Measuring completion quality and natural fracture indicators in horizontal wells using a new slim dipole sonic memory tool conveyed through the drillstring and bit

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Summary

Engineered completion design is increasingly recognized as the optimal method for efficient stimulation of horizontal wells drilled in unconventional resource plays (Slocombe et. al., 2013 and Ajisafe et. al., 2014). Key to this design are sonic measurements acquired in lateral wells as they serve as inputs for anisotropic stress profiling and fracture characterization which are used to assess completion quality.

In this study, a new slim dipole sonic tool is used that is specifically designed for acquiring rich acoustic data using a unique low risk and driller friendly conveyance system. The tool has been designed for the horizontal and unconventional logging environment using predictable acoustics where the tool effect in the hole is fully characterized. Horizontal well examples are shown where data from this slim dipole sonic tool were used to determine completion quality indicators based on anisotropic stress and also to determine independent indicators of natural fractures.

Introduction

Optimal engineered completions require compressional slowness as well as fast and slow shear slowness—two independent shear measurements—to fully quantify variations in anisotropy, stress, and completion quality along a horizontal wellbore. Engineers and geoscientists also need low frequency Stoneley wave measurements along with cross-dipole measurements to accurately detect and quantify the orientation and permeability of natural fractures. A 3-D acoustic characterization of the formation identifying fractures and borehole stress regimes is possible by combining dipole with Stoneley measurements as discussed by Donald and Bratton (2006) and Walsh et. al. (2006) for vertical wells. This applies to horizontal wells also.

Until now, in the absence of a specialized sonic logging technology, operators have based engineered completion designs on ad hoc methods of estimating shear, or use synthetic and offset well data to approximate missing acoustic measurements. To improve accuracy, standard wireline dipole sonic tools have been run in either open or cased holes. These typically require drill-pipe conveyed deployment techniques or tractors to log these lateral wells, incurring additional risks, time and costs. Hence there has been a strong need for a fit-for-purpose logging technology that fills this gap of providing direct compressional, cross dipole shear and low frequency Stoneley measurements.

The Slim Dipole Sonic Tool

The uniquely conveyed through-the-bit slim dipole sonic tool fills the aforementioned gap in technology and provides a detailed acoustic representation of the formations surrounding the borehole for horizontal and difficult-to-access wells. It is a small-diameter 2.125 inch [5.4 cm] sonic logging sonde that is capable of acquiring monopole P-wave and S-wave arrivals, and cross-dipole, and low-frequency Stoneley wave measurements, in a single tool.

The receiver section has an array of 12 receiver stations spaced 4in [10.16 cm] apart. The receiver array is 70.2 in [1.78 m] from the monopole transmitter and 78 in [1.98 m] from the dipole transmitters. Each receiver station consists of four azimuthal wideband piezoelectric hydrophones aligned with dipole transmitters. Summing the signals recorded by all the four hydrophones provides the monopole waveform, whereas finding the difference between a pair of opposing hydrophones cancels the monopole signal and provides the dipole waveform. Dipole flexural waveforms are recorded on both the inline and cross line hydrophone pairs with respect to the dipole transmitter orientation. Four sets of 12 waveforms can be acquired from the four basic operating modes fired in sequence.

The transmitter section houses two sets of transmitters and mechanical isolation assembly to prevent direct flexural wave transmission through the body of the tool. A piezoelectric monopole transmitter is fired at standard frequency and at a special low-frequency pulse for Stoneley wave acquisition. Two collocated, perpendicular, piezoelectric-bender-element dipole transmitters fire a wideband frequency spectrum to capture dipole data at a high signal-to-noise ratio.

An algorithm (Horne, 2013) is used to transform compressional, fast and slow shear and Stoneley slowness measurements with respect to the borehole axes to referenced anisotropic moduli in the target formation. The formation can then be classified as isotropic or anisotropic, along with determining the type and cause of the anisotropy – intrinsic or stress induced from the drilling process. The
low frequency Stoneley wave measurement is necessary for its sensitivity to open permeable fractures which can be evaluated by analyzing the reflection and transmission coefficients of the Stoneley wave. (Hornby et al., 1989, Endo et al. 1998) There are other independent natural fracture indicators that can be extracted out of the data as illustrated in the example case studies that follow.

**Example 1: Case Study in Wolfcamp Shale**

Compressional slownesses along with fast and slow shear slowness values from a cross-dipole sonic logging tool provide the necessary information to quantify the anisotropy usually observed in shale formations. This anisotropy is the critical input for determining the minimum anisotropic horizontal stress used in optimal completion design.

An operator in the Wolfcamp shale of west Texas was one of the early adopters of the small-diameter dipole sonic tool, despite having already achieved considerable success using monopole and synthetic shear data to plan engineered completions. Not only is the Wolfcamp reservoir deep and highly pressured, but it consists of laminated, clay-rich layers under variable stress. Historically, therefore, the company found efficiently producing this field to be a challenging endeavor. Additionally, the company’s petrophysicists had found it difficult to measure all of the reservoir’s acoustic properties directly and to fully and accurately quantify stress anisotropy. The new through-the-bit slim dipole sonic tool enabled them to reliably measure up to 30% anisotropy (example at xx150 and xx600) in one Wolfcamp well. This allowed the operator to further refine engineered completions, and gave completion engineers substantially greater confidence in the accuracy and reliability of their designs (Figure 1) as compared to using modelled/synthetic data in the past.

