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Unleashing geological sequestration potential of mature oilfield by enforcing 4-dimensional seismic model-based inversion in Widuri Field, Indonesia

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Abstract: Implementing reservoir characterization by undertaking seismic inversion on time-lapse surveys is very effective for observing the distribution and changes in the hydrocarbon reservoir. In mature oilfields, these changes are most likely influenced by the thermodynamic activities including the injection of fluid into the reservoir, which can change the volume, pressure, and composition of the geological formations. Fluid injection (in this case, water injection) into the reservoir is typically used as an oil and gas booster to increase production through EOR (Enhanced Oil Recovery). However, in light of CCUS (Carbon Capture Utilization and Storage) application, injecting CO_2 can be considered as a new EOR strategy development, with the dual objectives of increasing oil and gas production as well as lowering carbon emissions at the same time. The 4-dimensional (4D) seismic data available over Widuri Field covers an area of 125 km^2, with 884 inlines and 905 crosslines, acquired in 1991 and 2004 over the same area. The inversion algorithm is using seismic deconvolution to generate an acoustic impedance model before developing a geological reservoir model. Reservoir characterization was conducted in this study to obtain detailed information of the reservoir zones by determining the impact of water injection that replaces hydrocarbons. Intervals and areas with an abundance of water can be considered as potential CO_2 sequestration in the future, as a part of the CCUS application. In conclusion, the findings of increasing impedance from inversion data from 1991 to 2004 can indicate the presence of existing porosity and permeability. This evidence could indicate reservoir capability as CO_2 storage.

Keywords: 4D seismic, enhanced oil recovery, geology, inversion, sequestration

INTRODUCTION

Widuri Field is one of Indonesia's oldest offshore oil-producing fields located in the Southeast Sumatra Basin and has been producing oil for decades. The search for hydrocarbons in this field is relatively simple because the presence of oil is clearly indicated in seismic data. On seismic data, there are many bright spot amplitude characteristics in the reservoir zone.To ensure a clearer determination of reservoir filling fluids, however, additional analysis such as petrophysics studies and reservoir characteristics such as seismic inversion and attributes are required. Continuous oil production in the Widuri area caused a decrease in hydrocarbon reserves, and it proves that seismic methods in analyzing and characterizing reservoirs can support the production of millions of barrels of oil for many decades. The seismic method is also a very powerful tool in searching for hydrocarbons, and indicates the precise location for drilling wells to extract hydrocarbons. For decades, this field's management has never considered the possibility of utilizing depleted reservoir intervals in the Asri Basin as a carbon storage area.

In 2000, this field carried out an Enhanced Oil Recovery (EOR) scheme by injecting water into the reservoir to increase oil production. The seismic method plays an important role in identifying the accumulation zone of water injection, which could be utilized as a reference for selecting CCUS development areas by replacing the water injection fluid with CO_2. With adequate seismic data, it is very possible to develop CCUS technology in this field, such as determining the location of storage areas and reservoir characterization after injecting water into the reservoir, which will probably turn into CO_2 injection. The increase in emissions around the field brought the idea of transforming the field from an oil producer into a CO_2 storage, This will be an interesting stage of the field after the oil is depleted.

The workflow of this research is monitoring the water injection performed in 2000 using the model-based inversion method to define a quality area for accumulating water

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injection as a reference for determining suitable areas for CO_2 injection. The inversion method is used to determine reservoir changes when the reservoir filling fluid changes from oil to water, causing the impedance results between the two seismic data to change slightly. It is expected that by identifying the change of fluid from oil to water, the quality of a suitable reservoir for storing CO_2 can be determined. The indication of the fluid change is studied through a qualitative approach such as matching seismic data (cross-equalization). This method is used to carry out the inversion method for characterizing the reservoir. One of the most important reservoirs in this field is Talangakar (TAF) sand deposited as a meandering river system that streamed from the northwest to the southeast within the basin. Two main reservoirs, Zelda and Gita are correlated throughout the field and interpreted as Miocene fluvial-channel sands. These two depositional systems are thickened moderately from southwest to northeast and the grain changes from fine- to coarse, unconsolidated to friable, and low cementing materials (Ralanarko *et al*., 2021).

Geological setting

According to the regional geology, the Widuri Field is part of the Asri Basin, which is located at the southeastern tip of the Eurasian Plate and, more specifically, is part of the Sunda microplate. The Asri Basin is a Paleogene half-graben that is curved to the southwest. According to Sukanto *et al*. (1998), the Asri Basin is a back-arc basin that contains half graben rift system with N-S direction, as well as a complex extensional basin type of intracratonic or called a sag style basin. The sag extension becomes a symmetrical graben, then a half-graben rift, and finally stops.

The Asri Basin (as part of Sundaland) history can be divided into three tectonic mega-sequences, as defined by Longley (1997):

- An early continental collision during Stage I (50–43.5 Ma) was when many of the earlier syn-rift grabens were formed. A phase of extension in the nearby fore-arc and back-arc regions resulted from the India-Eurasia collision, which slowed the oceanic spreading rates in the Indian Ocean and decreased the convergence velocity in the Sunda Arc subduction system. The subduction slab would sink as a result of the velocity reduction, disconnecting the slab as a result, and creating an extensional environment in the arc zone, according to Daly *et al*. (1987).
- A younger population of rifts was formed and is currently subsiding during Stage II (43.5–32 Ma), a period of significant plate reorganizations. The basement heterogeneity had an impact on the shape and orientation of many half-grabens that were created as a result of this development. According to Hall (1996), South Sumatra's graben orientation today is the result of a rotation of around 15 degrees clockwise since the Miocene.
- Stage III (32—21 Ma) – This stage, which coincided with the South China Sea's seafloor spreading, was

