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4D Pre-stack Time Migration - Application to Thermal EOR Monitoring

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SUMMARY

In 4D seismic, the velocity model used for imaging and reservoir characterization can change over calendar time as the reservoir is produced. This is particularly true for heavy-oil reservoir produced by steam simulation (EOR).
We propose an automatic 4D update of the 3D velocity model using an efficient technique based on 4D pre-stack time migration (4D-PSTM) that describes the pre-stack differential kinematic effects by matching the 4D dataset.
On real continuous 4D seismic data, the 4D-PSTM allows us to quantify interval velocity variations that can be used to map temperature changes in the reservoir in agreement with petro-elastic model expectations.

Introduction

In 4D seismic, the velocity model used for imaging and reservoir characterization can change over calendar time as the reservoir is produced. This is particularly true for heavy oil reservoirs produced by steam stimulation (EOR).

In our onshore continuous seismic monitoring case studies, the seismic sources and sensors are always permanently buried. The seismic data are usually acquired and processed on a daily basis (sometimes over an interval of a few hours) to produce real-time well production action plans (Forgues et al. 2006 & 2011, Cotton et al. 2013). From one day to the next, we must decide: When and how should the velocity model be updated?

We propose here an automatic update of the 3D velocity model, on a daily basis, using a fast technique based on 4D pre-stack time migration (4D-PSTM). The 4D-PSTM has the great advantage of being very simple and efficient. It uses pre-stack data so the dynamic effects are better described than for post-stack data where these effects are completely lost. The method could also be used to solve time-alignment issues prior to reservoir characterization alternatively to the approach proposed by Williamson et al. 2007.

We apply 4D-PSTM on real continuous 4D data acquired for Shell for steam injection monitoring.

4D Context

A highly repeatable continuous 4D seismic has been recorded on a small steam-assisted heavy oil area with a limited number of buried sources (36) and sensors as described in Hornman et al. 2012. The sparse data configuration with a maximum offset of less than a kilometer leads to a very low fold (<6) and then to a very limited number of angle stacks. As the continuous acquisition produces a 3D seismic volume every day, the processing must be automatized and the daily changes in the reservoir are obviously very small (<10µs/day). Given the need for a fast method and the sparse data configuration, standard velocity analysis as well as more advanced 4D wave-equation based processing (Shragge & Lumley, 2013; Perrone and Sava, 2013) may not be feasible.

For this case study, Michou et al. (2013) have performed a post-stack 4D acoustic inversion and achieved the quantification of the 4D effect in terms of P-impedance (ΔIp) in agreement with the Petro Elastic Model (PEM).
However, ΔIp estimates only a bulk combination of the density and the P-velocity variations (ΔVp and ΔRho) and does not help to distinguish between temperature and steam saturation evolution. Indeed, many combined evolutions of steam saturation and temperature evolution could give the same ΔIp result (Figure 1).

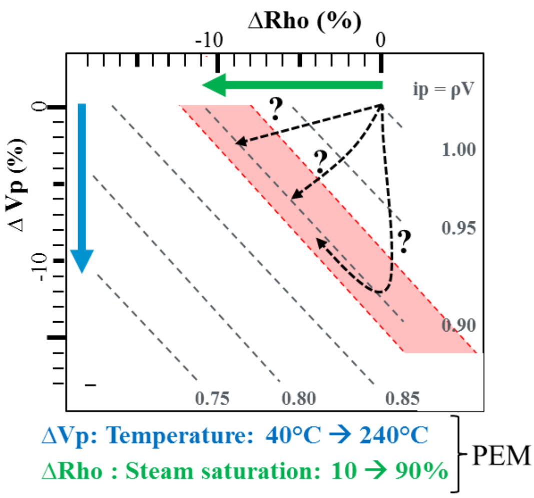

Figure 1: Vp vs Rho diagram vs P-impedance (dashed lines). The ΔIp results as described in Michou et al. (2013) are depicted by the red corridor.

To quantify the velocity variations in the reservoir, we use a 4D pre-stack time migration that we call "4D-PSTM." With the 4D-PSTM, we compute velocity variations that highlight thermal changes in the reservoir. The 4D-PSTM datasets are then free from velocity dynamic effects. The only remaining effect (ΔRho), essentially due to the steam saturation, can be estimated by a subsequent 4D inversion.

