

Advanced borehole dipole sonic imaging of complex lithology

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Summary

A new workflow for reflection sonic imaging uses dipole-induced shear waves to image near-borehole structures and fractures (Hornby, 2024). Like seismic processing, it relies on a multi-dimensional velocity model in Earth coordinates (TVD and Vertical Offset) for pre-stack migration of the data. This model is initially built from well data, including log data from vertical to horizontal sections and offset wells. It is then refined iteratively using imaging results, enhancing both the reflection image and near-wellbore velocity picture. This method is particularly impactful in extended-reach horizontal wells where traditional well data cannot establish location of relevant boundaries away from the wellbore. The imaging can guide completion engineers in making decisions, such as selecting optimal hydraulic fracturing locations. Examples will be shown for two extended-reach horizontal wells.

Another benefit is that by following the same workflow used to create an optimal sonic image, one can derive a near wellbore Earth model that accurately outlines formation properties, such as geo-mechanical properties, in high resolution away from the borehole.

Extended reach/horizontal well imaging

Two extended-reach horizontal wells are looked at. During both surveys the tool was oriented with a V-arm caliper that oriented the DY dipole source in the horizontal direction and the DX dipole source in the vertical direction, throughout the survey (Williams et al., 2010). This greatly facilitated the processing as in this case the DY data directly corresponds to the fast SH shear mode and the DX data corresponds to the slow qSV mode. As shown by Tang and Patterson (2009) the SH mode has the strongest and most consistent response while the qSV mode has a lower response which will tend to zero when the sonic tool is parallel to bedding as seen with this example of a horizontal well with flat bedding. For this study imaging using the SH mode is the focus.

Well #1

Figure 1 shows a 2-D shear velocity model created using well data recorded at the Hydraulic Fracturing Test Site (HFTS). HFTS-1 Phase 1 well SUGG A 171 6SM Horizontal was selected for this study (Hornby, 2023). The well penetrates an unconventional shale reservoir with significant anisotropy for recorded sonic velocities as well as related geo-mechanic properties. Two sections of interest are circled in Figure 1. The left-hand well section goes through a deviated section and

then transforms into the horizontal section of the well and the right-hand section covers a long 4000 ft section where the wellbore does not encounter any of the near-wellbore bedding.

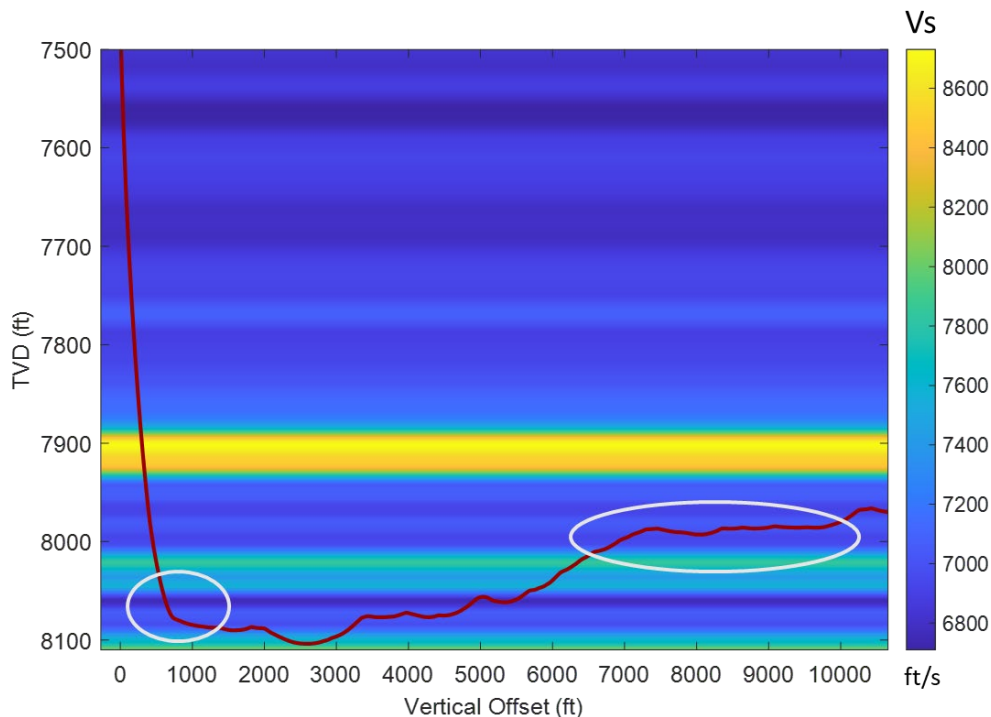


Figure 1. Shear velocity model plotted in TVD versus Vertical Offset coordinates. Circled intervals are the focus of our data and imaging analysis.

