Capturing the complexity of the Espirito Santo Basin using a narrow-azimuth dataset

Denis Ferreira, Jack Ng, Arthur Henrique, Rodrigo Fernandez, Ronaro Picoli, Eduarda Rego, Cleberton Oliveira and Florian Jouno, CGG

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Abstract

The Espirito Santo Basin, offshore Brazil, remains largely underexplored compared to other Brazilian offshore regions, especially when considering its deep waters. A complex salt geometry and the presence of volcanic intrusions render this environment a challenge for obtaining high quality seismic images. We present challenges and solutions related to processing a variable-depth narrow-azimuth towed-streamer (NATS) dataset acquired in the deep-water Espirito Santo Basin. The variable-depth profile of 10 m to 50 m streamer depth provides better low-frequency signal. Low frequencies are crucial for reliable full-waveform inversion (FWI), and we are only able to capture salt and volcanic complexities of this region if the data are preprocessed carefully. The preprocessing must preserve the larger bandwidth of the data, especially during steps such as 3D designature and deghost. The data contain other challenges for imaging, such as higher-order surface multiples from one shot which interfere with the next, and interbed multiples from the volcanic rocks which have higher energy and similar traveltimes to primaries. We describe how we resolved these challenges to obtain an improved velocity model from time-lag FWI and a much better image compared to the legacy.

Introduction

Located in the Espirito Santo Basin, offshore Brazil, our NATS data cover 10,000 km^2 of an underexploited and complex deep-water area (2500 m to 3200 m water bottom depth). Located below salt diapirs and below 6000 m, the pre-salt imaging is very challenging with narrow-azimuth (NAZ) streamer data of maximum 8 km offset. This variable-depth acquisition provides streamer depths ranging from 10 m to 50 m. The deep cables provide higher quality low-frequency content, and the variable streamer depth staggers ghost notches and improves broadband response.

Due to the complexity and the imaging challenges of the area, a complete reprocessing of the data was performed, using the latest high impact technologies available, including internal multiple attenuation (IMA) as described by Pereira et al. (2018), and velocity model building using time-lag FWI (TLFWI) as proposed by Zhang et al. (2018).

In the next section, we introduce the geological context of the area, illustrating the complex environment for seismic processing. Then we review the preprocessing sequence, demonstrating how the frequency spectrum was preserved and improved over the legacy, and how processing handled complex coherent noise attenuation from interbed and higher-order surface multiples.

Finally, we describe our velocity model building method. In this abstract we used TLFWI starting from a low frequency to capture the velocity variations in the volcanics, reshape the salt bodies and help guide the salt scenarios, similar to the strategy of Barragan et al. (2019) who used TLFWI to update complex pre-salt targets in the Santos Basin.

Study Area

Located at the southern edge of the Espirito Santo Basin approximately 175 km South-East of Vitoria, the survey lies in a transition zone between the continental and oceanic crust. This pattern can be seen through the gravity data (Figure 1). The gravity anomaly is represented by a NNE-SSW alignment and is subdivided into three different domains: West – continental crust (residual high and low

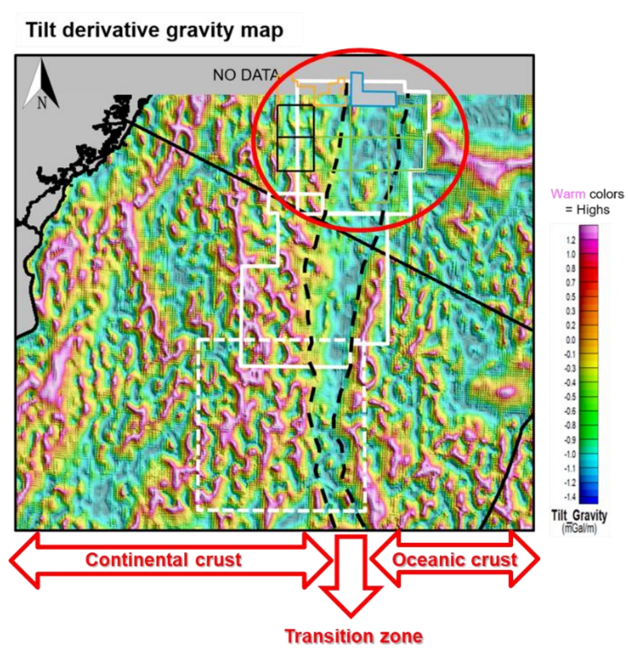

Figure 1. Gravity Map of the Espirito Santo Basin. The red circle highlights the survey area. The dashed lines separate the three different domains: West, Central and East.

