A Practical Application of Data-Driven 3D Automatic Fault Extraction for En Echelon Faults: A Case Study from Malay Basin*

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Abstract

Automatic Fault Extraction (AFE) methodology was implemented in a study area of Malay Basin and successfully contributed to reservoir characterization. Malay Basin was developed through several phases of structural deformation related to tectonic collisions and strike-slip shear from Palaeocene to Plio-Pleistocene. A series of N-S en echelon ridges and grabens sequentially hosted the E-W trending folds of later compressional episodes; where hydrocarbon deposits were subsequently trapped in the compartments of the transcurrent faults. Conventional seismic interpretation for en echelon faults has always been labor-intensive, affected by trace bias and interpreter's subjectivity, while the AFE approach generates fast and precise interpretation. The workflow consists of three major steps, the removal of noise; calculating structurally oriented edge detection attribute called Horizon Edge Stack (HES); and enhancement of the fault imaging in the discontinuity volume. The noise removal processes are structurally oriented de-striping and statistical filtering, preserving the seismic amplitude and condition the data to be more suitable for fault interpretation when noise has been taken out from the space of normalized discontinuity values. The faults are crafted out in the HES by using a sample to sample amplitude change calculation in the lateral directions and reiterate the cross shaped operator calculations for every sample position along the vertical axis. The fault images can be further refined by using windowed Radon transform, which computes and projects fault signals along arbitrary directions, before writing back into the sample space matrix. This accurately images fault regardless of dip and improves its resolution and signal strength. The fault enhanced volume supports the auto extraction of 3D fault planes with user defined planar feature and size. The co-planarity control is most critical to differentiate groups of points that are parallel but have distinct features: en echelon faults. In this study, the fault probability volume extracted 212 fault planes in one go and quality checked against the seismic data. The faults were used as input for stratigraphic model building, leading to better quality low frequency model (interpolation of well properties incorporating seismic velocity) for seismic inversion, and mapping distribution of reservoir sands. The result laid the foundation for strategic exploration and appraisal wells planning.

Introduction

Malay Basin is one of the major hydrocarbon-producing tertiary basins in South East Asia. It is located off the east coast of Peninsular Malaysia in the South China Sea (Figure 1). The basin was developed partly because of tectonic collisions and strike-slip shear of the Southeast Asia continental slabs, as the Indian Plate collided into Eurasia, and subsequent extrusion of lithospheric blocks towards Indochina. The earliest structural deformation of the Malay Basin was manifested by the Palaeogene W-E rift valleys formed during NW-SE sinistral shear of the region and subsequently the Eocene NW-SE dextral shear of Indochina Block against East Malaya Block (Mansor et al., 2014). A series of N-S en echelon ridges and grabens were developed within the Malay Basin. The grabens and some ridges, sequentially, host the W-E trending folds of later compressional episodes (Shahar, S., 2008).

Our study area is at the SE flank of Malay Basin, focusing on the 'H', 'I', and 'J' formation, with lacustrine to coastal plain depositional environment. Figure 2 shows the seismic slice and inline section where the fault images have been enhanced. The planimetric map revealed the grabens and half grabens are results of impact from two fault sets; one set parallel to and a second set trending oblique to the Hinge Fault Zone of Malay Basin (Tjia, 1994). The measured dipping angle of the half grabens faults ranges from 65-75 degree. Basement fractures are also observed at the pre-rift section, bounded by the top of basement.

Methodology

The interpretation workflow consists of three major steps. The removal of noise; calculating structurally oriented edge detection attribute; and improvement of the fracture imaging in the discontinuity volume with an enhanced Automated Fault Extraction (AFE) algorithm (Dorn et al., 2012). Noise removal is an important process of the workflow as the edge detection class attribute is particularly sensitive to noise. The interpretation result can be degraded and misguided by coherent and random noises in the data, especially legacy seismic data (Dorn et al., 2017). The noise removal process is structurally oriented, where the de-striping processes are done by considering the local dip and strike. This avoids the change of seismic amplitude in highly dipping areas after noise removal (Dorn, 2018). Figure 3 shows the comparison of seismic before and after conditioning.

