Title
Using frequency-dependent siesmic attributes in imaging of a fractured reservoir zone

Authors
Goloshubin, Gennady
Silin, Dmitry

Publication Date
2005-04-27

Using frequency-dependent seismic attributes in imaging of a fractured reservoir zone

Gennady Goloshubin, University of Houston, and Dmitry Silin, University of California, Berkeley*

Summary

Normal reflection from a fractured reservoir is analyzed using frequency-dependent seismic attributes. Processing of 3D low-frequency seismic data from a West-Siberian reservoir produced an accurate delineation of the fractured hydrocarbon-bearing zones. P-wave propagation, reflection and transmission at an impermeable interface between elastic and dual-porosity poroelastic media is investigated. It is obtained that the reflection and transmission coefficients are functions of the frequency. At low frequencies, their frequency-dependent components are asymptotically proportional to the square root of the product of frequency reservoir fluid mobility and fluid density.

Introduction

There is sufficient evidence that at low frequencies, frequency-dependent analysis of 3D seismic data from hydrocarbon reservoirs produces images, which accurately delineate permeable gas- and oil-rich reservoir zones (Goloshubin et al., 1998, 2001, and 2002, Korneev et al., 2004ab). Such analysis was carried out for "conventional" single-porosity reservoirs where matrix permeability is the factor determining rock transport properties. In this work, such a frequency-dependent seismic analysis is successfully applied for imaging a fractured reservoir. This result is then illustrated with asymptotic analysis of the frequency-dependent reflection coefficient component.

Theories describing wave propagation in fluid-bearing porous media are usually derived from Biot's theory of poroelasticity (Biot 1956ab). In Silin *et al.* (2003) the frequency-dependent attenuation of signal propagating in fluid saturating double-porosity medium has been expressed in an analytical form, assuming that the solid skeleton is disturbed only through porosity variations. This result does not help to investigate the reflection of a seismic signal from a fluid bearing formation because it does not account appropriately for the fluid-rock interaction. More recently, Silin *et al.* (2005) have carried out an asymptotic analysis of the reflection coefficient in case of compression p-wave propagating through the interface between elastic and fluid-saturated poroelastic media with full account of rock-fluid interaction. In this work, a similar asymptotic analysis is carried out for reflection from a dual-porosity reservoir.

The attenuation of seismic waves in a dual porosity medium was intensely studied over past decades, see Pride and Berryman (2003ab) and the references therein. Less, if any, works were published with theoretical analysis of the reflection from a dual medium. In this study, the classical model of fractured reservoir developed in petroleum engineering literature (Barenblatt *et al.*, 1960, Warren and Root, 1963) is employed. According to this model, the porous medium can be presented as a superposition of two media. Both of them are presented in every representation elementary volume. One medium, fractures, supports the transport properties of the rock, whereas the other one, matrix, provides the volume where the fluid is stored. The matrix permeability is low relative to that of the fractures and the flow between matrix blocks can be carried out through the fractures only. This model assumes transient flow that is very appropriate for the situation under consideration. In steady-state flow, dual permeability and single permeability models of porous media are equivalent. We extend this model by accounting for the effects resulting from simultaneous motion of the fluid and the rock.

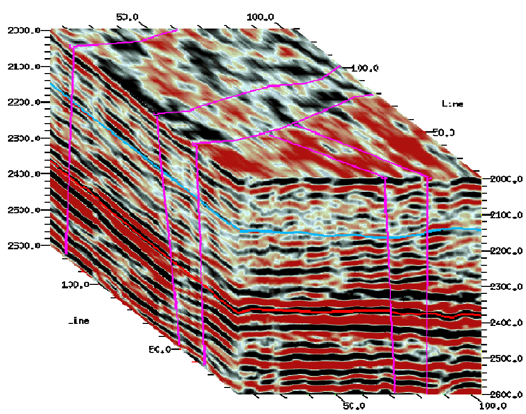
Field example

Our experience indicates that dual-permeability fluid-saturated media strongly reflect low-frequency seismic energy and can produce reflection signal, which is noticeable dependent on the frequency. This frequency-dependence phenomenon was, in particular, detected in 2D and 3D seismic data from a hydrocarbon field in Western Siberia.

