GC Impedance Inversion Transforms Aid Interpretation*

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General Statement

Seismic inversion for acoustic impedance is widely used in our industry today, mainly due to the ease and accuracy of interpretation of impedance data, but also because it allows an integrated approach to geological interpretation. This month's column refers to "inversion" as the transformation of seismic amplitude data into acoustic impedance data.

Seismic data represent an interface property wherein reflection events seen due to relative changes in acoustic impedance of adjacent rock layers. Such observed amplitude changes may not indicate if the amplitude changes relate to lithology variations above or below an interface. Acoustic impedance is a physical rock property, given as the product of density and velocity. Well logs measure both these entities directly, so that by dividing the density log with the sonic log, acoustic impedance log is obtained. Thus while acoustic impedance is a layer property, seismic amplitudes are attributes of layer boundaries.

Now, if quantitative interpretation of seismic data in terms of thin stratal interval properties (impedance) is to be attempted, then instead of the interface reflection properties, we resort to inversion. Acoustic impedance, being a layer property, simplifies lithologic and stratigraphic identification and may be directly converted to lithologic or reservoir properties such as porosity, fluid fill and net pay. In such cases then, inversion allows direct interpretation of three-dimensional geobodies. Inversion plays an important role in seismic interpretation, reservoir characterization, time lapse seismic, pressure prediction and other geophysical applications.

Method

Since the inversion process transforms seismic amplitudes directly into impedance values, special attention needs to be paid to their preservation, which ensures that the observed amplitude variations are related to geological effects. Clearly, the seismic data should be free of multiples, acquisition footprint, have high signal-to-noise ratio, zero-offset migrated and without any numerical artifacts.

Due to the band-limited nature of the seismic data, the lack of low frequencies will prevent the transformed impedance traces from having the basic impedance or velocity structure (low frequency trend) crucial to making a geologic interpretation. Also, the weak high frequency signal components or their absence thereof from the seismic data will find the impedance sections wanting in terms of resolution of thin layers.

The low frequency trend of acoustic impedance is usually derived from well logs or stacking velocities, and used as a priori information during the inversion process. This helps enhance the lateral consistency of the impedance data so produced.

The weak high frequency signal components indicate notches or roll-offs on the higher end of the amplitude spectra of seismic traces. Processing steps that tend to broaden the spectral band in an amplitude friendly way are usually adopted so that the data that is input to inversion has an enhanced effective frequency bandwidth.

Several different techniques methodologies are commonly used to perform impedance inversion. Whatever inversion approach is adopted, impedance volumes so generated have significant advantages. These include:

- Increased frequency bandwidth.

- Enhanced resolution and reliability of amplitude interpretation through detuning of seismic data.

- Obtaining layer property that affords convenience in understanding and interpretation.

These different impedance inversion techniques are:
(All the methods described below are post-stack inversion methods.)

- Recursive inversion – This is the most basic type of inversion and assumes that the seismic amplitudes are proportional to reflection coefficients and transforms the input seismic traces to acoustic impedance traces. As it does not remove the effects of the seismic wavelet, the method produces results that are within the seismic bandwidth – and so does not offer a significant advantage relative to interpreting seismic data.

- Model-based inversion – This method models the subsurface as layers in terms of acoustic impedance and time. The starting model is defined by a few 3-D main time horizons. Well log data are used to tie the main time horizons to the seismic data and define the impedance bounds for each layer. The impedance within each layer may vary laterally or vertically. The starting model is compared to the input seismic data and iteratively the model is updated to better match the seismic data.

- Sparse-spike inversion – This method gives an estimate of the reflectivity series that would approximate the seismic data with a minimum (sparse) number of spikes. As this method tends to remove the embedded wavelet from the data, the inversion results are broadband for the higher frequencies, maximizing vertical resolution and minimizing the tuning effects.

- Stratigraphic inversion – In an attempt to construct a stratigraphic model from seismic data, some inversion techniques introduce complex spatial stratigraphic relationships such as conformity, angular unconformity and baselap, for example, between layers.

- Geostatistical inversion – This method combines geostatistical data analysis and modeling with seismic inversion. Geostatistical analysis generates spatial statistics – vertical variograms are generated from well bore measurements and horizontal variograms are estimated from the acoustic impedance values afforded by starting impedance model generated from seismic data – for example, recursive inversion or colored inversion. Starting from the well log control points, geostatistical modeling simulates data at grid points. While carrying out the inversion, the simulated pointes are modified so as to concur both the well and seismic data.