The Horizon Edge Stack (HES) uses a sample to sample amplitude change calculation in the lateral directions and reiterates the cross shaped operator calculations for every sample position along the vertical axis. If a discontinuity calculation is calculated on a horizontal planar segment in a seismic volume, and local horizons are dipping, the transition as the horizontal calculation plane crosses from peak to trough in the dipping seismic event will be detected and imaged as a discontinuity. This attribute can be used for revealing the geomorphology of subsurface and relating geological discontinuities visualized on the horizon edge stack with faults or fractures.

Conventional interpretation methods have trace bias because en echelon fault trends at various strikes and dips, the image of the fault discontinuities rarely restricted to inline and crossline directions. Edge detection attribute also has stairs-steps alike feature at vertical direction due to its calculation approach. Therefore, the fault image can be further improved by using windowed Radon transform. The radon transform computes projections of an image matrix along specified directions. Arbitrary slices are extracted from the data where the fault signals are projected onto these preferred slice orientations. The improved fault probability is then written back into the sample space matrix. This accurately images fault, regardless of dip, improves its resolution and signal strength in the output fault probability attribute. The output probability volume supports the auto extraction of 3D fault planes. The planar feature of the fault, as well as its minimum accepted size can be user-defined. Maximum difference in orientation for two groups of sample points can have and still be considered part of the same planar feature if fall within the tolerance. The co-planarity control is used to differentiate groups of points that belong to parallel but distinct features, a key factor for en echelon fault interpretation.

Results

With 11 iterations of footprint removal, these have de-striped most of the overprinted inline, crossline and oblique footprints within the seismic. A one-time mild (3x3x1) edge preserving median filter has also removed the random noise. The noise removed seismic data is more suitable for fault interpretation as the coherent and random noise has been taken out from the space of normalized discontinuity values. In Figure 4, HES outlined the geomorphology of the study area, revealing evidently the en echelon faults and the fluvial features.

The fault enhanced volume generated from Automated Fault Extraction (AFE) workflow has an even crispier display of the en echelon fault (Figure 5). It can be quality checked against the seismic data. As it is also a probability volume, 212 fault planes have been auto-tracked and extracted in one go, with each interpretation differentiated as an individual fault plane and color-coded differently. The fault planes are closely-spaced, with the clear subparallel, overlapping or step-like minor structural features having oblique angle to the NW-SE overall structural trend.

The interpreted fault planes were used as input for stratigraphic model building. The stratigraphic model with faults ensures better interpolation for well properties as it reflects the fault throws correctly, resulting better quality low frequency model (well properties incorporating seismic velocity) for seismic inversion.

Discussion

With accurate outline of the geomorphology, interpretation of seismic inversion and facies prediction of sand and shale from Bayesian inference can be co-rendered with HES or fault enhanced attribute (Figure 6). The fluvial styles (braided/meandered) and dimensions (channel width, meander wavelength, sinuosity) can be imaged and studied (Miall, 2002). The result of facies probability analysis from deterministic simultaneous seismic inversion result, together with the geomorphology outline justified the distribution of the point bar sands, as observed in modern analogue. Exploration Well X and Well Y prior to this study may have missed most of the prospects and not giving full perspective of the subsurface, resulting bias in decision making. Result of seismic inversion and Bayesian inference can provide predict the sand distribution, comparing to just having conventional seismic attribute analysis.

Conclusions

Data driven seismic attributes analysis with 3D automatic fault extraction can provide a more detailed interpretation of the faults. The results of this interpretation can be used as foundation in strategically planning exploration or appraisal wells in the area.

