Objective oriented re-imaging for better seismic image of the sub-surface: A case study from Rajasthan's Bikaner-Nagaur basin

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ABSTRACT

Seismic data acquisition in desert areas is laden with challenges distinct to the region. These challenges when combined with the shallow basinal configuration (500m to 1500m) lead to a scenario wherein suitable seismic imaging plays a pivotal role in mitigating the risk of identified prospects' failures, and of mid-drilling complications. The work presented in this paper showcases the improvements obtained in seismic imaging using advanced algorithms that cater to the needs of data and the comparison of these improvements vis-à-vis the vintage processed dataset. The 3D dataset, on which this study has been carried out, was acquired in the year 2008 in the desert region of Indian state of Rajasthan. The dataset was originally processed in the year 2009 and was subsequently used for drilling various prospects. However, due to complex near surface challenges and drilling complications such as mud loss and karstification within the highly-fractured carbonate formation, which lies immediately above the producing sandstone formation, the dataset was re-processed using advanced algorithms to better understand the genesis of these complications using seismic data. The re-processing of the data yielded various improvements vis-à-vis the vintage output such as improvement in imaging and velocity of the shallow region through near surface velocity determination via refraction statics , regularization of Common Mid-Point (CMP) gathers through 4D interpolation scheme, improvement in imaging due to advanced noise attenuation schemes in various domains (viz. areal group) and improvement in overall resolution (both temporal and spatial) of the seismic data through a robust deconvolution and a pre-stack migration scheme. This case study highlights the enhancements that are achievable in a complex region through robust and data driven seismic processing and imaging algorithms.

INTRODUCTION

The survey area is located in Bikaner-Nagaur Basin of Rajasthan with close proximity to the India-Pakistan International border (Figure 1) and the first hydrocarbon discovery was made in this area in the year 1991. The 426 SQKM 3D seismic dataset used in this study was acquired in the year 2008 and thereafter processed (in pre-stack time domain) in the year 2009 with the then available processing algorithms. The dataset was acquired using vibroseis as a source and has a bin size of 25m X 25m and a nominal fold of 30 (5IL X 6XL).

Figure 1. Location of the Study Area

The dataset is fraught with various challenges (both surface and sub-surface) and they are mentioned below:

1. **Surface/ Near-surface challenges:** The surface topography of the region is highly undulating with the sand dunes rising as high as 30 meters and even more. The sand dunes, not only act as a major challenge during acquisition, but also pose a significant challenge in statics determination owing to the variance in the weathering and sub-weathering layer velocities. Also, the near surface challenges in the region are plenty such as several near surface velocity

anomalies due to the presence of salt/halite layers.

2. **Sub-surface challenges:** The region has a very shallow basin with basement coming as early as 1000msec in the seismic dataset. There is a presence of thick upper carbonate layer which acts as a strong reflector deposited above the target reservoir, thus diminishing its impedance contrast. Moreover, the reservoir pay zone is very thin (spanning from 5m to 50m in the region). These challenges when coupled with seismic dataset specific challenges such as shallow reflectors with varying impedance contrast, poor Signal-to-Noise Ratio (SNR), significant higher frequency random noise, made the overall complexity of imaging the sub-surface significant.

To handle above mentioned challenges, an innovative imaging approach was vital; This approach had to be robust in attenuating the significant noises, handling poor SNR, and reliable imaging of the sub-surface. Various advanced noise attenuation, deconvolution, regularization and pre-stack migration schemes have been tested and applied on the dataset to mitigate these challenges and to provide a geologically conformable seismic image.

