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Research on seismic fluid identification driven by rock physics

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Seismic fluid identification works as an effective approach to characterize the fluid feature and distribution of the reservoir underground with seismic data. Rock physics which builds bridge between the elastic parameters and reservoir parameters sets the foundation of seismic fluid identification, which is also a hot topic on the study of quantitative characterization of oil/gas reservoirs. Study on seismic fluid identification driven by rock physics has proved to be rewarding in recognizing the fluid feature and distributed regularity of the oil/gas reservoirs. This paper summarizes the key scientific problems immersed in seismic fluid identification, and emphatically reviews the main progress of seismic fluid identification driven by rock physics domestic and overseas, as well as discusses the opportunities, challenges and future research direction related to seismic fluid identification. Theoretical study and practical application indicate that we should incorporate rock physics, numerical simulation, seismic data processing and seismic inversion together to enhance the precision of seismic fluid identification.

fluid identification, rock physics, seismic inversion, fluid factor

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Seismic fluid identification is defined as identifying and describing the fluid characteristics of oil/gas reservoirs utilizing seismic data incorporating rock physics. It is one of the hot and difficult problems on the study of exploration geophysics as its particularity of research object, complexity of underground buried conditions and multiplicity of corresponding geophysical characteristics. Seismic fluid identification driven by rock physics mainly comprises of two parts. On the one hand, to characterize abnormal features related to the fluid characterization as fluid factor guided by rock physics theory or establish the quantitative relationship between fluid type and elastic parameters of reservoir with rock physics relationships. On the other hand, to implement the estimation of fluid factor and fluid type with seismic amplitude, frequency, phase variation with offsets or incident angles.

Seismic fluid identification starts from 1970s. The potential value of fluid identification with seismic data directly leads to the significant reform of seismic processing and interpretation technology, where the digitization of seismic technology is considered as the main power for the reform. The digitization of seismic technology makes it possible to maintain true amplitude or relative amplitude from seismic data acquisition to interpretation. The “bright spot” technology detecting gas-bearing layers with strong reflection amplitude higher than amplitude around attracted more attention. Later on, hydrocarbon indication methods such as “dark spot”, “phase reversal” and “flat spot” were further developed (Backus et al., 1975; Hilterman, 2001). However, the limitation and multiple interpretations of the “bright spot” technology inspired the emergence of AVO (Amplitude variation with offset) technology. Ostrander (1982) initially proposed a technology utilizing the variation of reflection coefficients with the incident angle to identify the “bright spot” type of gas-bearing sandstone, which marks

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the emergence of fluid identification with AVO technique. Ruthorford et al. (1989) divided the AVO response of gas-bearing sandstone into three categories and Castagna et al. (1998) divided it into four categories, which laid the foundation for AVO analysis. Later based on AVO analysis technique, the hydrocarbon detection method based on the cross plot with AVO intercept and gradient and AVO hydrocarbon detection factor method were further developed and so on. At present, the AVO analysis technology still works as one of mainstream methods of seismic fluid identification. "Bright spot" and AVO attribute analysis technology have made promising achievements in practical production, however, the current concealed-type lithological and unconventional tight reservoirs have brought more challenge for seismic fluid identification (Yin et al., 2008; Zong et al., 2012b; Yuan et al., 2013; Yin et al., 2014a). With the development of seismic inversion theory, especially the rise of rock physics theory, seismic fluid identification has become the mainstream direction of the research of the detection of oil/gas reservoirs (Zong et al., 2012a). Development of rock physics makes the transition of seismic fluid identification from "qualitative" description to "quantitative" prediction.

The form of existence, characteristics and distribution of fluid in the reservoirs has complex modification effect on seismic waves, which mainly effects the variation of kinematic or dynamic parameters of seismic wave such as travel time, amplitude, frequency and phase. Fluid identification works as an important object for oil/gas prospectors. In order to obtain reliably distribution of reservoir fluid and implement quantitative prediction of reservoir fluid, we need to understand the mechanism that how the form of existence, characteristic and its distribution characteristics of reservoir fluid modify seismic wave and develop geophysical theories and methods of seismic fluid identification. In this study, we summarize the key scientific problems of seismic fluid identification, and review the main development of researches of seismic fluid identification driven by rock physics, as well as discuss the opportunities, challenge and future study direction of seismic fluid identification.

1 Key scientific problems of seismic fluid identification

1.1 The influences of the reservoir fluid on seismic velocity

The impacts of the fluid in the reservoir on seismic velocity are generally discussed by the means of rock physics experiments and theoretical models. The fluid saturated oil/gas reservoirs are usually equivalent to porous medium including solid matrix and the fluid saturated in the porous rocks and so on. Different rock physics models lead to different impacts on seismic velocity. The porous rock can be regarded as the homogeneous and isotropic media when the wavelength of the seismic wave is comparable with the thickness of strata. The wave-induced fluid flow will cause attenuation and dispersion. The characteristic frequency of seismic-wave attenuation is dependent on the time scaling of wave-induced fluid pressure, when seismic wave propagates on the internal interfaces in the porous rocks (Brajanovski et al., 2005; Wenzlau et al., 2010). The attenuation and dispersion of seismic wave could be weaker with smaller contrast of fluids properties between both sides of interface, which depends on the rigidity of fluid in the patchy saturated rocks (Brajanovski et al., 2005; Masson et al., 2006). The patchy size and heterogeneity of gas saturation which has an obvious effect on the attenuation and dispersion when the patchy size becomes greater and the density of gas is lower have significant influence on the wave-induced fluid flow (Vogelaar et al., 2007; Rubino et al., 2011). The variation of attenuation and dispersion of compressional wave with the saturation of oil and gas are more continuous in the media of heterogeneous saturation than that in the case of homogeneous saturation (Hou et al., 2012). The compressional wave propagates faster in the porous media saturated with oil or water than that saturated with gas only, and the velocity of the seismic wave in the low-frequency limit would reduce with the decrease of rock stiffness when the gas saturation increases (Brajanovski et al., 2005). The density of the gas-saturated porous media will decline with increase of gas saturation when the gas saturation turns into a high level, leading to the increase of seismic wave velocity (Knight et al., 2010). Currently, researchers still don't have the common views on the existence type and distribution of fluid and the rock physics models. Therefore, how to get more reasonable interpretation about the influence of the fluid saturated rock on seismic velocity is one of the key scientific problems in seismic fluid discrimination.

1.2 The influences of the reservoir fluid on seismic responses

The influences of the properties and distribution of reservoir fluid on seismic responses are generally discussed utilizing physical or numerical simulation methods. The influences on seismic responses vary with different fluid properties. For example, the viscosity of the pore fluid is one of the main reasons for the attenuation of elastic waves in fluid-saturated porous materials (Sharma, 2005). The influences of the viscosity of pore gas and liquid are similar on the attenuation of two fast waves (fast P-wave, SV wave), while the influences of viscous liquid on the velocities of these waves are greater than that of viscous gas. With the increase of viscosity, the amplitude of liquid component of the S-wave increases slightly while that of solid component decreases slightly; and the amplitude of slow P-wave decreases gradually. The slow one is attenuated rapidly under the viscous boundary conditions and can't be seen in the wave field snapshots, which is the main cause of difficulty in observation of slow P-wave in seismic records as viscous boundary exists in most of the actual media (Lu et al., 2009). The permeability of pore fluid has direct impact on seismic response. The double-porosity model describes how the porosity and permeability affect wave dispersion and attenuation (Pride et al., 2003), and the relationship between frequency and the P-wave attenuation coefficient as well as the high sensitivity of its anisotropy to the permeability (Shapiro et al., 1999). The attenuation of S-wave increases obviously in impermeable geologic bodies and can be used as an indication of changes in permeability of the reservoirs (Wenzlau et al., 2010). With the decrease of permeability, the amplitude of slow P-wave reduces significantly. While the velocity has no obvious changes, the amplitude and velocity of fast P-wave and S-waves also have little changes (Lu et al., 2009). In addition, fluid type, distribution uniformity, saturation, temperature and pressure also have direct or indirect impacts on the responses of seismic waves. How to establish reasonable equations of mathematical physics based on the construction of rock physics models, and then develop the corresponding methods to simulate the influence of fluid on seismic waves is also the key scientific problems in seismic fluid identification.

1.3 Fluid information estimation method from seismic data

Seismic data contains substantial kinematics and dynamics information, which is the overall function of underground reservoir characteristic parameters concerning lithology, physical property, fluids and so on. There are mainly two approaches to get effective fluid information from seismic data, the model-driven approach and the data-driven approach. The former is a process that takes underground geological and geophysical features into consideration, and chooses proper model parameters and boundary condition to establish characteristic equation, and estimates effective fluid information with seismic inversion method. The latter is a process that uses observation data as seismic signals to estimate underground fluid information, based on signal theory and appropriate signal transformation methods. It can extract information related directly to fluid in the seismic data. Specifically, data-driven seismic inversion can estimate parameters that are both sensitive to fluid and related to seismic signal, based on relevant theories of signal (sparse representation, matching pursuit, basis pursuit, etc.) and proper use of signal atom or dictionary. Comparatively, seismic fluid method based on model-driven inversion can provide fluid-sensitive parameters that own rock physics meaning. However, this method still confronts challenges caused by observation data, model parameterization, forward operator, inversion optimization algorithm and so on.