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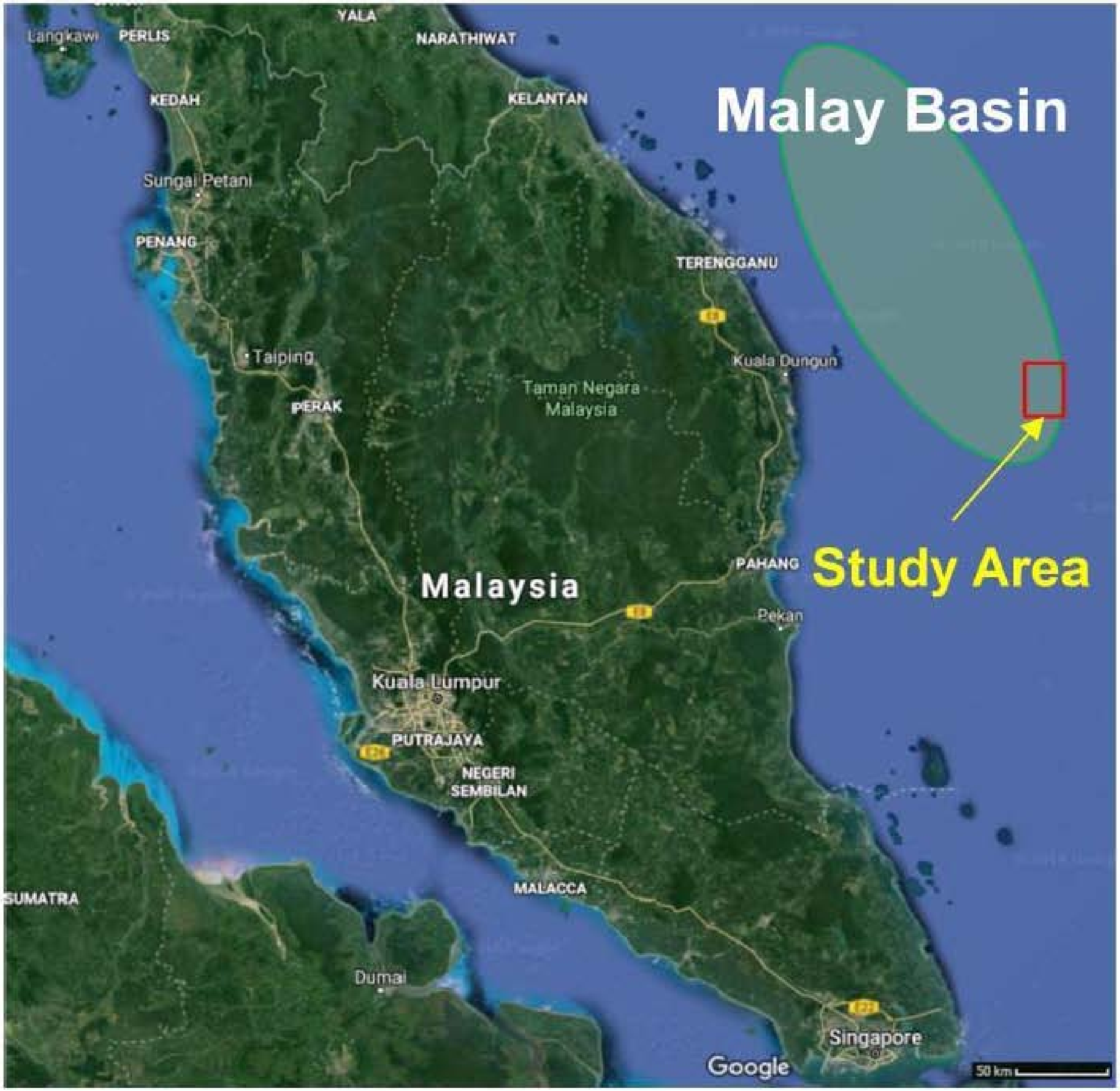

Figure 1. The study area is located offshore Peninsular Malaysia, at the SE part of Malay Basin (modified from Google map).