GEOLOGY OF THE STUDY AREA

The Bikaner-Nagaur basin falling in the Indian state of Rajasthan belongs to the platform regime of the Greater Indus Basin System. Structurally, Bikaner-Nagaur basin is bounded in the east by Delhi-Aravalli folding and in the south, south-west by Pokhran-Nachna high (separating Jaisalmer basin). This is a shallow Infracambrian-Palaeozoic basin with a Precambrian basement comprised of Malani Igneous Suite and Delhi Metamorphites. The igneous and metamorphic rocks at places are overlain and intruded by Malani Volcanics (Rhyolites) of Pre-Cambrian age. These rocks are uncomformably overlain by Marwar Super Group. The Marwar Super Group is comprised of the arenaceous Jodhpur group, the calcareous Bilara Group containing stromatolytic carbonates & clastics, Hanseran Evaporites & Salts (HEG) and argillaceous & arenaceous Nagaur Group of Infracambrian to lower Cambrian age. The Marwar super group is overlain by thick Upper Carbonate formation of Upper Cambrian age comprising of predominantly dolomites, and limestones with shales and evaporites (Figure 2).

This work covers a typical part of the said basin with discovered heavy oil fields wherein the geological objectives/target pay zones (primarily sandstone) are expected in times of 800 msec to 1500 msec on a seismic section, and are located underneath a salt/halite layer of varied thickness (ranging from 100 to 250 meters).

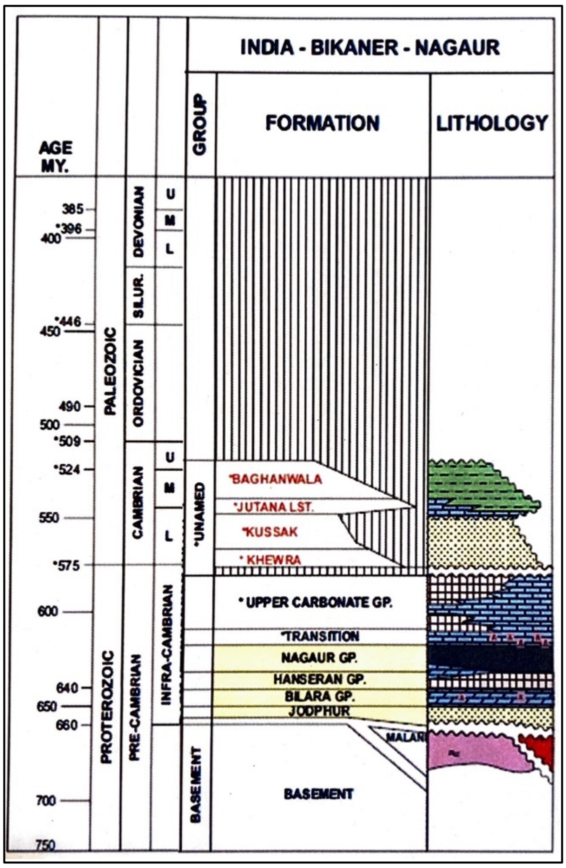

Figure 2. Generalized stratigraphy of the Bikaner Nagaur sub-basin (Taken from OIL's internal reports)

Processing Methodology Adopted:

Seismic data processing and imaging algorithms, en-masse, are imperative in providing geologically conformable seismic image of the sub-surface. However, with plethora of these algorithms available today, objective oriented seismic imaging has become need of the hour. The identification of most effective tools suited to a particular region or data type and the use of these tools to get the maximum information out of the dataset are useful skills today for a seismic processing team. The raw dataset in this study has modest SNR and is contaminated with high amplitude ground roll and other linear noises. Further, the dataset had a humble nominal fold of 30 which made shallow imaging a challenge owing to far offset stretching in CMP gathers, and significant velocity variations due to presence of halite and carbonates. These challenges were adequately handled by various processing algorithms applied at various stages of the seismic processing of this dataset. The methodology included in-depth focus on noise attenuation, spiking deconvolution, multiple passes of velocity analysis, regularization & 4D interpolation and pre-stack time migration. The main target for processing of this seismic dataset was to provide a set of pre-stack migrated data suitable to carry out further investigative studies like pore pressure and fracture network distribution studies; This shall facilitate identification of areas with probable karstification. This prior-information can then be considered for optimised well planning and can result in successful drilling of wells with minimal mud-loss.

