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4D Seismic Inversion and Rock Physic Modeling to Monitor CO_2 Injection at Carbon Capture and Storage Project in The Utsira Formation, Sleipner Field, North Sea, Norway

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Abstract

Carbon Capture and Storage (CCS) is used at Sleipner Field due to the implementation of a carbon emission tax off the coast of Norway. This project causes the fluid at the Utsira Formation as a reservoir to be replaced by CO_2, so the elastic property of the reservoir rock will change. Because of that, the 3D seismic survey was carried out in 1994 (baseline) and re-acquisition in 2001 (monitor) to observe CO_2 distribution and changes in rock properties. This study aims to monitor the distribution of CO_2 as well as changes in reservoir rock's acoustic and elastic parameters. This research performed the cross-equalization, 4D Seismic Inversion model-based, and rock physics modeling process. From data processing, obtained information that CO_2 spreads laterally, then moves to the northeast and does not penetrate the overburden. Also, we get the NRMS value of 0.443068 and the cross-correlation value of 0.907426. 4D Inversion results reveal a change in the reflector at the reservoir zone, as indicated by the velocity pushdown caused for a decrease in seismic velocity owing to CO_2. In addition, rock physics modeling provides that changes occur in bulk modulus, Vp, Vs, density, and AI. From the process, there are differences in AI values where the Inversion results show a decrease in AI values of 2.9%, while rock physics modeling shows a 12% reduction.

INTRODUCTION

CO_2 sequestration is one way to mitigate the high emission of carbon dioxide gas in the atmosphere. CO_2 sequestration reduces the greenhouse effect in the atmosphere by capturing CO_2 and depositing it into rock formations in subsurface. CO_2 Capture and Storage (CCS) is a method that involves separating CO_2 from industrial and energy-related sources, transporting it to storage sites, and isolating it from the atmosphere for a long time (IPCC, 2005).

In 1996, CCS was carried out where CO_2 was captured, stored, and injected into rock formations, precisely in the Utsira Sand Formation, Sleipner, North Sea, Norway, as a mitigation effort to reduce CO_2 in the atmosphere. The Sleipner project injects 1 million tons of CO_2 per year under supercritical conditions (P = 7.39MPa, T = 31.10^{o}C) through a single deviation injection well, so the reservoir rock is kept at pressure and temperature. Hence, the injected CO_2 remains in a supercritical state. The captured CO_2 was deposited into the Utsira Sand Formation in the late Pliocene and early Miocene zones with thin clay, highly permeable, porous, and thick sandstones. In this project, the 3D seismic survey is used for monitoring the movement of CO_2 injected into the reservoir. This method is known as a 4D seismic time-lapse.

4D seismic entails repeating 3D seismic in a time-lapse mode to see changes in the subsurface image over time, whether due to hydrocarbon reservoir injection or depletion, CO_2 injection and storage for a sequestration project, or other time-variant subsurface processes (Lumley, 2001). The Utsira Sand is an unconsolidated sandstone with high porosity and permeability with average porosity of 40% (Zweigel et al., 2004). This CO_2 injection process was carried out in 1996, and in 1994 the first seismic survey was

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conducted as the baseline survey. The size and mobility of the injected CO_2 plume can be tracked using 4D seismic technology by combining two 3D seismic data sets. So, in addition to the 1994 survey, this study uses the seismic data acquired in 2001 as the monitor survey (Figure 1).

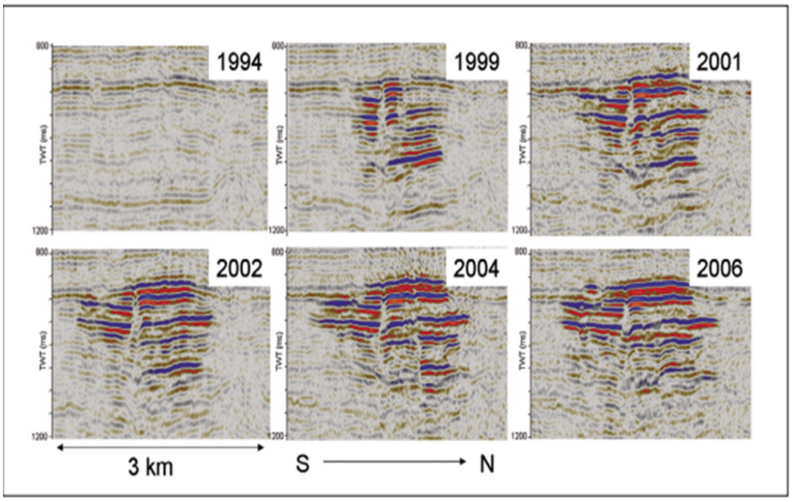

Figure 1. Seismic Image from Seismic Baseline 1994, and Seismic Monitor with Changes in CO_2 Plume until 2006 (Chadwick et al., 2008).

To conduct 4D seismic analysis, baseline and monitor must have at least fair – good repeatability. The difference in acquisition and processing parameters between the baseline and monitor can reduce the repeatability. One should perform a cross-equalization process in the overburden interval to reduce the differences between baseline and monitor due to the acquisition and processing effect. Cross-equalization is a phrase used to describe statistical techniques intended to reduce systematic discrepancies between surveys caused by non-repeatable acquisitions or processing (Ross et al., 1996). That makes sense because the fluid in the reservoir has changed, which affects the seismic image's response. These alterations include seismic image responses such as time shift, phase, amplitude, and frequency. Ideally, these alterations should only occur in the reservoir interval. If such alterations are observed above the reservoir, it could be due to the differences in acquisition and processing (Figure 2).

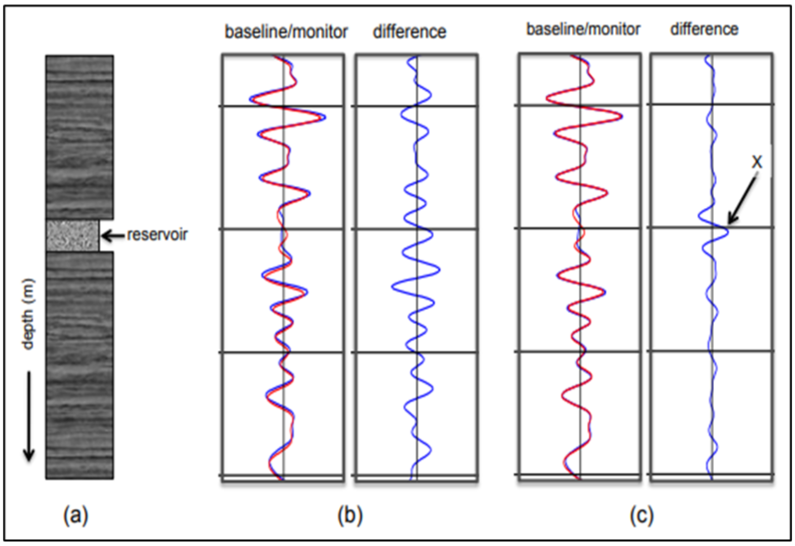

Figure 2. Cross-equalization Process Between Baseline and Monitor (Ayeni & Biondi, 2012).

