BOREHOLE SONIC INTERPRETATION IN HIGH ANGLE AND HORIZONTAL WELLS

Doug Murray, Liu Wei and Yang Xingwang
Schlumberger Oilfield Services

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ABSTRACT

A common concern with borehole sonic logs is their interpretation in high angle and/or horizontal wells. Due to acoustic anisotropy, compressional and shear velocity measurements can show considerable variation with wellbore deviation and/or formation dip.

Historically, due to the limitations of borehole sonic measurement technology and the deficiency of user friendly interpretation algorithms, the full benefit of sonic data acquired in high angle environments has been difficult to extract.

Innovations in the acquisition of high fidelity, broad band waveform sonic data, advanced waveform dispersion analysis, and approaches to more accurately quantify acoustic anisotropy are changing industry perspectives. Improved understandings of high angle borehole sonic data is readily applicable to surface seismic, well completion optimization and well placement.

The paper discusses some of the recently developed and developing sonic acquisition and interpretation techniques and their application to high angle borehole sonic well data.

INTRODUCTION

High angle (HA) and horizontal (HZ) wells are now commonplace. The motivation to drill these wells is driven by a combination of increased production, improved reservoir drainage and less environmental impact. In offshore reservoirs, economics are improved as HA and HZ wells can be drilled from a central structure which also enables the development of smaller satellite reservoirs. In step with these developments the industry has been required to develop conveyance and interpretation techniques applicable to HA/HZ wells (Passey, 2005).

Logging tools are now routinely conveyed via coil-tubing, drill pipe or Logging-While-Drilling (LWD). New interpretation approaches to account for HA/HZ measurements have been developed, and are being further enhanced as new understandings become apparent.

In the HZ/HA environment acoustic velocity changes due to wellbore deviation and/or formation dip can be substantial.

MODULAR WIRELINE SONIC TOOL

A source of optimism for the recently developed and developing borehole sonic answer products in HA/HZ wells is the data extracted from a newly commercialized acquisition tool (Figure 1). Some of the interpretation ideas have been considered previously but now with the new hardware their answers have become more precise.

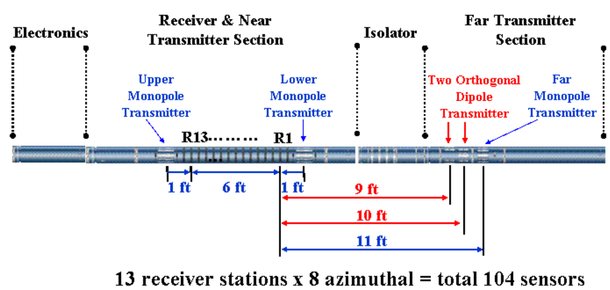

Fig. 1 *New Sonic Acquisition Tool Geometry.*

The new tool was designed to acquire high fidelity monopole and dipole waveforms over a wide range of receiver spacing with a wide frequency bandwidth.

Earlier generation tools utilized an outer slotted sleeve to reduce tool affects. This made for mechanically weak and acoustically complex tools that were difficult to characterize in all conceivable environments. The new tool takes an alternative approach in that it is constructed with an inner solid mandrel which makes for predictable acoustics that are relatively simple to model. Additional characteristics of the tool are the dipole shaking transmitters that generate high pressure pulses without any vibration in the tool as the action-reaction system is contained within the transmitters. These dipole transmitters can also be activated by a frequency sweep, or Chirp. The Chirp drive ensures that the maximum possible dipole bandwidth is transmitted to the formation. The dipole chirp drive frequency response is shown in Figure 2 (Pistre et al, 2005).

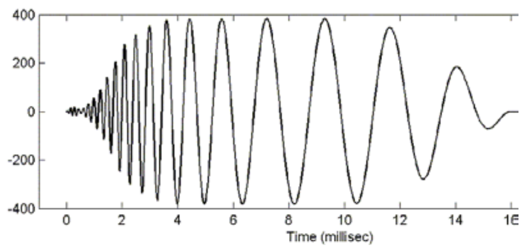

Fig. 2 *Dipole Chirp Drive response.*

CONVEYANCE

Good quality monopole *P* & *S* slowness logs have been acquired via LWD but for slow formations (where formation shear slowness is slower than borehole fluid slowness), wireline dipole tools are the measurement of choice. In recognition of industry requirements for more robust HA/HZ well wireline sonic measurements, recent wireline sonic tools have been designed with mechanical strengths that are double that of their predecessors. The mechanically stronger tools as well as other innovative measurement techniques unique to the latest generation tools have dramatically improved the measurement and interpretation of HA/HZ borehole sonic data (Pistre et al, 2005).

