Log Resistivity Measuring Devices Compared to S-waves from a Vertical-Force Source*

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Abstract

Induction and short normal log concepts will be compared to SV and SH particle motion vector concepts from a vertical-force source to propose the SV wavefield-velocity/SH wavefield-velocity (VS/VSH) ratio attribute in identification of fracture sweet spots in densely fractured reservoirs such as in the Pennsylvania Marcellus Formation, USA.

Introduction

The short normal log is a measuring device that passes current from an electrode on a sonde through the mud into the formation. Figure 1 shows a schematic of the electrode array. In reality the two surface electrodes B and N in Figure 1 are actually in the borehole but placed very far away from the deeper borehole electrodes A and M. The current flows from A to B, and the vertical-vector potential is measured between the M and N electrodes. The volume of material measured is approximately twice the distance of A-M (typically 16 inches) in diameter, which is usually the part of the formation that is invaded. The short normal log has better vertical resolution in thick conductive beds such as in a fracture, than its companion induction log. The short normal log provides a reasonable measurement of thick conductive beds, i.e. over 4 feet. Thin resistive beds are poorly measured.

By comparison, the SV wavefield's particle motion vector (Figure 3) from a vertical-force source is vertical, (which is orthogonal to its companion SH wavefield's particle motion vector), and thereby is parallel to vertical fractures. The SV wavefield has greater vertical resolution than its companion SH wavefield. When the SV wavefield encounters dense fracturing, its image surface area of elastic impedance will be greater vertically (with more dispersion and absorption of frequency) than its companion SH wavefield. This will result in the SV-velocity field being slower in dense vertical fractures than the SH-velocity wavefield. The SV vertical particle motion vector is similar to the short normal log's vertical-vector current flow from A to B electrodes where its vertical potential is measured between M and N electrodes (Figure 1). The SV wavefield's vertical particle motion images (measures or reads) more conductive surface area of the vertical formation with dense vertical-fractures and thereby travels slower through the formation fracturing than the SH wavefield.

The induction systems measure conductivity: C = 1000/R where C is conductivity in millimhos/meter, and R is resistivity in ohm meters. Induction systems are coils that induce currents into the formation (Figure 2). The oscillator supplies an alternating current to the transmitter coil, and this current in the coil creates an alternating field around the coil. This alternating field creates a current in conductors such as the horizontal ground loop shown in Figure 2 and thus, the horizontal ground loop has a horizontal alternating current flowing through it. This horizontal alternating current in the ground loop creates an alternating field that cuts the stationary receiver coil, and an alternating current is induced into the receiver coil. The horizontal alternating current in the ground loop is equivalent to waving a magnet along a horizontal wire, which would create horizontal-vector electricity. Because of this, the induction log primarily reads horizontal formation resistivity, while ignoring thin resistive beds.

Induction log vertical resolution is 5-6 feet in resistive beds, i.e. in beds with higher resistivity than its adjacent beds, and approximate 2 feet in conductive beds. This non-linear log response occurs because the induction system prefers low resistivity material.

By comparison, the SH wavefield's particle motion vector (Figure 3) from a vertical-force source is horizontal, which is orthogonal to its companion SV wavefield's particle motion vector, and thereby is orthogonal to vertical fractures. The SH wavefield has greater horizontal resolution than its companion SV wavefield. When the SH wavefield encounters dense fracturing, its image surface area of elastic impedance will be less vertically (with less dispersion and absorption of frequency) than its companion SV wavefield. This will result in the SH-velocity field being faster in dense vertical fractures than the SV-velocity wavefield. Similar to the induction log's primarily reading horizontal formation resistivity, the SH wavefield's horizontal particle motion images (reads) horizontally less surface area of the vertical formation with dense vertical-fractures and thereby travels faster through formation fracturing than the SV wavefield.

Although vertical-force sources are traditionally thought of as P-wave sources only, they also produced robust S wavefields that can be utilized in exploration and exploitation of unconventional resources.

The propagation velocities of the SH- and SV-wavefields differ by only a small percent; however, the SH wavefield has a faster shallow velocity, and the SV wavefield has a faster deeper velocity (VTI media Levin, 1979, 1980). In addition, both shear velocities are significantly less than the P-wave and converted wave (P-SV and SV-P) velocities.

A vertical-force source produces more SV energy than the P energy, and at take off angles of 20° and more the SV-SV mode is significantly stronger than the P mode. However, the SV radiation might not result in robust illumination of geology directly below the source station as does its companion P-wave radiation.