Rock physics modeling helps characterize reservoir rocks based on properties that will affect the movement of seismic waves through the rocks. Therefore, using several methods, Rock physics modeling will look for the relationship between geology, elastic properties, and seismic parameters using several methods. CO_2 injection causes a change in the rock pore-filling fluid which can affect the acoustic and elastic properties of the rock due to changes in CO_2 saturation variations and an increase in pore pressure. However, in this study, we only analyzed changes in rock's acoustic and elastic properties that were affected by variations in CO_2 saturation, such as bulk modulus, density, Vp, Vs, and acoustic impedance.

MATERIAL AND METHODS

The well and seismic data for this research are accessible at https://co2datashare.org. The data is published by Equinor ASA via SINTEF on behalf of the CSDC (CO_2 storage Data Consortium) under the CC BY 4.0 license. This study uses full-stack time-lapse re-processed 3D seismic surveyed from 1994 as a baseline and 2001 as a monitor. The coordinates are UTM X 436708.50 and UTM Y 6468253.00, with 248 inline (1701 -1949) and 467 xline (880 – 1347) in a time interval of 0 – 2000 ms. The monitor data was acquired five years after the CO_2 injection, so there are already approximately 4.6 million tons of CO_2 in the Sand Utsira Formation. This study uses two well data: a production well (15/9-13) and an injection well (15/9-A-16). Table 1 and Figure 3 explain the available well log data for each well.

As Furre (2019) described, both seismic data have been re-processed for Time-lapse analysis purposes. So, the starting NRMS value between the two data is relatively low. The 4D process is initiated by calibrating phase, time, frequency, and amplitude between baseline and monitor. After both data have been calibrated, the 4D seismic inversion is carried out to observe the acoustic impedance difference in the reservoir area. The 4D inversion method used is model-based inversion which is a deterministic inversion approach. The inversion model was created from a low-frequency acoustic impedance model generated from high-cut filtered impedance information from well data. This model is then guided by the picked Top and Base Horizon of Utsira Sandstone to provide a more realistic low-frequency model. The 4D inversion algorithm inverts the baseline and monitors data simultaneously. After getting the inverted baseline and monitoring, the volume difference in acoustic impedance is calculated.

Table 1. Well Data Information.

Well	Depth	TVD	CALI	DT-CKS	DT	GR	NPHI	PHIF	RFT	RHOB	RT	SAND	SP	SW	VSH
15/9-13	V	-	V	V	V	V	V	-	V	V	V	V	V	V	V
15/9-A-16	-	V	-	-	-	V	V	V	-	V	V	-	-	-	-

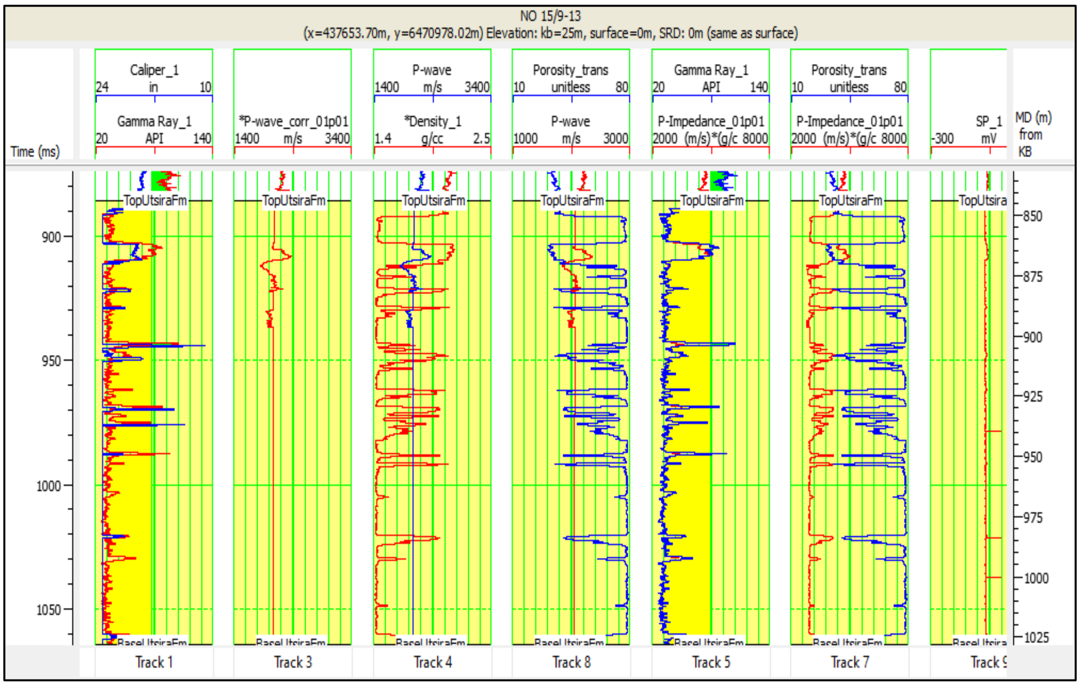

Figure 3. Utsira Sandstone Formation Marker in Well Data.

RESULTS AND DISCUSSION

Furre (2019) described that the baseline and monitor had been re-processed for 4D analysis. Therefore, the seismic volume of 2001 can be subtracted from the seismic volume of 1994 for seen that the changes are more evident in the reservoir interval. There is a contrasting amplitude which is probably due to fluid movement. Analysis of the subtraction process results was also carried out at overburden intervals, and there was no amplitude contrast due to CO_2 injection only in the reservoir. That process is called cross-equalization, which performs 4D calibration on seismic data. This process makes the phase, amplitude, time,

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and frequency the same between the baseline and monitor. Then a balancing process will be carried out above the reservoir. The window selection is carried out above the reservoir or in the overburden 200ms-750ms, marked with a red box in Figure 4. This selection is made so as not to touch the reservoir's surface.

