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## **The Magic of Depth Imaging in a Complex Geological Setting – A Case Study from Upper Indus Basin (Pakistan)\***

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### **Abstract**

This is a case study for a hydrocarbon exploration project from the structurally complex fold and thrust belt of the upper Indus Basin of Pakistan. Based on a workflow for pre-stack depth imaging, Anisotropic Reverse Time Migration (TTI RTM) was carried out to achieve a more reliable structural interpretation compared to what was achieved through the interpretation of legacy time-processed seismic data. A 2D dataset was processed using the workflow to reassess the size and dimensions of a deep-seated lead that previously could not attract E&P operators due to its small size and greater depth. Acquiring a 3D dataset would have been the best technical choice to confirm the results of the test performed on a 2D line, however, due to economic considerations, the idea of acquiring a 3D survey did not mature at that time. The 2D dataset was treated as a simulated 3D dataset to generate a 3D velocity field to estimate Thomsen's parameters and perform TTI-RTM. The mapping resulted in a completely different picture: a synclinal feature on time imaged data changed to an anticlinal feature at a depth of over 5600 m, and lateral movement of the anticlinal feature after proper depth imaging was in excess of four km. The overall size and resource estimates made this feature a drillable prospect.

The study area has a steeply dipping anticline at the surface with a complex crushed-zone directly beneath it. The Kirchhoff (KPSDM) depth imaged section showed better structural imaging, fault definition, and event continuity. The RTM section further enhanced resolution, particularly below the Eocene Kohat Formation and under steeply dipping flanks of the surface anticline. Mapping and interpretation resulted in a fault-bounded structure that was matured as a candidate for drilling. The drilling on this prospect, based on the workflow described above, resulted in the deepest hydrocarbon discovery in Pakistan.

The study demonstrates improvements that can be achieved by a TTI tomography approach and an RTM migration algorithm. Although this significant achievement was possible using a 2D dataset with all its imaging limitations, to fully exploit the potential of depth imaging

workflow a 3D dataset was recommended. The workflow relies on the soundness of the velocity model, which reinforces the need for azimuth-rich 3D acquisition and well-calibrated processing, followed by pre-stack depth imaging. This success calls for a revisit of the many comparable datasets under similar structurally complex geological settings in the area and in its analogs elsewhere in the world.

## **Introduction**

This case study is the continuation of a paper presented at the Annual Technical Conference by the author titled “Enhancement of 2D seismic imaging using RTM TTI anisotropy in thrust belt of Pakistan”, the conference was organized by Pakistan Association of Petroleum Geologists (PAPG) in 2011. In that paper, we discussed the detailed exploration history through which conventional time processing failed to provide reliable results, and could not solve structural complexities under the steeply dipping surface anticline.

The major exploration objective in the block was a lead identified at the Eocene level around 5200 m depth below the Jhammat surface anticline. Jhammat is a tight anticline trending east-west; the forelimb is thrust faulted and major vergence is southward. On the surface, the Chinji Formation of Miocene age is exposed in its core. A thick Siwalik sequence of about 5200 m is present above the Eocene Kohat Formation. The core of the anticline has a thick crush zone of sand-shale lithology of Siwalik sequence that causes abrupt lateral velocity variation.

After disappointing results with the time migrated dataset, a test for pre-stack depth imaging utilizing anisotropic Reverse Time Migration (TTI RTM) was performed on a 2D seismic line. The test produced a structural geometry that was much in accordance with the geological setting of the area. Depth migration improved the structural geometry under the surface anticline, and delineated the rollover feature under the core of the surface anticline.

Following the test, the whole 2D dataset was processed through the same sequence. The mapping and interpretation resulted in the resolution of the long-standing problem of imaging under the complex, steeply dipping geological feature.

## **Theory**

Based on the results of KPSDM/RTM on a test line ([Figure 3](#)), it was decided that all of the 2D data covering the Jhammat Lead should be reprocessed up to KPSDM/RTM levels, as PSTM was not able to handle complex ray paths through the geologically disturbed zone and would not provide reliable image under the crushed steeply dipping shallower strata. [Figure 1](#) and [Figure 2](#) show the major structural problems on time migrated datasets.

Interpretation was performed on the KPSDM/RTM imaged data. The mapping revealed the presence of a four-way closure under the steep Jhammat Anticline, with a size greater than mapped on PSTM dataset, where it also appeared as a syncline due to limited capability of time imaging in handling lateral velocity variations and complex ray path.

