Analysis of frequency-dependent seismic anisotropy from a multicomponent VSP

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Summary

In this study, we present results from the analysis of a multicomponent VSP for frequency-dependent anisotropy. The recorded four-component shear-wave data were first band-pass filtered into different frequency bands and then rotated to the natural coordinates to separate the fast and slow shear-waves. The polarizations of the fast shear-waves are found to be constant over the whole depth interval, and show no apparent variation with frequency. However, the time delays between split shear-waves decrease systematically as the frequency increases. We apply a time-frequency analysis method based on the wavelet transform with a Morlet wavelet to the data. A strong and consistent variation of shear-wave time delays with frequency is highlighted in the time-delay and frequency spectra. Two mechanisms are likely to explain the observation, i.e. scattering of seismic waves by preferentially aligned open fractures, and fluid flow in porous rocks with micro-cracks and macro-fractures.

Introduction

Recently, strong observational evidence suggests that the measured seismic anisotropy as inferred from time delays of split shear-waves does actually depend on frequency (Marson-Pidgeon and Savage, 1997; Chesnokov et al., 2001). This may appear initially to be surprising, but we can see later that this can be physically explained. Various equivalent medium theories have been proposed. These theories have provided the foundation of anisotropy analysis, but most theories fail to provide an adequate explanation of velocity dispersion at 'low' or seismic frequency and hence variation of anisotropy with frequency is not predicted. It is also not possible to determine the size of fractures from seismic data based on those theories. Two mechanisms which can introduce velocity dispersion and thus frequency-dependent anisotropy are the scattering of seismic waves in and fluid flow in fractured porous rock. The former has been investigated by Werner and Shapiro (1999); Chesnokov et al. (2001, 2002) while the latter has been the subject of Bayuk and Chesnokov (1998); Chapman (2002); Tod and Liu (2002).

In this study, we provide further evidence of frequency-dependent anisotropy through analysis of multicomponent VSP data from a fractured gas reservoir in the Bluebell-Altamont Field in northeastern Utah. Our work may be regarded as continuing and complementing early extensive studies by Lynn et al. (1999). Various techniques are used

in our analysis, including the time-frequency analysis method based on the wavelet transform with a Morlet wavelet to the data. A strong and consistent variation of shear-wave time delays with frequency is clearly visible, confirming the earlier observation of frequency-dependent anisotropy as reported and modeled by Chesnokov et al. (2001).

Data analysis

The geological setting of the Bluebell-Altamont field in Utah has been described in detail by Lynn et al. (1999), who have analysed extensive datasets as part of the US Department of Energy funded project. They have used both surface and borehole P-waves and shear-wave 3D-3C data to characterize naturally fractured gas reservoirs. We re-analyse the multicomponent shear-wave VSP data focusing on the variation of anisotropy with frequency.

Conventional analysis of multicomponent shear-wave data involves a simple rotation of horizontal four-component shear-wave data into the natural coordinate through the use of standard methods such as Alford rotation (Alford, 1986), with the aim of separating the two split shear-waves by minimising the off-diagonal energy. Once the shear-wave data are rotated into natural coordinate systems, the fast and slow shear-waves are separated. The rotation angle then represents the polarization angles of the fast split shear-waves, which are commonly interpreted as the fracture orientation. A cross-correlation can be applied to the fast and slow components to obtain the time-delays between the two split shear-waves (note that the sample rate is 2ms, and the data have been re-sampled to 0.5ms before a cross-correlation is applied). After the Alford rotation, the fast and slow components were band-pass filtered into five frequency bands. The polarizations are generally constant over the whole depth interval at 40° to 45° from the in-line direction, which agrees with the direction of predominant fracture orientations in the study area (Figure 1), and there is no apparent dependence of polarization on frequency. Figure 2 shows the variations of time delays between fast and slow shear-waves. We can identify three distinct intervals: In Interval I (from 2800 ft (853 m) to about 4000 ft (1219 m)), as receiver depth increases, time delays linearly increases, indicating this interval is seismically anisotropic. In Interval II between the depth of 4000 ft (1219 m) and 6800 ft (2072 m), the time delays remain almost constant, implying this interval is isotropic for the propagating waves as there is no further shear-wave splitting in this interval. Below the depth of about 6800 ft

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(2072 m), the time delays begin to increase abruptly. This interval (Interval III), which is also the target of the reservoir in Bluebell-Altamont field, thus shows strong anisotropy (about 3% to 4%), which is attributed to the presence of intense fracturing in the reservoir.

