Unusual negative seismic anisotropy: an example from offshore Suriname shallow waters

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Summary

A good estimation of velocity anisotropy is important in a pre-stack depth migration project in order to obtain proper focusing and accurate depthing of the seismic image. Considering that the velocity along the bedding is expected to be faster than across the bedding, the anisotropy parameter epsilon (Thomsen, 1986) is typically positive. We present an example of shallow water imaging from offshore Suriname, in which using negative epsilon was found necessary in order to achieve both seismic well tie and flat pre-stack depth migration image gathers. From well information, the negative anisotropy correlates well with the mostly unconsolidated sand layers. We then built a macro-scale anisotropy model based on the expected lithology change over the whole project area, which improved the depthing of our seismic image in the area. The observation and concept reported in this study could be applicable to other fields.

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Introduction

Anisotropy, defined using the Thomsen (1986) parameters delta and epsilon, is a fundamental component of velocity model building (VMB) in a pre-stack depth migration (PSDM) project. However, it is often challenging to derive reliable delta/epsilon in practice, especially without well controls. In a recent shallow water project offshore Suriname, we observed that negative delta/epsilon are required to achieve both reasonable depthing and gather flatness. Negative anisotropy is rarely thought of as possible; and therefore, in practice, the anisotropy is typically constrained to be positive. For this reason, the literature on negative anisotropy is very limited. Our investigation found that this negative anisotropy correlates well with the mostly unconsolidated sand layers present in certain areas, which gave us more confidence to build a macro-scale anisotropy model consistent with changes in lithology over the whole project area.

Surveys and Observations

Many significant oil discoveries in the deep-water regions of offshore Guyana and Suriname have transformed them into popular exploration areas in recent years. This enthusiasm has propagated to the adjacent Suriname shallow water basin, leading to the acquisition of new seismic as well as the reprocessing of existing data in that area. A new narrow-azimuth towed-streamer (NATS) survey with flip-flap-flop triple sources and ten 8 km-long cables was acquired from 2021 to 2022 to cover an area of about 11,000 km^2 over the Suriname shallow waters (Phase 1 in Figure 1). The water depths in this area are in the range of 30 m to 55 m. The Phase 2 NATS survey was subsequently acquired from 2022 to 2023, to cover an additional area of about 1,700 km^2 towards even shallower water depths of 20 m to 35 m (Phase 2 in Figure 1). These data were co-processed with an existing dataset acquired in 2013, hereinafter referred to as the Inpex survey, to cover a total area of about 15,100 km^2 (the red and green polygons in Figure 1). This project was successfully completed with the application of a dedicated demultiple flow and high-end technologies, including Time-lag FWI (TLFWI; Zhang et al., 2018) and high-frequency FWI Imaging (Yang et al., 2023).

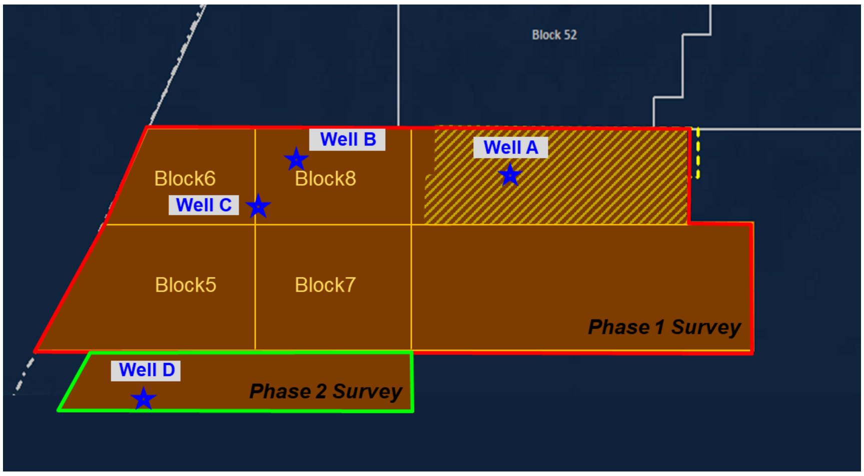

Figure 1 *Acquisition map. Brown color covers the new NATS survey, Phase 1 inside the red polygon and Phase 2 inside the green polygon. Yellow slanted line shaded area indicates the area of the existing Inpex survey. Blue stars indicate the well locations.*