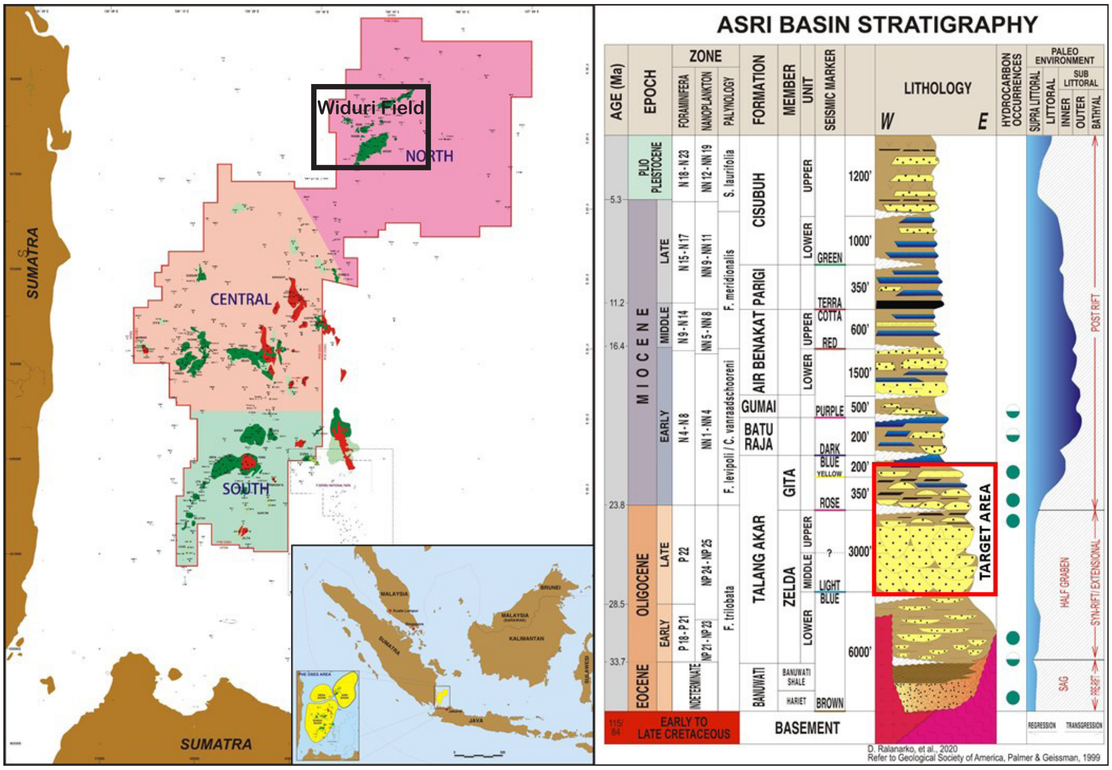

Figure 1: Location map of Widuri Field, Asri Basin (Sukanto *et al*., 1998) and Asri Basin stratigraphy (Ralanarko *et al*., 2020).

when the rift stopped, local inversion occurred, and a significant marine transgression signaled the start of post-rift evolution.

- Stage IV (21 - 0 Ma) - Characterized by a maximum transgression followed by several collision phases that resulted in inversions, uplift, and the development of regressive deltaic sequences. This corresponds to the early and late stages of the rift.

The Asri Basin is located in the northeast of the Sumatran fault system, covers approximately 3500 km^2, and has a sediment thickness of up to 4876 m. It was formed between the Paleocene and Pleistocene epochs (Figure 1). It is bounded to the east by a normal fault that runs north-south, and to the south by a wrench that runs northwest-southeast. On the north side of the basin the bedding forms an onlap, and monoclinic pattern in the western part.

The Talang Akar Formation, which is the reservoir in this field, is made up of two members, so called Zelda and Gita. The Zelda Member was formed during the Middle-Late Oligocene epoch and is made up of thick mudstone, siltstone, fine sandstone, and thin coal. The Zelda Member has three units: lower, middle, and upper. The middle-upper Zelda Member sandstones are the result of slowdown subsidence, and the large amount of sandstone content in the middle-upper Zelda has the potential to be a hydrocarbon reservoir. The Gita members, which consist of transgressive mudstone, shale, coal, and estuarine channel sandstones, were formed in the Early Miocene. The Gita Member has a thickness of 335 m and was deposited above the Zelda Member in a supratidal-intertidal environment. The middle to upper Zelda member reservoir has a large number of shale interspersed. The maximum thickness of this unit is around 914 m. Members of the Zelda and upper Gita formations (Talang Akar Formation) contain multistory fluvial sandstones with distributary or estuarine ribbon sand bodies to deltas, and they are the main reservoirs in the Asri Basin.

Literature review

This study employed literature from the Sleipner Field, which is a saline aquifer sandstone reservoir created during the Oligo-Miocene period and used the inversion method to characterize its reservoir. The Sleipner Field has been successfully injecting CO_2 for many years and can serve as an inspiration for the Widuri Field, which will later inject CO_2 as a replacement for water injection in the EOR scheme. It is hoped that the steps taken in the Sleipner Field can be replicated for monitoring water injection in the Widuri Field, and that the results of CO_2 monitoring in the Sleipner Field will be a lesson in the Widuri Field in terms of changes in impedance values, implications that will arise when later CO_2 is injected into the reservoir, and the factors that enable safe CO_2 storage in the reservoir.

Sleipner is the world's first commercial Carbon Capture and Storage (CCS) project, located off the coast of Norway, to reduce carbon emissions through CO_2 capture and storage. CO_2 injection in this project began on September 15, 1996, and it contributes to global efforts to reduce greenhouse gas emissions. The Utsira sandstone formation serves as a reservoir in the Sleipner Field. The Utsira Formation is a saline aquifer reservoir approximately 800 to 1000 m deep and 200 to 300 m thick in the earth (Chadwick, 2010).

In this research, studies have been performed to monitor CO_2 injection using 4-dimensional (4D) seismic data in 1994 and 2004 to monitor volume changes in the reservoir after the CO_2 injection in 1996. In order to monitor the CO_2 injection, 4D model-based inversion is used. This type of model-based inversion is perfect for tracking CO_2 distribution in the Sleipner field because it matches the model to the actual geological conditions beneath the surface. This research seeks to monitor water injection in the Widuri field and to determine the reservoir's properties following CO_2 injection.

The 4-Dimensional Model-Based inversion result in Sleipner Field is very appropriate for application in this CO_2 monitoring project to track the evolution of CO_2 injection in the Utsira sandstone formation because it fits the geological model under the surface.The purpose of this inversion process is to determine the impedance value of CO_2, to see the distribution process of CO_2, and to ensure that CO_2 is stored safely or does not leak in the top reservoir, and to see the pushdown effect in the base reservoir.

Pangestu (2022) presents the results of the inversion of the two seismic data in the Sleipner field (Figure 2),

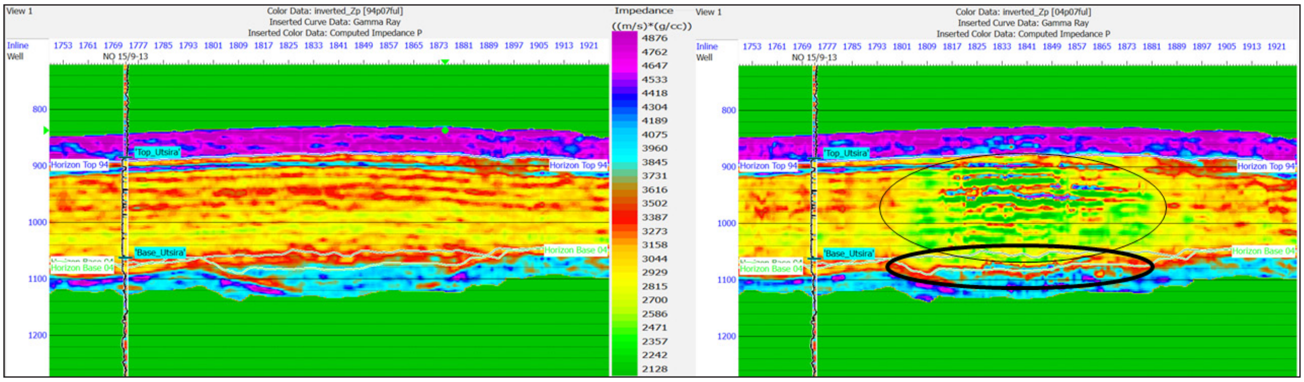

Figure 2: Inversion Model based Time Variant Shift Baseline 1994 (left) and Monitor 2004 (right) data in Sleipner Field (Pangestu, 2022).