Figure 1. Variation of polarisation of fast split shear-waves with depth after the data have been band-pass filtered into 5 frequency bands. The angles are relative to the in-line component.

Figure 2. Variation of time-delays of split shear-waves with depth and frequency..

The shear-wave traveltime anisotropy is interpreted to be caused by the presence of open, aligned, vertical fractures, striking northwest in the Upper Green River Formation. If we assume the magnitude of shear-wave anisotropy (time delays between split shear-waves) is proportional to the fracture density, then the highest density of open, gas-filled fractures is interpreted to be in the interval between 6800 ft (2072 m) and 8650 ft (2636 ft). A linear regression is applied to fit the time delays variation with depth for each frequency band. Figure 3 shows the variation of anisotropy (in percentage) with frequency estimated from the gradient

of the linear fit to the time-delay in the in target interval between the depth of 6800 ft (2072 m) and 8650 ft (2636 m), and we can see a clear decrease of anisotropy with frequency (in Figure 3, we have omitted the first point (0-10Hz) as it is considered to be unreliable).

Figure 3. Variation of anisotropy (in percentage) with frequency in the target interval between the depth of 6800 ft (2072 m) and 8650 ft (2636 m).

Time-frequency analysis

In this section, we shall present a technique to process multicomponent shear-wave data using a continuous time-frequency analysis. Considerable progress has been made recently in the analysis of non-stationary or time-varying signals by using the time-frequency signal representations. The procedure of our analysis is described below.

Firstly, the four component data are rotated into the natural coordinate system, i.e. fast and slow shear-waves are separated into different components as discussed in the previous section. The rotated components are denoted by $s_1(t)$ and $s_2(t)$. Secondly, we apply the wavelet transform with a Morlet wavelet to the fast and slow shear-wave components to obtain time-frequency spectra (or local spectra) of recorded waves. The transformed traces are denoted by $S_1(t,f)$ and $S_2(t,f)$. The number of samples used in the wavelet transform is 32 samples (note that the data were re-sampled from 2 ms to 0.5 ms). Examples from trace number 80 (receiver depth at 6800 ft or 2072 m) are shown in Figure 4. We can see a clear difference in travel times between the fast and slow shear-waves, and also the difference in frequency spectra between the fast and slow shear-waves. Thirdly, we pick the maximum amplitudes and their corresponding arrival times for each frequency in the transformed fast and slow components $S_1(t,f)$ and $S_2(t,f)$ [or power spectra $|S_1(t,f)|^2$ and $|S_2(t,f)|^2$]. Finally, the time delays between split waves for each frequency are obtained

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by subtracting the travel times corresponding to the maximum amplitudes (or power spectra) of the transformed components $S_1(t,f)$ and $S_2(t,f)$. This procedure is repeated trace by trace for all the depth intervals to build complete time-delay and frequency spectra.

Figure 4. Time-frequency spectra of the fast and slow shear-waves recorded at the receiver depth of 6800 ft (2072 m). Bottom figure is for the fast shear-wave, and top figure is for the slow shear-wave at this depth.

The result from the analysis described above is given in Figure 5. It shows a color-coded map of the variation of time-delays with frequency for all depth intervals. The color bar is time-delays in milliseconds. The results reveal clearly an increase of time-delay with depth (color changes from light yellow to red) and decrease of time-delays as frequency increases (color changes from yellow-red to light green-yellow). Clearly, we see an increase in time delays with depths (color changes from light yellow to red) and a decrease of time delays with frequency (color changes from red to yellow). This is basically the confirmation of the results in Figure 2, where a band-passing filter was applied.

The time-frequency analysis thus can give a continuous variation of time-delays with frequency.

Figure 5. Time-frequency analysis of shear-wave splitting. It shows a color-coded map of the time-delays and frequency spectra. The color bar shows the time delay in milliseconds.

