7th International Conference & Exposition on Petroleum Geophysics

"HYDERABAD 2008"

P - 163

Recent Advances in Borehole Sonic Technology

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Summary

Mehsana tectonic block located in the western Indian state of Gujarat is a fairly well explored, productive block of North Cambay Basin. Exploitation in Mehsana block has attained a mature stage. Large sized pools are in Kalol Formation occurring at shallower depths in structural plays and operate under water drive while small sized pools are concentrated at deeper depths in Mehsana and Mandhali Members of Kadi Formation controlled by strati-structural entrapment operating under depletion drive. The problems in these reservoirs are of contrasting nature.

Introduction

Borehole sonic data plays an important role in seismic exploration, drilling, wellbore stability, well completion, as well as reservoir management. **Seismic surveys** require borehole sonic data for obtaining accurate compressional slowness (slowness is inverse of velocity) estimates as a function of depth that are used in the time to depth conversion. Recent studies have also highlighted the importance of using anisotropic velocity models in generating AVO gathers for accurate target locations. Anisotropic velocity models require anisotropic moduli for calculating plane wave velocities as a function of propagation direction. Borehole sonic data from the Sonic Scanner tool in a vertical or deviated well has the potential of providing up to four anisotropy parameters for an assumed transversely-isotropic (TI) or orthorhombic formation (Sinha et al., 2004). Estimates of formation anisotropy parameters are made using the 3D-anisotropy module. Remaining elastic moduli can be obtained either from VSP surveys, core data, or known correlations to enable development of anisotropic velocity model using Kelvin-Christoffel's equations.

Wellbore stability during drilling is planned based on relevant failure models that require confined compressive and tensile strengths together with the far-field formation stresses to predict safe mud weight window to avoid tensile fractures or breakouts. Inversion of the Sonic Scanner data can provide estimates of formation stresses and strengths under suitable conditions. Estimates of formation stresses and strengths are obtained by inverting cross-dipole sonic data together with 3D-anisotropy output and radial profiling of shear slownesses (Bratton et al., 2004; Sinha 2002; Sinha et al., 2006a).

Optimal well completion for production requires both identification and estimation of the radial extent of alteration in reservoir intervals. Formation properties surrounding a borehole can be heterogeneous due to borehole stress concentrations, drilling damage, shale swelling, plastic yielding that might cause fluid mobility impairment. We can identify mechanically competent intervals as well as those exhibiting radial alteration in shear slownesses by inverting measured dipole and Stoneley dispersions. Near-wellbore alterations are characterized by differences between the far-field and near-wellbore slownesses. **Optimal depths for fluid sampling** are identified by mechanically competent intervals that exhibit nearly uniform shear slownesses away from the borehole surface. In contrast, intervals with near-wellbore softening caused by mechanical or mobility damage are prone to seal failures or might lead to tight pretest. Outputs from the monopole Compressional Velocity Radial Profiling (CRVP), dipole Shear Velocity Radial Profiling (SRVP) of the fast and slow vertical shear velocities, and Stoneley Radial Velocity Profiling (STRVP) of horizontal shear velocity help in an optimal depth selection for fluid sampling as well as optimal perforation tunnel design (Sinha et al., 2003; Sinha et al., 2006a).

Fast shear azimuth obtained from the processing of cross-dipole sonic data in the presence of dipole dispersion crossovers provides the maximum horizontal stress direction that is of help in planning for oriented perforation and stimulation projects. **Reservoir management** can benefit from an optimal drawdown pressure that maximizes sand-free production. Accurate estimates of confined rock compressive strength together with far-field formation stresses enable a more reliable estimate of optimal drawdown pressure that maximizes production with reduced risk of sanding (Bratton et al., 2004). Reservoir production can also benefit from the identification of fluid mobility barriers and estimates of the ratio of near-wellbore damaged to far-field mobilities. Radial profiling of fluid mobility in a reservoir interval can provide such estimates together with mobility logs obtained at an effective radial depth of investigation using either MDT pretest drawdown analysis or NMR derived permeability.