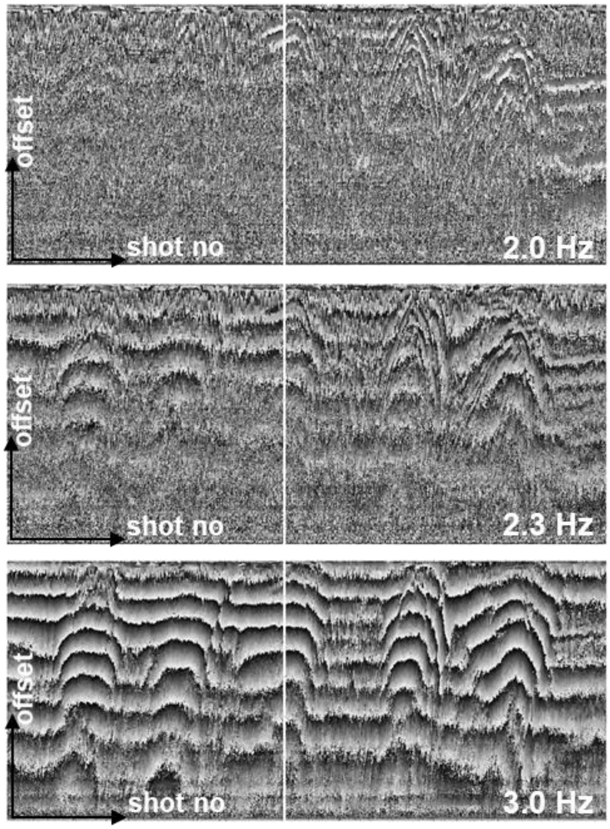

Figure 2. Phase QC of data. Top image shows phase QC for 2 Hz, middle image shows phase QC for 2.3 Hz and bottom image shows phase QC for 3.0 Hz. Far offset data shows usable data at 2.3 Hz.

gravity anomalies), Central – transitional zone (regional low gravity anomaly) and East – oceanic crust (N-S elongated high gravity anomaly). This behavior of the structural framework has a significant impact on the salt tectonics and these same domains are well observed in the seismic data and interpreted horizons: West – structural high (salt pillows, diapirs and less deformation), Central – structural low (salt canopies, allochthonous salt, deep minibasins and more deformation) and East – structural high (salt walls, salt endings and zones without salt).

Current interpretation shows the salt sliding from the eastern structural high (distensive domain) to the central structural low where it begins to compress as it reaches the distal structural high, which serves as a barrier for the salt. The survey area is surrounded by the Abrolhos Volcanic Complex at the eastern border which is also well represented in the gravity data. Those factors bring a high level of geological complexity, including strong salt tectonics and widespread igneous rocks. Marpeau and Belz (2019) showed how salt scenario interpretation, when combined with TLFWI updates, can improve the image in Brazilian basins, more specifically the Santos Basin. For an even more complex environment such as the Espirito Santo Basin, the salt scenario interpretation played a significant role in dealing with these challenges during all the steps of model building.