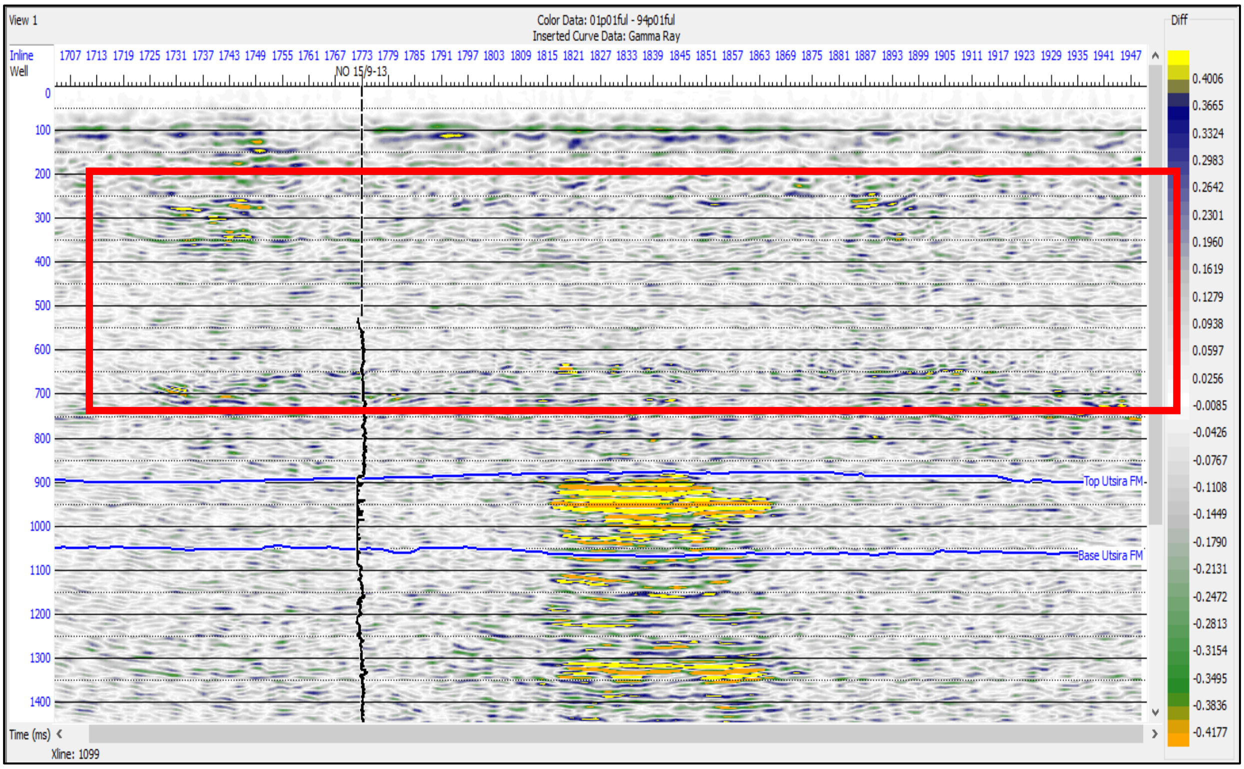
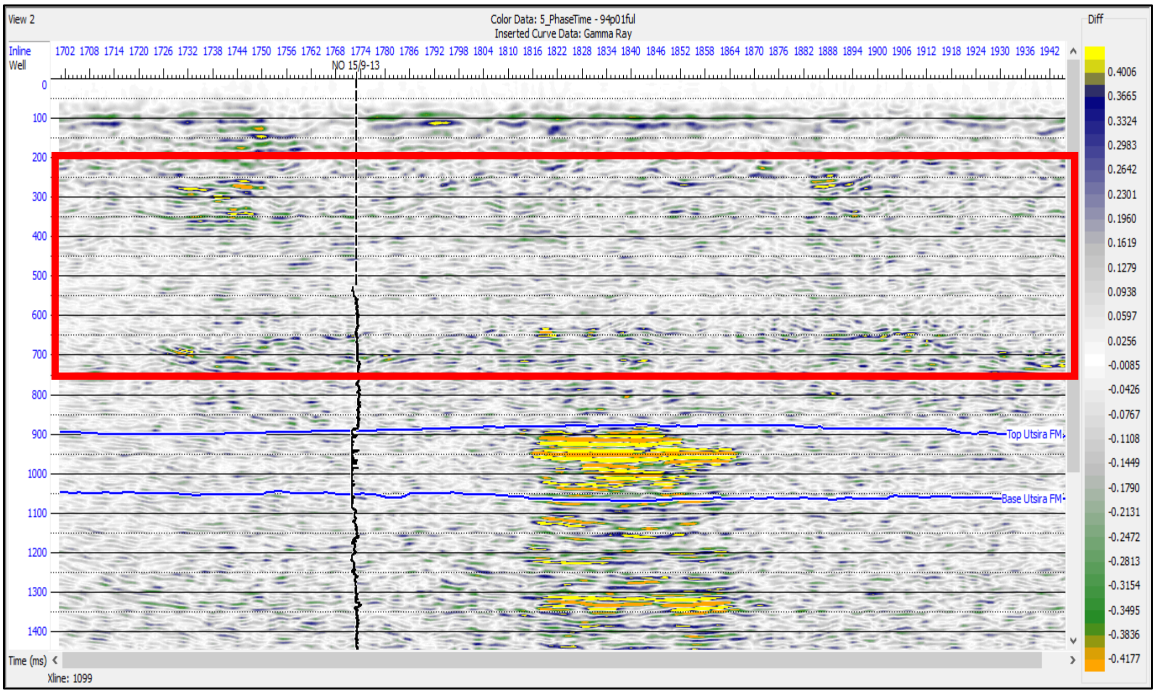


Figure 4. Seismic Volume Difference 2001 – 1994

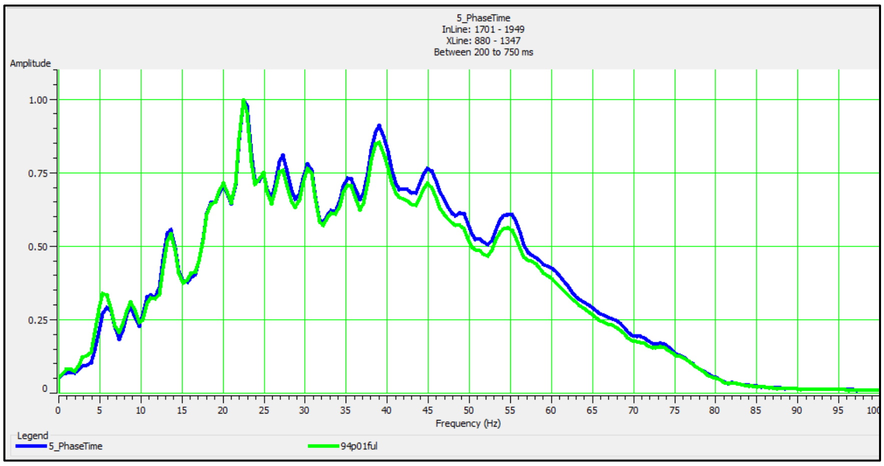
This step matches phase and timing to align the monitor's phase with the baseline. After performed this process, it turns out that there is no significant contrast between the difference as results of the PhaseTime process and the difference of previous results, as shown in Figure 4 and Figure 5 (a). The analysis window shown in the red box provides information that the result is similar. It indicates that phase and time are highly connected. Figure 5 (c) shows the Cross-correlation value of this process. The highest correlation is 0.9824, the lowest correlation is 0.8103, and the average correlation is 0.898106. Phase and time correction gives the NRMS value shown in Figure 5 (d), with the highest NRMS value being 0.6457, the lowest NRMS value being 0.2659, and the average NRMS being 0.459763. It indicates that the seismic data for 1994 and 2001 were processed with almost identical settings and had good repeatability.

