Pore pressure changes estimation and CO_2 detection using joint inversion of PP and PS data and dynamic rock physics modeling for monitoring Delhi Field reservoir

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Abstract

Delhi Field is a enhanced oil recovery (EOR) project with active monitoring by 4D multicomponent seismic technologies. The reservoir is composed of Paluxy and Tuscaloosa sandstones. The complex stratigraphy of the Tuscaloosa as well as the Paluxy sandstones represent a challenge for the dynamic reservoir characterization of this highly heterogeneous reservoir.

Dynamic rock physics modeling integrates the rich dataset of core, well logs, thin sections and facies providing a link between reservoir and elastic properties. We use Vp/Vs ratio and acoustic impedance to quantify pore pressure and to detect CO_2 saturation changes in the reservoir. PP and PS seismic data are used to jointly invert for Vp/Vs ratio and acoustic impedance. Combining of the inversion results from the monitor surveys of June 2010 and August 2011 provides impedance and Vp/Vs percentage differences. The time-lapse inverted response fits the predicted dynamic models (calibrated at the wells).

The results indicate that reservoir heterogeneities and pore pressure gradients control the CO_2 flow. Tuscaloosa Formation shows pressure increase close to the producers and Paluxy water injectors. CO_2 anomalies located above the Paluxy injector 148-2 indicates possible CO_2 migration from Paluxy up to the Tuscaloosa Formation. These facts make reservoir monitoring important for hydrocarbon recovery and reservoir management at Delhi Field.

Introduction

Delhi Field is located in northeastern Louisiana, 40 miles west of Louisiana-Mississippi border (Silvis, 2011) and 35 miles from Monroe (Figure 1). Geologically Delhi, lies at the western margin of the Mississippi Interior Salt basin (Alam and Pilger, 1988) and at the southern flank of the Monroe uplift (Bloomer, 1946) (Figure 1). The field is 15 miles long by 2–2.5 miles wide covering an area of 6200 acres. The original oil in place (OOIP) is about 357 MMbbl (Powell, 1988) and has an API gravity of 43.9 (Denbury Resources Inc.). The field was discovered in 1944, primary and second recovery was about 14% and 40% respectively (Bloomer, 1946). The peak production of the field was 18000 barrels per day (BOPD). The CO_2 continuous flooding program started in November 2009.

Figure 1: Delhi Field is located at northeastern Louisiana. It lies in the southern flank of the Monroe uplift and Mississippi Interior Salt Basin (MISB). Jackson dome is the CO_2 source for Delhi Field (modified from Denbury Resources Inc).

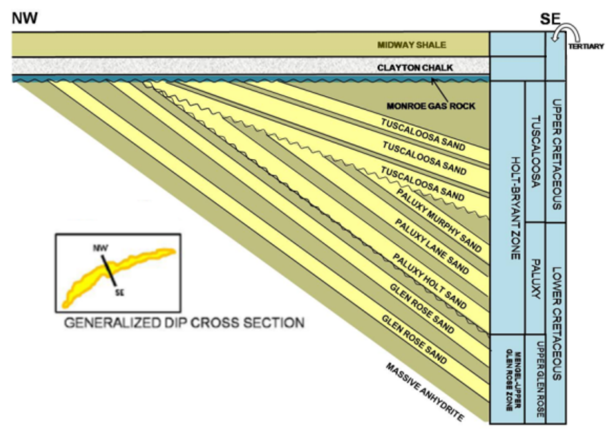

Figure 2: Northwest to southeast PP seismic cross-section showing the trap of the reservoir. The main reservoir is composed of Paluxy and Tuscaloosa sandstones. The top seal corresponds to the Midway Shale. Note that the pinch out is located from southwest to northeast (modified from Denbury Resources Inc).

The main reservoir is the Holt Bryant zone that lies at depths between 3,000 and 3,500 feet, which is composed by Tuscaloosa and Paluxy sandstones of Early and Late Cretaceous age respectively (Figure 2). In this study we focus the interpretation in the Paluxy and the lower Tuscaloosa Formation. The lower Tuscaloosa consists of transgressive marine deposits (Klepacki, 2012). The Paluxy represents a progradational deltaic depositional environment (Silvis, 2011). Paluxy and Tuscaloosa Formations range in thickness from 30 to 85 feet.