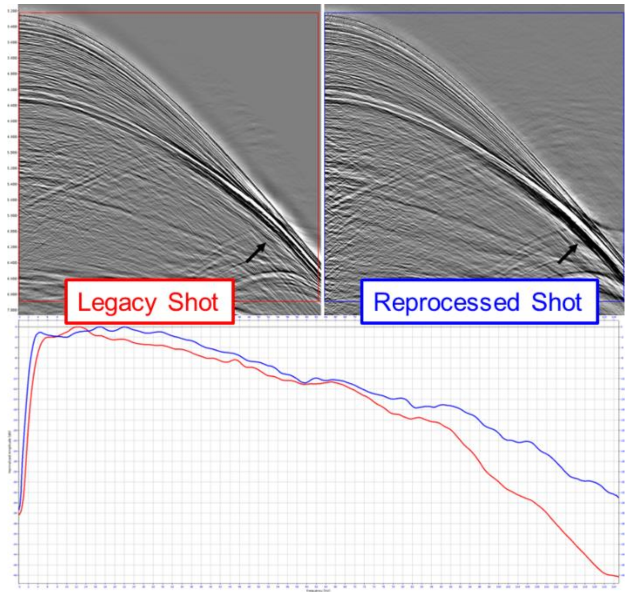

Figure 3. Frequency spectra comparison between legacy and reprocessing. Top left image shows a legacy shot. Top right image shows the reprocessing applied to the same shot. Bottom image shows the frequency spectra comparison. The event pointed by the arrow has richer low frequency on the reprocessed shot compared to the legacy shot.

Preprocessing

The acquisition was narrow-azimuth (NAZ) towed-streamer, with 8 km cable length and variable-depth profile ranging from 10 m to 50 m receiver depth. As discussed by Soubaras and Dowle (2010), due to the variable-depth and deep streamer profile, the data has staggered ghost notches in the frequency domain and low noise at lower frequencies, both of which are usually lacking in conventional streamer data. As shown in Figure 2, useful data can be obtained even below 2.5 Hz. Because of the broader frequency spectrum, careful 3D deghost and 3D designature using nearfield hydrophones are required to preserve the broad bandwidth of the data (Poole et al., 2015). Compared to the legacy data, Figure 3 shows that the low frequencies in the reprocessed data are much better preserved.

One of the biggest challenges in the preprocessing of this dataset is the multiple attenuation. Local geological features, such as channels, generate strong higher-order multiples (at least third and fourth orders) which contaminate the next shot in the firing sequence, as shown in Figure 4. These multiples manifest in the migrated stack as high frequency coherent noise. Figure 5 shows the higher-order multiples models as they appear on the pre-migrated shots. Removing this noise on the migrated stack without damaging the primaries is challenging since they appear as high frequency coherent noise with similar dips to the primaries. A longer multiples modeling (24 s) is

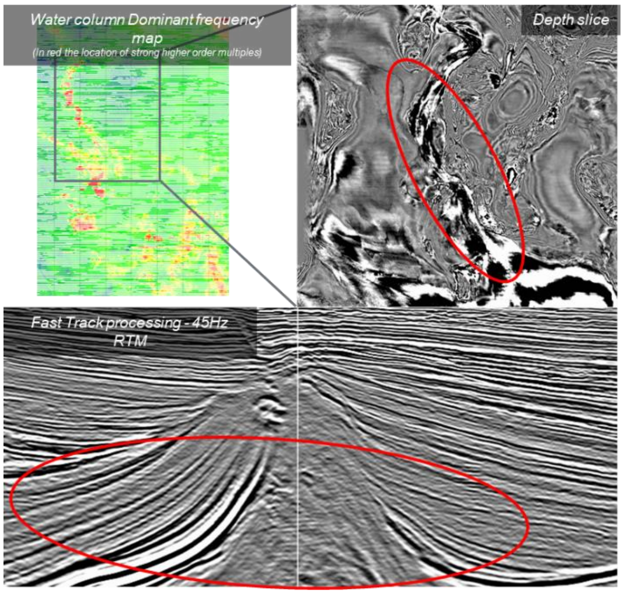

Figure 4. Correlation of higher order multiples and geology. Top left image shows the dominant frequency map of the water column. Top right image shows a depth slice around the water bottom. The red circle highlights a canyon on the same location where the higher order multiples are stronger. Bottom image shows the contamination of the higher order multiple on a 45 Hz RTM stack.

required to properly attenuate these multiples without damaging the primaries.

Interbed multiples also present a challenge in the area, especially in the eastern part of the survey. IMA requires a horizon to separate overburden (whose multiples will be estimated) from target (where multiples will appear). Geological complexities of the area preclude using commonly used choices such as top of salt (TOS) and base of salt (BOS). Instead we performed various tests to optimize the bespoke placement of the horizon following the geology. An additional challenge for IMA is the fine layering, as it becomes nontrivial to separate primaries from multiples.