To provide the aforementioned answer products, we have developed several data processing algorithms:

1. 3D-anisotropy for obtaining a sub-set of transversely-isotropic (TI) elastic moduli from a vertical or deviated well,
2. Compressional Radial Velocity Profiling (CRVP) of compressional velocity,
3. Shear Radial Velocity Profiling (SRVP) of shear velocities in the two orthogonal planes containing the borehole axis,
4. Stoneley Radial Velocity Profiling (STRVP) of shear velocity in the borehole cross-sectional plane,
5. Maximum horizontal stress magnitude estimation using the three shear moduli, and
6. Horizontal stress gradient estimation using differences between velocity dispersions at two depths.

3D-Anisotropy

The 3D-anisotropy module outputs up to 4 anisotropic moduli of an orthorhombic or TI formation using the compressional, fast-shear, slow-shear, and Stoneley slownesses obtained from a single-well data with known well deviation from the vertical and true stratigraphic dip from an imaging tool. The 3D-anisotropy algorithm yields verifiable far-field compressional and shear moduli outside any near-wellbore altered annulus caused by stress concentrations or plastic yielding of the formation etc. The output of this module is checked against the far-field values that are outside any near-wellbore altered annulus from the Compressional Velocity Radial Profile (CRVP), Shear Velocity Radial Profile (SRVP) and Stoneley Velocity Radial Profile (STRVP) algorithms (Pistre et al., 2005). Consequently, results from the 3D-anisotropy can be combined with borehole seismic data (walk-away/walk-around VSPs) to obtain a complete set of transversely-isotropic (TI) elastic moduli. A complete set of formation moduli for a given lithology interval can then be used to obtain an anisotropic velocity model that would yield plane wave velocities as a function of propagation direction with respect to the anisotropic axes. Anisotropic velocity models can then be used to generate AVO synthetic gathers to determine accurate location of reservoir targets.

More importantly, the three shear moduli c_{44}, c_{55}, and c_{66} as a function of depth can be used to obtain the following formation attributes:

1. Classification of formation anisotropy,
2. Qualitative indicator of fluid mobility in porous sand reservoirs,
3. Far-field formation stresses, and
4. Relative shear rigidity of the three orthogonal planes.

Figure 1a shows schematic diagram of a vertical and horizontal sections of a wellbore trajectory and identifies the shear moduli that would be determined from the cross-dipole sonic data from a well parallel to the X_3- , X_1- , and X_2-axis. Note that the shear modulus in the cross-sectional plane of the wellbore trajectory is obtained from the Stoneley data.

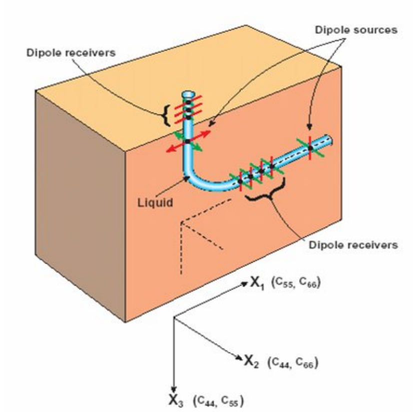

Figure 1a: Schematic diagram of a vertical well parallel to the X_3-axis and a horizontal well parallel to the X_1-axis. Cross-dipole data from a well parallel to the X_3-axis yields the shear moduli C_{44} and C_{55} in the two orthogonal vertical planes. Similarly, cross-dipole data from a well parallel to the X_1-axis yields the shear modulus C_{55} in the vertical X_1-X_3 plane, and C_{66} in the horizontal X_1-X_2 planes.

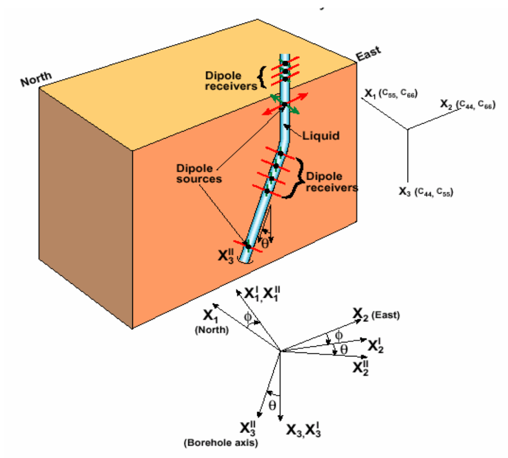

Figure 1b: Schematic diagram of a vertical well parallel to the X_3-axis and a deviated well with azimuth ϕ and deviation θ.

