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TTI Anisotropic PSDM in a Permafrost Region - A Case Study of Point Thomson, North Slope, Alaska

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SUMMARY

The Point Thomson field, located on the North Slope of Alaska, covers the transition zone from onshore to a frozen lagoon. This complexity in the near-surface poses many challenges to proper imaging of the reservoir. Unground ice on the lagoon causes very poor signal-to-noise ratio (S/N) over a critical portion of the field. The rapid lateral variation in permafrost thickness introduces strong lateral velocity gradients in the near-surface. Onshore, the presence of ice lakes create highly localized anomalies. We present a workflow that we developed to address these near-surface issues during the recent reprocessing of the vintage low-fold data. Aided by modern imaging technology for noise attenuation, statics, and velocity model building, we were able to address many of these issues and produce a significantly improved image.

Introduction

The Point Thomson Field located east of Prudhoe Bay in Alaska and discovered in 1975 by Exxon is currently estimated as Alaska's largest undeveloped oil and gas field. Permafrost environments cause significant imaging challenges (Abma, 2001). In particular, the unground ice offshore in the lagoon causes very poor signal-to-noise ratio (S/N) over a critical portion of the field and requires careful attention in noise attenuation. The rapid lateral variations in permafrost thickness induce a strong velocity gradient in the near-surface resulting in imaging distortion of the deeper reflectors. An accurate depth velocity model for pre-stack depth migration (PSDM) imaging is critical for future well planning to mitigate the risk of drilling on false structures created by near-surface velocity anomalies.

We present a case study of the tilted transverse isotropy (TTI) anisotropic PSDM in this area by concentrating on surface wave noise attenuation and TTI anisotropic model building. The narrow azimuth data was acquired in 1989 and covers approximately 70 square miles using vibroseis with a 330-ft shot interval and 165-ft station interval. It lays partially onshore (thick permafrost) to partially offshore lagoon (thin to absent permafrost) to offshore barrier islands (thickening permafrost). The acquisition has an offset range of 461.5 ft to 10,149 ft and the targets at the Thomson reservoir are approximately 13,000 ft deep. The surface elevation varies smoothly in the survey from 0 ft to 52 ft.

Surface Wave Noise Attenuation

Surface wave noise is one major cause for a low S/N in onshore data. Two commonly observed surface waves in land acquisition are the ground roll and guided waves. Ground roll is the result of interfering P and SV waves traveling along the interface of subsurface. It is characterized by low velocity, low frequency, and high amplitude. Ground roll can be strongly dispersive and aliased and can act as guided waves. Besides ground roll and guided waves, data acquired on permafrost offshore in the winter and onshore ice lakes may also be highly contaminated with flexural waves. The ice flexural waves are caused by energy trapped within ice sheets that usually float on a layer of liquid water. It consists of combined P-SV modes internally reflecting within ice sheets. It can be highly dispersive depending on the source spectrum and ice thickness, and it can be difficult to remove using standard filtering options because its frequency content overlaps with typical signal frequencies (Molino *et al*., 2008).

The near-surface conditions vary dramatically over the Point Thomson survey, especially across the coastline, resulting in very different surface wave noise characteristics (Figure 1). A three-dimensional adaptive ground roll attenuation algorithm was adopted (Le Meur *et al*., 2008). This data-driven approach attenuates the surface waves by extracting the ground roll characteristics via a frequency-velocity phase-diagram. It can effectively remove noise even in the presence of irregular sampling or aliasing, i.e, in the lagoon area. To enhance the S/N of data input to PSDM, we applied several passes of noise attenuation, including surface wave attenuation and random noise attenuation.

Anisotropic TTI Velocity Model Building

The complex near-surface condition causes many issues in depth velocity model building. Besides the near-surface complexity, there are additional challenges caused by the abnormal pressure presented in intervals above the Thomson reservoir and the significantly lower velocity in PA-50 shale than its surrounding material (Figure 2). The major objectives in the depth model building are to:

- Improve depth conversion accuracy with a geologic model;
- Improve the base of reservoir imaging;
- Provide better identification and more accurate lateral positioning of faults and potential stratigraphic-related events.

We used an iterative top-down approach for the velocity model building and spent extensive efforts on the shallow velocity model.