We use a curvelet-based prestack adaptive subtraction such as that of Krueger et al. (2018) which vastly improves discrimination of multiples. Figure 6 shows IMA results from the eastern area of the survey. Although the multiples and primaries have very similar energy level, the subtraction of the multiples improved the image without damaging the primaries.

Velocity Model Building

The velocity model building flow was designed to globally improve the velocity model over the area using several passes of TLFWI, a tomographic update, salt scenarios and a complete top-down salt interpretation.

In order to update the velocity model in the presence of high-velocity contrasts such as salt bodies and volcanic intrusions, we used TLFWI (Zhang et al. 2018), which promotes higher quality travel time measurements thus

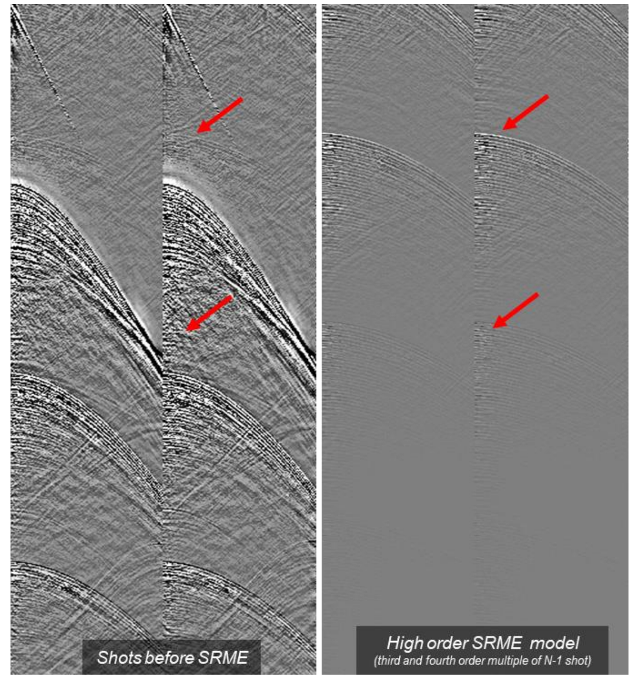

Figure 5. Higher-order multiples contamination. Left image show the shots before SRME. Right image shows the higher-order multiples model from the previous shot.

mitigating cycle skipping and amplitude discrepancy in this challenging environment.

The analysis of the quality of the low frequency in the data, as shown in Figure 2, allowed the TLFWI update to start at 2.3 Hz. Even though the diving wave penetration is limited by the 8 km streamers, TLFWI was able to better capture the volcanic layers and the igneous intrusions. It also reshaped the shallow salt bodies and helped guide the salt scenarios. Figure 7 and Figure 8 show the improvement of the velocity model in the image. Figure 7 shows a crossline from the eastern part of the survey. The highlighted yellow circle shows how the events below the salt body are more focused and more geologically consistent. The arrow shows how the TLFWI was able to better capture velocity variations in the volcanics.

For the pre-salt update, an initial gradient model was created from the base of salt to the basement. This model was updated using a low frequency TLFWI that was able to generate a more geologically consistent model in the pre-salt, improving the image as shown in Figure 8.

Discussion

The reprocessing of the Espirito Santo data showed improvements in the final image compared with the legacy processing. However, the uplift in the image is still very much limited by the characteristics of the NATS data. Even with better low frequency content, it is still lacking when compared with acquisitions with longer offsets and more azimuthal coverage. These limitations impact the TLFWI updates and consequently its success.