The deviated well section in Figure 2a shows a log display along with iso-offset variable density displays of recorded dipole data, band pass filtered data and data with direct arrival attenuated. Red arrows highlight reflected arrivals from near-wellbore bedding. Note that the faster slowness is the DY (SH) mode, as expected. Here reflected data are clearly seen as oblique arrivals on the bandpass filtered and direct arrivals attenuated displays.

Figure 2b shows pre-stack depth migration imaging results for the deviated well section relative to the wellbore reference. Here bedding crossing the wellbore is clearly seen. Red arrows highlight 2 strong bedding events crossing the borehole with the angle relative to the borehole highlighted on the right. These angles are consistent with wellbore wall imaging at those depths.

This verifies the validity of the imaging in a section where we know the relative bedding using borehole wall imaging.

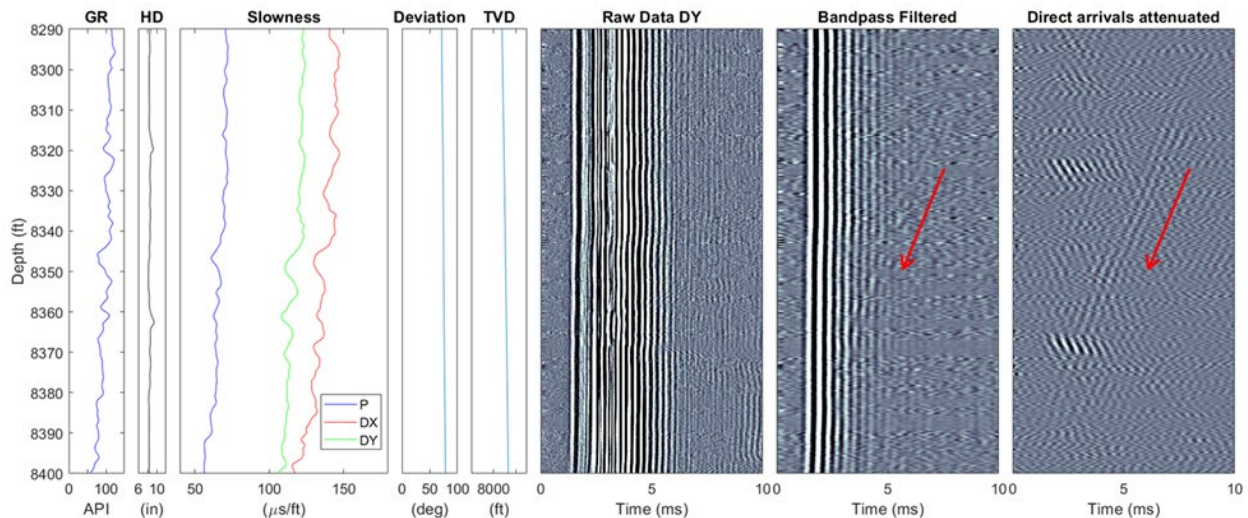


Figure 2a. Deviated well section. Log display along with iso-offset variable density displays of recorded dipole data, band pass filtered data and data with direct arrival attenuated. Red arrows highlight reflected arrivals from near-wellbore bedding

Figure 3a shows imaging results for a section of the wellbore in the right-hand section circled in Figure 1. For this example, data are simply band pass filtered before imaging. In this case the image of the near-wellbore reservoir boundary is clearly seen from ~25 to 40 ft from the well. Straight line events near the wellbore are simply artifacts from the direct arrivals. Equivalent VO for this well section is 7650 to 8248 ft.

Figure 3a is presented relative to the wellbore reference as is commonly used for sonic imaging. Another option is to display the imaging results in Earth coordinates, as a function of TVD and VO. Figure 3b shows a plot of imaging results in the long horizontal well section in Earth coordinates, TVD versus VO. The red line is the wellbore trajectory. Of particular interest is the clear image of the reservoir boundary as the well crosses the lower boundary at around 6020 ft VO and then proceeds up to 40 ft from the borehole with variations back to around 10 ft from the borehole in this interval. The advantage of this display is that the wellbore and structural images away from the wellbore are in correct Earth coordinates. Note that the images presented relative to the wellbore are affected by both the distance from the well and any change in well direction in the imaged interval.

