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Spectral Decomposition of Prestack Gathers: *FAVO (QVO) & FAVOAz*

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Summary

Fractured reservoirs always show anisotropic amplitude features. The study of seismic anisotropy provides a means to infer properties of fracture networks, such as the dominant orientation of fracture sets and fracture compliances. The reflection coefficient study has been extended to different models, which we analyze reflectivity variations on. In order to characterize the anisotropic amplitude variances on different offsets and azimuths, we derive approximated functions in both time and frequency domains. As different Thomsen-type anisotropic coefficients show different frequency dependence, we purpose to employ frequency domain based AVO and AVOAz inversion. (In the FAVO, attenuation has also been considered.) Commonly, spectral analysis of seismic signal is focused on post-stack data, with the development of seismic processing techniques and computer hardware, spectral analysis of pre-stack gathers becomes possible. Through pre-stack spectral analysis, we can develop new prestack attributes to measure rock properties.

Theory

Ruger (1998) proposed an approximate formula to describe the dependence of the amplitude of a reflection event on a shot-receiver azimuth and angles of incidence:

$$R_{pp}(i,\phi)=\frac{1}{2}\frac{\Delta Z}{\bar{Z}}+\frac{1}{2}\left\{\begin{matrix}\frac{\Delta\alpha}{\bar{\alpha}}-\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2\frac{\Delta G}{\bar{G}}+\\ \left[\Delta\delta^V+2\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2\Delta\gamma\right]\mathbf{cos}^2(\phi-\phi_{sym})\end{matrix}\right\}\mathbf{sin}^2 i \quad (1)$$

$$+\frac{1}{2}\left\{\begin{matrix}\frac{\Delta\alpha}{\bar{\alpha}}+\Delta\varepsilon^V\mathbf{cos}^4(\phi-\phi_{sym})+\\ \Delta\delta^V\mathbf{sin}^2(\phi-\phi_{sym})\mathbf{cos}^2(\phi-\phi_{sym})\end{matrix}\right\}\mathbf{sin}^2 i\,\mathbf{tan}^2 i+\cdots$$

where, $\Delta\varepsilon^V,\Delta\delta^V,\Delta\gamma$ denote the Thomsen parameters; α, β are P-wave and S-wave velocity; ϕ is acquisition azimuth of the survey line; ϕ_{sym} is the fracture direction; i denotes the incidence angle (Figure 1); $Z=\rho\alpha$ is the vertical p-wave impedance; and $G=\rho\beta^2$ denotes the vertical shear modulus.

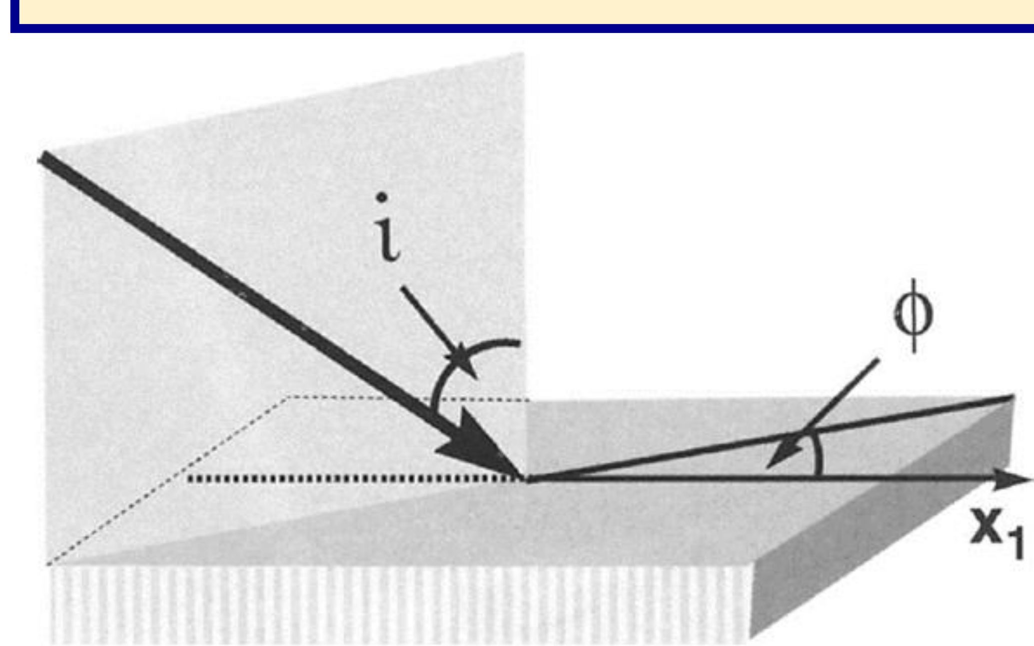

Figure 1: The angle between the incident wave and vertical i . The azimuthal angle ϕ is defined with respect to the symmetry axis pointing in the X1 direction.

