geoconvention
Calgary • Canada • May 13-17 2019

# Enhanced resolution and earth properties estimation using least-squares imaging: a Mexico land case study

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## Summary

Currently in oil exploration, as easy targets are exhausted, seismic imaging is commonly relied on in areas that suffer from variable illumination due to complex overburden such as subsalt imaging. At the same time, seismic data are increasingly expected to reveal subsurface rock properties and fluid information in the form of travel time, reflection amplitude, and phase variations.

As the time when the seismic information was used only for structural interpretation has passed, the ultimate objective of acquiring a seismic survey is to estimate reservoir properties to enable reduced risk in exploration and efficient field development. To achieve this, rock physics analysis together with elastic property estimation using seismic inversion techniques is essential, but these methods assume that changes in seismic amplitudes reflect changes in lithology. This might not be the case in a Mexico land data set with imaging challenges such as non-uniform illumination coming from different survey acquisitions and a complex overthrust (tectonic front) with high-velocity contrasts between shallow sediments and deeper carbonates.

In this case study, we seek to eliminate the disconnection between imaging and inversion, which can compromise the fidelity of the attributes derived from seismic inversion. One way to achieve this is to use least-squares migration. In this case, we performed least-squares migration in the image domain (LSMi) using a reverse time migration (RTM) algorithm with point-spread functions (PSFs). These were used to capture and mitigate the variability in phase and illumination in the RTM image to retrieve the underlying subsurface pseudo–reflectivity. This variability can be confirmed by extracting PSFs at specific locations across different geological levels in the seismic image, which clearly show the influence of spatially varying illumination effects. The image improvement from LSMi was tested in a simple poststack inversion exercise that shows much better continuity of the carbonates and improved acoustic impedance estimation, compared to the same exercise carried out using the legacy seismic volume. This illustrates that LSMi helped us to obtain a more reliable true amplitude image in the depth domain.

This Mexico land case study is located in a very promising area onshore south of Veracruz State, where, as of today, most of the production is from the shallow Tertiary sediments. One important reason for this is that these shallow sediments form the ideal place for hydrocarbons to accumulate in easy-to-reach stratigraphic traps. According to information published from the energy sector opening in Mexico, PEMEX is increasing the level of investment in their fields to stay competitive and stem the declining oil production in the country, this could trigger that deeper carbonates can now become the focus of attention for new discoveries. The latest imaging technologies are now playing a key role because the amount of detail required in the seismic images is constantly increasing.

The seismic data for this study are composed of three different land acquisitions from 2002 to 2004, with maximum offsets up to 5 km. In 2012, this area was processed for shallow Tertiary objectives. The velocity model was created using global tomography updates that were heavily influenced by good-quality shallow data. Reprocessing was required to take into account the deeper structures. Our depth velocity model was constructed using newly available technologies such as offset vector tile migrations for multi-azimuthal tomography, 5D regularization and interpolation for image resolution, near-surface modeling to consider the weathering layers in the model, and including traveltime constraints from sonic logs in tomography. Using these technologies helped us construct a robust velocity model and a more accurate image of the deep carbonate targets, which are crucial for point-spread function (PSF) generation. The velocity improvements are evident in Figure 1.

The interest in this land data set is related to the X-1 complex structural-stratigraphic trap within a Cretaceous carbonate formation at a depth of 7000 m under a complex overthrust (tectonic front) with a high velocity contrast between shallow sediments and deeper carbonates. This is a complex imaging scenario that was overcome by using a least-squares RTM technique more commonly known as least-squares migration in the image domain (LSMi). This method uses PSFs that can capture and compensate for variability in phase and amplitude caused by variations in illumination or acquisition.

## Theory / Method / Workflow

Image improvement by reprocessing with latest technologies. RTM migration at 40 Hz.

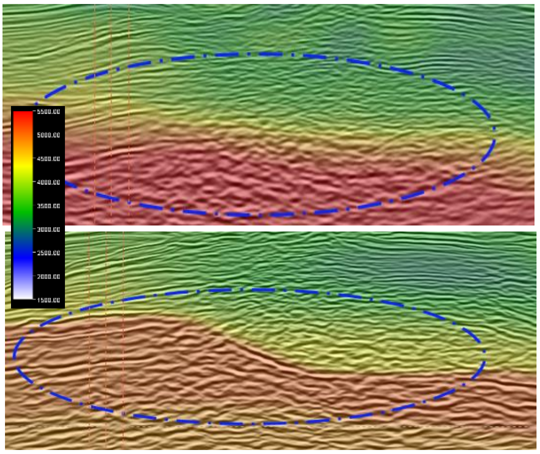

Figure 1. Image improvement in the target deep structure by reprocessing using new technologies. Above is legacy processing (2012) and bottom reprocessing (2017).