The data processing for the SV- and SH-wavefields (direct source S-wave data) produced directly at the point of application of a vertical-force source differs from the processing of converted wave P-SV data. The direct source S-wave data are processed as a single data set, not as two separate data sets (i.e., positive and negative offsets) as with the P-SV data. Direct source S-wave data are processed with common-midpoint (CMP) methods, and P-SV data are processed with common-conversion-point (CCP) methods. Velocity analyses are also different: direct source S-wave velocity in the CMP domain and the P-SV velocity in CCP domain utilizing Vp/Vs ratios, the gamma function. S energy from a vertical-force source is generated directly at the force application point, and the P-SV energy is generated at sub-surface interfaces.

Conclusions

Although the propagation velocities of the SH- and SV-wavefields differ by only a small percent, a VSV/VSH ratio in densely fractured reservoirs can still be used as a tool for imaging fracture sweet spots. For example, in the Pennsylvania Marcellus 3D multicomponent SV and SH data from a vertical-force source, fracture-dense sweet spots generally occur when VSV/VSH < 1 (Figure 4, blue below 500 ms). The VSV/VSH ratio is a better rock property attribute in the Pennsylvania Marcellus reservoir with 2 sets of fractures than other attributes such as Poisson’s ratio and Young’s modulus, where shale brittle and ductile rock properties are measured. In its application, relatively low Poisson’s ratio and high Young’s modulus correlate to brittle shale zones, and high Poisson’s ratio and low Young’s modulus correlate to ductile shale zones. The brittle shale zones are more likely to be naturally fractured and more likely to accept and sustain induced hydraulic fractures.

Acknowledgment

Gary Engler, GEDCO Calgary, Canada, and BEG at the University of Texas, Austin.

Selected Reference

Hilchie, Douglas, 1982, Applied Openhole Log Interpretation for Geologists and Engineers, 328 p.