Two multicomponent seismic surveys that cover 4mi^2 were acquired in June 2010 and August 2011 after the CO_2 flooding began. The seismic surveys were processed by using a time-lapse processing sequence. Normalized root-mean-squared (NRMS), a commonly metric used to measure the similarity between the two different surveys was calculated above the reservoir. NRMS values around 0.2 and 0.3 for PP and PS data, respectively, show excellent to good data repeatability (Lumley, 2009) in our data set.

The dynamic reservoir characterization has the objective of evaluating the CO_2 movement and pressure changes between the seismic surveys (August 2011 and June 2010). We present a workflow based on dynamic rock physics modeling in order to make an integrated interpretation using well log, core data, facies modeling and joint post-stack seismic inversion of 4D multicomponent data.

Dynamic rock physics modeling

We use the unconsolidated and the cemented sandstone models based in granular media to study the high porosity Paluxy sandstones, developed by Dvorkin and Nur (1996) and Dvorkin et al. (1994), respectively. Although none of these models represents the real rocks they are very powerful to link reservoir and elastic properties allowing to predict the seismic signature in the reservoir when carefully applied.

Two wells, X-ray diffraction (XRD), thin sections, core and facies data information were used to calibrate the rock physics model. The rock physics model used the Paluxy and lower Tuscaloosa unit average composition of 85% quartz and 15% clay. Figure 3 shows the shear bulk modulus and the unconsolidated and cemented model. One can note that the model falls mainly in the red line that indicates unconsolidated sandstone model. This observation is consistent with the thin sections information shown in Figure 4 where one can see minor compaction and no cementation.

The scope of the dynamic rock physics modeling for Delhi Field consists of quantifying elastic properties percentages changes to mimic the changes in the reservoir due to CO_2 injection. Usually pore pressure and CO_2 saturation changes occur at the same time while the field is being flood with CO_2. Therefore, we model both scenarios at the same time. We use the unconsolidated sandstone model for the pore pressure changes modeling and Gasmmann's equation for the fluid substitution (Gassmann (1951)). We use 12.5 MPa as initial pore pressure and model changes ranging from between -3 Mpa to 6 MPa. For the fluid substitution, the initial saturation is 35% oil and 65% brine and then, we replace with CO_2.

Vp/Vs ratio and acoustic impedance crossplot is used to evaluate the modeling results (Figure 4 *a*). Note that a small amount of CO_2 decreases dramatically both elastic

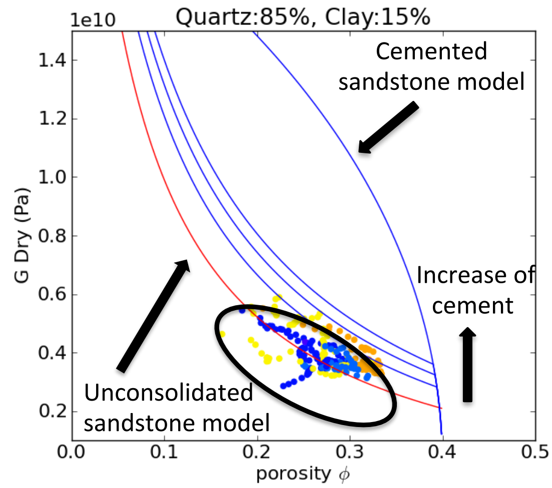

Figure 3: Rock physics model calibration for the Paluxy and lower Tuscaloosa facies. The scatter points represent the shear modulus values obtained from the well logs. Note that the values fit the unconsolidated sandstone model.