To quantify the illumination in the deep target located at 8 km of depth (mid Cretaceous), a ray-tracing analysis was conducted using the new velocity field and the acquisition geometry (Figure 2) to make a comparison of:

1) The number of rays passing through sediment *ONLY* and touching the target horizon.

2) The number of rays passing through sediment, penetrating the tectonic front and touching the target horizon

Ray tracing analysis conducted to measure the number of rays hitting the target horizon, as a representation of the illumination distribution in mid Cretaceous.

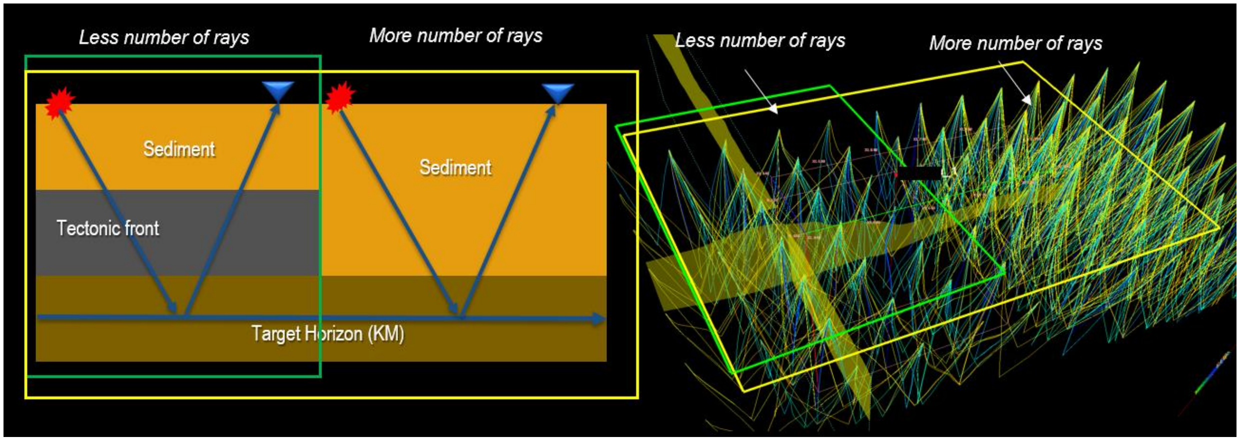

Figure 2: Comparison between the number and distribution of rays passing through the sediment and touching the target horizon versus the number of rays passing through sediment into the tectonic front and touching the horizon. Left is a schematic representation, right is an example of the actual ray-tracing experiment performed.

The results of this analysis are shown in Figure 2. It is easy to distinguish between the highly-illuminated areas and the poorly illuminated ones and, therefore, infer potentially problematic areas.

The variable subsurface illumination observed in the X-1 area is a common scenario in complex geological environments, or it can also be caused by poor acquisition geometry, factors that may have detrimental effects on the amplitudes and phase of the migrated image (Letki, et al., 2015). Such effects lead to incorrectly estimating the subsurface elastic properties by means of conventional inversion techniques.

Transferring the results of this experiment into the seismic image, some of the main challenges observed are:

1. Illumination variability in the Tertiary.
2. Chaotic behavior inside the tectonic front (allocthonous carbonates).
3. The amplitude character of the target (KM) is different in the area below the sediment, when compared to the one below the complex tectonic front.

These challenges are expected to be minimized using the LSMi method that uses PSFs to model and compensate dip-dependent illumination effects caused by acquisition geometry and complex geology to output a pseudo-reflectivity image corrected for illumination effects (Letki, 2016). PSFs can be seen as a blurring operator, a measure of the illumination effects due to velocity variations and acquisition geometry that blurs the reflectivity to give the migrated image.