Well #2

A second example for an extended reach horizontal well highlights this challenge (Hornby et al., 2024). Figure 4a shows imaging relative to the wellbore for a depth range from 12060 to 15000 ft. Reviewing the well deviation in the 4th panel we see the well is near-horizontal throughout this section, however, note the abrupt back and forth changes in deviation from ~89 to 93 degrees along the section. In this case, the shear image is indeed capturing the location of the bedding images relative to the borehole, however the strong changes seen on this image are strongly affected by the changes in wellbore angle throughout the section.

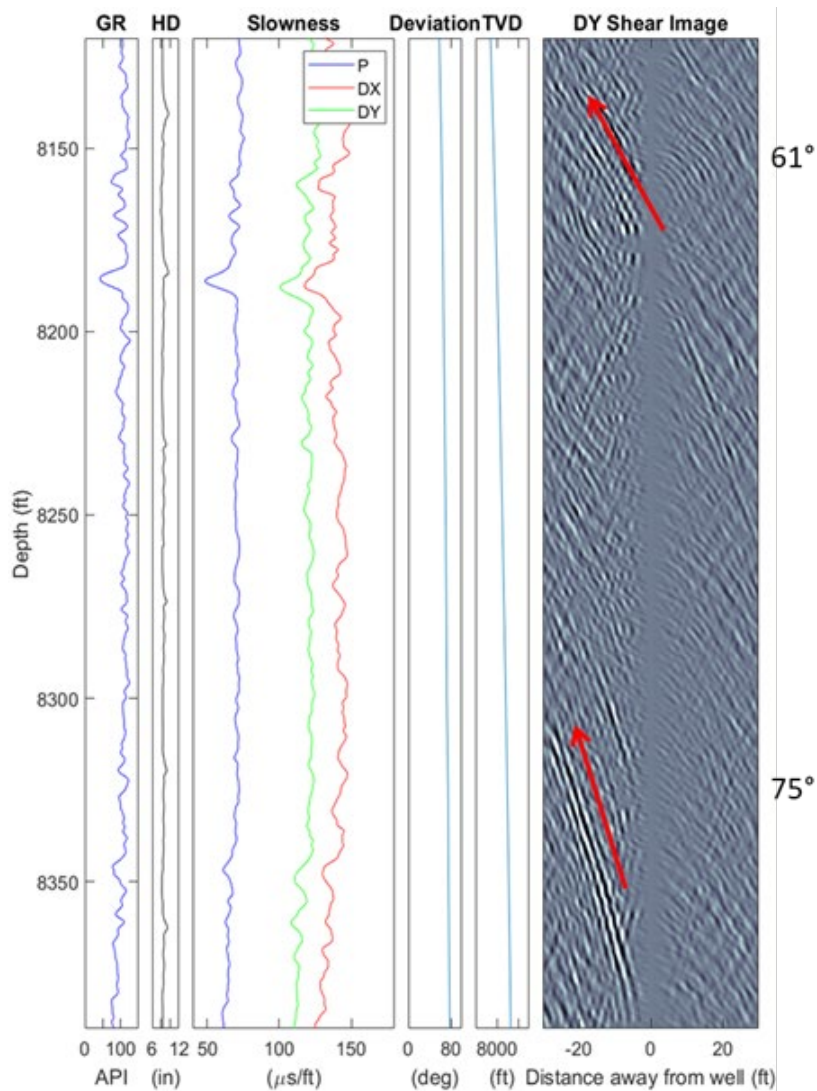


Figure 2b. Imaging results for the deviated well section relative to the wellbore reference. Red arrows highlight 2 strong bedding events crossing the borehole with interpreted bedding angle relative to the borehole.

Figure 4b shows the picture in Earth coordinates along a ~3000 ft Vertical Offset section, equivalent to the wellbore depth range shown in Figure 4a. Here we see quite a different picture – with the well deviation changes taken out of the picture we see a thin bed that smoothly changes direction along the section with bedding intersecting the wellbore around 3000 ft VO, almost touching the wellbore at 4500 ft VO, and extending to the image maximum of 40 ft at the beginning and near the end of the image.

Clearly for this example the most accurate picture of the well and bedding is the display in Earth coordinates.