The major processing steps carried out on this dataset are elaborated below:

A) Noise Attenuation in Areal Group Domain

Noise attenuation using conventional ground roll modeling and anomalous amplitude attenuation was carried out on the dataset. However, owing to noise characteristics and significant remnant noise present in the dataset, an evolving procedure of sorting the dataset into areal groups/cross-spread domain was adopted (Vermeer, 2008). Cross spread gathers or an areal group consists of all traces from one source line that are recorded on one detector line. Typically, each areal group covers a large subsurface area with trace midpoints spatially distributed at half the source spacing by half the detector spacing. This spatial distribution is like a single fold 3-D CMP stack (see Figure 3). Also, zero source-to-detector offset distance is located at the centre of the areal group and increases outwardly from the centre. This offset distribution shows how offsets are distributed within a source gather. The cross-spread (Xspread) gathers before and after noise attenuation in areal group domain are shown in Figure 4. Note the modeling and the removal of noise (especially the ground roll) in Figure 4c. This distribution allowed better modeling of noise present in the dataset and subsequent attenuation of it, albeit in various steps.

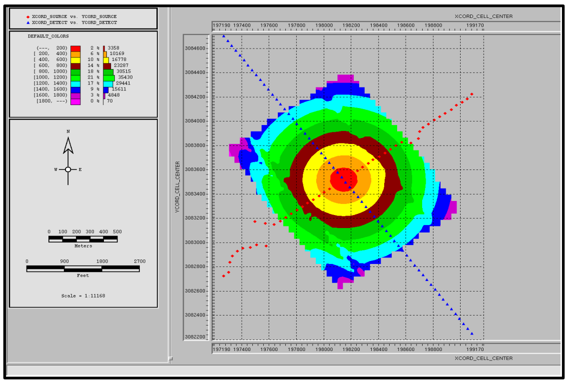

Figure 3. One areal group with shots (in red) and receivers (in blue). Note the distribution of near offsets to far offsets in the areal group.

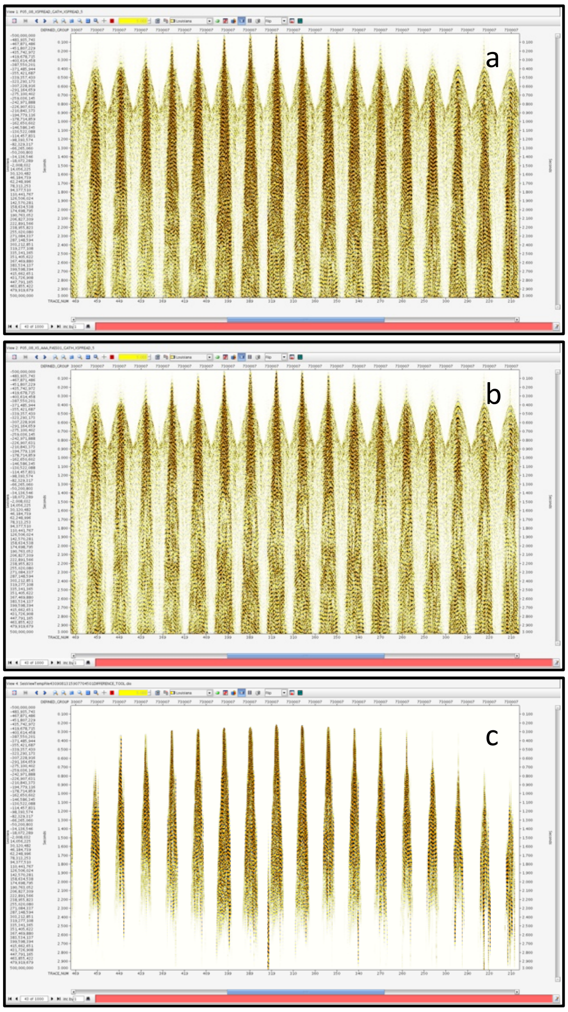

Figure 4. Xspread gathers (a) before noise attenuation, (b) after noise attenuation, and (c) difference before and after noise attenuation in Xspread domain.

