Seismic low-frequency effects from oil-saturated reservoir zones

Gennady M. Goloshubin, ZapSibNIIGG, Tyumen, Russia, and AMROS Inc., Houston, Texas;
Valeri A. Korneev, Lawrence Berkeley National Laboratory, Berkeley, California;
Vjacheslav M. Vingalov, ZapSibNIIGG, Tyumen, Russia.

Summary

We consider the frequency dependence of seismic reflections from a thin (compared to the dominant wavelength), fluid-saturated reservoir for the cases of oil and water saturation. Reflections from a thin, water or oil -saturated layer have increased amplitude and delayed travel time at low frequencies if compared with reflections from a gas-saturated layer. This effect was observed for both ultrasonic lab data and seismic field data. One set of field data revealed high correlation of low frequency processed image for two different production horizons represented by fractured shale and sandstone. Another set was processed for the purpose of contouring of oil/water contact, and reveal very good correlation with available well data. The frequency dependent amplitude and phase reflection properties can be used for detecting and monitoring thin liquid saturated layers.

Theory

Consideration of reflection properties of an elastic layer, which is placed between two elastic half-spaces with the same material properties is especially simple for normal incidence of a plane wave. In this case the total reflection wave field consists of an infinite series of multiples with decaying amplitudes. If the duration of the incident seismic signal is less than the time interval between multiples then all these multiples are resolved and can be recorded separately. With increase of the incident signal duration, multiples interfere and the resulting signal becomes frequency dependent. Such frequency dependence due to interference of multiples is known as tuning. At low frequencies all multiples cancel each other, the reflection coefficient approaches zero, and the layer becomes invisible for seismic waves. The cancellation occurs due to the different sign (i.e. polarity) of reflections from the top and the bottom of the layer. If the reflections have the same sign, the correspondent reflection coefficient approaches a constant value for the reflection between two contacting half-spaces in the low frequency limit. Tuning, expressed as a frequency dependence of a reflection coefficient, does not explain the observed increased amplitude in low-frequency reflections for the water-saturated case as compared to the dry case. To explain this result we use a frictional attenuation mechanism described in Goloshubin and Korneev (2000, 2001), which is consistent with the observed frequency dependence of Q, when Q approaches zero at low frequencies. Strong attenuation in the layer affects summation of multiples and they do not cancel out completely. Our theoretical formulation with frictional loss term matches the physical model data reasonably well.

Physical modeling

A set of laboratory ultra-sonic experiments was conducted to investigate the differences of reflections from dry-, water- and oil-saturated layers. The investigation was done in such a way that the wave propagation in the laboratory model approximated wave propagation in standard practice. The scaling factor was set to 1:1000, i.e. 1 mm in the model corresponded to 1 m in the field and 1 kHz in the modeling experiment corresponded to a field frequency of 1 Hz. Plexiglas was used as a homogeneous constant-velocity background medium. The porous layer was made of artificial sandstone with cemented sand and clay grains, and was hermetically sealed to allow its saturation by different fluid. . The layer was $h =$ 7 mm thick and had 0.32 porosity and about 300 mDarcy permeability. The velocities and densities of the used materials were: Vp=1700 m/s, Vs=1025 m/s, ρ=1800 kg/m^3 (dry layer); Vp=2100 m/s, Vs=1250 m/s, ρ=2500 kg/m^3 (water-saturated layer); and Vp=2300 m/s, Vs=1340 m/s, ρ=1200 kg/m^3 (plexiglas). To prevent an increased lateral boundary flow, sand was previously glued to the surfaces of contact. The sandstone was not vacuumed and therefore some (up to 10%) residual moisture was present for the dry case, and correspondingly some small amount of trapped air was present in the material in the liquid-saturated case. This allows a more realistic partially saturated case, which seems closer to the conditions of real rocks. The physical modeling data were recorded using common offset gather observation system shown on Fig.1 for both water and oil saturation. The offset was much smaller than depth of the layer and reflection angle was practically equal to zero. A significant difference is seen between the seismic response of the porous layer dry zone, water-saturated zone, and oil-saturated zone. The very low frequency "bright spot" with phase shift is associated with oil saturation.