2 Development of rock physics theory

There are mainly three kinds of fluid saturated rock physics equivalent models: Effective medium theory by calculating the average volume of minerals properties (Wood, 1941; Wyllie et al., 1956; Raymer et al., 1980), contact medium theory based on particle contact relation (Walton, 1987; Dvorkin et al., 1996), equivalent self-adaptive theory based on internal minerals, pore shapes, and fluid properties in the rock (Gassmann, 1951; Biot, 1956a, 1956b; Berryman, 1995).

Biot-Gassmann theory laid the foundation for the study of porous media. It is built under the condition of connected pores and no friction and chemical reaction between flowing fluid and rock skeleton. This theory divides porous media into four parts: rock matrix, dry rock skeleton, saturated rock and fluid in pores (Figure 1). Bulk modulus and shear modulus of saturated rocks in low frequency can be estimated from skeleton modulus and fluid modulus in the pores, and then velocities of compressional wave and shear wave related to the properties of fluid can be yielded. Nolen-Hoeksema (2000) analyzed the relationship between modulus of saturated rock and fluid modulus, skeleton modulus. Han et al. (2004) indicated the inaccuracy of input parameters tend to result in the change of shear modulus of rocks and derived the simplified Gassmann relation. Adam et al. (2006) studied the fluid substitution and shear modulus of carbonate rocks in the seismic and ultrasonic measurements of laboratory and found that fluid substitution could lead to the change of shear modulus in carbonate rocks. Grochau et al. (2009) carried out the sonic and ultrasonic measurements for turbidite rock samples, confirming the consistency between Gassmann fluid substitution and measurement data, and indicated the time-lapse effect using Gassmann theory to interpret sandstone reservoir. Li (2012) established the linear equation of AVO attributes before and after fluid substitution and utilized cross plots between attributes to implement the identification of gas reservoir. However, it is only suitable for particular porosity, fluid viscosity as well as frequency band, which means that the low frequency Biot-Gassmann theory cannot be applied in the case of low porosity, poor pores connectivity situation. Ciz et al. (2007) derived the generalized Gassmann equation by extending the anisotropic Brown-Korringa formula (Brown et al., 1975), which can explain the shear moduli of fluid which is not being ignored. The shear moduli calculated by generalized Gassmann equation was different with skeleton shear moduli. Xu et al. (1996) put forward the Xu-White model to better describe the clastic rock, which divide the pore type of siliceous clastic rock into sandstone pores and shale pores (Keys et al., 2002). Zhang G Z et al. (2013) and Xu et al. (2010) developed the rock physics model for fracture-pore carbonates (Figure 2), which characterized the distribution of fluid in pores better by applying

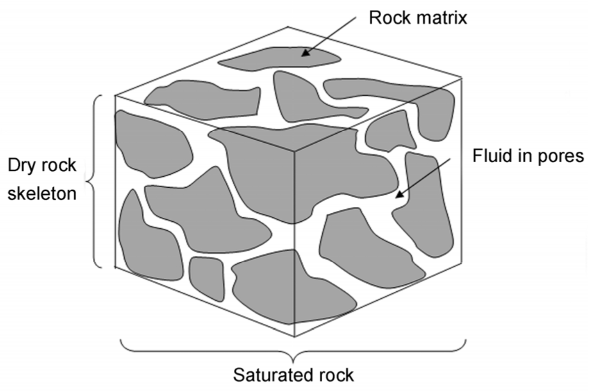

Figure 1 Four components of poroelastic media model in Gassmann theory.

the inversion of porosity and aspect ratio of different pores. Ruiz et al. (2009) published the fluid substitution method in high porosity marine carbonate by using contact model.

The attenuation and dispersion (Aki et al., 1980) phenomenon of amplitude exists in seismic wave propagating in the earth medium, which can be induced to the macroscopically "internal friction" and the decrement of the total energy for the particle motion. Pride et al. (2004) summarized the mechanism of seismic attenuation into two aspects, the attenuation caused by scattering and the inherent attenuation caused by stratigraphic absorption. Scattering attenuation transfer energy by tail wave, which is relevant to the heterogeneous geologic body scale. High frequency components will weaken due to the destructive interference when the heterogeneous geologic body scale is much smaller than seismic wave length. The attenuation caused by the presence of fluid in the pores is very important for oil/gas exploration with seismic data. It is supposed that the seismic wave will attenuate with the flowing of the fluid in pores rather than with dry rock, by propagating through rock skeleton. Fluid flow leads to the attenuation by converting partly energy into heat energy, which is caused by friction. The attenuation is more obviously in gas partially saturated rocks, and seismic attributes related to attenuation and velocity dispersion have been applied to seismic interpretation and reservoir characterization (Taner et al., 1979; Castagna et al., 2003; Ebrom, 2004; Chapman et al., 2006; Odebeatu et al., 2006; Chen et al., 2009).

Müller et al. (2010) considered wave-induced fluid flow (WIFF) as the main reason of seismic attenuation and velocity dispersion. WIFF occurs as a passing wave creates pressure gradients, because of heterogeneous distribution of rock skeleton or pore fluid, resulting in seismic attenuation and dispersion. Fluid related rock physics attenuation mechanism can be divided into three scales: macroscopic, mesoscopic and microscopic scale. Mesoscopic scale attenuation mechanism is the most important among them considering the dominant frequency of seismic data (tens of Hertz) and limited band width. The research related to this theory has been developed from one-dimensional layered medium to three-dimensional heterogeneity distribution medium (White, 1975; Dutta et al., 1979; Müller et al., 2005). WIFF is essentially caused by relaxation of fluid pressure. Some authors attempt to use viscoelastic medium to describe the attenuation and dispersion features, such as the standard linear solid (SLS) model (Mavko et al., 2009). However, they could not interpret the measured rock properties for the lack of the physical meaning. White et al. (1975) constructed spheral patchy saturated model containing gas pockets and patchy saturated model periodic over-

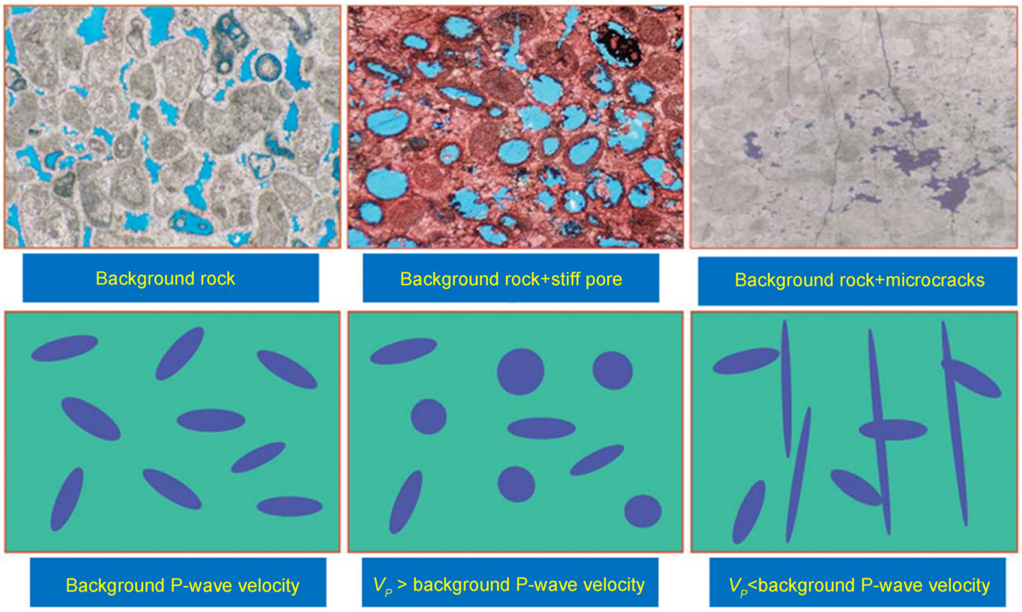

Figure 2 Illustration of different pore types in carbonate rocks. From Xu et al. (2010).

lapped between water bearing and gas bearing porous medium layers based on meso-scale rock physics theory. Dutta et al. (1979) improved the patchy model later. In addition to the meso-scale heterogeneity rock physics model based on multi-phase fluid flowing and patchy saturation, the rock skeleton, pore shapes and distribution can also result in meso-scale attenuation, in which the most representative model is double-porosity media model. Berryman et al. (1995) initially studied the govern equation and parameters definition of double-porosity media model. Pride et al. (2003) derived the govern equation of fluid flow in isotropic double-porosity media based on volume-average assumption, and pointed out that there were two modes of fluid flow. And then Pride et al. (2004) studied the seismic attenuation and velocity dispersion in detail, and pointed out that the P-wave velocity dispersion calculated by both meso-scale heterogeneity skeleton rock physics model and multi-phase patchy saturated model in seismic frequency band satisfied the actual dispersion observed well.

