ABSTRACT

Slow formations are defined as those formations where the shear velocity is slower than the borehole fluid velocity. In order to measure shear velocities in such formations, sonic tools incorporating dipole transmitters were developed. Since their introduction more than a decade ago, dipole sonic logging tools have provided a wealth of information about the acoustic properties of slow formations, including the detection of anisotropy and inhomogeneity. The latter mechanism manifests itself as radial variations in compressional and shear slownesses, which is now possible to quantify.

The Cymric field is located in the San Joaquin valley near Bakersfield, California. One of the producing zones, the Opal A diatomite, is an extremely slow formation with compressional slownesses approaching 200 µs/ft and shear slownesses approaching 800 µs/ft. In this paper, we examine the results from a wideband crossed dipole sonic tool that was recorded in a well drilled in the Cymric field. The tool is specifically designed for 3D acoustic characterization of formations. This is achieved through a formation typing scheme that classifies formations into one of four categories: A) isotropic homogeneous, B) isotropic inhomogeneous, C) anisotropic homogeneous, and D) anisotropic inhomogeneous. Slowness frequency dispersion analysis is used in the classification scheme as each of these categories has a unique signature when dispersion analysis is employed.

When inhomogeneity is present, a new technique known as dipole radial profiling, can be applied to measure the radial variation of shear slowness away from the borehole. This can be used to determine the extent of possible formation damage, alteration, or filtrate invasion and to provide a measure of the far field shear slowness.

These techniques are applied to acoustically characterize the Opal A diatomite formation.

INTRODUCTION

The ability to measure formation shear velocities in slow formations was first realized with the development of array sonic tools employing dipole transmitters (Harrison, et. al. 1990). Such measurements have led to a greater understanding of the acoustic behavior of slow formations. Anisotropy is often observed, as is inhomogeneity.

Anisotropy may arise from intrinsic structural effects, such as aligned fractures and layering of thin zones, or from local biaxial or triaxial tectonic stresses within the formation. Therefore, acoustic anisotropy in rocks can be divided into two broad categories: intrinsic and stress-induced. A method for distinguishing between these two categories was described by Plona, et. al. (2000). This technique, dispersion analysis, can also be used to identify radial gradients of shear slowness (inhomogeneity) that are related to mechanical damage in the formation (Plona et al, 2002).

An example of a slow formation where both anisotropy and inhomogeneity are observed is the Antelope in the Cymric oil field, which is located in the San Joaquin valley near Bakersfield, California. The lithology in the Antelope formation consists of Opal A (diatomite) and Opal CT (cristobalite). Winterstein and De (1995) reported varying differences in S-wave birefringence ranging from 6 degrees to 16 degrees in the Cymric diatomites, which they attributed to differences in stress magnitudes. They also observed changes in fast shear-wave polarization with depth and well location. (De, et. al., 1998) (Fig. 1)

Anisotropy in the Cymric field has been observed from both shear-wave VSPs and crossed-dipole sonic logs (Hatchell, et. al., 1995). Hatchell’s comparison found that both measurements generally agreed and he again confirmed variation of the fast shear-wave polarization with depth. Shear-wave slownesses in the diatomites exceeded 800 µs/ft in some intervals. A goal in Hatchell’s paper was to compare the fast-shear polarization azimuth to the maximum horizontal stress direction determined from borehole breakout and tiltmeter data. These measurements, and other stress data acquired in this field, indicate that differential stress is the principal mechanism causing the shear-
wave anisotropy. Recent developments incorporating advanced frequency domain processing now provide the capability to characterize the acoustic behavior (and hence mechanical state) of the formation around the borehole (Plona, et. al., 2004). These methods are employed in this paper to characterize the Cymric diatomites. Where inhomogeneity exists, radial measurements of shear slownesses are computed. These additional measurements provide new insight concerning the acoustic behavior of these anisotropic rocks.

FIELD DATA

Sonic waveform data were recorded in a well located near the crest of the Cymric anticline. The sonic tool utilized for this recording is a new generation dipole/monopole sonic tool designed for measuring 3D (axial, radial, and azimuthal) formation acoustic properties (Pistre, et. al., 2005). The logged interval extends from 972 to 1650 ft. The formation from 972 ft to TD is Miocene-age Antelope Shale, which is a member of the Monterey Formation. It is in the Opal A phase from 972' to around 1500'. There is a transition zone from Opal A to Opal CT between around 1500' to 1590'. Geologic beds between these depths alternate between Opal A and CT, depending on composition. From around 1590' to TD, the Antelope is in the Opal CT phase.

Figure 2 shows that formation shear slownesses in the Antelope formation average 700 µs/ft and approach 900 µs/ft in some sections. Let us study this display in more detail. The first five tracks show the results of crossed-dipole anisotropy processing (Esmersoy, 1994). In track 1, the minimum cross-line energy approaches 0% and there is large separation between the minimum and maximum cross-line energy. This is good indication that the data fit the Alford rotation model and that anisotropy may be present. Track 3 shows the fast shear-wave polarization azimuth. Azimuth values for the Opal A range from N35°W to N15°W, which is in general agreement with Hatchell’s paper for the extremely slow zone observed in his data. (Hatchell, et. al., 1995) Track 4 shows the fast- and slow- shear-wave slownesses computed after Alford rotation. Note the separation between the fast-shear slowness, denoted by the red curve, and the slow-shear slowness denoted by the blue curve. This separation is the most concrete indication of shear-wave anisotropy. The shading on the left side of track 3 is normally color coded to indicate different percentages of slowness anisotropy. Large anisotropy causes the curve to increase to the right and correlates directly with the separation observed between the fast- and the slow- shear slowness curves. Slowness anisotropy is computed by dividing the difference between the fast- and slow- shear slownesses by the average of the two slownesses. The other shaded curve on the right side of the depth track is a measure of time anisotropy, which is computed by looking at the phase shift between the fast and slow in-line waveforms after Alford rotation has been applied. Color-coded by percentage of anisotropy, it correlates with the phase shift seen on the waveform overlay in track 5. In the Antelope formation, 4 to 8% anisotropy is observed. This is consistent with the findings of previous papers that have studied anisotropy in the Cymric field.