B) Surface Consistent Deconvolution

Theoretically, it is generally understood that since seismic data in deserts is acquired using vibroseis as a source, it does not need application of deconvolution as the source effect has already been removed after correlation of the recorded trace with the recorded sweep (Vedanti et. al., 2020). However, in the present study, spiking deconvolution was applied on minimum phase converted dataset which helped in major improvement in vertical resolution of the dataset (Figure 5). The need for application of spiking deconvolution on this dataset is adequately supported by auto-correlation plots (Figure 6). The stack sections before and after deconvolution are shown in Figure 7.

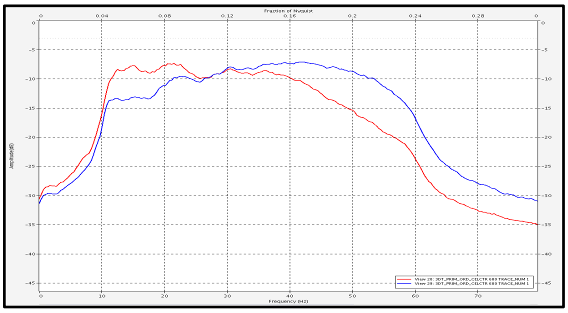

Figure 5. Amplitude Spectrum before (in red) & after SCD (in blue)

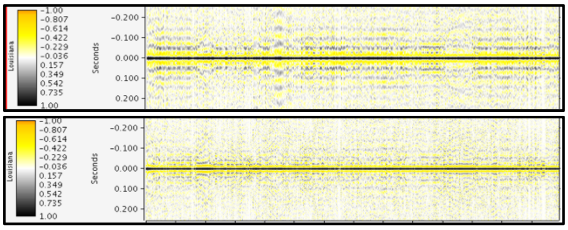

Figure 6. Autocorrelation plots before (above) and after (below) deconvolution. Note the compression of wavelet and improvement in vertical resolution after deconvolution.

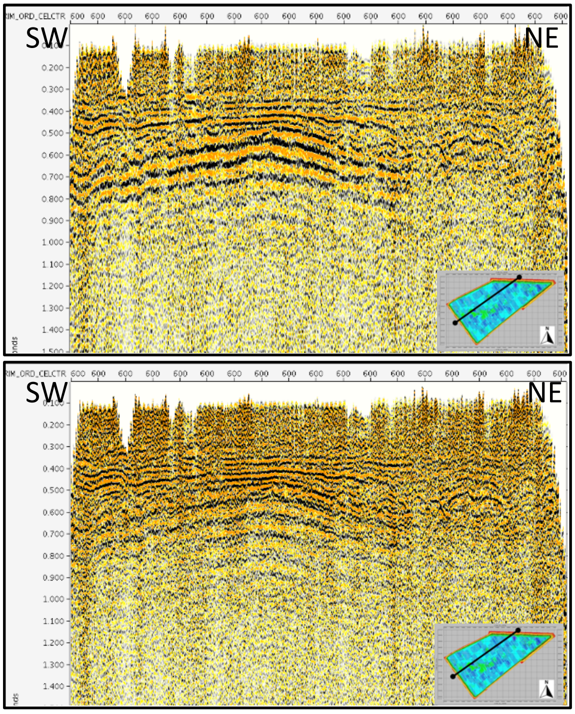

Figure 7. Stack sections before (above) deconvolution and after (below) deconvolution. Note the improvement in temporal resolution.