After this new development, it was decided to acquire additional infill 2D seismic lines to reduce the grid spacing from 6 km to 3 km in order to further improve the velocity model, and with larger offset up to 6 km, as limited offset of old datasets was also considered as a deterrent to proper imaging. The whole dataset was processed through TTI-RTM workflow.

The Dhok Sultan X-1 Well was drilled in 2015 and resulted in the deepest oil discovery in Pakistan; the adopted workflow changed the fate of an exploration concession. After discovery, the operator acquired a 3D dataset to appraise the discovery and also to mature another prospect for drilling close to the first discovery. As expected, the processing of the 3D dataset through a similar processing sequence that was earlier tested on a 2D dataset provided much improved structural definition of the sub surface. A second exploration well on the same structure is now being planned.

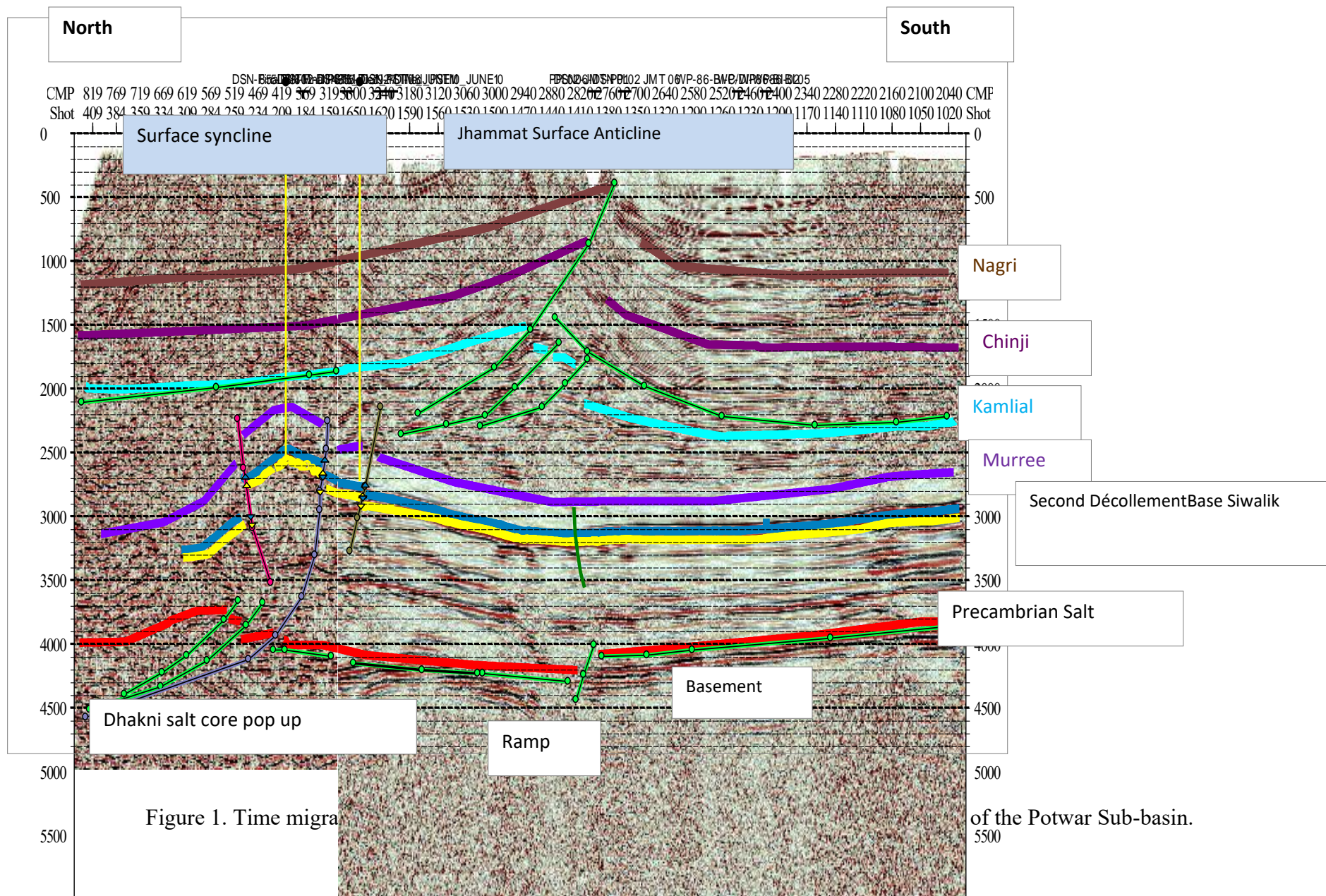
## **Results**

Three to five iterations of velocity tomography were applied, which resulted in delineating/differentiating steeply dipping flanks more precisely on KPSDM and RTM versions ([Figure 4](#)). This resolved the structural geometry below the Jhammat surface anticline and also improved the fault definition at basement and Eocambrian levels. KPSDM/RTN processing confirmed the presence of a four-way geological structure.

Based on 2D PSDM-RTM dataset, the area was re-mapped and the structure appeared as a separate four-way closure. At this prospect, first Exploration well was drilled to the TD of 5800 m., which resulted in the deepest oil discovery in Pakistan from Paleocene carbonate reservoir in 2015. Velocity model used was without any well control, and yet it was so accurate that error in prognosis was less than 20-30 meters.

## **Conclusions**

- In complex geological settings such as fold and thrust belt areas, where time migration fails to provide the reliable solution for imaging under steeply dipping geological features, pre-stack depth imaging algorithms are extremely useful for proper exploration of deep-seated prospects under structurally complex overburden.
- In such areas, depth migration with advanced processing methods like TTI-RTM can provide the proper imaging solution.
- Imaging can be greatly improved after RTM, that even small faults can be recognized, and can be tied with FMI interpretation.
- Depth conversion was found to be extremely accurate during drilling of the well.



