Pre-Stack Inversion: An Extension of AVO for Lithology and Hydrocarbon Fluid Quantification

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Over the past two decades post-stack seismic inversion, the process of deriving rock properties from seismic measurements, has evolved significantly. Recent advances in amplitude versus offset (AVO) technology have demonstrated that significant information is also contained in the pre-stack seismic data with regard to fluids and lithology. Our pre-stack inversion methodology, augments the qualities of AVO and inversion to accurately quantify sand/shale lithology and hydrocarbon fluid properties directly from pre-stack seismic data. The method is demonstrated on models and Canadian and international seismic data.

Past Methods of Inversion Relied on Modeling

Early methods of recursive inversion converted seismic traces to well log traces, providing a measurement of the "pseudo acoustic impedance." The acoustic impedance could also be expressed as "pseudo-acoustic velocity" by assuming a simple relationship between velocity, density and acoustic impedance. In any event though, the inverted property was still acoustic impedance. While the property of acoustic impedance is more of a geophysical measurement than a geologic rock property, it did yield some indication of actual rock types. Most importantly, it demonstrated that valuable physical information was present in seismic data that was being overlooked by conventional wiggle traces.

The resolution of recursive inversion was limited to the bandwidth of the seismic data (hence the name band-limited inversion). By using spike detection algorithms to convert the seismic trace to a high frequency sparse reflectivity series prior to inversion, sparse-spike inversion algorithms could achieve high resolution. The "blocky" lithologic boundaries created by sparse-spike methods most accurately modeled actual geologic conditions although the output physical quantity was still "pseudo-acoustic impedance."

Recently, model-based inversion schemes have evolved, which essentially relies on the fact that the forward model of a "good" inversion should very closely match the actual seismic data. Using iterative forward modeling schemes, these methods perturb an initial acoustic impedance model until its forward model matches the seismic traces. These methods have the advantage of allowing some degree of control over the starting point and hence the resulting inversion. Once again though, model-based inversions still derive acoustic impedance.

New Technique Using AVO Gives Better Results

AVO techniques have demonstrated that, with pre-stack seismic data, the measurement of the conversion of compressional energy to shear energy at interfaces can yield information about the fluids and lithology present. More recently, advances in pre-stack imaging and analysis have resulted in significantly improved post-stack signal quality with better preservation of lithologic information.

This pre-stack inversion technique combines inversion and AVO technology with anisotropic petrophysics. This technique uses pre-stack seismic data as well as sonic, density and gamma ray logs to directly derive elastic rock properties including sand/shale content, gas saturation, water volume, and effective porosity. More recently, we extended the technique to detect oil versus gas using absorption information.

Inverting the P-and S-wave stacks, with low-frequency constraints from sonic, density and gamma ray logs, yields P-impedance (IP) and S-impedance (IS). Petrophysical well log analysis, based on volume averaging, allows inversion of the inverse P- and S-impedance to yield mineral volumes.

Calculating Sand, Clay and Hydrocarbons

Where, V_{ss} end V_{clay} are the fraction of sand and clay (respectively) in the matrix, the remaining factors are the physical properties corresponding to the impedances of pore water, sandstone, and shale. The constants for water and sandstone remain relatively constant while the impedances of shale may vary slightly with the geologic setting and are usually adjusted as part of the calibration.

This inversion is applied to the entire pre-stack seismic data set after careful pre-processing and migration to preserve AVO effects. The resulting data set gives sand, clay, fluid, and gas volumes for the entire seismic section. The net/gross sand volume can be represented by a ratio and indicates the quantity of sand present out of the total mineral content.

The method has been successful on Canadian and international seismic data. The input gathers were pre-stack migrated with a Kirchhoff migration algorithm and processed to retain AVO effects. A cross-plot was used to calibrate the inversion. The inversion indicates the gas saturation in red (at the top of the sand member under the well location) and the sand/shale content in shades from yellow (pure sand) to green (pure shale). The prospect, on the downthrown side of the fault, indicates good gas saturation and highly porous sand that pinches out becoming tighter and forming the trap. This prospect has not yet been drilled.

Conclusions

Pre-stack inversion demonstrates that significantly more information is contained in the seismic wavefield than simply acoustic impedance and that we can reliably quantify rock and fluid properties from seismic data. The method has been successfully applied to numerous 2-D and 3-D data sets from Canada, the U.S., and international targets.

Biographical Sketch

Rick Wallace graduated with a B.Sc. electrical engineering (1982) from the University of Calgary, Canada. He has worked for Western Geophysical as special projects geophysicist, Veritas Seismic as manager of research and software services, and is now president of Ulterra Geoscience.

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