Seismic inversion is a non-unique process, meaning that there are a large number of possible impedance outcomes on inversion. In other words, if the reflectivity derived from these impedance outcomes were convolved with a wavelet, the results would be very similar.

In simple terms we also can say that there is a certain level of uncertainty in the reservoir models that are built from different impedance outcomes. Of course, we try and lower the uncertainty by introducing some constraints in the inversion process. In geostatistical inversion we try and describe these possible outcomes, and by examining them we get an idea of the uncertainty inherent in the inversion process for the dataset under process.

- Colored inversion – It has been observed that the amplitude spectra of the acoustic impedance log can be described as fα, where f is the frequency and α is a constant. Given the acoustic impedance logs in the area of interest, the value of α can be calculated so as to determine the spectral function.

A colored inversion operator is determined by mapping the mean log amplitude spectra to the mean amplitude spectra of seismic traces that have a phase change of minus 90 degrees. Once the operator is determined, it is run on the input seismic data so as to obtain impedance data – colored inversion is fast and easy to implement.

Example

In Figure 1, we show a segment of a seismic section from the Montney-Dawson area of British Columbia, Canada, where the Lower Triassic Montney and Doig play has garnered attention in the last decade or so. The Montney Formation consists of interbedded shale, siltstone and sandstone in variable amounts. It is sub-divided into an Upper interval that is predominantly shale and the Lower interval that has siltstone-sandstone dominance. The two intervals are separated by an unconformity that resulted from the tectonic uplift of the area.

The Upper Montney interval can be seen at the lower level of lithostrip to the left of the impedance section shown in Figure 1b. Overlying the Upper Montney interval is the Doig Formation, which is divided into three litho units, namely, the lower phosphate zone, middle siltstone shale zone, and the upper calcareous siltstone.

Overlying the Doig Formation is the Halfway clean sandstone unit. The Halfway and the Doig interval comprise the Middle Triassic zone. A siltstone and shale interval overlies the Halfway, which in turn has a thin layer (20 meters) of salt above it. This salt is interbedded with anhydrites and siltstone and shows a slight lowering in velocity on the sonic curve, but has an appreciable lowering of density in the same zone. As a result, the impedance curves log curves overlain on Figure 1a exhibit a lowering of impedance in the salt interval.

A close examination of the reflection events in the Montney, Doig and Halfway zones shows some lateral amplitude variation – however, it is difficult to interpret this in terms of impedance variation corresponding to lithology, porosity or fluid changes in those intervals. A quick run of three different types of inversion was carried out, and the equivalent displays shown in Figures 1b, c and d. The recursive inversion display shown here exhibits the lateral impedance variation within the Montney, Doig and Halfway intervals, as well as the salt zone. Their corresponding correlation with the overlaid impedance log curves on the sections is encouraging.

Figure 1c shows the colored inversion display, wherein we notice that while the blue siltstone zone above the Halfway is somewhat better defined, variation in the Montney zone may not be very convincing. Finally in Figure 1d, we show the model-based impedance inversion display. We notice that the impedance variation in the Montney interval appears more detailed than the recursive or colored displays.

Conclusion

The transformation of seismic amplitudes into impedance comes in as a big aid to their interpretation. Such inversion results, when correlated/calibrated with the available well control, lend confidence in the interpretation that is carried out on them.

Acknowledgment

We would like to thank AAPG members James Keay and Hossein Nemati for helpful discussions that led to the making of the lithology strip show in Figure 1b.

