation interpreted is The Gumai Shale, which was deposited during a regional Middle Miocene marine transgression and is present in all wells. The top of it is at about 1200-1250 m depth and is a thick caprock that is known as an important regional seal throughout the western Indonesian basins. It is thick and continuous, making it very suitable to store injected CO₂ in this region.

Below the Gumai Formation, there is Upper-Middle Zelda Member of the Talang Akar Formation (TAF) that serves as the primary reservoir target. This targeted group is situated between around 1,500 and 2,600 m depth. This interval consists of sandstones interbedded with shale. This formation represents deposition in fluvial–deltaic to shallow-marine environments as it is characterized by heterogeneous but relatively easy to correlate successions. The entire formation is typically found in half-graben systems where syn-depositional faulting provides variable accommodation space and affects sediment

distribution patterns (Pulunggono & Cameron, 1984). In the correlation panel, the shale intervals in Well B are thicker than in the other wells, reflecting the fact that it is located in the most westward and toward the half-graben structural margin where finer-grained deposition is more prevalent (Figure 2.2). The thickness of the Upper–Middle Zelda Member is about 1,000 m in the depocenter. The Lower Zelda Member underlies this interval and reaches a depth of about 3,200 m. It is part of the Talang Akar stratigraphy, but this deeper part is less favorable for storage because the group is generally reduced reservoir quality sandstone as opposed to the upper part.

From the correlation (Figure 2.2), a depositional trend can be seen: the Zelda Member becomes progressively thinner toward the half-graben margin. This geometry is typical of western half-graben sedimentation where more accommodation by the fault and variable sediment supply result in lateral thinning and higher shale content toward the deeper side of the basin.

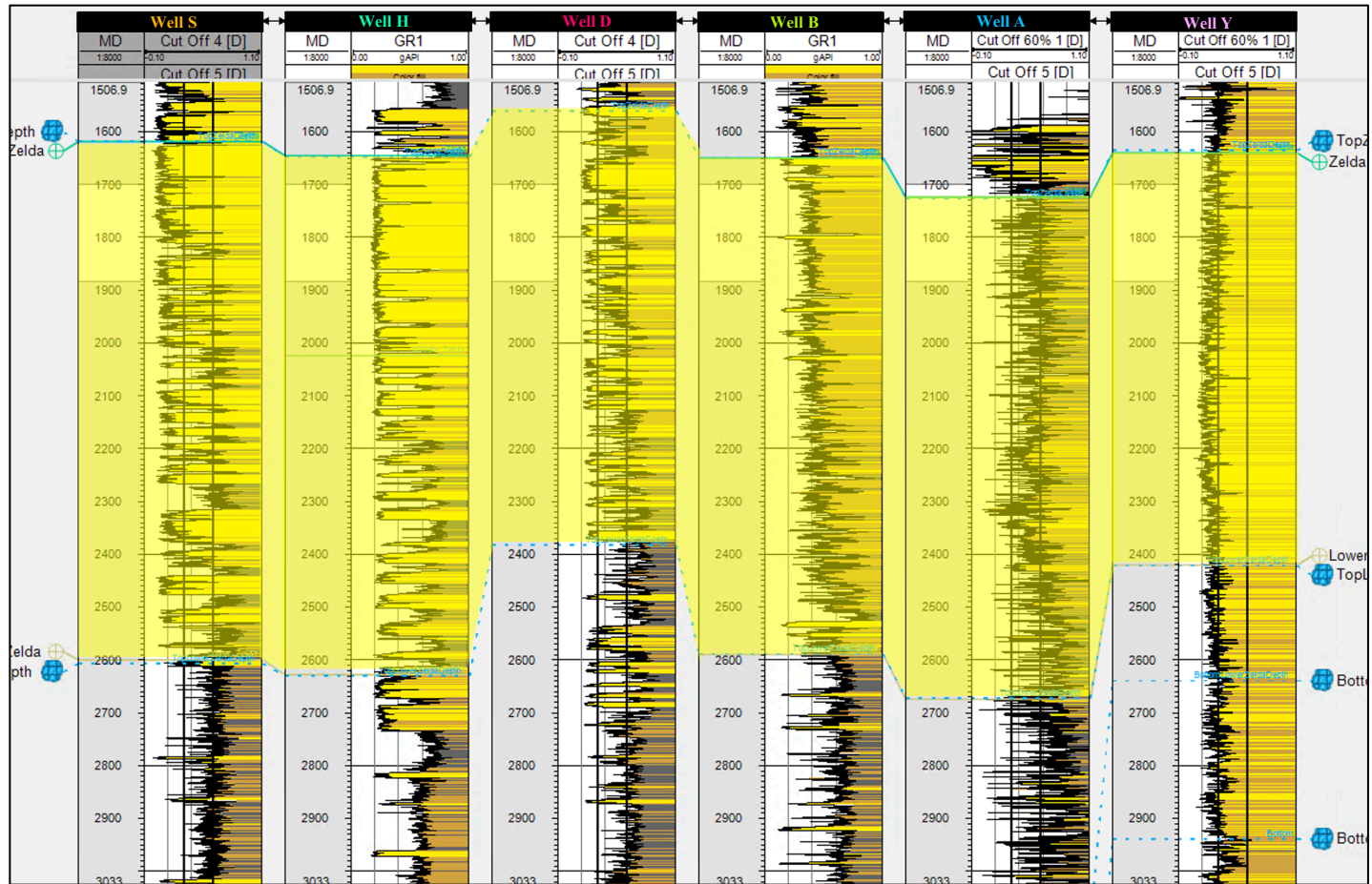


Figure 2.2. Well Log Correlation of Well S – Well H – Well D – Well B – Well A – Well Y, showing the Upper-Middle Zelda Member of the TAF (highlighted yellow) as the targeted zone for CO₂ injection with vertical scales in meters

2.3. SEISMIC DATA AND INTERPRETATION

The seismic data used in this study is both 2D and 3D seismic data. The 2D seismic data covers about 1050 line-km and the 3D seismic survey covers about 600 km² (Figure 2.3). The 2D seismic data are generally located in the depocenter area and were acquired in a number of survey packages acquired in every year from 1988 through 1996, while 3D seismic data are located in the adjacent of the half-graben area and was acquired in 1991.

Figure 2.3. shows the northeast area of the Sunda Strait Basin (zoomed from Figure 1.7). While the CCS target is prioritized in the Central Area due to the substantial TAF thickness, the majority of the available 3D seismic data is concentrated in the northern part of the area due to its historical focus on hydrocarbon exploration. The challenge is to interpret the central area using only 2D seismic data, although the 3D data will help the 2D interpretation as the 2D seismic lines are connected to the 3D seismic of the area. The research area spans 50 x 31 km².

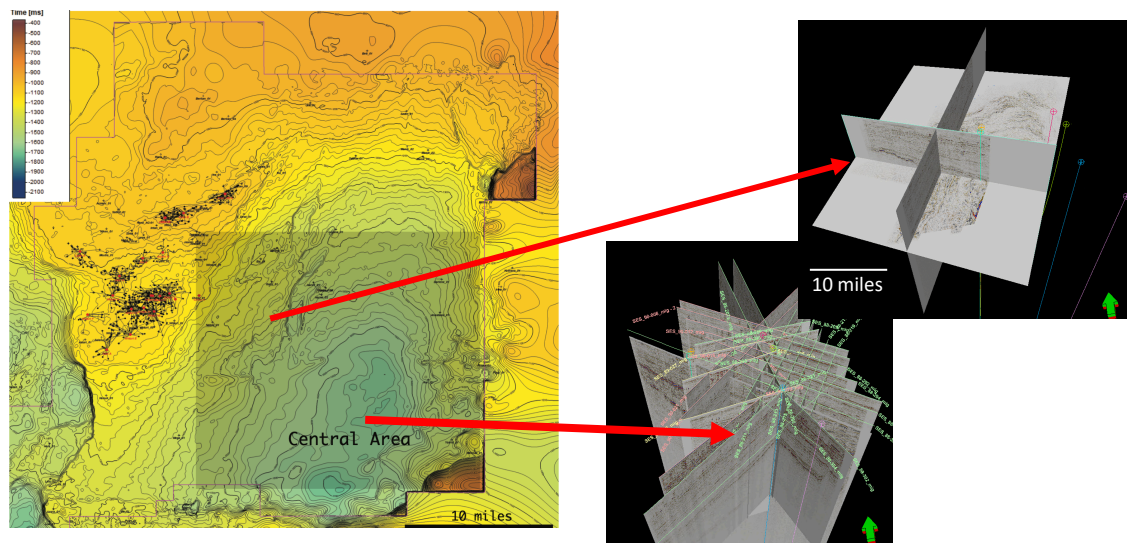


Figure 2.3. 2D (lower) and 3D (upper) Seismic Data of the Sunda Strait Area

The seismic data were supplied in two-way travel time and all seismic interpretation in this study was carried out in the time domain. The available checkshot data was then used to convert interpreted horizons and structural surfaces to depth. There is no detailed information of the original seismic processing workflow, so this study relied on the processed time domain seismic data provided and emphasized the horizon interpretation, structural mapping and depth conversion for reservoir characterization.

Seismic Horizon Interpretation

The horizon interpretation was performed in Petrel with a combination of manual picking, interpolation and limited autotracking. The study area is very faulted and continuous autotracking was not feasible for the entire seismic data set. The study area is very faulted and continuous autotracking was not feasible for the entire seismic data set. Hence, the primary interpretation was done manually to ensure geological consistency, particularly in structurally complex areas and near faults. Key horizons were manually picked on selected inlines and crosslines in the 3D seismic volume and the picks were then interpolated to form continuous horizon surfaces. Horizon picking was also done manually in the 2D seismic data, but in relatively flat and laterally continuous areas where the reflectors were clear enough to be picked automatically, they were seeded. All autotracked results were manually checked and edited as needed. Seismic horizon interpretation was conducted to map the horizons as key stratigraphic surfaces that define the seal, reservoir, and structural features of the study area (Figure 2.4).

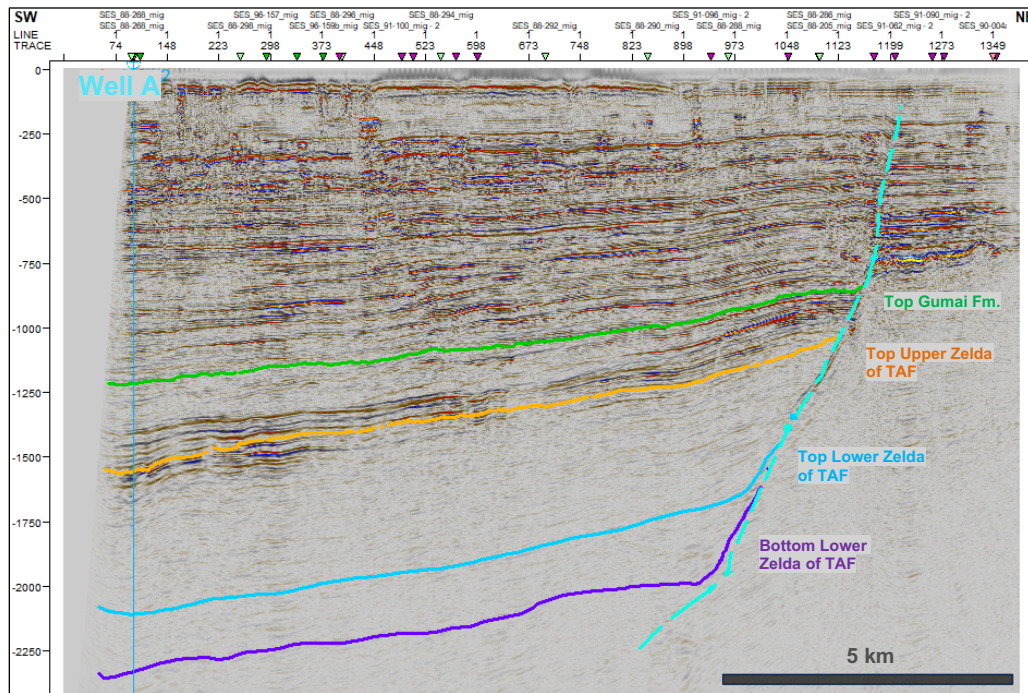


Figure 2.4. Seismic horizons interpreted in the area of interest with vertical scale in meters

The main goal of this step is to examine the distribution of Gumai Formation's and the TAF's geometry and spatial distribution, namely the Zelda Member. Each formation or group were selected at the top or upper part, and then later become the basis for constructing the 3D structural model of the Sunda Strait Area.

The Top Gumai Fm. Horizon (Figure 2.5.a) is the shallowest interpreted horizon in the seismic data set and is the main regional seal for the underlying reservoir units. This horizon appears relatively flat with about 800 m difference between the highest and lowest depth (in the middle directly in the storage target) and laterally continuous, consistent with widespread marine shale deposition during the Middle Miocene transgression. The depth of the Top Gumai Fm horizon is structurally close to the upper limit of the eastern half-graben (around -1,200 m depth in the seismic), which is the upper formation filling the half-graben structure.

The Top Upper Zelda (Figure 2.5.b) is the upper limit of the primary storage interval that is found at depths of about 1,500–2,000 m throughout the study area. This horizon is more structurally complex and shows many fault offsets related to the extensional deformation of the half-graben system. The higher number of faults in this interval was an ideal example of syn-depositional characteristic and localized accommodation during Talang Akar sedimentation. Although the horizon is structurally complex, it is deeper in the depocenter of this horizon.

Top Lower Zelda horizon (Figure 2.5.c) corresponds to the lowest surface of the planned CO₂ injection zone. This horizon extends to depths slightly deeper than 2,500 m across the study area. Compared to the Upper and Middle Zelda units, this interval exhibits lower reservoir potential due to its higher shale content and reduced net-to-gross ratios. The seismic character of the Top Lower Zelda horizon is generally subtler, with weaker reflectivity that reflects the finer-grained, compacted nature of the sediments at depth, and also because it is located deeper in the stratigraphy where seismic signal is weaker compared to the shallower rocks. While it forms part of the broader Talang Akar stratigraphy, the Lower Zelda is considered less favorable for CO₂ storage and thus serves more as a stratigraphic and structural base for defining the effective injection zone.

Bottom Lower Zelda horizon (Figure 2.5.d) indicates the lowest stratigraphical unit before getting into basement. The geometry is extremely deep in the depocenter with more than 3,000 m depth.

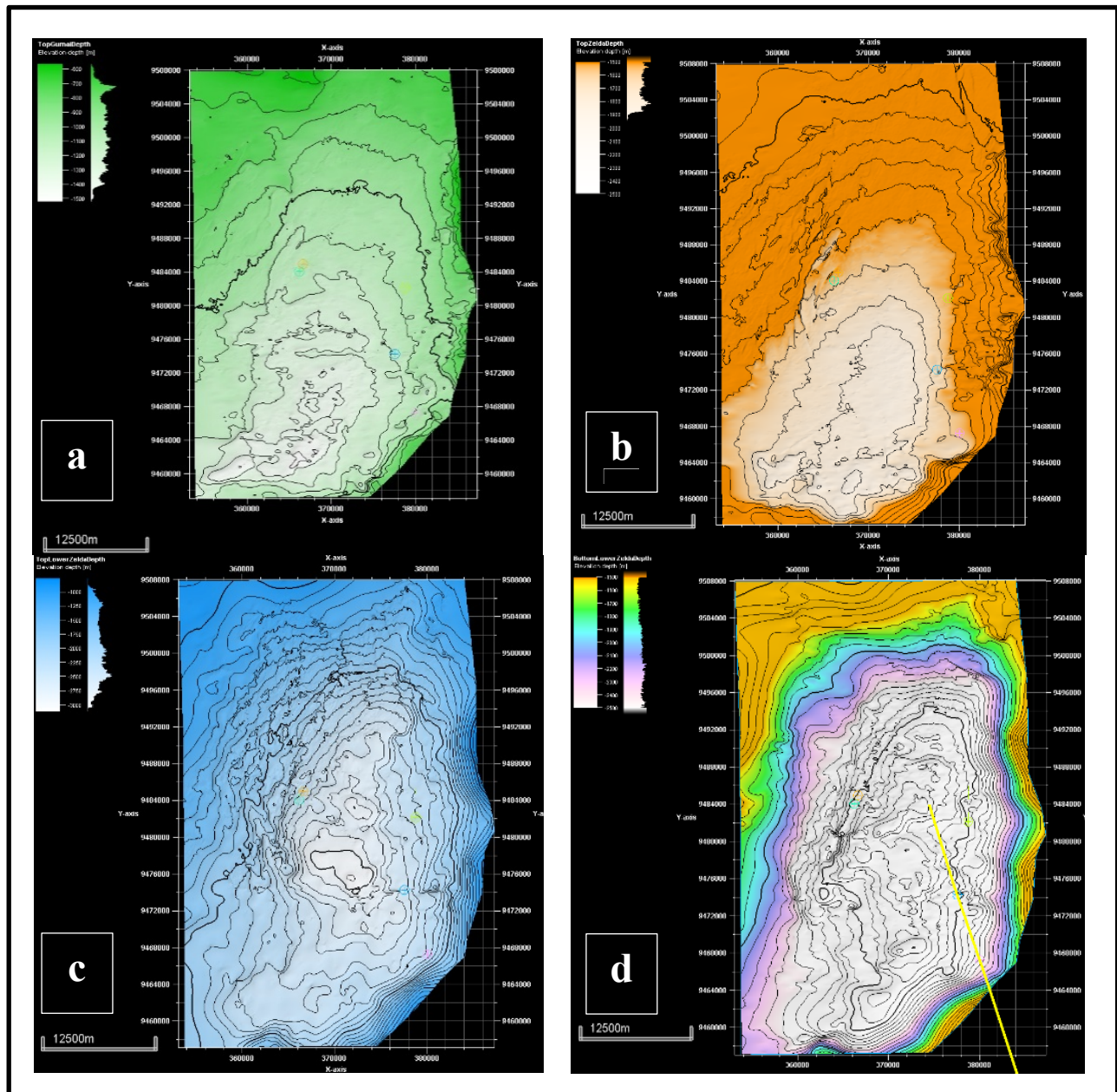


Figure 2.5. Structural map of: Top Guman Fm (a), Top Upper Zelda Member of the TAF (b), Top Lower Zelda Member of the TAF (c), and Bottom Lower Zelda of the TAF (d)

Fault Interpretation

The objective of the fault interpretation was to identify and characterize existing structural compartmentalization of the reservoir section. Understanding the structural framework is essential as it controls reservoir thickness and eventually storage potential in the study area. The fault interpretation was done by picking them manually in Petrel. Faults were mapped using the identification of reflector discontinuities, offsets, terminations and changes in seismic character in both 2D and 3D seismic data.

Using 2D and 3D seismic interpretation, the half-graben structural framework will be illustrated, similar to earlier regional research by Sukanto (1998). A major depositional axis of the half graben exists on the eastern side of the basin (Figure 2.6).

This structural setting influences sediment deposition and the different thickness within the Zelda Member and TAF depth range. The Zelda Member of the (TAF) tend to be thicker within the half-graben area as it reflects the repeated material infilling by fluvial–deltaic systems deposited during the syn-rift period. Coarser clastic material was trapped in the deepest part of the half graben, and finer-grained facies was deposited along the structurally higher margin as sediments prograded into the basin.

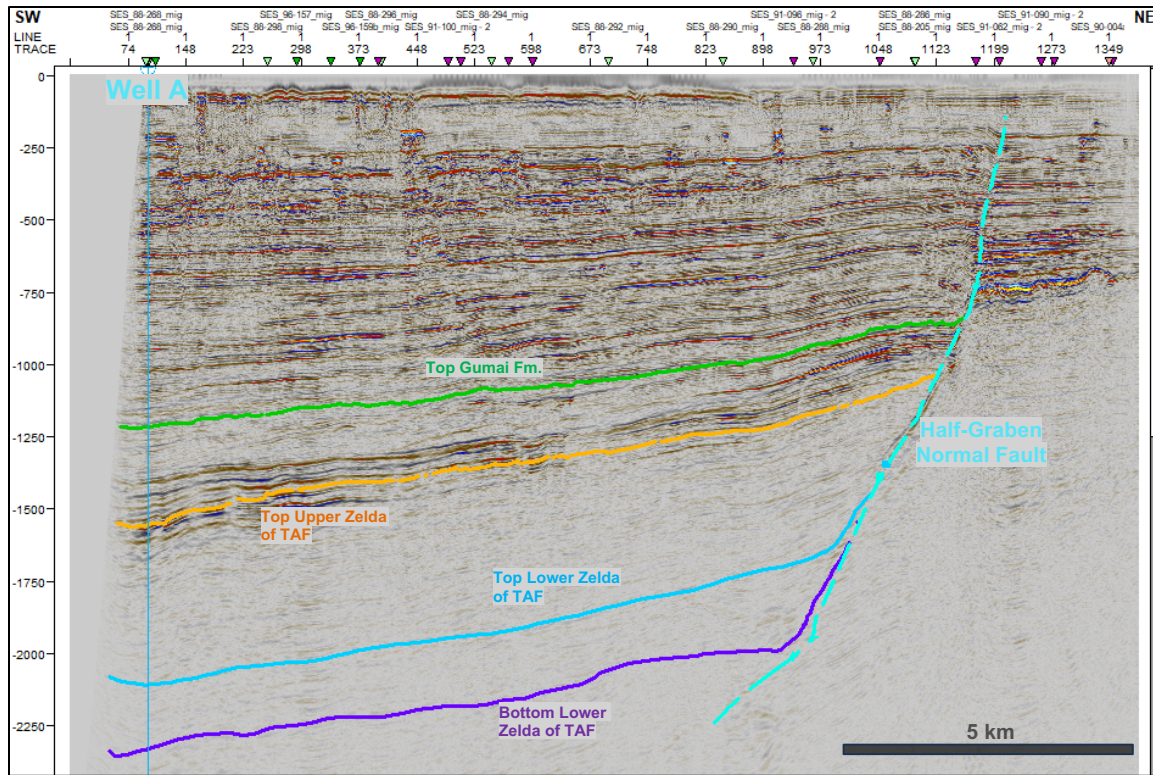


Figure 2.6. 2D Seismic image indicating half-graben normal fault with vertical scale in meters

Secondary structural are also developed as normal faults in this half-graben system in the adjacent to the main eastern half-graben, forming a stepped structural geometry (Figure 2.7). At minimum four normal faults have been identified in this zone by seismic interpretation. Three of these faults exhibit a parallel orientation to the main basin-bounding fault which suggests that they formed as synthetic faults during the same extensional phase. Only one fault positioned in opposing dip direction as an antithetic fault that formed to accommodate local strain balancing within the half-graben system. This system of faults is typical in extensional basins and usually contributes to internal compartmentalization and thickness and quality variations in reservoir rocks.