C) Regularization and Interpolation:

The major challenge with this dataset was to carry out shallow imaging and velocity determination (see Figure 8). However, due to scattered ground roll predominantly present in the shallow part of the data, its attenuation through data regularization and interpolation was imperative. The vintage dataset was not regularized and not interpolated leading to poor imaging in the shallow part. The dataset has a nominal fold of 30 and is irregular in distribution (Figure 9). Thus, in order to improve imaging, the dataset was regularized through distribution of CMP gathers in offset classes. Thereafter, 3D and 4D Matching Pursuit Fourier Interpolation (MPFI) (Schonewille et. al., 2013) was thoroughly tested and subsequently 4D interpolation was found to provide better result (see improvement on time slice at 250 msec in Figure 10).

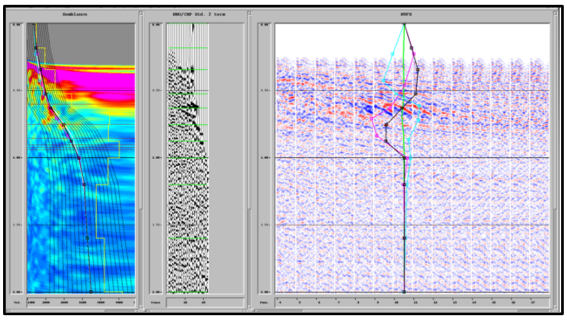

Figure 8. Semblance plot, CMP gathers and Multi-Velocity Fan Stacks (MVFS) during 2nd pass velocity analysis. Please note the lack of reflections upto 250 msec and hence low confidence in picking the velocity trend.

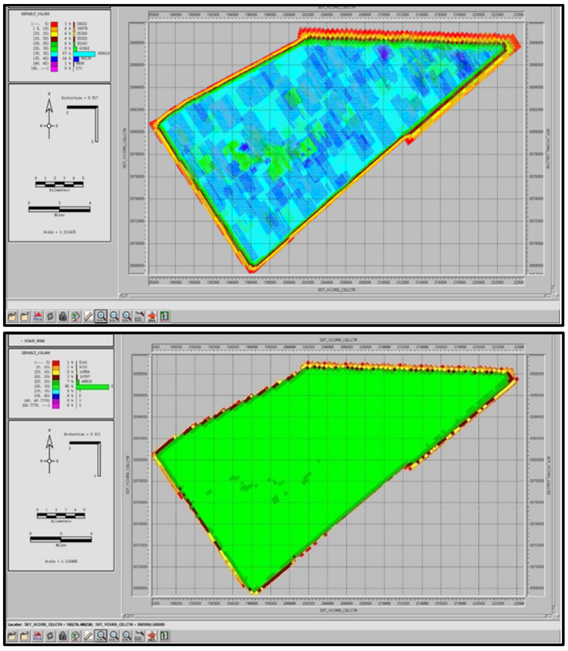

Figure 9. Fold plot before (above) interpolation and after (below) interpolation. Note the irregular fold distribution before interpolation and regular fold after.

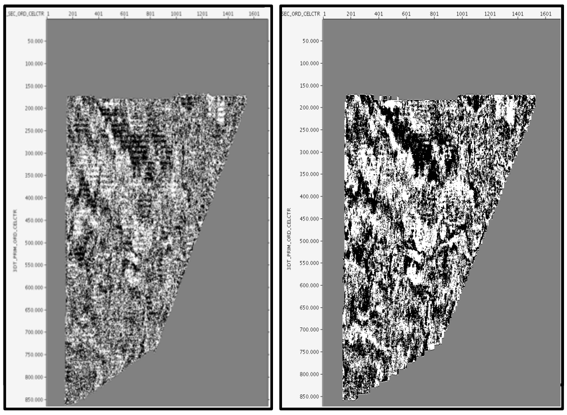

Figure 10. Time slice at 250 msec before (left) and after (right) 4D interpolation. Note the prominent acquisition footprints before interpolation and subsequent improvement observed in this shallow time after interpolation.

D) Pre-Stack Time Migration:

Pre-stack time migration was carried out on this dataset and brought out subtle details and structural features present in the dataset (Figure 11) that were not seen previously and helped in carrying out post-migration velocity analysis. This in-turn shall provide, among others, a detailed sub-surface velocity model necessary for future depth imaging projects on the dataset. (Figure 12).

