Stress induced anisotropy in sandstone reservoir and shale overburden - AVO modeling

Miroslav Brajanovski, Curtin University of Technology, Dariush Nadri, CSIRO Petroleum, Boris Gurevich, and Andrej Bona, Curtin University of Technology,*

Summary

The influence of asymmetric horizontal stress on seismic signatures was investigated. We targeted the thin sandstone reservoir below the thick shale overburden. The presented data are based on the laboratory approach, as well as theoretical computations. Laboratory measurements were carried out on shale spherical samples from overburden under confining stress up to 400MPa, by means of ultrasonic soundings in 132 independent directions. Such an approach enables to determine 3D P-wave elastic anisotropy. From the measured velocities, the stiffness tensor was inverted, assuming VTI symmetry approximation. Since the sandstones were partly unconsolidated, it was not possible to take ultrasonic measurements, so we invented a method (algorithm) for stress induced anisotropy estimation using only cross-dipole logging data, which allows us to make HTI approximation in the presence of asymmetric horizontal stress. These two results give the possibility for anisotropic correction in AVO analysis.

Introduction

The unusual seismic wave anisotropy as a consequence of the special rock structure in the presence of anisotropic stress is the aim of this work. In order to explain this effect a new rock physics model was built.

The existing measured data show seismic characteristics in scale of tens of kilometers (surface seismic) down to the borehole logs in the scale of a meter. General structure of the whole basin consist of thin sandstone reservoirs, very purely consolidated, up to 20 meters and thick overburden made of shale, which is also anisotropic.

There are different causes of anisotropy at different scale, but most important one (having highest magnitude) is stress induced anisotropy, confirmed by cross-dipole shear wave measurements in boreholes. Anisotropy of shear waves goes up to 25% in sandstone reservoir and up to 2-3% in shale making overburden. Stress stratified packing of grains in sandstone can cause also anisotropy of permeability, which would be valuable information for making drilling decisions.

Anisotropy of shale was computed from the measured velocities on spherical samples from different depths assuming VTI symmetry approximation. Since the sandstone sample was impossible to make (too lossy), we invented a method (algorithm) to compute HTI anisotropy using cross-dipole sonic data only. This method is based on anisotropic Gassmann theory (Gurevich, 2003) and generalized idea of "plain of weakness" developed by Brajanovski (2004) and based on the fact that asymmetric lateral stresses may cause rock to fracture or to have a different "elastic grain contact quality" in different directions, with such deformations commonly aligned with the dominant horizontal stress direction. Azimuth of such a fractures or "planes of weaknesses" formed by contact voids depends on azimuth of dominant stress direction in horizontal plane. We use term "plane of weakness" rather than fracture because it describes softness of medium in general, independently is it made by tens of meters long fractures or hundreds of micrometers small contact voids, which can sum up to "plane" in the presence of external laterally anisotropic stress.

Anisotropy significantly affects AVO response, so knowing it we can do corrections in AVO analysis.

Experimental evidence of anisotropy

From marine data anisotropy of traveltimes was reported (stripes in Figure 1 (a), (b) and (c)) and estimated anisotropy of velocity was approximately 5%.

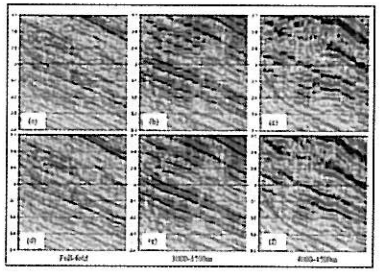

Figure 1: Marine data after Hung *et al.* (2006)

After application of the mentioned azimuthal anisotropy correction image is much better (Figure 1 (d), (e) and (f)).

Target reflector is the top of reservoir. From the fact that same stress field produces very different degree of shear wave anisotropy in sand and shale (Figure 2) we conclude that shale behaves to some extent as plastic material (no or low shear wave stress-induced anisotropy) for slow processes (isothermal deformation). This allows us to use VTI symmetry for elastic tensor representing shale overburden.

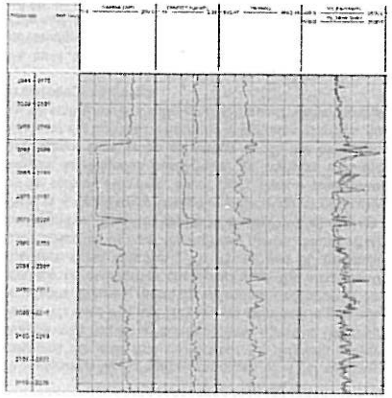

Figure 2: The fraction of cross-dipole well data showing huge shear wave anisotropy (the last column) in sand and small one in shale (above and below).