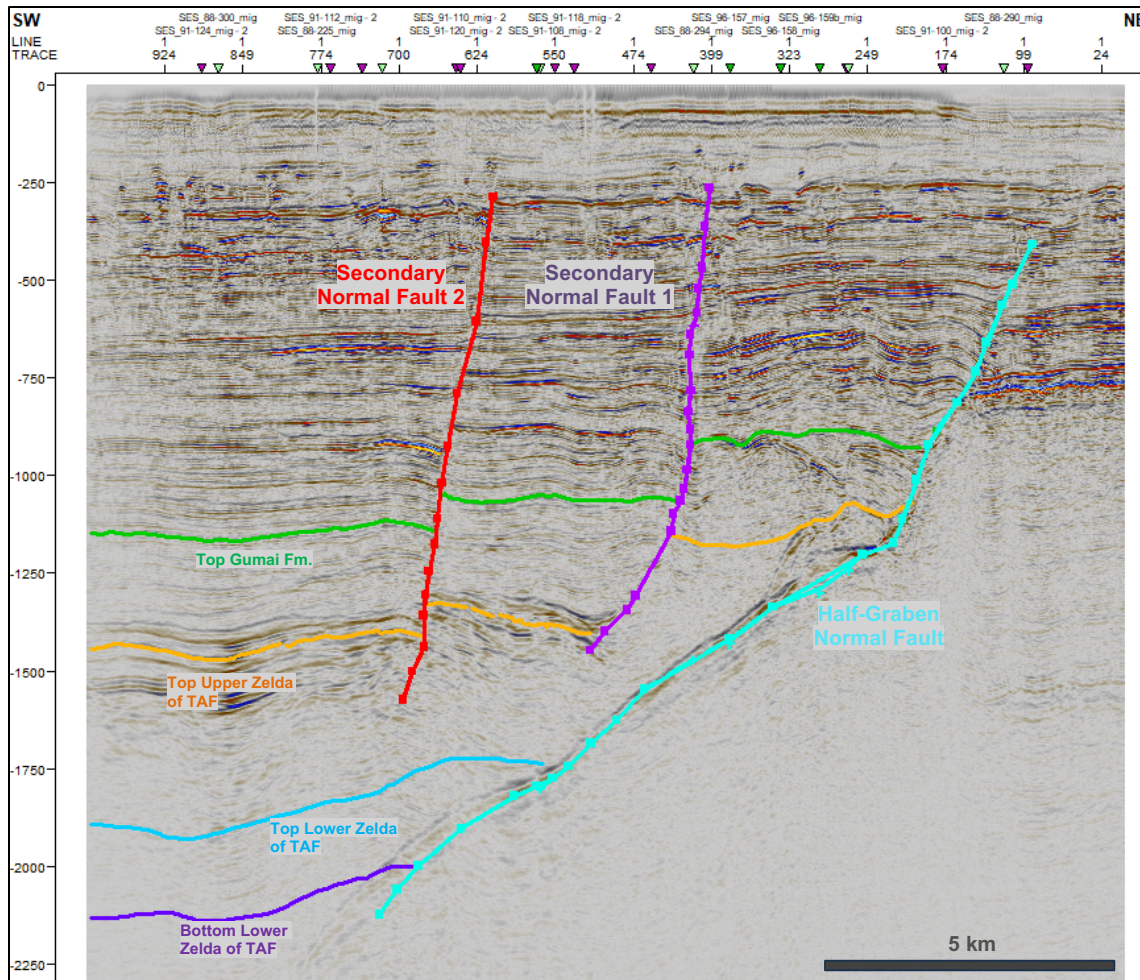


Figure 2.7. Secondary Normal Faults adjacent to the half-graben with vertical scale in meters

The overall extensional framework structural model of the area is presented in Figure 2.8. The entire eastern side of the research area is occupied by a major half-graben normal fault, which is the main structural control on sedimentation and accommodation. A set of secondary normal faults described above are immediately adjacent to this boundary fault. On the western side of the depocenter, the structural model also depicts other synthetic and antithetic normal faults along the western edge of the half-graben. This network of main, secondary, and distributed faults characterizes the structural system

influencing reservoir quality (thickness, lateral continuity, and potential compartmentalization relevant to CO₂ storage assessment).

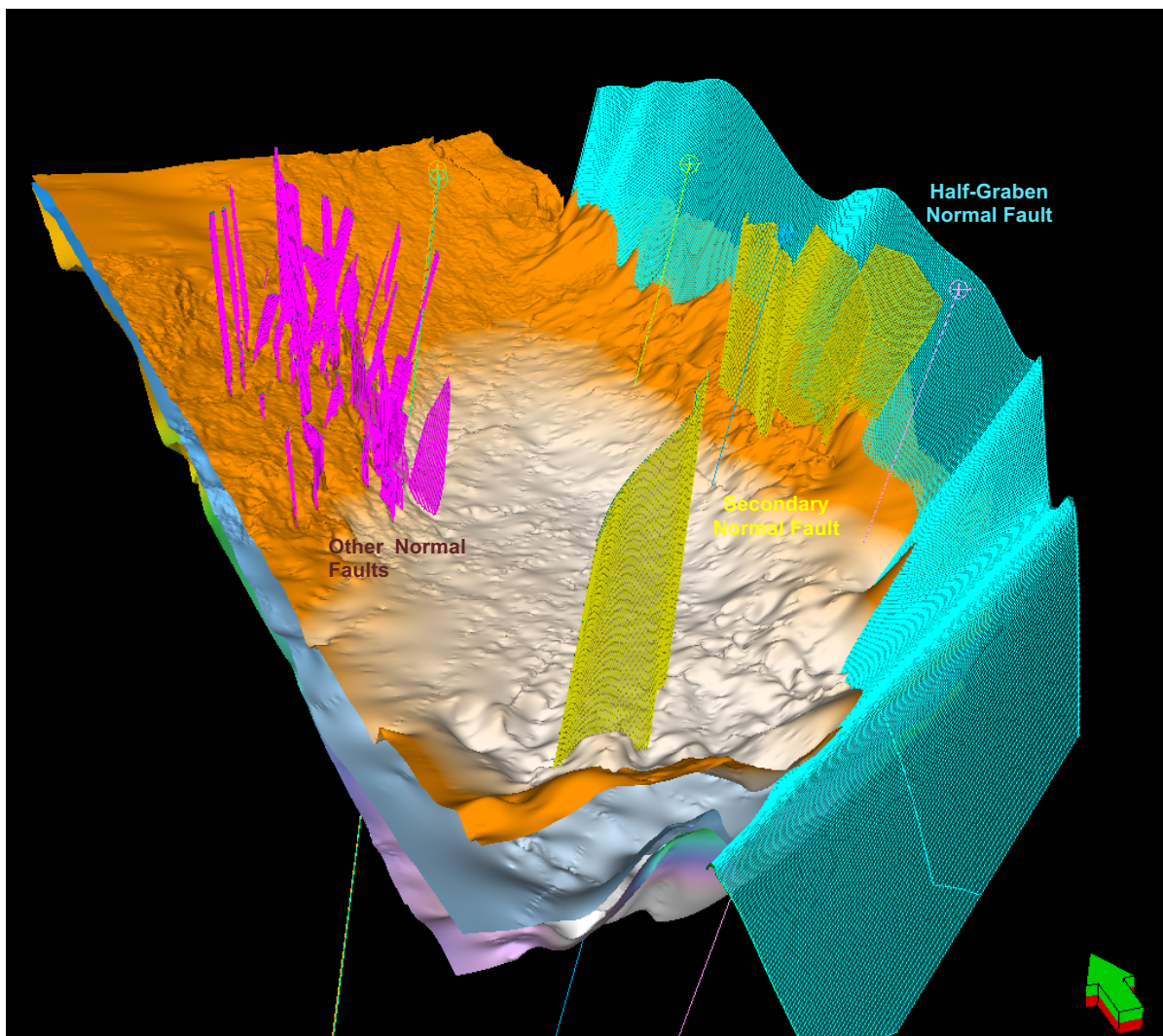


Figure 2.8. Structural framework in within the area of study displayed with Top Upper Zelda Horizon

Seismic Attribute Interpretation

Root Mean Square (RMS) Attribute

Root Mean Square (RMS) amplitude is a seismic attribute obtained from the square root of the average of the squared seismic trace amplitudes over a user-defined window. It is widely used to identify zones of high reflection energy that may correspond to reservoir-quality facies (Chopra & Marfurt, 2007). RMS also can be used to see the sand containment in a certain area. Some previous studies have demonstrated that high RMS amplitudes strongly correspond to sand-prone lithology when calibrated with well data. Hossain (2020) applied RMS amplitude to his research maps with seismic and well logs and found that high RMS amplitudes in the depocenter area of half-graben structure were related to sandstone at well location.

The RMS amplitude maps generated correspond to three different surfaces; Top Gumai Fm, Top Upper Zelda Member of TAF, and Bottom Lower Zelda (Figure 2.9). Those three RMS surfaces show the same results of the depocenter containing more sand-prone lithology than the surroundings. Because the seismic dataset was compiled from multiple acquisition and processing packages, all the amplitude values were normalized to a 0–1 scale to keep the consistency. The normalized RMS amplitude values highlight areas of relatively stronger reflectivity, which commonly correspond to cleaner, sand-prone intervals within Upper-Middle Zelda Member of the TAF. The map shows a zone of higher RMS amplitude (blue-green-yellow color) located in the central portion of the study area. The results align with the interpreted depocenter of the half-graben. This amplitude suggests greater sand development and more enhanced quality of sandstone reservoir within this region, consistent with the correlation and structural interpretation toward Upper-Middle Zelda Member.

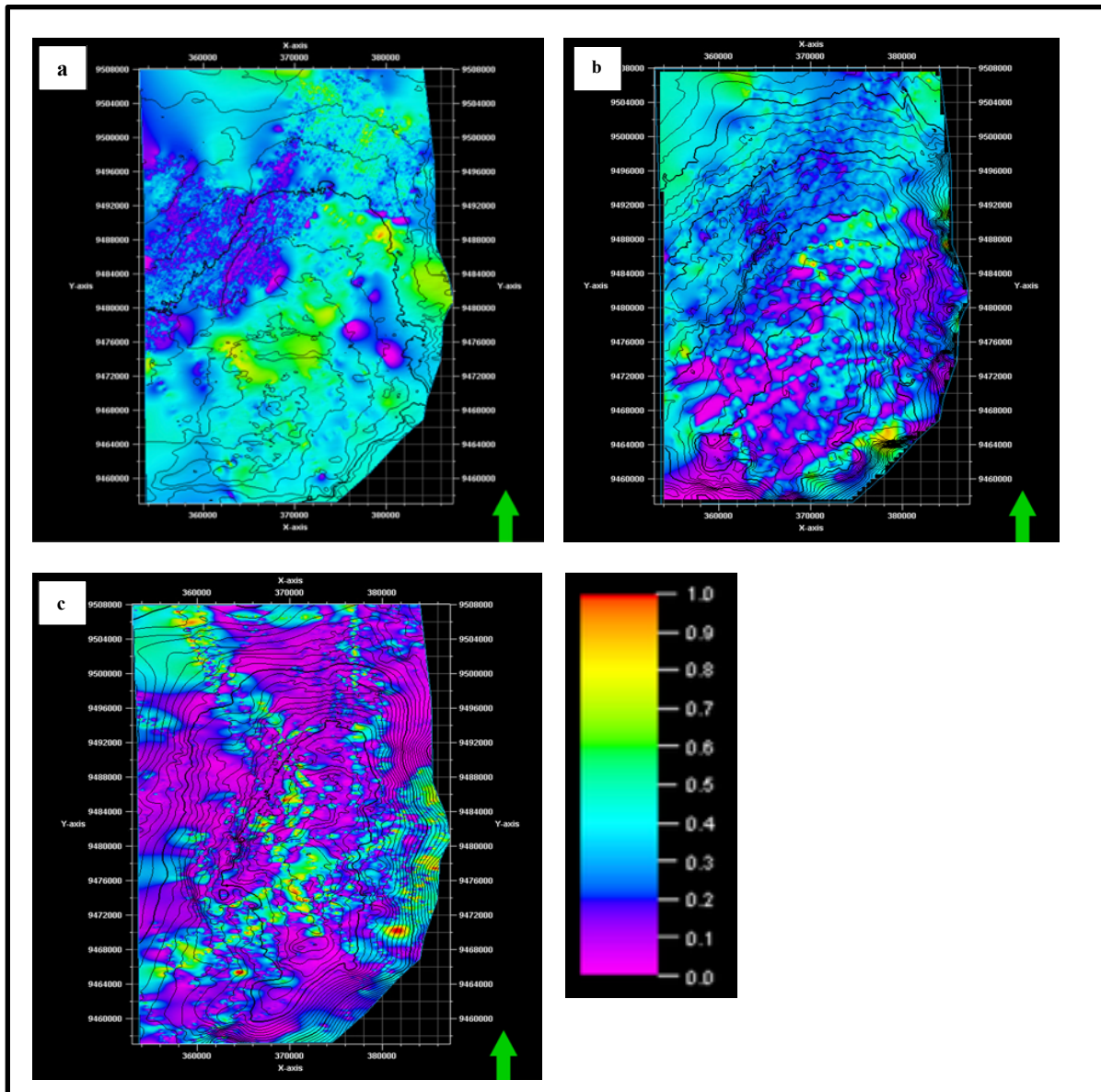


Figure 2.9. RMS Amplitude Map corresponding to: (a) Top Gumai Fm. (b) Top Upper Zelda Member of TAF (c) Bottom Lower Zelda Member of TAF

2.4. SUMMARY

This chapter gives the geological and geophysical characterization of the Sunda Strait Area to delineate the major reservoir, seal, structural framework and prospective area for CO₂ storage. The study is based on the approximately 50 x 31 km research area where six wells (S, H, D, B, A and Y) and available 2D and 3D seismic data were combined to interpret the subsurface. The Gumai Formation at ~1200-1250 m is the regional sealing unit, and the Upper-Middle Zelda Member of the Talang Akar Formation at ~1500-2600 m is the main CO₂ storage interval identified by well-log correlation, mainly using the Gamma Ray log. The Upper–Middle Zelda is about 1,000 m thick over the depocenter of half graben setting and is mostly composed of sandstone interbedded with shale, whereas the Lower Zelda is mostly shale and has lower reservoir quality.

The seismic data has been structurally interpreted and the study area is dominated by an extensional half-graben system, with a major basin-bounding normal fault along the eastern side of the study area, and several secondary synthetic and antithetic normal faults. Four seismic horizons, Top Gumai Formation, Top Upper Zelda, Top Lower Zelda, and Bottom Lower Zelda, were interpreted to define the geometry of the study area. The Top Gumai is generally continuous and acts as the regional seal, while the Upper Zelda horizon is more complex with many faults occurring related to the half-graben system. The lower Zelda horizons mark the lower and less promising portion of the storage period. Finally, normalized RMS amplitude maps were used to assess lateral variations in seismic facies and suggested that the depocenter is relatively more sand-prone. The Upper–Middle Zelda interval in the central half-graben depocenter is thus the most likely interval for the next steps of the research which is 3D geocellular modeling and CO₂ storage assessment.

CHAPTER 3: 3D GEOCELLULAR MODELLING

3.1. INTRODUCTION

This chapter involves geological characterization and assessment of CO₂ storage resources. The geological characterization in “Chapter 2” will be the main input for building a 3D geocellular model in Petrel. “Chapter 3” will discuss about the building of this 3D geocellular model which will be the main determining aspect to assess the storage resources that will be discussed in “Chapter 4”. A 3D geocellular model represents the three-dimensional distribution of the reservoir in the subsurface and it is composed of millions of 3D cells. Performed in Petrel, this model is constructed using the seismic surfaces which have been converted into 3D grids. The grids will subsequently be populated with petrophysical properties, especially effective porosity obtained from the upscaled well logs. The upscaled grids ensure that well-scale measurements are appropriately represented at the grid scale in the model. Such measurements will be distributed to the entire cells using the RMS seismic attribute as the main trend. Following this, the targeted area will be selected to move forward to the CO₂ storage assessment.

3.2. PETROPHYSICAL ANALYSIS

Petrophysical analysis is fundamental in reservoir characterization. Steps in this analysis include lithofacies determination, effective porosity estimation, and calculation of the distribution of the properties to populate the 3D-Geocellular model.

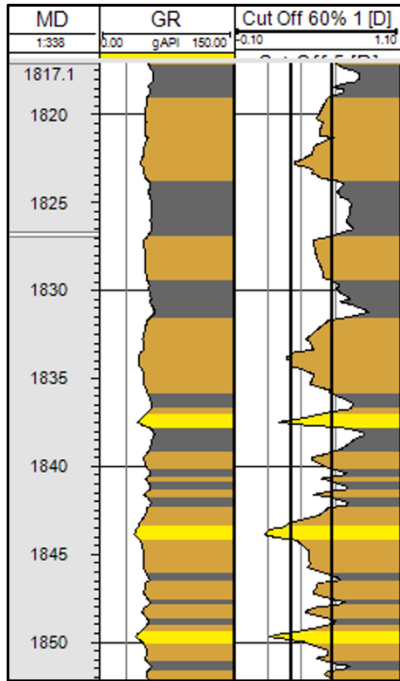


Figure 3.1. Gamma Ray log before (left) and after (right) being normalized.

The lithofacies identified earlier in Sub Chapter 2.2 used the Gamma Ray (GR) logs. As all the wells used in the study have GR logs, this is the most effective and consistent way to interpret the lithofacies. Prior to that, GR logs were normalized considering that some wells have unplausable trends. This normalization process ensures that all the gamma ray log curves are comparable by rescaling the GR values to a standardized range of 0 to 1, rather than the original 0–150 gAPI range (Fig. 3.1). The normalized logs therefore provided a consistent basis for lithofacies classification across the dataset. The

formula used to normalize the GR log is:

$$GR_{norm} = \frac{GR - GR_{min}}{GR_{max} - GR_{min}} \quad (1)$$

Where:

GR_{norm} = normalized Gamma Ray value

GR = original Gamma Ray log value

GR_{min} = minimum Gamma Ray value within the dataset

GR_{max} = maximum Gamma Ray value within the dataset

After normalizing all the GR logs from all the six wells, three cutoff values were distinguished to differentiate three lithofacies (shale, silty sand, and clean sand). The three lithofacies were determined based on author's understanding of clastic depositional environments similar to the study area. The general trend of volume of shale (Vshale) values suggested 0.3 for sandstone, 0.6 for silty sand, and values greater than 0.6 for shale (Figure 3.1). From the normalized GR logs applying those values, lithofacies distribution could be determined.