In our case study, we focus on the challenge of obtaining a reliable anisotropy field over such a large project area with data acquired in different phases. Deriving a good anisotropy field is important in a PSDM project, in order to ensure proper depthing of targets for drilling purposes. Nevertheless, it can be challenging to get a reliable anisotropy. FWI could be helpful for updating it. However, it requires adequate diving wave penetration, and the cross-talk between the update of velocity and epsilon makes it difficult to solve for both on its own (Allemand et al., 2021). Well calibration is still needed in practice to update the anisotropy in order to achieve both reasonable well ties and gather flatness. Our project started with the re-imaging of the existing Inpex survey in the North-East, then proceeded with the different blocks of Phase 1, starting from Block 5 and following the acquisition order. Well A in the Inpex survey (Figure 1) was the only well covered by data at the initial stage of the project, and therefore was used to derive the starting delta/epsilon fields, which were then extended to the entire survey following the main geological horizons. During the VMB of later blocks, we observed large well mis-ties using the anisotropy derived from Well A. The Well C in Blocks 6&8 had mis-ties of 25 m to 130 m (Figure 2c), and Well D in the Phase 2 area showed even larger mis-ties varying from 50 m to 320 m (Figures 2a & b). In Well D, we also observed that the derived velocity was slower than the checkshot/ sonic profiles above the mid-Cretaceous level, yet the Kirchhoff migrated gathers were reasonably flat (Figure 3a). By performing well mis-tie tomography, we found that negative delta as small as about -10% and negative epsilon of about -8% were necessary to achieve reasonable well ties and produce even slightly better gather flatness (green arrows). The velocity was also increased during this process and became much closer to the observed checkshot/sonic profiles (Figure 3b). To help validate this observation, we performed a test by clipping anisotropy fields to zero while maintaining the velocity

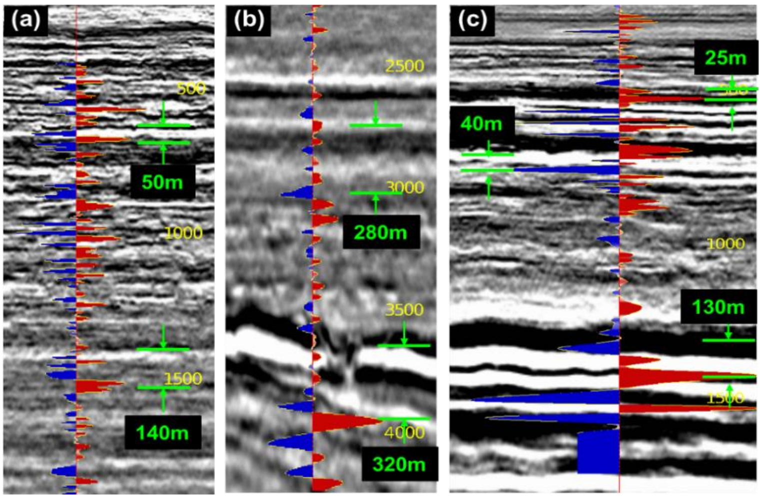

***Figure 2** Large well mis-ties, in green, were observed in the wells located in later processed blocks. The wavelets in red (positive)/blue (negative) are synthetics generated from the well sonic and density logs. The black in seismic is positive and white is negative. (a) the shallow section of Well D; (b) the deep section of Well D; (c) Well C.*