Discussion

Evidence of frequency-dependent anisotropy has also been reported by Marson-Pidgeon and Savage (1997) for earthquake data. We shall discuss the two most likely mechanisms that can cause velocity dispersion, and hence frequency-dependent seismic anisotropy.

Frequency-dependent anisotropy is related to the scattering of seismic waves in heterogeneous rocks. One typical example is wave propagation in finely-layered media (Werner and Shapiro, 1999). This leads to the conclusion that any heterogeneous materials with certain alignment or ordered distributions must behave like an anisotropic medium to elastic waves at some frequencies. The scale of heterogeneities can be constrained by the fact that they need to be small enough to cause effective anisotropy instead of scattering. This requires a quasi-homogeneous propagation regime which can be expressed mathematically as $ka < 0.1$, where k is the wavenumber, and a is the scalelength of the heterogeneities. For the data presented in this paper, the dominant frequency is 25 Hz, and the average shear-wave velocity is about 7000 ft/s (2133 m/s), therefore we would expect scalelengths smaller than around 10 m will cause effective anisotropy. Heterogeneities larger than 80 m will cause scattering of seismic waves, thus reduce the time delays due to effective anisotropy. Chesnokov et al. (2001, 2002) have presented a model addressing frequency dependent seismic anisotropy that arises when there is an order in the orientation of contrasting inhomogeneities. Anisotropy can only be observed when the wavelengths of propagating waves (P or S) are much greater than at least one (of possibly many)

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scale lengths associated with the sizes of inhomogeneities, i.e. in the case where the assumptions of the long wavelength approximation are satisfied. As frequency increases and wavelengths become commensurate with these scalelengths, anisotropy becomes smaller and smaller. Beyond a certain transition frequency, it becomes minimal, with the propagation being better characterized by discrete scattering effects. Using the correlation approximation, A surprising result is that treating the density as a dynamic quantity (frequency dependent) lowers this transition frequency (from anisotropic to scattering dominated propagation). They compare the results from our paper with theoretical modeling results based on the two different models, and found that a model with randomly distributed isotropic and fractured layers gives a better fit to the frequency dependent anisotropy estimated from the data than a model with only large vertical fractures.

The other likely cause of frequency-dependent anisotropy is related to the fluid flow in fractured porous rock. Bayuk and Chesnokov (1998) investigate the correlation of elastic wave anisotropy of P- and shear-waves and transport properties of cracked porous rock and conclude that seismic waves can be used to distinguish fluid properties (oil, gas) of reservoir rocks. Chapman (2002) demonstrated that in the presence of larger scale fractures (in the order of meters), substantial frequency dependence can be expected in the seismic frequency ranges, and therefore it is not safe to treat seismic frequency as a low frequency limit. The percentage of anisotropy change can be up to 5 to 10% for gas filled, and 2% for brine-filled fractures at multi-scale fluid flow. Tod and Liu (2002) have presented a model that describes a fluid flow mechanism between elliptical cracks (bed-limited cracks) that produces a frequency-dependence in the resulting effective material parameters, and hence in the shear-wave splitting. They demonstrate that the effects of fluid flow, whether that be gas or liquid, are non-negligible and an important contributing factor to observed frequency-dependent anisotropy.

Conclusions

We have provided strong observational evidence showing the variation of shear-wave anisotropy with frequency from analysis of multicomponent VSP data in a fractured gas reservoir. We have presented a processing technique based on the time-frequency representation of transient signals to extract time-delays and frequency information. Time-frequency analysis of shear-wave splitting enables us to detect multiple arrivals in time, and variations in shear-wave splitting with frequency. The method can be potentially used to analyse anisotropy and shear-wave splitting, and to attribute multicomponent seismic attributes. Frequency-dependent anisotropy is a very interesting phenomenon and it is related to wave dispersion.

Two mechanisms, i.e. seismic scattering by heterogeneities, such as open aligned fractures, and fluid flow in fractured porous rock, are both likely to contribute to the observed variation of anisotropy with frequency. If the proper mechanism is understood, it may provide the means of going beyond the concept of the conventional static equivalent medium concepts to potentially map the size of meso-scale fractures whose lengths are much larger than the microcracks or grain boundary pores, but less than the seismic wavelength, and to extract information about fluid transport in reservoir rocks.

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