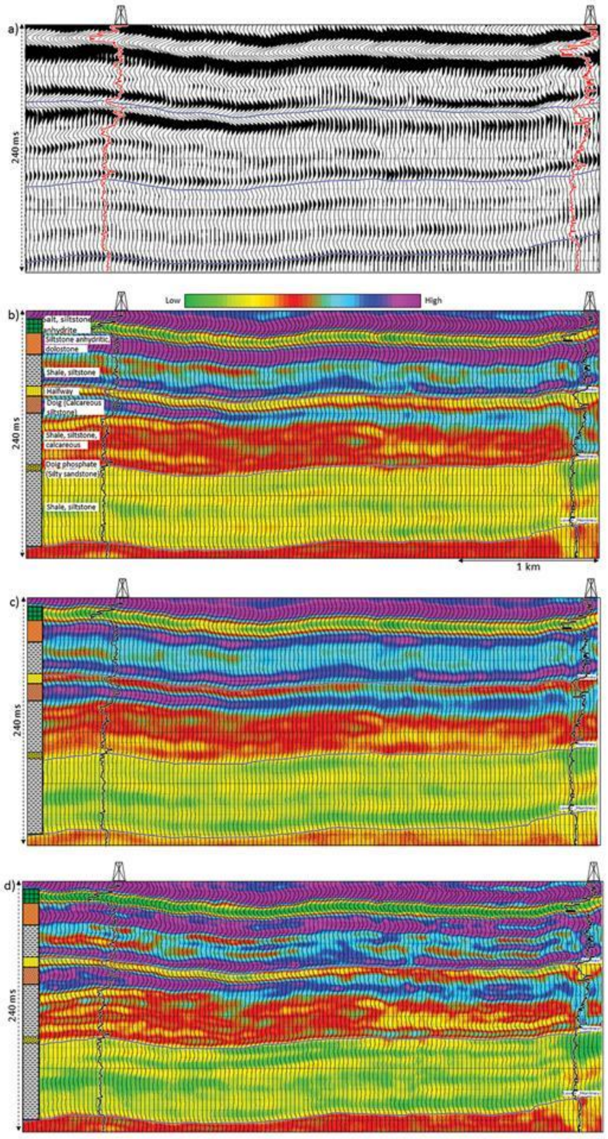

Figure 1. Segment (a) of a seismic section from the Montney-Dawson area in British Columbia, Canada. Equivalent impedance sections from (b) band-limited, (c) colored inversion, and (d) model-based techniques are shown correlated with two impedance logs. The log curve on the left was used in the inversion process, while the curve on the right serves as a blind well test. A litho-column is inserted alongside the log curve to the left as shown in Figure 1b. Notice the low impedance zones on the log curves corresponding to the salt, and the sand intervals correlate well with the low impedance seen on the impedance sections.