This process filters the volume of the PhaseTime correction to make a more appropriate balance. This process is a continuation of the PhaseTime correction. Where this process can produce a better correlation value than the previous process, the cross-correlation results can be seen in Figure 6 (c), where the highest correlation is 0.9828, the lowest is 0.8134, and the average correlation is 0.899875. This formation process will subtract the amplitude value around the overburden analysis from the previous process. It is excellent because the quality of the process carried out is quite successful in equalizing or balancing the two seismic volumes. As more clearly shown by Figure 6 (b), the amplitude spectrum has matched between the monitor and the baseline. The bright spots shown in the red circle in Figure 6 (a) are the effect of subsurface natural gas because natural gas has a lower acoustic impedance than the original saline formation fluid. With this filter correction form, Figure 6(d) shows that the highest NRMS value is 0.6403, the lowest NRMS value is 0.2629, and the average NRMS is 0.455525. With this process, monitoring and baseline data have a better repeatability rate. The next step is the time-variant shift process.

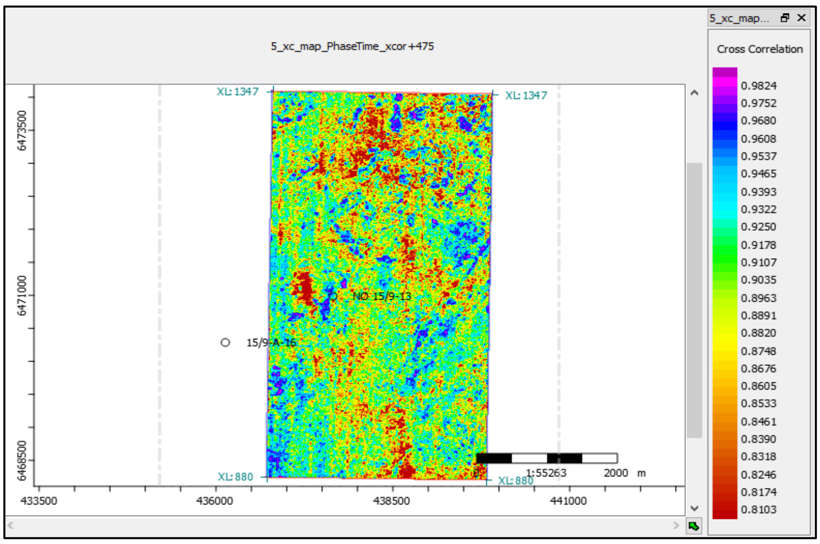
PhaseTime Correction



(a)



(b)



(c)

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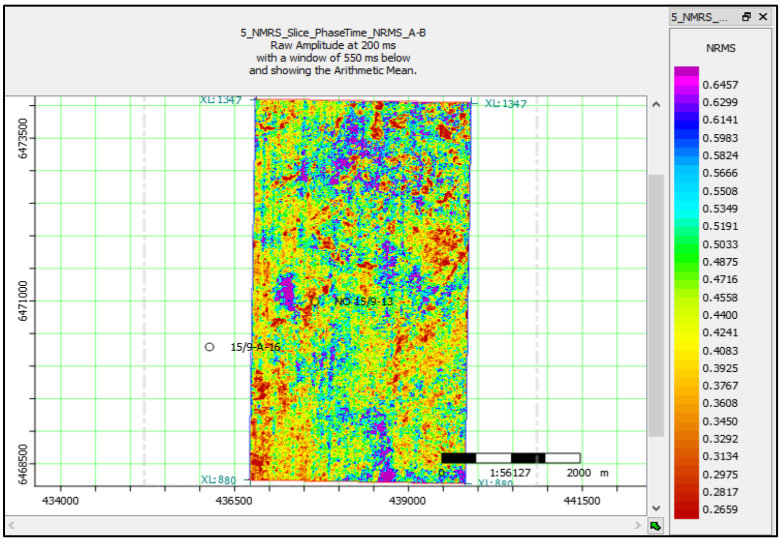
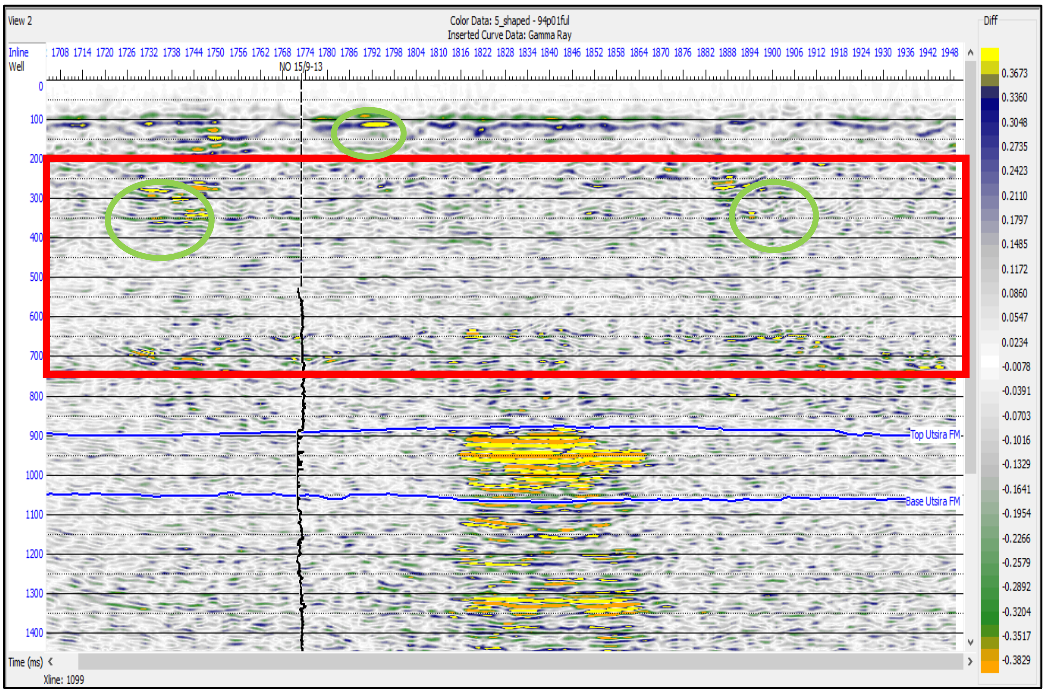