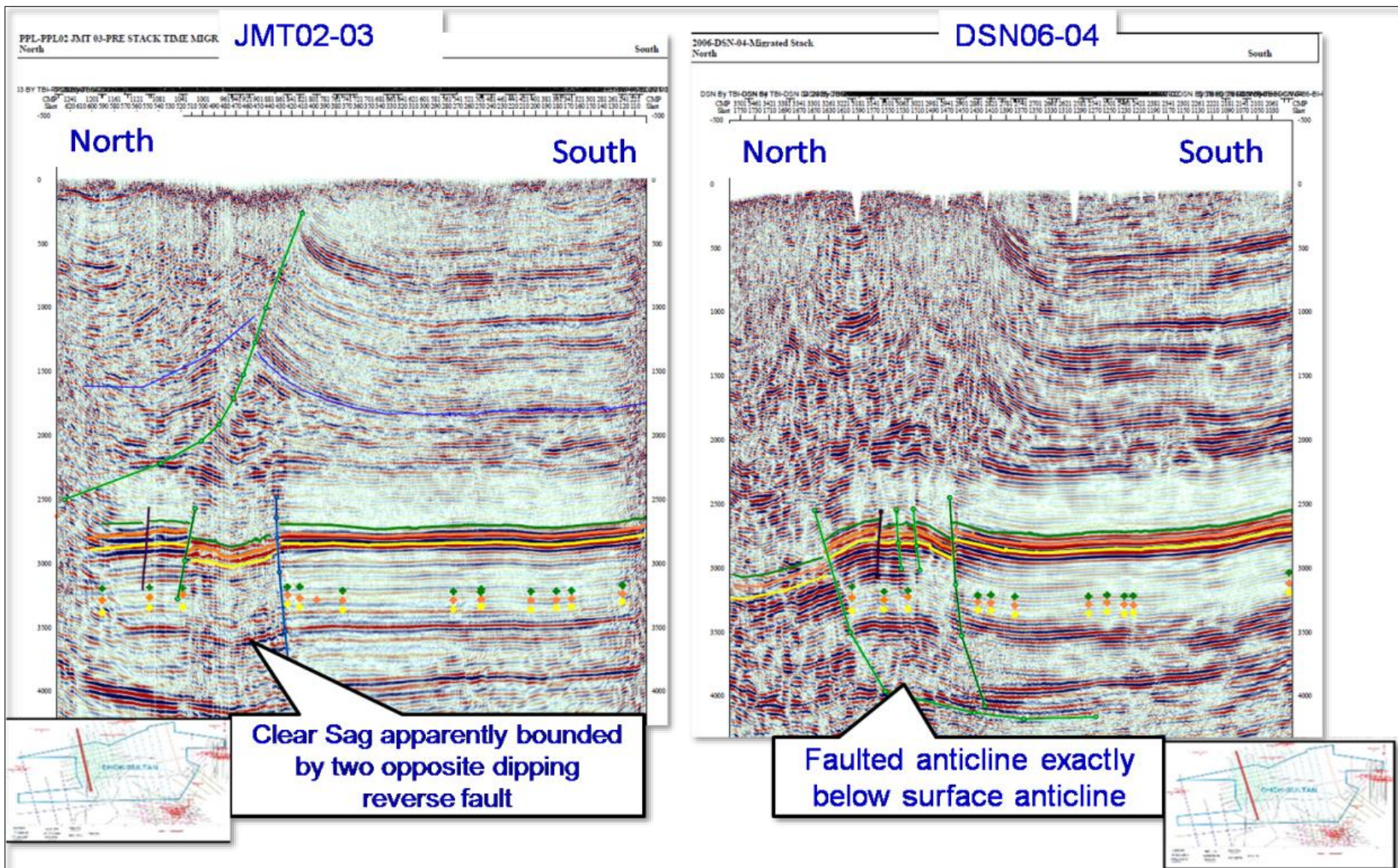


Figure 2. Two parallel dip lines with a difference in structural geometry PSTM