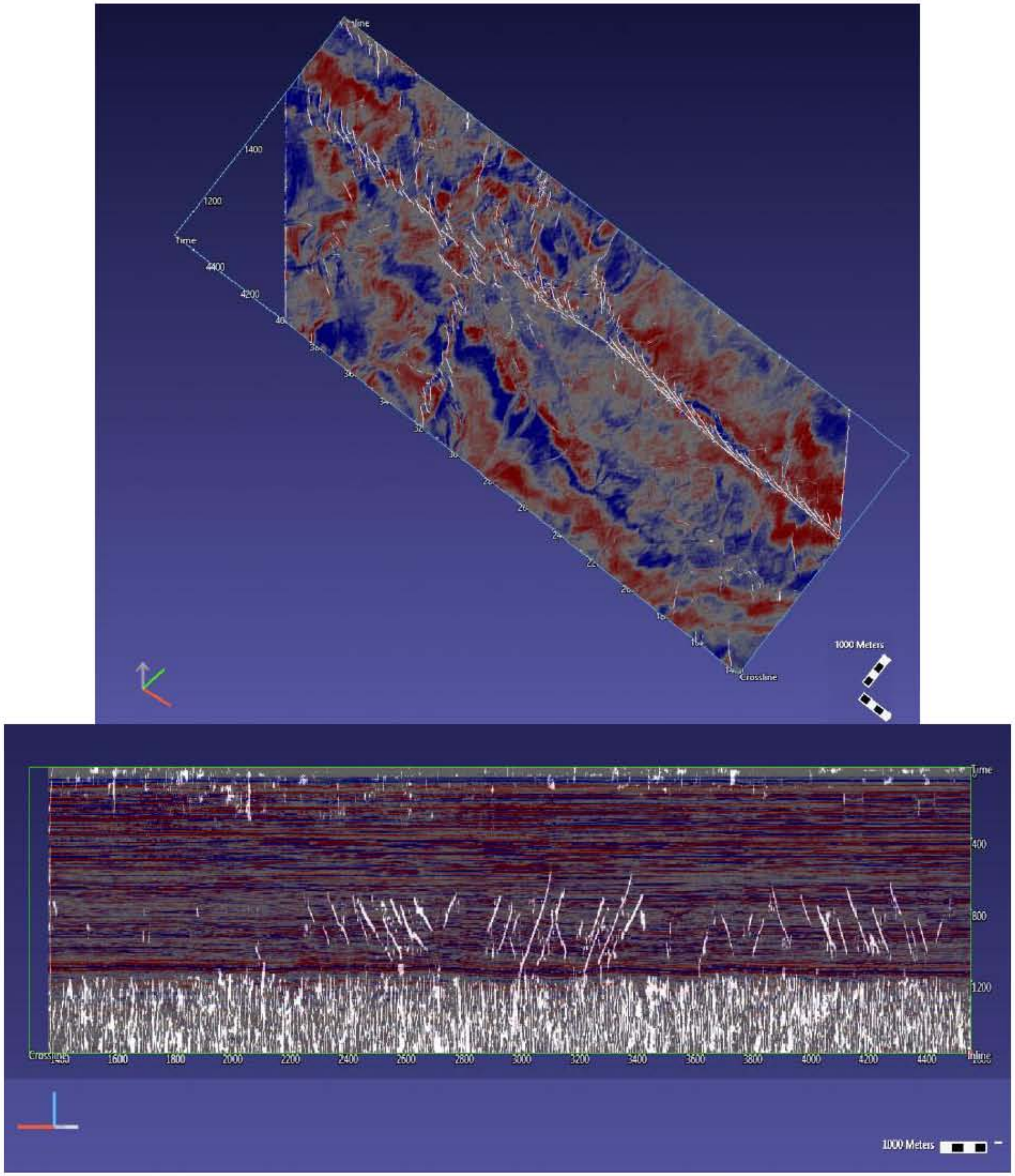

Figure 2. Time slice and inline section co-rendered with fault enhanced attribute reveals the geological structure of the area.

