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

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Summary

The influence of anisotropic horizontal stress on seismic wave propagation was investigated. We targeted the thin sandstone reservoir below the thick shale overburden. The presented data are based on laboratory approach, as well as theoretical computations. Laboratory measurements were carried out on shale samples under confining stress up to 40MPa, by means of ultrasonic soundings in 137 independent directions. Such an approach enabled to determine 3D P-wave elastic anisotropy. From the measured velocities, the stiffness tensor was inferred, 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 anisotropy approximations in the presence of anisotropic horizontal stress. These two results give the possibility for anisotropy correction in AVO analysis.

Introduction

The unusual seismic wave anisotropy as a consequence of the special rock structure in the presence of anisotropic stresses 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 terms of tens of kilometers (surface seismic) down to the borehole level in the scale of a meter. General structure of the whole basin consist of thin sandstone reservoirs, very poorly consolidated, up to 20 meters and thick overburden muds 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 bore hole measurements in boreholes. Anisotropy of shear waves goes up to 20% in sandstone reservoir and up to 5-7% 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 polarized samples from different depths assuming VTI symmetry approximation. Since the sandstone sample was impossible to make (too soft), we invented a method (algorithm) to compute VTI anisotropy using cross-dipole sonic data only. This method is based on anisotropic Green’s function theory (Gareovich, 2001) and generalized idea of "planes of weakness" developed by Buljanowski (1984) and based on the fact that anisotropic horizontal stress may cause planes to form or to have a different "clastic grain contact quality" in different directions, with such deformations commonly aligned with the dominant horizontal stress direction. Anisotropy of such a fracture or "planes of weakness" formed by contact could depend on azimuth of dominant stress direction in horizontal plane. We use term "planes of weakness" rather than fracture because it describes stiffness of medium in general, independently if it is made by tens of meters long fracture or hundreds of micrometers small contact voids, which can sum up to "planes" in the presence of external, intensity anisotropic stress.

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

Experimental evidence of anisotropy

From marine data analysis of traveltimes was reported (in Figure 2 (a), (b) and (c)) and estimated anisotropy of velocity was approximately 2%

Figure 1: Marine data after Hung et al. (2000)

After application of the mentioned azimuthal anisotropy correction image is much better (Figure 2 (d), (e) and (f)).

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

From P-wave traveltimes measured on the spherical 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 TTI symmetry, we estimated the elastic tensor using the Simulating Anisotropic followed by quasi-Newton algorithm (Nadle et al., 2009).

Figure 3: A measured and interpreted P-wave velocity (km/s) on the sphere of shale under confining pressure 40MPa. The red dot shows vertex (c) axis.

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

As 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 anisotropic horizontal stress. So, dense wave-polarization 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.
Stress induced anisotropy in shale and sandstone


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