where the impedance obtained ranges from 4876 to 2128 ((m/s)*(g/cc)). There is an impedance difference in the two data, namely on the monitor data the appearance of a low impedance value is indicated by a thin black circle, the low impedance value is suspected to be CO_2 stored in the Utsira sandstone formation. When CO_2 is injected, the CO_2 will automatically move straight to and approach the top of the reservoir and then spread laterally to cause a supercritical effect where CO_2 pushes the saline aquifer and replaces it on the spot. The thick black circle in Figure 2 depicts a pushdown effect on the base reservoir caused by continuous supercritical CO_2 injection, resulting in a depressed base reservoir that will eventually experience downward compression.

METHODOLOGY

The seismic method used in this study is 4D seismic (time-lapse), which utilized two 3-dimensional (3D) seismic that was acquired and processed at different times. In the 4D seismic, there is an additional time dimension from the 3D seismic. Typically, this 4D seismic must have a baseline data from the initial 3D seismic acquisition and processing taken for the exploration phase, as well as monitoring data for further 3D seismic acquisition and processing in the same place but at different time periods. These data are useful for monitoring the subsurface, particularly in the reservoir to visualize the difference between two seismic data, specifically the seismic amplitude caused by changes in the acoustic impedance in the reservoir due to production wells and injection well activities (Pangestu, 2022). As in Figure 3, the result of monitoring CO_2 developments using 4D seismic were acquired in 1996, 2001, 2004, 2006 and 2008, but in this study, 4D seismic was used to monitor the EOR (Enhanced Oil Recovery) water injection scheme in an oil reservoir.

Numerous 3D seismic acquisitions has been conducted in the Widuri Field to monitor the reservoir, including the first acquisition in 1991, the second acquisition in 1996, the third acquisition in 2000, and the fourth acquisition in 2004. In 2000, the first EOR scheme including water injection into the reservoir was started. In 1991, the first acquisition was made to discover the presence of hydrocarbons (initial exploration), the second acquisition was made to monitor hydrocarbon reserves, the third acquisition was made to monitor reservoirs that had undergone water injection EOR, and the fourth acquisition was made with the intention of monitoring water injection that had been running for four years. The 4D seismic data selected for monitoring water injection in this study are data from 1991 and 2004 because they would indicate changes in the reservoir for 13 years induced by continuous oil production and water injection that had occurred for 4 years.

The Widuri field is covered by 3D seismic, acquired in 1991 and 2004. This study only focused on areas where there was a lot of oil and covered in the 4D seismic project which is only 125 km^2. The area was previously used to monitor the remaining oil reserves (in the dotted black box in Figure 4) and will now be used to search for potential areas for CO_2 storage. This survey was conducted four years after the startup of water injection in 2000 with two full stack 3D seismic data sets acquired and processed at the same location in 1991 and 2004. Each measurement area

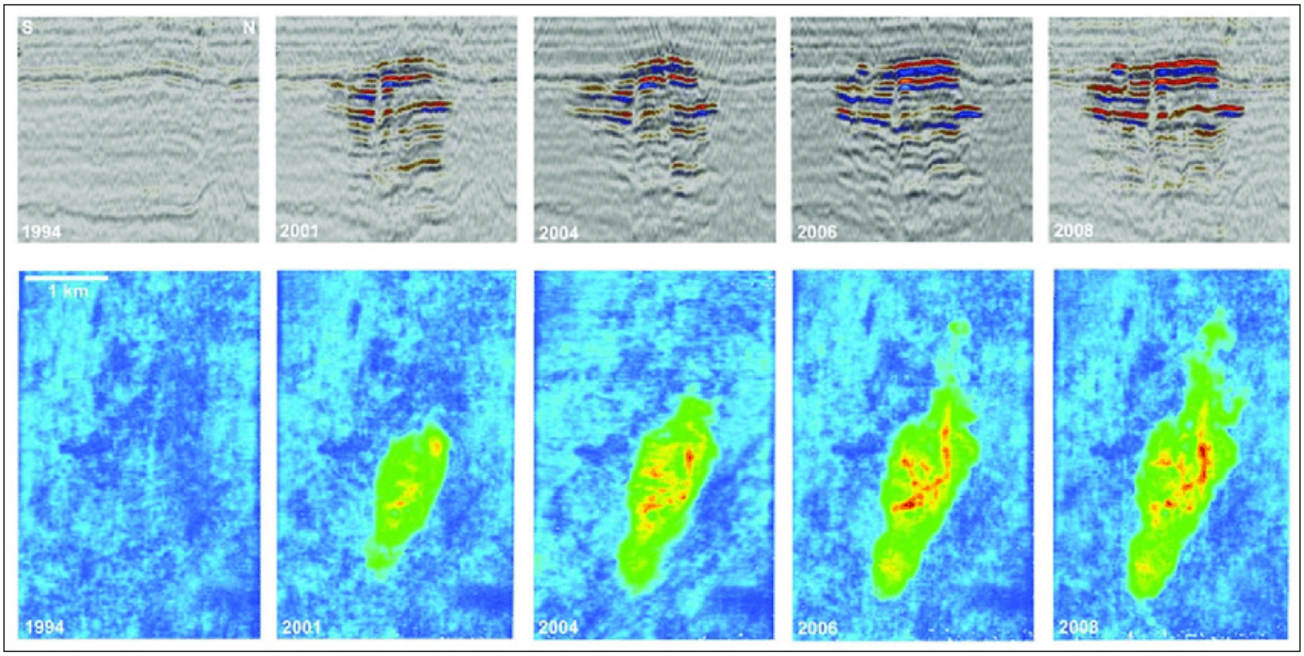

Figure 3: 4D seismic example of Sleipner Field showing the change in reflectivity after injecting CO_2 into the reservoir in 1996 (Pangestu, 2022).