Figure 1b displays schematic diagram of a vertical and deviated sections of a wellbore trajectory. The deviated well azimuth ϕ is measured from the north, and well deviation θ is referred to the vertical. If we assume a layer-cake model for a given lithology interval with a vertical TI-symmetry axis, the well azimuth does not affect the TI-anisotropy moduli because of the rotational invariance about its symmetry axis.

Stress magnitudes using borehole sonic

Formation stresses play an important role in geophysical prospecting and development of oil and gas reservoirs. Both the direction and magnitude of these stresses are required in (a) planning for borehole stability during directional drilling, (b) hydraulic fracturing for enhanced production, and (3) selective perforation for prevention of sanding during production.

The formation stress state is characterized by the magnitude and direction of three principal stresses. Figure 2 shows a schematic diagram of a vertical borehole in a formation subject to the three principal stresses. Generally, the overburden stress (SV) is reliably obtained by integrating the formation mass density from the surface to the depth of interest. Consequently, estimating the other two principal stresses (SHmax and Shmin) in the horizontal plane is the remaining task necessary to fully characterize the formation stress state.

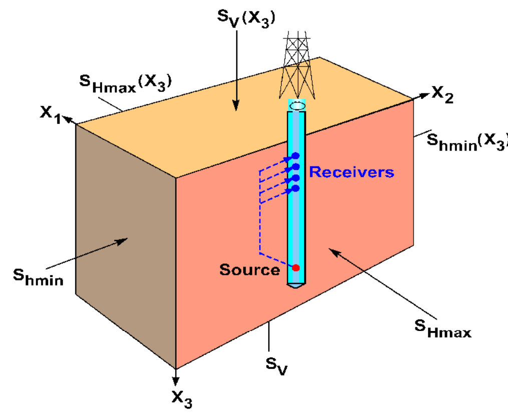

Figure 2: Schematic of a borehole in the presence of formation principal stresses with the borehole axis parallel to the overburden stress.

Sonic velocities in formations change as a function of rock lithology/mineralogy, porosity, clay content, fluid saturation, stresses, and temperature. To estimate changes in the formation stress magnitudes from measured changes in sonic velocities, it is necessary to select a depth interval with a reasonably uniform lithology, clay content, saturation and temperature so that the measured changes in velocities can be related to corresponding changes in formation stress magnitudes. Any change in porosity caused by normal compaction is accounted for by corresponding changes in the formation effective bulk density and stiffnesses. Assuming that the measured changes in sonic velocities are largely caused by changes in stresses, it is possible to invert borehole sonic velocities for the estimation of changes in formation stress magnitudes (Sinha, 1997, Sinha et al., 2000a).

The underlying theory behind the estimation of formation stresses using borehole sonic data is based on acoustoelastic effects in rocks. Acoustoelasticity in rocks refers to changes in elastic wave velocities caused by changes in pre-stress in the propagating medium. Elastic wave propagation in a pre-stressed material is described by equations of motion for small dynamic fields superposed on a statically deformed state of the material. These equations are derived from the rotationally invariant equations of nonlinear elasticity (Norris, Sinha and Kostek, 1994). The linear equations of motion for isotropic materials contain two independent elastic stiffnesses that are defined by the dynamic Young's modulus (Y) and Poisson's ratio (ν), or equivalently, the two Lame parameters, (λ and μ).

The equations of motion for pre-stressed isotropic materials contain three additional nonlinear elastic constants (C_{111}, C_{144}, and C_{155}) together with the biasing stresses (Sinha, 1982; Norris et al., 1999). A forward solution of equations of motion in pre-stressed materials yields plane wave velocities as a function of principal stresses in the propagating medium.