Here is an example of frequency-dependent seismic imaging of the oil-saturated reservoir. A 3D seismic and well data set was used to investigate frequency-dependent effects from the reservoir zone. The 3D seismic data were recorded using conventional acquisition technology. The frequency-dependent processing and interpretation were carried out to get frequency-dependent images, in particular, in low-frequency domain. There were several important aspects of the processing: a) the relative amplitudes of the seismic data were preserved throughout the entire procedure; b) the processing retained the broadest possible signal band in the data, preserving the low-frequency domain of the spectrum. Frequency decomposition technique was used for frequency-dependent imaging of the reservoir zone. Fig.1a illustrates the result. Frequency-dependent attribute maps along with the reservoir surface are presented in Fig.1b and Fig.1c, respectively.

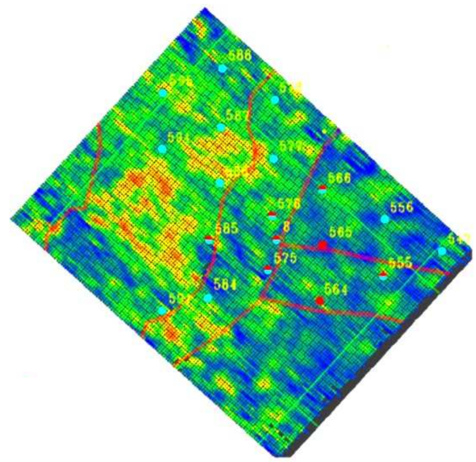
The data from the well logs indicate that the reservoir is 10-12 m thick, consist of sandstone, and is 3 km deep. The reservoir rock porosity varies between 0.16 and 0.18 and the permeability does not exceed 100 milli-Darcy. The produced fluid composition and production rates vary from well to well. Core analysis shows that the clay content within the pore space increases with depth. Clay content has a strong impact on the reservoir transport and mechanical properties. High-porosity and high-permeability material is distributed close to crest of the structure.

Analysis of seismic data suggests that the wells with the highest oil production rate are located close to the fault zones. This observation implies that fractures resulting from faulting may contribute significantly to the permeability of the reservoir. The first map resulting from seismic imaging (Fig.1b) shows variation of the amplitude of the target reflected wave at high frequency (50 Hz). There is a link between the amplitude anomalies and clay content, since the presence of clay modifies the impedance contrast. The wells with the highest oil production rate (red circles) are located near the zones of the high deviation of the map of the first derivative with respect to the frequency obtained at low frequency (10 Hz). It is clear that frequency decomposition and frequency-dependent analysis at low frequency domain enhances detection of the hydrocarbons and provides information about reservoir properties.

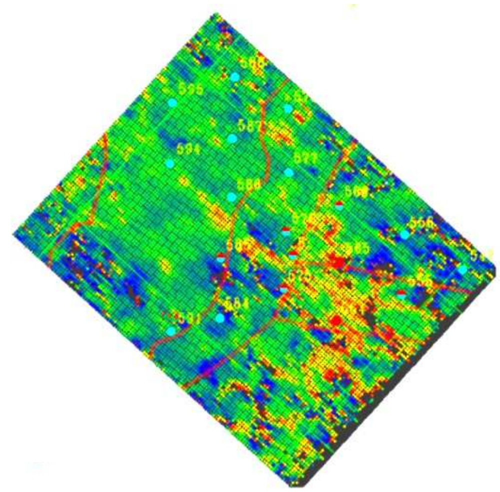


1a

Figure 1. 3D seismic data (a) are used for reservoir imaging. The map (b) presents the result of the high frequency (50 Hz) amplitude image. The map (c) shows the image of the first derivative over frequency at low frequency (10 Hz). Both (b) and (c) images are done along reservoir surface. Red lines indicate faults and red circles show the positions of the wells with relatively high oil production rate. Amplitude anomalies at high frequency are connected with clay content within reservoir pore space. Anomalies of low-frequency image indicate oil-saturated reservoir zone with high permeability.



1b



1c

Reflection coefficient asymptotic investigation

Here, we only briefly overview the obtained asymptotic expression which provide a tool for frequency-dependent seismic analysis. A more detailed report will be published elsewhere.

