Illuminating imperfections of imaging inversion
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Summary

Various types of imaging inversion are of significant benefit for extracting subtle information from seismic data. But the methods are can produce significant errors in some situations. We present several examples of imaging inversion imperfections that illuminate how one must be careful with inversion. We suggest methods to analyze the reliability of inversion. We propose that using these methods to produce reliability and uncertainty information from inversion can be as important as the inversion result itself.

Our examples are from sparsity inversion signal enhancement, imaging illumination compensation, velocity inversion, and impedance inversion.

Introduction

Most processes that we call inversion seek to find subtle but consistent features in the data. The role of inversion is to boost these subtle features into possibly big model/image changes that these subtle data features imply. Inversion can be very useful for extracting information from the seismic data that resolves key geologic objectives.

However, the math of inversion is often based on imperfect assumptions. These assumptions can be:
1. avoiding the more challenging complexities of wave propagation (elasticity, anisotropy, attenuation, multiples),
2. simplifying the model by disallowing certain heterogeneities, or
3. expecting convenient, white noise when seismic noise is often not white.

Since inversion aggressively tries to fit data, incorrect assumptions can produce the consistent subtle data features that result in significant artifacts in the result.

As the industry moves to using inversion more, we argue that part of the inversion process should be to produce basic reliability/uncertainty information, which is needed for the important risk management that interpreters perform.

Methods for producing basic reliability/uncertainty information are:
- testing the inversion reliability by producing realistic synthetic 3D pre-stack data with noise for a known model,
- using only a portion of the well data in the inversion and analyzing how well the inversion predicts the hidden well information.

Sparsity inversion example:

Sparsity inversion is an effective noise reduction technique that assumes in some domain your noise is spread out and low amplitude while your signal is localized and high amplitude. You can then apply a non-linear scaling that preserves the high amplitude signal while reducing or eliminating the low amplitude noise.

Figure 1a shows a standard sub-salt image where signal quality below salt is poor. Applying pre-stack sparsity inversion in the image domain produces the result of Figure 1b, which shows general dramatic improvement of signal quality. But it also shows two glaring artifacts that are marked by the arrows. In these locations, signal has not been improved. The spurious vertical noise burst could have been incorrectly interpreted as a fault in a slightly different circumstance. Although the sparsity inversion has been generally effective, it is not robust in the tricky subtle subsalt area where we are most interested. Sparsity inversion does not always enhance only signal, especially when your signal of interest is subtle.

In this case, the errors of the sparsity inversion are obvious since the inversion was performed in the image domain and the result can be easily analyzed. However, often sparsity inversion is performed in a different domain and artifacts are not so obvious.

Imaging illumination inversion

Figure 2a & 2b show RTM imaging with illumination inversion for two different OBN acquisition geometries using the synthetic SEAM data. Figure 2a has a node spacing of 600m x 600m while Figure 2b has a node spacing of 1200m x 1200m. The images are very similar, which can lead one to conclude that sparse node spacing is acceptable for a good image when using illumination inversion. However, if we reproduce the images adding a moderate amount of noise (1:1 signal/noise random values) to the synthetic data, the results of Figure 2c & 2d lead to a very different conclusion that sparse node spacing is not acceptable for a good image.
Imperfections of imaging inversion

Figure 1a: A standard sub-salt image where signal quality below salt is poor.

Figure 1b: Same sub-salt image as in Figure 1a, but with pre-stack sparsity inversion applied in the image domain to improve signal quality. Signal quality is generally improved, but there are two artifacts marked by the arrows. At the left arrow, some noise is favored over signal and enhanced. At the right arrow, the reflector signal is removed.

Figure 2a: RTM image with illumination inversion using an OBN acquisition geometry with 600m x 600m node spacing. This image is produced using the synthetic SEAM data with no additional noise. This is the reference image.

Figure 2b: RTM image with illumination inversion using OBN acquisition with 1200m x 1200m node spacing. The image is nearly as good as that of Figure 2a, which can lead to the incorrect conclusion that sparse node spacing is adequate for subsalt imaging in this situation.

Figure 2c: RTM image with illumination inversion using OBN acquisition with 600m x 600m node spacing. A mild amount of white noise is added to the SEAM synthetic data. The image is moderately degraded over the corresponding no-noise image in Figure 2a.

Figure 2d: RTM image with illumination inversion using OBN acquisition with 1200m x 1200m spacing. A mild amount of white noise is added. The image is much worse than the corresponding 600m x 600m image with noise in Figure 2c. It is clear that sparse node spacing is not adequate for subsalt imaging in this situation.

Impedance inversion

A variety of impedance inversion methods use seismic reflection amplitudes and wavelet character, often combining them with NMO & log data, to produce a 3D image of reservoir acoustic impedance. The impedance is often closely correlated with porosity or other lithologic property of the reservoir.
Imperfections of imaging inversion

The seismic reflection amplitude is a key input to impedance inversion, which assumes the amplitude to be a function of reservoir reflectivity properties. However, other factors can cause reflection amplitude variations which can be inverted as false reservoir properties.