ACOUSTIC RESPONSE IN DEVIATED WELLS

In general one does not need to consider anisotropy affects on sonic logs until the relative dip between wellbore and the bedding plane begins to exceed 20°. In environments where relative dips are greater than 20° anisotropic affects can be large. To quantify this affect calibration may be required in multiple wells with contrasting deviations. For very high deviations wellbore image logs are necessary to help define the relationship of the wellbore with the bedding.

From surface geophysical processes and interpretations it is known that vertical and horizontal velocities can be quite different. This is particularly true of shales, which in general represent approximately seventy percent of the interval intersected by wellbores drilled for hydrocarbon exploitation. When relative formation dip is greater than 20° the affect on sonic measurements needs to be considered. An appropriate understanding of this is of benefit for more accurate geophysical interpretations.

Sonic data acquired in wells that intersect relatively low formation dips effectively measure vertical slowness. Sonic data acquired in horizontal wells where the relative formation dip is near 90° effectively measure horizontal slowness while data acquired in wells at a significant wellbore deviation measure some combination of the two.

Most shales encountered in the earth can be described to a good approximation as being transversely isotropic with a vertical axis of symmetry (VTI). Specifically, VTI refers to formations where the vertical shear stiffness is less than the horizontal shear stiffness and is caused by the strong alignment of clay platelets within shale. An allowance for this anisotropy needs to be included in geophysical analysis including migration and amplitude-versus-offset (AVO). Failure to do so can result in large errors (Walsh et al, 2006).

Transverse-isotropic anisotropy, also referred to as polar anisotropy, can be quantified by the three Thomsen parameters epsilon (ε), gamma (γ) and delta (δ) (Thomsen, 1986). The γ parameter can be derived from borehole sonic data in terms of the vertical and horizontal shear moduli. Vertical shear moduli can be obtained from cross-dipole sonic logs and the horizontal shear moduli can be estimated from Stoneley log data. In general, a positive γ is an indicator of shale anisotropy and a negative γ is an indicator of permeability (Walsh et al, 2006).

The physics of acoustic waves in anisotropic formations is well understood, however determining the anisotropy parameters is more challenging. In terms of elastic properties the Thomsen parameters can be written as:

$$\varepsilon = \frac{c_{11} - c_{33}}{2c_{33}} \tag{1}$$

$$\gamma = \frac{c_{66} - c_{55}}{2c_{55}} \tag{2}$$

$$\delta = \frac{(c_{13} + c_{55})^2 - (c_{33} - c_{55})^2}{2c_{33}(c_{33} - c_{55})} \tag{3}$$

A graphical representation for a VTI shale is shown in Figure 3. Differences in the *P*-wave propagation between vertical and horizontal can be described by the Thomsen ε parameter. Note that the horizontal *P*-wave slowness is faster than the vertical, hence ε is always positive. γ is related to differences between the vertical and horizontal polarized *S*-wave, in a VTI medium γ is always positive. δ is more difficult to describe, when δ and ε are equal, the shape of the *P*-wave slowness surface is elliptical and the anisotropy is described as elliptic. For most shales, ε is greater than δ, and is termed positive anellipticity. For anelliptcity, the *P*-wave phase slowness surface bulges out and the S_V-wave slowness surface bulges in (Walsh et al, 2006).

An interesting observation of Figure 3 is that there is little variation in slowness until approximately 20º. Above 20º the compressional *P*-wave slowness starts to decrease and the shear wave splits into two distinct components S_V and S_H.

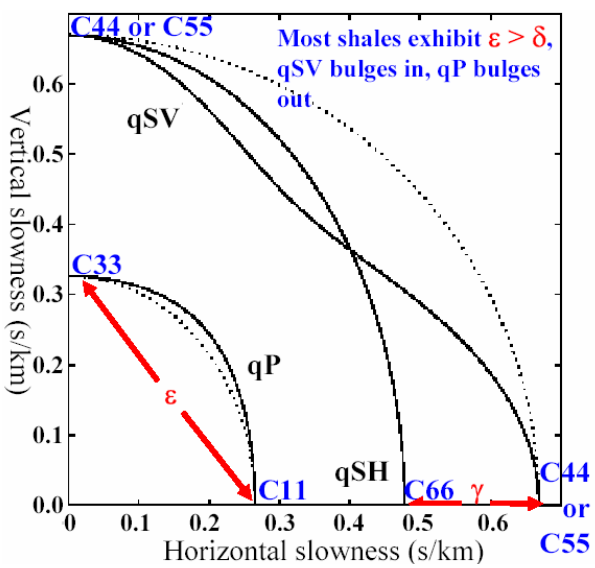

Fig. 3 *Diagram of P- and S-wave slownesses for VTI anisotropic shale.*

COMPRESSIONAL SLOWNESS IN WELLS DRILLED AT VARYING DEVIATIONS

Consistent with the above Hornby reviewed compressional slownesses in three wells in Alaska that penetrated the same shale formation at 0°, 39° and 67°. The compressional slownesses in the shale showed significant variations. The compressional slowness decreased (became faster) as well deviation increased. Also, with the same dataset Hornby, estimated the Thomsen anisotropy parameters ε and δ and used these derived parameters to estimate sonic log responses in a vertical well. Hornby showed that sonic data acquired in multiple high angle wells in the same formation could be used for significant additional geophysical information (Hornby et al, 2003).