Another significant log used in this research was Effective porosity logs (EPHI). EPHI was the primary input for the 3D geocellular model. In order to obtain effective porosity logs, some calculations needed to be performed. The first approach was to determine the Density Porosity (DPHI) which estimates the fraction of pore space within the rock formation. Using the RHOB logs, the formula applied by Hartmann (1999) is below:

$$\Phi_D = \frac{\rho_b - \rho_m}{\rho_f - \rho_m} \quad (2)$$

Where:

Φ_D = Density Porosity

ρ_b = Bulk density (g/cm³)

ρ_m = Matrix density (quartz = 2.65 g/cc)

ρ_f = Fluid Density (water = 1.00 g/cc)

After obtaining the PHID logs, Total Porosity (TPHI) is a crucial step using formula calculated by Hartmann (1999). Using both Total Porosity (DPHI) and Neutron Porosity (NPHI) logs to remove any hydrocarbon effect in case we have hydrocarbon within the bulk, this estimates the total porosity in the rock formation.

$$\Phi_T = \sqrt{\frac{\Phi_D^2 + \Phi_N^2}{2}} \quad (3)$$

Where:

Φ_T = Total Porosity

Φ_D = Density Porosity

Φ_N = Neutron Porosity

EPHI is, by definition, pore space that is connected to fluid movement. In this study, the objective was to determine the effective porosity of the sand units as primary reservoirs for CO₂ sequestration. Therefore, the shale content is removed from the total porosity to obtain a more representative value. The equation used to calculate EPHI proposed by Marsan and Pratama (2015), is as follows:

$$\Phi_E = \Phi_T \times (1 - V_{sh}) \quad (4)$$

Where:

Φ_E = Effective Porosity

Φ_T = Total Porosity

V_{sh} = Volumetric shale from normalized GR logs

Among all six wells, only 3 wells have Φ_E logs (Well D, Well A, and Well Y). Well H has core data that provided us with some porosity values in certain intervals that will be discussed later for the vertical trend of the grid population. The values of EPHI from these wells relatively reflect the GR logs with the average effective porosity of 0.155. All these values will be the main values for the upscaled grids within the 3D geocellular Model.

3.3. 3D GEOCELLULAR MODEL BUILDING

Grid Building

The 3D Geocellular Model was made using the interpreted surfaces generated by seismic interpretation in this study. The workflow was adapted from Ruiz (2019), from depleted oil and gas to this saline-aquifer study. The previous study featured using a hydrocarbon footprint as there was hydrocarbon existence within the area, whereas no such hydrocarbon accumulation has been identified in the Sunda Strait's research area. The 3D model constructed in this research follows the interpreted structural framework in "Chapter 2". Ruiz (2019) generated ten facies realizations, and in this study nine realizations were done. They include three different sand and silty-sand proportions that will be explained later in this Chapter.

All the seismic surfaces and fault framework as explained in "Chapter 2" were completed in Petrel. The structural geometry, parameters, and property modeling inputs were independently defined in order to be more suitable for the Sunda Strait study area. Using those four surfaces featured earlier in "Sub Chapter 2.4", the geocellular was built and divided into four different zones: Top Gumai-Top Upper Zelda zone, Top Upper Zelda-Top Lower Zelda zone, Top Lower Zelda-Bottom Lower Zelda zone, and Below Bottom Lower Zelda zone (Table 3.1).

#	Zone Name	Top Surface	Bottom Surface	Layers	Layer Thickness
1	Gumai	Top Gumai	Top Upper Zelda	20	~10 m
2	Upper Zelda	Top Upper Zelda	Top Lower Zelda	50	~20 m
3	Lower Zelda	Top Lower Zelda	Bottom Lower Zelda	20	~15 m
4	Bottom	Bottom Lower Zelda	Bottom	10	~30 m

Tabel 3.1. Zone details in the grid construction

The 3D grid was constructed with the structural grid workflow by inserting the surfaces and all the faults and determining the size of the grids. The area of this model is approximately ~1,900 km² with the length of ~50 km and width of ~38 km. For this model, the author used specific dimensions for the grids of 200 m x 200 m with distinct numbers of layer each zone. With the depth of approximately 1,500–1,600 m, Upper Zelda has a dominant frequency of around 31 Hz and an interval velocity of approximately 2,900 m/s. The values are at the vertical seismic resolution of 25 m.

These thicknesses of the grid layers were adjusted to this resolution to prevent the model from suggesting more stratigraphic detail than necessary. The number and thickness of each layer were selected according to the geological thickness and significance of each zone to maintain a rational number of grid cells (Figure 3.2). The Gumai Zone has been divided into 20 layers of approximately 10 m each, to show enough detail of the regional seal within the area. The Upper Zelda zone was divided into 50 layers of approximately 20 m, more numbers than the others in order to see more detail of the zone since this zone acts as the main storage unit. The Lower Zelda and the deeper Bottom interval were modeled coarsely as they are not the most relevant zone to the main storage assessment.

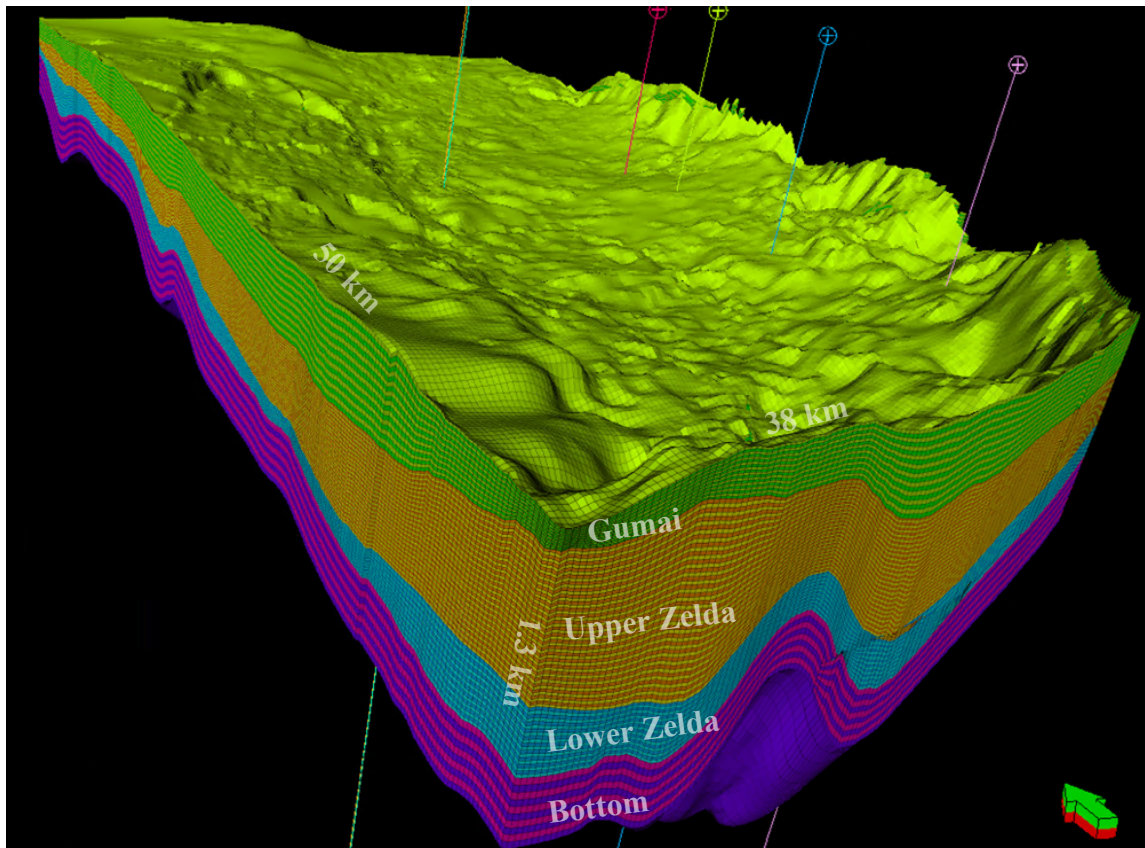


Figure 3.2. 3D Geocellular models of four zones divided into 100 layers vertically and horizontally in many layers of 200 m x 200 m.

The reservoir volume was divided into grid cells representing spatial distribution of each geological property. By dividing them, it allowed structural interpretation to be applied to the well data and petrophysical parameters within a unified modeling framework (Pyrz and Deutsch, 2014). Appropriate grid resolution was essential to ensure the key geological features are represented in the model while maintaining computational efficiency during the generation of the grid, well upscaling, and attribute population within the modeling workflows (Cannon, 2018).

Well Log Upscaling

After building the cells, the next step involved upscaling properties (lithofacies and EPHI) from the well logs. The grid cells corresponding to the well trajectories were populated with the values determined from the well logs (see prior analysis). Figure 3.3.a shows lithology logs that was generated based on lithofacies cutoffs, where Sandstone having lower than 0.3, silty sand is between 0.3 – 0.6, and shale lies higher than 0.6. The lithofacies interpretation is generated from log Gamma Ray (GR) response. Discrete logs use categories instead of number ranges. In this case, the logs only divide the value as either sandstone, silty sand, or shale based on the cutoffs above. This classification illustrated in the red columns in Figure 3.3 was the foundation of facies modeling.

Well log upscaling projects lithofacies properties of well logs to grid cells that are intersected by wells. This is done to make sure that the discrete lithofacies data is appropriately incorporated into the model scale simulation grid. Figure 3.3.b shows the outcome of well log upscaling procedure. As lithology is a discrete (categorical) property, and not a continuous property, geostatistical simulation techniques which maintain categorical distributions are needed. Sequential Indicator Simulation (SIS) is used to simulate lithofacies distribution in this study and will be explained later.

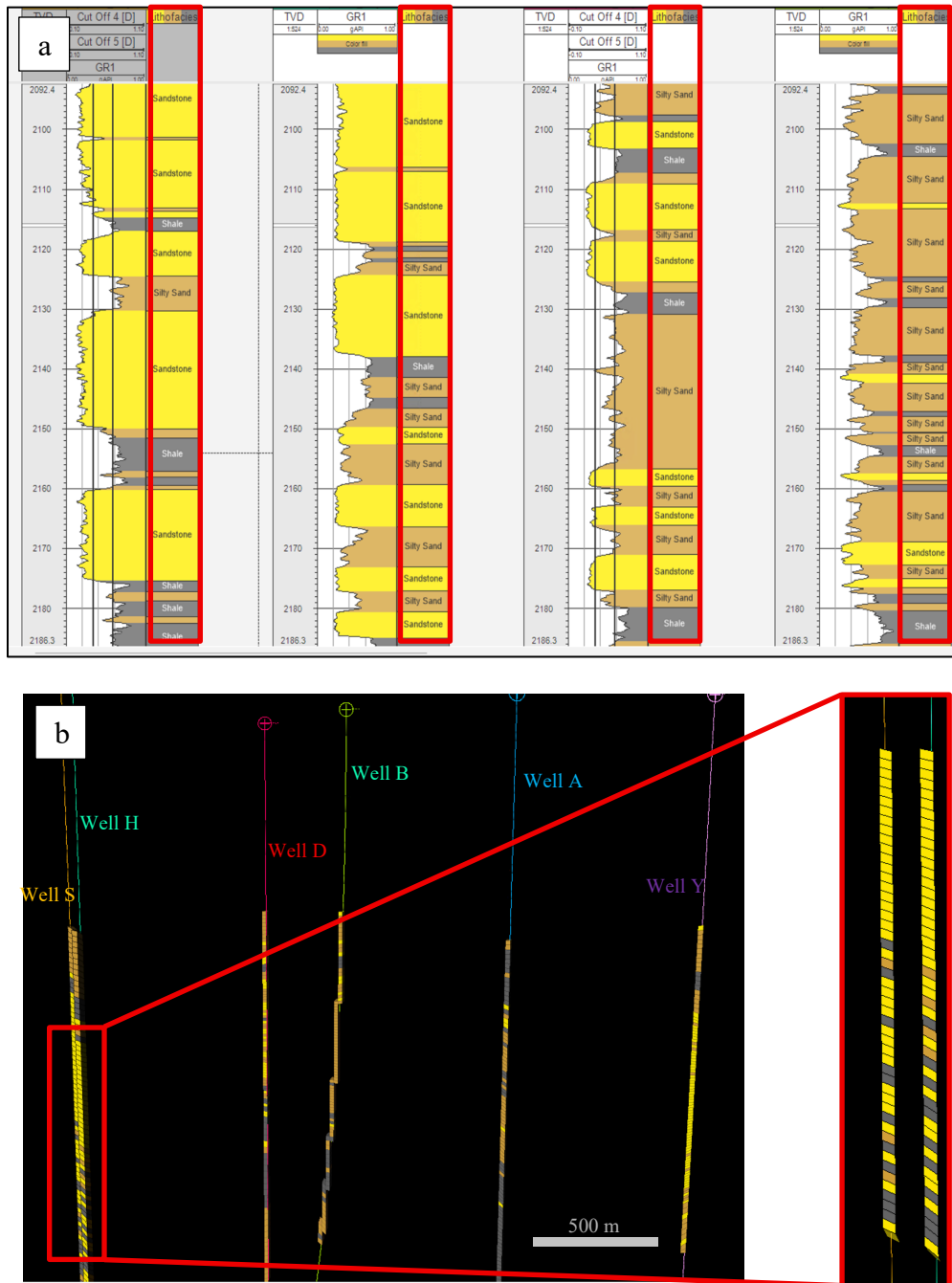


Figure 3.3. (a) Sample of Lithofacies Logs (b) Upscaled lithofacies well logs in 3D view

Along with lithology, the effective porosity (EPHI) logs were also scaled to the grid model with the values obtained based on the previous calculations. The three wells, i.e., Well D, Well A, and Well Y, provided the EPHI data (Figure 3.4.a). Unlike lithofacies, EPHI is a continuous property, i.e. its values can be smooth and can assume any value within a given range. The process guarantees that the variation at sub-grid scale is represented accordingly and is consistent with the geological model resolution. Consequently, EPHI offers a realistic depiction of porosity distribution to be used in the geostatistical modeling and simulation.

Figure 3.4.b illustrates the well log upscaling process for effective porosity (EPHI). As EPHI is a continuous property, geostatistical methods that preserve the statistical distribution and spatial continuity of continuous variables are required. In this study, Gaussian-based simulation, Gaussian Random Function (GRF), is applied and will be explained further later in this chapter.

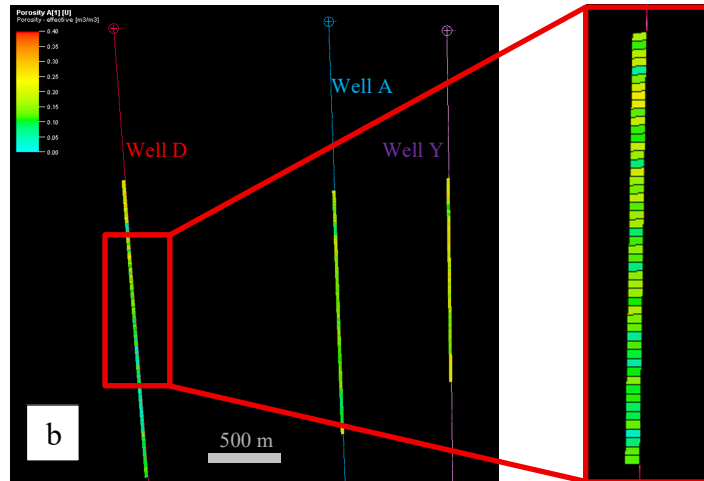
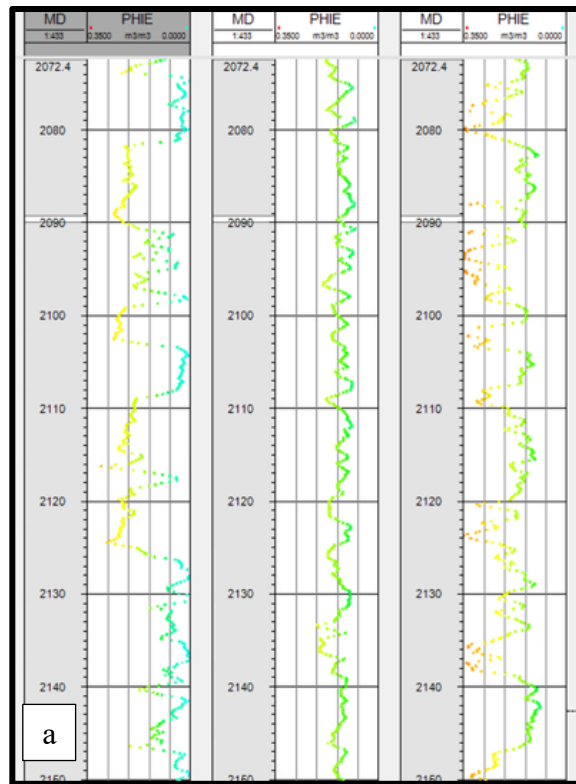


Figure 3.4. (a) Sample of EPHI Logs (b) Upscaled EPHI well logs in 3D view

3.4. PROPERTY MODELLING

Lithofacies Modelling

Sequential Indicator Simulation (SIS)

Sequential Indicator Simulation (SIS) method is a stochastic method using geostatistics to generate multiple probable realizations of variables by sampling from the upscaled grid corresponding to the wellbores (Pyrz and Deutsch, 2014). The distribution of this modelling is based on previously discussed upscaled lithofacies logs. The lateral facies distribution was constructed using facies' proportions and continuity as specified by a variogram (discussed below). This approach is especially appropriate for lithofacies modeling because it respects well data, accounts for heterogeneity, and preserves the discrete nature of the variable (Journel, 1983; Deutsch & Journel, 1998). For the SIS approach, spatial variability is created based on the statistical distribution of facies (mean, standard deviation, and type of distribution probability). Lithofacies logs are included to discrete type, which assigned all values to a specific facies category, in this case sand, silty sand, or shale, rather than having them as a continuously numerical property. The input for the SIS approach is generated from the discrete lithofacies logs based on the GR logs, using the RMS attribute that will be explained in "Trend" section below.

Variogram

Variograms are a key aspect in geostatistical modeling since they define the spatial distribution of properties in all grid cells. Variograms populate property values based on distance and direction. Three major parameters define a variogram: the sill, range and nugget. The sill is the plateau of the variogram, which is the total variance where the spatial correlation is no longer present. The range is the distance over which the data points are spatially correlated, and outside this range the values are essentially independent. The

nugget captures variability on very small scales, such as measurement errors and sub-grid heterogeneity that is beyond the capability of the model to resolve. Combining these parameters regulates the continuity and variability of the modeled property, and thus, the distribution and realism of the populated reservoir properties.

For the models built in this study, all facies variograms were defined by different values of Sill, Range and Nugget. The parameters of each facies variogram were determined by the interpretation of the depositional environment and the related spatial continuity. The Gumai Formation has a laterally extensive and homogeneous marine shale that is modeled with an isotropic variogram, major and minor ranges of 8,000 – 12,000 m and a vertical range of 15 -30 m, indicating high lateral continuity and low vertical variability.

The Upper Zelda is an anisotropic interval, representing a stacked sand bodies channelized fluvial system with a major range of 6,000 - 7,000 m, a minor range of 2000 - 3000 m, and a vertical range of 6 -10 m, indicating elongated channel continuity and vertically non-homogenous layering. For the Lower Zelda interval, heterogeneity is higher and sand connectivity is lower, leading to shorter ranges, a major range of 4,000 – 6,000 m, a minor range of 1,500 – 2,500 m and a vertical range of 6 – 10 m. The less organized and heterogeneous sedimentation of deeper intervals below Zelda is interpreted as early basin fill deposits with a major range of 3,000 – 5,000 m, a minor range of 1,500 – 2,500 m and vertical range of 5 – 8 m.

Trends

Root Mass Square (RMS) can help the process of sandstone distribution when calibrated with well data (Chopra and Marfurt, 2007). In order to set a vertical trend using RMS, it is important to note that there is an inverse relationship between the RMS attribute values and the GR log because those two datasets respond differently to lithology. Due to this contrasting relationship between RMS values and lithofacies classification, the RMS surfaces had to be inverted prior to interpretation to ensure consistency between the seismic attribute response and the lithofacies distribution. After applying the variogram and RMS attribute as the lateral trend, the lateral and vertical distribution of facies were assigned throughout the all the model cells. Figure 3.5 is the result of the distribution using SIS method based on the numbers discussed above.

As discussed previously, the SIS method can be used to generate more than one probable model. Given that there were only six wells with needed data, multiple realizations helped assess the model uncertainty in terms of lithology, geometry, and distribution to capture the heterogeneity that cannot be uniquely determined from the existing well data alone by exploring a variety of possible scenarios. This method minimized the chance of misinterpretation based on one deterministic model, resulting in multiple consistent but unique distributions of sand, silty sand, and shale in the area.

In this study, nine different realizations were generated from three different lithology ratios to account for the limited data availability and resulting uncertainty in facies distribution. The ratios are 80%, 60%, and 40% sand and silty sand. Each ratio produced three different model; Model A, B, and C corresponding to 80% sand and silty sand, Model D, E, and F to 60%, and Model G, H, and I honoring 40%. Each Model will determine the Effective Porosity Model, elaborated in the next sub chapter.