4D-PSTM

Pre-Stack Time Migration (PSTM) can be written as in Equation 1 where m is the migrated image of the observated data p_{obs} , **M*** is the migration operator and $(v0)$ is the velocity model. For the 4D-

PSTM, we define an objective function that describes the 4D matching between datasets as in Equation 2.

$$m = \mathbf{M}^*_{(v0)}\, p_{obs} \tag{1}$$

$$J(\Delta \boldsymbol{v}) = \sum ||\mathbf{M}^*_{(v0)}\, p_{obs1} - \mathbf{M}^*_{(v0+\Delta v)}\, p_{obs2}\, ||^2 \tag{2}$$

The optimal velocity $(v0 + \Delta v)$ is found when the objective function J is minimized. At this step, $(v0 + \Delta v)$ corresponds to a 4D RMS velocity model (VRMS4D) that integrates velocity changes (ΔVRMS4D) over the entire time section. We derive the interval velocity (VINT4D) between geological horizons using Dix's formula to estimate the velocity change in the reservoir (ΔVINT4D).

The 4D-PSTM is applicable in the case of small VRMS4D variations (ΔVRMS4D <=1%). For higher values of ΔVRMS4D, amplitude changes may have to be jointly modeled. The same strategy could be used to match simultaneously all the available datasets (instead of "2 by 2") to constrain the process in the calendar time.

Results

In this case study, the 4D-PSTM was done by matching each daily dataset with the same reference dataset (05/25/2012). The interval velocity layer thickness was fixed (Figures 2 and 3).

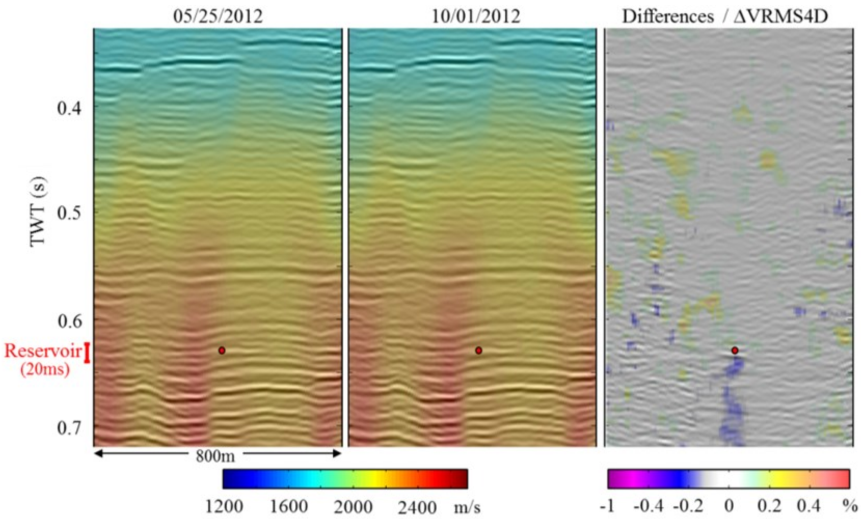

Figure 2: *PSTM sections for 05/25/2012 (left) and 10/01/2012 (middle). The VRMS4D values are overlaid on the seismic. Right panel: the seismic (gray scale background) represents the differences x3 between the two PSTM sections. The ΔVRMS4D are overlaid using the color scale. A small cumulative ΔVRMS4D decrease (<1%) is observed below the horizontal injector (red point).*