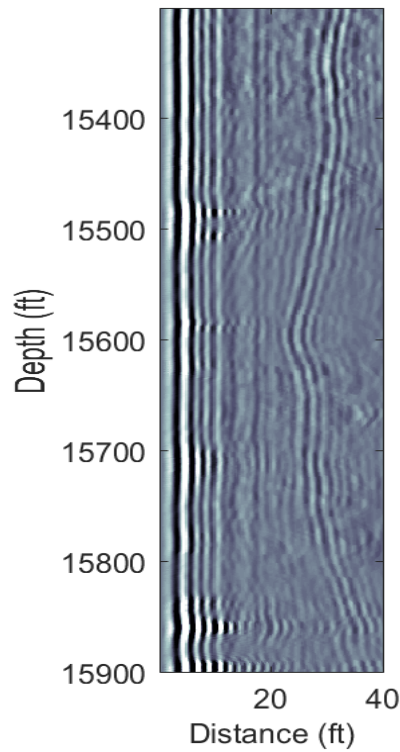


Figure 3a. Imaging results for the horizontal section of the wellbore circled in Figure 1. Strong images of bedding are clearly seen from ~25 ft to 40 ft from the wellbore

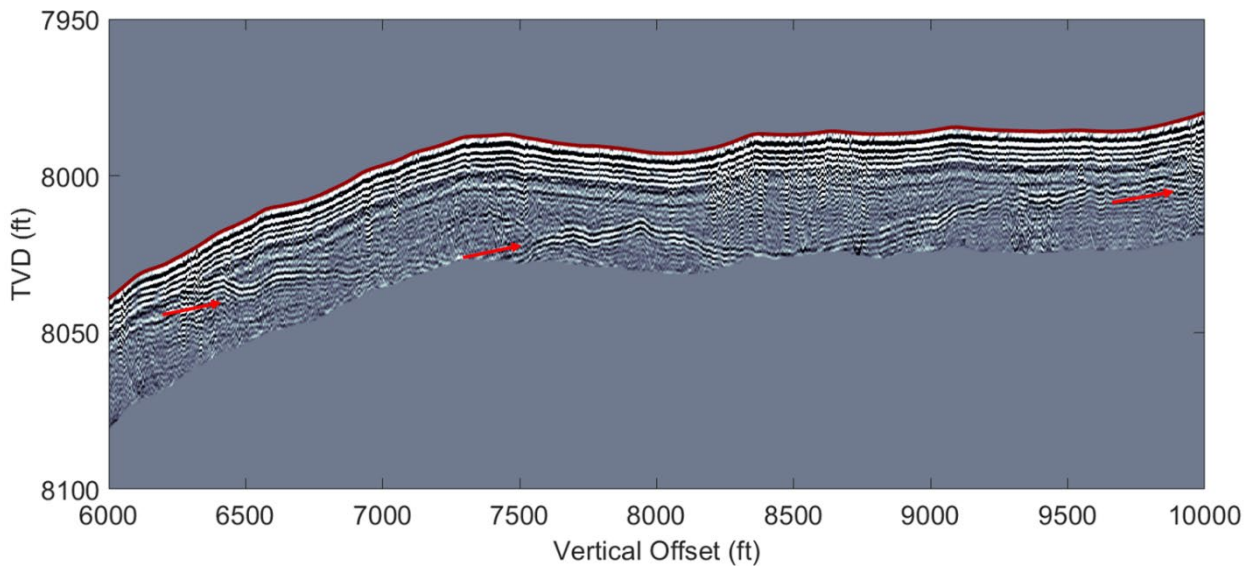


Figure 3b. Imaging results in the long horizontal well section in Earth coordinates, TVD versus VO. The red line is the wellbore trajectory and arrows point to reservoir boundaries away from the well.