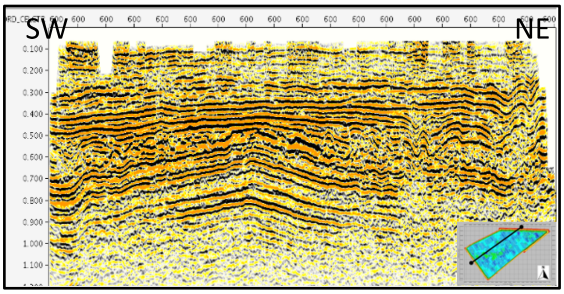

Figure 11. Stack section after Pre-stack time migration.

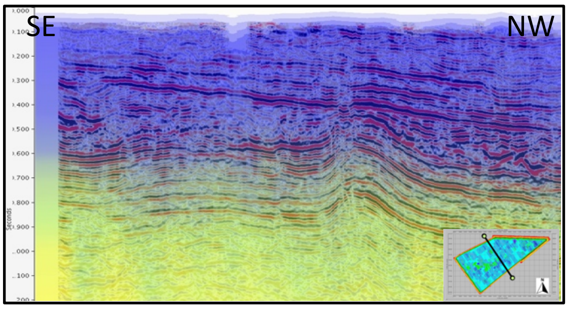

Figure 12. Stack section after migration and overlain with final migration velocity. Notice the detailed velocity available throughout the seismic section.

DISCUSSIONS

The vintage dataset was processed with pre-stack time migration, but it had various limitations such as very low frequency in the shallow part of the sub-surface (Figure 13) and low amplitudes in migrated CMP gathers (Figure 14). These shortcomings constrained the AVO/pre-stack inversion studies on the dataset and were adequately handled in this objective oriented re-processing (as shown in Figures 13 & 14).

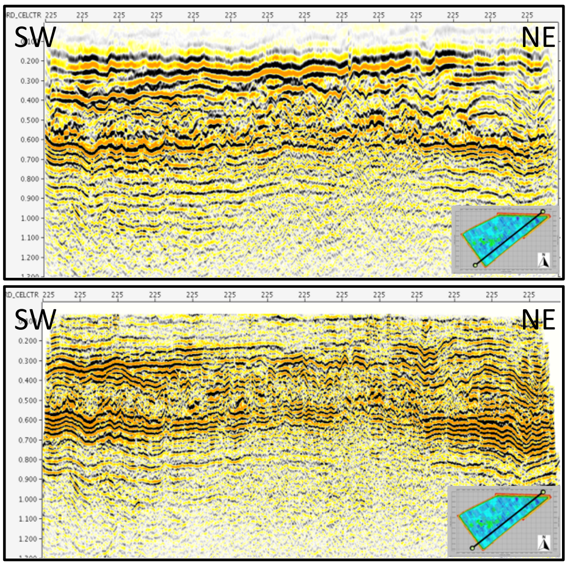

Figure 13. Vintage stack section (above) after migration and newly processed migrated section (below). Note the stark improvement in the shallow imaging and improvement in temporal resolution.