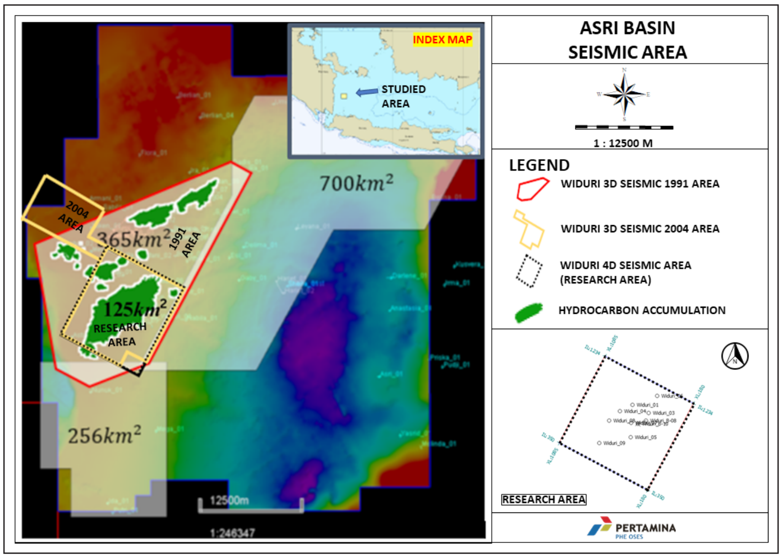

Figure 4: Seismic acquisition area in Widuri Field Asri Basin, showing the 1991 and 2004 3D seismic coverage, and the study area (in dotted black box).

was equalized to match the area of the 4D seismic study, requiring the 1991 3D survey to be trimmed to match the 2004 3D survey area so the observed area shares a similar spatial extent to the black box boundary. The 1991 3D seismic data was used as the baseline data while the 2004 3D seismic data was utilized as the monitoring data.

The total number of lines used in the 4D seismic area is inline 350-1234 (804 lines) and crossline 180-1085 (905 lines), covering an area of 125 km^2. A positive reflection coefficient is represented by a central trough which is a negative number on the tape. This is called negative standard polarity (Europe standard). Well data in this field uses 8 wells, namely Widuri_01, Widuri_03, Widuri_04, Widuri_05, Widuri_06, Widuri_07, Widuri_08, and Widuri_09.

The 1991 3D seismic was primarily aimed for oil exploration in the area which covered an area of 365 km^2. The seismic acquisition used a recording length of 3 seconds, with a sample rate of 1 ms. The source used for this survey was Airguns, sunk at a depth of 4 m below sea level with a volume of 2x1960 cu.in and a resulting pressure of 2000 psi. The seismic recording used dual streamers with a group sensitivity of 34 V/B, the total trace of the streamer stretch is 2x128 with a group length of 16.15 and a group interval of 12.5 which was changed to 18.75 because there were technical infrastructure and operational obstacles during the acquisition. The seismic streamer was submerged five meters below sea level. During the acquisitions, some issues related to the weather conditions, such as storms, arose which impeded the acquisition process. Another frequent issue during the process was the malfunctioning of the streamer, necessitating repair work as well as the replacement of the streamer with fresh reserves imported from Norway. Throughout the survey, a controlled streamer was used to improve the streamer's balance, as its 1600 m length was insufficient to stabilise it in the water. The solution taken was by adding more stretch to the streamer's tail. The ship also faced problems such as power outages, which stopped the function of the data processing equipment because the generator lacked power.

The 2004 3D seismic was acquired in 2004 to monitor the remaining oil reserves in reservoirs that have shrunk as a consequence of continuous production. This seismic has a record length of 4 seconds and a sample rate of 2 milliseconds, resulting in a nominal fold record of 22 and a recording filter of 2.7 Hz in every 6 dB (octave low cuts) and 400 Hz in every 400 dB (octave high cuts). It used airguns of the 1500 LL and 1900 LLX types, which had an explosive volume of 1940 cu.in and an explosion pressure of 2000 psi. The airguns used were placed into the water at a depth of roughly 4 m, and it exploded every 7 seconds, creating 4.80 knots with each blast. The distance of the energy produced by the airguns is 14.7 m, with a separation of 50 m (center to center). The streamers were spread out in the water at a depth of 5 m and separated 100 m apart for this survey, with a streamer length of 1600 m and a 12.3 m gap between groups (25 m bin width). The employed streamer features a hydrophone-type sensor with a sensitivity of 17.4 V/Bar and a group of 16.

The seismic acquisitions taken in 2004 tended to have general constraints, based on lessons learned from the problems that arose during the 3D seismic acquisitions in 1991, 1996, and 2000. As such, extensive preparation was carried out to ensure optimal readiness before the acquisition in 2004. General constraints such as extreme weather are beyond human control, so it still hinders the acquisition process. In the meantime, a new streamer backup has been prepared to resolve the non-functioning streamer problem.

Cross-equalization

Cross-equalization is an attempt to balance the differences in source wavelets and amplitude so that the two seismic data have the same energy level in terms

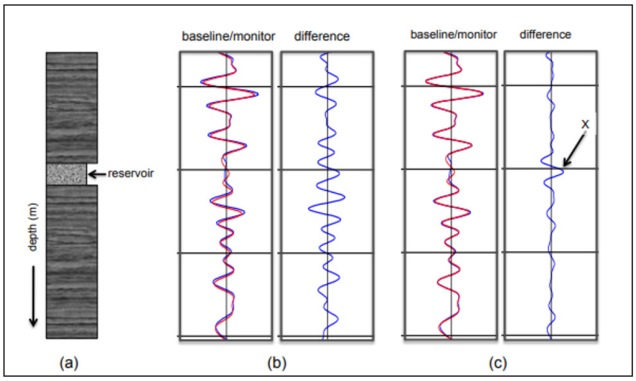

Figure 5: (a) Geological model below the earth's surface, (b) Trace seismic database and monitor (left) the difference between the two data (right), (c) Seismic trace of the two data after the cross-equalization process (left) the difference between the two data after the cross-equalization process (right) (Ayeni & Biondi, 2012).

of wavelength (frequency) and phase equalization. The cross-equalization procedure necessitates the estimation of a wavelet operator at a specific time frame (static zone, non-reservoir) both shallow and deep, such that the phase, amplitude, and frequency of the two seismic data are exactly the same (Abdullah, 2009).

The purpose of the cross-equalization is to match seismic data due to amplitude differences caused by well activity or acquisition effects by matching phase, time shift, amplitude, and frequency on both baseline and monitor seismic data. In this study, matching the two data sets is in the overburden zone, because the overburden zone does not change significantly during the water injection processes. As in Figure 5, during the cross-equalization process, the reservoir zone is ignored because there has been a change in fluid and volume here, while other zones are matched. This cross-equalization process matches the phase, time, amplitude, and frequency of the monitor data from 300 ms to 950 ms TWT window (overburden zone). The process is divided into three stages. The first stage is the phase-time shift, which aims to match the time shift and phase in the overburden zone. The second stage is a shaping filter, which aims to match the seismic frequency and amplitude from the previous phase-time shift process, and the final stage is a time-variant shift, in which the monitor data movement moves randomly shift, rather than in bulk shifts to match the baseline data in all windows. The baseline is based on repeated acquisition and processing time range.

Normalized Root Mean Square (NRMS)

The repeatability value is calculated using the Normalized Root Mean Square (NRMS) Amplitude value, a low NRMS value has a high repeatability value, meaning that when NRMS is low, the monitor data and the baseline data have almost the same match. Processing factors influence the size of the NRMS value.

$$\mathrm{NRMS} = \frac{2\,\mathrm{RMS}\,(a-b)}{\mathrm{RMS}(a) + \mathrm{RMS}(b)} \qquad (1)$$

where: a is monitor data, b is baseline data.