Consider a seismic p-wave of frequency ω arriving at an impermeable interface between fractured reservoir and the overlying formation at a normal direction. We assume that both media are homogeneous. Let the displacement associated with the incident wave be defined by $u_1 = U_1 e^{i(\omega t - kx)}$, where x is the coordinate in the direction of wave propagation. Inside the reservoir, the signal is transmitted as the sum of two waves

$u_2 = U_2^s e^{i(\omega t - k_s x)} + U_2^f e^{i(\omega t - k_f x)}$, the slow and the fast one. The superscripts *s* and *f* stand, respectively, for the slow and fast waves. In the liquid, a pressure wave also propagates in the form of the sum of two waves $p = p_2^s e^{i(\omega t - k_s x)} + p_2^f e^{i(\omega t - k_f x)}$, so does the Darcy velocity wave $W = W_2^s e^{i(\omega t - k_s x)} + W_2^f e^{i(\omega t - k_f x)}$. In fact, two slow and two fast pressure waves propagate in the fluid: one in the system of fractures, and the other one in the matrix blocks. The difference between matrix and fractures pressures determines the rate of fluid exchange between the media. At the interface, no-flux condition is imposed. Mass and momentum conservation laws result in three equations

$$u_1\big|_{x=0} = u_2\big|_{x=0}$$

$$-\frac{1}{\beta_1}\frac{\partial u_1}{\partial x}\bigg|_{x=0} = -\frac{1}{\beta_2}\frac{\partial u_2}{\partial x}\bigg|_{x=0} + \phi_m p_m\big|_{x=0}$$

$$W\big|_{x=0} = 0$$

Here, x=0 is the coordinate of the interface, ϕ_m is matrix porosity, p_m is the matrix fluid pressure, and coefficients β_1 and β_2 characterize the compressibility of the rock without fluid pressure influence. The relationship of these coefficients to the Biot-Willis moduli is discussed in Silin *et al*. (2005).

In the above formulae, both, k_s and k_f, are complex wave numbers whose imaginary parts define the respective attenuation coefficients. Complex velocities $v_s=\omega/k_s$ and $v_f=\omega/k_f$ are related, although not immediately, to the actual phase velocities. It turns out that the complex velocity of the slow wave is asymptotically proportional to the square root of ω, whereas v_f has a finite limit at $\omega\to 0$. More specifically,

$$v_{slow} = v_1^{slow}\sqrt{\varepsilon} + O(\varepsilon)$$

Where

$$\varepsilon = i\frac{\rho_f \kappa \omega}{\eta}$$

is a dimensionless parameter, κ is the permeability of the system of fractures, ρ_f is the density of the fluid, and η is fluid viscosity. It has been demonstrated in Silin *et al.* (2005) that ε is a small number if the permeability is of the order of 1 Darcy and the frequency does not exceed 1 kHz. A similar asymptotic scaling holds for the real slow-wave phase velocity as well. Consequently, the slow-wave wave length is scaled at low frequencies as $1/\sqrt{\omega}$.

The coefficient v_1^{slow} is a real parameter depending on the mechanical properties of the medium

$$v_1^{slow} = \sqrt{\frac{1}{\beta\rho_f}\cdot\frac{1}{1+\phi_m\rho_f/\rho_b}}$$

where ρ_b is the bulk density of the fluid-saturated medium.

The obtained asymptotic solution leads to an asymptotic formula for the reflection coefficient

$$R = R_0 + R_1\sqrt{\varepsilon} + O(\varepsilon)$$

Here R_0 and R_1 are parameters independent of the frequency of the signal and fluid mobility. The last equation has a form similar to the one obtained in Silin *et al.* (2005) for reflection from a conventional porous medium. It is interesting to note that in Silin *et al.* (2005), the asymptotic coefficients implicitly involve the permeability coefficient because porosity and permeability are usually related (Nelson, 1994). In the dual rock model, the porosity of the system of fractures is negligibly small and only the matrix porosity is involved in the formulae. Therefore, the rock permeability is entirely decoupled from the mechanical parameters. Also, in conventional media, it is naturally to define the small parameter ε through the bulk density of fluid-saturated medium, whereas in the fractured medium bulk porosity is replaced with the density of the fluid.

Note that the independent of the frequency component of reflection, R_0, is independent of the fluid viscosity and reservoir permeability, but still involves fluid density and compressibility. Since two waves are generated in the reservoir, there are two transmission coefficients. It is interesting to note that the first-order asymptotic approximations of the fast-wave transmission coefficient and reflection coefficient are equal. The asymptotic formula for the slow-wave transmission coefficient starts with terms linear in ε. The asymptotic coefficients are real number, whereas ε is a complex number. Therefore, both transmission and reflection generate a phase shift relative to the incident signal.