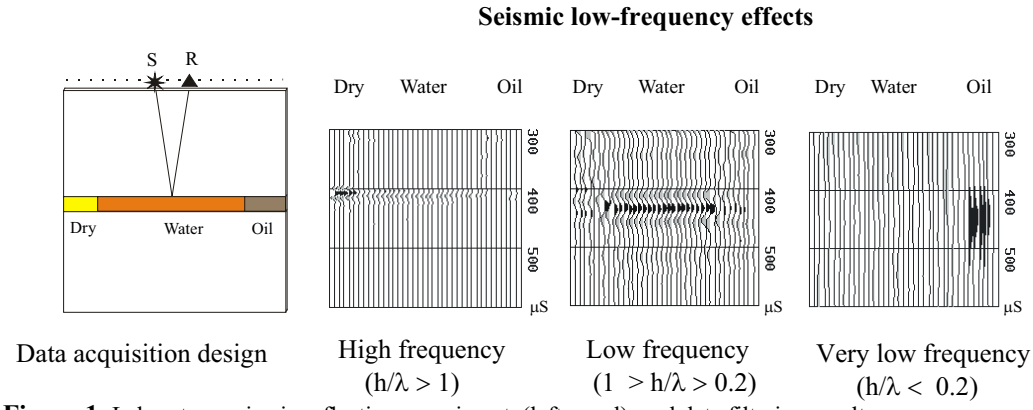


Figure 1. Laboratory seismic reflection experiment (left panel), and data filtering results.

Field data

We used 2D seismic data to investigate the low-frequency effects from oil-saturated reservoir zones. The seismic data were recorded using conventional acquisition technology with 10 Hz receivers. The frequency-dependent processing was done to get low frequency images of the reservoirs. There were 3 important aspects of the processing: a) the relative amplitudes of the seismic data were preserved throughout the processing; b) the processing retained the broadest possible signal band in the data with preserved low frequency domain of the spectrum; c) the wavelet transforms were used for frequency dependent velocity analysis and imaging. Figures below illustrate the results of frequency dependent processing of the experimental data. The data were recorded in oil fields of Western Siberia. The seismic and log data for processing and interpretation are courtesy Surgutneftegas Oil Company. A seismic line from Ay-Pim oil field was used to image two different types of oil-saturated reservoirs (Fig.2). The well data indicate that the upper reservoir AC11 consist of an 11-15 m thick sandstone with varying fluid content. The lower reservoir Ju0 is represented by 15-20 m thick fractured shale. As we can see in the Fig.3 the oil-saturated domains of the both sandstone reservoir AC11 and fractured shale reservoir Ju0 create low-frequency (<15 Hz), high amplitude effects (red) for reflected seismic energy. Next example shows the Frequency-Dependent Processing and Interpretation (FDPI) capability to map oil-water contact using low-frequency part of seismic data. Presented Fig.4 is result of FDPI at low frequencies. The map includes the seismic low frequency reflectivity at 12 Hz relatively to reflectivity at 40 Hz centered frequency, predicted oil-water contact, and location of calibration wells and wells used for testing purposes.