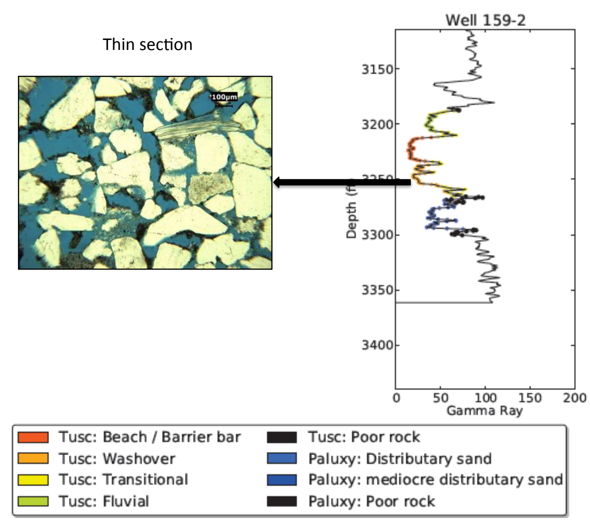

Figure 4: Lower Tuscaloosa unit thin section at 3250 ft. Color code represents the facies definition done by Klepacki (2012). Note that there is minor compaction and no cementation.

properties. The non-linear behavior of CO_2 makes it easy to detect but difficult to quantify. Pore pressure changes have almost linear behavior. We extend the modeling for 100% CO_2 replacing oil and brine and then, use natural neighbor interpolation in order to interpolate pore pressure changes (Figure 4 *b*).

4D Joint PP and PS inversion

Joint PP and PS inversion has been demonstrated to be a powerful tool for reservoir characterization in complex geologic fields due to its ability to discriminate between fluid and lithology. Acoustic impedance is more sensitive to fluids and shear impedance to lithology (Dang, Yufang and Lou, Bing and Miao, Xiaogui and Wang, Pu and Zhang, Sihai and Shen, Liang, 2010; Fraquelli and Stewart, 2013).

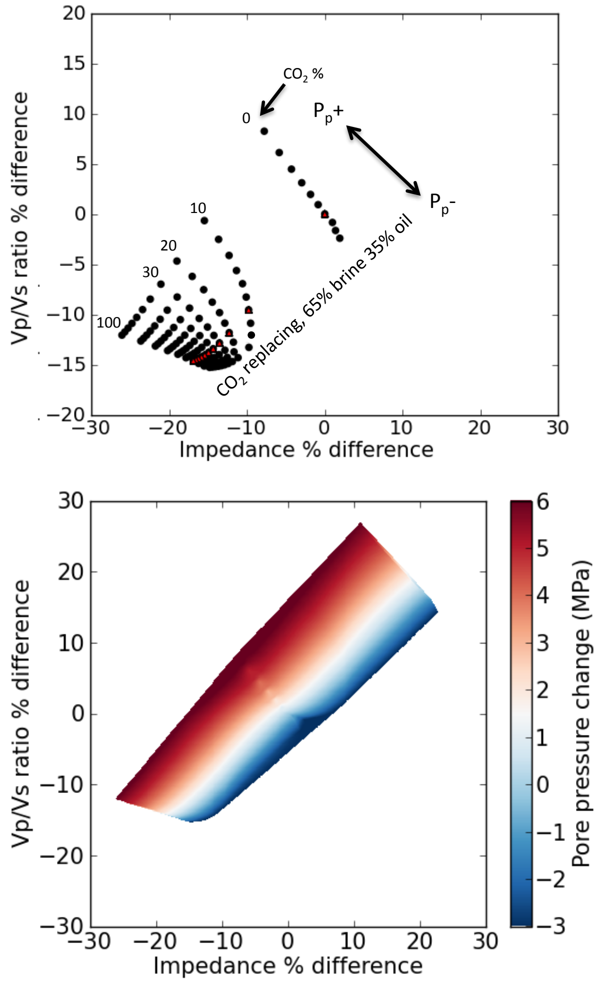

Figure 5: *a)* Top, Vp/Vs and acoustic impedance crossplot of pore pressure and CO_2 saturation changes. Pore pressure ranges from -3 to 6 MPa using a pore pressure reference of 12.5 MPa. The initial saturation is 35% oil and 65% brine and then, we replace up to 100% CO_2. *b)* pore pressure interpolation from *a)* and for brine and oil replacing CO_2.