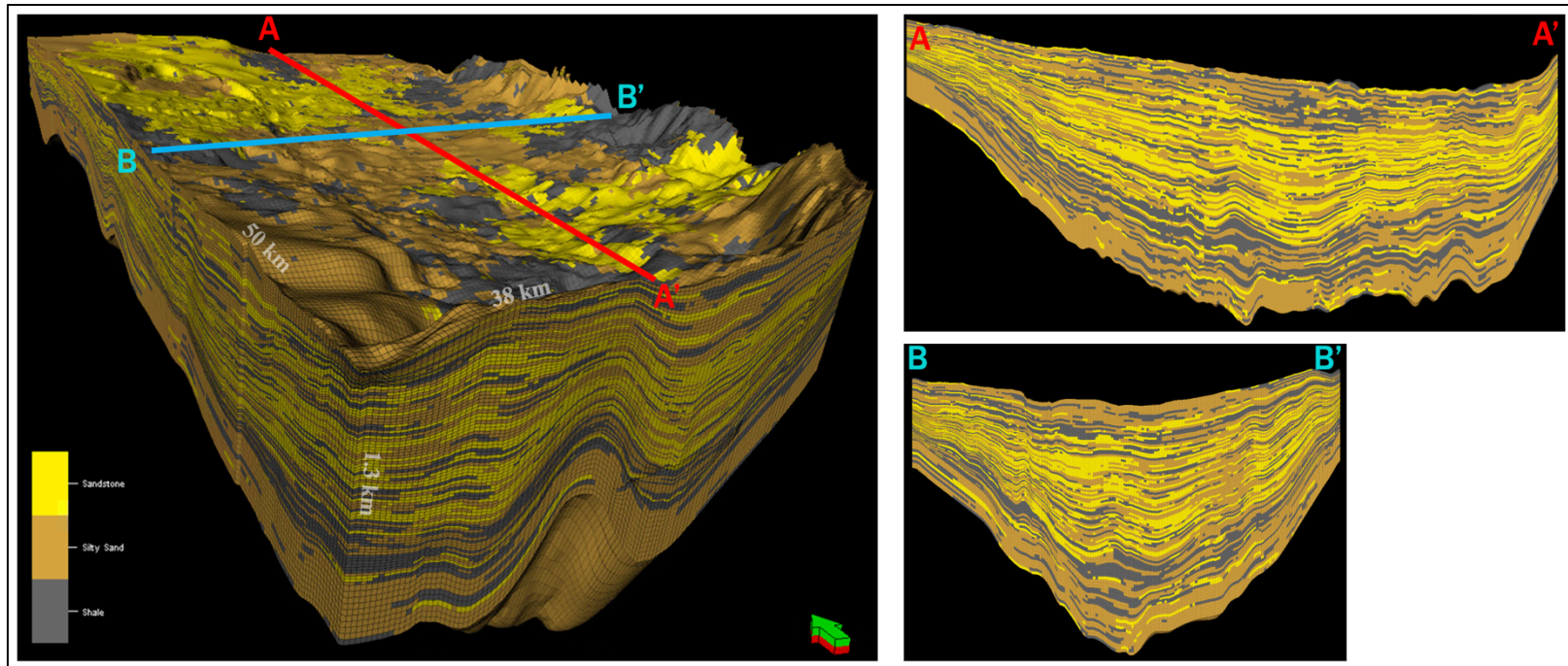


Figure 3.5. 3D Geocellular Model populated by lithofacies logs distributed with Sequential Indicator Simulation (SIS) method

Effective Porosity Modelling

Effective porosity (EPHI) is the most crucial log to populate as this depicts porosity that it is connected, which ultimately determine the volume of CO₂ stored in the area. As discussed previously, only Well D, Well A, and Well Y have EPHI values.

Following facies distribution, the porosity properties needed to be assigned. This process populates the facies in the 3D model with the values of Effective Porosity (EPHI) that are consistent with the characteristics of sand, silty sand, and shale. The property-modeling workflow involved upscaling the EPHI well logs to the 3D model's grid honoring the statistical distributions and variogram. Two different trends of RMS amplitude (horizontal trend) and core measurements (vertical trend) were also applied. A Gaussian Random Function (GRF) simulation was applied separately within each facies' (sand, silty sand, and shale) framework to distribute EPHI values throughout the model. The resulting porosity model was all based on respective statistical and spatial characteristics with the value of the cells corresponding to the well-log and core data.

Gaussian Random Function (GRF)

After the EPHI logs were upscaled to the model, a Gaussian Random Function (GRF) was applied. GRF is based on converting the original data to a normal (Gaussian) distribution and simulating the values according to the specified variogram. The method enables the model to respect well data and replicate the histogram, resulting in generating horizontal variability of the property. Continuous reservoir properties like porosity are frequently modeled by the method because it can represent heterogeneity and realistic spatial correlations (Deutsch & Journel, 1998; Pyrcz and Deutsch, 2014). This method basically assumes that the distribution of EPHI can be represented as a stochastic process

with Gaussian properties with its statistical value (mean and standard deviation). The goal is to extend the spatial representation of EPHI and reach the area beyond the well's control.

Variogram

The parameters of variograms of effective porosity (EPHI) in the interval of the Upper Zelda were determined by the characteristics of the geometry and distribution across the reservoir using some parameters namely range, sill, and nugget as explained before. The sand facies is the major unit of the reservoir that has moderate spatial continuity with local variability, indicating internal heterogeneity within channel bodies. The silty sand facies had less continuity, as the content of clay is higher and the depositional features are more transitional, which leads to more irregular porosity distribution.

Based on the fact that porosity is expected to be less continuous and more heterogeneous for both sand and silty sand facies, shorter variogram ranges were assigned to EPHI. For sand facies, a variogram with approximately a major range of 4,000 m, a minor range of 2,000 m, and a vertical range of 8 m was assigned. These values represent moderate porosity continuity along the channel direction, while still allowing local heterogeneity within the sandstone bodies. A shorter range variogram was assigned for silty sand, with a major range of 2,500 m, a minor range of 1,000 m, and a vertical range of 6 m, reflecting higher clay content.

Core Data

This core measurement values were utilized to validate the porosity model by utilizing them as vertical trend of EPHI distribution. The calculation of effective porosity (EPHI) in the core data was based on the statistical analysis of EPHI values obtained from the three wells previously described (Well D, Well A, and Well Y). The initial step involves

assigning representative values to each lithofacies from the values of gamma ray (GR) log data using predefined cutoff values of 0.3 and 0.6. Based on these thresholds, lithofacies were classified into three categories as previously mentioned: sand (GR values between 0.0 and 0.3), silty sand (GR values between 0.3 and 0.6), and shale (GR values between 0.6 and 1.0). With all the GR values from those wells combined, the distribution of these lithofacies was quantified using percentage to assist the EPHI's estimation in all the wells.

On the basis of the statistical distribution of the lithofacies based on the gamma ray (GR) log, the percentages of each of the facies were calculated as follows: sand makes 22.75 percent (GR: 0-0.3), sandy silty makes 51.28 percent (GR: 0.3-0.6), and shale makes 25.97 percent (GR: >0.6) (see Table 3.2.).

Lithofacies	Range (GR)	Percentage
Sand	0 – 0.3	22.75%
Silty Sand	0.3 – 0.6	51.28%
Shale	0.6 – 1	25.97%

Tabel 3.2. Percentage of the amount of each lithofacies in all well logs

A cumulative distribution analysis of the cumulative effective porosity (EPHI) of the three wells combined was done using these proportions (Figure 3.6). The lithofacies nomenclature using EPHI was then determined using percentile ranges. In particular, the shale was attributed to the lowest 25.97% of EPHI values (below P26), silty sand was attributed to the next 51.28% of values (between P26 and the P77), and sand was attributed to the highest 22.75% of EPHI values (above P77). This will provide consistency between lithofacies proportions derived by GR and the classification of EPHI.

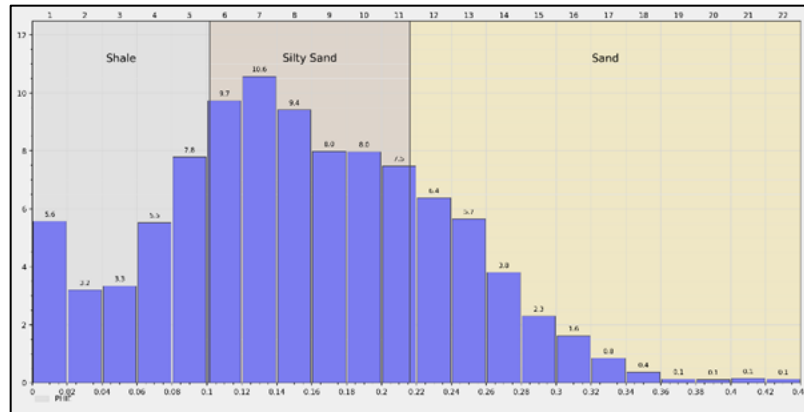


Figure 3.6. Cumulative EPHI values from all three wells divided into three lithofacies

The effective porosity (EPHI) values histogram was divided based on the proportional distribution of lithofacies based on the gamma ray (GR) analysis. The percentile scores in Table 3.2 were used to categorize the EPHI data into three lithofacies shown in Table 3.3. According to this classification, the shale is characterized by EPHI values, which are below 0.102 and 25.97 percentile of the distribution. Silty sand is illustrated by EPHI values of between 0.102 and 0.216, which includes the mid-range 51.28% of the data. Sand has EPHI values above 0.216, which is the 22.75 percentile of the distribution. This categorization makes sure that the EPHI-based lithofacies distribution aligns with the proportions derived using the GR log analysis, and the petrophysical and statistical interpretations coexist.

Lithofacies	Mean (EPHI)	Std
Shale	0.056	0.33
Silty Sand	0.155	0.33
Sand	0.265	0.05

Table 3.3. The values of mean and standard deviation of each lithofacies designated EPHI based on the division in Figure 3.8

After the histogram was segmented into three different facies corresponding to sand, silty sand, and shale, the mean and standard deviation for each facies were calculated. The data in Table 3.3 was reasonable and realistic for typical deltaic and fluvial depositional environment. The numbers were input into the petrophysical property distribution.

Trends

Similar to how lithofacies continuity was treated, RMS Amplitude was used as the horizontal trend, only this time the RMS Amplitude correlation was not reverse as the original scale aligned with how EPHI works (higher value of RMS meaning more sand prone lithology).

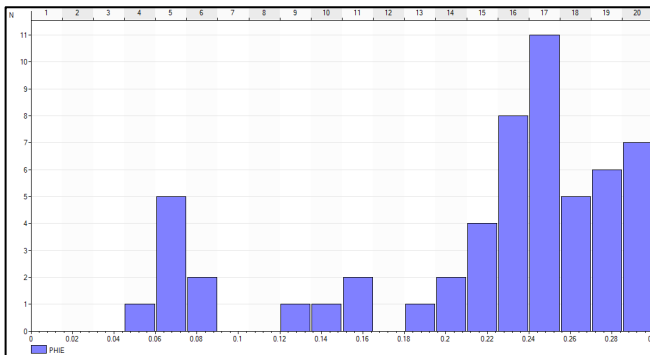


Figure 3.7. Porosity data values from core samples of Well H

For vertical trend, core data from Well H was utilized (Figure 3.7). Among six wells in the study, well H has core data over a deep range of 1,597 m to 3,167. This measurement of porosity was measured directly from the core samples, so needs to be reflected in

the porosity assignments. This core data can be used as the vertical trend of the EPHI distribution that can be applied in the whole model.

Figure 3.8 depicts the distribution of Well H's porosity data from core samples. As shown in the figure, the core data of this well provided a set of core porosity values for overlapping depth intervals. There are only four different ranges: 1,597 – 1,602 m, 2,181 – 2,182 m, 2,816 – 2,825 m, and 3,159 – 3,167 m.

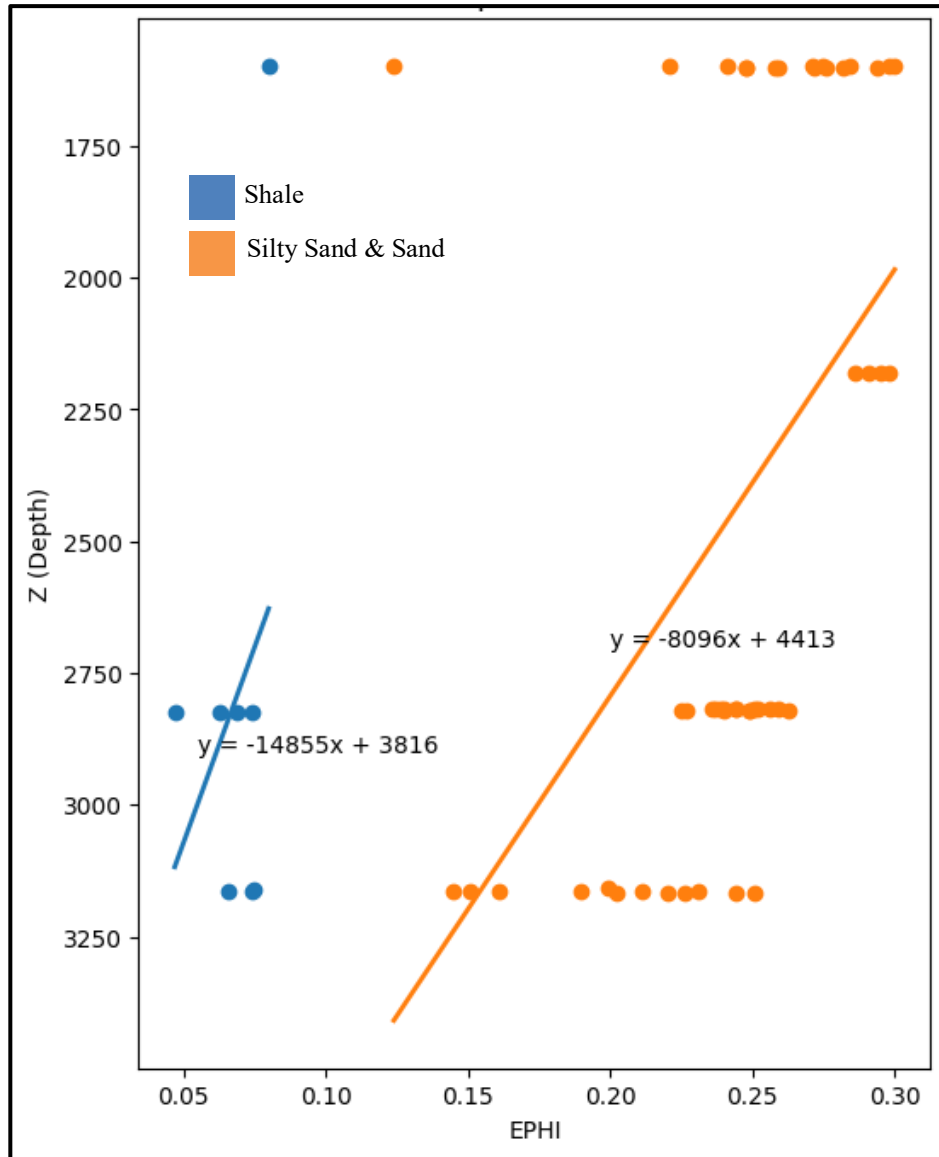


Figure 3.8. Porosity values from Well H's Core Data vs Depth with equations

The overall porosity data ranges from about 0.05 to about 0.30. Based on the lithofacies percentage in Table 3.2, porosity data was also divided into Shale (< 0.102) colored as blue and Silty Sand & Sand (> 0.102) colored as orange. Each lithofacies corresponds to a different linear function applied to respective lithofacies as a vertical trend ($y = -14,855x + 3,816$ for Shale and $y = -8,096x + 4,413$ for Silty Sand and Sand).

After obtaining all the data, the distribution was executed with GRF method based on the variogram and statistical numbers (mean, standard deviation, and type of distribution). To make the distribution more realistic, RMS was utilized as the horizontal trend and the linear function from core data was also applied as the vertical trend, resulting in EPHI model as shown in Figure 3.9. Each Model (A through I) produces five different realizations, meaning that there were forty-five realization of EPHI models.

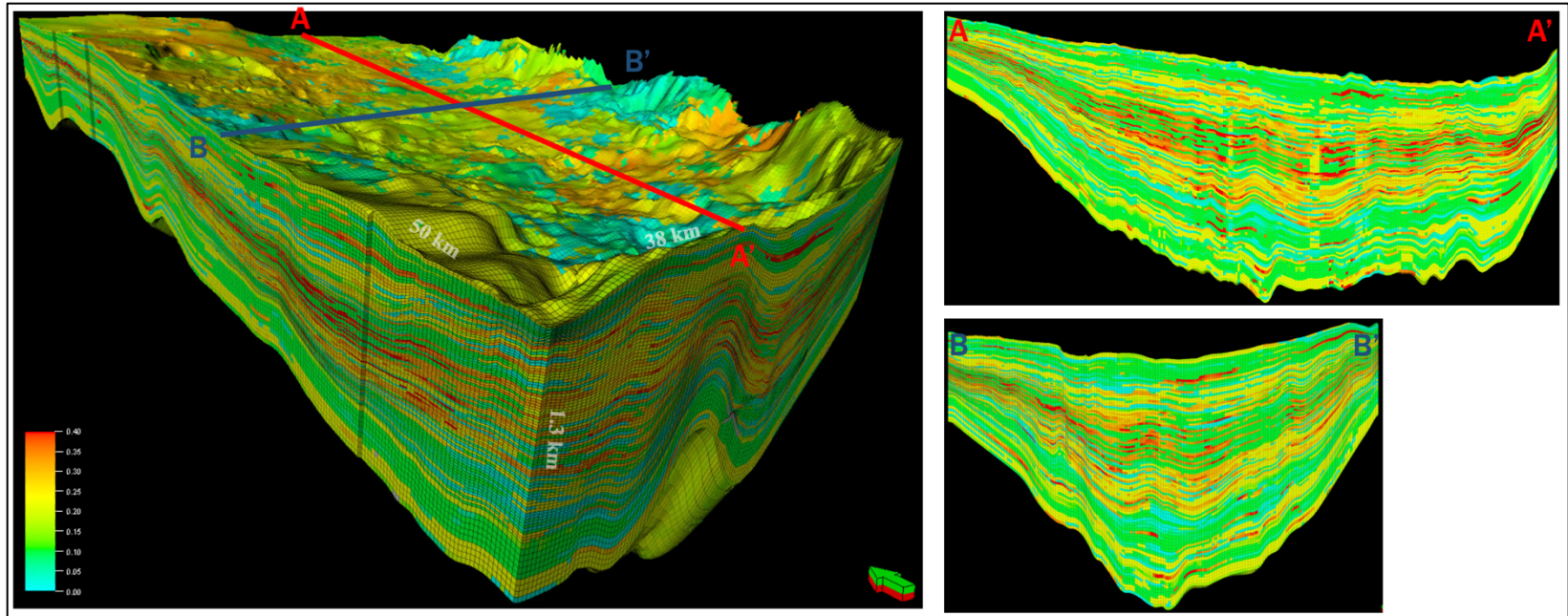


Figure 3.9. 3D Geocellular Model populated with EPHI logs distributed with Gaussian Random Function (GRF) method

3.5. SUMMARY

This chapter showed the framework of a 3D geocellular model development in Petrel using seismic surfaces and fault for the structure, whereas well logs, core porosity, and the RMS seismic attribute were used for the content. The structural grid covers approximately 1,900 km² with horizontal cells of 200 m × 200 m, divided into four different groups of Gumai, Upper Zelda, Lower Zelda, and Bottom zones with their respective roles with a total of 100 vertical layers. The Upper Zelda Zone was modeled in more numbers of grid because it acts as the primary storage interval. GR logs from six wells were normalized to make the unit uniform (0 – 0.1) and classified into three different lithofacies of sand, silty sand, and shale using cutoff values of 0.3 and 0.6. EPHI values, as the cell content, were calculated from the available density and neutron logs and upscaled to the grid.

In order to generate a lithofacies model, Sequential Indicator Simulation (SIS) was used to distribute lithofacies with sand and silty sand proportions and variograms with inverted RMS attribute as the lateral trend. Nine facies realizations were generated from three different sand and silty-sand proportions of 80%, 60%, and 40%, with three realizations for each proportion. Effective porosity was also then distributed using Gaussian Random Function (GRF) simulation, with variogram as the distribution control. RMS was also used as the horizontal trend and Well H core data as the vertical trend. Five EPHI realizations were generated for each facies model, resulting in forty-five porosity models. These realizations represent distributions of facies and porosity with different possibility that will be used as the main tool for the CO₂ storage-capacity assessment in the next chapter.

CHAPTER 4: CO₂ STORAGE RESOURCES ANALYSIS

4.1. INTRODUCTION

After geological interpretation, petrophysical evaluation, and three-dimensional reservoir characterization and modelling in the previous chapters, storage resources analysis is the primary result sought in this research. In this chapter, the capacity of the Talang Akar Formation to store injected CO₂ was assessed both using a static volumetric method as well as a semi-analytic dynamic approach. A 3D geocellular volumetric approach and the EASiTool methodology were both performed to estimate the potential CO₂ storage resources statically and dynamically, respectively. When applied together, both approaches allow comparison of storage resource estimates using different methods.

The static volumetric approach of this estimation was based on the theoretical amount of CO₂ stored in the pore space within the area of interest, using a volumetric formula. The dynamic volume assessment, on the other hand, used some dynamic parameters namely model pressure buildup, injection rate through time, plume migration, and well configuration. Eventually, a comparison between static and dynamic estimates were compared to ultimately determine the accuracy of the estimates. The hypothesis is that the two methods should yield somewhat similar storage resource estimates in terms of the storage efficiency.