Domestic scholars also studied a lot about the attenuation of rock physics theory and velocity dispersion. They mostly concentrated on the macro-and micro-scale. Yang (1998) studied the macro-quirt theory and expanded the application range of BISQ theory. Zhu et al. (2001) derived the seismic wave propagation equation of two phase (oil and water) porous media, and implemented the numerical simulation. Nie et al. (2010) studied the BISQ model in partially saturated rocks based on equivalent medium theory. Tang (2011) extended the Biot's theory and BISQ theory and analyzed the influence of fracture on dispersion and attenuation (Figure 3). Ba et al. (2012) simulated seismic wave field of the porous medium with double-porosity model and pseudo-spectral method, and analyzed the seismic velocity attenuation caused by fluid flow in mesoscopic scale. Liu et al. (2010) studied the attenuation and dispersion features by utilizing different patchy models. We can establish the multi-scale rock physics model and explored the effective attenuation theory suitable for seismic frequency band, by considering fluid flow attenuation influence incorporating macroscopic, mesoscopic and microscopic scale based on seismic attenuation mechanism study. Meanwhile, we can get the quantitative relationship between stratigraphic absorption parameters, reservoir properties and pore fluid parameters by combining the pore fluid medium elastic wave equation by choosing the reasonable boundary conditions and solving the appropriate mathematical and physical equations. Figure 4 displays the relationship between stratigraphic absorption parameters and reservoir permeability of multi-scale under full frequency band condition. The attenuation dominant frequency of seismic wave decreases with the decrease of reservoir permeability, which builds the theoretical foundation of fluid identification in tight oil and gas reservoirs by utilizing the attenuation attributes such as absorption parameters.

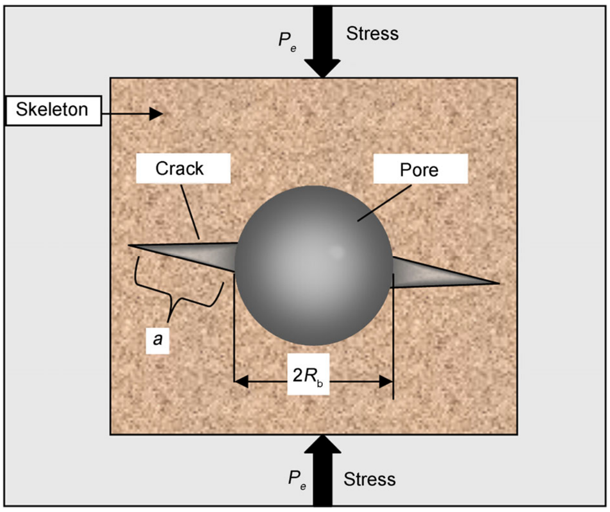

Figure 3 Schematic diagram of fracture-pore unified model. Modified from Tang (2011).

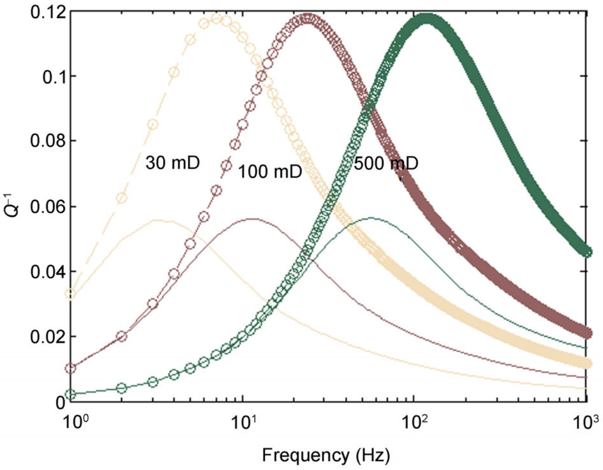

Figure 4 Relationship between stratigraphic absorption parameters and permeability of oil and gas reservoir with multi-scale rock physics model.

3 Seismic-wave responses and sensitive indicator of fluid-filled reservoir

Seismic wave responses of fluid-filled reservoir are of great importance to analyze the impact of the distribution and viscosity of fluids and permeability of porous rocks on the seismic wave. It set the foundation of the construction of the sensitive indicator of fluid-filled reservoir. White (1975) analyzed the sonic properties of P-wave at low frequencies while propagating perpendicularly to the interior interfaces in the patchy saturated rocks. Murphy et al. (1986) indicated that local fluid flow had influence on sonic properties and viscous fluid flow results in energy dissipation. Cadoret et al. (1995) got the impact of partially saturated fluid on sonic properties and variation of velocity with water saturation related to frequency in different frequency and displayed the obvious dispersion in the case of high water saturation. Gurevich et al. (1995) and Gelinsky et al. (1998) obtained attenuations caused by wave-induced fluid flow in the permeably layered media which are different from that resulting from the periodic layered medium model. Pham et al. (2002) established the relationship between the wave velocities and attenuation with pore pressure and fluid saturation of porous elastic solid. Carcione et al. (2003) simulated the relaxation phenomena by numerical experiments with White's spherical model and get the similar results. Gei et al. (2003) calibrated the fluid mixing law and spherical patchy saturated model at high frequencies and defined the velocities and attenuation as a function of pore pressure, temperature, frequency and partial saturation. Müller et al. (2005) analyzed the impact of wave-induced fluid flow on the attenuation and dispersion of seismic wave and illustrated that P-wave attenuation was proportional to the square of frequency at low frequencies and was inversely proportional to it at high frequencies. Brajanovski et al. (2005) obtained P-wave attenuation and dispersion in a porous medium permeated by aligned fractures and demonstrated that the characteristic frequency of the attenuation and dispersion depended on the background permeability, fluid viscosity, as well as fracture density and spacing. Sun et al. (2011) simulated the seismic wave in the heterogeneous porous medium and analyzed the impact of porosity and the type of fluids on the seismic-wave reflection. They illustrated that porosity had great influence on the amplitude and phase of seismic-wave reflection and the travel time of seismic wave would change and the amplitude of reflection could heighten with the increase of porosity on the interface of two phase medium. The travel time raises with the increase of water saturation when water and oil coexist in the porous media and the amplitude of seismic-wave reflection will rapidly become bigger with the increase of gas saturation when gas and water fill in the pores of rocks and get the maximum value of amplitude of reflection when the gas saturation increases to about 10% and slightly descends with the increase of gas saturation after that. The digital rock physics (DRP) simulates the physical properties of the rock with modern microscopic imaging and advanced numerical methods (Saenger et al., 2011; Madonna et al., 2012). DRP carries out 3D digital modeling for the structure of the rock in different scales and uses numerical methods to calculate the effective elastic parameters of the rock at the same time completing experimental measurement (Ringstad et al., 2013). DRP technology can provide accurate information of the rock more quickly than experiments and can be utilized to implement sensitivity analysis, fracturing design and pressure variation analysis for reservoir in pore scale and reservoir description, improving the accuracy of reservoir prediction, production prediction and determination of well position and enhancing the rate of oil and gas recovery (Kalam et al., 2011).

Taking the fluid viscosity into consideration, Borcherdt (1977, 1982) studied the reflection and diffraction of heterogeneous waves in viscoelastic solid. Sharma et al. (1991) discussed the reflection coefficients in the viscoelastic isotropic porous rocks with viscous fluids saturated. Gurevich (2002) analyzed the impact of fluid viscosity in the porous rocks on seismic-wave attenuation. Liu et al. (1990) proposed that due to the viscous effects of fluid, in addition to relative translation of solid-liquid phase, there is relative rotation. Therefore, the second kind of shear wave appears at the interface of solid phase and fluid phase in porous media, and its strong frequency dispersion and attenuation also works as a reason to cause energy dissipation in porous medium. Lu et al. (2009) analyzed the dispersion and attenuation of elastic wave in porous medium with viscous fluid saturated and indicated that shear wave mainly propagated in the pore fluid, owning high phase velocity at high frequency and low porosity. Taking fluid permeability into consideration, Shapiro et al. (1999) pointed out that the P-wave attenuations were relevant to frequencies and the change of permeability was sensitive to the anisotropy of the porous media. The low permeability of fluids could cause significant attenuation and it may indicate the change of permeability in the reservoir. Numerical simulation results showed that, when the permeability decreased, amplitude of slow wave decreased obviously, while the fast P-wave and shear wave changed little.

Anomalies related to interstitial fluid can be regarded as fluid factors for fluid identification, through rock physics model construction and seismic response analysis of reservoir fluid. Therefore, the construction of fluid factor also works as a key problem in seismic fluid identification. Smith et al. (1987) utilized the weighted stacking of relative changes of P-wave and S-wave velocities as the fluid factor initially for reservoir hydrocarbon identification. Smith et al. (2003) came up with the concepts of fluid factor angle and cross plot angle. Goodway et al. (1997) proposed LMR method that recognized reservoir fluid type using stretching characteristic anomalies of underground strata. Quakenbush et al. (2006) put forward the Poisson's ratio concept. Russell et al. (2003) defined the parameter ρf as the fluid factor with the rock physics theory of porous elastic medium (Russell et al., 2011). Researches have demonstrated that Gassmann fluid term f was highly sensitive to fluid in common well consolidated clastic reservoir, whereas Zhang et al. (2010) found that Gassmann fluid term f might be subject to pseudomorph in pore fluid identification in complicatedly consolidated areas due to the complex reservoir porosities in the application of actual data. Figure 5(b) displays that f is determined by pore fluid and intrinsic solid rock skeleton concerning rock matrix, porosity and so on. Meanwhile, the variation f with water saturation is distorted by porosity changes.