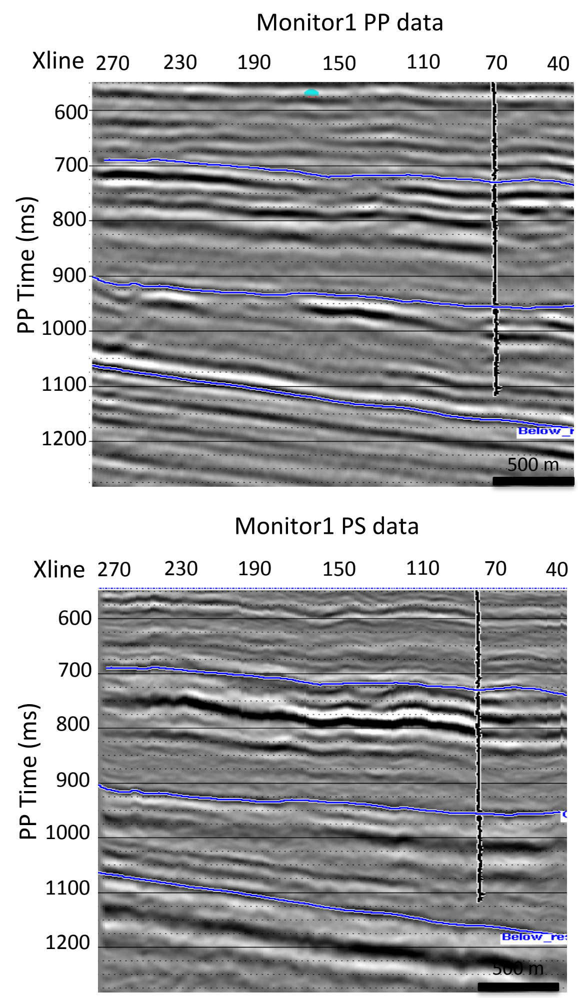

Figure 6: *a)* PP seismic section. *b)* PS seismic section registered at PP time. The blue horizons corresponds to the horizons used in the registration process. These horizons are located above, at top and below the reservoir.

PS data have also been used to discriminate pressure and fluid saturation for reservoir monitoring in synthetic data (Landro et al., 2003; Shahin et al., 2008).

The joint inversion was applied using commercial software. Inversion has the advantage of constraining PP and PS data, meaning that more information is added to an ill-posed problem. The reader is referred to Hampson et al. (2005) for a complete review of this inversion method.

In order to generate the inputs we create synthetic seismograms of PP and PS wave to update the time-depth conversion. Then, we registered PS data to PP time by tying 3 horizons between these data. Figure 5 *a* and *b* shows the registration for monitor1 survey (June 2010), this process was done for both surveys. P impedance and density low frequency model were generated from the well logs and horizon picking. The shear impedance initial model was generated combining the low frequency model of P impedance and density with the Vp/Vs ratio generated in the registration.

The inversion was performed in the two multicomponent seismic surveys. The inversion validation consisted in calculating a difference volume for the acoustic impedance and Vp/Vs ratio between the monitors. One should expect to find differences in the reservoir zone related to the changes in the reservoir due to CO_2 saturation and pressure, this can be observed in Figures 6 *a* and *b* where no main differences are present in the overburden.

The Vp/Vs ratio and acoustic impedance percentage difference results in the Paluxy and lower Tuscaloosa unit are shown in Figure 7. Note that inversion results fit the predicted dynamic rock physics modeling.

Integrated interpretation

Paluxy Formation

The amount of CO_2 injected between the two seismic surveys or 13 months of continuous injection is approximately 24 billion cubic feet (BCF) in the Paluxy Formation. The amount of produced CO_2 is 4.5 BCF.