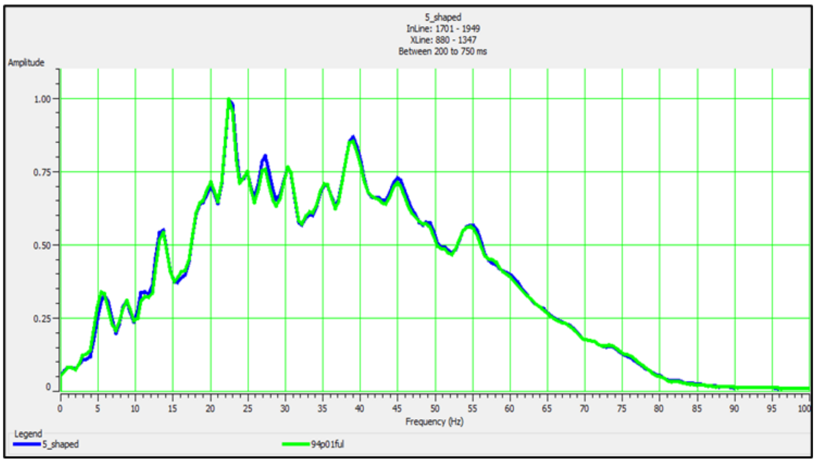
(d)

Figure 5. (a) Result of PhaseTime for display Volume Difference Between Baseline and Monitor, (b) Compare of PhaseTime amplitude spectrum between the monitor and baseline. (c) Cross-correlation map between monitor and baseline generated by PhaseTime process, (d) NRMS map between monitor and baseline generated by PhaseTime process.

Shaping Filter



(a)



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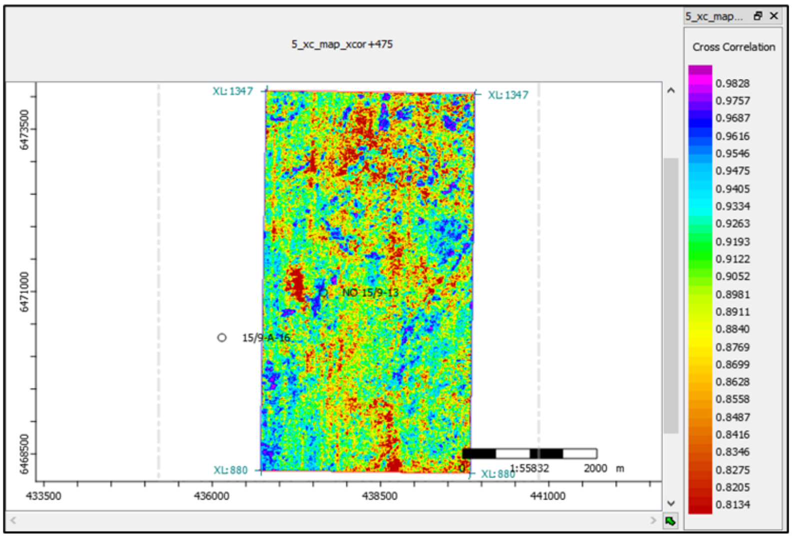

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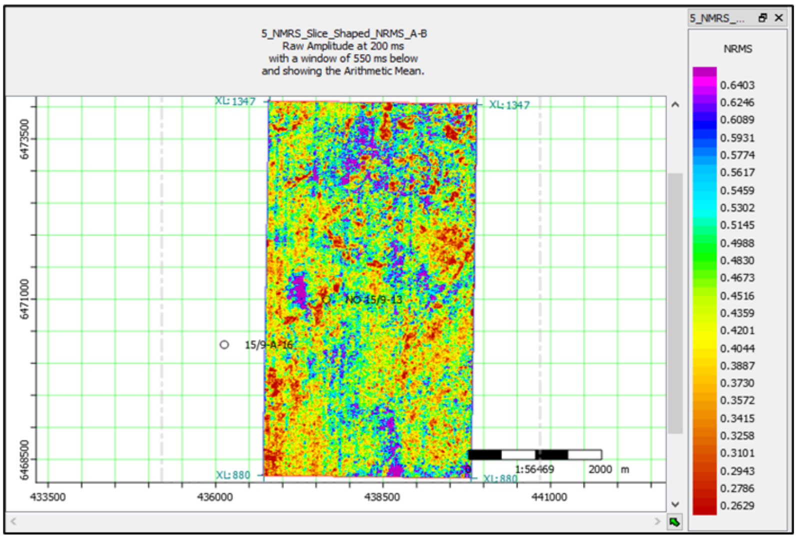

(d)

Figure 6. (a) Result of shaping filter for display Volume Difference Between Baseline and Monitor, (b) Compare of Shaping Filter amplitude spectrum between the monitor and baseline, (c) Cross-correlation map between monitor and baseline generated by Shaping Filter process, (d) NRMS map between monitor and baseline generated by Shaping Filter process.

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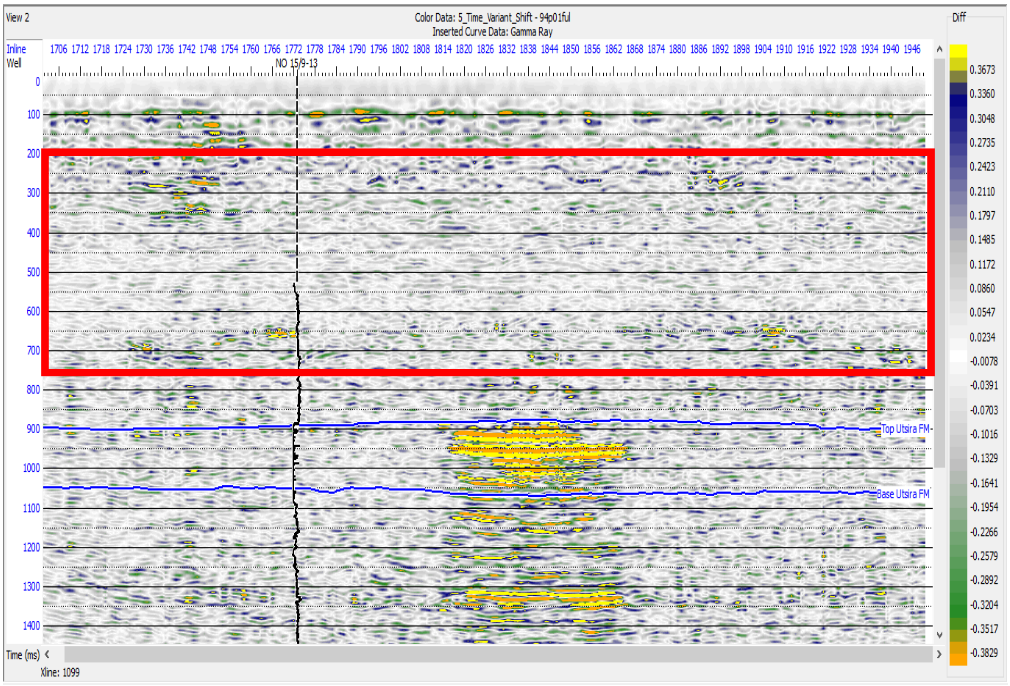
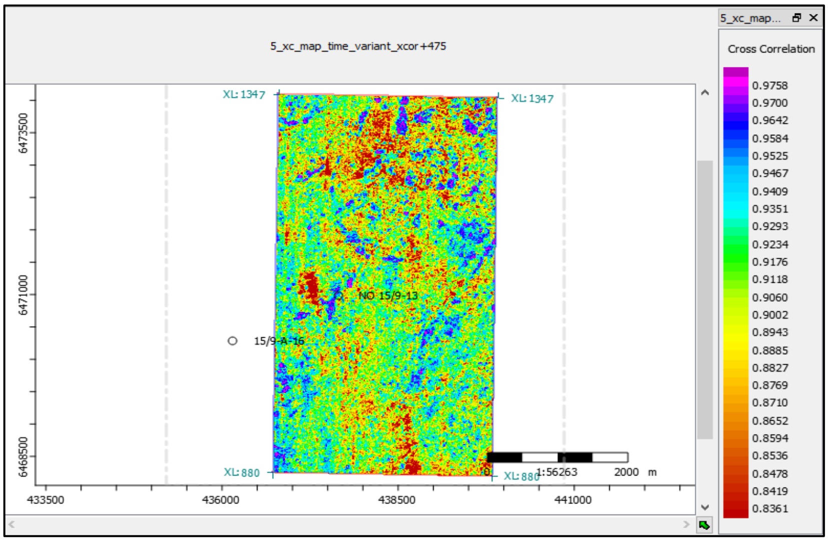
Time-Variant Shift