SHEAR WAVE AZIMUTHAL ANISOTROPY ORIENTATION

Crossed-dipole sonic logging tools measure formation azimuthal shear-wave anisotropy. An understanding of the presence of anisotropy and its source can have important implications for geomechanical and geophysical evaluations as well as completion engineering and drilling practices (Brie et al, 1998).

Processing of shear wave azimuthal anisotropy requires that the measurements be oriented with an inclinometry tool. In wells where the relative formation dip is near vertical the computed fast and slow shear polarization azimuths are primarily influenced by the horizontal components and can be oriented relative to tool azimuth which can then be referenced to geographical north. However in wells with large relative dip and/or horizontal wells a geographical referencing system based on tool azimuth is not relevant. In acquisition environments with large relative dips the fast shear polarization is influenced by the vertical as well as horizontal components. Hence in these situations a more appropriate referencing system would be based on the tool relative bearing which is then referenced to the top side of the borehole. The use of an inappropriate referencing system would result in erroneous and misleading shear slownesses and polarization azimuths

A point of interest then is when should a geographical or top of the hole referencing system be used. In the industry a cutoff considered was a relative dip of 20°. However, a more in-depth analysis performed by De and Schmitt suggested that this cutoff is closer to 30°. In addition, De and Schmitt completed a case study on a dataset from a highly deviated well. It showed that for a low dipping shale the horizontal plane had the highest strength. The same case study also highlighted a thick sand which had a maximum in-situ stress direction of vertical. The interpretation re-enforced their recommendation that for highly deviated wells a top of hole orientation system should be employed (De and Schmitt, 2005).

c_{44}, c_{55} AND c_{66} FROM BOREHOLE SONIC LOGS

Sinha showed that the two vertical shear moduli c_{44} and c_{55} in an anisotropic formation with a vertical axis could be obtained from cross-dipole sonic, and that the horizontal shear modulus c_{66} could be estimated from asymptotic analysis of Stoneley-waves (Sinha et, 2006).

Borehole Stoneley wave propagation is also affected by logging tool presence and near-wellbore alteration. To compute c_{66} from Stoneley the above influences must be eliminated. One can account for the tool presence with the latest generation sonic tool mentioned previously. It has been fully characterized and has predictable acoustics and as such is relatively simple to model. Additionally, a new Stoneley radial profiling (SRP) algorithm has been developed. This algorithm accounts for near-wellbore alteration and enables the computations of horizontal shear slowness and hence c_{66} (Sinha et al, 2006).

EXAMPLE IN CHINA

Figure 4 shows the elastic parameters c_{44} and c_{66} computed from data acquired with the latest borehole sonic tool in a well in the South China Sea. The horizontal shear was computed from Stoneley radial profiling that fully accounts for near wellbore alteration and tool presence (Murray et al, 2007 and Sinha et al, 2006).

Track1 of Figure 4 contains the caliper and gamma ray, Track2 the compressional, fast and slow shear, and Stoneley slownesses, Track 3 has c_{44} (red) and c_{66} (green), Track4 the petrophysical volumetric analysis and Track 5 contains γ computed from c_{66} and c_{44}.

Assuming the vertical axis lies along the axis of rotational symmetry, then $c_{44} = c_{55}$. As expected, γ is less than 1 in the permeable sand intervals A1 and A2. One can also observe that $c_{66} < c_{44}$.