The presence of a borehole in a triaxially stressed formation causes near-wellbore stress distributions that can be obtained from linear elastic deformation theory. Near-wellbore stress distributions can be mapped into corresponding sonic velocity distributions provided stress coefficients of velocities in terms of the formation nonlinear constants are known (Sinha et al., 2006b). The stress coefficients of velocities are defined in terms of formation nonlinear constants referred to a reference state close to the in-situ stress state of the formation. Changes in cross-dipole dispersions caused by near-wellbore stress distributions can be inverted to estimate far-field stresses and formation nonlinear constants referred to a local reference state.

Formation stresses using the three shear moduli

A reservoir sand in the absence of formation stresses and fluid mobility behaves like an isotropic material characterized by a shear and bulk moduli. However, a complex shaly-sand reservoir is characterized by anisotropic elastic stiffnesses. Anisotropic elastic stiffnesses and the three shear moduli are affected by (a) structural anisotropy; (b) stress-induced anisotropy; and (c) formation mobility. Structural anisotropy caused by clay microlayerings in shale is described by transversely-isotropic (TI-) symmetry that exhibits the horizontal shear modulus C_{66} to be larger than the vertical shear moduli C_{44}=C_{55}, in the absence of any stress-induced effects. Shales are impermeable and do not constitute part of a producing reservoir. Here we analyze effects of formation stresses on the effective shear moduli that can be measured with the axi-symmetric Stoneley and flexural waves in a fluid-filled borehole.

The acoustoelastic theory relates changes in the effective shear moduli to incremental changes in the biasing stresses and strains from a reference state of the material (Sinha, 2002). The three shear moduli can be estimated from borehole sonic data. With the recent introduction of algorithms for the Stoneley radial profiling of horizontal shear slowness and cross-dipole radial profiling of vertical shear slownesses, we can unambiguously estimate the virgin formation shear moduli C_{44}, C_{55}, and C_{66}. These algorithms account for the sonic tool bias and possible near-wellbore alteration effects on the measured sonic data.

Differences in the effective shear moduli are related to differences in the principal stress magnitudes through an acoustoelastic coefficient defined in terms of formation nonlinear constants referred to a chosen local reference state and for a given formation lithology. The following three equations relate changes in the shear moduli to corresponding changes in the effective principal stresses (Nur and Byerlee, 1971):

$$C_{44} - C_{66} = A_E(\sigma_V - \sigma_H), \quad (1)$$

$$C_{55} - C_{66} = A_E(\sigma_V - \sigma_h), \quad (2)$$

$$C_{55} - C_{44} = A_E(\sigma_H - \sigma_h), \quad (3)$$

where

$$A_E = 2 + \frac{C_{456}}{\mu}, \quad (4)$$

is the acoustoelastic coefficient, C_{55} and C_{44} denote the shear moduli for the fast and slow shear waves, respectively; C_{456}=(C_{155}-C_{144})/2, is a formation nonlinear parameter that defines the acoustoelastic coefficient; and μ represents the shear modulus in a chosen reference state.
There are two ways to estimate the acoustoelastic parameter A_E for a reasonably uniform lithology sand reservoir:

1. Cross-dipole sonic log provides shear moduli C_{55} and C_{44} in the two orthogonal planes containing the borehole axis. The acoustoelastic parameter A_E is then given by equation (3)

$$A_E = \frac{C_{55} - C_{44}}{\sigma_H - \sigma_h}, \quad (5)$$

where C_{55} and C_{44} denote the fast and slow dipole shear moduli, respectively; and σ_H and σ_h represent the maximum and minimum horizontal effective stress magnitudes, respectively.

2. When we have estimates of the minimum horizontal and overburden stress magnitudes as a function of depth, we can determine the acoustoelastic parameter A_E in terms of the far-field shear moduli C_{55} and C_{66} using the equation (2)

$$A_E = \frac{C_{55} - C_{66}}{\sigma_V - \sigma_h}, \quad (6)$$

where we assume that the effects of permeability on these shear moduli are essentially similar and small to be negligible.