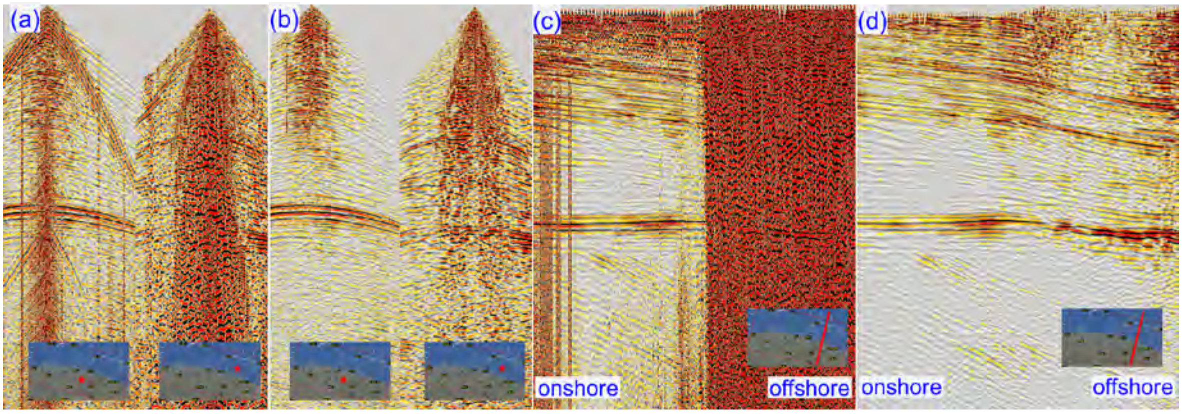

***Figure 1** Surface wave noise attenuation with different wave characteristics onshore and offshore. Shot gather (a) before noise attenuation and (b) after noise attenuation. Raw stack (c) before pre-processing and (d) after several passes of noise attenuation and surface consistent amplitude correction, which significantly improved the signal-to-noise ratio.*

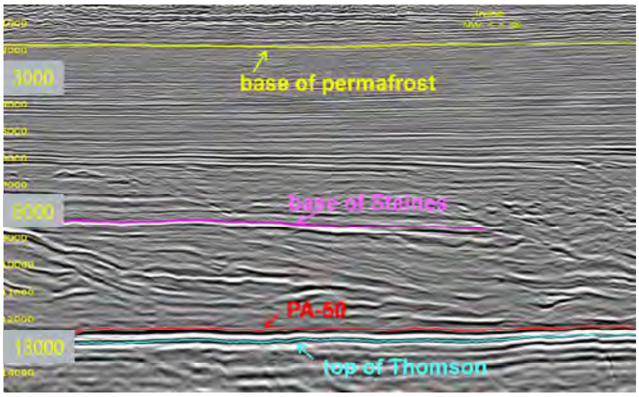

***Figure 2** Cross-section of Point Thomson survey overlaid with several key horizons.*

Shallow Model Building: First Arrival Tomography

The rapid lateral variations in permafrost thickness and numerous isolated ice lakes onshore introduce large variations in the near-surface velocity. The large velocity contrast in the near-surface can cause instability in ray tracing, degrade the overall image and cause errors in fault positioning. The traditional method of using a smoothed near-surface model while compensating the travel time difference by statics loses details of shallow velocity model and introduces distortion in deep reflectors caused by incorrect ray-tracing paths through the near-surface. To incorporate the near-surface velocity complexity, either full waveform inversion (FWI) (Mei *et al*., 2014) or first arrival tomography can be used to derive the near-surface model (Taillandier *et al*., 2011). A small area was tested with FWI. As shown in Figure 3, FWI-updated model was able to capture the near-surface velocity contrasts and improved the imaging. However, FWI was tested as an option close to the end of processing and therefore was not applied in production due to the time limit. The first arrival tomography is accurate and robust in modeling turning waves even for extremely heterogeneous media (e.g., permafrost environments) where the first break picks vary significantly over the survey (Zhu *et al*., 2011). A depth slice at 300 ft through the first arrival tomographic model demonstrates a close match with the aerial photo and proves its capability for capturing large lateral variations and local anomalies in the near-surface velocity (Figure 4).