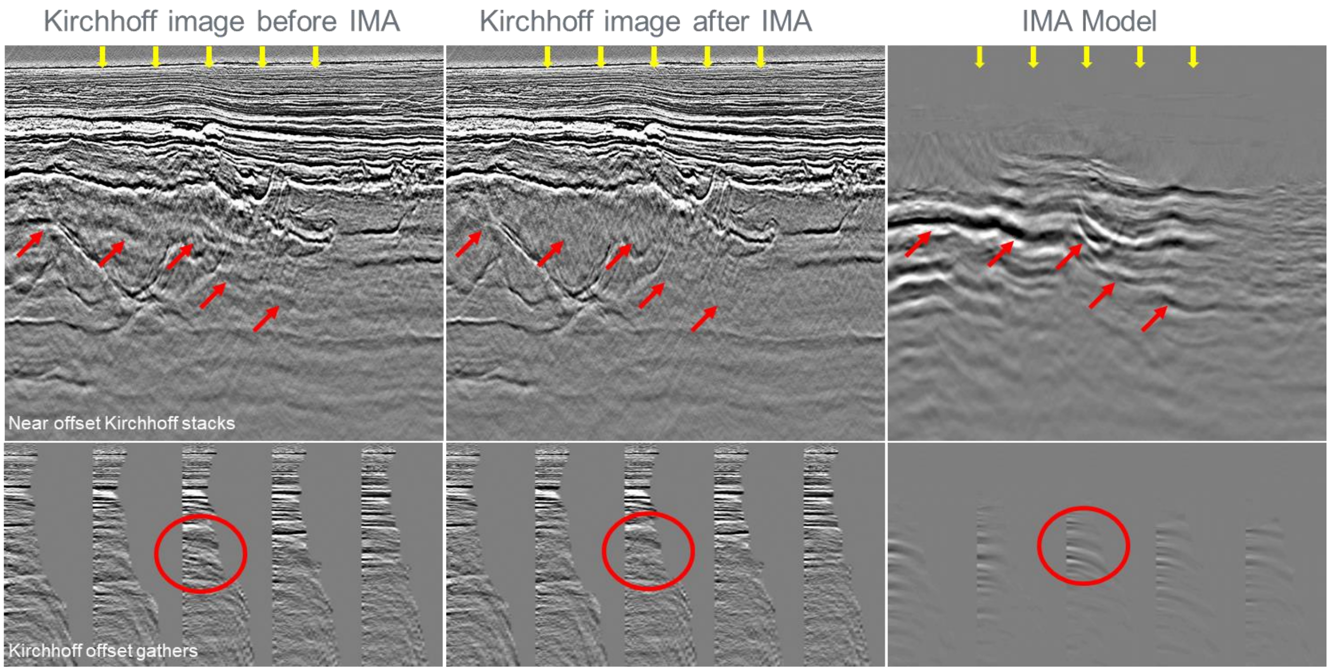

Figure 6. Examples of interbed multiples observed in the eastern survey area. Top images show Kirchhoff migrated stacks. Bottom images show Kirchhoff migrated gathers. Left images show before IMA, middle images show after IMA and right images show the IMA model. Yellow arrows indicate the gather locations. Red arrows highlight the interbed multiples attenuated on the stack. Red circle highlights the interbed multiples attenuated on the gathers.

Conclusions

In a very complex environment such as the Espirito Santo Basin, careful preprocessing can extract more information out of a narrow-azimuth towed-streamer dataset.

Additional processing, such as surface and interbed multiple attenuation, plays a key role in obtaining a clear image of the subsalt and pre-salt of the area. We presented some peculiar challenges for this dataset and our strategy to overcome them.

Thanks to the high-quality acquisition with lower frequency content, together with a TLFWI algorithm, it was possible to obtain a velocity model that better captures the complex geological structures, such as salt structures, volcanic layers and igneous intrusions.

Naturally, the final quality of the image is still very much limited by the restrictions of a NAZ acquisition. Better azimuthal coverage and deeper diving wave penetration, e.g., from an OBN acquisition, are the keys to fully solve the complexities of the area.