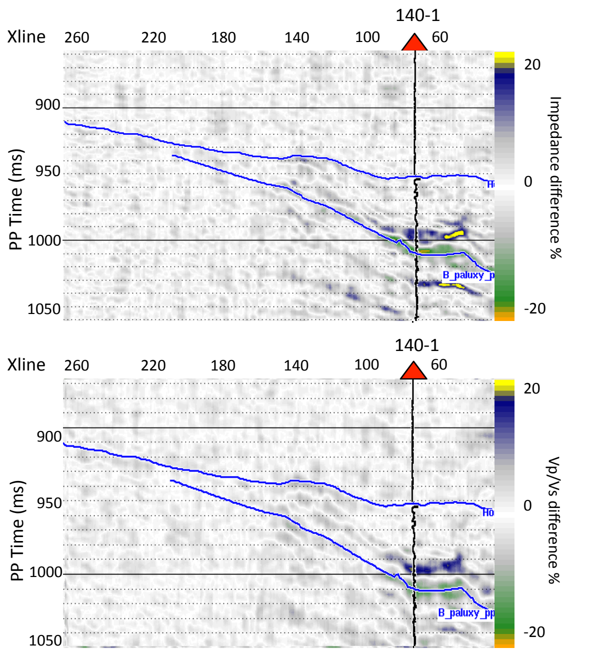

Figure 7: Difference volume between the seismic surveys for *a)* inverted acoustic impedance and *b)* Vp/Vs ratio. Note that the main differences is located in the reservoir zone. The red triangle indicates the location of the injector well 140-1

Hence, there is a lot of CO_2 that we need to track. Acoustic impedance negative changes are used to detect CO_2.

Figure 8 *a* shows the 4D acoustic impedance difference. The blue dashed line indicates the oil water contact (OWC) interpreted by Denbury Resources Inc. The arrows indicates the direction of anomalies observed near injectors 140-1 and 148-2. Note that CO_2 is moving downdip in the opposite direction from where the producers are. These anomalies are following a path correlated with the low pseudo gamma ray values obtained by (Ramdani, 2012). Low pseudo gamma ray values indicates high quality reservoir. The dashed lines to the right indicates a possible distributary channels in Figure 8 *c* . The black ellipsoid indicates in Figure 8 *a* an area where there is not much CO_2 production and corresponds to a low quality reservoir.

The water injectors located in the south are flooding the Paluxy Formation with the objective to pressure up the reservoir in this zone to force the CO_2 to move updip. Nevertheless, no positive acoustic impedance was observed in this zone.

Figure 8 *b* shows the pore pressure map in the Paluxy Formation. Note that in general the reservoir is pressuring up, especially around the producers and close to the pinch out in the north east. Also note, that the pore pressure gradient and the reservoir heterogeneities controls the CO_2 flow.

Bottom hole pressure data was checked to verify the results. However, these data did not correspond to the dates when seismic was acquired. Another limitation is that there are no zonal measurement for each well.

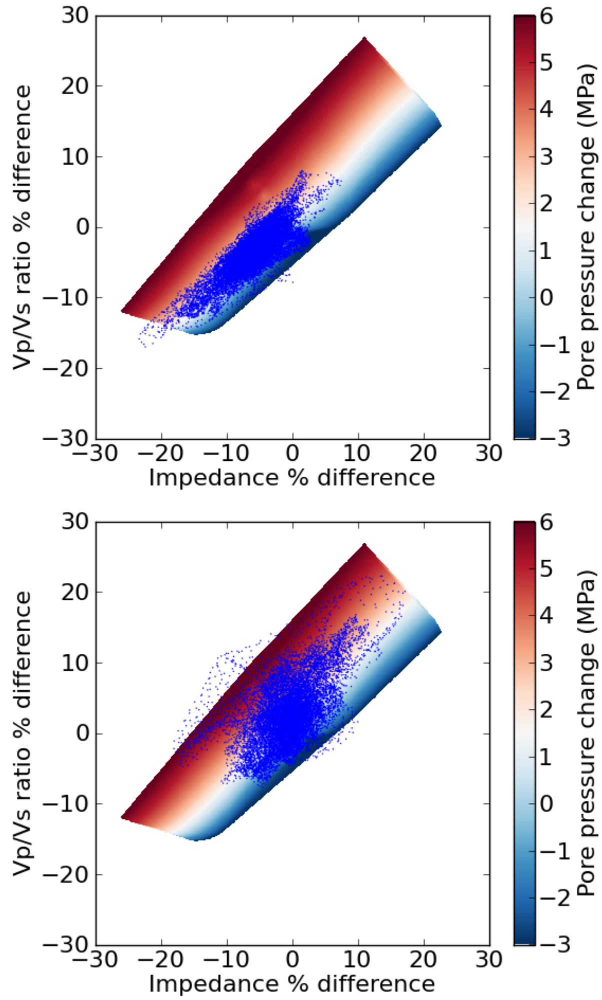

Figure 8: Crossplot of Vp/Vs ratio and acoustic impedance of the 4D inversion results (scatter points) overlay with the predicted model for *a)* Paluxy Formation and *b)* lower Tuscaloosa unit

Lower Tuscaloosa unit

The injection pattern in the Tuscaloosa Formation is complex due to the sandstone bodies that are not continuous throughout the field. Delhi Field has five Tuscaloosa injectors in the RCP area. There are two injectors in the lowermost Tuscaloosa interval.