The first arrival turning ray mostly travels horizontally. A comparison of the first arrival tomographic model with the well shallow sonic information reveals the anisotropy in permafrost. Accordingly, the first arrival tomographic model was scaled down to convert to vertical velocity, which was then merged with a smoothed depth layer model to create the initial model. Compared with the depth layer velocity, which was highly smoothed in the permafrost layer, the model merged with the first arrival tomographic model yielded better shallow structure and reduced distortion to deep reflectors (Figure 5).

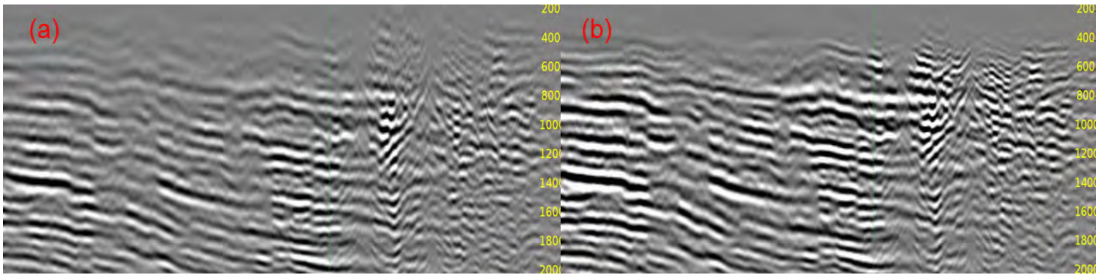

Figure 3 *Pre-stack depth migration (PSDM) stack with (a) initial model and (b) FWI-updated model.*

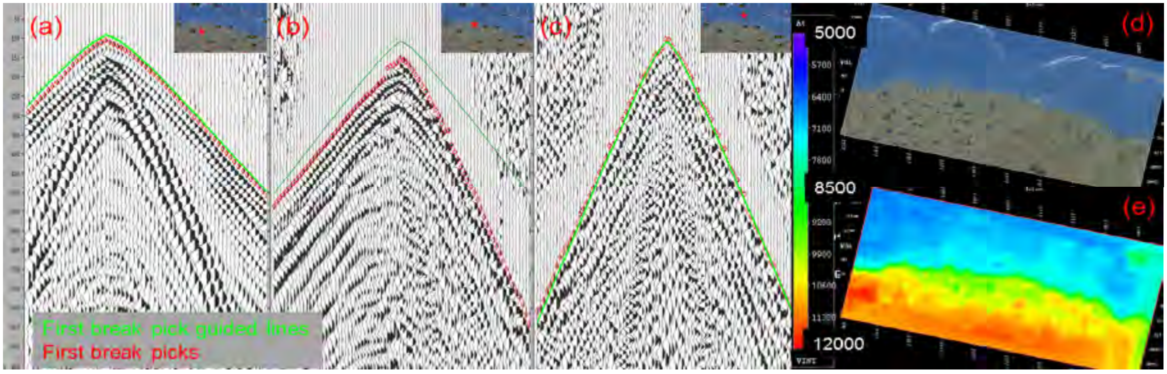

Figure 4 *Accurate and robust performance of first arrival tomography in a permafrost environment. First break picks on shot gathers (a) onshore, (b) in the transition zone, and (c) offshore. (d) Aerial photo of Point Thomson survey. (e) Depth slice through the first arrival tomographic model at 300 ft.*

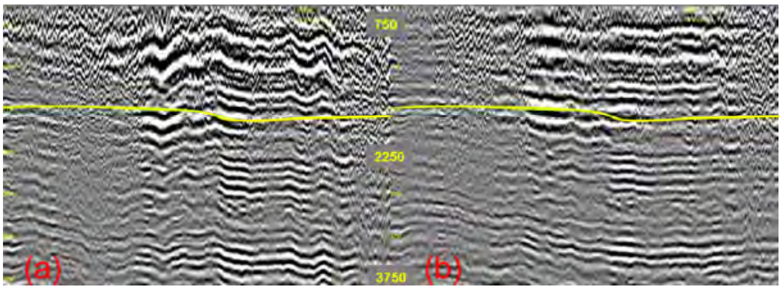

Figure 5 *Crossline view of PSDM results using (a) a smoothed depth layer model only and (b) smoothed depth layer model merged with scaled first arrival tomographic model at the near-surface. Yellow horizon: base of permafrost interpreted from wells.*