Using the acquisition geometry and the new velocity model, a grid of PSFs was produced with a spacing of 500 m in X, Y, and Z directions. As a rule of thumb, the PSFs should be close enough to capture the variations in illumination, but should not touch each other. After testing, 500 m was found to be a good spacing between PSFs (Figure 3). PSFs are modelled by propagation through the velocity model using the real acquisition geometry. These modelled data are then imaged using the same imaging algorithm and velocity model that is used to migrate the seismic data, outputting the grid of PSFs (Letki, 2012).

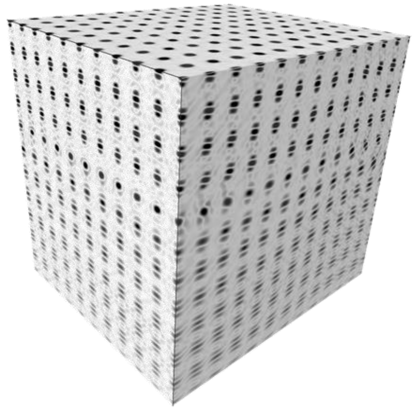

Figure 3. PSF cube every 500m in X, Y and Z direction.

The degree of blurring can be confirmed by extracting PSFs at specific locations across different geological levels in the seismic image (Figure 4), which clearly show the behavior of captured spatial illumination effects.

Point-spread function (PSF) examples in different geological levels.

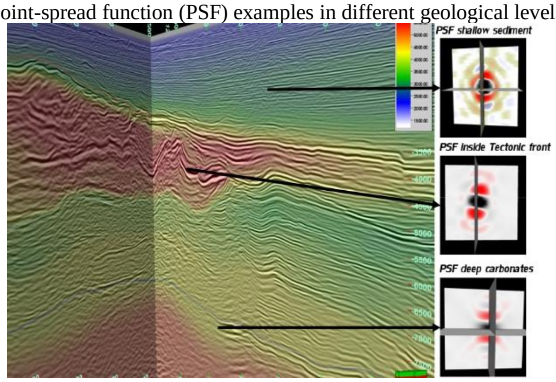

Figure 4: PSF behavior in three different geological levels. First, in the shallow sediment, the PSF looks very symmetric and focused, so we can assume that all dips are well illuminated; next, the PSF inside the tectonic front shows a dip dependent component, and finally, the PSF located in deep carbonates shows significant amplitude and phase distortion.

Figure 5 displays the seismic reflectivity image produced from LSMi compared with a conventional RTM. In general, LSMi shows improved imaging, more broadband resolution of some of the key reflectors, and overall more-balanced amplitudes that are more reliable for use in quantitative interpretation.

## Results, Observations,

The first step in this QC was a comparison between the LSMi RTM and the conventional RTM image at the well location. Figure 6 shows the synthetic seismogram compared with seismic data from the two volumes. In the conventional RTM image, the highlighted event has poor lateral continuity and lower amplitude than the synthetic traces.As a quality control measure, poststack acoustic inversion was performed on both seismic images − conventional RTM and LSMi RTM − using the only well available in the area that was logged down to the deep carbonates.