The processing factor that can ascertain the match between the baseline and monitor data is the cross-equalization method, which matches seismic data because of variations in amplitude in the overburden zone brought on by well activity or acquisition effects. This method is performed first in order to obtain the NRMS and repeatability values. Baseline and monitoring seismic data are matched in terms of phase, time shift, amplitude, and frequency to ensure that both sets of data are comparable to the overburden zone.

The 1991 and 2004 seismic data should have the same characteristics in the overburden zone in terms of phase, time shift, amplitude, and frequency because the overburden zone is unaffected by oil production and water injection activity in the field. If changes or differences are found, the two data must be matched before moving on to the next step.

4-dimensional (4D) inversion

4-dimensional inversion is an inversion used to obtain information on changes in acoustic impedance on the baseline and monitor data so that changes in acoustic impedance on both seismic data can be seen in detail. However, due to the time lag between monitoring data collection and water injection in this 4D inversion, the velocity in the target zone will automatically differ between the baseline data and the monitor data, affecting the inversion comparison of the two data. Information on acquisition and processing delay time can be used for processing. Inversion and information on the lower half of the seismic bandwidth are also provided. It is possible to determine the change in velocity using the cross-correlation and time shift cubes, and then multiply it by the initial model to obtain the low-frequency model, which can increase the difference in the inversion of the monitor data to the baseline data.

Table 1: NRMS value of the match between baseline and monitor data (Lumley, 1996).

NRMS	Comment
<0.1	Outstanding Repeatability
<0.2	Excellent Repeatability
0.2 - 0.4	Very Good Repeatability
0.4 – 0.6	Reasonable Repeatability
0.6 - 0.8	Poor Repeatability
0.8 - 1.2	Highly non-Repeatability
1.40	Equivalent to two random data sets
2.00	Data sets are identical, but polarity reversed

The inversion technique is named model-based Full-stack inversion, and this technique involves deterministic inversions with the objective of minimizing errors between synthetic and seismic data. It can also be used to compare geological models with seismic data and iteratively update models to fit the seismic data. This inversion requires data from a previous low- frequency model to bring up the impedance distribution value in the inversion results, the results of this inversion do not invert directly from the seismic data but invert the geological model.

RESULTS

Cross-equalization result

The controlling factor for each process (phase-time shift, shaping filter, time-variant shift) in this cross-equalization step is the NRMS value, the lower the NRMS value, the more suitable the two seismic data will be for 4D analysis. According to Table 1, the two seismic data are still classified as reasonable repeatability in the original data, with a NRMS value of 0.48.

Both data had relatively high NRMS values before the cross-equalization process, but after the cross-equalization process, the shift difference between time and phase was minimized to obtain an NRMS value of 0.39 in the overburden zone at the interval 300ms – 950ms. A volume difference was performed in the cross-equalization process to show the difference data. This volume of difference process examines the difference in the amplitude of seismic data in which the monitor data has an amplitude change from the baseline data with a 13-year interval, which is caused by the effects of oil production and water injection in 2000. The amplitude difference data on the two seismic data is shown in Figure 6. A positive difference result indicates that the amplitude of the monitor data at the same time and bin is greater than the amplitude of the baseline data. Meanwhile, the negative difference result indicates that the baseline data amplitude is greater than the monitor data amplitude. It can be observed that in the seismic data before the cross-equalization process, both data still have a lot of high and low difference values, indicating that the two data do not match, so it is essential to minimize the mismatch with the cross-equalization process. Following the cross-equalization process, it is apparent that the target (overburden zone) has been minimized, so that the difference between the two data is eliminated in the window 300ms – 950ms, which means

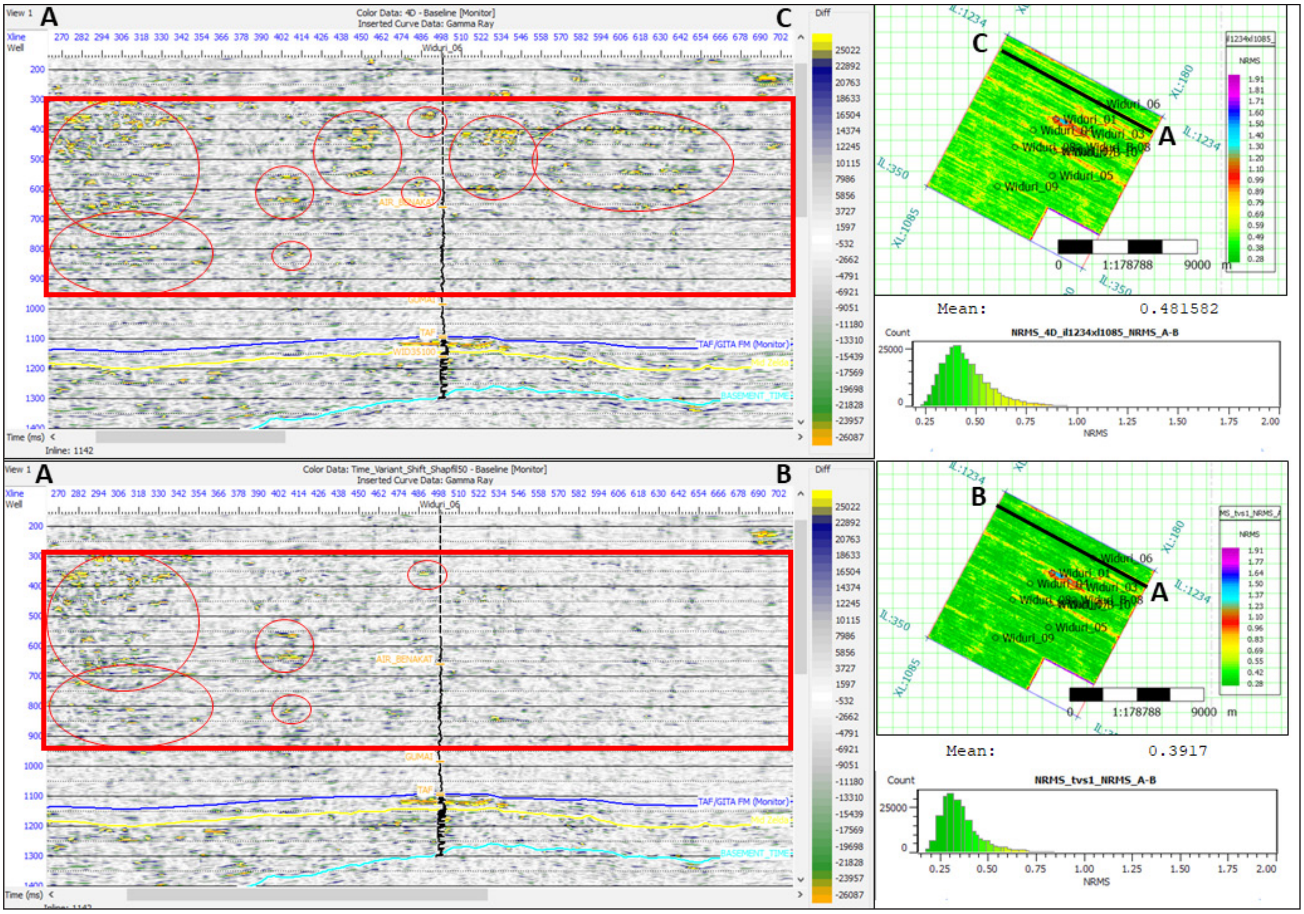

Figure 6: Volume difference before cross-equalization/original seismic monitor - baseline (above), and volume difference after cross-equalization seismic monitor - baseline (below) at inline 1142 of Asri Basin, Seismic 3D seismic data.