When the incidence angle is not large, $\mathbf{sin^2 i tan^2 i}$ is relatively small, the third term in Eq (1) can be neglected. Then, Eq (1) can be given by:

$$R_{pp}(i,\phi)=A+\left[B^{iso}+B^{ani}\mathbf{cos}^2(\phi-\phi_{sym})\right]\mathbf{sin}^2 i \quad (2)$$

where, $A=\frac{1}{2}\frac{\Delta Z}{\bar{Z}}$, $B^{iso}=\frac{1}{2}\left[\frac{\Delta\alpha}{\bar{\alpha}}-\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2\frac{\Delta G}{\bar{G}}\right]$, $B^{ani}=\frac{1}{2}\left[\Delta\delta^V+2\left(\frac{2\bar{\beta}}{\bar{\alpha}}\right)^2\Delta\gamma\right]$.

A represents reflection coefficient of vertical incident wave; B^{iso} is the isotropic term in reflection coefficient gradient which is azimuthally invariant; B^{ani} represents the anisotropic term in reflection coefficient gradient and is also the fracture density to be inverted.

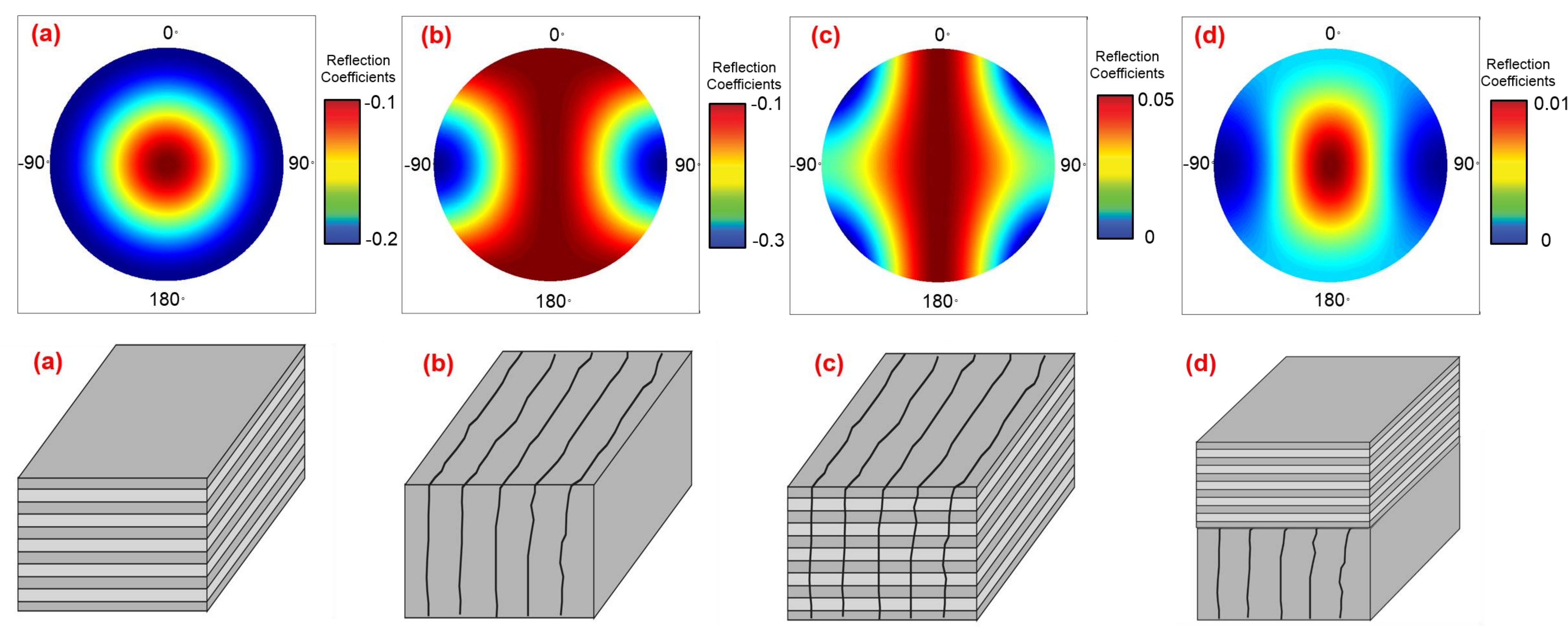

Figure 2: Synthetic seismic P-wave reflection coefficients for: (a) VTI anisotropy due to horizontal layering/fabric; (b) HTI anisotropy due to aligned vertical fractures, (c) orthorhombic anisotropy due to vertical fractures in a horizontally layered medium, and (d) VTI medium overlaying on HTI medium. The radius is the incidence angle, and the azimuth values are also denoted. The fracture strike directions are 0.

FAVO & QVO

Sometimes, we don't have the wide azimuth data, and the only prestack information is offset, then Eq (2) becomes:

$$R_{pp}(i)=A+B\,\mathbf{sin}^2 i\ , \quad (3)$$

which is the well known AVO expression.

For a CMP gather, suppose AVO effect is not relevant to frequency.

$$S(i,f)=Z(0,f)\left(A+B\,\mathbf{sin}^2 i\right), \quad (4)$$

where, S(i,f) is the time-frequency distribution of the i offset trace, and Z(0,f) is the time-frequency distribution of the zero-offset trace.