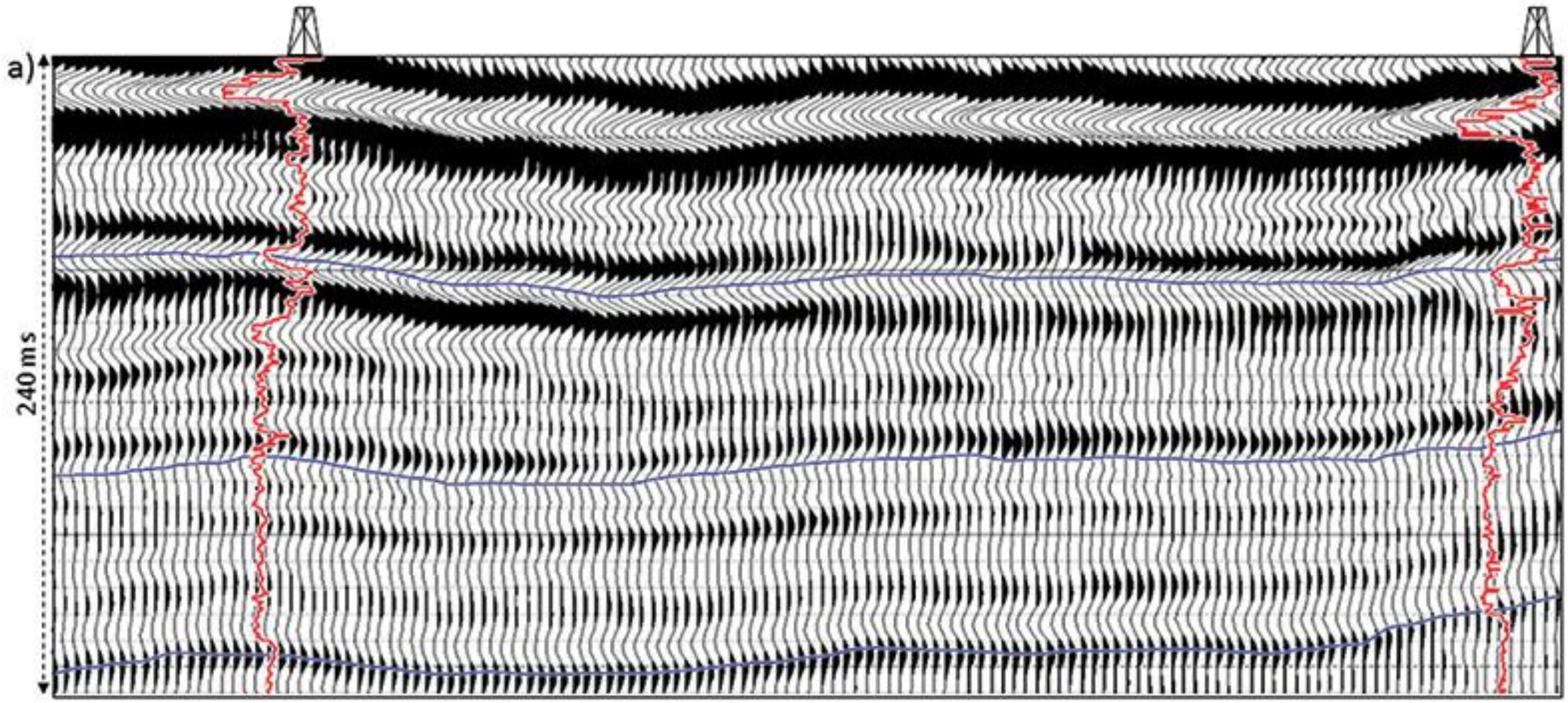

Figure 1a. Exhibit a lowering of impedance in the salt interval.