that both data indicate a match at the same time and seismic in between the baseline and monitor data when there is no difference value.

The volume difference on the original seismic shows that there are still many low and high difference values in the overburden zone, indicating that the differences between the two seismic data are still very different. After performing the cross-equalization process, the low and high difference values have been reduced, indicating that both data have seismic amplitude at the same time and bin for each seismic data, indicating that the two seismic data matches, also discernible is a decrease in the NRMS value from 0.48 to 0.39 in the cross-equalization results, or a change from the data's classification of reasonable repeatability to very good repeatability. The results of this cross-equalization will later be used in the 4D inversion process as the seismic input.

4-dimensional (4D) inversion result

The model-based post-stack (full-stack seismic) inversion result shows that the lithology of the rocks in the reservoir zone in this field is diverse, with medium to high impedances being red to purple, indicating a lot of shale lithology, and low impedances being yellow to green indicating sand, but still dominated by shale layers. The large quantity of shale layers in the reservoir zone can prevent the accumulation of water injection. The results of the inversion of the two data are relatively similar on the line around the Widuri_06 well, as seen in Figure 6. The difference value that occurs due to changes in the reservoir zone in the Widuri_06 well only occurs in the top reservoir area that is touched by the well (Figure 7), whereas the many changes in the reservoir and seal occur around the Widuri_01 well, shown in Figure 8. Changes in reservoir characteristics observed mostly in Widuri_01 well area were caused by a four-year continuous injection of water, which caused the impedance around the Widuri_01 well to change and changes in the seal indicate water injection which fills the fracture gap in the seal zone. Of all the existing seismic volumes, a very significant change can be seen around the Widuri_01 well, a medium impedance change that is red in the baseline data inversion changes to a low impedance in yellow in the monitor data inversion.

DISCUSSION

Widuri Field inversion result analysis

The inversion results obtained in this field appear to be very good in characterizing the reservoir, indicating the amount of shale content present. In contrast to the Sleipner Field as a reference, which has a reservoir composition that is entirely sandstone with only a thin layer of shale to allow CO_2 accumulation, the Widuri Field has many shale layers in the reservoir, causing water injection to spread unevenly. Figure 9 shows that they are evenly distributed and accumulated around Widuri_01 well but the accumulations are not connected due to the presence of many shale layers in the reservoir zone.

The presence of water injection alters the condition of the reservoir; firstly the water saturation as the reservoir was previously filled with oil and then replaced by water. Secondly, the pore pressure had also changed. Pore pressure in the reservoir will increase. This is caused by the pore space being filled with new fluid (water). This is also called "effective pore pressure". All of these affect the impedance value obtained because the density of water is greater than that of oil, and the velocity will also increase when seismic waves propagate through media filled with water rather than oil, thus increasing the density and velocity, causing the impedance value to increase from baseline to monitor inversion result. The difference in impedance between the two data sets can be seen by subtracting the monitoring data from the baseline data, with a positive difference value indicating an increase in impedance at the same time and bin, and negative difference value indicating a decrease in impedance.

The reservoir conceptual model describes the distribution and accumulation of water injection in the reservoir, which is separated by many layers of shale, causing the water to be disconnected from each other (Figure 9). The results of the different impedance monitors and baselines at the bottom is thought to be the distribution of water injection that has occurred in the reservoir zone and there are indications of impedance changes in the seal zone, it is likely that water injection is entering the seal region, which is influenced by the fault. This is done by comparing the inversion results of the two seismic data sets as was done in the Sleipner field, then only taking the value of the difference in impedance that increases and also depicts the percentage of water that replaces oil in reservoirs with fluid turnover rates ranging from 18% to 37% and illustrates the zone of spreading water injection, and it can be seen that there are a lot of increasing impedance differences in the area around Widuri_01, indicating that water accumulates around the well in a northwest-southeast direction.

Widuri Field CO_2 storage analysis

This study has observed an accumulation of high difference values (increase impedance from baseline to monitor data) around the Widuri_01 area, which is thought to be the distribution of water in the reservoir (Figure 9). Changes in fluid saturation in the reservoir are more dominant than changes in pore pressure because they occur in the interval area with normal gradient pressure, whereas the zone with high pressure occurs in the center part of the Asri basin (east of the Widuri field). The difference is also shown on a seismic time slice (Figure 10), which indicate numerous changes in impedance increase in this area, which are suspected to be the distribution and accumulation of much water injection (black circles). Because the amount of visible water distribution can determine the quality of the reservoir for storing CO_2 later, as well as the location of the wells to be used as CO_2 injection wells, this can be