Once we have determined the acoustoelastic parameter for a given lithology interval, we can determine the maximum horizontal stress σ_H magnitude as a function of depth from the following equation

$$\sigma_H = \sigma_h + \frac{(C_{55} - C_{44})}{A_E}, \qquad (7)$$

where C_{55} and C_{44} denote the fast and slow dipole shear moduli, respectively. Similarly, the minimum horizontal stress σ_h magnitude as a function of depth from the following equation

$$\sigma_h = \sigma_V - \frac{(C_{55} - C_{66})}{A_E}. \qquad (8)$$

Hence, we can estimate formation horizontal stress magnitudes as a function of depth in terms of the three shear moduli C_{44}, C_{55}, and C_{66}, and the acoustoelastic coefficient A_E. Effective stresses are converted into total stresses by adding pore pressure weighted by the Biot coefficient α (Nur and Byerlee, 1971).

Analysis of Field Data I: 3D-Anisotropy Results

The 3D-Anisotropy algorithm yields up to 4 elastic moduli of an orthorhombic formation using borehole sonic data from a vertical or deviated well as shown in Figure 1b. When we assume a layer-cake model of the formation characterized by a transversely-isotropic (TI) anisotropy, the algorithm outputs C_{44}, C_{66}, N, and C_{33}* as shown in Figure 3.
Figure 3 shows a standard output of 3D-anisotropy algorithm that shows the shear moduli C_{44} and C_{66} referred to a TI-anisotropy axes. When $C_{66} < C_{44}$, the Thomsen parameter gamma is negative in a sand interval, it is an indicator of higher fluid mobility. In contrast, when $C_{66} > C_{44}$, the corresponding interval is characterized by higher clay content typical of a shale interval.

Figure 4 shows a composite log of gamma-ray, caliper, lithology, porosity, density, and a sub-set of TI anisotropic moduli in a vertical exploratory well A. The first track shows gamma-ray (green), neutron porosity (blue), and density (red), with gray shading denoting shaly intervals and yellow shading showing sandy intervals. The second track shows the measured compressional (blue), fast-shear (red), and Stoneley (green) slownesses. The third track shows the vertical (C_{44}, red) and horizontal (C_{66}, green) shear moduli logs for a TI-medium. The fourth track displays measured dipole shear moduli C_{44} and C_{55}, and an equivalent C_{66}* derived from the Stoneley data, all shear moduli in this track are referred to the borehole axis. Smaller values of C_{66} relative to C_{44} in the third track are indicators of larger horizontal mobility than depths where C_{66} is close to or larger than C_{44}. Differences between C_{66} and C_{44} can provide a quick-look indicator of fluid mobility in a sand reservoir.

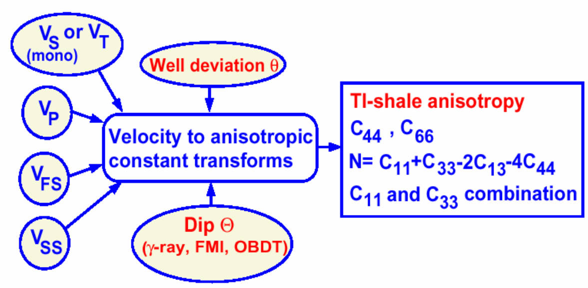

Figure 3: 3D-Anisotropy workflow: Compressional, fast-shear, slow-shear, and Stoneley slownesses together with well deviation and true stratigraphic dip are the input parameters that are transformed into the four TI-parameters of a shaly formation – c44, c66, N, and a combination of c11 and c33, referred to the earth anisotropic axes.

Analysis of Field Data II: Estimation of Shmax

Generally, the overburden stress is obtained by integrating the formation bulk density from the surface to the depth of interest. The minimum horizontal stress can also be reliably obtained using minifrac or extended leakoff tests at chosen depths. When we have estimates of the overburden stress, minimum horizontal stress, and pore pressure in a sand reservoir, the maximum horizontal stress can be calculated using equations (6) and (7). Note that while the shear moduli C_{44} and C_{55} are readily calculated from the low-frequency cross-dipole sonic data, the shear modulus C_{66} in the borehole cross-sectional plane must be