4.2. ZELDA MEMBER OF TAF STORAGE RESOURCES

Consisting of about 1,000 meters of interbedded sandstone and shale, Zelda Member of TAF is the primary target of CO₂ storage. Based on the well data, the combination of sandstone and silty-sandstone has a net thickness of 400 – 800 meters, while the net sand of this formation is around of 135 - 550 meter. This variation in net reservoir thickness reflects the vertical and lateral heterogeneity of the reservoir; therefore, a single deterministic geological model would never be sufficient to represent the ideal subsurface conditions. For the static resource estimate methodology, as mentioned in “Chapter 3”, multiple lithofacies and effective porosity (EPHI) model realizations were generated to quantify the effect of geological uncertainty on the estimated CO₂ storage resources, while for the dynamic methodology different permeability values were used to see the conservative and optimistic cases.

Static Volumetric Methodology

Three-Dimensional Geocellular Volumetric Methodology

The three-dimensional geocellular storage assessment used the structural and property models created in Chapter 3. The effective pore volume in all cells will be used to calculate the mass of stored CO₂ based on an assumed density of CO₂ (defined below).

Using the facies and EPHI models previously generated in Chapter 3 (Figure 4.1.a), different realizations of facies and porosity distribution were generated. The static capacity was calculated only in the Upper Talang Akar zone within the area of interest of 17.7 km x 18.9 km (Figure 4.1b), which lies within the half-graben setting described previously in “Chapter 2” as the ultimate storage target. Within the AOI area, the Upper Talang Akar Zone was the only depth interval used in this volumetric calculation.

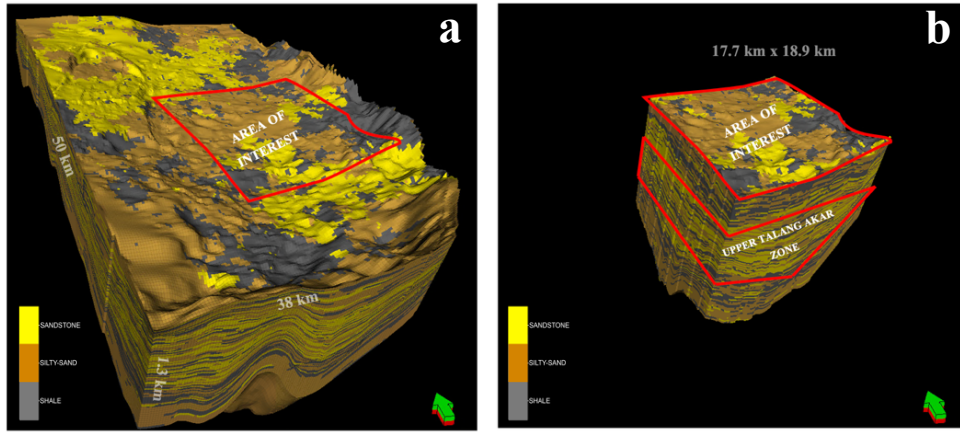


Figure 4.1.a. Facies Model of the whole research area; b. Area of Interest for Static Method Calculation with the Upper Talang Akar thickness of 1,000 m.

The prospective total CO₂ mass was calculated using an individual cell-based volumetric equation by the U.S. Department of Energy applied to all EPHI models. The formula was:

$$M_{(CO_2)} = \sum_{(i=1)}^N (V_{(b,i)} \times \phi_{(e,i)} \times F_{(f,i)}) \times \rho_{(CO_2)} \times E_{(saline)} \quad (5)$$

Where:

M_{CO_2} = prospective CO₂ storage resource (Mt)

$V_{b,i}$ = bulk volume of grid cell i (km³)

$\phi_{e,i}$ = effective porosity of grid cell i

$F_{f,i}$ = facies-dependent pore-volume multiplier

ρ_{CO_2} = in-situ CO₂ density (kg/m³)

E_{saline} = saline-formation storage-efficiency factor

The formulation uses the regional volumetric equation proposed by Goodman (2010), which is the product of reservoir elements including formation area, thickness, porosity, CO₂ density, and storage efficiency. The volumetric calculation was performed

with a cell-by-cell basis in the area of interest. The pore-volume contribution of each grid cell was estimated by multiplying the bulk volume by the effective porosity of the cell and the pore-volume multiplier for each facies. The individual cell contributions were then added together to give the total effective pore volume for use in the CO₂ storage resources calculation.

The volumetric formula was applied separately for sand and silty sand assigned cells. Different pore-volume multipliers were used for sandstone and silty sandstone cells. Following Ruiz (2019) work, a 100% value of the calculated effective pore volume was contributed by the sandstone cells while 15% of the calculated effective pore volume was contributed by the silty sandstone cells. These percentages are not the percentage of CO₂ saturation in the pores of each facies, but rather the percentage of the pore volume that was used in the calculation of the storage resources.

Density

CO₂ density in the subsurface is a function of pressure and temperature variations with depth, which will directly affect volumetric storage estimates. Uncertainty in subsurface pressure and geothermal conditions can cause variations in the calculated CO₂ storage mass because CO₂ density is strongly controlled by pressure and temperature. Below about 1 km, CO₂ is typically in a supercritical state and is generally found to have densities of approximately 500–700 kg/m³, depending on local reservoir conditions (Burruss, 2008). In this study, a sensitivity range of 600–800 kg/m³ was used for the Upper Zelda reservoir at a depth of around 1.65 km. This range is comparable to published values for supercritical CO₂ under general reservoir conditions.

Five values of CO₂ density (600, 650, 700, 750 and 800 kg/m³) were used as sensitivities. Since there are five realizations in each model and there are five values of

density, each model's realization was applied a different value and that single CO₂ density value was used for all grid cells in the modeled Upper Zelda interval. This is an approximation and the CO₂ density values assigned are based on the average in-situ CO₂ density across the reservoir interval, with uncertainty in the pressure and temperature conditions from the top to the bottom of the model.

Esaline

Esaline represents the fraction of the available effective pore volume occupied by CO₂ in a static calculation. According to Goodman et al. (2011), CO₂ storage efficiency factors are a parameter that reflects a total pore volume fraction filled by CO₂, meaning only some percentage of the pore space can be expected to be available for CO₂ presence. Esaline reflects incomplete sweep efficiency, brine displacement limitations, and variations in reservoir lateral and vertical connectivity. In this research, different Esaline values were applied. For every EPHI realization, three different saline storage-efficiency values were assigned. The values were chosen according to the DOE-NETL concept of storage efficiency in the saline-formation efficiency factors for the conservative, base, and optimistic cases are reported as 0.51%, 2.0% and 5.4% for clastic reservoirs (Goodman et al., 2011). Thus, the 1%, 3% and 5% values used in this study round those sensitivity values within the conservative range of published values for saline storage-efficiency factors by the DOE-NETL by Goodman (2011). Furthermore, since there are forty-five EPHI realizations (see Chapter 3), 135 static capacity volume estimations in million tons of CO₂ were generated (Table 4.1, 4.2, and 4.3).

Sand & Silty Sand Proportion of net AOI reservoir thickness	Model	Realization	Pore Volume (m ³)		CO ₂ Density (kg/m ³)	Esaline	Mass CO ₂ (kg)		CO ₂ (Tons)	CO ₂ (Mt)
			Sand	Silty Sand			Sand	Silty Sand		
80%	A	1	4.39E+10	2.92E+09	800	1%	3.51E+11	2.34E+10	3.75E+08	3.75E+02
						3%	1.05E+12	7.02E+10	1.12E+09	1.12E+03
						5%	1.76E+12	1.17E+11	1.87E+09	1.87E+03
		2	4.40E+10	2.93E+09	750	1%	3.30E+11	2.20E+10	3.52E+08	3.52E+02
						3%	9.90E+11	6.60E+10	1.06E+09	1.06E+03
						5%	1.65E+12	1.10E+11	1.76E+09	1.76E+03
		3	4.40E+10	2.92E+09	700	1%	3.08E+11	2.05E+10	3.29E+08	3.29E+02
						3%	9.24E+11	6.14E+10	9.86E+08	9.86E+02
						5%	1.54E+12	1.02E+11	1.64E+09	1.64E+03
		4	4.40E+10	2.92E+09	650	1%	2.86E+11	1.90E+10	3.05E+08	3.05E+02
						3%	8.58E+11	5.70E+10	9.15E+08	9.15E+02
						5%	1.43E+12	9.50E+10	1.53E+09	1.53E+03
		5	4.42E+10	2.93E+09	600	1%	2.65E+11	1.76E+10	2.83E+08	2.83E+02
						3%	7.95E+11	5.27E+10	8.48E+08	8.48E+02
						5%	1.33E+12	8.78E+10	1.41E+09	1.41E+03
	B	1	4.43E+10	2.84E+09	800	1%	3.54E+11	2.28E+10	3.77E+08	3.77E+02
						3%	1.06E+12	6.83E+10	1.13E+09	1.13E+03
						5%	1.77E+12	1.14E+11	1.88E+09	1.88E+03
		2	4.43E+10	2.85E+09	750	1%	3.32E+11	2.13E+10	3.54E+08	3.54E+02
						3%	9.96E+11	6.40E+10	1.06E+09	1.06E+03
						5%	1.66E+12	1.07E+11	1.77E+09	1.77E+03
		3	4.43E+10	2.84E+09	700	1%	3.10E+11	1.99E+10	3.30E+08	3.30E+02
						3%	9.31E+11	5.97E+10	9.91E+08	9.91E+02
						5%	1.55E+12	9.94E+10	1.65E+09	1.65E+03
		4	4.44E+10	2.84E+09	650	1%	2.89E+11	1.84E+10	3.07E+08	3.07E+02
						3%	8.67E+11	5.53E+10	9.22E+08	9.22E+02
						5%	1.44E+12	9.22E+10	1.54E+09	1.54E+03
		5	4.45E+10	2.84E+09	600	1%	2.67E+11	1.70E+10	2.84E+08	2.84E+02
						3%	8.01E+11	5.11E+10	8.52E+08	8.52E+02
						5%	1.33E+12	8.52E+10	1.42E+09	1.42E+03
	C	1	4.54E+10	2.81E+09	800	1%	3.63E+11	2.25E+10	3.86E+08	3.86E+02
						3%	1.09E+12	6.74E+10	1.16E+09	1.16E+03
						5%	1.82E+12	1.12E+11	1.93E+09	1.93E+03
		2	4.58E+10	2.81E+09	750	1%	3.44E+11	2.11E+10	3.65E+08	3.65E+02
						3%	1.03E+12	6.33E+10	1.09E+09	1.09E+03
						5%	1.72E+12	1.05E+11	1.82E+09	1.82E+03
		3	4.57E+10	2.80E+09	700	1%	3.20E+11	1.96E+10	3.40E+08	3.40E+02
						3%	9.60E+11	5.89E+10	1.02E+09	1.02E+03
						5%	1.60E+12	9.81E+10	1.70E+09	1.70E+03
		4	4.59E+10	2.80E+09	650	1%	2.98E+11	1.82E+10	3.16E+08	3.16E+02
						3%	8.95E+11	5.47E+10	9.49E+08	9.49E+02
						5%	1.49E+12	9.11E+10	1.58E+09	1.58E+03
		5	4.58E+10	2.80E+09	600	1%	2.75E+11	1.68E+10	2.92E+08	2.92E+02
						3%	8.25E+11	5.04E+10	8.75E+08	8.75E+02
						5%	1.37E+12	8.40E+10	1.46E+09	1.46E+03

Tabel 4.1. Static Capacity Volume using 80% sand and silty sand proportion with variations of density within the range of 600 – 800 kg/m³ and three variations of 1%, 3%, and 5% Esaline

Sand & Silty Sand Proportion of net AOI reservoir thickness	Model	Realization	Pore Volume (m ³)		CO ₂ Density (kg/m ³)	Esaline	Mass CO ₂ (kg)		CO ₂ (Tons)	CO ₂ (Mt)
			Sand	Silty Sand			Sand	Silty Sand		
60%	D	1	3.99E+10	2.76E+09	800	1%	3.51E+11	2.34E+10	3.75E+08	<u>3.75E+02</u>
						3%	1.05E+12	7.02E+10	1.12E+09	<u>1.12E+03</u>
						5%	1.76E+12	1.17E+11	1.87E+09	<u>1.87E+03</u>
		2	4.00E+10	2.76E+09	750	1%	3.30E+11	2.20E+10	3.52E+08	<u>3.52E+02</u>
						3%	9.90E+11	6.60E+10	1.06E+09	<u>1.06E+03</u>
						5%	1.65E+12	1.10E+11	1.76E+09	<u>1.76E+03</u>
		3	4.00E+10	2.76E+09	700	1%	3.08E+11	2.05E+10	3.29E+08	<u>3.29E+02</u>
						3%	9.24E+11	6.14E+10	9.86E+08	<u>9.86E+02</u>
						5%	1.54E+12	1.02E+11	1.64E+09	<u>1.64E+03</u>
		4	4.00E+10	2.76E+09	650	1%	2.86E+11	1.90E+10	3.05E+08	<u>3.05E+02</u>
						3%	8.58E+11	5.70E+10	9.15E+08	<u>9.15E+02</u>
						5%	1.43E+12	9.50E+10	1.53E+09	<u>1.53E+03</u>
		5	4.02E+10	2.75E+09	600	1%	2.65E+11	1.76E+10	2.83E+08	<u>2.83E+02</u>
						3%	7.95E+11	5.27E+10	8.48E+08	<u>8.48E+02</u>
						5%	1.33E+12	8.78E+10	1.41E+09	<u>1.41E+03</u>
	E	1	3.83E+10	2.82E+09	800	1%	3.54E+11	2.28E+10	3.77E+08	<u>3.77E+02</u>
						3%	1.06E+12	6.83E+10	1.13E+09	<u>1.13E+03</u>
						5%	1.77E+12	1.14E+11	1.88E+09	<u>1.88E+03</u>
		2	3.85E+10	2.83E+09	750	1%	3.32E+11	2.13E+10	3.54E+08	<u>3.54E+02</u>
						3%	9.96E+11	6.40E+10	1.06E+09	<u>1.06E+03</u>
						5%	1.66E+12	1.07E+11	1.77E+09	<u>1.77E+03</u>
		3	3.85E+10	2.84E+09	700	1%	3.10E+11	1.99E+10	3.30E+08	<u>3.30E+02</u>
						3%	9.31E+11	5.97E+10	9.91E+08	<u>9.91E+02</u>
						5%	1.55E+12	9.94E+10	1.65E+09	<u>1.65E+03</u>
		4	3.86E+10	2.82E+09	650	1%	2.89E+11	1.84E+10	3.07E+08	<u>3.07E+02</u>
						3%	8.67E+11	5.53E+10	9.22E+08	<u>9.22E+02</u>
						5%	1.44E+12	9.22E+10	1.54E+09	<u>1.54E+03</u>
		5	3.85E+10	2.82E+09	600	1%	2.67E+11	1.70E+10	2.84E+08	<u>2.84E+02</u>
						3%	8.01E+11	5.11E+10	8.52E+08	<u>8.52E+02</u>
						5%	1.33E+12	8.52E+10	1.42E+09	<u>1.42E+03</u>
	F	1	4.06E+10	2.75E+09	800	1%	3.25E+11	2.20E+10	3.47E+08	<u>3.47E+02</u>
						3%	9.75E+11	6.60E+10	1.04E+09	<u>1.04E+03</u>
						5%	1.62E+12	1.10E+11	1.73E+09	<u>1.73E+03</u>
		2	4.07E+10	2.75E+09	750	1%	3.05E+11	2.06E+10	3.26E+08	<u>3.26E+02</u>
						3%	9.15E+11	6.19E+10	9.77E+08	<u>9.77E+02</u>
						5%	1.53E+12	1.03E+11	1.63E+09	<u>1.63E+03</u>
		3	4.06E+10	2.74E+09	700	1%	2.84E+11	1.92E+10	3.04E+08	<u>3.04E+02</u>
						3%	8.53E+11	5.76E+10	9.11E+08	<u>9.11E+02</u>
						5%	1.42E+12	9.60E+10	1.52E+09	<u>1.52E+03</u>
		4	4.08E+10	2.75E+09	650	1%	2.65E+11	1.78E+10	2.83E+08	<u>2.83E+02</u>
						3%	7.96E+11	5.35E+10	8.49E+08	<u>8.49E+02</u>
						5%	1.33E+12	8.92E+10	1.42E+09	<u>1.42E+03</u>
		5	4.09E+10	2.74E+09	600	1%	2.46E+11	1.65E+10	2.62E+08	<u>2.62E+02</u>
						3%	7.37E+11	4.94E+10	7.86E+08	<u>7.86E+02</u>
						5%	1.23E+12	8.23E+10	1.31E+09	<u>1.31E+03</u>

Table 4.2. Static Capacity Volume using 60% sand and silty sand proportion with variations of density within the range of 600 – 800 kg/m³ and three variations of 1%, 3%, and 5% Esaline

Sand & Silty Sand Proportion of net AOI reservoir thickness	Model	Realization	Pore Volume (m ³)		CO ₂ Density (kg/m ³)	Esaline	Mass CO ₂ (kg)		CO ₂ (Tons)	CO ₂ (Mt)
			Sand	Silty Sand			Sand	Silty Sand		
40%	G	1	2.84E+10	1.93E+09	800	1%	3.51E+11	2.34E+10	3.75E+08	3.75E+02
						3%	1.05E+12	7.02E+10	1.12E+09	1.12E+03
						5%	1.76E+12	1.17E+11	1.87E+09	1.87E+03
		2	2.84E+10	1.93E+09	750	1%	3.30E+11	2.20E+10	3.52E+08	3.52E+02
						3%	9.90E+11	6.60E+10	1.06E+09	1.06E+03
						5%	1.65E+12	1.10E+11	1.76E+09	1.76E+03
		3	2.84E+10	1.93E+09	700	1%	3.08E+11	2.05E+10	3.29E+08	3.29E+02
						3%	9.24E+11	6.14E+10	9.86E+08	9.86E+02
						5%	1.54E+12	1.02E+11	1.64E+09	1.64E+03
		4	2.85E+10	1.93E+09	650	1%	2.86E+11	1.90E+10	3.05E+08	3.05E+02
						3%	8.58E+11	5.70E+10	9.15E+08	9.15E+02
						5%	1.43E+12	9.50E+10	1.53E+09	1.53E+03
		5	2.86E+10	1.93E+09	600	1%	2.65E+11	1.76E+10	2.83E+08	2.83E+02
						3%	7.95E+11	5.27E+10	8.48E+08	8.48E+02
						5%	1.33E+12	8.78E+10	1.41E+09	1.41E+03
	H	1	2.56E+10	2.04E+09	800	1%	3.54E+11	2.28E+10	3.77E+08	3.77E+02
						3%	1.06E+12	6.83E+10	1.13E+09	1.13E+03
						5%	1.77E+12	1.14E+11	1.88E+09	1.88E+03
		2	2.57E+10	2.04E+09	750	1%	3.32E+11	2.13E+10	3.54E+08	3.54E+02
						3%	9.96E+11	6.40E+10	1.06E+09	1.06E+03
						5%	1.66E+12	1.07E+11	1.77E+09	1.77E+03
		3	2.57E+10	2.04E+09	700	1%	3.10E+11	1.99E+10	3.30E+08	3.30E+02
						3%	9.31E+11	5.97E+10	9.91E+08	9.91E+02
						5%	1.55E+12	9.94E+10	1.65E+09	1.65E+03
		4	2.57E+10	2.03E+09	650	1%	2.89E+11	1.84E+10	3.07E+08	3.07E+02
						3%	8.67E+11	5.53E+10	9.22E+08	9.22E+02
						5%	1.44E+12	9.22E+10	1.54E+09	1.54E+03
		5	2.57E+10	2.03E+09	600	1%	2.67E+11	1.70E+10	2.84E+08	2.84E+02
						3%	8.01E+11	5.11E+10	8.52E+08	8.52E+02
						5%	1.33E+12	8.52E+10	1.42E+09	1.42E+03
	I	1	2.78E+10	2.03E+09	800	1%	2.23E+11	1.62E+10	2.39E+08	2.39E+02
						3%	6.68E+11	4.86E+10	7.16E+08	7.16E+02
						5%	1.11E+12	8.11E+10	1.19E+09	1.19E+03
		2	2.79E+10	2.03E+09	750	1%	2.09E+11	1.52E+10	2.24E+08	2.24E+02
						3%	6.27E+11	4.56E+10	6.73E+08	6.73E+02
						5%	1.04E+12	7.61E+10	1.12E+09	1.12E+03
		3	2.78E+10	2.02E+09	700	1%	1.95E+11	1.42E+10	2.09E+08	2.09E+02
						3%	5.85E+11	4.25E+10	6.27E+08	6.27E+02
						5%	9.75E+11	7.08E+10	1.05E+09	1.05E+03
		4	2.79E+10	2.02E+09	650	1%	1.82E+11	1.31E+10	1.95E+08	1.95E+02
						3%	5.45E+11	3.94E+10	5.84E+08	5.84E+02
						5%	9.08E+11	6.57E+10	9.74E+08	9.74E+02
		5	2.80E+10	2.02E+09	600	1%	1.68E+11	1.21E+10	1.80E+08	1.80E+02
						3%	5.04E+11	3.64E+10	5.40E+08	5.40E+02
						5%	8.40E+11	6.07E+10	9.00E+08	9.00E+02

Table 4.3. Static Capacity Volume using 40% sand and silty sand proportion with variations of density within the range of 600 – 800 kg/m³ and three variations of 1%, 3%, and 5% Esaline

Static Result

The result indicates a wide range of Upper Zelda's prospective CO₂ storage resources due to variation in lithofacies proportion of net thickness, effective pore volume, CO₂ density, and Esaline factor. Across all models, the estimated storage resources range from 180 Mt (colored red in Table 4.3) to 1,928 Mt CO₂ (colored blue in Table 4.2). The highest estimations of CO₂ mass are produced by models with 80% sandstone and silty-sandstone proportion (Table 4.1) with CO₂ density of 800 kg/m³ and an Esaline value of 5%. In contrast, the lowest is produced by the most pessimistic case represented by models with 40% proportion of sandstone and silty-sandstone proportion (Table 4.3) using CO₂ density of 600 kg/m³, and an Esaline value of 1%.