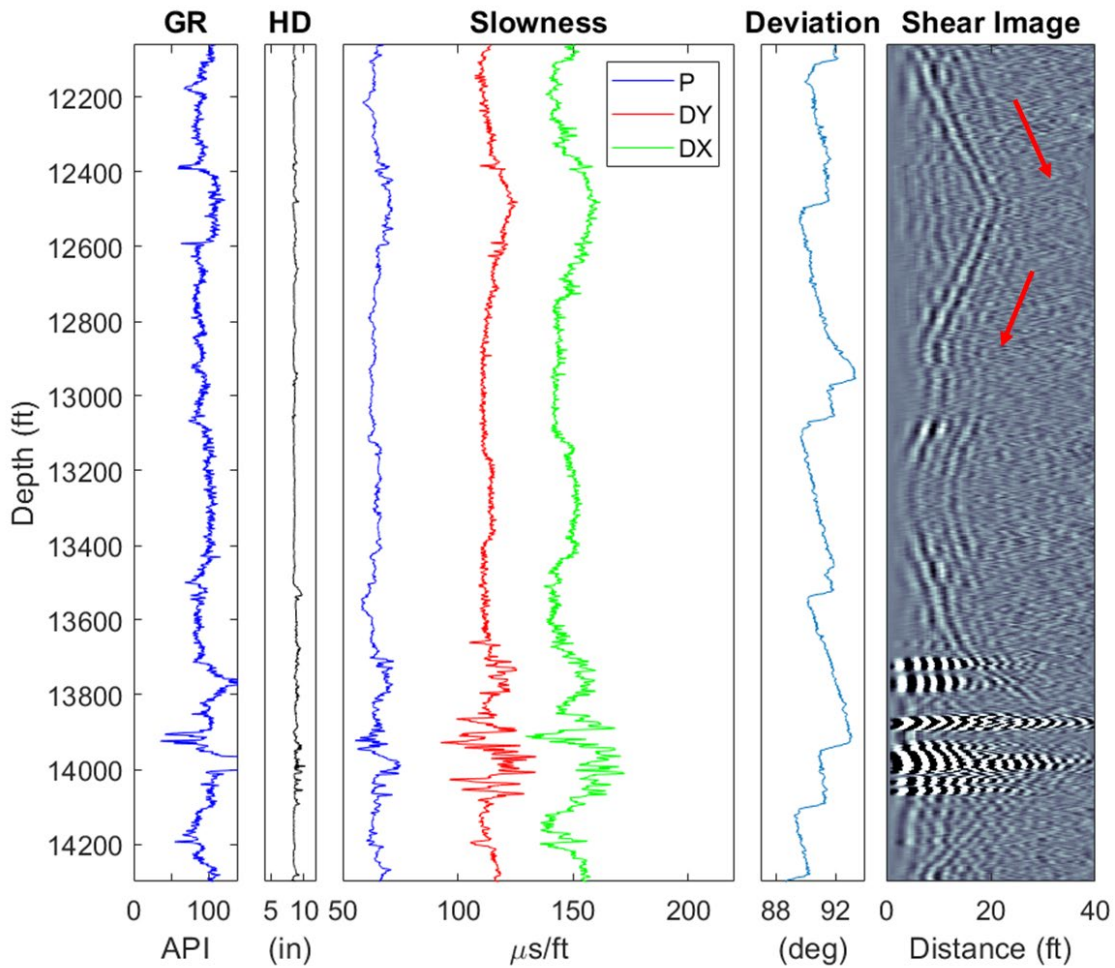


Figure 4a. Second extended reach horizontal well. Clear imaging of multiple bed boundaries away from the well is seen. Image is affected by rapid changes in borehole deviation.