Therefore, for real data, we should pay special attention to fluid identification pseudomorph due to consolidation effect (especially porosity) of reservoir rock. Pore fluid

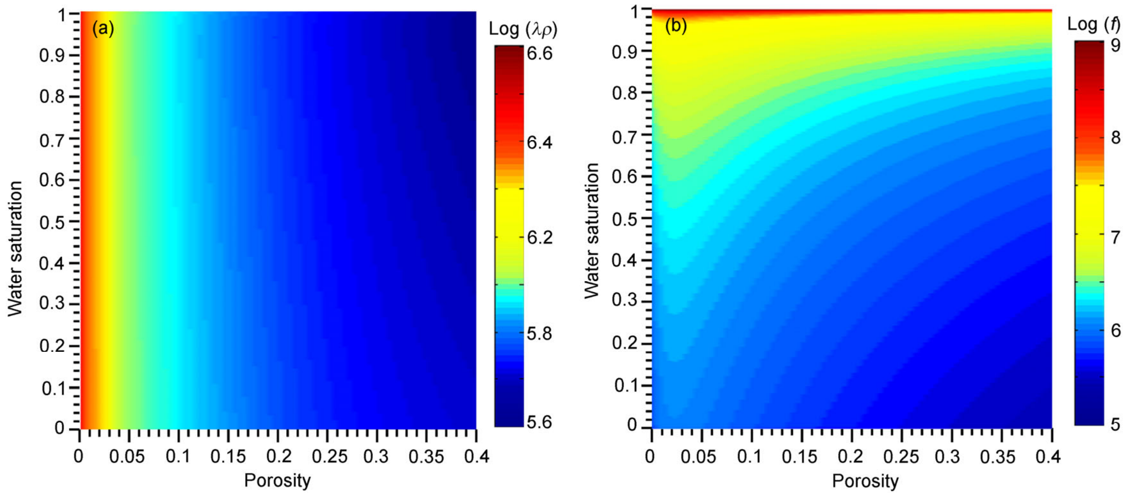

Figure 5 Trend of fluid factor with changing porosity and water saturation (rock pore is saturated by water and gas). (a) $\lambda\rho$ (unit: N/m^2·kg/m^3); (b) Gassmann fluid term *f* (unit: N/m^2).

bulk modulus and porosity of solid skeleton generally determine the value of Gassmann fluid term *f*. Here K_f is estimated using logging data according to empirical relationship from rock physics experiments. Figure 6 displays the trend of K_f with changing porosity and water satuation. Obviously, K_f is linearly dependent on water saturation and independent of porosity. Therefore, we can utilize proper geophysical methods to estimate the fluid bulk modulus K_f from seismic data, and then take it for fluid identification so as to decouple fluid elastic effect from solid skeleton and improve reliability of seismic fluid identification. Specially, for tight reservoir, layer absorption parameters constructed in full frequency band can be considered as the fluid factor for hydrocarbon identification. Figure 7 displays the comparison of different fluid indicators coefficient of one tight reservoir, where $\mu\rho$ is the product of shear moduli and density, I_P is the P-wave impedance, *f* is the Gassmann fluid term, $f\rho$ is the product of Gassmann fluid term and density, ρQ^{-1} is the product of density and attenuation parameter, Q^{-1} (reciprocal of absorption parameter) indicates attenuation, $\lambda\rho$ is the product of Lamé parameter and density from which we can see the layer absorption parameter is much more sensitive to tight reservoir than other parameters.

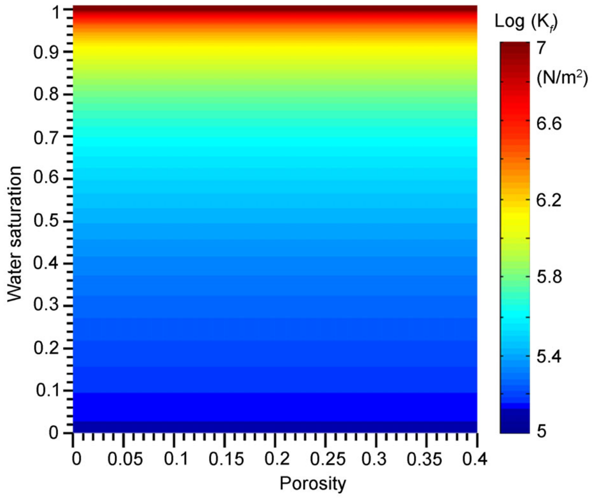

Figure 6 Trend of fluid bulk modulus with changing porosity and water saturation.

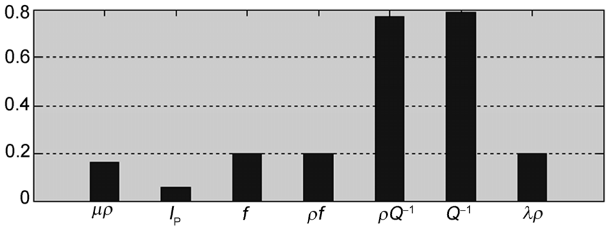

Figure 7 Sensitivity indication coefficients of different fluid factors.

4 Seismic methods for fluid identification

Seismic methods for fluid identification focus on how to get effective reservoir fluid information with amplitude, frequency and phase analysis of seismic data. In seismic data interpretation, amplitude information is generally applied for wave comparison. For example, amplitude of thin layer reflection that is used for thin layer thickness estimation, and lateral and horizontal variation of reflection amplitude can be used for reservoir prediction and hydrocarbon detection (Wang, 2007). Pre-stack seismic inversion works as the main approach for model-driven fluid identification. Many scholars focus on inversion algorithms to improve inversion precision (Liu et al., 2010; Hou et al., 2011). Elastic wave inversion theory based on wave equation came out earlier. It utilizes seismic shot records directly and makes use of all types of waves for reservoir elastic parameter inversion. Based on seismic wave dynamics and kinematics theory, Kennett (1986) proposed reflection coefficient model inversion method by propagation matrix method. Tarantola (1986) improved this method using prior constraint information, which minimizes error between observation data and modeling results according to least square rule. Sen et al. (1991, 1992) discussed waveform inversion with simulation annealing, genetic algorithm and gradient optimization algorithm. Mallick (1995) solved the maximum posterior probability density function (PDF) of model using genetic algorithm in elastic parameter inversion. Although these nonlinear elastic wave inversion methods are theoretically mature, the low computational efficiency and stability lead to less application in practical production.

Pre-stack seismic inversion based on ray theory is still prevalent in practical application at present. It comprises of AVO/AVA inversion based on reflection coefficient and its approximation equation (Yin et al., 2013; Zong et al., 2012c, 2013a, 2013b) and pre-stack elastic impedance inversion based on elastic impedance equation (Zong et al., 2012b, 2013c). Buland et al. (2003) introduced Bayesian theory into pre-stack AVO inversion for three-term simultaneous inversion of P-wave velocity, S-wave velocity and density. Downton et al. (2001, 2005) studied the two-term and three-term AVO inversion based on Bayesian theory, and discussed the influence of prior constraint distribution on inversion results. Zhang (2004) studied waveform inversion method of half-space layered media. Yin (2006) carried out further research of parallelization of pre-stack elastic wave modeling and inversion, and developed parallelized seismic inversion software system on microcomputer cluster. Chen (2007) studied three-term AVO waveform inversion and simultaneous inversion in Baysian scheme and got good results. Yang (2008) proposed the concept of blind seismic inversion and developed the sparse spike pre-stack inversion with point constraints and non-linear quadratic programming pre-stack inversion. Cao (2008) set up the multi-scale seismic joint inversion scheme. Zhang (2009) started from Xu-white model and arrived at accurate S-wave prior information for pre-stack seismic inversion through combination of reconstructed logging inversion and pre-stack waveform inversion. Zhang G Z et al. (2011) studied the nonlinear AVO inversion method based on MCMC and got good practical application results. Elastic inversion by Connolly (1999) combined both advantages of post-stack impedance inversion and AVO inversion. Cambois (2000) thought elastic impedance had better noise immunity and better inversion result than AVO inversion by utilizing angle stack gathers. Whitcombe (2002) modified Connolly's elastic impedance equation through normalization, and solved the problem that numerical dimension varies with different angles. Yin et al. (2004) developed the elastic parameter estimation method using elastic impedance. For deep reservoir, Li et al. (2009) put forward P-wave and S-wave impedance inversion method using two-angle elastic impedance. Wang et al. (2007) derived elastic impedance equation expressed by Lamé parameter, improving the accuracy of Lamé parameter. Yin et al. (2010) put forward elastic impedance equation containing Gassmann fluid term, and estimated fluid term accurately and directly through elastic impedance inversion. The Gassmann fluid term estimated for hydrocarbon detection of one survey's Es25 sand body is displayed in Figure 8. Zong et al. (2012a) proposed poroelastic theory and reflection coefficient equation based on P-wave and S-wave modulus, and developed fluid identification method based on P-wave and S-wave modulus AVO inversion. Zhang (2012) developed seismic fluid identification method based on fluid- matrix decoupled AVO approximation, overcoming the pseudomorph of common fluid identification methods due to porosity disturbance (Figure 9). Yin et al. (2014b) put forward the fluid identi-