processed by two different contractors.

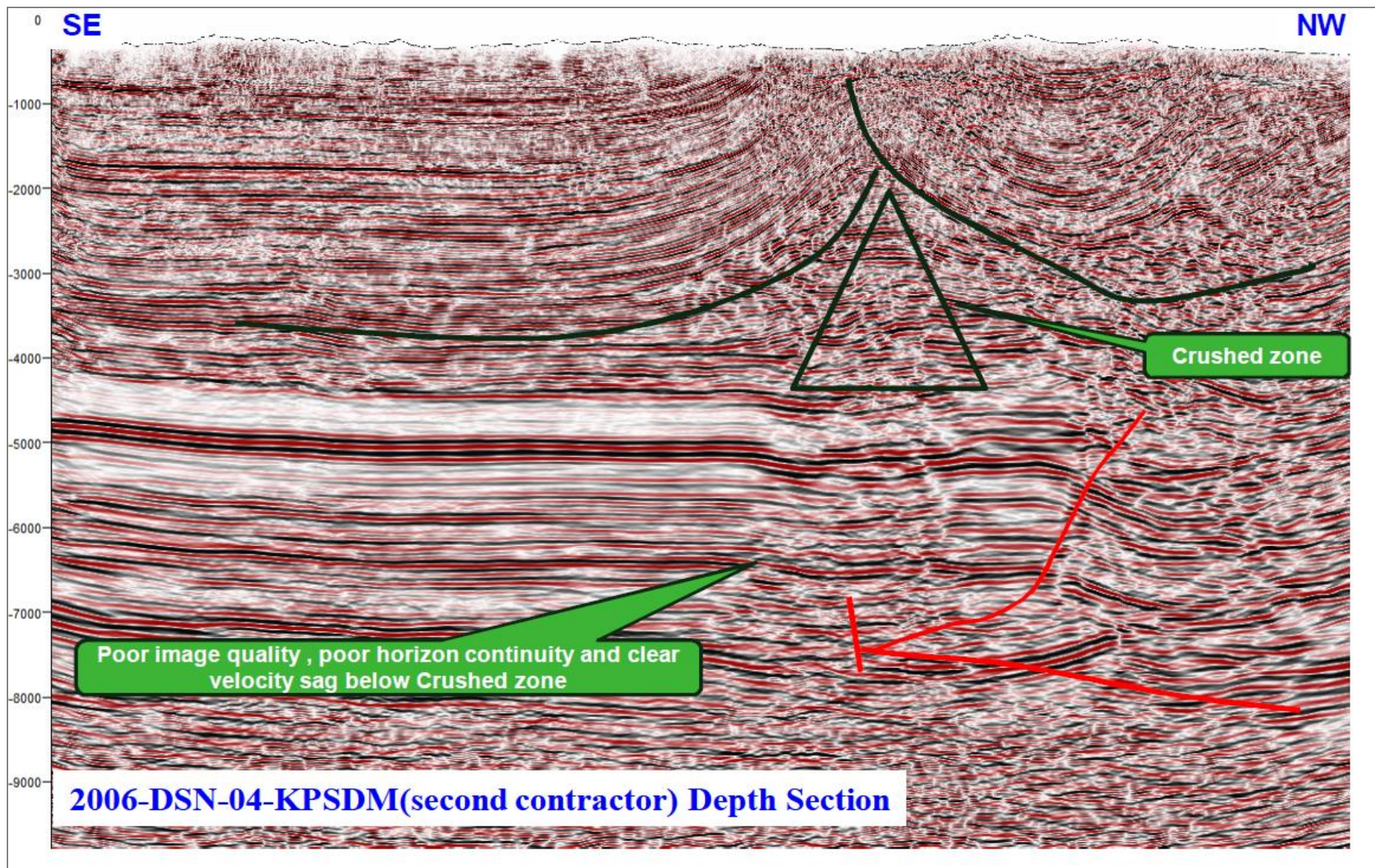
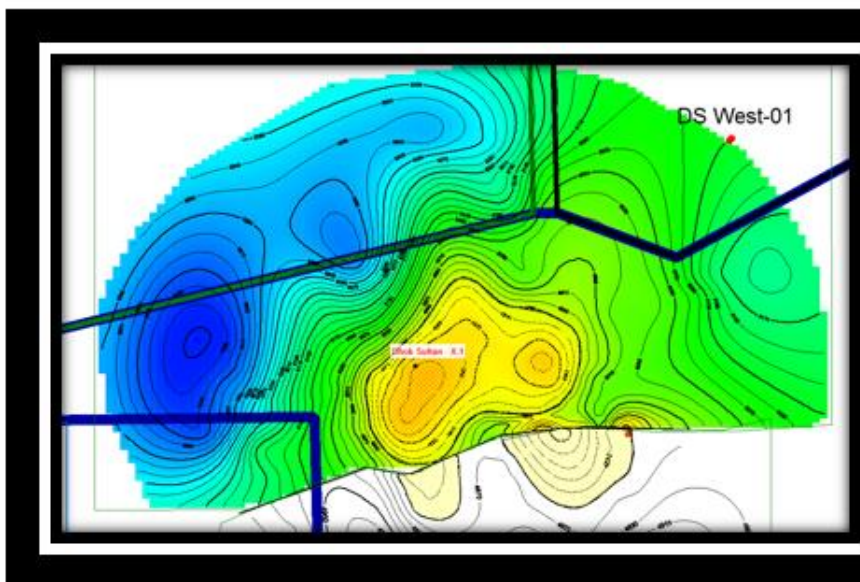