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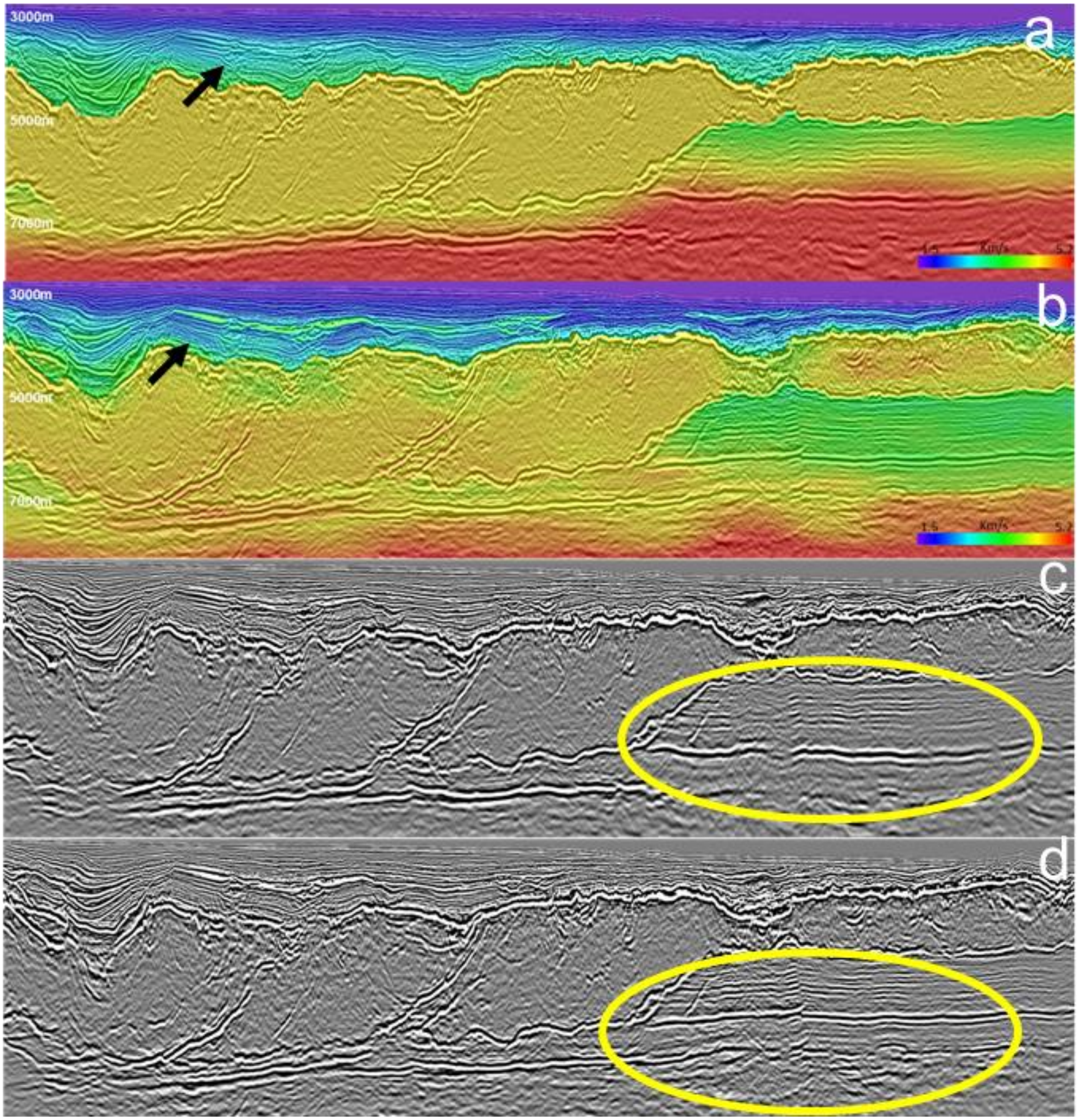

Figure 7. Velocity update from the eastern part of the survey. A) Legacy velocity model overlaid on 20 Hz RTM stack. B) Updated velocity model overlaid on 20 Hz RTM stack. C) Legacy 20 Hz RTM stack. D) Updated 20 Hz RTM stack. The yellow circle shows an area where the events are better focused and more continuous after TLFWI update. The arrow shows how the TLFWI can capture better the velocity in the shallow volcanics.