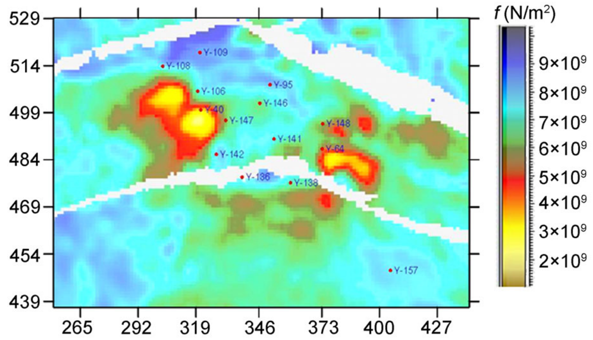

Figure 8 Estimation of *f* of one survey's Es25 sand body.

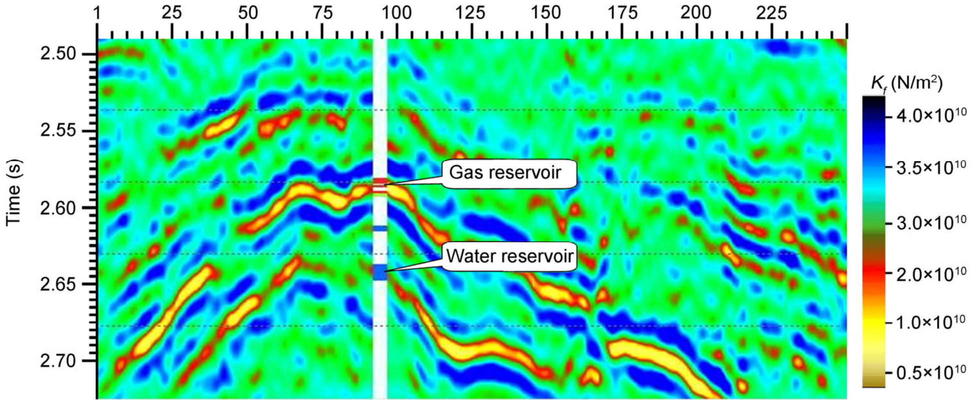

Figure 9 Profile of effective bulk modulus of fluid.

fication method facing heterogeneous reservoir and obtain good results in real application.

AVO inversion and analysis based on seismic amplitude play an important role in fluid identification. However, there are still some problems that traditional AVO technique cannot solve. Geophysicists have been paying attention to low frequency anomaly related to reservoir (Goloshubin et al., 2000; Castagna et al., 2003; Korneev et al., 2004; Chapman et al., 2006). A great number of researches have suggested that when seismic wave propagates through oil/gas reservoirs, wave attenuation will lead to frequency anomaly. Hydrocarbon saturated layers with strong attenuation generally have low quality factor (Klimentos, 1995; Dasgupta et al., 1998; Dasios et al., 2001; Maultzsch et al., 2003; Rapoport et al., 2004). Meanwhile, seismic dispersion accompanies attenuation in oil/gas reservoirs. Some researchers studied Amplitude Versus Frequency (AVF) theory systematically, based on the mathematical relationship between velocity dispersion and seismic reflection characteristics (Cooper, 1967; Krebes, 1984; Nechtschein et al., 1997; Ursin et al., 2002; Sidler et al., 2007). Ren et al. (2009) studied how amplitude and phase angle vary with frequency at the interface between non-dispersive media and dispersive media under normal incidence, and generalized three kinds of AVF response corresponding to three different models. Innanen (2011) studied reflection coefficient variation with incident angle, frequency and quality factor based on absorption reflection coefficient equation, and further discussed AVF/AVA inversion of quality factor Q. Some scholars came up with dispersion attribute extraction methods from seismic data for fluid identification. Wilson et al. (2009) proposed a practical dispersion attribute computation method. Wu et al. (2010) carried out frequency-dependent AVO (FAVO) inversion of pre-stack seismic data. Zhang S X et al. (2011) proposed reflection coefficient approximation expressed by P-wave dispersion extent and gradient, and did P-wave velocity dispersion inversion. Chen S Q et al. (2012) analyzed AVO response of different pore fluid using physical model. Cheng X H et al. (2012) derived a series of FAVO attributes and constructed the FAVO calculation formula. Zhao et al. (2012) applied FAVO to thin low-permeability tight sand gas reservoir in Sulige. Zhang Z et al. (2013) proposed frequency-dependent fluid term reflection coefficient equation and developed the corresponding inversion method. Real data tests showed good application results (Figure 10). Others scholars develop frequency-dependent fluid identification method based on data-driven, directly extracting seismic attributes related to frequency to identify hydrocarbon (Xu et al., 2011; Chen X H et al., 2012; Ahmed, 2012; Wang X J et al., 2012; Wang et al., 2013).

In addition to seismic amplitude and frequency information, seismic phase may also provide fluid information. Rafipour et al. (1986) studied the relationship between phase and pore fluid, incident angle and frequency in horizontally layered porous media. Mazzotti (1991) combined AVO analysis, PVO analysis and FVO analysis, and estimated fluid information using amplitude, frequency and phase indicators. Ravagnan et al. (1992) described reflection from gas-bearing sandstone, brown sandstone and benthic tuff by AVO response as well as PVO and FVO indicators. Zhu et al. (2012) tested PVA inversion method using model and compared three modeling methods (planar wave method, spherical method and reflection coefficient method), and finally proved through RTM that PVA information enjoyed better fidelity than AVA information. This means phase of deep reflection from multi-layered media is less influenced by transmission loss than amplitude. And PVA

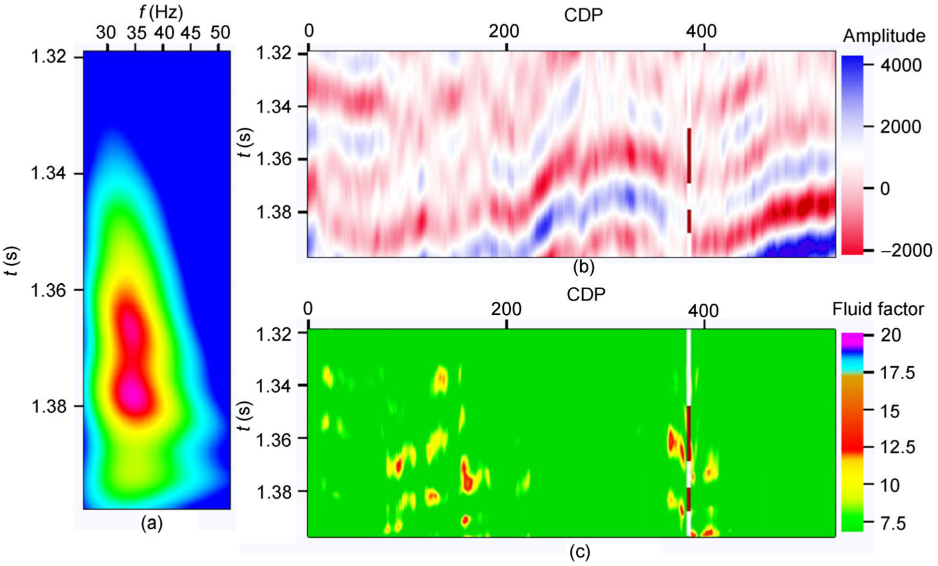

Figure 10 Estimation of frequency-dependent fluid factor. (a) time-frequency analysis; (b) seismic angle stack gather; (c) frequency-dependent fluid factor.

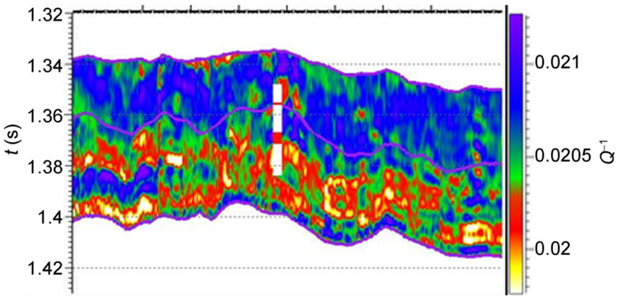

Figure 11 Frequency-dependent multi-scale quality factor profile of tight gas.

data can provide far-angle reflection information necessary for inversion. Similarly, multi-scale layer absorption parameters constructed in full frequency band can be used for tight reservoir fluid identification. As shown in Figure 11, multi-scale layer quality factor in full frequency band is rewarding for tight reservoir fluid identification.

