Anisotropic P-wave attenuation measured from a multi-azimuth surface seismic reflection survey

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Abstract

A system of aligned vertical fractures produces azimuthal variations in stacking velocity and amplitude-variation-with-offset (AVOA), characteristics often reported in seismic reflection data for hydrocarbon exploration. Studies of associated attenuation anisotropy have been mostly theoretical, laboratory-, or VSP-based. We used an 11 CMP-long portion of each of four marine surface-seismic reflection profiles, intersecting each other at 45° within c.100m of a common location, to measure azimuthal variation of effective attenuation, Q_{eff}^{-1}, and stacking velocity, in a shallow interval, about 100m thick, in which consistently orientated vertical fracturing was expected due to underlying salt diapirism. We found qualitative and quantitative consistency between azimuthal variation in attenuation and stacking velocity, and published AVOA results. The 135° azimuth line showed the least apparent attenuation ($1000Q_{eff}^{-1}=16\pm7$) and the fastest stacking velocity, hence we infer it to be closest to the fracture trend: the orthogonal 45° line showed the most apparent attenuation ($1000Q_{eff}^{-1}=52\pm15$) and slowest stacking velocity. The variation of Q_{eff}^{-1} with azimuth ϕ is well fitted by $1000Q_{eff}^{-1}=34-18\cos[2(\phi+40°)]$ giving a fracture direction of 140±23° (±1SD, derived from 'bootstrapping' fits to all 11^4 combinations of individual CMP/azimuth measurements), compared to 134±47° from published AVOA data. Effects of short-window spectral estimation, and choices of spectral ratio bandwidth and offset ranges used in attenuation analysis, individually give uncertainties of up to ±13° in fracture direction. This magnitude of azimuthal variation can be produced by credible crack geometries (e.g. dry cracks, radius 6.5m, aspect ratio 3×10^{-5}, crack density 0.2) but we do not claim these to be the actual properties of the interval studied, because of lack of well control (and its consequences for choice of theoretical model and host rock physical properties), and the small number of azimuths available here.

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Introduction

Analysis of seismic reflection surveys in an anisotropic framework is becoming more common in hydrocarbon exploration, where geological settings that produce anisotropic seismic properties (such as fractured rocks or interbedded fine layers) are present. Anisotropic analyses are often needed simply to improve imaging of reflecting interfaces (e.g. Alkhalifah *et al.* 1996) because much conventional seismic processing assumes isotropic conditions. Anisotropic properties can themselves be of interest and yield other information. For example, the Thomson parameters as combined in the effective anisotropy parameter η, (Thomsen 1986: Alkhalifah and Tsvankin 1995) is used by Alkhalifah and Rampton (2001) as a sand:shale discriminator and correlation tool; Raymer *et al.* (1999, 2000) predict and observe anisotropy in salt bodies due to halite deformation. Mapping fracture, and hence permeability, trends using seismic anisotropy is a promising tool for evaluating some hydrocarbon reservoirs (e.g. Lynn *et al.* 1995).

Much interest has focussed on sets of parallel vertical fractures (HTI media), leading to azimuthally-varying wavespeeds expressed in reflected P wave travel-time moveout (Grechka and Tsvankin 1998, 2002; Vasconcelos and Tsvankin 2006). Much effort has also been devoted to development of anisotropic reflection coefficients (e.g. Sayers and Rickett 1997) and characterisation of amplitude variation with source-to-receiver offset and azimuth (AVOA). Rüger (1998) offered an analytic approximation to reflection coefficients in azimuthally anisotropic media. Supported by synthetic modelling experiments of Mallick *et al.* (1998), these results suggested that, at a fixed source-receiver offset, reflected wave amplitudes have a simple "cos(2θ)" dependence on θ, the shooting direction relative to the fracture system strike, thus presenting a simple method for exploiting AVOA to extract the principal direction of anisotropy. Hall (2000) finds a possible 90° ambiguity in fracture

trends derived this way, while Harwood *et al.* (1998) combine this approach with conventional AVO analysis to estimate fracture trends and AVO characteristics simultaneously.