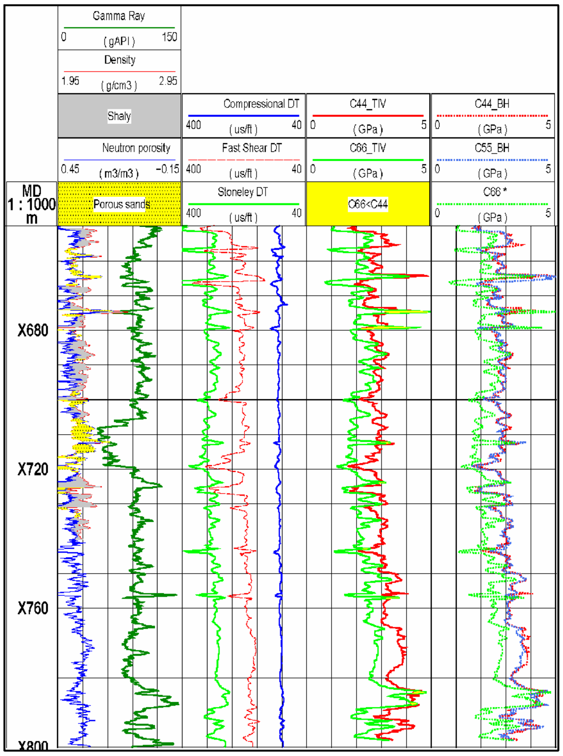

Figure 4: Processed logs showing gamma-ray, formation bulk density, and porosity in track 1; compressional, shear, and Stoneley slownesses in track 2; C44_TIV and C55_TIV referred to TI-axes in track 3; and C44, C55, C66* referred to the borehole axes in track 4 (Sinha et al., 2006b)

obtained from the Stoneley data and requires an accurate estimate of mud compressional slowness and compensation for the sonic tool structure, fluid mobility effects, and any possible near-wellbore alteration. Figure 5 displays an updated Mechanical Earth Model that includes the maximum horizontal stress magnitude (red circles) obtained using the three shear moduli together with the overburden (black circles), minimum horizontal (blue circles) stresses, and pore pressure (green circles) as a function of depth. Inverted stress magnitudes have been checked for consistency with wellbore stability predictions using the internal friction angle and UCS from core data and drilling events observed for mud weights used (Moos and Zoback, 1990).

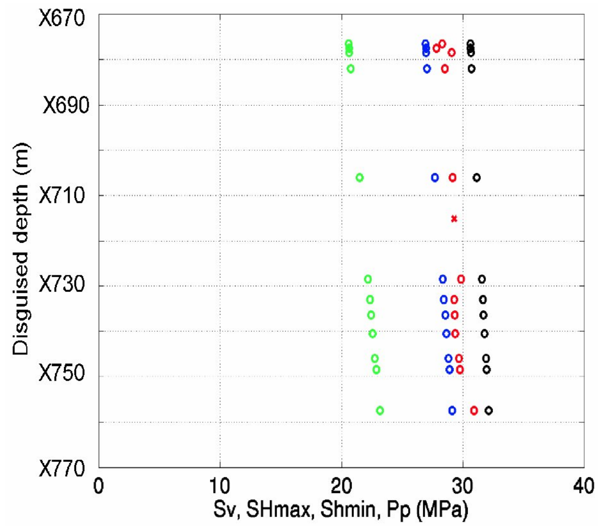

Figure 5. Updated Mechanical Earth Model for an exploration well: The black, red, blue, and green markers denote the overburden stress, maximum horizontal stress, minimum horizontal stress, and pore pressure, respectively.
(Sinha et al., 2006b)

Summary and conclusions

We have presented a brief overview of geophysical, geomechanical, and petrophysical applications of new answer products from the Sonic Scanner tool. In particular, we have described illustrative examples from the 3D-anisotropy and the SHmax magnitude estimation algorithms using sonic data from an exploration well in the North sea. Yet other applications include estimation of both the SHmax and Shmin magnitudes and in-situ rock strength using radial profiles of the three shear moduli (Bratton et al., 2004; Sinha et al., 2007).

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Acknowledgments

We acknowledge with thanks close collaboration and help from many Statoil and Schlumberger staff in the development and testing of these new applications of borehole sonic data.