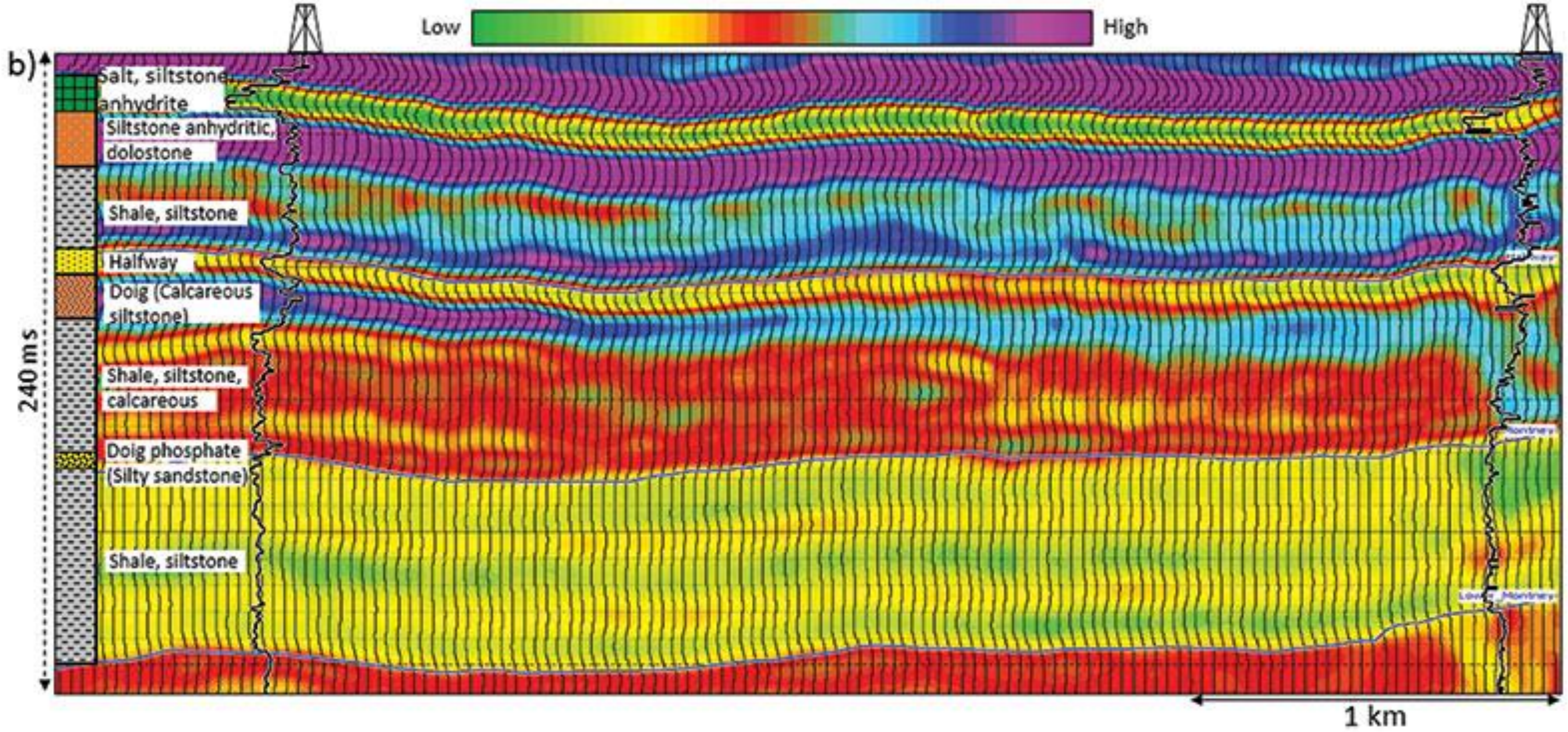

Figure 1b. The Upper Montney interval can be seen at the lower level of lithostrip to the left of the impedance section.