Attenuation has long been known to be sensitive to fractures (e.g. Silaeva and Schamina 1960; Rathore *et al.* 1995; Hudson *et al.* 1996; Maultzsch *et al.* 2007). Therefore, mapping azimuthal anisotropy of attenuation could complement AVOA as means of determining fracture direction and properties, as well as informing other analyses such as azimuthal NMO and shear-wave birefringence. Simultaneously, however, such attenuation variations might complicate AVOA by introducing azimuthal variations to AVO gradients and, if uncorrected, a bias to AVOA-derived results. Therefore, there is a need to investigate whether azimuthal variation of attenuation may be measurable, and correlated with other fracture-related data characteristics. In this paper, we aim to do so, by studying a 3D, marine, towed-streamer surface-seismic dataset whose acquisition geometry makes measurement of azimuthal anisotropy of P-wave attenuation especially easy. Beginning with a suite of attenuation measurements and associated fracture-strike estimates made by Benson (1998), we find significant azimuthal variation of attenuation, and furthermore excellent correspondence between this, travel-time moveout, and previously-reported AVOA results, from which a likely fracture orientation can be inferred, and which statistical tests suggest is quite robustly estimated.

Attenuation measurements

Anisotropic intrinsic attenuation is predicted theoretically and seen in laboratory ultrasonic and field VSP studies (e.g. Samec and Blangy 1992, Wulff *et al.* 1999, Pointer *et al.* 2000, Chapman 2003, Maultzsch *et al.* 2003; Chichinina *et al.* 2004; Zhu and Tsvankin

2007; Zhu *et al.* 2007): Grechka and Kachanov (2006) review and compare competing effective-media theories for fractured rocks. Azimuthal variations may arise in apparent as well as intrinsic attenuation: in a model study of thin gas sands within shales, Schoenberg *et al.* (1999) show azimuth- and offset-dependent tuning effects. [Note that, in this paper, we refer to tuning and scattering as 'apparent attenuation', and the combined effect of this and intrinsic attenuation as 'effective attenuation', Q_{eff}^{-1}. It is effective attenuation that is measured by most field seismic experiments.] Shen *et al.* (2002) study a carbonate reservoir with aligned vertical fractures, through both model and field data: they find that fracture-normal azimuths show a large negative frequency-versus-offset gradient but in the fracture strike direction this gradient is small. Most field attenuation measurements are made on borehole data (Tonn 1991, Leaney *et al.* 1999) giving only limited spatial coverage.

Dasgupta and Clark (1998) introduced a method, which they termed "QVO", for estimating attenuation from routinely-acquired surface seismic reflection surveys. Its basis is the spectral ratio method (e.g. Tonn 1991), applied to a chosen reflection event trace-by-trace across a suitably pre-processed CMP gather rather than a stacked trace – effects of path-length increase with offset, instead of smearing the attenuation signature in a stacked trace, are exploited quantitatively to estimate effective attenuation. On each trace, the spectrum of the windowed event $A(\omega)$ is divided by that of a reference spectrum $A_0(\omega)$, usually the nominal or measured source signature, giving

$$\tag{1}$$

where *x* is distance travelled, *c* is phase velocity, ω is angular frequency, and the constant term includes all frequency-independent effects such as geometric spreading. Under the

assumptions made, resultant $\log_e$(spectral ratio) slopes are proportional to offset[2] (for small-spread conditions) due to path-length (i.e. travel time) effects in a 1-D structure where intrinsic Q in each layer is constant and isotropic. Linear regression gives a zero-offset $\log_e$(spectral ratio) slope and the source-to-reflector effective attenuation, Q_{eff}^{-1}. Alternatively, Carter (2003) removes the travel-time component explicitly from each offset's spectral ratio and simply averages the resultant ensemble of Q_{eff}^{-1} estimates, thereby relaxing the small-spread requirement. Applied separately to pairs of reflections, Q_{eff}^{-1} of the interval between is then estimated. Dasgupta and Clark (1998) caution that Q_{eff}^{-1} includes effects due to scattering and tuning.

