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Inversion for radial variations of formation shear velocity from borehole sonic measurements

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Sonic measurements play an important role in estimating the mechanical attributes of rocks that are crucial in geophysical exploration. Borehole sonic data can provide the continuous measurements of acoustic properties along the borehole. Conventionally sonic data has been analyzed assuming the formation is homogeneous isotropic. However, recent studies showed the formation around the borehole can be radially heterogeneous due to alteration and also azimuthally anisotropic. Radial heterogeneity can be caused by stress concentration, mechanical damage, or fluid invasion. Azimuthal anisotropy can be caused by tectonic stress, intrinsic microstructual effects, such as layering of thin layers and aligned micro-fractures. In order to obtain the intrinsic properties of the formation without alteration and to know the mechanical state around the borehole, we need to analyze the radial and azimuthal variations of acoustic velocities.

Advanced sonic tools can record full waveforms with monopole/dipole transmitters and azimuthal receivers at multiple axial positions. These waveform data enables the detailed analysis of dispersive borehole modes such as flexural wave and Stoneley wave. Flexural wave is excited by dipole source and is flexing of the borehole and propagate along the borehole wall. Low frequency asymptote of flexural wave velocity coincides with the formation shear velocity. Stoneley mode is primarily excited by low-frequency monopole source. Stoneley wave propagates along the borehole wall and it becomes the tube wave at the zero frequency. Both the flexural mode and Stoneley mode dispersion are significantly perturbed in the presence of radial heterogeneities and formation anisotropy.

Shear waves travel fastest when the direction of particle motion is aligned with the formation's stiffest direction. If there is one direction that is stiffer than another, then the shear-wave aligned in the stiff direction travel faster than one aligned in the other, more compliant direction. As a result, the shear wave splits into two components, one polarized along the formation's stiff (or fast) direction and the other polarized along the formation's compliant (or slow) direction. Processing of recorded waveforms at the two pairs of orthogonal receivers produced by two orthogonal dipole sources (Cross-dipole measurements) yields the azimuthal orientation of the fast shear direction and the fast and slow shear velocities. Cross-dipole sonic data from a borehole parallel to the X3 axis provides estimates of the shear anisotropy in terms of shear moduli c44 and c55 in the two orthogonal planes. In addition, Stoneley wave provides the shear modulus in the cross-sectional plane (c66).

Radial variation of formation shear velocity can be obtained by a proposed technique of inverting measured borehole flexural/Stoneley velocity dispersions. This technique also provides information about the volume of investigation, amount of radial alteration, and undisturbed shear wave velocity in the far-field. The Backus-Gilbert inversion technique yields an estimate of the radially varying formation shear velocity from a finite number of points on the flexural/Stoneley dispersion. In the technique a theoretical model predicts the corresponding changes in the dispersion relation caused by perturbations in the formation properties. This theoretical model is a perturbation scheme that relates changes in the borehole dispersions to changes in material parameters.

In this presentation, we will first review borehole sonic measurements, then describe the radial shear velocity inversion method. We show theoretical validation using dispersions for known variations in the compressional and shear velocities. Finally we illustrate the radial shear profiling results with field examples in oil wells (Attached figure shows composite log of the far-field dipole shear slowness in the second track together with a differential shear slowness image in the third track.).