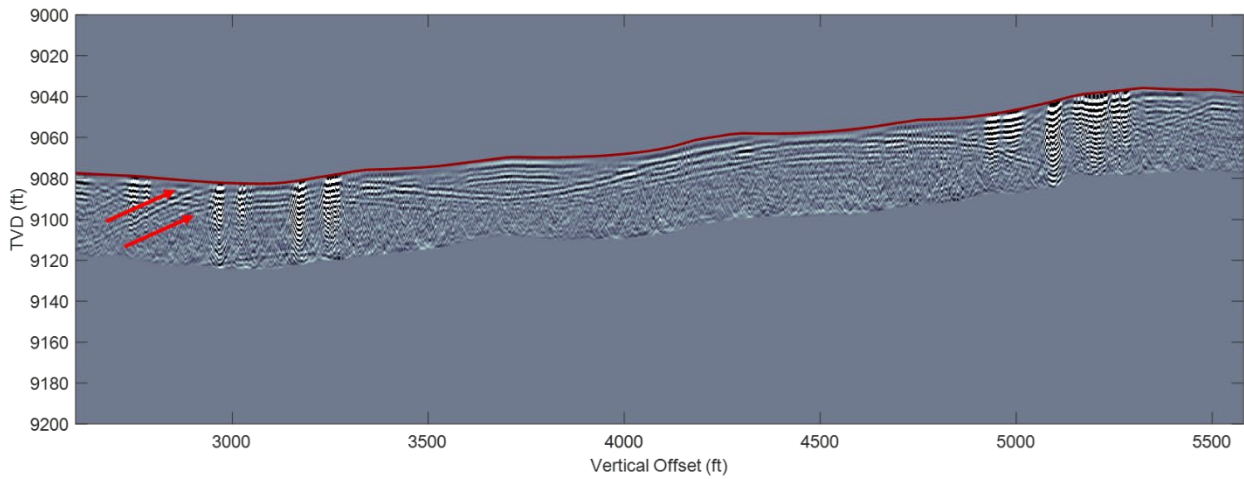


Figure 4b. Second extended reach well example. With this display well deviation changes are taken out of the picture. We see a thin bed that smoothly changes direction along the section from wellbore to 40 ft from well.

Novel/Additive Information

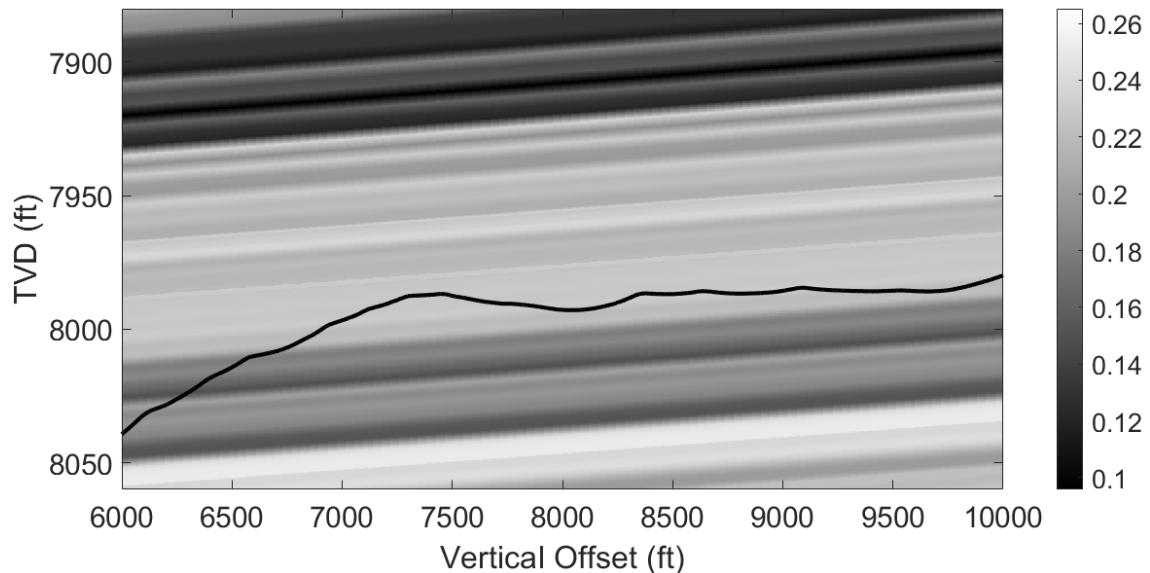


Figure 5. Example Earth model created using final workflow for velocity mode and Youngs' modulus derived from log data.

Figure 5 shows a first cut at an Earth model created using Young's modulus along with the same workflow used to achieve the final velocity model used for the imaging of the first extended-reach horizontal well. In this case the final velocity model was tilted by 3.5 degrees to match the imaged structure and then a final reflection image was produced. There was little difference seen with the reflection images with this change, however for the application of creating an Earth model small changes are important. Ongoing work will further enhance this product.

Conclusions

A new workflow for improved imaging of near-borehole structure using dipole induced shear waves is detailed. Critical for this process is the creation of a multi-dimensional velocity model which is updated during imaging for best result. Application to extended-reach horizontal wells was shown with imaging displayed both relative to the wellbore and in Earth coordinates (TVD and Vertical Offset). Images presented relative to the wellbore were shown to be sensitive of any change in deviation of the well in the imaged section and in that case the display in Earth coordinates revealed the best image. An additional product that may be extracted after imaging is finished is an Earth model that is created using, for example, high-resolution Petrophysical or Geomechanical data. Here the same flow that is used to create the velocity model is applied to the product of interest resulting in a picture of the bedding and formation properties away from the well.

Acknowledgements

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References

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