The authors' experience using QVO as published has led to the realisation that one of the methods' implicit assumptions (i.e. that both upper and lower analysis windows contain only strong and isolated reflections) often breaks down, as such truly isolated events are rarely encountered (e.g. Anstey and O'Doherty 2002). The method would still recover Q_{eff}^{-1} if the spectra of the primary reflectivity sequence (and the effects of any multiples not removed in processing) contributing to the two analysis windows were equal. In practice, this assumption may also often be violated and hence Q_{eff}^{-1} can be strongly influenced by multiples and by local layering around the reflectors of interest. In general, Q_{eff}^{-1} values obtained from QVO will not correspond to the constant-Q component of the frequency-dependent attenuation experienced by the seismic wave over the interval studied.

However, Clark *et al.* (2001) observed that if the method were applied in an appropriate comparative sense, such as in a multi-azimuth comparison, relative differences in Q_{eff}^{-1} would remain meaningful. Our experiment extends over only a *c.*100m diameter areal scale, so we assume that the spectrum of the primary reflectivity around the reflections of interest is not changed strongly with azimuth, because of velocity anisotropy due to

fracturing (e.g. Chichinina *et al.* 2006), lateral velocity variations, or dipping structures. Under these assumptions, the relative change in Q_{eff}^{-1} is meaningful in terms of fracture orientation (Vasconcelos and Jenner 2005). The short-window Fourier Transform used in the QVO method is not ideal for extracting time-localised spectral content (recent work (e.g. Wang 2004) has investigated, for example, the Gabor Transform (Gabor 1946) as an alternative) but we carry out some simple tests to confirm that our short-window Fourier-based results are sufficiently robust.

Here, we measure azimuthal variation of apparent attenuation, using the QVO method of Dasgupta and Clark (1998), in the marine seismic reflection dataset used by Harwood (1997) for an AVOA study. Consistently-orientated vertical fracturing is expected in a target interval across which 4 seismic reflection profiles at 45° from each other intersect within some 100m of a common location. Based on indications from the operator of the license, we assume that, on the scale of this study, there is no significant overall dip, and the medium demonstrates HTI anisotropy only, i.e. the fracturing is consistently-orientated and vertical and that there is no VTI contribution from the host rock matrix. We then compare the attenuation characteristics to the velocity field derived during processing (through residual moveout, RNMO) and to published AVOA analyses (Harwood *et al.* 1998). After the 90° rotation of the AVOA result as suggested by Hall (2000), amplitude, velocity and attenuation anisotropy are in excellent quantitative agreement, and we conclude that a dominant fracture trend has been identified.

The dataset and spectral ratio processing

The geological succession comprises some 100m of water overlying about 500m of overburden material followed by a target interval, around 100m thick, believed to be

carbonate sediments, and clearly defined by horizontal reflectors at approximately 650ms and 750ms TWT. ("Target" is used in the context of this study, and does not imply an expectation of hydrocarbons present.) Emplacement of a salt diapir some 500m beneath the target is expected to have caused fracturing, along a consistent regional trend. There is no well control at this location. Four full 3D towed-streamer surveys, with sail-lines at 45° to each other, had been carried out over this area during a single acquisition campaign, all with identical acquisition parameters (such as streamer cable, source wavelet, etc.): a so-called multi-azimuth (MAZ) survey. Extraction of quasi-2D, i.e. sail-line, profiles from these data made attenuation measurement especially easy, because it was not necessary to account for any frequency- and azimuth-dependent source and receiver directivity, as was shown by Hustedt and Clark (1999) to be necessary for very shallow 2D data analysed with the QVO method. Data were available only as amplitude-preserved pre-stack depth-migrated CMP gathers in both depth and time domains. Processing used the same isotropic P-wave velocity field, derived from the 135° azimuth line, for all four azimuths and CMPs, specifically in order to reveal anisotropic characteristics as differences between lines (azimuths). P-wave speeds in the overburden and target intervals are about 1800ms^{-1} and 2300ms^{-1} respectively. Four 11-CMP (125m) long sail-line profiles, intersecting at 45° intervals within about 100m over a common location, were extracted (Figure 1). A representative set of spectral ratios and the variation of log$_e$(spectral ratio) with (offset)^2 are shown in Figure 2. All spectral ratios were computed relative to the same, contractor-supplied, far-field source signature, which had a bandwidth of 30-100Hz at least (peak spectral amplitude at around 65Hz, falling off to *c.*4dB down at 30Hz and 100Hz). Due to the 'layer-stripping' approach in the method of Dasgupta and Clark (1998), errors in this signature will not map into systematic errors in estimated Q_{eff}^{-1} values. Observed spectral