(a)

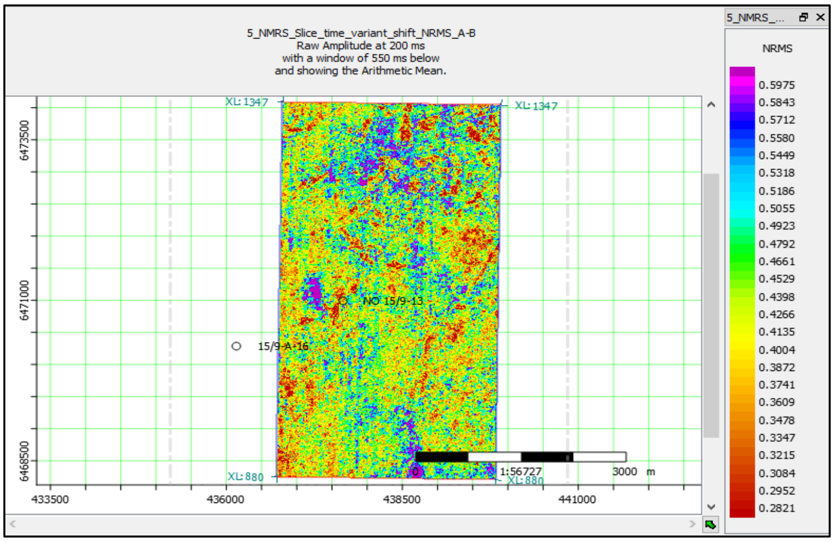


(b)

The time-variant shift process corrects the misalignment of the time calendar used. Timeshift calculates the time value and cross-correlation. This process will increase the correlation value, as seen in Figure 7 (b). The highest correlation value is around 0.9758, the lowest correlation is 0.8361, and the average is 0.907426. Time-variant shift process makes the NRMS value that previously changed, as shown in Figure 7 (c), the highest NRMS value is 0.5975, the lowest NRMS value is 0.2821, and the average NRMS is 0.443068. It means that the process successfully improves the quality of repeatability.

Table 2. Cross-Equalization Process Analysis.

No	Cross-Equalization	Time-Shift (ms)	Cross-Correlation	NRMS
1	2001-1994	0.035384	0.898106	0.459763
2	Phase-Time	0.035384	0.898106	0.459763
3	Shape Filter	-0.03252	0.899875	0.455525
4	Time-Variant Shift	-0.04711	0.907426	0.443068



(c)

Figure 7. (a) Result of Time-Variant Shift for display Volume Difference Between Baseline and Monitor, (b) Cross-correlation map between monitor and baseline generated by Time-Variant Shift process, (c) NRMS map between monitor and baseline generated by Time-Variant Shift process.

4D Inversion

This 4D inversion process will perform a seismic inversion using a model-based to see the difference between the Time-variant-shift (monitor) acoustic impedance difference and 1994 seismic (baseline) by following the flow chart in Figure 6. Before the inversion process, first form a low-frequency model.

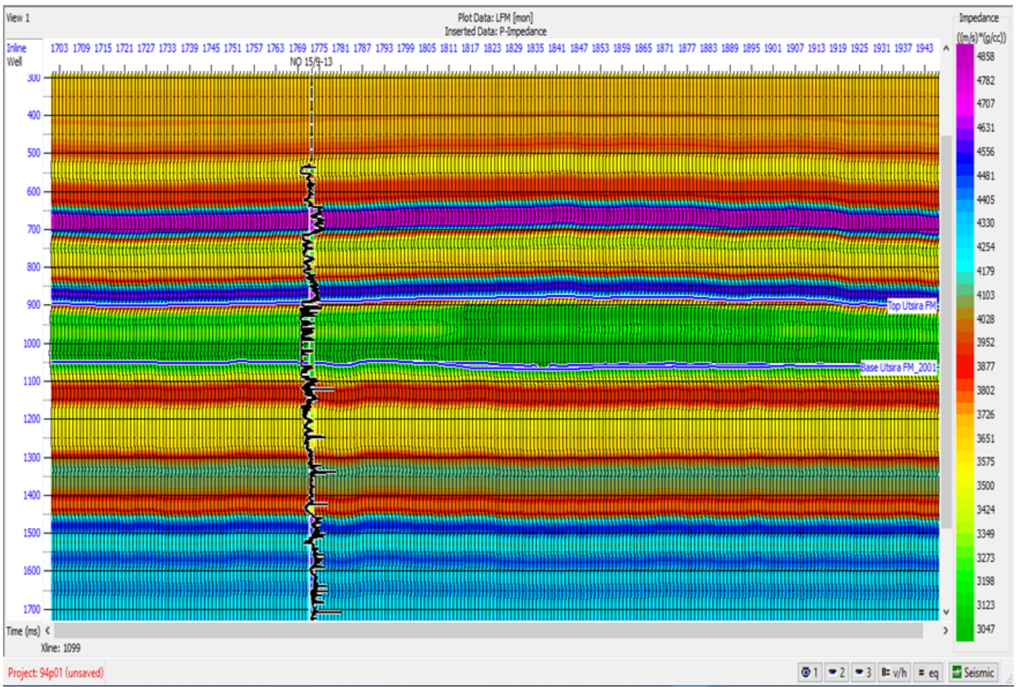


Figure 8. Low-frequency Model P-impedance

After creating a low-frequency model, we will do the inversion process. Acoustic impedance is limited to the upper or upper constraint of 30% and the lower limit or lower constraint of 30%. Since this process performs a 4D inversion process, it will be carried out once by inputting the time-variant shift (monitor) volume with the 1994 seismic volume as the baseline. Present the results of the 4D volume inversion, and limitations are also imposed around the reservoir from top to bottom. The top reservoir layer will be limited to above 50 ms, and the base reservoir layer will be below 50 ms.