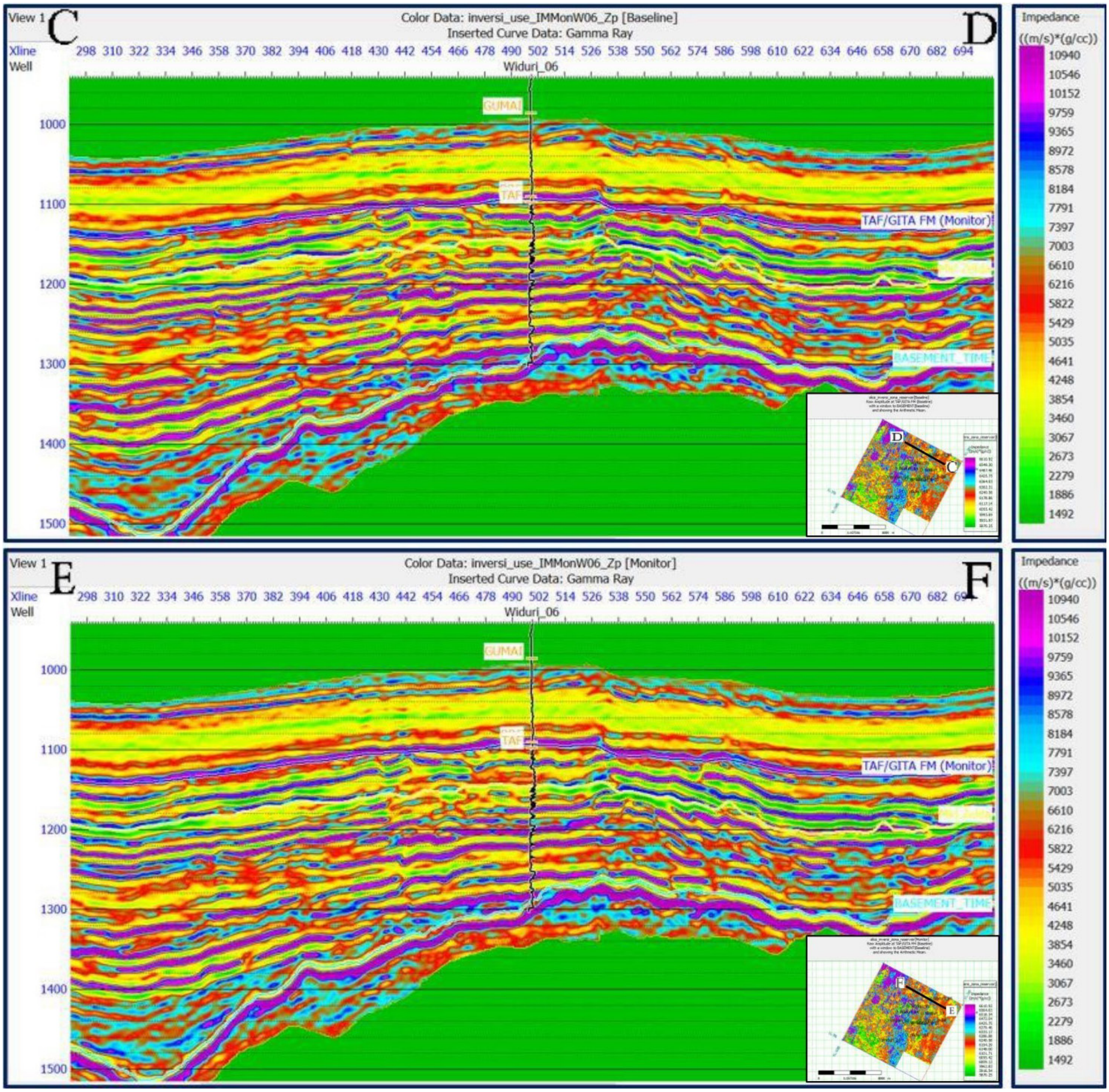

Figure 7: Widuri Field data inversion results in Widuri_06, Inversion Baseline data (above) and Inversion Monitor data (below) at inline 1142 of 3D Asri seismic data. The black circle is the difference/change in the impedance value between the two data.

used as a reference to select areas for CO_2 injection in the future. When CO_2 is injected in this field, the impedance decreases similarly to the inversion result in the Sleipner Field, and the remaining oil and water in the reservoir were replaced by CO_2 and pushed the oil, making it easier to produce. Oil and water have a higher impedance and will change to CO_2, which has a low impedance due to a drastic decrease in density and velocity. This is what causes CO_2 to have a lower impedance, as in the Sleipner field.

The reservoir in the Widuri_01 area is very suitable for CO_2 storage. From the seismic interpretation and analysis, the reservoir injectivity seems to be proven and later CO_2 will be stored more in the plume than scattered in the reservoir.The containment is also proven because it can hold water without creating excessive leaks in the seal region. The CO_2 injection will help to increase oil production. When CO_2 injection is carried out later, the 4D inversion method can also be used again to monitor the CO_2 distribution which has similar reservoir and fluid type characteristics to Sleipner Field, and monitor the impact of CO_2 application on the Widuri field.

This study was successful in answering the research objectives to monitor water injection identified by an increase in impedance changes, and being able to locate reservoir of high quality with the potential to store CO_2.

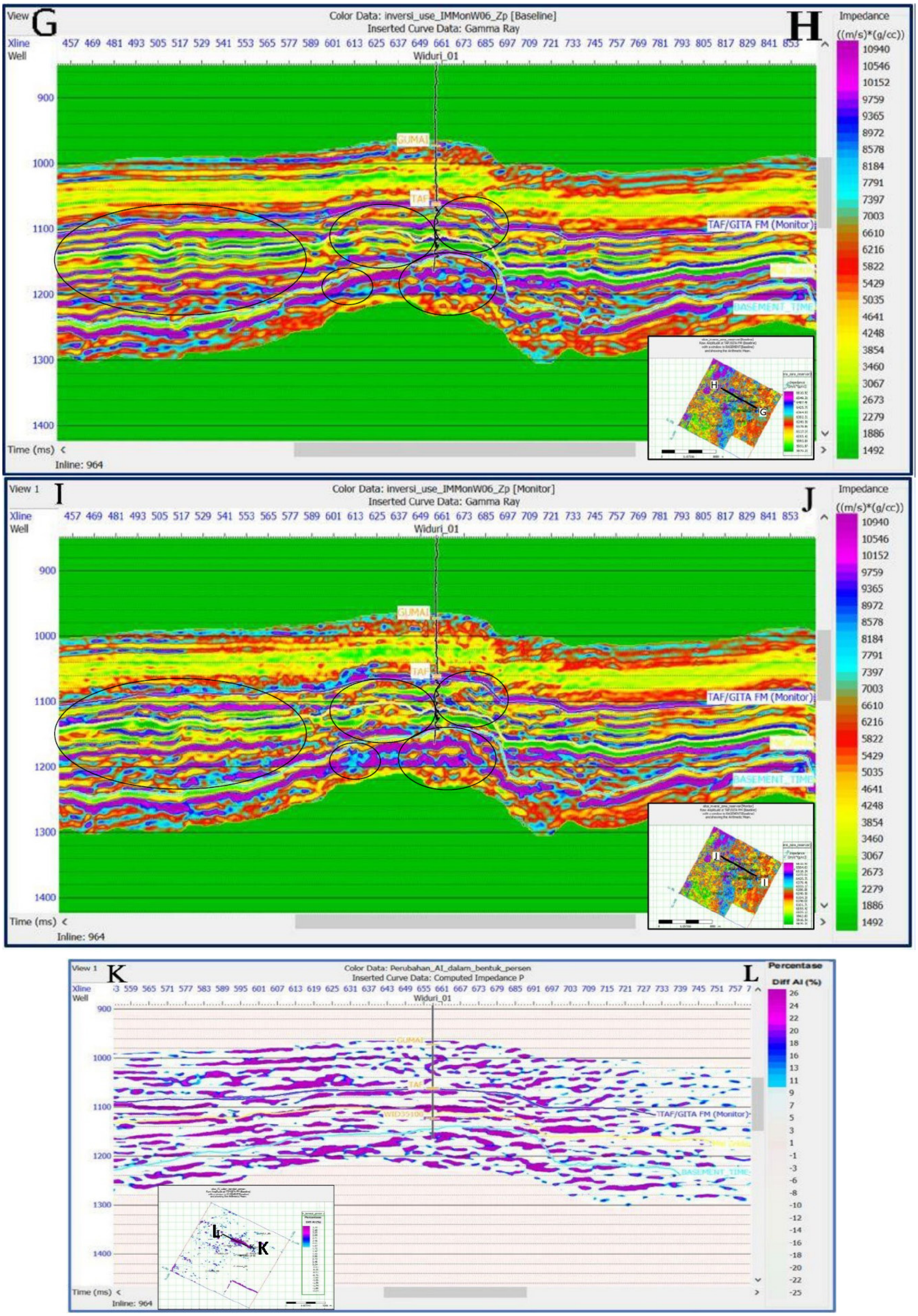

Figure 8: Widuri field data inversion results in Widuri_01, Inversion Baseline data (G-H) and Inversion Monitor data (I-J) at inline 964. The black circle is the difference/change in the impedance value between the two data and the K-L section is the detail of the difference in the increase impedance value between the two data.