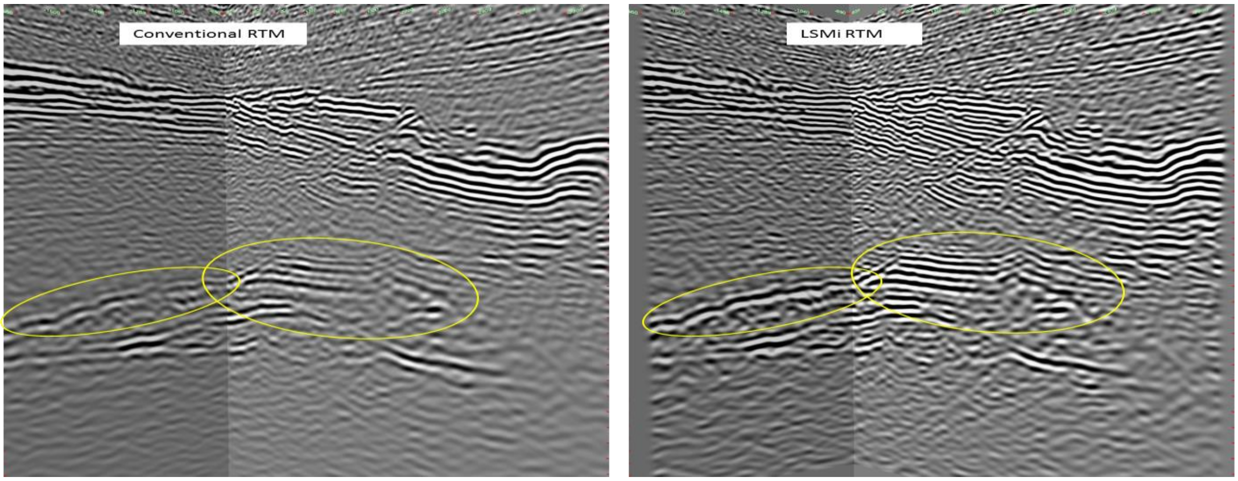

Figure 5. A comparison between a conventional RTM image (left) and the output reflectivity from LSMi (right). Vertical resolution is increased and overall spatial amplitude is more balanced. Blue arrows indicate some key improvements.

In the LSMi RTM image, the same event is more continuous and the seismic amplitude matches much better with the synthetic.

Poststack inversion results for LSMi RTM also show better agreement with a filtered acoustic impedance log than conventional RTM, which is shown in Figure 7. We believe that the inversion results will be further improved by applying the depth domain inversion, which is proposed for future work on this project.

## Conclusions

Seismic data in areas of complex geology are commonly affected by variations in illumination that cause amplitude and phase distortions in time and depth images. Least-squares migration in the image domain (LSMi) is a depth imaging method that uses point-spread functions (PSFs) to correct these distortions and produce images that more closely reflect the subsurface geology.

The survey described in this work suffered from poor illumination below the tectonic front, which caused poor imaging and reduction of amplitudes below. LSMi RTM was applied on the survey, producing a reliable image of the subsurface, suitable for obtaining accurate estimates of earth properties

Poststack acoustic inversion was applied in the time domain to conventional RTM and LSMi RTM volumes and the acoustic impedances for both were compared with log information at the well location. The LSMi volume inversion gave a closer match with the well data. We believe the inversion result will be further improved by applying depth-domain inversion, which is planned for future work.

Comparison of Conventional and LSMi RTM image. LSMi RTM image shows seismic reflectors with higher lateral continuity than conventional RTM.

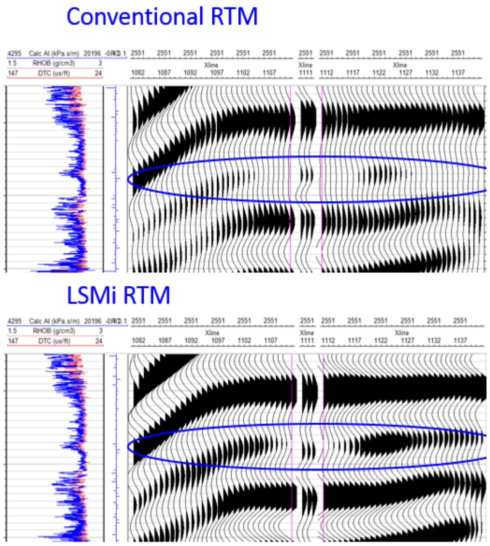

Figure 6: Comparison of conventional and LSMi RTM images with synthetic seismogram.

Quality control of seismic inversion in time domain.

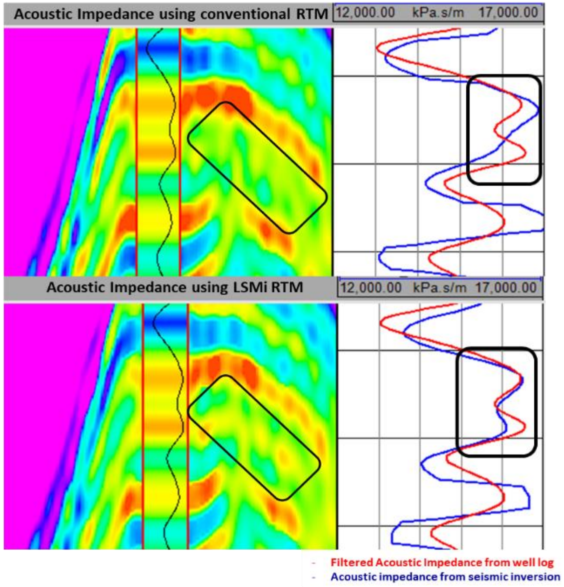

Figure 7: Quality control of seismic inversions in the time domain shows that the acoustic impedance (AI) volume computed using LSMi matches the filtered AI from a well log better than from conventional RTM.

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