ratio slopes generally flatten or become erratic above some 90Hz or so, suggesting there is no signal present: we used lower limits of 30-40Hz and upper limits of 75-85Hz for our regressions. The sensitivity of results to the analysis bandwidth is assessed below. The target interval is only c.100m thick, yet imposes fractional losses of c.25% in amplitude during two-way transit at the dominant frequency at typical Q_{eff}^{-1} (Table 1) or as much as 75% at the highest frequencies and lowest Q_{eff}^{-1}. Along a given profile, the individual Q_{eff}^{-1} values at each of the 11 CMPs are averaged to yield a single Q_{eff}^{-1} value for the profile, although since (at the target level) the migrated Fresnel Zone radius is only about 30m, some lateral variation in seismically imaged structure may have been incorporated into these averages.

Results

Harwood (1997) applied the AVOA method of Mallick *et al.* (1998), albeit with an isotropic velocity field, to these four short profiles. Harwood *et al.* (1998) studied the whole 3D survey area, finding irregularly shaped patches of internally consistent principal directions at one or the other of two orthogonal azimuths. At this intersection, it is 44±47°, reworked using conventional directional statistics (as applied to e.g. palaeomagnetic directions: Fisher *et al.* 1987) from the portfolio of individual results given by Harwood (1997). Uncertainty bounds cited are 63% probability, analogous to one standard deviation (McElhinny, 1973). However, the recognition by Hall (2000) of a 90° ambiguity in inferences from the Mallick *et al.* (1998) method makes this result inconclusive: the fracture direction could be 134±47°.

This ambiguity is apparently resolved by the azimuthal variations in moveout velocity that we find for the same event. All azimuths except 135° are under-corrected by the

isotropic NMO correction (Table 1). A least-squares "cos 2ϕ" fit to the residual moveout

(RNMO) percentages (Table 1) gives 138±2° as the azimuth of fastest velocity, i.e. the

fracture trend, suggesting that the principal direction given by AVOA results is orthogonal to

the fracture trend. However, while the most under-corrected (and least hyperbolic) azimuth

is indeed 45°, there are only small RNMO differences between the 0°, 45°, and 90° lines.

The 135° result could be regarded an 'outlier', rendering this evidence inconclusive.

Apparent attenuation for the target interval, though, shows significant azimuthal

variation (Table 1, Figure 3). The 45° line, inferred to be most orthogonal to the fracture

trend, exhibits the largest apparent attenuation ($1000Q_{eff}^{-1}$=52±25, or Q_{eff}=19±3, different

from the remainder at >99% confidence level). The 135° line, closest to the fracture trend,

shows the smallest apparent attenuation ($1000Q_{eff}^{-1}$=15±12, or Q_{eff}^{-1}=64±15). The 4

azimuths are fitted very well by $1000Q_{eff}^{-1}$=34-18cos(2[ϕ+40°]), (where ϕ is sail-line

azimuth), a form of variation that it is not unreasonable to expect (e.g. Hudson 1981; Zhu

and Tsvankin 2007) although admittedly too few azimuths are available to identify a unique

analytic form (in neither the attenuation nor the moveout results). The fit is repeated for all

possible combinations of the 11 individual observations at each azimuth. The resulting

distribution (Figure 4) has a mean of 140±23° and offers a measure of the uncertainty in the

inferred fracture direction). Azimuthal variation in dominant frequencies (averaged over all

offsets) supports qualitatively the attenuation results.