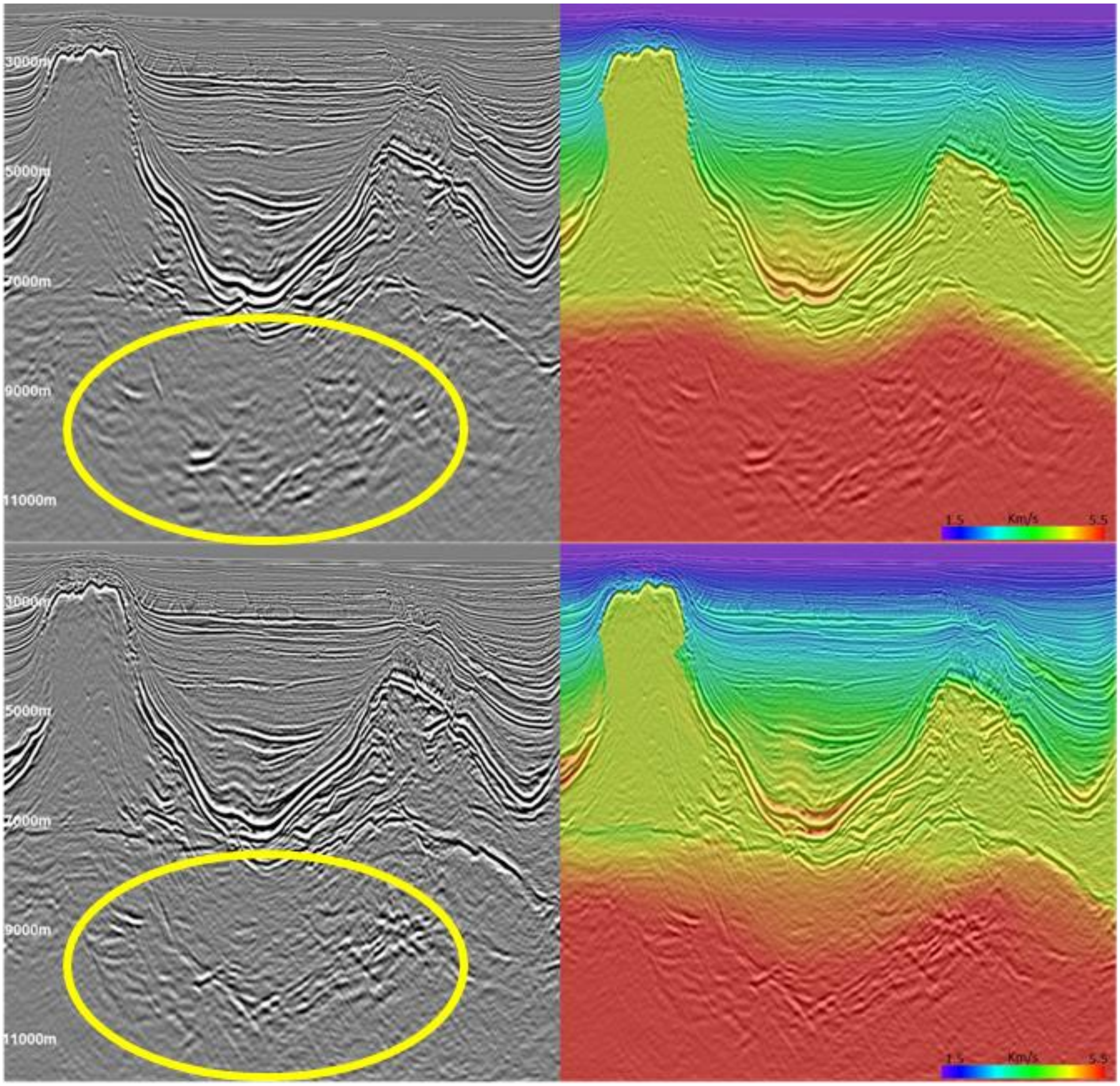

Figure 8. Velocity update on pre-salt. Left images show 20 Hz RTM stacks. Right images show 20 Hz RTM stacks overlaid with the velocity models. Top images show the legacy velocity and stack. Bottom images show the updated velocity and stack. Yellow circle highlights the pre-salt events getting more focused and more continuous after the TLFWI update.