The tables also show a common trend that the Esaline factor strongly controls the storage estimation. For the 1% Esaline scenario, the volume capacity estimation ranges from 180 to 385 Mt CO₂, with an average of 314 Mt CO₂. Increasing Esaline to 3%, the volumes produced raise to the range between 540 and 1,157 Mt CO₂, with an average of 94 Mt CO₂ which is approximately three times from 1% value of Esaline. The highest Esaline value assigned, 5% Esaline, produces the largest estimates as expected, ranging from 900 to 1,928 Mt CO₂, with an average of 1,572 Mt CO₂, around 1.5 times bigger than 3% and five times bigger than 1%.

The ascending values scale linearly with Esaline, meaning that Esaline is very influential on mass estimation. The resulting masses and the trend with Esaline provided by static methodology demonstrate that the Upper Zelda interval can provide significant storage potential even under the most pessimistic assumptions.

Dynamic Methodology (EASiTool)

Enhanced Analytical Simulation Tool (EASiTool) is a web-based platform for generating CO₂ storage resources estimates and support early-stage evaluations for CCS projects. It is a dynamic analytical software developed by the Gulf Coast Carbon Center (GCCC) at the Bureau of Economic Geology (BEG), non-commercial and publicly available. EASiTool was utilized to model the pressure buildup associated with CO₂ injection (Ganjdanesh and Hosseini, 2017, 2018). EASiTool allows for rapid site screening, assists in site selection, and provides a preliminary dynamic capacity estimate incorporating pressure buildup, Area of Review (AoR), and potential plume extent considering multiple injection scenarios. These calculations allow the plume lateral distribution and pressure effects during CO₂ injection, which is critical for regulatory compliance and long-term storage security. The latest EASiTool 5.1 version contains significant web enhancements and new functionality that has been created to meet the CCS regulatory and project-evaluation needs. The key updates in this study are primarily technical and regulatory screening such as pressure buildup, Area of Review (AoR), plume extent, injectivity, pressure limits and well-configuration evaluation.

The conceptual model of EASiTool is a simplified analytical reservoir representation, as opposed to the static geocellular model. EASiTool does not directly simulate the facies and porosity distribution of the 3D geocellular model, which is heterogeneous. Rather, the storage interval is modeled as a homogeneous, isotropic, isothermal, horizontal reservoir with constant thickness, with average reservoir properties for the modeled interval, unlike to the static volumetric where lithofacies and effective porosity were calculated cell to cell variable in the grid. Both methods are, however, applied to the same Upper Zelda storage interval, and have similar reservoir-scale inputs such as thickness, porosity, storage area, and CO₂ density. For this reason, the static model

accounts for geological heterogeneity in the estimation of pore-volume, while EASiTool offers a simplified pressure-limited dynamic comparison to estimate injectivity, AoR, plume behavior, and pressure response.

In order to properly utilize EASiTool, several static and dynamic inputs are needed, namely depth, pressure, thickness, porosity, permeability, salinity, etc. to evaluate plume migration and pressure evolution around AoR. The dynamic capacity calculation was performed to make a pressure-limited comparison with the static volumetric estimate. This comparison was performed to determine which static ESaline scenario is most similar to the EASiTool result for storage resources. The static calculation was adjusted to make the comparison meaningful, using reservoir parameters that are similar to the EASiTool input, such as the same general storage interval, reservoir area, porosity basis, CO₂ density, and sandstone and silty-sandstone percentage. Although both approaches are not the same conceptually (explained later), the comparison is focused on the closest static equivalent to the dynamic result.

Reservoir Properties

a. Initial Reservoir Pressure (Hydrostatic Pressure)

Initial formation fluid pressure is calculated using a hydrostatic gradient. Well B has a well pressure data in the well report file and the gradient of the data was used as the Pressure Gradient (Figure 4.2). The available pressure data in the well report exhibits scatter and do not establish a very reliable pressure-depth trend due to quality limitations and measurement uncertainty. However, a lower end pressure gradient of 10.67 MPa/km was chosen based on extrapolating the deeper well data in Well B to shallow intervals of the TAF.

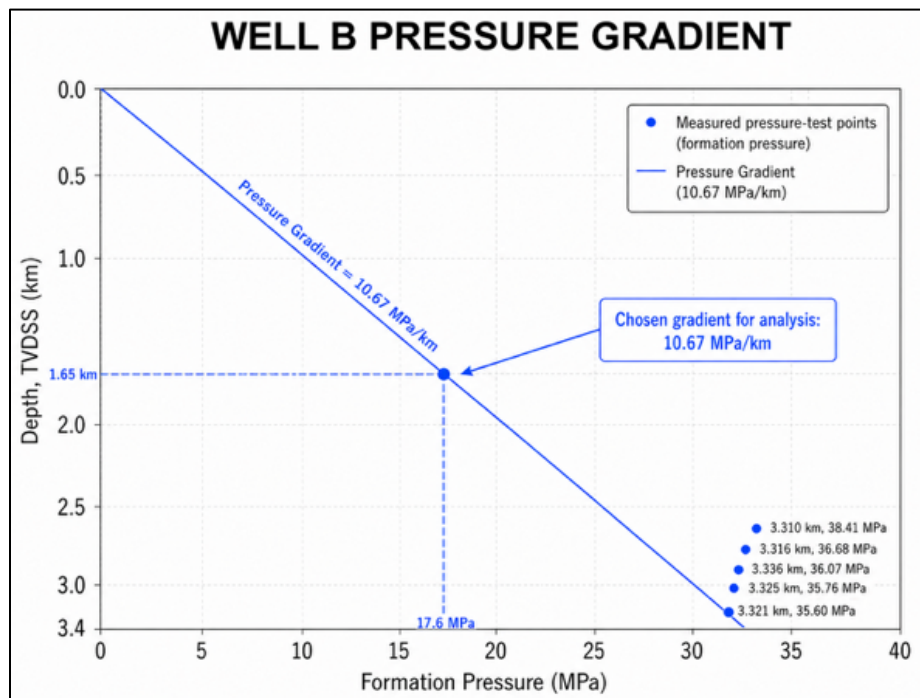


Figure 4.2. Pressure Gradient from Well B. The depth of the TAF is shown to be 1.65 km, and the resulting gradient extrapolated from the deeper data suggest a value of 10.67 MPa/km.

The gradient was chosen as the smallest possible gradient based on the data because it will be the safest option to inject CO₂ underground, considering that the Sunda Strait Area is tectonically active. Using the gradient above, the initial pressure is computed as:

$$P_h = P_g \times h \quad (6)$$

Where:

P_h = Pressure in a certain depth (MPa)

P_g = Pressure Gradient (MPa/km)

h = Depth (km)

These pressures represent hydrostatic conditions of the TAF in the area prior to significant CO₂ injection. With the reservoir depth of 1.65 km and the gradient of 10.67 MPa/km, the Initial Pressure value used in EASiTool was 17.6 MPa.

b. Initial Reservoir Temperature

No well temperature data are available from the well reports across the area. Therefore the average storage reservoir interval needs to be estimated. The initial temperature was estimated using a geothermal gradient of 16°C/km. The value was based on the study in the Sunda Strait Area by Soenandar (1997), suggesting that the geothermal gradient in the area is between 12 – 20°C/km since the Plio-Pleistocene. Thus, in this study, a value of 16°C/km was used as a mid-point approximation of the range of published values for the region. The formula to determine initial storage reservoir temperature is:

$$T_h = 25^{\circ}C + (T_g \times h) \quad (7)$$

Where:

T_h = Temperature in a certain depth ($^{\circ}C$)

T_g = Temperature Gradient ($^{\circ}C/km$)

h = Depth (km)

Given an assumed surface temperature is $25^{\circ}C$, the EASiTool input for temperature was $51.4^{\circ}C$ at the midpoint depth of the storage reservoir interval which is 1.65 km.

c. Thickness

The maximum thickness input allowed in EASiTool is 500 m. Therefore, dynamic calculations were performed to be compared to the models having thickness less than 500 m. Since the Zelda Member has an approximate total thickness of 1,000 m regionally, the conservative case of 40% proportion of sandstone and silty-sandstone model corresponds to approximately 400 m, while the others two proportions have more than 500 m thickness and could not be directly calculated using EASiTool. Therefore, EASiTool was used to calculate the dynamic storage resources using a 400 m interval, representing the model with 40% proportion of sandstone and silty-sandstone. The only eligible models are Model G, H, and I (Table 4.3). This is the most direct way to compare the EASiTool result with the static resource estimate calculated previously, since all the static realizations and calculated masses cannot be evaluated in EASiTool.

However, EASiTool only represents the reservoir as a homogeneous interval and uses a single porosity input. The thickness of the sand and silty-sand was not directly assigned as the thickness of the EASiTool in this study because the porosity value used in EASiTool is for sandstone. The static geocellular result indicates that sandstone accounts

for about 93.16% of the total pore volume of sandstone and silty-sandstone (Table 4.1, 4.2., and 4.3). The 400 m combined reservoir thickness was thus multiplied by 0.9316 to get a sandstone-equivalent thickness of 372 m for the EASiTool model. This is not a new measured thickness, but an adjusted thickness to make the simplified EASiTool model more similar to the static geocellular calculation.

d. Salinity

Since there are no direct measurements of the salinity of the brines in the study wells, the value of 0.18 mol/kg was assumed in the EASiTool model. The input was assumed to be NaCl-equivalent molality because EASiTool requires formation-brine salinity to be input as molality. The value of 0.18 mol/kg NaCl corresponds to about 10,500 ppm NaCl-equivalent salinity, similar to the salinity of formation water reported from the TAF where the salinity of the formation water ranges from about 10,000 ppm to 35,000 ppm in low-resistivity Talang Akar reservoirs (Zaemi et al., 2022).

e. Porosity

EASiTool only expects homogenous reservoir properties with a single porosity. On the other hands, the static model used EPHI models which assigned different values of porosity each cell based on the trends. In order to compare static and dynamic, the porosity value utilized for EASiTool input had to be as comparable as possible. The mean value of effective porosity of the sandstone facies applied to the geocellular modelling, derived from the petrophysical analysis in “Chapter 3” (Table 3.3), was assigned as the most representative value for EASiTool, which was 25.6% or 0.256.

f. Permeability

The EASiTool model was used with a permeability value of 200 mD as a conservative value representing a moderate-permeability sandstone. This is a reasonable value within the range of moderate permeability (1 mD to 1 Darcy) for CO₂ storage reservoirs as defined by the USGS, and also within the range of medium permeability (50–500 mD) for sandstones as defined by the industry (USGS, 2013; et al., 2025).

There is also a more technical approach to determine the value of permeability. One of the methods uses the Kozeny–Carman equation that relates the intrinsic permeability to the effective porosity and specific surface area of a porous medium (Kozeny, 1927; Carman, 1937, 1956). In this study, an average effective porosity of 0.256 was used to represent the sandstone facies. The Kozeny–Carman equation can be written as:

$$k = \frac{\phi^3}{c S_v^2 (1 - \phi)^2} \times \frac{1}{mD} \quad (8)$$

Where:

k = intrinsic permeability (mD)

ϕ = effective porosity (fraction)

c = Kozeny constant (0.55)

S_v = specific surface area per unit solid volume (m⁻¹)

mD = Permeability constant (9.869233×10^{-16} m²)

Specific surface area (S_v) is the surface area of the grain divided by the volume of the solid rock. Since the specific surface area could not be measured directly, the value of S_v was estimated from a representative grain size, using the formula of six divided by the grain size. If it is assumed that the grains are approximately spherical, a very fine sandstone grain diameter of 0.063 mm (6.3×10^{-5} m) was used based on the lower limit of the very

fine sand (0.0625–0.125 mm) grain-size class of Wentworth (1992) grain-size classification. The use of a very fine sand grain size is deemed appropriate for the TAF in the Sunda Strait Area, based on the core descriptions indicating the presence of fine- to very fine-grained sandstones (Saputra et al., 2024). After that the value of S_v was about 95,238 m⁻¹. With the value of ϕ is 0.256 and the constate of c is 5.55, the Kozeny–Carman equation estimates the permeability to be approximately 610 mD.

This value is a theoretical estimate of permeability based on reservoir porosity and idealized grain geometry and not a laboratory measurement. Given there are two values of permeability (200 mD and 610 mD), both numbers were used as EASiTool parameters as conservative and optimistic scenario, respectively.

g. Reservoir Area

The storage reservoir area value in EASiTool was based on the local reservoir area (Figure 4.1.a) developed for this project located in the northeast area of the Sunda Strait Area. It is honoring specific boundaries of the leasing area of Pertamina OSES, suggesting that the extend of the TAF reservoir could extend up to 2500 km².

Maximum Storage resources

This category controls the maximum storage and pressure limits within the project area. There are several inputs in this category affecting the Maximum Storage resources, including:

a. Project Area

The Project Area in EASiTool is set to the appointed area of interest inside the research area discussed previously with the dimension of 17.7 x 18.9 km (Fig. 4.1.b), which is 334.53 km². Project area is different from the reservoir area as reservoir area represents the broader connected storage reservoir extent in the area while the project area is only in a local operational scoop.

b. Maximum Allowable Pressure

Maximum allowable pressure defines the biggest allowed pressure possibly applied to CO₂ injection. In EASiTool, this is very important to calculate the allowable injection rate so that pressure buildup surrounding the injection wells will not exceed the geomechanical limit. Additionally, this input will prevent the excessive pressure buildup that may increase the risk such as existing faults.

Sunda Strait Area is highly faulted, suggesting pressure buildup may influence dynamic injection. The maximum allowable pressure was determined as 20.2 MPa according to the geomechanical assessment made by Ridhandi et al. (2025). Pore pressure, fracture pressure, seal integrity, and fault stability of the Talang Akar Formation were assessed for geological storage of CO₂ to prevent fault instability, fault reactivation and leakage during CO₂ injection. Mohr-Coulomb determined that the range of permissible injection pressure in the area is 12.9–20.2 MPa in order to maintain the fracture and fault

stability. Thus, 20.2 MPa was chosen as the maximum pressure limit for the EASiTool screening model in this study based on the literature.

c. Number of Injection Wells

The minimum and maximum numbers of wells considered in the EASiTool simulations are 1 and eighty-one, respectively. These are default settings. The range of 1-81 were chosen to explore the minimum and maximum values possible using EASiTool. To compare the result to the static volumetric result, the highest possible volume from the simulation was chosen as the theoretical volume of injected CO₂, represented by the most upper estimation of dynamic capacity which is possessed by 81 wells.

d. Minimum Extraction Pressure

Since there are no extraction wells, this parameter was not considered to be included into the simulation.

e. Injection Duration

The EASiTool model was run for an injection period of twenty years, as this is a reasonable screening level period for assessing CO₂ storage resources and injectivity without assuming an overly long commercial operation period. A period of twenty years is a defensible operational assumption for preliminary dynamic capacity evaluation, consistent with the EASiTool final report, which applies a 20-year simulation time in its model validation example (Hosseini et al., 2018).

f. Boundary Conditions

In EASiTool simulation, there are two boundary-condition scenarios were taken into account: closed boundary and open boundary. A closed boundary assumes that the pressure response from CO₂ injection is confined to the basin area modeled and that the pressure does not escape beyond the modeled boundary, typically resulting in a more conservative storage estimate, as the greater pressure rise is bigger, but more representative case for comparison with the static geocellular model as the modeled reservoir area is a local storage fairway and not the entire regional basin.

An open boundary, on the other hand, estimates that the response to the pressure can extend beyond the area of the reservoir into the surrounding basin. This will allow the pressure to dissipate freely and thus leading to an overestimate of the storage. An open-boundary case was also analyzed as a sensitivity case to gain insight into the impact into the surrounding basin on the EASiTool storage estimate.

Project Settings			Project Settings		
Project Name	Sunda Strait Area		Project Name	Sunda Strait Area	
Select a simulation module	Maximum Storage Capacity		Select a simulation module	Maximum Storage Capacity	
Select a unit system	SI Units		Select a unit system	SI Units	
Reservoir Properties			Reservoir Properties		
	SI Value	SI/Field Unit		SI Value	SI/Field Unit
Initial Pressure	17.59	MPa	Initial Pressure	17.59	MPa
Initial Temperature	51.40	°C	Initial Temperature	51.40	°C
Thickness	372.00	m	Thickness	372.00	m
Salinity	0.18	mol/kg	Salinity	0.18	mol/kg
Porosity	0.26	-	Porosity	0.26	-
Permeability	200.00	mD	Permeability	200.00	mD
Rock Compressibility	5.00E-10	1/Pa	Rock Compressibility	5.00E-10	1/Pa
Reservoir Area	2500.00	km ²	Reservoir Area	2500.00	km ²
For Maximum Storage Capacity Module Only			For Maximum Storage Capacity Module Only		
	SI Value	SI/Field Unit		SI Value	SI/Field Unit
Project Area	334.53	km ²	Project Area	334.53	km ²
Max Allowable Injection Pressure	20.20	MPa	Max Allowable Injection Pressure	20.20	MPa
Number of Injection wells (min)	1	-	Number of Injection wells (min)	1	-
Number of Injection wells (max)	81	-	Number of Injection wells (max)	81	-
Number of Extraction wells	0	-	Number of Extraction wells	0	-
Min Extraction Pressure	18.00	MPa	Min Extraction Pressure	18.00	MPa
Injection Duration	20.00	year	Injection Duration	20.00	year

Table 4.4. Full EASiTool inputs for the two EASiTool simulations, with permeability of 200 mD (left) and 610 mD (right)

Dynamic Storage Resource Result

Figure 4.3. shows EASiTool results for closed and open boundaries with both 200 mD and 610 mD for scenarios with 1 to 81 wells injecting for 20 years. The most optimistic estimate considers eighty-one wells and indicates the theoretical maximum volume CO₂ injected possible using an EASiTool method (336 for 200 mD and 391 Mt for 610 mD; Table 4.5). Less than 20 wells result in significant decreases.

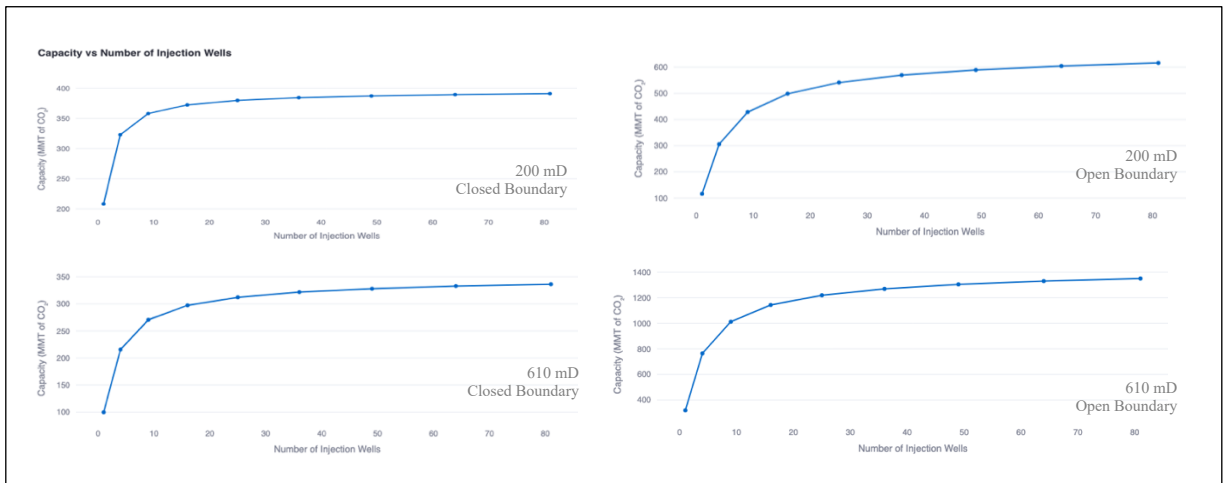


Figure 4.3. Storage resources under different numbers of wells

Table 4.5. summarizes all the values from EASiTool simulation. For 200 mD, closed boundary resulted in 336 Mt and open boundary went up to 616 Mt, while 610 mD produced 391 Mt in closed boundary and a high number of 1,433 Mt in open boundary.