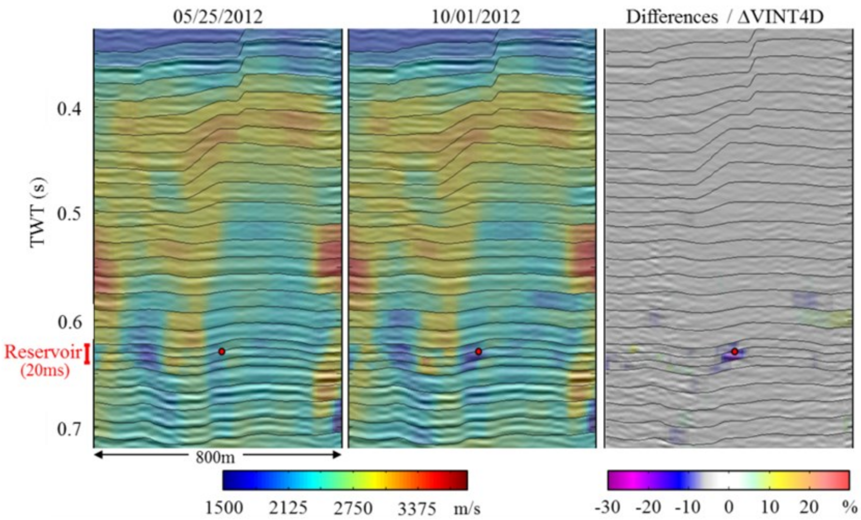

Figure 3: *Same display as in Figure 2 but with VINT4D values overlaid on the seismic. The black curves represent the geological horizons used for derivation of VINT4D. A 12% decrease on VINT4D is observed focused at the injector.*

In Figures 2 and 3, we illustrate the conversion from VRMS4D to VINT4D. In all figures, the horizontal injector well, symbolized by a red dot, perpendicularly intersects the time sections. Compared to ΔVRMS4D which cumulates small velocity changes below the injector, ΔVINT4D is focused at the injector location (Figure 3) with higher values (~12%) in agreement with the PEM (~10% ΔVp corresponds with a temperature increase of 40^{o}C to 240^{o}C).

The result of the 4D energy minimization on the PSTM section and the macro-CMP gather is illustrated in Figure 4. No prior information was used and the 4D energy minimization works uniformly over the whole time section. The slowdown in the reservoir shifts the events below the injection well and is not described by a unique 3D velocity model over calendar time (Figure 4b) whereas this residual energy has disappeared using the 4D velocity model (Figure 4c).

It is important to note that the 4D-PSTM reveals the velocity changes but does not remove all 4D effects (Figure 4e and f) and particularly the one linked with ΔRho (and steam saturation). We also observe that the residual energy below the injection well has significantly decreased using the 4D velocity model: a unique 3D velocity model over calendar time is not sufficient. The result of 150 daily 4D-PSTM (over 5 months) is shown for one location (Figure 4g). Each curve represents a daily VINT4D from May to October with different colors. We see a clear decrease of the VINT4D (ΔVINT4D = -12%) at the reservoir level.