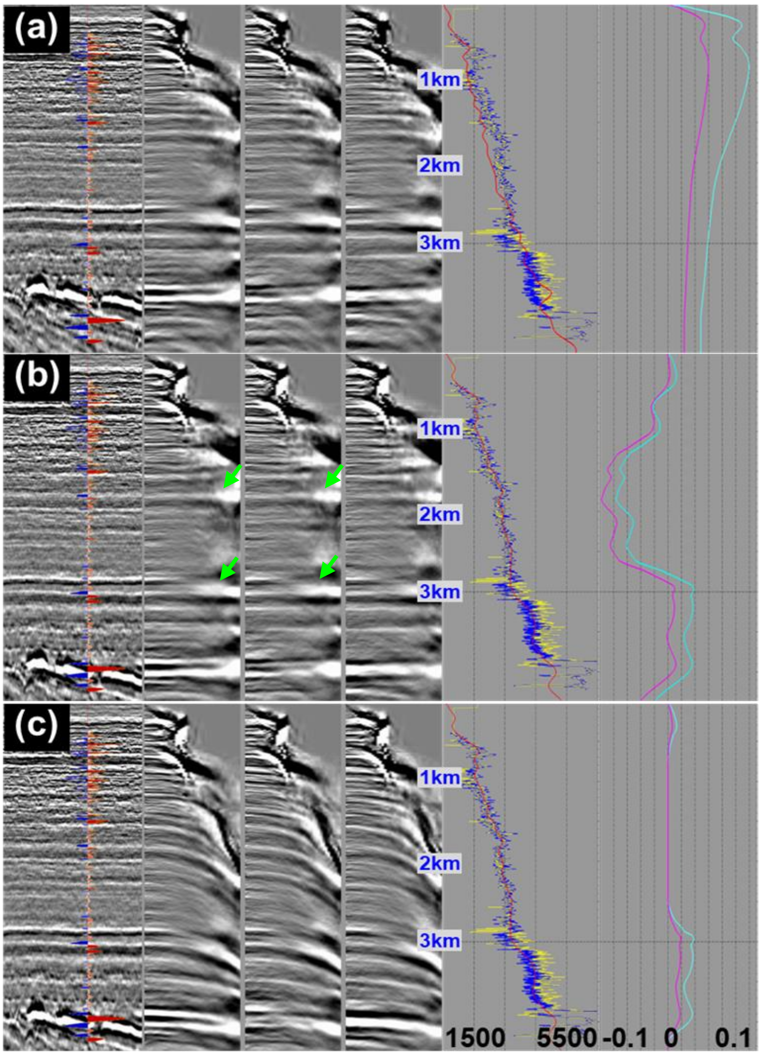

***Figure 3** Well D calibration QC. From left to right panels: well synthetic overlaid on Kirchhoff stack, Kirchhoff gathers, comparison of velocity (red) with check-shots (yellow)/sonic (blue), and delta (pink)/epsilon (cyan). (a) starting anisotropy; (b) adjusted anisotropy with negative as small as about -10%; (c) clipping of the negative delta/epsilon to zero.*

tying the well (Figure 3c). The result was substantial move-out on gathers at the well, indicating that a zone of negative anisotropy was really required to produce flat gathers. Since negative anisotropy fields, especially negative epsilon, are generally thought of as rare occurrences, considering that velocity along the bedding is expected to be faster than across the bedding, we had to carefully consider possible geologic rationales for including such anisotropy in our model.

Anisotropy Geological Correlation

After an extensive review of the well lithology reports in our study area, we found a good correlation of the negative anisotropy with the mostly unconsolidated sands (Figure 4). The Well D in Phase 2 shows clastic rock dominated with unconsolidated sands, in which we observed the largest well mis-ties within the project and where strongly negavie delta and epsilon were required (Figure 3). Towards Well C in Blocks 6&8, we start to see interfingering of Miocene carbonates, which tends to make the sands potentially more indurated, while the Pliocene above the carbonates remains relatively unconsolidated. We observed about 25 m to 130 m mis-ties (Figure 2c) in this unconsolidated layer, and negative delta/epsilon of about -6%/-4% were found to be necessary. Going towards Well B, we find more clays, carbonates, and hardened sands, in which the negative anisotropy is no longer needed, although we still found it necessary to use values smaller than our starting anisotropy. Further towards Well A, in the Inpex survey, the Miocene becomes carbonate dominated and the Pliocene sands have given way to a more shale-prone shelf mud system, where typical positive anisotropy worked well.

Although negative anisotropy, especially negative epsilon, is very unusual, laboratory studies have found that unconsolidated sands can exhibit negative epsilon when submitted to stress-induced anisotropy (Vega et al., 2006; Narongsirikul et al., 2014). For example, Narongsirikul et al. found that epsilon could vary from -0.15 to -0.03 on sand samples, depending on mineral compositions and textural differences. In addition, Asaka et al. (2016) also reported the observation of negative delta/epsilon in the depth interval of thick unconsolidated sandstones, offshore Western Australia.