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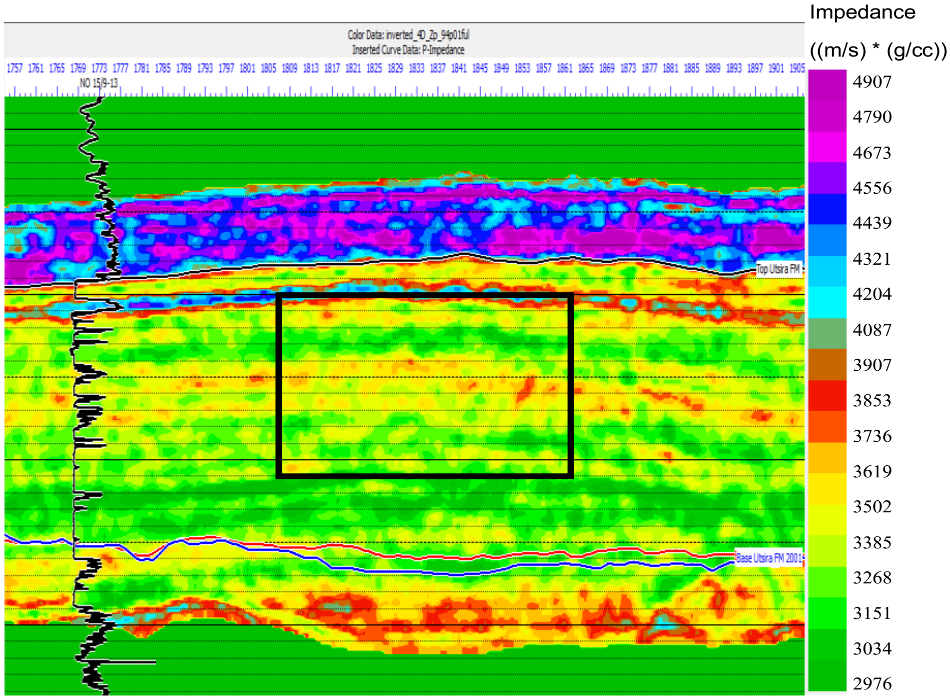
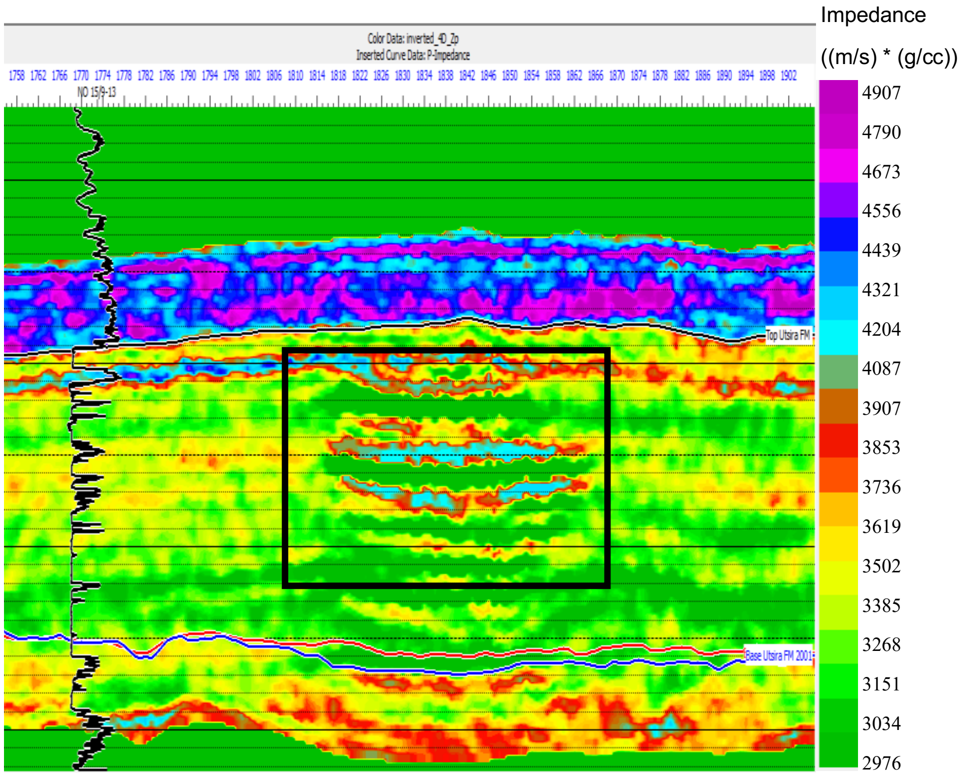


(a)



(b)

Figure 9. (a) Results of the 1994 Seismic Inversion Model-based, (b) Time-Variant Shift Inversion Results with Model-Based.

With the inversion process, the results of the 4D seismic inversion are shown in Figures 9 (a) and (b). By being marked with a black box, it can be seen in Figure 9 (b), which is the response of the amplitude of CO_2, lateral distribution under the top reservoir.

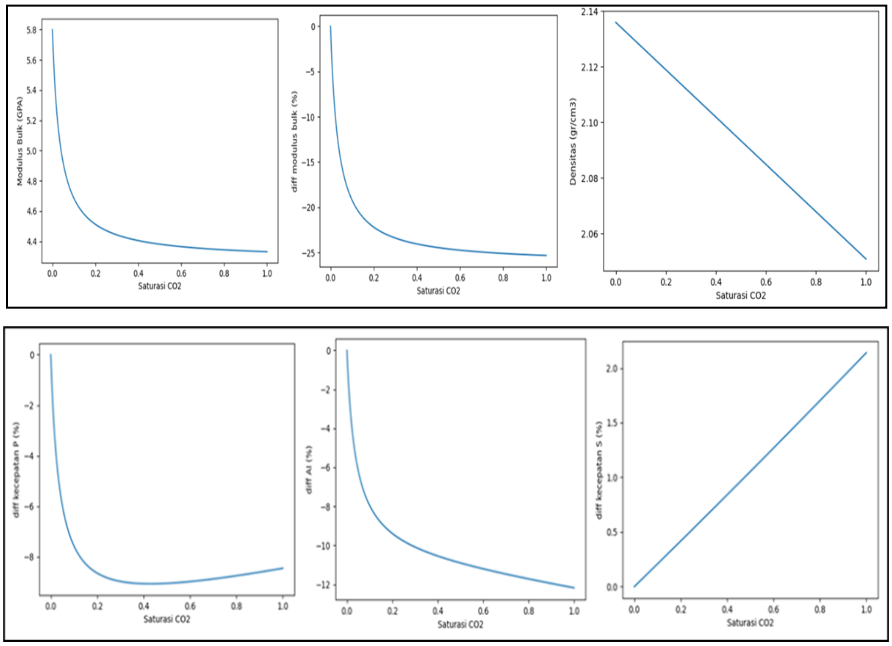


Figure 10. changes in the acoustic and elastic properties of rock were affected by variations in CO_2 saturation such as bulk modulus, density, Vp, Vs, and acoustic impedance.