We follow the interpretation workflow used in the Paluxy Formation for the dynamic characterization of the lowermost Tuscaloosa interval. First CO_2 is evaluated and then we show the pore pressure map. Figure 8 *a* shows the acoustic impedance difference maps between the surveys. There is CO_2 around the two injectors indicated by the red triangles. Note there is CO_2 far from the injector locations, for example, in the pinch out zone and close to well 148-27. There is a possibility of Paluxy injectors losing CO_2 into Tuscaloosa at Paluxy injector well 148-2. These observations were noticed by Robinson (2012) where she analyzed amplitudes time-lapse anomalies between the monitor1 and a baseline shot before the CO_2 flooding started.

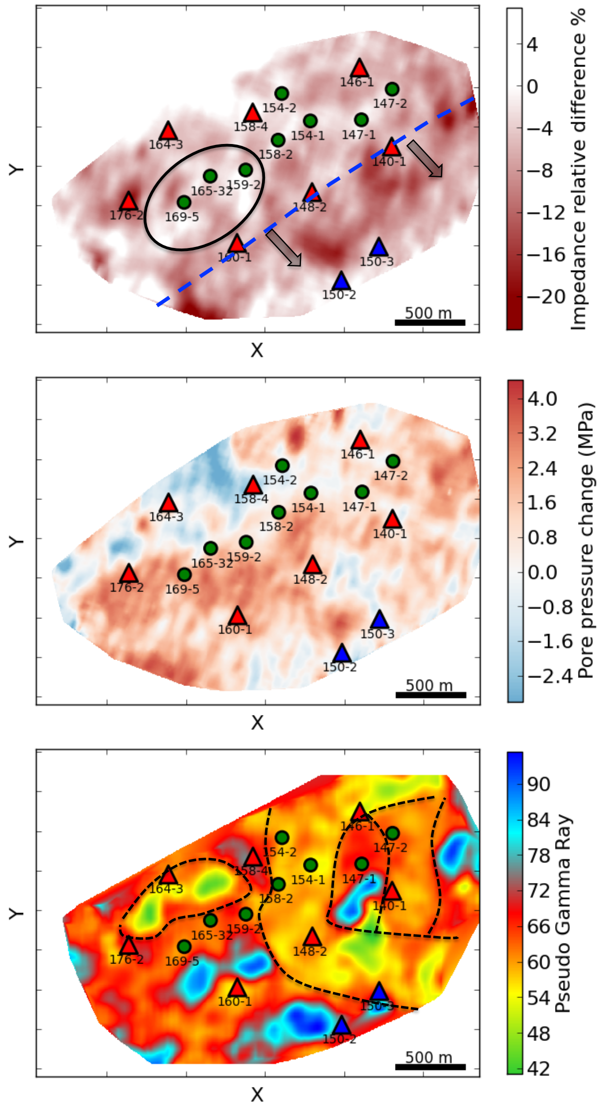

Figure 9: Paluxy interpretation of *a)* 4D acoustic impedance difference. The ellipsoid indicates an area with low acoustic impedance anomaly that is related with few CO_2 time-lapse changes *b)* interpreted pseudo gamma ray, modified from Ramdani (2012) *c)* pore pressure changes map. The red triangles are the Paluxy CO_2 injectors. The blue triangles are the Paluxy water injectors. The green circles are the Paluxy producer wells.