Discussion

Amplitude and phase reflection properties can be used for detecting and monitoring oil, water and gas saturation changes in underground reservoirs. While in the purely elastic case all multiple reflections tend to cancel each other at low frequencies, the friction attenuation mechanism changes the cancellation balance and observation of reflections from very thin layers becomes possible. The reflection amplitude effect is also complimented by an increasing phase delay of the reflected phase. In the presented field examples standard data processing did not reveal any significant changes for fluid saturated reservoir, while the changes in reflectivity are substantial at low frequencies. The observed increase in amplitude and travel-time delay as frequency decreases is in agreement with theoretical predictions and laboratory studies. In both the laboratory and field data, the observed effects can be attributed to the target reservoir horizon and are not present on other parts of seismic record. These findings are especially important since there was no significant change found in the full frequency content of seismic reflections from the fluid reservoir. This low-frequency reflection variation can be a useful indicator of thin liquid-saturated layers. Attenuation for such layers strongly depends on liquid saturation. Layers with higher attenuation create travel time delays, which increase as frequency approaches zero. This property was observed in field data and can serve as an additional indication of liquid saturation in porous layers. The difference between dry, water and oil saturated layer reflectivities are clearly seen using imaging of common offset gathers at high and low frequencies in physical experiment. Physical interpretation of the frictional dissipation term remains uncertain. We can speculate that high compressibility, and, correspondently, relatively high deformation of granulated porous or fractured media leads to strong mechanical friction between rock composing elements because most of the deformation is caused by a change in the relative position of adjacent elements rather than by deformations within the elements themselves. The presence of wetting fluid in contact areas increases friction because energy is being spent on deformation of fluid droplets. This additional energy loss increases as viscosity of the fluid increases. The attenuation mechanism in fluid saturated materials should be further investigated at all practical frequencies to find its relation to micro scale parameters.

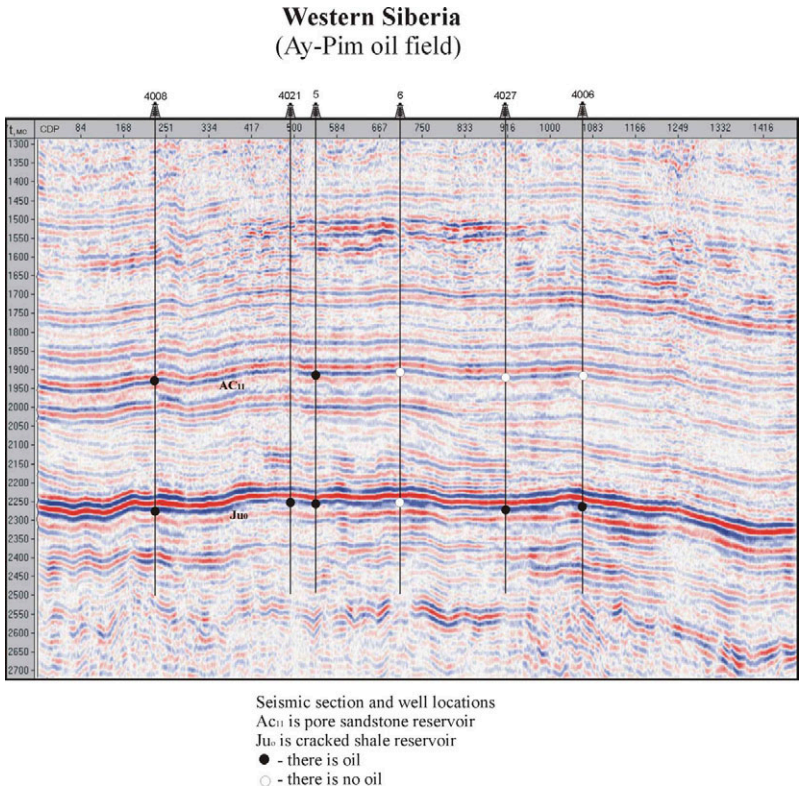


Figure 2 Standard processed seismic sections for West-Siberian oil field showing well locations.