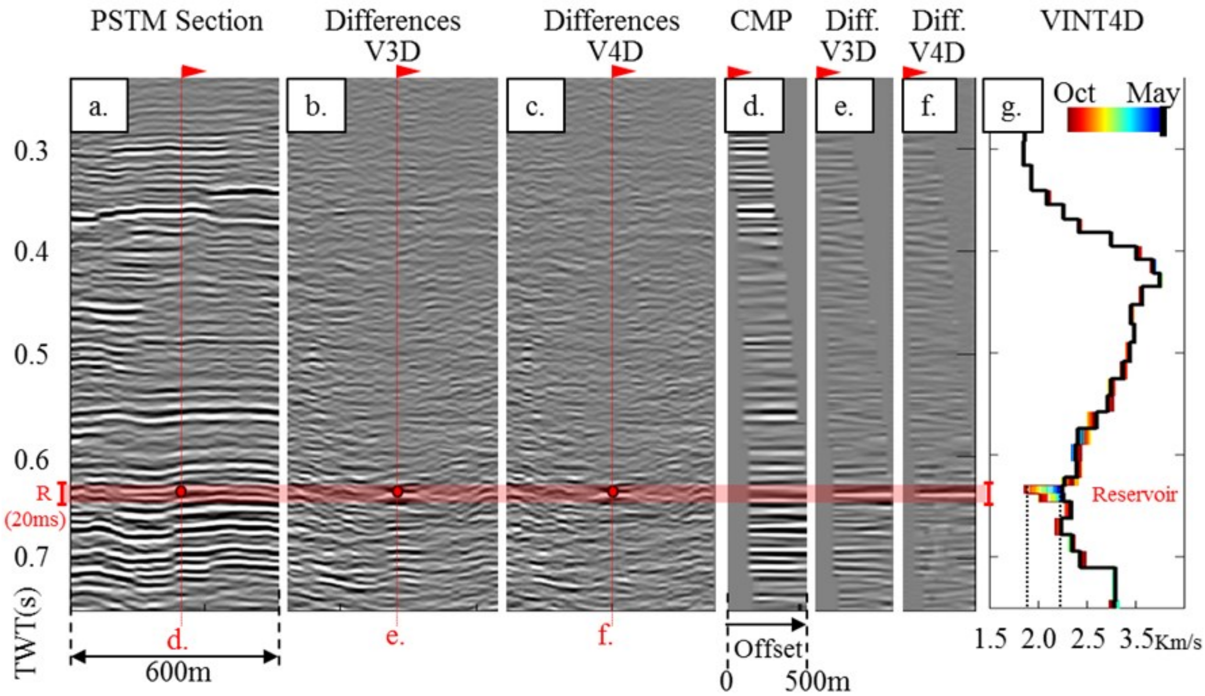

Figure 4: ***a.*** *PSTM section.* ***b.*** *differences between two PSTM sections acquired on the 05/25/2012 and on the 10/01/2012 and migrated with a unique 3D velocity model over the calendar time (V3D).* ***c.*** *Same differences as in* ***b.*** *but with the 4D velocity model (V4D). In* ***d.****, a migrated macrobin is presented. The locations of the macrobins are shown by the vertical red lines in* ***a.****,* ***b.,*** *and* ***c.*** *In* ***e.****, a difference macrobin is presented with the constant 3D velocity model. In* ***f.****, the same difference macrobin is presented with the 4D velocity model. In* ***g.****, the 4D interval velocity variation at the location of the injector.*

In a map view (Figure 5), we observe connectivity between the injector and the north-west part of the survey that confirms and supplements the conclusions proposed by Michou et al. 2013. As we measure a decrease on VINT4D, the observed connectivity is mostly due to a thermal effect according to the PEM. A 4D acoustic inversion as proposed by Michou et al. 2013, but this time performed on the 4D-PSTM data, could be valuable to determine if density changes occur in the reservoir as well.

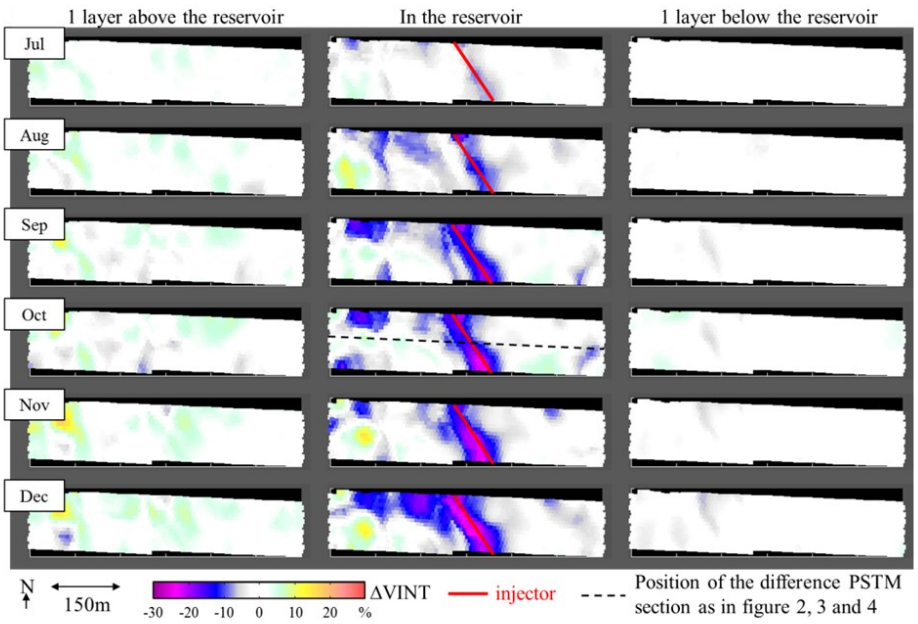

***Figure 5:** Map view of ΔVINT-4D for several layers over months (July to December from top to bottom). Left: One layer above the reservoir. Middle: A layer in the reservoir. Right: One layer below the reservoir.*

Conclusion

4D-PSTM has the great advantage of being very simple and efficient. It allows us to quantify velocity changes by using pre-stack data whereas for post-stack data, this information is lost. The method could be used to solve time-alignment issues prior to reservoir characterization. For our case study, the 4D-PSTM allowed us to compute interval velocity variations that can be used to map temperature changes in the reservoir and that are in agreement with modeling expectations. In the future, a 4D acoustic inversion, but this time performed on this 4D-PSTM data, could be valuable to estimate the density variation and determine if steam saturation changes occur in the reservoir as well.

Acknowledgements

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