Geological Layer-Constrained High-resolution Tomography

To update the deep velocity, we used a geological layer-constrained high-resolution tomography (Guillaume *et al*., 2011)**.** The updated velocity conformed to the geology while yielding good gather flatness and stack response. The well information was incorporated into depth model building. We carried out several recursive iterations between high-resolution TTI tomography and well mis-tie tomography to derive a velocity model meeting the requirements in image quality and depth conversion accuracy (Figure 6). The final TTI PSDM volume provided an improved structural image with better event definition and fault delineation than the legacy volume (Figure 7). The volume also has more accurate depth conversion, which may reduce the risk for future well decision.

Conclusion

In presence of strong surface wave noise, the adaptive ground roll attenuation demonstrates its ability to greatly enhance the S/N. Extensive effort was put in the shallow velocity model. The near-surface model was derived from the first arrival tomography, which captured the large lateral variations and vertical gradient in near-surface velocity. The geological layer constrained high-resolution tomography was used in the velocity update. This work successfully addressed issues observed in the legacy PSDM volume, such as near-surface imaging failure, deep reflector distortion from the near-surface velocity error, fault shadow at the reservoir, and the large well mist-tie. The resulting PSDM volume provides improved structural imaging and interpretation confidence for the field.

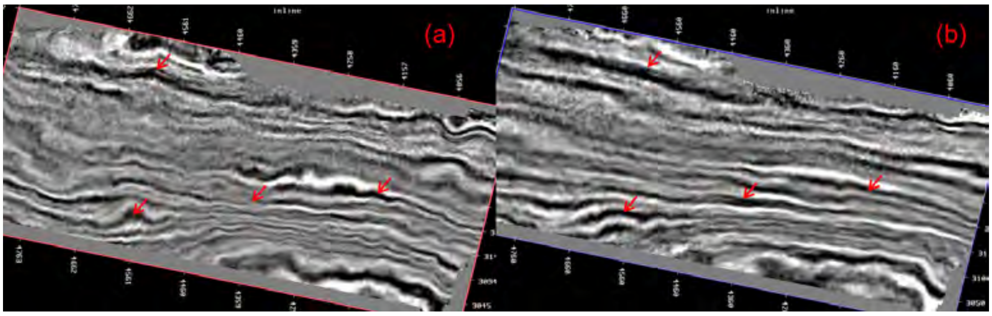

Figure 6 *Depth slices at 5000 ft (a) before and (b) after two passes of high-resolution tomography.*

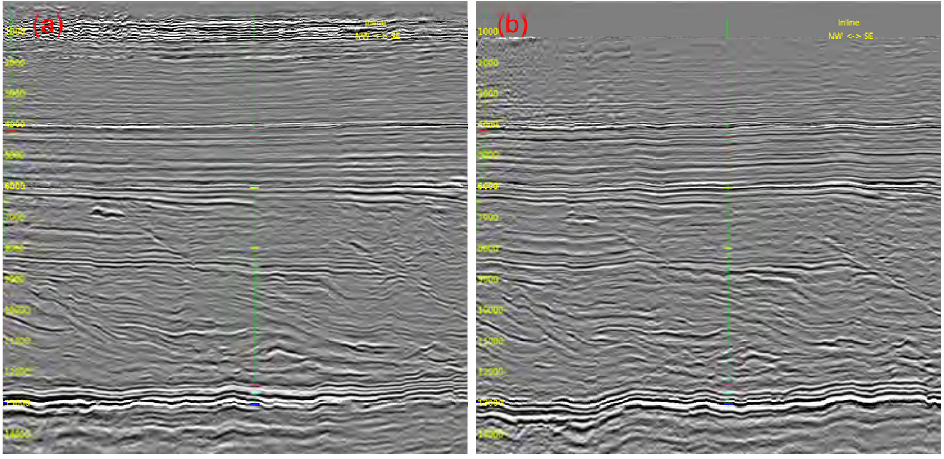

Figure 7 *Crossline view of (a) final Kirchhoff TTI PSDM and (b) legacy PSDM.*

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