One non-reservoir factor that can cause reflection amplitude variations is gentle velocity variations in higher layers that create a “lens” effect that either focus or defocus reflection energy from a lower reflector. This lens effect can be strong relative to reservoir impedance variations.

Figure 3a shows a gentle velocity variation (-8% velocity change) at a depth of 4000 feet in an otherwise constant background velocity. The velocity variation acts as a lens. Beneath the velocity variation are 10 flat, uniform density reflectors at depths ranging from 5000-9400 feet. We compute 3D pre-stack narrow azimuth synthetic data from this model, perform amplitude preserving pre-stack migration using a constant velocity without the lens, carefully stack the data removing non-hyperbolic moveout effects, and analyze the reflectivity amplitudes. Figure 3b shows the resulting image. The push down artifact from the unaccounted velocity variation is apparent in the middle of the section.

The unaccounted velocity variation also produces false lateral amplitude variations in the reflectivity. Figure 3c is a plot of the average amplitudes of the flat reflectors at different depths. The amplitude plots should be uniform across the model, but because of the unaccounted velocity lens, the amplitudes contain significant variations. The variations are strongest for the shallowest reflector at depth of 5000 ft.

Figure 3a: 3D narrow azimuth synthetic data is collected for this velocity model with a velocity lens of -7% change. Several uniform flat reflectors exist below the velocity lens.

In this example, the 50-70% amplitude errors caused by the 8% velocity variations are much stronger than are often caused by reservoir lithology variations, which are often in the 10-20% range. Smaller amplitude, subtle, unresolved velocity variations above the reservoir can also corrupt impedance inversion. An interpreter may want to consider the likelihood of shallower velocity variations and corresponding error when using impedance inversion.

Figure 3b: Amplitude preserving pre-stack migration using a constant velocity field without the velocity lens. Not accounting for the lens produces significant amplitude artifacts in the image.

Figure 3c: Plot of average amplitudes for the reflectors at different depths in Figure 3b. Black color is average amplitude in the depth range of 4800-5800 ft. Green is 5800-6800 ft. Blue is 6800-7800 ft. Red is 8800-9800 ft. The unaccounted velocity variations produce significant false apparent amplitude variations on the reflectors that are larger than one would expect from reservoir impedance variations. Weaker, less obvious velocity variations can also distort impedance inversion.

MVA velocity inversion

The main QC mechanism for resolving velocities are the flatness of events on the image gathers. However, significantly different velocities and reflector structure can produce flat events on the image gathers. As a result, velocity inversion using MVA reflection tomography is non-unique.

We present a demonstration of the velocity non-uniqueness using the model of Figure 4a. This model contains 4 elliptical +10% velocity variations in a background velocity of 2000 m/sec. After collecting synthetic data for this model, Figure 4b shows the common image gathers produced by migrating the data using a velocity field without the +10% elliptical variations. As a result of the incorrect velocity field, the events on the image gathers are not flat and serve as a reference for comparison with later image gathers.

Figures 4c & 4e show two other velocity fields that are produced by “pushing” the MVA tomography in different directions. The model of Figure 4c is close to the correct model, but the model of Figure 4e is not close. The corresponding image gathers for these velocity fields are...
Imperfections of imaging inversion

shown in Figure 4d & 4f. The events are nearly flat when compared with the reference image gathers of Figure 4b. Based on the image gathers, we are not able to differentiate between these velocity models or the corresponding different reflector structure.

Figure 4a: Original model used to produce synthetic data. The ellipses are ±10% velocity change.

Figure 4b: Image gather from migrating the data of the model in Figure 4a using velocity without the ellipses.

Figure 4c: One velocity model produced from MVA tomography. This is close to the correct original model.

Figure 4d: Image gathers for the model in Figure 4c. The events are largely flat showing we have a good model.

Figure 4e: Another velocity model produced from “pushing” MVA tomography in a different direction. This is not close to the original model.

Figure 4f: Image gathers from the model in Figure 4e. The events are mostly flat, showing that the model is consistent with the data. The data cannot differentiate between model in Figure 4e & the model in Figure 4c.

The bounds of possible error are important information if a significant decision is made based on the velocity or reflector structure.

Conclusion

Inversion is imperfect and should not be taken for granted. While inversion is a very effective process for extracting subtle information from seismic data, it can produce significant errors.

Interpreters would be well served to be skeptical of inversion results, especially if the results are presented as the “solution”. Treating inversion as an imperfect process is not so daunting.

In fact, inversion can be an effective tool for identifying the reliability/uncertainty of a result. Inversion can tell us how much the data requires or precludes certain key features of a model.

Methods for using inversion to provide reliability/uncertainty information are: a) generating more than one result by attempting to “push” the inversion in different directions, b) adding noise, c) testing with realistic synthetic data, and d) using only a portion of the well data or other information.

Since interpreters are in the business of risk management, this reliability/uncertainty information is valuable to produce along with the inversion result.
EDITED REFERENCES
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REFERENCES