Permeability (mD)	Porosity	CO ₂ Volume in Closed Boundary (Mt)	CO ₂ Volume in Open Boundary (Mt)
200	0.256	336	616
610	0.256	391	1,433

Table 4.5. EASiTool Results of conservative (200 mD) and optimistic (610 mD)

Figure 4.4 shows the 2D map of the pressure distribution and plume extension of the case with 200 mD and 9 injection wells. In the closed-boundary case, the pressure is localized around the injector pattern and is relatively localized within the project area with plume radii around 0.4–0.5 km, which does not reach the reservoir boundary. In an open-boundary case, the pressure contour still indicates the highest pressure around the injector pattern, but the open-boundary condition allows the pressure to spread out beyond the local project area. The CO₂ plume radii slightly expand to about 0.5–0.6 km, but still well contained within the project area.

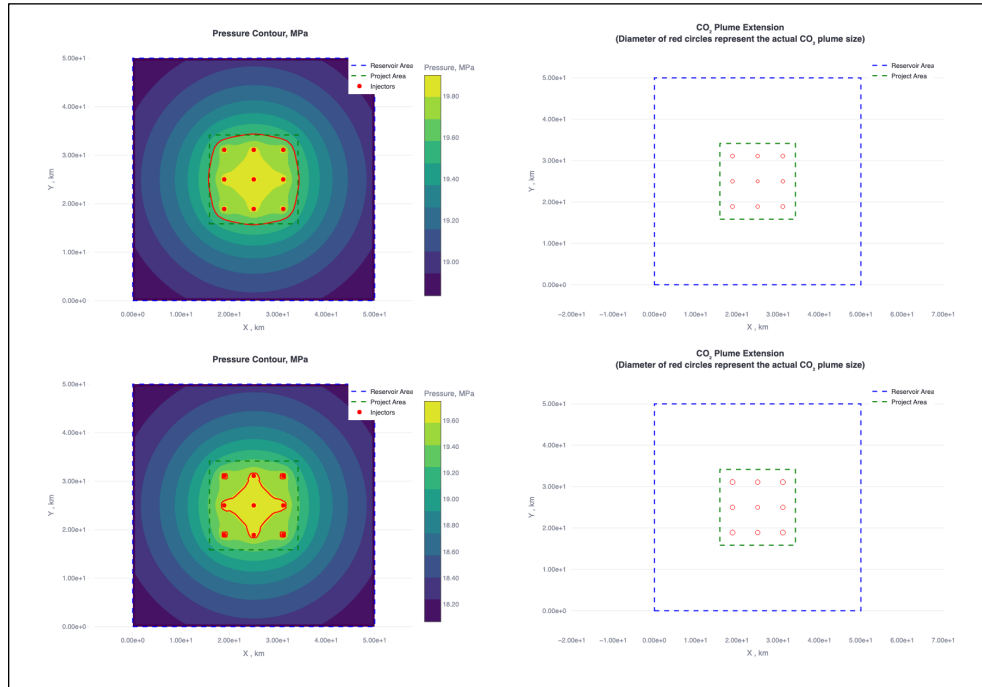


Figure 4.4. Pressure contour and plume extension under 200 mD permeability (Upper: Closed boundary. Lower: Open Boundary)

Figure 4.5 presented results of the pressure and plume extent using permeability of 610 mD. The higher permeability results in better injectivity and more uniform pressure distribution around the injectors than the 200 mD closed-boundary case. The plume is still contained within the reservoir area, indicating that the dynamic capacity is still more pressure buildup than lateral plume migration. In the open boundary case, much more CO₂ can be injected as the permeability is high and the pressure dissipation is open boundary. The plume radius is larger in the other scenarios, about 1.1–1.3 km around each injector, but it is still within the project area and does not reach the reservoir edge. This case is the best possible scenario for dynamic storage since both the injectivity and the pressure dissipation are good.

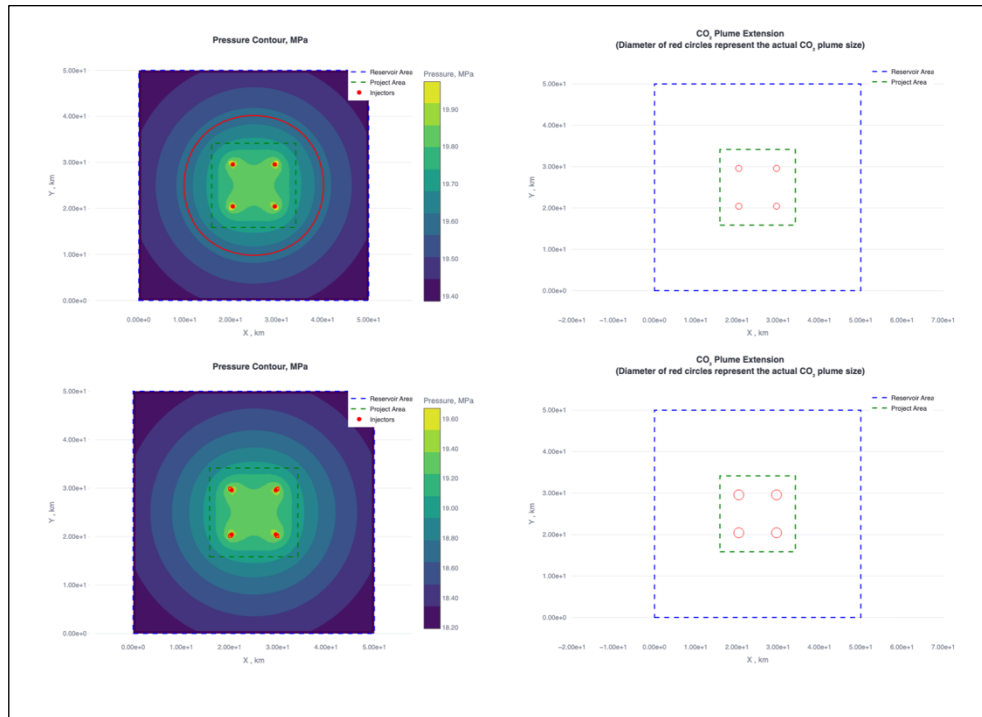


Figure 4.5. Pressure contour and plume extension under 610 mD permeability (Upper: Closed boundary. Lower: Open Boundary)

Based on the results above, plume extension is similar for both closed and open-boundary cases, indicating that the plume extent is large enough to fit the selected project area for both boundary conditions. This is reasonable because the project area is about 334.53 km² while the modeled plume radius is less than 1 km around each injector. The large project area selected does not allow the plume to approach the project boundary in either the closed or open boundary cases, although boundary conditions often have a large impact on storage mass, pressure distribution, and AoR.

Different permeability values might result different suggestion well numbers. The 200 mD case can accommodate 9 injection wells due to limited pressure communication between wells, while the 610 mD case can only accommodate 4 wells, as each injector has a larger AoR. The number of injectors varies among the permeability scenarios due to the fact that the higher the permeability, the more pressure can be distributed throughout the reservoir. If more wells are added to the 610 mD case, the pressure interference will increase and the model may reach the maximum allowable pressure sooner. This suggests that pressure interference in a multi-well system does not allow the total injectivity to be increased linearly with the number of injectors (Hosseini et al., 2018).

From the result above, the closed-boundary case is the more conservative and representative case for comparison with the static geocellular model. The open-boundary case was analyzed only as a sensitivity case to gain insight into the impact into the surrounding basin on the EASiTool storage estimation because open-boundary condition decreases the pressure build-up by dissipating the pressure beyond the local reservoir area. This interpretation is in line with the EASiTool final report by Hosseini et al. (2018) which states that the boundary condition influences the way injected CO₂ is accommodated in the reservoir: in closed-boundary formations, injected CO₂ is stored mainly by compressing the formation fluid and rock, while in open-boundary formations, more CO₂ can be stored

by displacing native brine from the host formation. In this study, however, the influence of boundary condition on plume extent is not as significant as it might be in other situations, since the project area is sufficiently large to accommodate the plume modeled in both the closed- and open-boundary scenarios. Thus, the boundary condition has a primary influence on the estimated dynamic storage mass, particularly for the higher permeability scenario, but not on the plume containment.

Static and Dynamic Method Comparison

Two different estimates of storage resource have been calculated: static volumetric and dynamic analytical. It is interesting to compare these results for similar storage formation characteristics, but different methodology. Similarity would suggest additional confidence in the estimates, while large difference would suggest the storage resource depends on the method applied, which is problematic as it may introduce confusion for understanding the storage prospect performance. Prior to comparing the static geocellular result with the EASiTool result, the static capacity inputs were adjusted to make the inputs comparable. That is, for reasonable comparison, the two methods need to consider similar reservoir dimensions and properties.

As discussed above, conservative 40% sand and silty-sand scenarios (Models G, H, and I) were chosen because they are consistent with the adjusted EASiTool input thickness used, as discussed above. The pore volume of only sandstone was calculated for each static model by averaging the pore-volume value from five different realizations. All three models were then given a CO₂ density of 733 kg/m³ calculated based on the initial reservoir pressure of 17.6 MPa and initial reservoir temperature of 51.4°C to better match the pressure and temperature condition used in the EASiTool model. The Esaline values of 1%, 3%, and 5% were used for consistency with literature values.

Table 4.5 shows the variation of static storage inputs across the area of interest to be comparable with the EASiTool results below. The overall range of the adjusted and recalculated static capacity for the 40% reservoir scenario is 188 to 1,044 Mt CO₂, with the variation primarily due to the sandstone pore volume and the Esaline value used. The CO₂ storage estimates for each of the three Esaline scenarios were averaged across Models G, H, and I, since each model used the same Esaline values (1%, 3%, and 5%). The averaged static capacities are 201 Mt CO₂ (1% Esaline), 602 Mt CO₂ (3% Esaline), and 1,003 Mt CO₂ (5% Esaline).

Model	Pore Volume of Sand (m ³)	CO ₂ Density (kg/m ³)	Esaline	Mass CO ₂ (kg)	CO ₂ (Mt)
G	2.85E+10	733	1%	2.09E+11	209
			3%	6.26E+11	626
			5%	1.04E+12	1044
H	2.57E+10	733	1%	1.88E+11	188
			3%	5.65E+11	565
			5%	9.42E+11	942
I	2.79E+10	733	1%	2.04E+11	204
			3%	6.13E+11	613
			5%	1.02E+12	1022

Table 4.6. Adjusted result of static capacity volume

These average values were then taken as the primary static-capacity reference values for comparison with the EASiTool result. Figure 4.6 shows the relationship between the applied ESaline value and the static CO₂ storage resources for the 40% sand and silty-sand scenario. With the graphs presented above, EASiTool result's numbers will be overlayed to understand the comparison more.

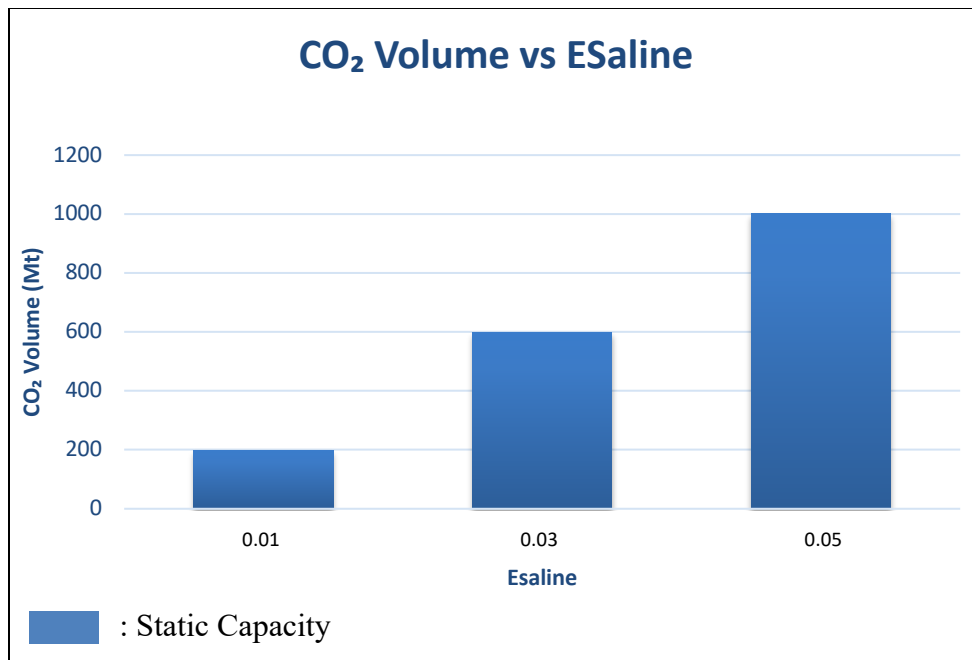


Figure 4.6. Static Capacity plot of CO₂ volume under 1%, 3%, and 5% ESaline

Figure 4.7. shows the relation between EASiTool's 200 mD permeability case and adjusted static capacity. The closed-boundary condition gives a CO₂ storage volume of 336 Mt, which is far higher than the result of 1% but still below the 3%. Under the open-boundary condition, the estimated storage volume goes up to 616 Mt and very close to the 3% static value. This showcases that with 200 mD permeability, the closed-boundary and open-boundary case behaves similarly to the 3% ESaline in static calculation.

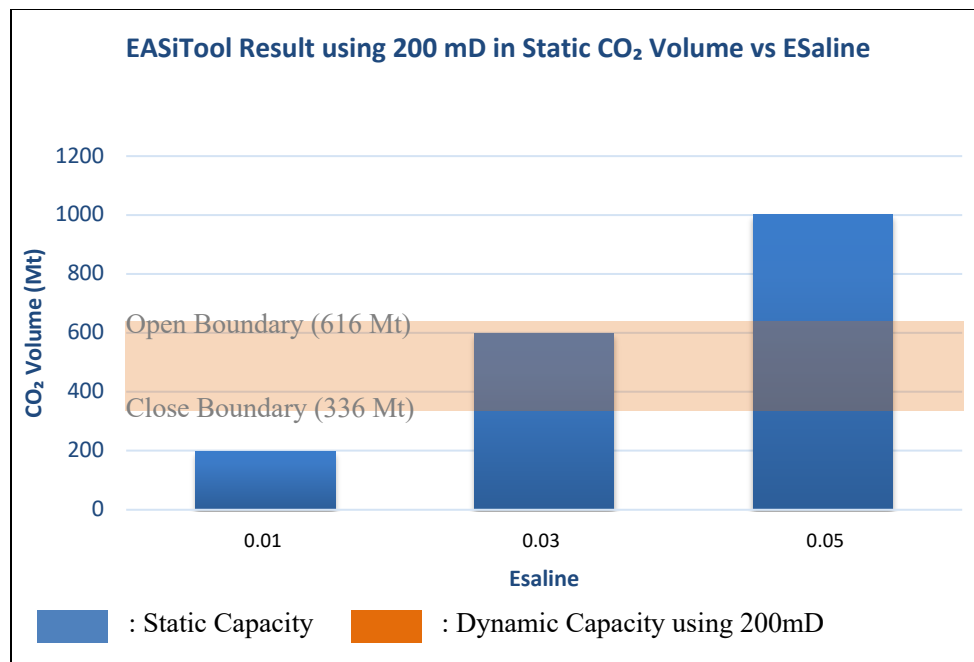


Figure 4.7. Static Capacity plot of CO₂ volume compared to EASiTool CO₂ volume result for 81 wells over 20 years with permeability of 200 mD under close and open boundary

Figure 4.8 presents the closed-boundary result of 391 Mt for the 610 mD permeability case, still within the range of the 3% Esaline static estimates but higher than the 200 mD closed-boundary case. In contrast, the open-boundary result increases significantly to 1,433 Mt, exceeding the 5% static estimate of 1,003 Mt and mathematically close to reaching 7%. It is obvious that higher permeability results in higher volume estimation. The result indicates that the closed-boundary assumption still underestimates dynamic capacity even with higher permeability. This large increase shows that the permeability and the boundary condition have a strong interaction on the dynamic storage estimate.

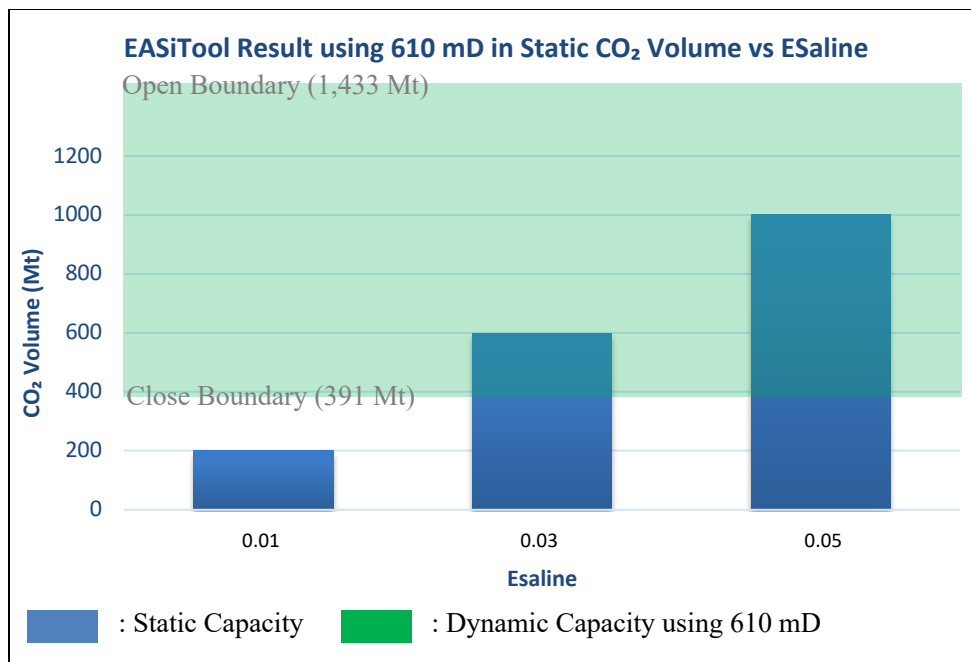


Figure 4.8. Static Capacity plot of CO₂ volume compared to EASiTool CO₂ volume result for 81 wells over 20 years with permeability of 610 mD under closed and open boundary

4.3. SUMMARY

In summary, this chapter evaluates the CO₂ storage resources of the Talang Akar Formation, especially the Upper Zelda interval, using both static geocellular volumetric calculation and dynamic EASiTool simulation. The static method honored the pore volumes (obtained from EPHI models) with CO₂ density and ESaline. The dynamic method was based on pressure-limited storage behavior, which includes pressure buildup, boundary condition, permeability, and injection duration. Comparison of those two different approaches indicated that for the same reservoir conceptualizations, the dynamic results are equivalent to the static calculations using 3% to 5% storage efficiency factors.

The estimated storage resources for the entire static models were between 180 and 1,928 Mt CO₂, depending on the sand and silty sand proportion, density, and ESaline values. The static model was then adjusted using the conservative 40% sands and silty sands scenario to be more comparable to dynamic simulation, yielding average capacities of 201, 602 and 1,003 Mt CO₂ for 1%, 3% and 5% ESaline, respectively. The EASiTool results indicate that dynamic capacity is higher with higher permeability and open-boundary conditions, from 336 to 616 Mt CO₂ for the 200 mD case and from 391 to 1,433 Mt CO₂ for the 610 mD case.

CHAPTER 5: DISCUSSION

5.1. RESULT DISCUSSION

The goal of this research is to estimate storage resources using two different approaches: Static (Volumetric) and Dynamic (EASiTool) with an ultimate result of direct comparison between those two different methods. The comparison of the static capacity using the static volumetric method with the EASiTool dynamic method shows that the most representative ESaline range for this study is around 3-5%. The most reasonable central ESaline value is 3%, while the 5% is a higher but still plausible case for the Upper Zelda reservoir. This interpretation is generally in line with the internal static–dynamic comparison research from Gulf Coast Carbon Center from the Bureau of Economic Geology. GCCC’s internal research showed that the EASiTool dynamic capacity was generally between the static 1% and 3% efficiency estimates, suggesting that 1–3% is a common or typical range for their controlled cases.

The results of this study are slightly higher, however, especially under open-boundary conditions because Upper Zelda interval of the TAF was represented by a very thick and high-quality sandstone reservoir with relatively good porosity and permeability. The only case that comes close to ESaline of ~7% is the 610 mD open-boundary case with a production of 1,433 Mt CO₂. It is an optimistic dynamic scenario resulting from the combination of increased permeability and an open-boundary assumption. From this comparison, 3% is considered the most representative central ESaline value for this research, 5% is a reasonable higher value, and approximately 7% is an optimistic value that is physically plausible under high permeability open boundary conditions.

5.2. ADDITIONAL CONSIDERATIONS

Static and dynamic capacity calculations may be comparable, and this research indicates that both approaches suggest that 3% Esaline would be representable for static capacity and be consistent with the dynamic capacity result. However, those two different approaches work differently in terms of conceptualization of the CO₂ saturation and distribution. The static volumetric method assumes that CO₂ occupies 3% of the pore volume in all eligible sandstone and silty-sandstone cells, with an ESaline value of 3%. Thus, the CO₂ is modeled to be spread to the whole reservoir interval with each cube occupied by CO₂ as much as 3% of its pore volume (Figure 5.1).