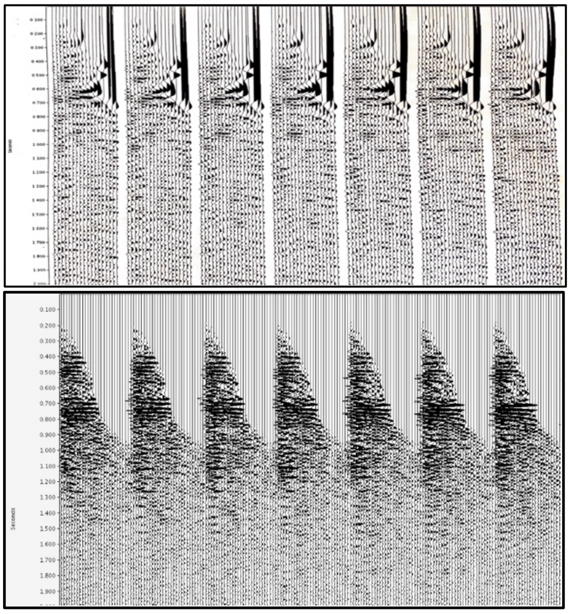

Figure 14. Vintage migrated CMP gathers (above) and newly processed migrated CMP gathers after final-mute application (below). Notice the improvement in terms of reflection flatness and decent amplitude in part due to 4D interpolation and in part due to robust noise modeling and attenuation schemes.

Further, time slices at target times (both upper carbonates and Jodhpur Sandstone) are shown in Figures 15 & 16 respectively.

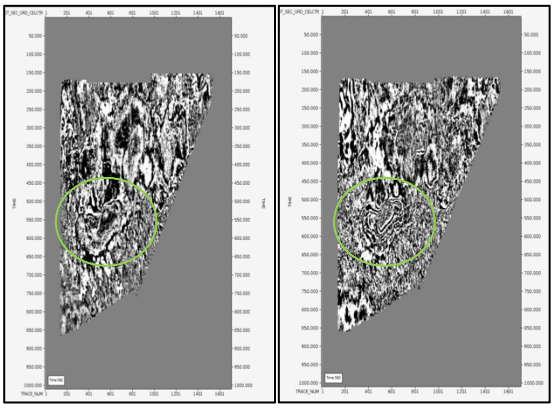

Figure 15. Time slice at 592 msec (approximate zone of Upper Carbonates) of scaled outputs of vintage (left) and newly processed data (right). Note the enhancement in the structural resolution (highlighted in green circle) in the newly processed output vis-à-vis the vintage output.

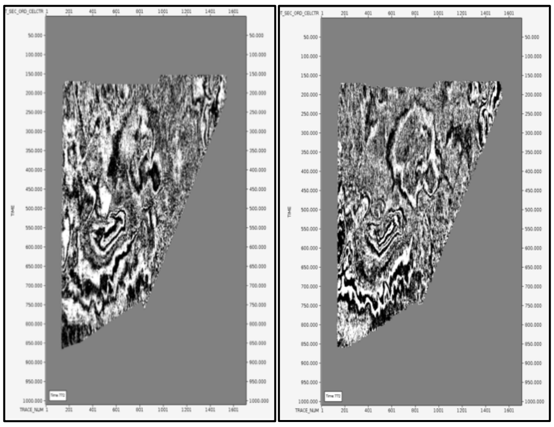

Figure 16. Time slice at 772 msec (approximate zone of Jodhpur Sandstone) of scaled outputs of vintage (left) and newly processed data (right). Note the overall enhancement in the structural resolution in the newly processed output vis-à-vis the vintage output.

Apart from improved imaging and generation of relative amplitude preserved migrated CMP gathers suited to AVO/pre-stack inversion studies, this work also showcases the improvements that are achievable from utilization of advanced processing algorithms; These algorithms can help provide newer insights into a development area and a fresh impetus to field development plans of a field. Further, availability of near surface velocity obtained from statics solution shall help in performing depth imaging on this dataset.

CONCLUSION

It has been shown that a considerable improvement in seismic image is achievable through an optimized workflow, i.e. the one with algorithms most aligned to a particular project's objectives. Seismic data processing is generally seen as a mere intermediary process to generate interpretable seismic sections; It is a means to an end. However, we have showcased that two superficially similar processing projects i.e., each with a Pre-stack time migrated output can provide significant improvement in terms of the final delivery. The selection of the algorithms and their optimized usage are the keys in generation of a better processed output. Thus, it is imperative for decision makers to fathom that to obtain greater insights into the sub-surface without the added cost of fresh acquisition, continuous development and growth of the seismic processing & imaging technologies and expertise are pivotal and are more than merely a bare necessity for improving the exploration and development assortment of an E&P company.

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