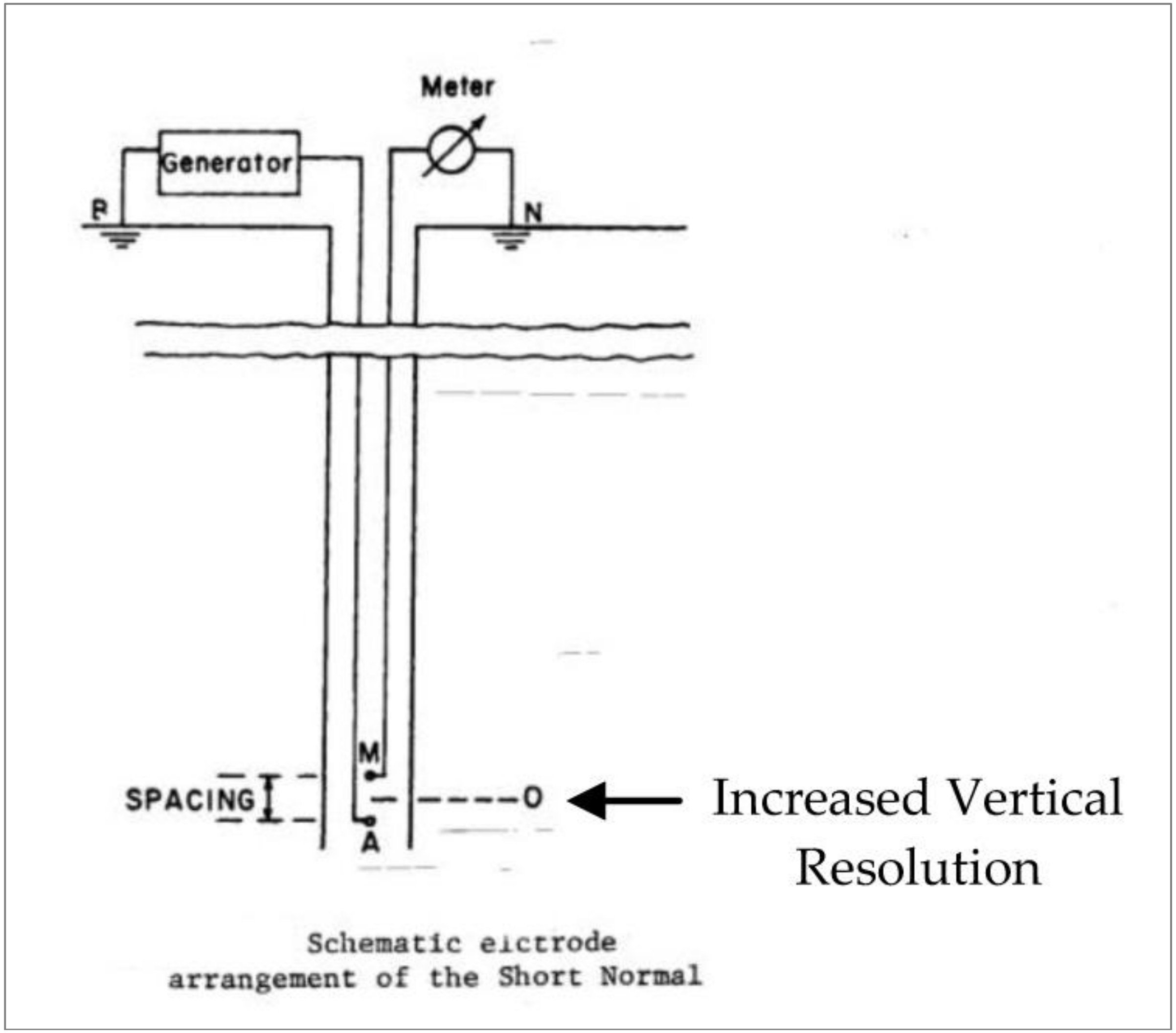

Figure 1. Schematic electrode arrangement of the Short Normal sonde.