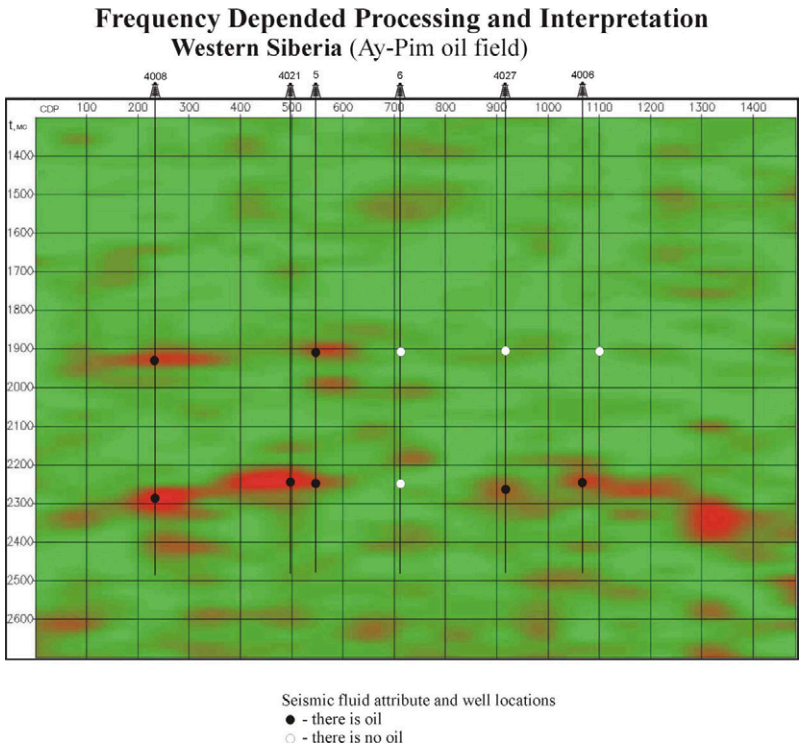
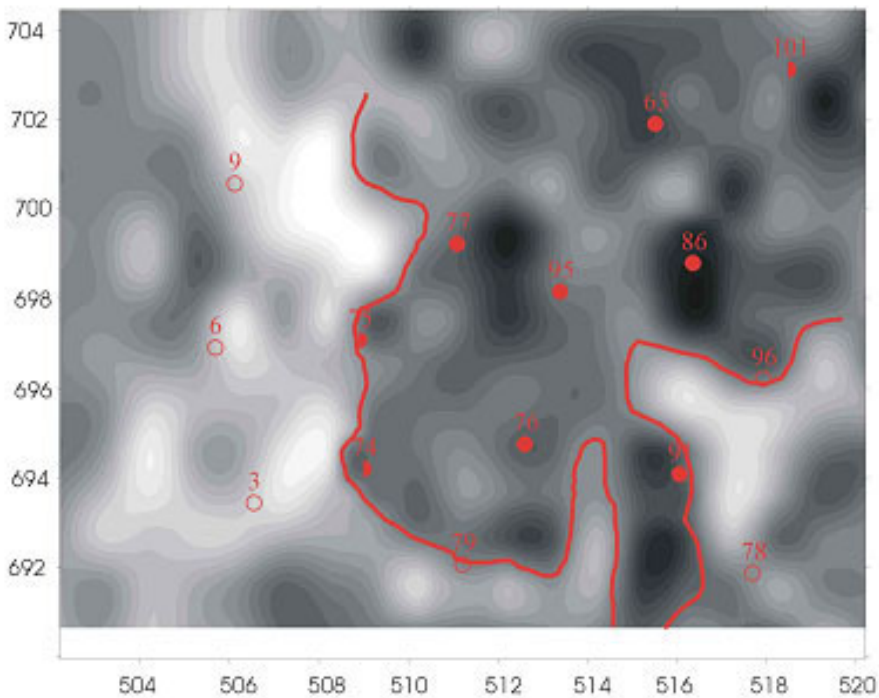


Figure 3 Similar to Figure 2, this time using low-frequency processed reflection data;



Map of seismic fluid attribute for Ju₁ and predicted oil-water contact

- oil-water contact
- water
- oil
- water & oil

Figure 4 Low-frequency reflective image mapping of a water-oil contact boundary and well content. Wells # 9, 76, 91, 95 were used for seismic fluid attribute calibration. Information for wells # 3, 5, 63, 74, 75, 77, 78, 79, 86, 96, 101 was disclosed after processing and interpretation.

References

[1] G.M.Goloshubin, T.M.Daley, and V.A.Korneev, 2001, Seismic low-frequency effects in gas reservoir monitoring VSP data: Expanded Abstracts, SEG Meeting, San Antonio.
[2] G.M.Goloshubin, and V.A.Korneev, 2000, Seismic low-frequency effects from fluid-saturated reservoir: Expanded Abstract, SEG Meeting, Calgary.

Acknowledgments

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