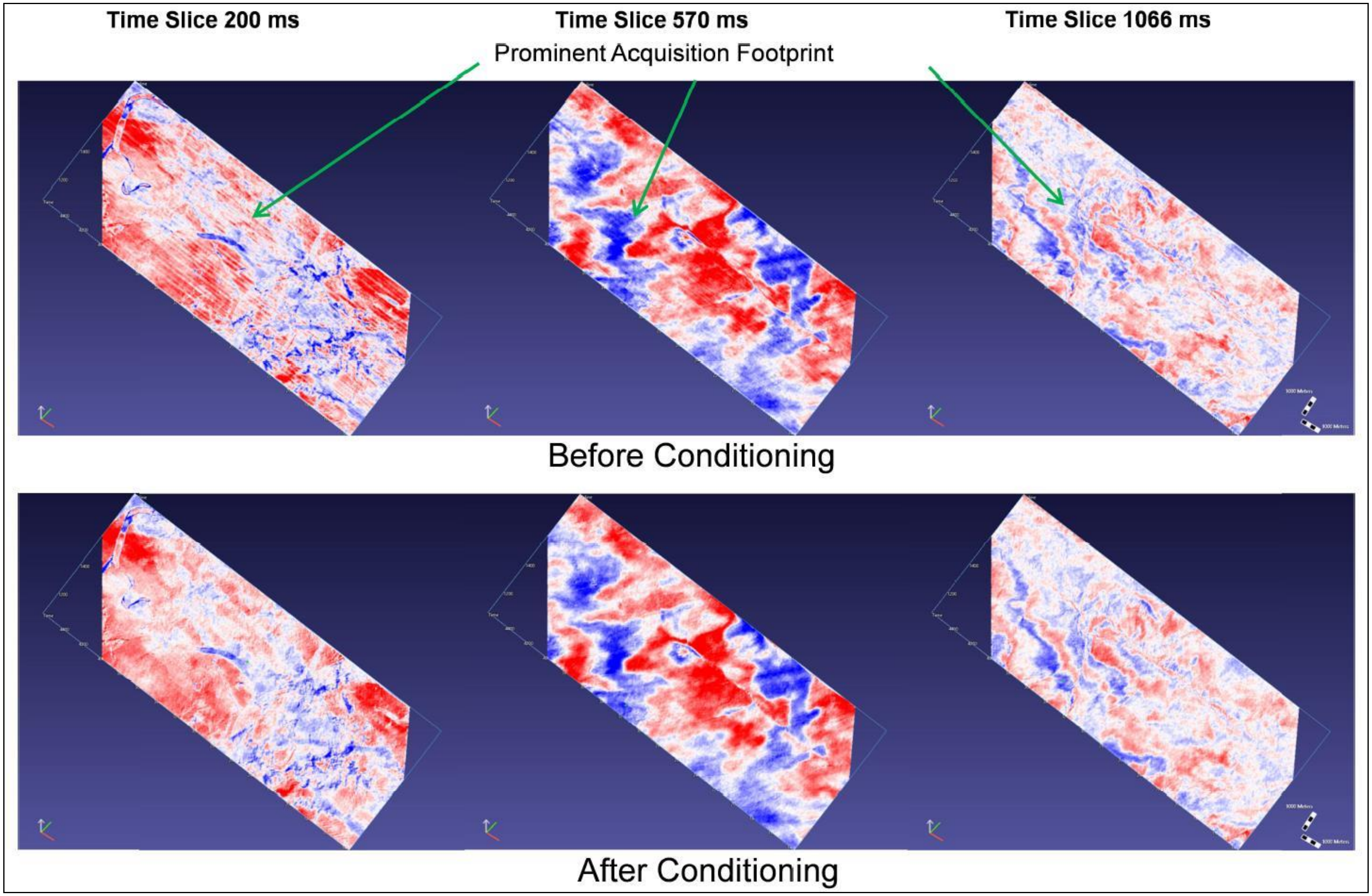

Figure 3. Comparison of the acquisition footprints observed in original seismic (pointed out by green arrows) and the noise removed seismic.