The AVOA signature of the base-overburden reflector ("Reflector 1" in Figure 1)

suggested that the overburden was azimuthally isotropic (Harwood 1997), yet an

azimuthally varying RNMO pattern is seen. However, we preferred not to make attenuation

measurements for the overburden interval with the data available here. Simple "source-to-

base-overburden" results will include systematic biases such as differences in noise levels,

sea-bed reflectivity and source signature between or within lines. Such effects are only circumvented by analysis of an interval, but to do so needs a top-overburden reflector (such as the sea-bed or other very shallow event, above 'reflector 1', to be defined. However, any such event would be so shallow that its spectra would require correction for source/receiver directivity (Hustedt and Clark 1999): also, the top mute limited the range of offsets available, and/or the numerical limits of NMO stretch corrections (see 'Discussion') would be violated. Note that the 'layer-stripping' element of Dasgupta and Clark's (1998) "QVO" process means that any irregularity in the overburden results does *not* corrupt results from the target interval.

The unit underlying the target was too thin to give stable attenuation measurements. Furthermore, its lower part shows variations in wavelet shape and timing even at the shortest offsets. This suggests that, below the 'target' interval, our assumption of an HTI-only medium with no zero-offset azimuthal variation in velocity and reflectivity is violated. Thus, we do not process this interval.

To assess how much our results were distorted by use of a short-window FFT for spectral estimates, we carried out a simple numerical test on noise-free synthetic wavelets, produced from a typical bandwidth airgun wavelet, attenuated using a Kjartansson (1979) constant-Q operator for the travel times and mean Q_{eff}^{-1} values we found in these data (Table 1), then analysed with the same short-window FFT approach. We found an average discrepancy of only 3% between input and estimated Q_{eff}^{-1} values, 2% in the magnitude of the coefficient of the "cos 2θ" term, and <1° in the azimuth of least attenuation. These values increase to 7%, 10%, and 4° respectively for noisy (SNR 5:1) synthetics. Noting that our cited field results are averages of 11 measurements, we have confidence that results we report are sufficiently reliable.

Discussion

These data show a striking qualitative and quantitative consistency between measured anisotropic velocity, AVO, and attenuation for the 'target' interval. First, we re-state that, with only 4 azimuths available for analysis, reconstruction of any particular analytic form of aziumthal variation (whether in velocity or attenuation) is not robust (e.g. Lynn, 2007): furthermore, the magnitude of azimuthal velocity variation is small and the ±0.1% given in a statistical fit probably underestimates the real uncertainties. Outcomes of statistical tests on fracture direction based on our attenuation data as well as published AVOA data are summarised in Table 2. In future analyses, it would be highly desirable to have a richer population of azimuths.

Our primary aim with this work is to investigate attenuation-derived fracture azimuth and compare it to AVO-derived results. Nevertheless, it is useful to show that our attenuation characteristics can apparently be derived from credible subsurface characteristics. Clark *et al.* (2001) pointed out that, due to the biasing effect of apparent attenuation on the 'background' level of measured, or effective, attenuation, it is *relative* attenuation that is meaningful in the azimuthal anisotropy context. Hence, the results of Chichinina *et al.* (2004, 2006), who succeed in modelling the magnitude of the azimuthal change in our attenuation observations, (using the interconnected crack model of Hudson *et al.* (1996) with cracks of aspect ratio 0.1, crack density 0.05) support the credibility of our measurements. Here, we too succeed in matching this aspect of our measurements (Figure 3), with the Hudson (1996) model but using different crack properties (tabulated with Figure 3). However, there is a great deal of non-uniqueness in such matching (exacerbated here

by the lack of well control to constrain more parameters). Furthermore, there is a lack of consensus as to which fractured-medium model (if any) is universally appropriate (see, for example, discussion in Grechka and Kachanov 2006). These factors, added to non-uniqueness in the fitted "cos 2ϕ" solution (discussed further below), we stress that we make no claim that these estimates of fracture parameters are authoritative.