5 Opportunities and challenges

Seismic fluid identification is the frontier basic subject in the field of oil/gas exploration geophysics. However, with the further refinement of oil/gas exploration and the demanding of energy recourses, oil/gas exploration converts from conventional structure reservoir to concealed lithologic reservoir and unconventional reservoir, from shallow exploration to deep-sea exploration and from ground exploration to mountain exploration onshore. Seismic exploration technology demanding turns from exploration to development, from shallow to deep and from reservoir prediction to fluid identification and physical property prediction. To reduce the exploration risk to a great extent, the request for the accuracy and reliability of seismic fluid identification becomes higher. Particularly, the strong transversely discontinuous of heterogeneity, vertically superimposed tight sandstone reservoir, fractured and cavernous carbonate reservoir as well as the emergence of unconventional reservoir bring new challenges for seismic fluid identification. To yield further breakthrough in seismic fluid identification, seismic fluid identification researchers still need make greater efforts in the following three aspects.

(1) For rock physics study, we should develop the experiment equipments of rock physics in seismic frequency range and multi-scale rock physics model in full frequency range. In literatures, only a few institutes represented by Colorado School of Mines published the rock physical experiment measurement data within seismic frequency range, which laid the foundation for the research of multi-scale rock physics model. In recent years, seismic attenuation mechanism within seismic frequency range has become one hot topic for exploration geophysicists, in order to define the relationship between seismic wave attenuation, seismic attributes related to seismic frequency and reservoir fluid or skeleton. Rock physics in full frequency range is just starting to take off in China. A few reports related to rock physical model within seismic frequency range are published domestically. However, it is difficult to be supported by our own experimental data. Therefore, it is urgent to carry out the research and development of rock physical measurement instrument within seismic frequency range with independent intellectual property rights, which will lead the domestic seismic rock physics study to the world. In addition, rock physics theories about unconventional tight, shale oil and gas are just starting. Therefore, it is urgent to develop the seismic rock physics experiment and theory study of unconventional oil and gas reservoir on the basis of the comprehensive consideration of particularity of domestic unconventional oil and gas reservoir.

(2) In the aspects of fluid identification methods based on seismic inversion, besides amplitude information, some scholars attempt to utilize more information such as frequency or even phase information to estimate fluid factor. However, the basic theory of fluid factor estimation with seismic frequency information remains demanding. Although the approaches to yield frequency dependant fluid factors demonstrated great potential in real data tests. However, the physical meaning of this kind of fluid factors need further discussed. Besides, the instability of phase information extraction from seismic data limits the fluid factor estimation with seismic wave phase information.

(3) In the aspects of practical application of seismic fluid identification in complex oil/gas reservoirs, we need develop the seismic inversion theory and methodology of heterogeneous media, because most of the seismic inversion approaches available are developed under the hypothesis that the formations underground are uniform or horizontal layered, which lead to the instability and unreliability of the estimation of fluid factors. Furthermore, seismic fluid identification approaches for moderate-deep oil/gas reservoir, tight reservoir and unconventional reservoir are also need further studied.

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Adam L, Batzle M, Brevik I. 2006. Gassmann's fluid substitution and shear modulus variability in carbonates at laboratory seismic and ultrasonic frequencies. Geophysics, 71: F173–F183

Ahmed F. 2012. Gas detection using matching pursuit spectral decomposition seismic attribute. 74th EAGE Conference & Exhibition. Copenhagen

Aki K, Richards P G. 1980. Quantitative Seismology: Theory and Methods, vol. 1 and 2. New York: WH Fremman

Backus M M, Chen R. 1975. Flat spot exploration. Geophys Prospect, 23: 533–577

Ba J, Carcione J M, Cao H, et al. 2012. Velocity dispersion and attenuation of P waves in partially-saturated rocks: Wave propagation equations in double-porosity medium (in Chinese). Chin J Geophys, 55: 219–231

Berryman J G. 1995. Mixture theories for rock properties. In: Ahrens T J, ed. Rock physics and phase relations. Washingtion: American Geophysical Union. 205–228

Berryman J G, Wang H F. 1995. The elastic coefficients of double-porosity models for fluid transport in jointed rock. J Geophys Res, 100: 24611–24627

Biot M A. 1956a. Theory of propagation of elastic waves in a fluid-saturated porous solid. I, Low-frequency range. J Acoust Soc Am, 28: 167–178

Biot M A. 1956b. Theory of propagation of elastic waves in a fluid-saturated porous solid. II, Higher frequency range. J Acoust Soc Am, 28: 179–191

Borcherdt R D. 1977. Reflection and refraction of type-II S waves in elastic and anelastic media. Bull Seismol Soc Amer, 67: 43–67

Borcherdt R D. 1982. Reflection-refraction of general P- and type S- waves in elastic and anelastic solids. Geophys Roy Astron Soc, 70: 621–638

Brajanovski M, Gurevich B, Schoenberg M. 2005. A model for P-wave attenuation and dispersion in a porous medium permeated by aligned fractures. Geophys J Int, 163: 372–384

Brown R J S, Korringa J. 1975. On the dependence of the elastic properties of a porous rock on the compressibility of the pore fluid. Geophysics, 40: 608–616

Buland A, Omre H. 2003. Bayesian linearized AVO inversion. Geophysics, 68: 185–198

Cadoret T, Marion D, Zinszner B. 1995. Influence of frequency and fluid distribution on elastic wave velocities in partially saturated limestones. J Geophys Res, 100: 9789–9803

Cambois G. 2000. AVO inversion and elastic impedance. Seg Tech Prog Exp Abs, 142–145

Cao D P. 2008. Methods of multiscale seismic data modeling and inversion (in Chinese). Doctoral Dissertation. Qingdao: China University of Petroleum (Huadong)

Carcione J M, Helle H B, Pham N H. 2003. White's model for wave propagation in partially saturated rocks: Comparison with poroelastic numerical experiments. Geophysics, 68: 1389–1398

Castagna J P, Sun S, Siegfried R W. 2003. Instantaneous spectral analysis: Detection of low-frequency shadows associated with hydrocarbons. The Leading Edge, 22: 120–127

Castagna J P, Swan H W, Foster D J. 1998. Framework for AVO gradient and intercept interpretation. Geophysics, 63: 948–956

Chapman M, Liu E, Li X Y. 2006. The influence of fluid-sensitive dispersion and attenuation on AVO analysis. Geophys J Int, 167: 89–105

Chen J J. 2007. Methods of three-term AVO inversion (in Chinese). Doctoral Dissertation. Qingdao: China University of Petroleum (Huadong)

Chen S Q, Li X Y, Wang S X. 2012. The analysis of frequency-dependent characteristics for fluid detection: A physical model experiment. Appl Geophys, 9: 195–206

Chen X H, He Z H, Huang D J, et al. 2009. Low frequency shadow detection of gas reservoirs in time-frequency domain (in Chinese). Chin J Geophys, 52: 215–221

Chen X H, He Z H, Zhu S X, et al. 2012. Seismic low-frequency-based calculation of reservoir fluid mobility and its applications. Appl Geophys, 9: 326–332

Cheng B J, Xu T J, Li S G. 2012. Research and application of frequency dependent AVO analysis for gas recognition (in Chinese). Chin J Geophys, 55: 608–613

Ciz R, Shapiro S A. 2007. Generalization of Gassmann equations for porous media saturated with a solid material. Geophysics, 72: A75–A79

Connolly P. 1999. Elastic impedance. The Leading Edge, 18: 438–452

Cooper Jr H F. 1967. Reflection and transmission of oblique plane waves at a plane interface between viscoelastic media. J Acoust Soc Am, 42: 1064–1069

Dasgupta R, Clark R A. 1998. Estimation of Q from surface seismic reflection data. Geophysics, 63: 2120–2128

Dasios A, Astin T, McCann C. 2001. Compressional-wave *Q* estimation from full-waveform sonic data. Geophys Prospect, 49: 353–373

Downton J E. 2005. Seismic parameter estimation from AVO inversion. Doctoral Dissertion. Calgary: University of Calgary

Downton J E, Lines L. 2001. Constrained three parameter AVO inversion and uncertainty analysis. Seg Tech Prog Exp Abs. 251–254

Dutta N, Seriff A. 1979. On White's model of attenuation in rocks with partial gas saturation. Geophysics, 44: 1806–1812

Dvorkin J, Nur A. 1996. Elasticity of high-porosity sandstones: Theory for two North Sea data sets. Geophysics, 61: 1363–1370

Ebrom D. 2004. The low-frequency gas shadow on seismic sections. The Leading Edge, 23: 772–772

Gassmann F. 1951. Elastic waves through a packing of spheres. Geophysics, 16: 673–685

Gei D, Carcione J M. 2003. Acoustic properties of sediments saturated with gas hydrate, free gas and water. Geophys Prospect, 51: 141–158

Gelinsky S, Shapiro S, Müller T, et al. 1998. Dynamic poroelasticity of thinly layered structures. Int J Solids Struct, 35: 4739–4751