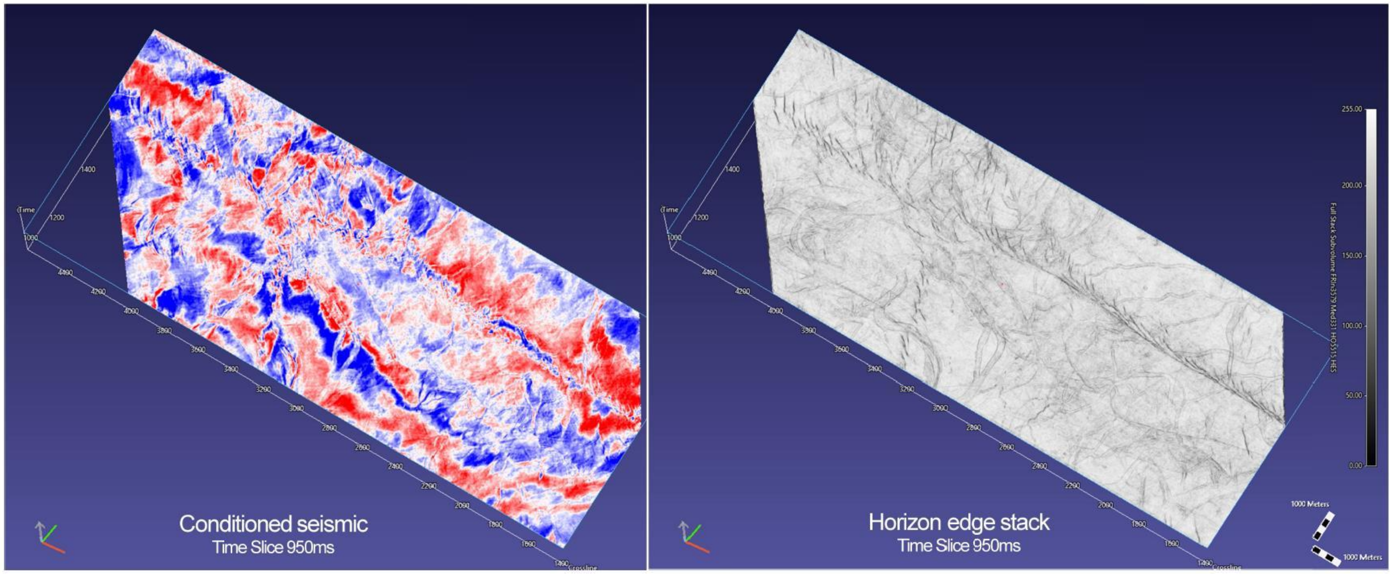

Figure 4. The Horizon edge stack (HES) outlined the geomorphology, illuminating the en echelon faults and the fluvial features.

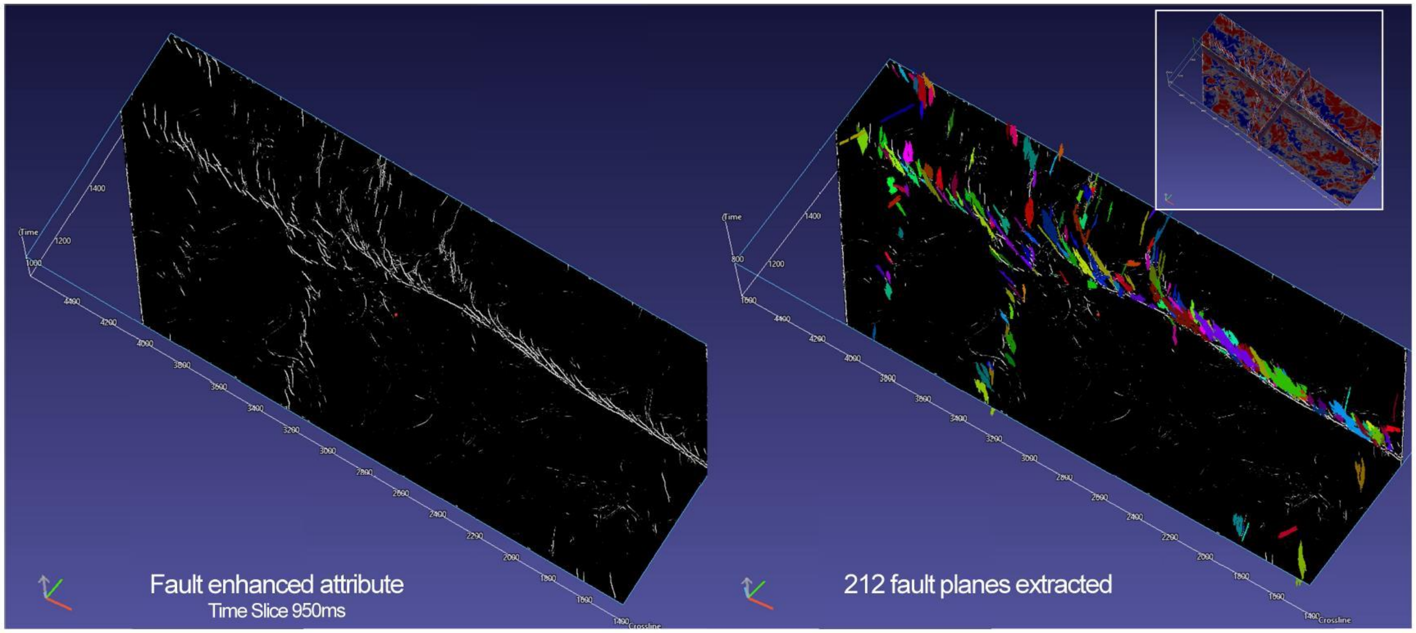

Figure 5. Fault enhanced attribute with and without the extracted 212 fault planes. The inset illustrates the quality check against the seismic.