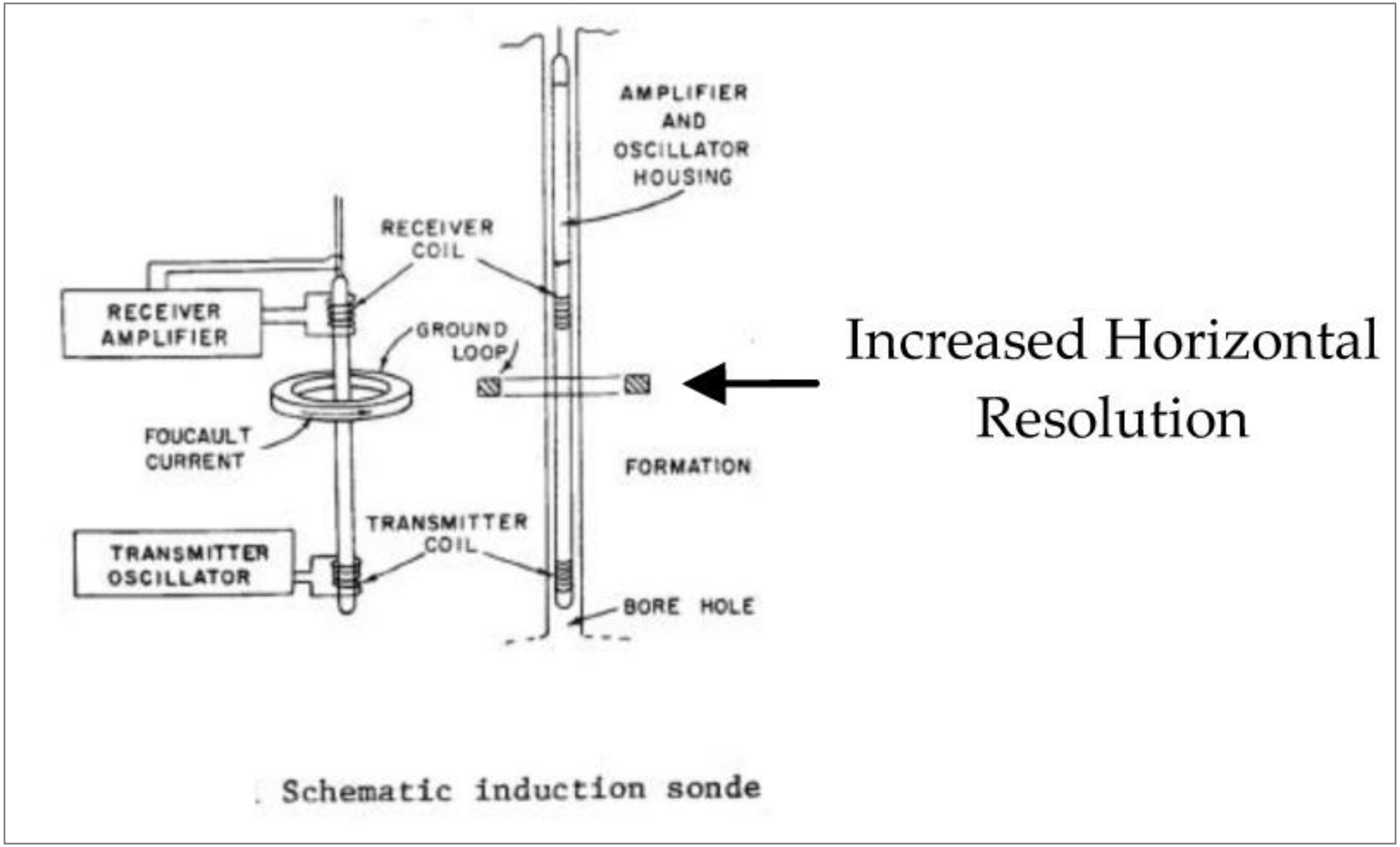

Figure 2. Schematic of the Induction sonde.

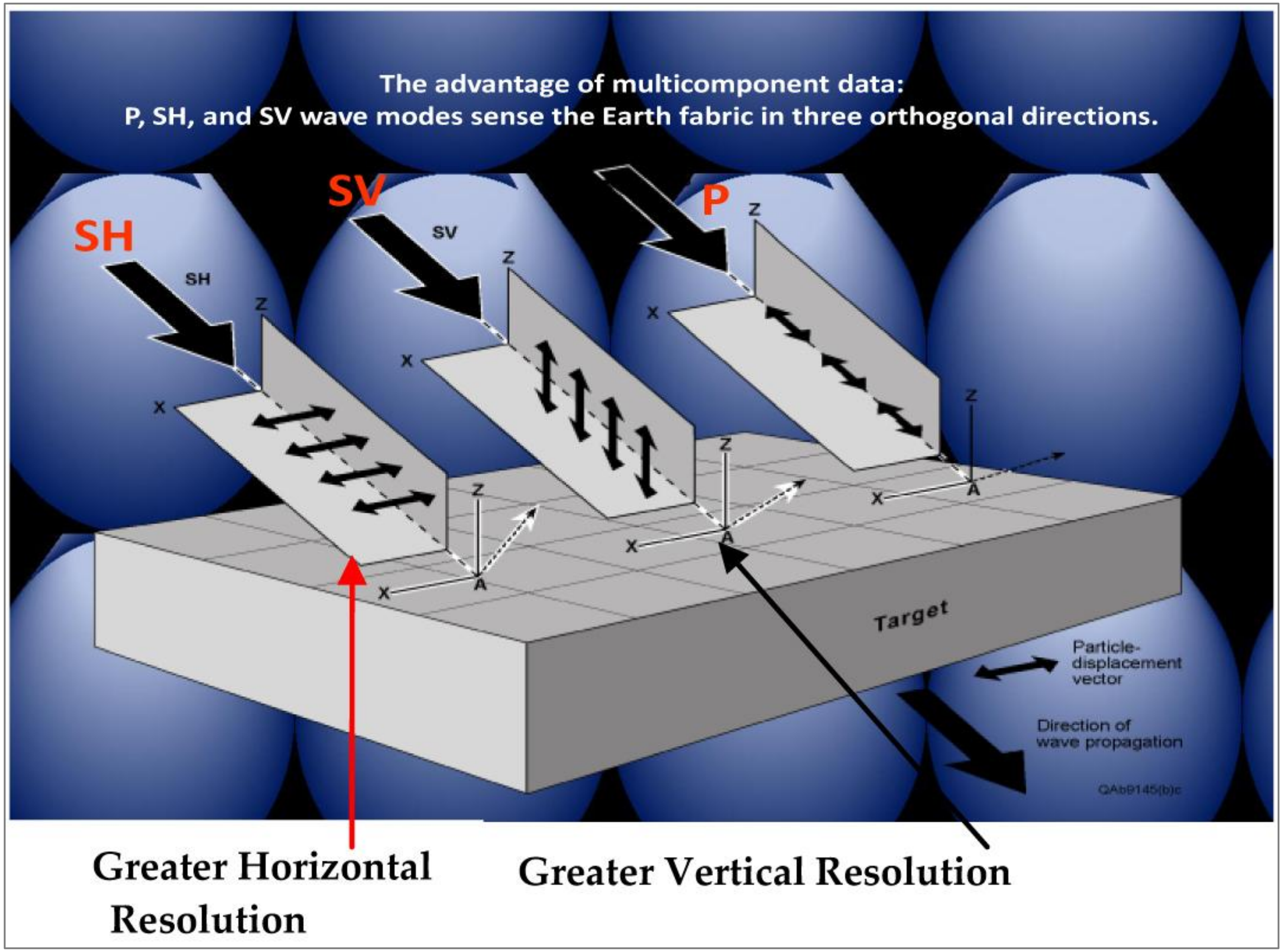

Figure 3. Schematic showing advantage of multi-component data.