Conclusions

Frequency-dependent seismic data processing has been successfully applied for 3D imaging of a fractured reservoir zone. Anomalies of low-frequency (of the order of 10 Hz) image indicate oil-saturated reservoir zones with high permeability. Amplitude anomalies at high frequencies (of the order of 50 Hz) are associated with high clay content in the rock.

The results of data processing that low-frequency reflection anomalies are related to high attenuation due to friction caused by fluid flow, rather than classical seismic imaging effects, like tuning. A model of elastic wave propagation at the interface between elastic and fluid-saturated fractured porous media shows that the frequency-dependent component of the reflection coefficient is asymptotically proportional to the square root of the frequency of the signal multiplied by the fluid mobility in the system of fractures. The fractured porous rock is modeled within the classical approach proposed by Barenblatt et al. (1960). It turns out, that matrix contributes to the obtained asymptotic expression only through the variations in porosity caused by solid deformation and resulting in fluid cross-flow between the matrix blocks through the connected system of fractures. In low-frequency asymptotic expression of the reflection coefficient from a fractured reservoir, the transport properties of the rock are entirely decoupled from the mechanical properties. This property distinguishes a dual porosity medium from a conventional rock.

References

Barenblatt, G.I., Zheltov, I.P., and Kochina, I.N., 1960, Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks: Journal of Applied Mathematics, v. 24, 1286-1303.

Biot, M.A., 1956a, Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range: Journal of the Acoustical Society of America, v. 28, 168-178.

Biot, M.A., 1956b, Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range: Journal of the Acoustical Society of America, v. 28, 179-191.

Goloshubin, G. M., and Bakulin, A.V., Seismic reflectivity of a thin porous fluid-saturated layer versus frequency, 68th SEG Meeting (New Orleans, LA), 1998, pp. 976–979.

Goloshubin, G. M., Daley, T. M., and Korneev, V. A., 2001, Seismic low-frequency effects in gas reservoir monitoring VSP data, 71st SEG Meeting (San Antonio, TX).

Goloshubin, G. M., and Korneev, V. A., 2000, Seismic low-frequency effects from fluidsaturated reservoir, 70th SEG Meeting (Calgary).

Goloshubin, G. M., Korneev, V. A., and Vingalov, V. M., 2002, Seismic low-frequency effects from oil-saturated reservoir zones, 72nd SEG Meeting (Salt Lake City, Utah).

Hubbert, M.K., 1956, Darcy's law and the field equations of the flow of underground fluids: Transactions AIME, v. 207, 222-239.

Korneev V.A., Goloshubin G.M., Daley T.M., Silin D.B., 2004a, Seismic low-frequency effects in monitoring fluid-saturated reservoirs. Geophysics. 69(2):522-532.

Korneev, V. A., Silin, D. B., Goloshubin, G. M., and Vingalov, V. M., 2004b, Seismic imaging of oil production rate, 74th SEG Meeting (Denver, CO).

Mandelis, A., 2001, Diffusion waves and their uses: Physics Today, v. 54, 29-34.

Nelson, Philip H. 1994, Permeability-porosity relationships in sedimentary rocks, The Log Analyst 35, no. 3, 38–62.

Pride, S. R. and Berryman, J. G., 2003a, Linear dynamics of double-porosity and dual-permeability materials. I. Governing equations and acoustic attenuation: Physical review. E v. 68, 036603-1-10.

Pride, S. R. and Berryman, J. G., 2003b, Linear dynamics of double-porosity and dual-permeability materials. II. Fluid transport equations: Physical review. E v. 68, 036604-1-10.

Silin, D. B., Korneev, V. A., and Goloshubin, G. M., 2003, Pressure diffusion waves in porous media, 73rd SEG Meeting (Dallas, TX).

Silin, D. B., Korneev, V. A., Goloshubin, G. M., and Patzek, T. W., 2005, Low-frequency asymptotic analysis of seismic reflection from a fluid-saturated medium: Transport in Porous Media, to appear

Warren J. E., and Root P. J., 1963, The behavior of naturally fractured reservoirs, SPEJ, 245–255.

Acknowledgements

This work has been performed at the University of Houston and University of California, Berkeley and Lawrence Berkeley National Laboratory under Grant No. DE-FC26-04NT15503, U.S. Department of Energy. The authors are thankful to Sibneft for providing field data and would like to thanks to Igor Kosirev and Alexey Nezhdanov for the help in raw data interpretation.