In order to invert elastic tensor of shale we use laboratory measurements carried out on the spherical samples. For this particular borehole (and huge number of others) measurements of core samples of sand cannot be done because rock is almost unconsolidated and it is impossible even to make sample. This is exactly one of the problems, which we have solved in this work.

Sample measurements and TI tensor estimation for shale

To prepare a spherical sample, a core sample was cut and polished to obtain a sphere with 50mm in diameter. The spherical sample has been placed in pressure chamber to measure the ultrasonic velocities in a broad range of confining pressures from ambient pressure up to 400MPa. Traveltimes were measured over the spherical sample at every 15 degrees in azimuthal and polar directions using the transducers at resonant frequency of 2MHz. This acquisition pattern produced 132 records of P-wave traveltimes, which were interpolated on the surface of the sphere (Figure 3). We measured three samples from same borehole and from depth range of 100m in order to get better representation of the overburden.

From P-wave traveltimes measured on the spherical shale sample at 40MPa (in situ stress) we find the symmetry axis. We transform the ray velocities from the measurement coordinate system to the symmetry axis coordinate system and then assuming TI symmetry, we estimated the elasticity tensor using the Simulating Annealing followed by quasi Newton algorithm (Nadri *et al.*, 2009).

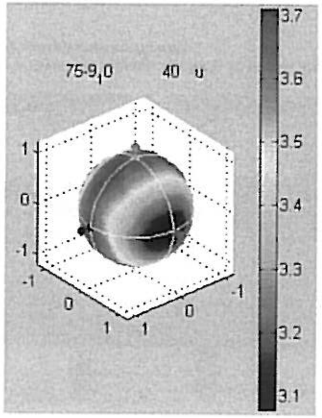

Figure 3: A measured and interpolated P-wave velocities [km/s] on the sphere of shale under confining pressure 40MPa. The red dot shows vertical (z) axis.

From Figure 3 we see 3-4% of relative velocity difference in bedding plane, which confirms anisotropy of traveltimes shown in Figure 1.

An additional interesting phenomenon can be seen from these measurements, i.e. amplitude response in bedding plane of shale depends much on the azimuth (Figure 4). This is surprising result but, on the other hand, it can be understood as a consequence of asymmetric horizontal stress. So, shear wave splitting induced by stress in shale is negligible but amplitude response (quality factor) dependency is certainly not. For full understanding of this phenomenon more complicated constitutive relation describing shale behavior would be needed and this result could be an inspiration in order to find it.

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Brajanovski, M., 2004, Effects of Fractures on Seismic Waves in Poroelastic Formations: PhD Thesis, Curtin University of Technology.

Brajanovski, M., B. Gurevich, and M. Schoenberg, 2005, A model for P-wave attenuation and dispersion in a porous medium permeated by aligned fractures: Geophys. J. Int., 163, 372–384, doi:10.1111/j.1365–246X.2005.02722.x

Gurevich, B., 2003, Elastic properties of saturated porous rocks with aligned fractures: Journal of Applied Geophysics, 54, 203-218.

Hung, B., F. M. Zhang, J. Sun, and M. Stanley, 2006, An Automated 3D Method for Azimuthal Anisotropy Analysis in Marine Seismic Data: EAGE 68th Conference & Exhibition — Vienna, Austria, 12 - 15 June 2006

Nadri, D., A. Bona, and M. Brajanovski, 2009, Estimation of elasticity tensor from the inversion of traveltimes in spherical shale samples: submitted to the CPS/SEG Beijing 2009 International Geophysical Conference & Exposition.

Rasolofosaon, P., 1998, Stress-Induced seismic anisotropy revisited: Revue De L'Institut Francais Du Petrole, 53, 5, 679-692.

Schoenberg, M., and J. Douma, 1988, Elastic-wave propagation in media with parallel fractures and aligned cracks: Geophys. Prospect., 36, 571–590.

Schoenberg, M., and J. Protázio, 1992, Zoeppritz rationalized and generalized to anisotropy: Journal of Seismic Exploration, 1, 125-144.