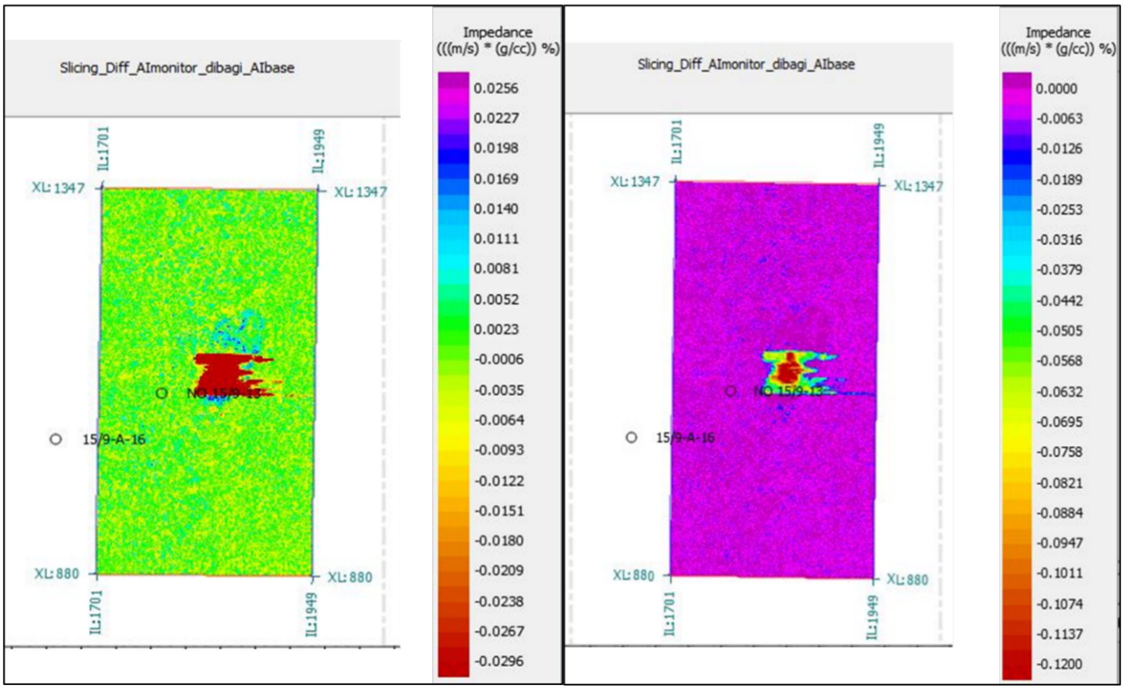


Figure 11. AI Difference Slicing from 4D Seismic Inversion (left) and AI Difference Slicing from Rock Physics Modeling (right).

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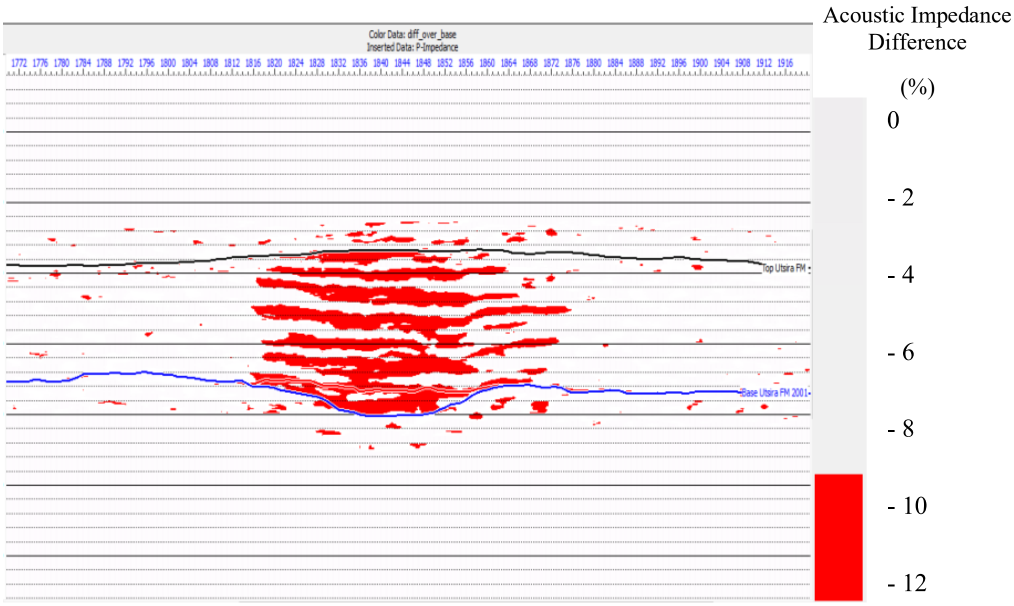

Figure 12. Relative Change in Acoustic Impedance.

Rock physics modeling in Figure 10 shows changes in bulk modulus, density, Vp, Vs, and AI because of the injection of CO_2. The analysis shows a decrease in bulk modulus of the saturated rock, bulk density, Vp, and acoustic impedance but a slight increase in Vs. Changes in the acoustic and elastic properties of rock due to CO_2 injection activities can be seen in the sharp decrease in bulk modulus of saturated rock by 25%, Vp 8%, and acoustic impedance by 12% when CO_2 saturation increases from 0 – 20%. Figure 11 shows AI Difference Slicing, and there are differences between the results of 4D Seismic Inversion and rock physics modeling. The area around the CO_2 injection point can be identified more specifically from the results of rock physics modeling. Therefore, the results of rock physics modeling are more suitable to be used to see the distribution of CO_2. In the injection point area, 100% CO_2 saturation causes a 12% reduction in AI. The presence of CO_2 causes a pushdown velocity in the reservoir. This display selection is more clearly visible in the xline 1120, which can be seen in Figure 12. The focus is a form of decreasing the acoustic impedance of the reservoir, which is characterized by a negative amplitude. This same decrease is interpreted as approximately 12%, as shown in Figure 12 when it is observed that CO_2 spreads laterally beneath the top reservoir.

CONCLUSION

This Research gives information that changes in the acoustic and elastic properties of rock due to CO_2 injection activities can be seen in the sharp decrease in bulk modulus of saturated rock by 25%, Vp 8%, and acoustic impedance by 12%. CO_2 saturation increases from 0 – 20%. In the injection point area, 100% CO_2 saturation causes a 12% reduction in AI. The presence of CO_2 causes a pushdown velocity in the reservoir. CO_2 spreads laterally, then moves to the northeast, and does not penetrate the overburden.

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