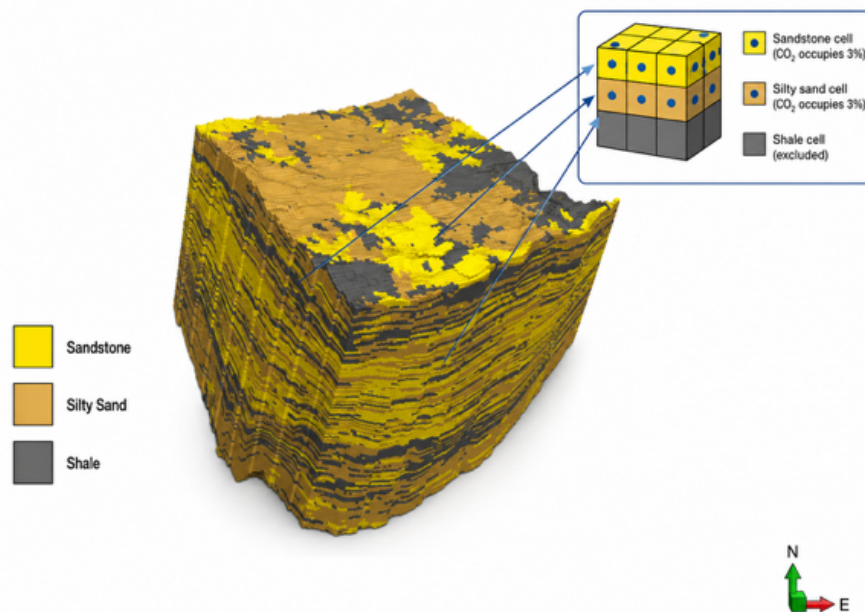


Figure 5.1. Static capacity conceptualization

The dynamic EASiTool result, on the other hand, is a plume-based and pressure-limited CO₂ injection process. In this case, the CO₂ can locally fill the full available pore space in the plume area, but the plume only occupies a small portion of the total reservoir

volume. So, if the dynamic result is similar to the 3% static ESaline result, this does not imply that CO₂ is filling exactly 3% of pore space throughout the entire volume. Rather, it is the total volume of CO₂ injected that is about 3% of the total pore volume in the static model, but the filled area is within the CO₂ plume area (Figure 5.2).

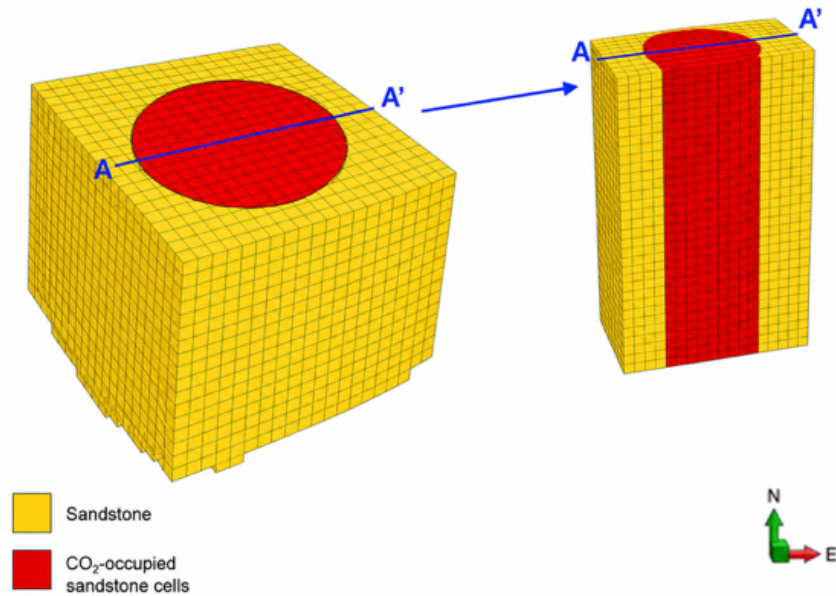


Figure 5.2. Dynamic capacity conceptualization

This would take a lot more time and effort to simulate correctly and was beyond the scope of this research. However, future work could perform this simulation to compare to the static and dynamic assessments presented in this study.

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1. CONCLUSION

Carbon Capture and Storage (CCS) is an important technology for the reduction of industrial CO₂ emissions by capturing the CO₂, transporting it, and permanently storing it in the subsurface, where the characterization of the subsurface is a key element in the identification of suitable reservoirs and seals. This study is set in the context of the ongoing CCS development in Indonesia and is limited to the Sunda Strait Area, an extensional half-graben offshore basin formed during Eocene–Oligocene rifting. The sandstone rich Talang Akar Formation (TAF), particularly the Upper – Middle Zelda Member, is recognized as the primary saline-aquifer storage target within its stratigraphy, and the overlying marine shale of the Gumai Formation is the regional seal. The TAF is known to be thick and has good reservoir potential from previous petroleum exploration and geological studies, especially in the depocenter of the basin. This research seeks to define the stratigraphic framework, interpret seismic horizons and faults, define potential storage areas and finally estimate the CO₂ storage resources. The objectives are met using approximately 1,050 line-km of 2D seismic, approximately 600 km² of 3D seismic, and well-log data from six wells, all of which are used in conjunction with well correlation, seismic interpretation, structural characterization, 3D geocellular modeling, and storage resources assessment.

The geologic interpretation was conducted within the northeastern Sunda Strait Area with well-log and seismic data were the main input. There are several formations in the Sunda Strait Area: The Gumai Formation at around 1200-1250 m is interpreted to be a thick, laterally continuous regional seal, and the Upper–Middle Zelda Member of the TAF at ~1500-2600 m is the principal storage interval, comprising a succession of heterogeneous sandstones and shales with an overall thickness of ~1000 m. Seismic

interpretation confirms that the study area is controlled by an extensional half-graben system dominated by a major normal fault to the east and several secondary faults that could be a potential compartmentalization. The TAF is structurally deepening toward the depocenter and structural complexity. In addition, RMS seismic-attribute, normalized to a 0–1 scale, also suggest higher amplitude and more sand prone intervals within the central depocenter, which makes this area the most promising for further reservoir modeling and CO₂ storage evaluation.

A 3D geocellular model of the interpreted subsurface was built to estimate the geological heterogeneity and to define the geologic volume for static storage-capacity calculations. The approximately 1,900 km² model was built in Petrel based on the seismic surfaces and fault framework from Chapter 2. Horizontal cell resolution in the model is 200 x 200 m and the vertical extent covers the major storage interval of the Upper Zelda. Within six wells in the area, available petrophysical logs were used to calculate effective porosity (EPHI) and upscale into the grid, and Gamma Ray logs were normalized to a 0–1 scale and classified as sand, silty sand and shale with cutoffs of 0.3 for sandstone and 0.6 for shale. Nine lithofacies realizations were created using Sequential Indicator Simulation (SIS) with facies-specific variograms and an RMS-derived lateral trend for three different sand and silty sand proportions, 40%, 60%, and 80%, resulting in Model A through I. The effective porosity was then filled in using Gaussian Random Function (GRF) simulation, with RMS amplitude the horizontal trend and core porosity the vertical trend. Five EPHI realizations were created for each facies model for a total of 45 combined geological realizations to map geological uncertainties.

After generating all realizations of EPHI models, the Upper Zelda interval of the Talang Akar Formation was assessed CO₂ storage resources, using both static geocellular volumetric calculations and dynamic simulations on EASiTool. The goal was to compare

both different approaches. The static capacity assessment was performed using all the EPHI models assigned with different CO₂ densities of 600–800 kg/m³, and ESaline values of 1%, 3%, and 5% to account for geological and storage-efficiency uncertainty. The estimated capacity varies from about 180 to 1,928 Mt CO₂ across the entire set of static models. The results showed that lithofacies proportion, pore volume, CO₂ density, and especially ESaline have a significant impact on the static volumetric estimate.

The conservative 40% of sand and silty sand scenario (Model G, H, and I) was the only comparable models with less than 500 m sandstone thickness due to thickness constraint of EASiTool that requires less than 500 m. The models were adjusted as sandstone with porosity of 0.256 as the mean porosity used in the static method and a CO₂ density of 733 kg/m³. The results compared to EASiTool at 1%, 3%, and 5% ESaline static values, which yield average capacities of 201, 602, and 1,003 Mt CO₂, respectively. The dynamic assessment yielded permeability values of 200 mD and 610 mD, with both open and closed boundary. The capacities were 336 (closed) and 616 (open) Mt CO₂ for the 200 mD cases and 391 (closed) and 1,433 (open) Mt CO₂ for the 610 mD cases. The modeled CO₂ plumes are still contained within the project area, but higher permeability leads to better injectivity and an open boundary allows for more pressure dissipation and significantly increases dynamic storage resources.

A comparison of the two approaches suggests that an Esaline range of 3–5% is the most representative for the Upper Zelda reservoir, with 3% being the most reasonable central value and 5% being a plausible higher case. Only the most optimistic combination of high permeability and an open-boundary condition allow for an efficiency of near 7%.

6.2. FUTURE WORKS

The static model already accounts for reservoir heterogeneity in this study by using different facies and porosity realizations, and EASiTool offers a simplified pressure-limited dynamic estimate. But these two ideas are still considered separately. Future work should combine the static geocellular model with a complete dynamic flow simulation. There is a reservoir simulation that would combine those different concepts, it is called full physics reservoir simulation.

The difference between the reservoir conceptualizations for the dynamic and full physics conceptualizations are the heterogeneity, where EASiTool perceives all the reservoir body has the same porosity and permeability. Full physics includes the facies and porosity value differences in the simulation. The primary differences between the conceptualization of the storage reservoir in the static, dynamic, and full-physical methods is presented in Table 6.1 below.

Method	Similarity	Difference
<u>Static volumetric method</u>	Comparing the potential CO ₂ storage resources of the same storage interval, using the same general reservoir properties and framework to compare the conceptualization of the available pore volume to inject CO ₂ .	Representing CO ₂ as a fraction of the reservoir in the modelled sandstone and silty-sandstone cells, accounting for facies and porosity variation but not for pressure or plume movement. The efficiency percentage suggesting the percentage of all cells' pore volume cross the model.
<u>Dynamic analytical method with EASiTool</u>		Simplified homogeneous reservoir with a single porosity and permeability value, representing CO ₂ as a plume-based, pressure-limited injection process with pressure buildup, AoR, plume extent, boundary condition and well configuration, but not cell-by-cell heterogeneity.
<u>Full-physics dynamic simulation</u>		Simulating CO ₂ flow directly in the heterogeneous 3D model, where facies, porosity, permeability and connectivity influence the migration of the plume and the pressure buildup.

Table 6.1. Comparison of static, dynamic, and full-physics reservoir conceptualizations

This more-sophisticated approach would simulate CO₂ flow directly in the heterogeneous geocellular model, in which the sandstone, silty sandstone and shale facies are explicitly represented with different physical properties (Figure 6.1). This would provide more constraints on the storage resources assessment as the simulation would not only consider the pressure build-up and plume migration, but also the influence of facies distribution, permeability contrast, reservoir connectivity and internal heterogeneity on CO₂ movement and long-term containment.

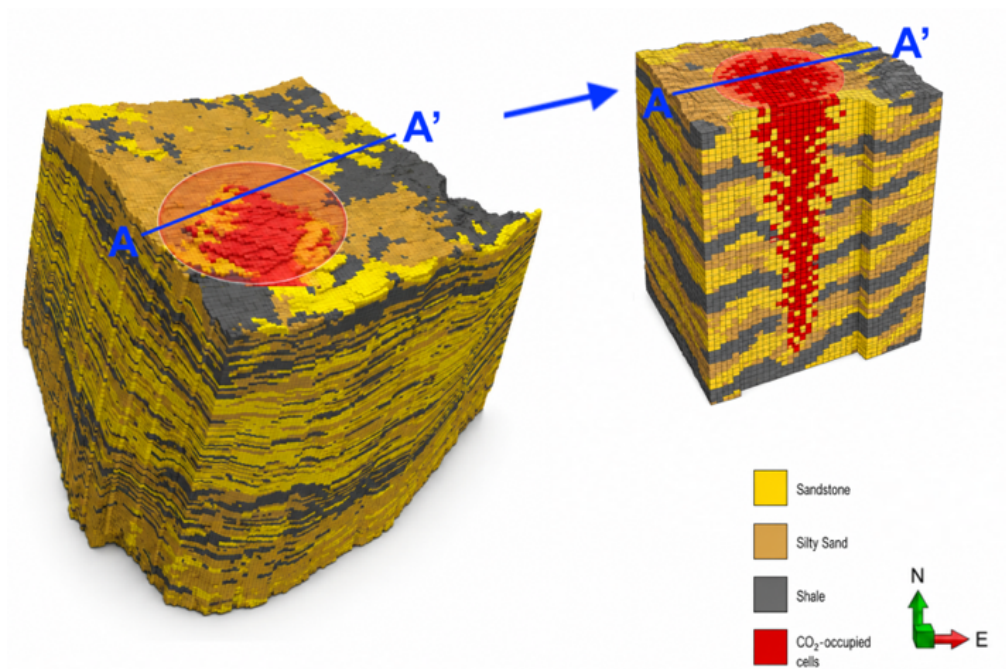


Figure 6.1. Conceptualization of a full physics reservoir simulation possible distribution of saturation.

REFERENCES

- Bachu, S. (2015). *Hydrodynamics of deep saline aquifers in geological carbon storage*. Elsevier.
- Bishop, M. G. (2000). *Petroleum systems of the Northwest Java Province, Java and offshore Southeast Sumatra, Indonesia*. U.S. Geological Survey Bulletin.
- Blondes, M. S., Brennan, S. T., Merrill, M. D., et al. (2013). National assessment of geologic carbon dioxide storage resources: Methodology implementation. U.S. Geological Survey Open-File Report 2013–1055.
- Burruss, R. C. (2008, July 24). Statement of Dr. Robert C. Burruss. In Carbon sequestration: Risks, opportunities, and protection of drinking water. U.S. House of Representatives, Subcommittee on Environment and Hazardous Materials.
- Cannon, S. (2018). *Reservoir modelling: A practical guide*. Wiley-Blackwell.
- Carman, P. C. (1937). Fluid flow through granular beds. *Transactions of the Institution of Chemical Engineers*, 15, 150–166.
- Carman, P. C. (1956). *Flow of Gases Through Porous Media*. Butterworths.
- Chopra, S., & Marfurt, K. J. (2007). *Seismic attributes for prospect identification and reservoir characterization*. Society of Exploration Geophysicists.
- De Silva, P. N., & Ranjith, P. G. (2012). *Geological storage of carbon dioxide (CO₂): A review*. Environmental Engineering Science.
- Deutsch, C. V., & Journel, A. G. (1998). *GSLIB: Geostatistical software library and user's guide* (2nd ed.). Oxford University Press.
- Ganjdanesh, R., & Hosseini, S. A. (2017). Geologic carbon storage resources estimation using Enhanced Analytical Simulation Tool (EASiTool). *Energy Procedia*, 114, 4690–4696. doi:10.1016/j.egypro.2017.03.1601.
- Ganjdanesh, R., & Hosseini, S. A. (2018). Development of an analytical simulation tool for storage-capacity estimation of saline aquifers. *International Journal of Greenhouse Gas Control*, 74, 142–154. doi:10.1016/j.ijggc.2018.04.017.
- Gulf Coast Carbon Center (GCCC). (n.d.). *EASiTool: Enhanced Analytical Simulation Tool*. Retrieved from <https://gcccc.beg.utexas.edu/research/easitool>
- Goodman, A., Hakala, J. A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B., &

- Guthrie, G. (2011). U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. *International Journal of Greenhouse Gas Control*, 5(4), 952–965. doi:10.1016/j.ijggc.2011.03.010.
- Hartmann, D. J., & Beaumont, E. A. (1999). Predicting reservoir system quality and performance. In E. A. Beaumont & N. H. Foster (Eds.), *Exploring for oil and gas traps* (Chapter 9, pp. 9-1–9-154). American Association of Petroleum Geologists.
- Hosseini, S. A., Ganjdanesh, R., & Kim, S. (2018). Enhanced Analytical Simulation Tool (EASiTool) for CO₂ storage resources estimation and uncertainty quantification: Final report. U.S. Department of Energy, National Energy Technology Laboratory.
- Hossain, S. (2020). Application of seismic attribute analysis in fluvial seismic geomorphology. *Journal of Petroleum Exploration and Production Technology*, 10(3), 1009–1019. doi:10.1007/s13202-019-00809-z.
- IEA. (2023). *CO₂ Emissions and Carbon Capture Report*. International Energy Agency.
- Indonesian Ministry of Energy and Mineral Resources. (2023). *Indonesia Energy Transition Outlook*. Jakarta: ESDM.
- IPCC. (2005). *Special Report on Carbon Dioxide Capture and Storage*. Intergovernmental Panel on Climate Change.
- Journel, A. G. (1983). Nonparametric estimation of spatial distributions. *Mathematical Geology*, 15, 445–468.
- Kozeny, J. (1927). Über kapillare Leitung des Wassers im Boden. *Sitzungsberichte der Akademie der Wissenschaften in Wien*, 136, 271–306.
- Longley, I. (1997). *The tectonic evolution of SE Asia and Australasia*. Geological Society of London Special Publications.
- Marbun, B., et al. (2019). *Characterization of reservoir properties in Indonesian basins*. Indonesian Journal of Geoscience.
- Noble, R. A., et al. (1997). *Assessment of petroleum systems in Western Indonesia*. Proceedings of the Indonesian Petroleum Association.
- Nordbotten, J. M., & Celia, M. A. (2012). Geological storage of CO₂: Modeling approaches for large-scale simulation. John Wiley & Sons. doi:10.1002/9781118137086.
- Prayitno, S., et al. (1992). *Stratigraphy and tectonics of the South Sumatra Basin*. Indonesian Petroleum Association.

- Pulunggono, A., & Cameron, N. R. (1984). *Sunda Shelf and Java–Sumatra Forearc structural framework*. Indonesian Petroleum Association.
- Pyrzcz, M. J., & Deutsch, C. V. (2014). *Geostatistical reservoir modeling* (2nd ed.). Oxford University Press.
- Ralanarko, D., et al. (2020). *Geological characterization for CO₂ storage potential in Indonesia*. Jurnal Geologi Kelautan.
- Ralanarko, D., et al. (2021). *Updated assessment of CO₂ storage sites in the Java and Sumatra regions*. Indonesian Journal of Earth Sciences.
- Ridhandi, F. (2025). Evaluasi pore pressure untuk penentuan kelayakan penyimpanan karbon pada Formasi Talang Akar, Cekungan Asri, Sumatra Tenggara [Undergraduate thesis, Institut Teknologi Sepuluh Nopember].
- Ringrose, P., & Meckel, T. A. (2019). *Geological storage of CO₂: A focused review of capacity and performance*. Earth-Science Reviews.
- Ruiz, I. (2019). Characterization of the High Island 24L Field for modeling and estimating CO₂ storage resources in the offshore Texas State Waters, Gulf of Mexico [Master's thesis, The University of Texas at Austin].
- Saputra, A. D., Surjono, S. S., Winardi, S., Setyadi, A. L., & Ralanarko, D. (2024). Lithofacies, facies association, and depositional environment of 34-1, 33-6, and 33-4 sandstone, Wida Field, Gita Member, Talang Akar Formation, Asri Basin, offshore Southeast Sumatra. Jurnal Ilmiah Geologi PANGEA, 11(1). doi:10.31315/jigp.v11i1.12011.
- SKK Migas. (2021). *Indonesia Upstream Oil and Gas Annual Report*. Special Task Force for Upstream Oil and Gas Business Activities.
- Soenandar, H. B. (1997). Thermal history of the western Indonesian basins (Sunda–Asri, Northwest Java, and Southwest Java): Evidence from fission-track geochronology of apatite. In *Proceedings of the Indonesian Petroleum Association International Conference on Petroleum Systems of Southeast Asia and Australasia* (pp. 601–629).
- Sukanto, R. (1998). *Structural evolution of the South Sumatra Basin*. Indonesian Petroleum Association.
- Tarkowski, R. (2019). *Geological storage of CO₂: Capacity, safety, and long-term monitoring*. Environmental Geology.

- Turabian, K. L. 1987. *A Manual for Writers of Term Papers, Theses, and Dissertations*. 5th ed. Chicago: The University of Chicago Press.
- Wang, S., Jin, K., Zhao, W., Ding, L., Zhang, J., & Xu, D. (2025). Mechanism, modeling and challenges of geological storage of supercritical carbon dioxide. *Energies*, 18(16), 4338. doi:10.3390/en18164338.
- Wentworth, C. K. (1922). A scale of grade and class terms for clastic sediments. *The Journal of Geology*, 30(5), 377–392.
- Zaemi, F. F., Rohmana, R. C., & Atmoko, W. (2022). Uncovering the potential of low-resistivity reservoirs through integrated analysis: A case study from the Talang Akar Formation in the South Sumatra Basin. *Scientific Contributions Oil and Gas*, 45(3), 169–181. doi:10.29017/SCOG.45.3.1258.