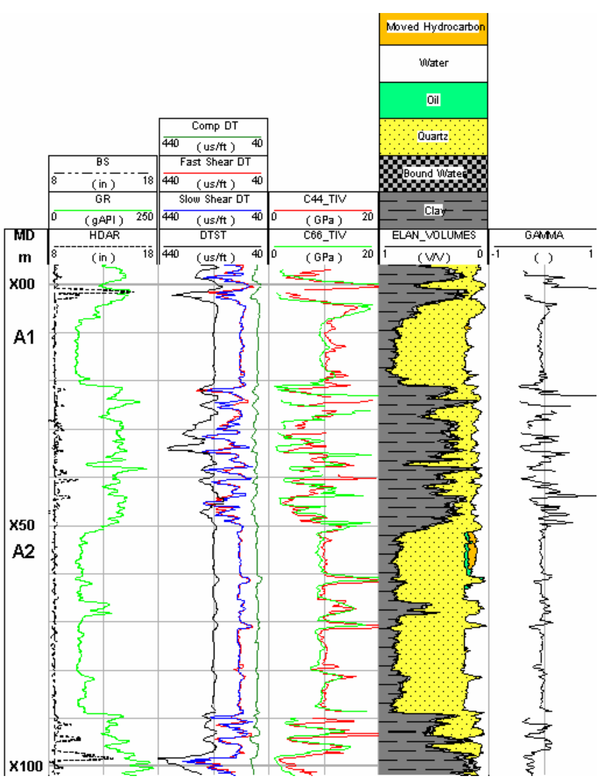

Fig. 4 *Well A - c_{44}, c_{66} and γ computations for permeable sand intervals shown previously.*

An interesting observation can be made of a deeper shale section of Well A, shown in Figure 5. The log display is the same as per Figure 4. Here $c_{66} >> c_{44}$ and γ is >> 0 and is an indicator of a strongly VTI anisotropic interval. This suggests that S_H is much faster than S_V. An allowance for this relatively large amount of anisotropy needs to be included in any geophysical interpretation.

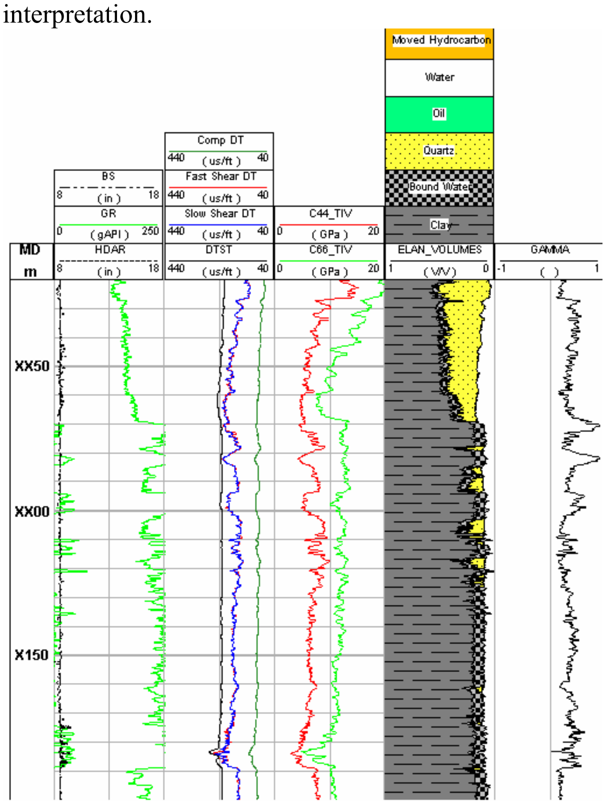

Fig. 5 *Well A - $c_{66} >> c_{44}$ and γ is >> 0, indicates a strongly VTI anisotropic interval.*

SUMMARY

The acquisition, processing and interpretation of HA and HZ borehole sonic log data brings additional understanding to reservoir properties.

Innovations in the latest generation of acquisition tools and associated algorithms enable maximum benefit of HA and HZ borehole sonic log data.

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ABOUT THE AUTHORS

Doug Murray is a Principle Petrophysicist with Schlumberger in Beijing, China. Since joining Schlumberger in 1982, he has had a variety of experience, first as a wireline field engineer in Canada and Algeria, and then as a log analyst and log interpretation center manager in Nigeria, Saudi Arabia, Trinidad and Tobago, and Argentina. He then became involved with new sonic interpretation methodologies and answer products, as well as hydrate formation evaluation with Schlumberger in Japan. He has a BSc degree in electrical engineering from Lakehead University, Canada and an MA degree from Hull University, England. He is a member of SPWLA, SPE, and SEG.

Wei Liu began his Schlumberger career as a Borehole Seismic Geophysicist in 2002. He has a BSc and a MSc degree in Geophysics from the University of Petroleum of China and has experience with a multitude of borehole seismic and borehole sonic acquisition, processing and interpretation techniques. In his current role with the Schlumberger China Data and Consulting Services group he provides a broad range of technical support for all Schlumberger wireline and Logging-While-Drilling (LWD) borehole acoustic services.

Xingwang Yang is a Senior Petrophysicist and Petrophysical Group Leader with Schlumberger in Beijing, China. He joined Schlumberger in 1999 as a Log analyst. Before joining Schlumberger he was a field engineer with PetroChina. He has a BSc degree in Petrophysics from China Petroleum University.