Goloshubin G M, Korneev V A. 2000. Seismic low-frequency effects from fluid-saturated reservoir. Seg Tech Prog Exp Abs. 1671–1674

Goodway B, Chen T, Downton J. 1997. Improved AVO fluid detection and lithology discrimination using Lamé petrophysical parameters; "λρ" , μρ, λμ fluid stack" , from P And S inversions. Seg Tech Prog Exp Abs. 183–186

Grochau M, Gurevich B. 2009. Testing Gassmann fluid substitution: Sonic logs versus ultrasonic core measurements. Geophys Prospect, 57: 75–79

Gurevich B. 2002. Effect of fluid viscosity on elastic wave attenuation in porous rocks. Geophysics, 67: 264–270

Gurevich B, Lopatnikov S. 1995. Velocity and attenuation of elastic waves in finely layered porous rocks. Geophys J Int, 121: 933–947

Han D, Batzle M L. 2004. Gassmann's equation and fluid-saturation effects on seismic velocities. Geophysics, 69: 398–405

Hilterman F J. 2001. Seismic amplitude interpretation: 2001 distinguished instructor short course. Houston: Geophysical Development Corporation

Hou B, Chen X H, Li J Y. 2012. Acoustics simulation and analysis of three phase fluid patchy saturations porous rock (in Chinese). Sci Sin-Phys Mech Astron, 42: 259–270

Hou Z Z, Yang W C. 2011. Multi-scale inversion of density structure from gravity anomalies in Tarim Basin. Sci China Earth Sci, 54: 399–409

Innanen K A. 2011. Inversion of the seismic AVF/AVA signatures of highly attenuative targets. Geophysics, 76: R1–R14

Kalam Z, Dayyani T, Grader A, et al. 2011. Digital rock physical analysis in complex carbonates. World Oil, 232: 1–5

Kennett B. 1986. Seismic wave propagation in stratified media. Geophys Roy Astron Soc, 86: 219–220

Keys R G, Xu S. 2002. An approximation for the Xu-White velocity model. Geophysics, 67: 1406–1414

Klimentos T. 1995. Attenuation of P-and S-waves as a method of distinguishing gas and condensate from oil and water. Geophysics, 60: 447–458

Knight R, Pyrak-Nolte L, Slater L et al. 2010. Geophysics at the interface: Response of geophysical properties to solid-fluid, fluid-fluid, and solid-solid interfaces. Rev Geophys, 48: RG4002

Korneev V A, Goloshubin G M, Daley T M, et al. 2004. Seismic low-frequency effects in monitoring fluid-saturated reservoirs. Geophysics, 69: 522–532

Krebes E. 1984. On the reflection and transmission of viscoelastic waves-Some numerical results. Geophysics, 49: 1374–1380

Liu J, Ma J W, Yang H Z. 2010. Research on P-wave's propagation in White's sphere model with patchy saturation (in Chinese). Chin J Geophys, 53: 954–962

Liu Q R, Katsube N. 1990. The discovery of a second kind of rotational wave in a fluid-filled porous material. J Acoust Soc Am, 88: 1045–1053

Li A S, Yin X Y, Lu N, et al. 2009. Application of elastic impedance inversion with two angle stack gathers to predict gas-bearing reservoir of mid-deep layer (in Chinese). Oil Geophys Pro, 44: 87–92

Li J Y. 2012. Gas reservoir identification by seismic AVO attributes on fluid substitution. App Geophy, 9: 139–148

Lu M H, Ba J, Yang H Z. 2009. Propagation of elastic waves in a viscous fluid-saturated porous solid (in Chinese). Eng Mechan, 26: 36–40

Madonna C, Almqvist B S G, Saenger E H. 2012. Digital rock physics: Numerical prediction of pressure-dependent ultrasonic velocities using micro-CT imaging. Geophys J Int, 189: 1475–1482

Mallick S. 1995. Model-based inversion of amplitude-variations-with-offset data using a genetic algorithm. Geophysics, 60: 939–954

Masson Y J, Pride S R, Nihei K T. 2006. Finite difference modeling of Biot's poroelastic equations at seismic frequencies. J Geophys Res, 111: B10305

Maultzsch S, Chapman M, Liu E, et al. 2003. Modelling frequency-dependent seismic anisotropy in fluid-saturated rock with aligned fractures: Implication of fracture size estimation from anisotropic measurements. Geophys Prospect, 51: 381–392

Mavko G, Mukerji T, Dvorkin J. 2009. The rock physics handbook: Tools for seismic analysis of porous media. New York: Cambridge University Press

Mazzotti A. 1991. Amplitude, Phase and frequency versus offset applications. Geophys Prospect, 39: 863–886

Müller T M, Gurevich B. 2005. Wave-induced fluid flow in random porous media: Attenuation and dispersion of elastic waves. J Acoust Soc Am, 117: 2732–2741

Müller T M, Gurevich B, Lebedev M. 2010. Seismic wave attenuation and dispersion resulting from wave-induced flow in porous rocks—A review. Geophysics, 75: 75A147–75A164

Murphy III W F, Winkler K W, Kleinberg R L. 1986. Acoustic relaxation in sedimentary rocks: Dependence on grain contacts and fluid saturation. Geophysics, 51: 757–766

Nechtschein S, Hron F. 1997. Effects of anelasticity on reflection and transmission coefficients. Geophys Prospect, 45: 775–793

Nie J X, Yang D H, Ba J. 2010. Velocity dispersion and attenuation of waves in low-porosity-permeability anisotropic viscoelastic media with clay(in Chinese). Chin J Geophys, 53: 385–392

Nolen-Hoeksema R C. 2000. Modulus-porosity relations, Gassmann's equations, and the low-frequency elastic-wave response to fluids. Geophysics, 65: 1355–1363

Odebeatu E, Zhang J, Chapman M, et al. 2006. Application of spectral decomposition to detection of dispersion anomalies associated with gas saturation. The Leading Edge, 25: 206–210

Ostrander W J. 1982. Plane wave reflection coefficients for gas sands at nonnormal angles of incidence. Seg Tech Prog Exp Abs. 216–218

Pham N H, Carcione J M, Helle H B, et al. 2002. Wave velocities and attenuation of shaley sandstones as a function of pore pressure and partial saturation. Geophys Prospect, 50: 615–627

Pride S R, Berryman J G. 2003. Linear dynamics of double-porosity dual-permeability materials. I. Governing equations and acoustic attenuation. Phys Rev E, 68: 036603

Pride S R, Berryman J G, Harris J M. 2004. Seismic attenuation due to wave-induced flow. J Geophys Res, 109: B01201

Quakenbush M, Shang B, Tuttle C. 2006. Poisson impedance. The Leading Edge, 25: 128–138

Rafipour B, Herrin E. 1986. Phase offset indicator (POI): A study of phase shift versus offset and fluid content. Geophysics, 51: 679–688

Rapoport M B, Rapoport L I, Ryjkov V I. 2004. Direct detection of oil and gas fields based on seismic inelasticity effect. The Leading Edge, 23: 276–278

Ravagnan G, Mazotti A, Melis A, et al. 1992. Prestack seismic signatures of actual and synthetic reflections from different petrophysical targets. 54th EAGE Conference & Exhibition. Paris

Raymer L, Hunt E, Gardner J. 1980. An improved sonic transit time-to-porosity transform. SPWLA Tech Prog Exp Abs

Ren H, Goloshubin G, Hilterman F J. 2009. Poroelastic analysis of amplitude-versus-frequency variations. Geophysics, 74: N41–N48

Ringstad C, Westphal E, Mock A, et al. 2013. Elastic properties of carbonate reservoir rocks using digital rock physics. 75th EAGE Conference & Exhibition incorporating SPE EUROPEC 2013. London

Rubino J G, Velis D R, Sacchi M D. 2011. Numerical analysis of wave-induced fluid flow effects on seismic data: Application to monitoring of CO_2 storage at the Sleipner field. J Geophys Res, 116: B03306

Ruiz F, Dvorkin J. 2009. Sediment with porous grains: Rock-physics model and application to marine carbonate and opal. Geophysics, 74: E1–E15

Russell B H, Gray D, Hampson D P. 2011. Linearized AVO and poroelasticity. Geophysics, 76: C19–C29

Russell B H, Hedlin K, Hilterman F J, et al. 2003. Fluid-property discrimination with AVO: A Biot-Gassmann perspective. Geophysics, 68: 29–39

Rutherford S R, Williams R H. 1989. Amplitude-versus-offset variations in gas sands. Geophysics, 54: 680–688

Saenger E H, Enzmann F, Keehm Y, et al. 2011. Digital rock physics: Effect of fluid viscosity on effective elastic properties. J Appl Geophys, 74: 236–241

Sen M K, Stoffa P L. 1991. Nonlinear one-dimensional seismic waveform inversion using simulated annealing. Geophysics, 56: 1624–1638

Sen M K, Stoffa P L. 1992. Rapid sampling of model space using genetic algorithms: examples from seismic waveform inversion. Geophys J Int, 108: 281–292

Shapiro S A, Müller T M. 1999. Seismic signatures of permeability in heterogeneous porous media. Geophysics, 64: 99–103