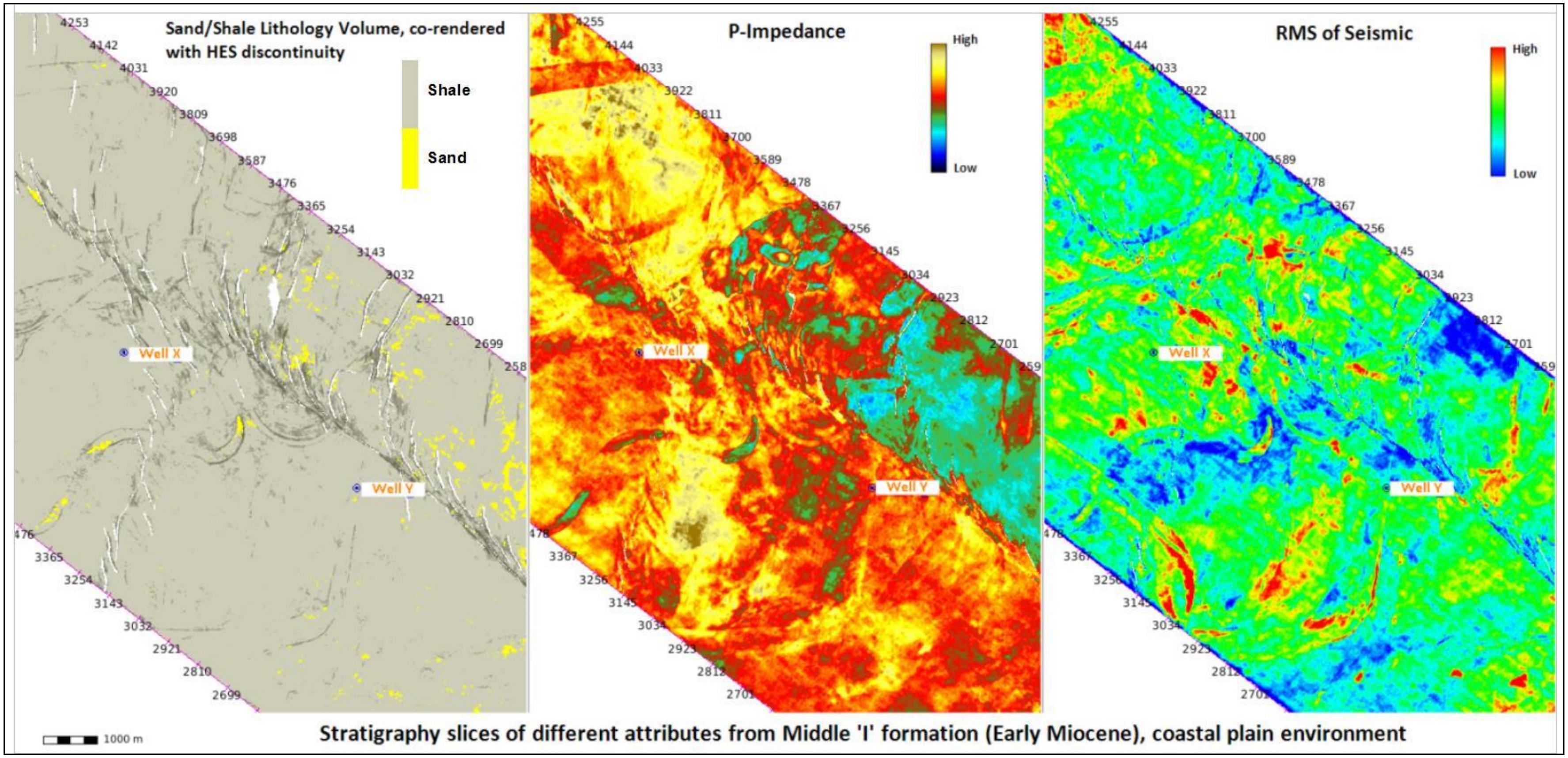

Figure 6. Stratigraphy slices of different attributes from Middle 'I' formation. By only referring to the RMS of seismic, exploration Well X and Well Y have missed the point bar sands. Result of seismic inversion and Bayesian inference can provide better indication of the sand distribution.