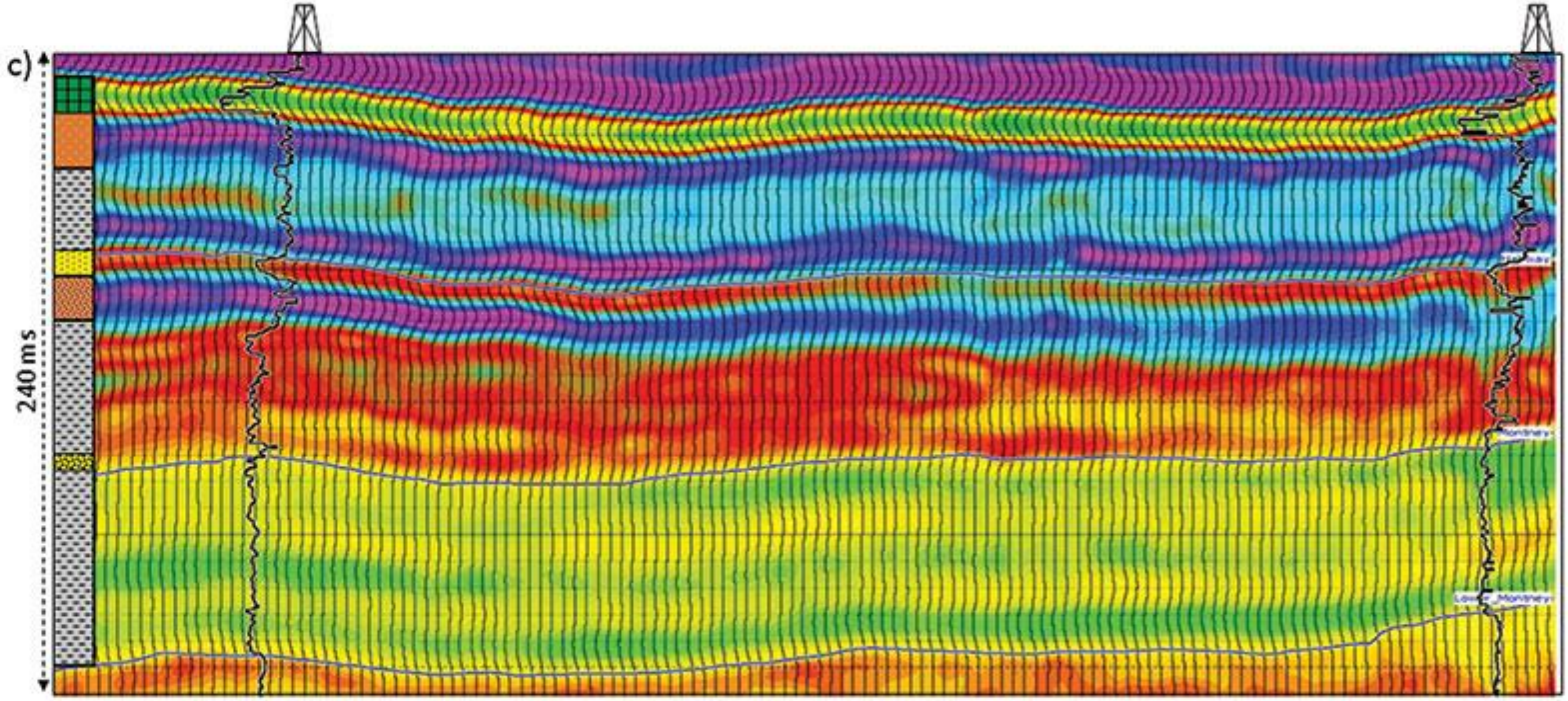

Figure 1c. Shows the colored inversion display, wherein we notice that while the blue siltstone zone above the Halfway is somewhat better defined, variation in the Montney zone may not be very convincing.

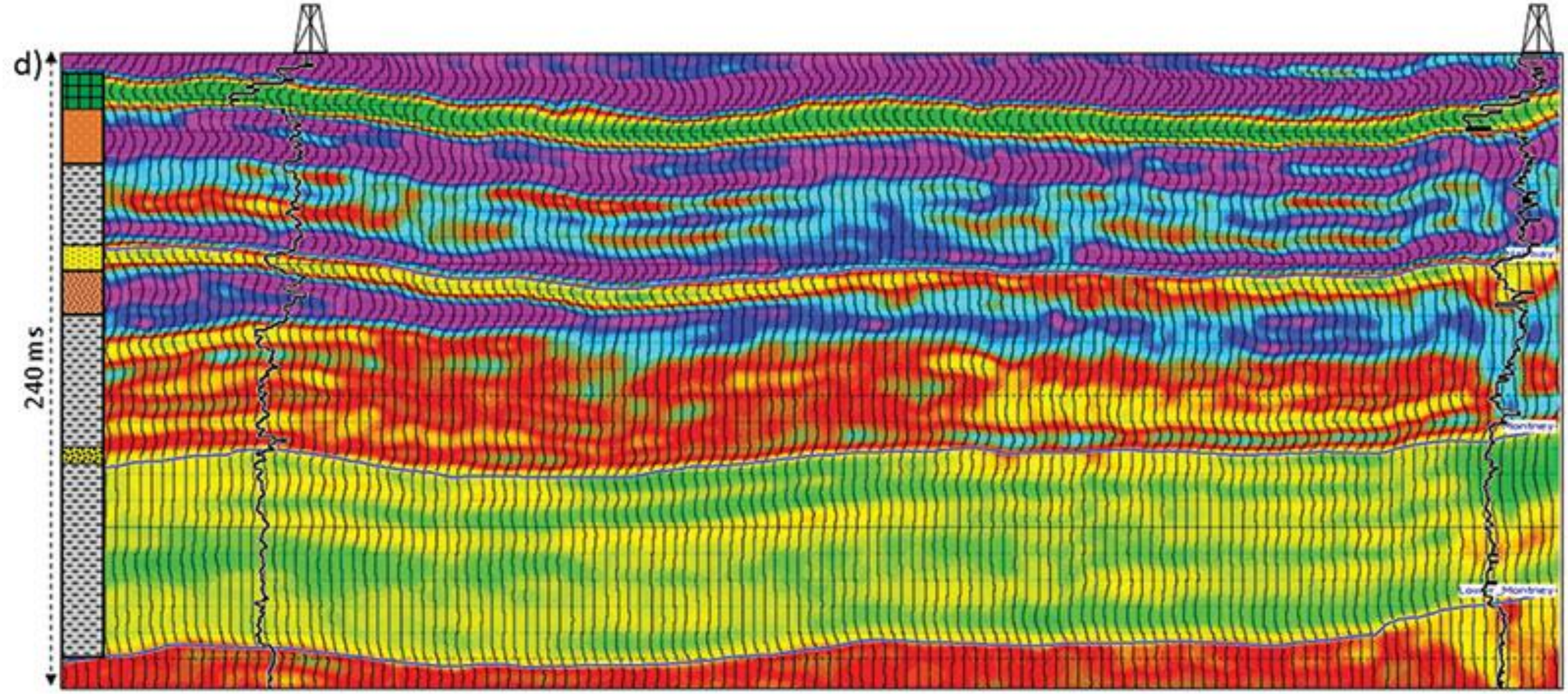

Figure 1d. We show the model-based impedance inversion display. We notice that the impedance variation in the Montney interval appears more detailed than the recursive or colored displays.