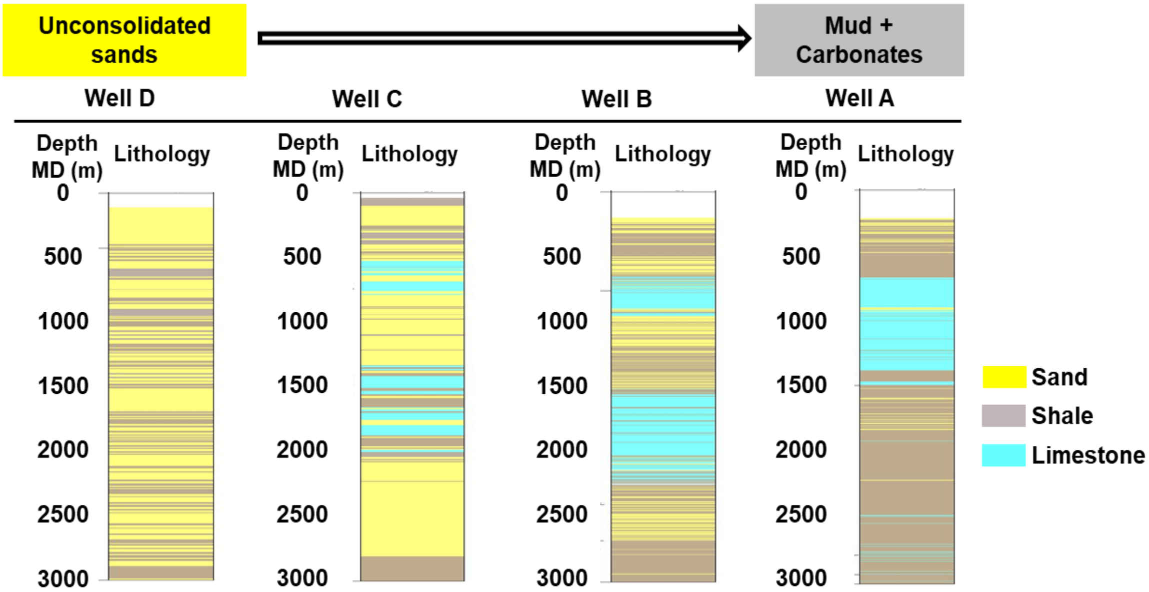

Figure 4 *Shallow stratigraphy summarized based on well lithology reports.*

The good correlation of the negative anisotropy with the mostly unconsolidated sands gave us guidance to build macro models of delta/epsilon based on both the expected lithology and observed velocity changes over the large project area (Figure 5). The macro-model of anisotropy resulted in much improved well ties with flat gathers at the different well locations. It also helped to obtain a more plausible depthing of our seismic image in-between the wells, which was consistent with clients' expectations established from an independent well-based study outside our project area.

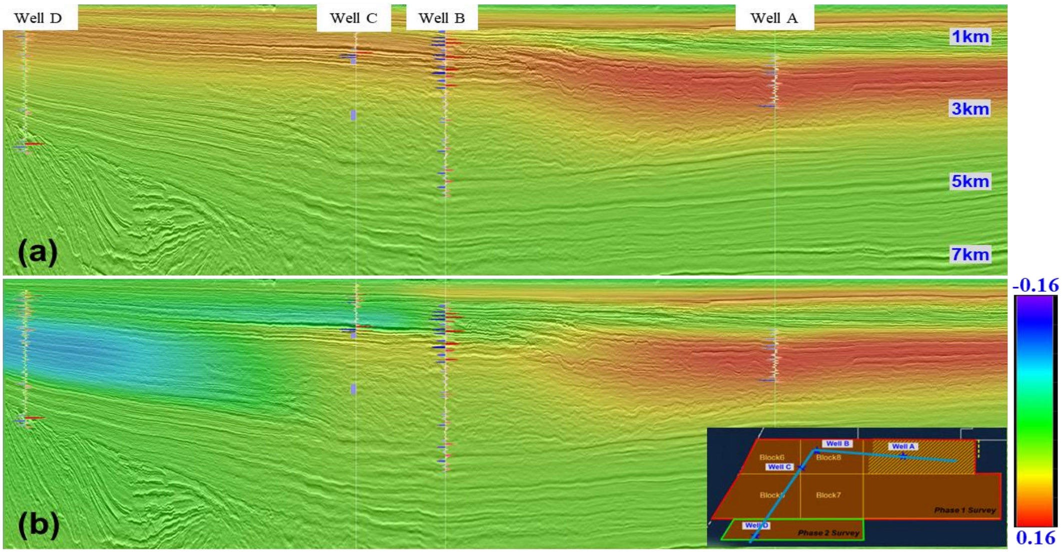

Figure 5 *A macro-model of epsilon was built based on the lithology change over the large project area. (a) the starting epsilon; (b) the updated epsilon. The Kirchhoff stack displayed under the models corresponds to the associated anisotropy.*

Conclusions

In this case study, we showed that negative delta/epsilon were necessary in certain areas of Suriname shallow waters to simultaneously achieve good depthing and gather flatness. We also found that this negative anisotropy correlates well with the mostly unconsolidated sand layers, which can be quite thick in our area of interest. Examples of negative anisotropy from the literature, though very limited, appear to corroborate our findings. All of the above drove us to build a macro anisotropy model consistent with expected lithology change, which improved the depthing of the final image. Though this is a step further towards a more accurate representation of the anisotropy in this area, its implementation requires good geological understanding and an acknowledgement that uncertainty remains, especially for the areas away from well controls.

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