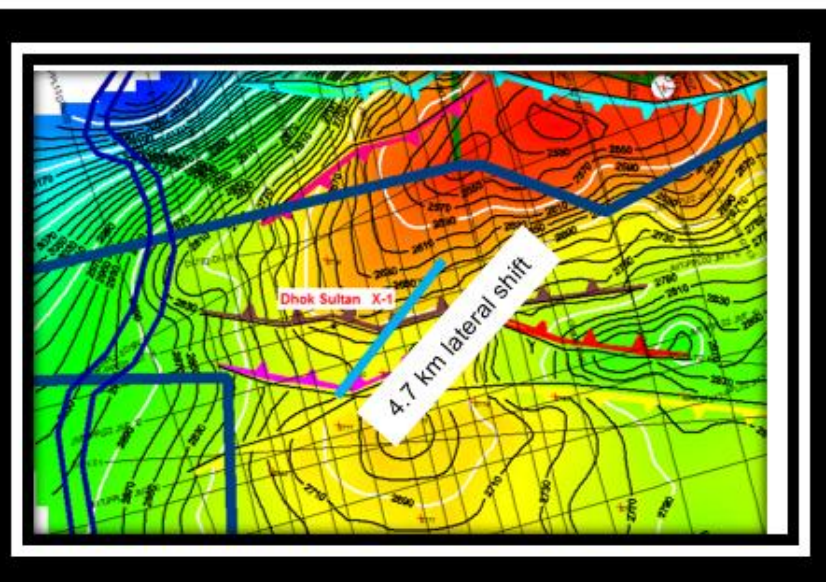
Figure 3. Test line; KPSDM time converted section using model-based approach for tomography.

Depth Map based on RTM Data Set



On Depth Imaged Data Set Four Way Closure is evident below Tight surface Anticline.

Depth Map based on PSTM Data Set



On time imaged Data set well location is at southern plunge of Northern Structure

**Structure map comparisons between legacy PSTM and RTM**

Figure 4. Structure map comparisons between legacy PSTM and RTM.