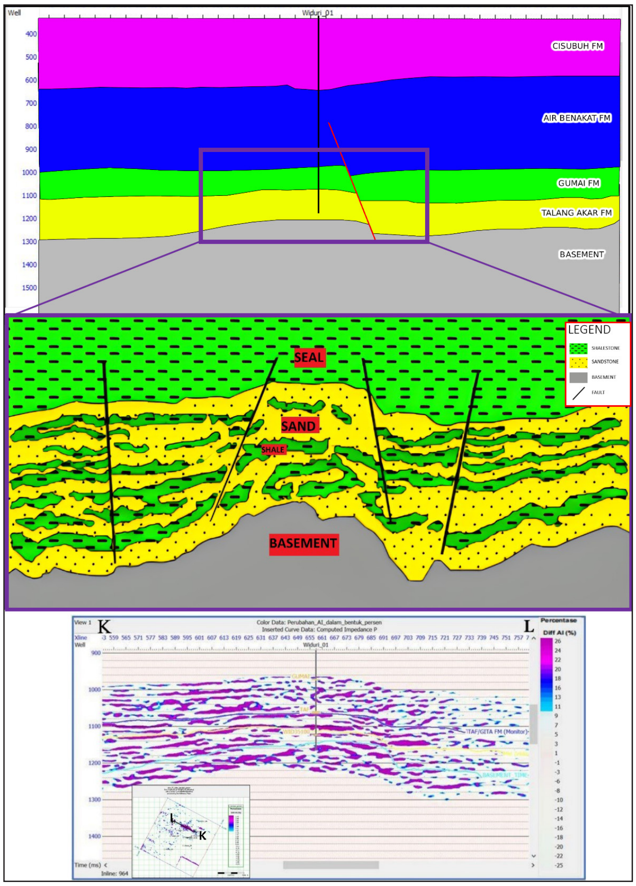

Figure 9: Conceptual model of the reservoir and results of difference Impedance Monitors and Impedance Baseline at inline 964 to indicate water accumulation.

CONCLUSION

Water injection monitoring in Widuri Field was indicated by an increase in impedance from baseline to monitor inversion result because the water injection increased the density and velocity of the rocks. Upon conducting a water injection to observe the dispersion of water and the reservoir's quality for storing fluid, a significant build-up of potentially contaminated water was seen at the Widuri_01 well. Due to several layers of shale, the water injection was evenly distributed and accumulated, but the accumulations were not connected.

The quality of the Widuri Field reservoir for storing water injection in the area around the Widuri_01 well is good. This area also has the potential to store a large amount of CO_2, thus the EOR scheme that was carried out by injecting water can be changed by injecting CO_2 into the reservoir. There are more benefits of CO_2 injection, it not only boosts oil production but also reduces emissions in Indonesia.

Taking into account the features of the Norwegian Sleipner Field reservoir described in the literature, the impedance value changes as soon as the Widuri field starts injecting CO_2 into the reservoir. When CO_2 replaces water or oil in the reservoir, the density and velocity values decrease, causing the impedance value to decrease.

To provide additional support in proving the properties of CO_2 in the reservoir, rock physics modeling is the best solution for identifying fluid substitution. However, another aspect of this research that should be considered in determining the location of CO_2 storage is the existence of additional research concerning the possibility of faults in the reservoir that can cause CO_2 to leak.

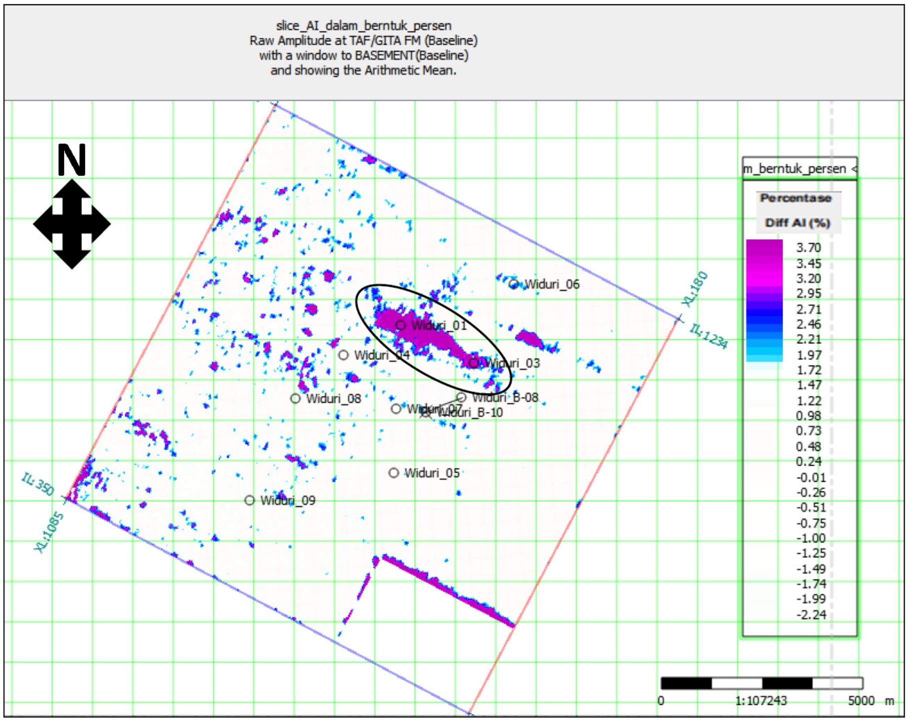

Figure 10: Slicing results of difference impedances at reservoir zone (TAF/GITA FM – Basement) and water injection accumulation in black circle.

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AUTHOR CONTRIBUTIONS

DR: Main contributor, analyse and coordinated field data requirements, interpretation feasibility of key wells, and results, coordinated the data analysis, geological interpretation, results, validations and presentation of results; BA, P: Conceptualization, methodology, geophysical analysis; ES, IS, BGA : Validation and presentation of results.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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