Sharma M. 2005. Propagation of inhomogeneous plane waves in dissipative anisotropic poroelastic solids. Geophys J Int, 163: 981–990

Sharma M, Gogna M. 1991. Seismic wave propagation in a viscoelastic porous solid saturated by viscous liquid. Pure Appl Geophys, 135: 383–400

Sidler R, Carcione J M. 2007. Wave reflection at an anelastic transversely isotropic ocean bottom. Geophysics, 72: SM139–SM146

Smith G C, Gidlow M, 2003. The fluid factor angle and the crossplot angle. Seg Tech Prog Exp Abs, 185–188

Smith G C, Gidlow P M. 1987. Weighted stacking for rock property estimation and detection of gas. Geophys Prospect, 35: 993–1014

Sun L J, Yin X Y. 2011. A finite-difference scheme based on PML boundary condition with high power grid step variation (in Chinese). Chin J Geophys, 54: 1614–1623

Taner M T, Koehler F, Sheriff R. 1979. Complex seismic trace analysis. Geophysics, 44: 1041–1063

Tang X M. 2011. A unified theory for elastic wave propagation through porous media containing cracks—An extension of Biot's poroelastic wave theory. Sci China Earth Sci. 54: 1441–1452

Tarantola A. 1986. A strategy for nonlinear elastic inversion of seismic reflection data. Geophysics, 51: 1893–1903

Ursin B, Stovas A. 2002. Reflection and transmission responses of a layered isotropic viscoelastic medium. Geophysics, 67: 307–323

Vogelaar B, Smeulders D. 2007. Extension of White's layered model to the full frequency range. Geophys Prospect, 55: 685–695

Walton K. 1987. The effective elastic moduli of a random packing of spheres. J Mech Phys Solids, 35: 213–226

Wang B L, Yin X Y, Zhang F C. 2007. Gray approximation-based elastic wave impedance equation and inversion (in Chinese). Oil Geophys Pro, 42: 435–439

Wang K Y, Xu Q Y, Zhang G F, et al. 2013. Summary of seismic attribute analysis (in Chinese). Pro Geophys, 28: 815–823

Wang X J, Yin X Y, Wu G C. 2012. The application of an S transform-based absorption and attenuation technique for prediction of gas-bearing reservoir (in Chinese). Geophys Pros Petrol, 51: 37–42

Wang Y G. 2007. Methods for Seismic Data Comprehensive Interpretation (in Chinese). Dongying: China University of Petroleum Press

Wenzlau F, Altmann J B, Müller T M. 2010. Anisotropic dispersion and attenuation due to wave-induced fluid flow: Quasi-static finite element modeling in poroelastic solids. J Geophys Res, 115: B07204

Whitcombe D N. 2002. Elastic impedance normalization. Geophysics, 67: 60–62

White J. 1975. Computed seismic speeds and attenuation in rocks with partial gas saturation. Geophysics, 40: 224–232

White J E, Mikhaylova N G, Lyakhovitskiy F M. 1975. Lowfrequency seismic waves in fluid saturated layered rocks. Izv Acad Sci USSR Phys Solid Earth, 11: 654–659

Wilson A, Chapman M, Li X Y. 2009. Frequency-dependent AVO inversion. Seg Tech Prog Exp Abs. 341–345

Wood A B. 1941. A textbook of sound: being an account of the physics of vibrations with special reference to recent theoretical and technical developments. NewYork: Macmillan Company

Wu X, Chapman M, Wilson A, et al. 2010. Estimating seismic dispersion from pre-stack data using frequency-dependent AVO inversion. Seg Tech Prog Exp Abs. 425–429

Wyllie M R J, Gregory A R, Gardner L W. 1956. Elastic wave velocities in heterogeneous and porous media. Geophysics, 21: 41–70

Xu D, Wang Y, Gan Q, et al. 2011. Frequency-dependent seismic reflection coefficient for discriminating gas reservoirs. J Geophys Eng, 8: 508–513

Xu S, Saltzer R, Keys R. 2010. Integrated anisotropic rock physics model. WO Patent, US7676349B2, 2010-03-09

Xu S, White R E. 1996. A physical model for shear-wave velocity prediction. Geophys Prospect, 44: 687–717

Yang D H. 1998. Elastic wave propagation theory and finite element method based on BISQ model in porous anisotropic medium (in Chinese). Postdoctoral Research Report. Beijing: China University of Petroleum

Yang P J. 2008. Seismic wavelet blind extraction and non-linear inversion (in Chinese). Doctoral Dissertation. Qingdao: China University of Petroleum (Huadong)

Yin X Y, Yuan S H, Zhang F C. 2004. Petrophysical parameters extracted from elastic wave impedance (in Chinese). CPS/SEG 2004 International Geophysical Conference, Beijing, China

Yin W. 2006. Study of pre-stack elastic wave modeling and inversion parallel method (in Chinese). Doctoral Dissertation. Qingdao: China University of Petroleum (Huadong)

Yin X Y, Yang P J, Zhang G Z. 2008. A novel prestack AVO inversion and its application. Seg Tech Prog Exp Abs. 2041–2045

Yin X Y, Zhang S X, Zhang F C, et al. 2010. Utilizing Russell approximation-based elastic wave impedance inversion to conduct reservoir description and fluid identification (in Chinese). Oil Geophys Pro, 45: 373–380

Yin X Y, Zong Z Y, Wu G C. 2013. Improving seismic interpretation: A high-contrast approximation to the reflection coefficient of a plane longitudinal wave. Petrol Sci, 10: 466–476

Yin X Y, Zhou Q C, Zong Z Y, et al. 2014a. AVO inversion with t-distribution as prior constraint (in Chinese). Geophys Pros Petrol, 53: 84–92

Yin X Y, Zong Z Y, Wu G C. 2014b. Seismic wave scattering inversion for fluid factor of heterogeneous media. Sci China: Earth Sci, 57: 542–549

Yuan S Y, Wang S X. 2013. Spectral sparse Bayesian learning reflectivity inversion. Geophy Pro, 61: 735–746

Zhang F C. 2004. Method research of elastic wave inversion with pre-stack seismic data (in Chinese). Doctoral Dissertation. Dongying: China University of Petroleum

Zhang G Z, Chen H Z, Wang Q, et al. 2013. Estimation of S-wave velocity and anisotropic parameters using fractured carbonate rock physics model (in Chinese). Chin J Geophys, 56: 1707–1715

Zhang G Z, Wang D Y, Yin X Y, et al. 2011. Study on prestack seismic inversion using Markov Chain Monte Carlo (in Chinese). Chin J Geophys, 54: 2926–2932

Zhang L. 2009. Application of rock physics theory in seismic reservoir discrimination (in Chinese). Doctoral Dissertation. Qingdao: China University of Petroleum (Huadong)

Zhang S X, Yin X Y, Zhang F C. 2010. Quasi fluid modulus for delicate lithology and fluid discrimination. Seg Tech Prog Exp Abs. 404–408

Zhang S X, Yin X Y, Zhang G Z. 2011. Dispersion-dependent attribute and application in hydrocarbon detection. J Geophys Eng, 8: 498–507

Zhang S X. 2012. Research and application of fluid identification method based on seismic information (in Chinese). Doctoral Dissertation. Qingdao: China University of Petroleum (Huadong)

Zhang Z, Yin X Y, Zong Z Y. 2013. A new frequency-dependent AVO attribute and its application in fluid identification. 75th EAGE Conference & Exhibition. London

Zhao W J, Yang W Y, Zhang Q F, et al. 2012. A frequency-domain AVO hydrocarbon detection method (in Chinese). Oil Geophys Pro, 47: 436–441

Zhu J W, He Q D, Tian Z Y. 2001. BISQ-based seismic wave equation in oil-and-water-bearing porous media (in Chinese). Geophys Pro Petrol, 40: 8–13

Zhu X, McMechan G A. 2012. Elastic inversion of near- and postcritical reflections using phase variation with angle. Geophysics, 77: R149–R159

Zong Z Y, Yin X Y, Wu G C. 2012a. AVO inversion and poroelasticity with P- and S-wave moduli. Geophysics, 77: N17–N24

Zong Z Y, Yin X Y, Wu G C. 2012b. Fluid identification method based on compressional and shear modulus direct inversion (in Chinese). Chin J Geophys, 55: 284–292

Zong Z Y, Yin X Y, Zhang F, et al. 2012c. Reflection coefficient equation and pre-stack seismic inversion with Young's modulus and Poisson ratio (in Chinese). Chin J Geophys, 55: 3786–3794

Zong Z Y, Yin X Y, Wu G C. 2013a. Direct inversion for a fluid factor and its application in heterogeneous reservoirs. Geophys Pro, 61: 998–1005

Zong Z Y, Yin X Y, Wu G C. 2013b. Multi-parameter nonlinear inversion with exact reflection coefficient equation. J App Geophys, 98: 21–32

Zong Z Y, Yin X Y, Wu G C. 2013c. Elastic impedance variation with angle inversion for elastic parameters. J Geophys Eng 9: 247–260