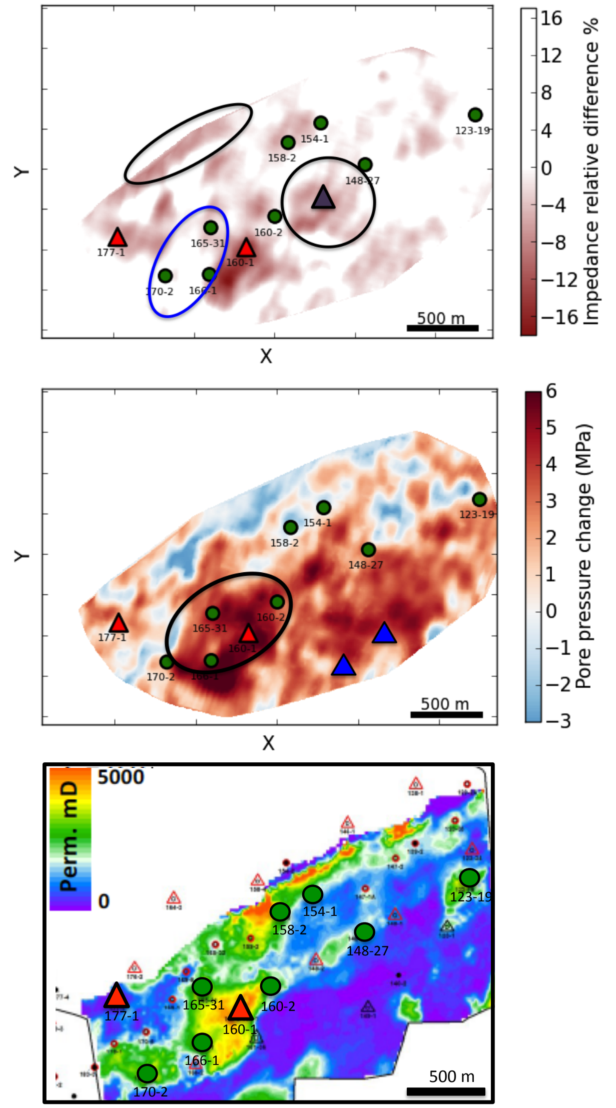

Figure 10: Lower Tuscaloosa unit interpretation of *a)* 4D acoustic impedance difference. The black ellipsoids indicates CO_2 anomalies. The blue ellipsoids indicates an area of few CO_2 time-lapse changes *b)* pseudo permeability map, modified from Klepacki (2012) *c)* Pore pressure changes map. The black ellipsoid indicates the area where pore pressure increased the most. The red triangles are the Tuscaloosa CO_2 injectors. The blue triangles are the Paluxy water injectors. The purple triangle is the Paluxy injector 148-2. The green circles are the Tuscaloosa producer wells.

A pseudo permeability map obtained through seismic-driven facies inversion Klepacki (2012) for this interval is shown in Figure 8 *c*. From this permeability map we can recognize that the producing wells are located in high permeability zones. Nevertheless, the CO_2 has not reached yet important areas marked by the blue dashed lines in Figure 8 *a*.

The pore pressure map is shown in Figure 8 *c* where we see that this interval is pressuring up, especially in the zone highlighted zone that corresponds to high permeability. In the southeast zone we observe pressure in up and no CO_2 this can lead to think that water is being bypassed through the Paluxy injectors located below this interval.

Conclusions

From this work we have shown a workflow to quantify pore pressure changes and to track CO_2 for time-lapse reservoir monitoring, combining dynamic rock physics modeling and joint inversion of PP and PS data in Delhi Field. This workflow can be used as an example for monitoring unconsolidated reservoir sandstone fields.

The dynamic rock physics modeling showed that the non-linear behavior of CO_2 when replacing brine and oil makes CO_2 detection easy but difficult to quantify. Pore pressure changes behave almost linear in the Vp/Vs ratio and acoustic impedance domain.

Joint inversion showed reliable quantification of Vp/Vs ratio and acoustic impedance percentage differences values that fit in predicted dynamic models consistent with the geological model for the Paluxy Formation.

Paluxy injectors 148-2 and 140-1 showed CO_2 is going downdip following a possible distributary channel and induced by differential pressure from an updip injector or a barrier caused by a heterogeneity in the reservoir.

Tuscaloosa Formation showed CO_2 anamolies located above the Paluxy injector 148-2 related with possible CO_2 migration from Paluxy up to the Tuscaloosa Formation.

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