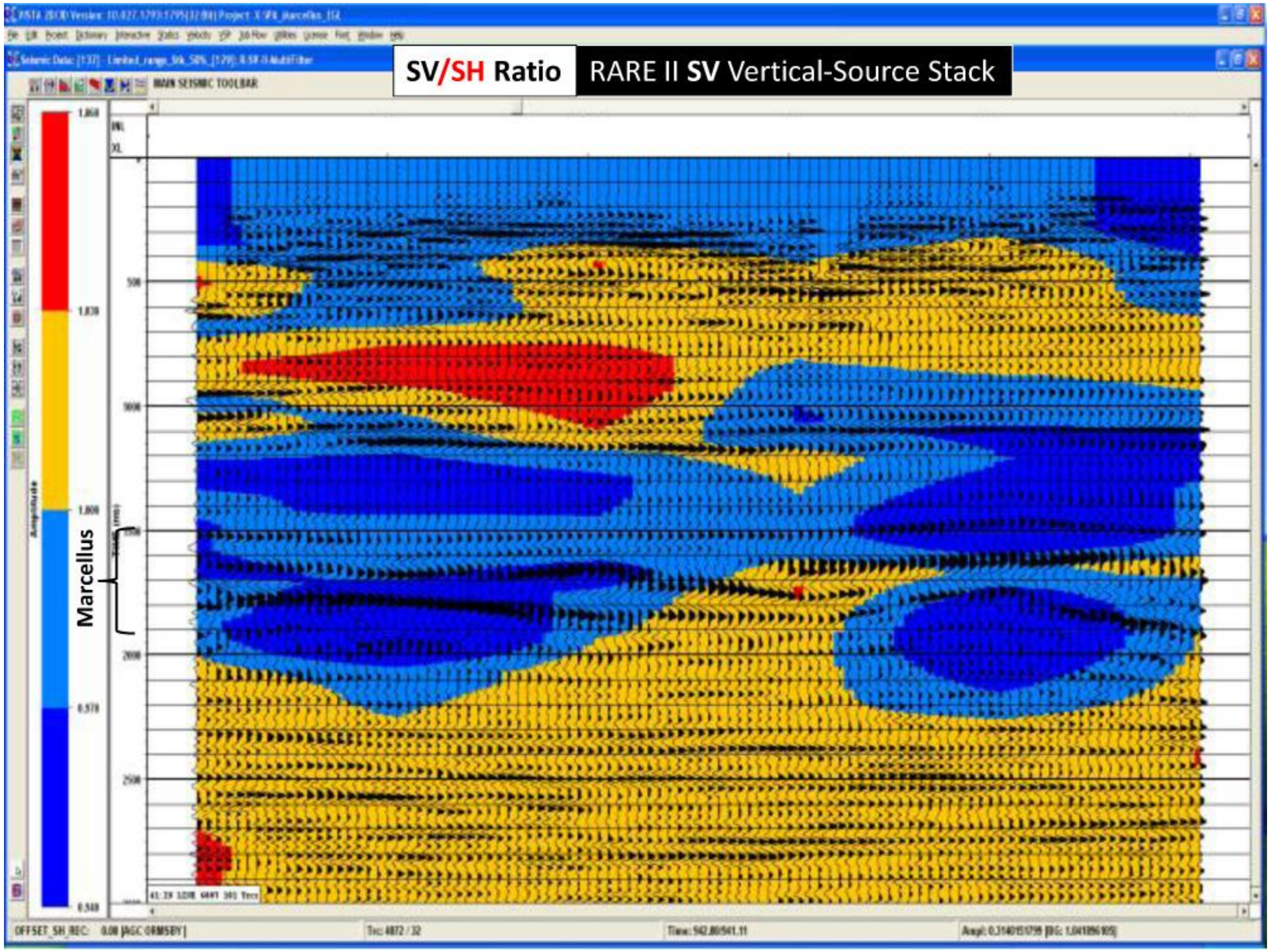

Figure 4. RARE II SV-velocity/SH-velocity ratio Vertical-Source stack section.