**Example 2: Case Study in Buda Limestone**

During a recent multi well study in the Eagle Ford, the fractures encountered along a horizontal well were clearly seen to impact completion design (Slocombe et. al., 2013). Low frequency Stoneley measurements acquired in such wells can reliably identify potential open natural fractures. The study found that the highest performing perforation clusters as observed on the production log are associated with fractures interpreted from the Stoneley waveform data. The Stoneley variable density log (VDL) exhibits chevron patterns, which are often an indicator for open permeable fractures. (Endo et al., 1998)

With lessons learnt from the Eagle Ford study in mind, an operator, targeting the Buda limestone in South Texas, is now using Stoneley wave measurements from through-the-bit dipole technology for independent natural fracture detection, especially in the absence of borehole imaging. This helps in optimizing the design of completion stages and consequently has a significant positive impact on economics of the operation. Not only do Stoneley measurements confirm the presence and location of fractures, but increases in Stoneley slowness (example just above X900 ft in Figure 2) indicate probable gas entry points in the horizontal well.

In addition to direct acoustic property measurements, many other independent fracture indicators are computed along the horizontal well, which make the interpretation related to fracture identification more robust. These other indicators (see around X800, Y050 and Y250 ft) indicate attenuation of energy on the vertical shear slowness frequency analysis (SFA) log, negative Thomsen’s gamma (Thomsen, 1986) computation, chevron patterns observed on the Stoneley VDL waveform plot, and reflection coefficients (RC) computed from the low frequency Stoneley wave. Attenuation of the high frequency component of the dipole flexural wave has been noted as a potential fracture indicator in vertical wells (Donald and Bratton, 2006). For fractures embedded in isotropic formations, such as the Buda limestone, Thomsen’s gamma parameter is predicted to read negative (Schoenberg and Sayers., 1995). All these fracture indicators show strong correlation in a fractured zones in Figure 2.

After initial through-the-bit dipole sonic logging, the operator confirmed these results by logging the interval again using standard-size sonic and formation micro-imaging tools. The last two tracks on the right in Figure 2 show results from this second run over the same interval. Note that the Stoneley slowness on the second run has increased from what was observed on the initial through-the-bit dipole sonic logging run. This is due to additional gas entry in the wellbore during the time period separating the two runs.

**Conclusions**

The presented case studies clearly demonstrate a low risk fit-for-purpose solution for measuring completion quality and natural fracture indicators in horizontal wells, which can be easily integrated in existing drilling and tripping plans while allowing for circulation, rotation, retrieval and use of Lost Circulation Materials (LCM) in the mud. The unique deployment system allows for connectivity until final deployment and thus ensures reliability (Reischman, 2011). The capability for retrieval at any time allows fast decisions and the ability to safely react to unexpected changes. The logs acquired in the case study wells provide high quality open hole data, critical for detailed evaluation of petrophysical and mechanical properties for reservoir
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quality and completion quality. Integration of the acoustic measurements taken in-situ into completion workflows has demonstrable value in reducing screen outs, improving perforation efficiency and increased production.

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Figure 1: Anisotropic stress characterization of a horizontal well in Wolfcamp shale by using through-the-bit slim dipole sonic data in the open hole. Track 2 (2nd from left), gamma ray. Track 3, bulk density and neutron porosity. Track 4, lithology. Track 5, compressional, fast shear and slow shear slownesses and slowness based anisotropy indicator. Track 6, Thomsen’s gamma. Track 7, C66 is horizontal shear modulus and C44 is vertical shear modulus. Track 8, vertical and horizontal dynamic Young’s modulus. Track 9, vertical and horizontal static Young’s modulus. Track 10, vertical and horizontal dynamic Poisson’s ratio. Track 11, pore pressure, minimum horizontal isotropic stress, minimum horizontal anisotropic stress and vertical (overburden stress) gradient, transverse isotropic anisotropy flag. Track 12, minimum horizontal anisotropic stress profile with Blue/Red corresponding to high/low stress. Track 13, Reservoir Quality (RQ) Red/Blue as Bad/Good. Track 14, Completion Quality (CQ) Red/Blue as Bad/Good

Recommended zones for perforations with low stress and high oil saturation
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Figure 2: Stoneley fracture analysis of a horizontal well in Buda limestone by using through-the-bit slim dipole sonic data in open hole, indicating natural fractures, along with other independent fracture indicators - SFA attenuation, negative Thomsen’s gamma and chevrons on Stoneley VDL. The multiple independent fracture indicators increase interpretation robustness and confidence. The operator confirmed these results by logging the interval again using standard-size sonic and formation micro-imaging tools. Track 2 (2nd from left), gamma ray, caliper, bit size. Track 3, bulk density and neutron porosity. Track 4, horizontal shear and its SFA. Track 5, vertical shear and its SFA. Track 6, Stoneley reflection coefficient, STRC, from the receiver. Track 7, negative Thomsen’s gamma, fast shear and slow shear slownesses. Track 8, Stoneley VDL. Track 9, Stoneley slowness and coherency. Track 10, formation micro-imager log with fracture aperture. Track 11, Stoneley slowness and coherency from standard-size sonic.
EDITED REFERENCES
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REFERENCES