Consider the attenuation effect, Eq (4) becomes to

$$S(i,t,f)=Z(0,f)\left(A+B\,\mathbf{sin}^2 i\right)\mathbf{exp}\left(-\frac{\pi f}{Q}\Delta t\right) \quad (5)$$

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When we have azimuth and offset, we can run frequency domain offset and azimuth joint inversion.

First, substitute Eq (2) with D1, D2, D3 and D4:

$$R_{pp}(i,\phi)\approx D_1+D_2\,\mathbf{sin}^2 i+D_3\,\mathbf{cos}(2\phi)\mathbf{sin}^2 i+D_4\,\mathbf{sin}(2\phi)\mathbf{sin}^2 i$$

$$A=D_1$$

$$B^{ani}=\pm 2\sqrt{D_3^2+D_4^2}$$

$$B^{iso}=D_2-\frac{B^{ani}}{2}$$

$$\phi_{sym}=\frac{1}{2}\mathbf{arctan}\frac{D_4}{D_3}$$

Then, we assume A and B are relevant to frequency

$$R_{pp}(i,\phi,f)\approx D_1(f)+D_2(f)\mathbf{sin}^2 i+D_3(f)\mathbf{cos}(2\phi)\mathbf{sin}^2 i+D_4(f)\mathbf{sin}(2\phi)\mathbf{sin}^2 i$$

First-order Taylor series at a reference frequency:

$$R_{pp}(i,\phi,f)-R_{pp}(i,\phi,f_0)\approx(f-f_0)\frac{\partial D_1(f)}{\partial f}+(f-f_0)\frac{\partial D_2(f)}{\partial f}\mathbf{sin}^2 i+(f-f_0)\frac{\partial D_3(f)}{\partial f}\mathbf{cos}(2\phi)\mathbf{sin}^2 i+(f-f_0)\frac{\partial D_4(f)}{\partial f}\mathbf{sin}(2\phi)\mathbf{sin}^2 i$$

$$\frac{\partial A(f)}{\partial f}=\frac{\partial D_1(f)}{\partial f}$$

$$\frac{\partial B^{ani}(f)}{\partial f}=\frac{4\left(\frac{\partial D_3(f)}{\partial f}+\frac{\partial D_4(f)}{\partial f}\right)}{\pm\sqrt{D_3(f)^2+D_4(f)^2}}$$

$$\frac{\partial B^{iso}(f)}{\partial f}=\frac{\partial D_2(f)}{\partial f}-\frac{1}{2}\frac{\partial B^{ani}(f)}{\partial f}$$

$$\frac{\partial\phi_{sym}(f)}{\partial f}=\frac{\frac{\partial D_4(f)}{\partial f}D_3(f)-\frac{\partial D_3(f)}{\partial f}D_4(f)}{D_3(f)^2+D_4(f)^2}$$

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