Track 7 shows the Slowness-Time-Coherence (STC) projection plot for the fast-shear waveform data with the fast shear slowness computed from dispersive STC processing (Brie, et. al., 1997). In track 8, a new QC display is shown: the slowness frequency analysis (SFA) projection plot (Plona, et. al., 2005). In SFA, a dispersion curve is generated at each depth from the recorded waveforms, slowness versus frequency information of the dispersion curve is projected onto the slowness axis, and then the slowness projection at each depth is plotted as a log versus depth. The estimated slowness log from time-based coherence processing is then overlaid. For dipole flexural signals, if the estimated slowness log lies at the lowest limit of the SFA projection, then the estimated slowness matches the low-frequency limit of the dipole flexural signal and the slowness log is consistent. It is also most likely correct because it is consistent with the dispersion curve that describes the data. Note that the estimated shear slowness log (black curve), overlays the lowest slownesses that are indicated by the high-energy orange color. This is indicative of the low frequency limit of the dipole dispersion curve. Theoretically, the low-frequency limit is the shear slowness of the formation and this example provides confirmation that the shear slowness computed from dispersive STC processing is correct.

Tracks 10 and 11 show the processing results for the slow-shear and are analogous to tracks 8 and 9 for the fast-shear.

Another observation that can be made from the SFA projection log is the large amount of dispersion seen in the Opal A: the zone above 1500 ft. This zone exhibits “wide slowness projection” (Plona, et. al., 2005), compared to the deeper zone, which is indicative of inhomogeneity due to alteration or mechanical damage in the formation. In such situations, the dipole flexural dispersion data over a frequency band can be inverted using a Backus-Gilbert technique for estimating radial variations in formation shear slownesses (Sinha, 2003). We refer to this method as dipole radial profiling (DRP).
Figure 3 is a display of the dipole radial profiling (DRP) results for the Opal A. The tracks on the left correspond to the fast-shear and those on the right correspond to the slow-shear. The color map represents the difference from the far field slowness, which is displayed in green. The blue shading indicates 15 percent difference from the far field slowness. The zone at 1270 ft, for example indicates significant variation between the far field and near field slownesses for both the fast-shear and slow-shear. This variation extends approximately one foot into the formation. The tracks to the left and right of the color maps show the inverted slownesses for the fast and slow shear respectively. These are computed at specific depths of investigation into the formation. The dark blue curve is computed at 25 inches into the formation and represents the far field slowness. The light colored curves are slownesses computed very close to the borehole. At 1270 ft, we observe a large separation between these curves, indicating radial variation in formation shear slowness. The difference is more pronounced for the slow-shear than the fast-shear.

Although the discussion thus far has focused on the flexural shear, slow formations can pose a challenge for compressional slowness processing. Monopole compressional logging in fast formations involve the excitation of non-dispersive head waves. In slow formations, the compressional head wave becomes weak and real tools generally excite the leaky compressional wave. Leaky compressional modes are dispersive, starting at a certain cutoff frequency with the formation compressional slowness and increasing towards either the borehole fluid slowness or an interface mode at high frequency. The correct compressional slowness of the formation is the low-frequency limit of the dispersive leaky compressional mode.

In the slower zone at 1470 ft, this is not the case. The compressional slowness is approximately 192 µs/ft, just slightly faster than the fluid arrival. Conventional STC processing will yield an incorrect result as it will mix these two events together. Dispersive STC processing of the leaky-P mode is required when the formation compressional slowness approaches the fluid slowness. Incidentally, the SFA projection log can be used to ascertain whether compressional slowness computed from the leaky-P is correct. As with the flexural mode, the processed compressional value will track the faster slowness of the SFA projection log, indicating that the correct formation compressional slowness has been computed.

**SUMMARY**

Using a new generation dipole sonic tool together with new processing methodology, extremely slow formations, such as the Cymric diatomites, can be acoustically characterized in a 3D sense: that is, axially, azimuthally, and radially. The radial measurement represents the new dimension that was previously unavailable.

Inhomogeneity and anisotropy are clearly present in this formation. Radial variation of 15 percent in shear slowness is observed and the radial extent of this variation is over one foot.

New QC displays provide confidence that the computed shear and compressional slowness values are correct.

These measurements allow for greater understanding of the acoustic behavior of slow rocks and can be used to potentially identify mechanically damaged and altered formations.

**ACKNOWLEDGMENTS**

The authors wish to thank ChevronTexaco and in particular Dale Julander and the San Joaquin Valley Business Unit for permission to publish the data.

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Fig. 1 Structure on a horizon in the Antelope formation below the P-M unconformity. Solid bars show directions of maximum horizontal compressive stress below the unconformity. (from De et. al., 1998)

Fig. 2 Shear-wave processing; Anisotropy results are displayed in the first five tracks. Fast shear results are shown in the next three tracks and slow shear results in the final three tracks.
Fig. 3. Dipole Radial Profiling results. Tracks 2 and 6 show slownesses computed at different depths of investigation for the fast and slow shear, respectively. Tracks 3 and 5 show the difference from the far field slowness (displayed in green) for the fast and slow shear, respectively. The blue shading indicates a 15 difference from the far field slowness.
Fig. 4 Comparison of standard monopole processing and "leaky P" processing