AVO (and hence AVOA) data need correcting for attenuation effects (e.g. Luh 1993). Because the signal bandwidth is quite large, attenuation effects ought to be removed using a proper inverse-Q deconvolution (e.g Wang 2002). Here, travel times are short and the anisotropic interval is rather thin, so we adjusted the picked amplitudes of Harwood (1997) using the azimuth-dependent measured apparent attenuation (Table 1) as expressed at a fixed frequency of 40Hz, rather than using inverse-Q deconvolution. Hence, despite choosing a frequency higher than the dominant one, amplitude changes were very small, modifying the 2-term Shuey (1985) AVO slope and gradient terms by a maximum of 5-10%. Whilst this may be important where AVO attributes are used quantitatively to infer pore-fill characteristics, it is not enough to suggest that the original AVOA inferences would be wrong by 90°.

We now critically assess the robustness of our results (using the closest CMP to the geographic intersection of all lines as a representative dataset) then discuss more sophisticated analyses that might be used to investigate such datasets.

First, we use this representative CMP to test our choice of regression bandwidth for spectral ratio slopes. We re-computed azimuthal variation of spectral ratios for all offsets, and for 22 bandwidths of 30Hz or greater between lower limits of 10-40Hz, and upper limits of 40-100Hz, each in steps of 10Hz. The amplitude of azimuthal variation, as expressed by

the coefficient of the cos2(ϕ+α) term, varied by ±32%. The inferred fracture direction (i.e. direction of minimum attenuation) was 169±13°. Thus our fracture direction appears robust to bandwidth choice, although the magnitude of azimuthal variation (from which fracture geometries may be estimated) is less well measured.

Following Dasgupta and Clark (1998), an NMO Stretch correction (Dunkin and Levin 1973, Barnes 1992), was applied during attenuation analysis, with the same velocity field that was used for NMO correction. Because this velocity field is isotropic, concern over RNMO effects is confined to issues of windowing the events easily, and not of using a 'wrong' velocity in stretch corrections. However, Dasgupta and Clark (1998) limited their analyses to offsets where NMO stretch was ≤20%, to have confidence in the correction algorithm. Our data exceed that limit (reaching roughly 30-40% and 25-30% in the top and base target reflectors respectively) *but* because of our azimuth-invariant velocity field, errors induced by the inexact correction will be consistent at all azimuths – *relative* attenuation effects will be preserved, and our fracture direction estimates will be robust. To avoid NMO stretch effects, we could use pre-NMO gathers and an analysis window that tracks a chosen event along its moveout trajectory (Guerrero Moreno 2006) but this introduces additional complications over the offset-dependence of thin-bed effects (Carter 2003). For our azimuthal variation case, either approach is appropriate.

For an interval containing an ensemble of parallel vertical fractures, wave propagation models (e.g. Tod, 2001; Chapman 2003) predict that the attenuation imposed on a ray crossing the fractures set will be a function of both source-receiver azimuth *and* offset, i.e. the angle of incidence of the ray on the fractures. For this reason, Maultzsch (2005) and Maultzsch *et al.* (2007), in VSP data, measures azimuthal variation of attenuation by

applying the spectral ratio method to events recorded at a fixed source-receiver offset but various azimuths, seeking a "cos 2ϕ" variation in spectral ratios, thereby avoiding a complex offset dependence in single-azimuth walkaway data.

In our data, the longest offsets give an angle of incidence, ϕ, from the vertical of about 54°. At a fixed source-receiver azimuth, the change in accumulated attenuation with offset will contain not only a simple path-length contribution, but also an offset-dependent contribution from the fractures. The former is, but the latter is *not*, incorporated into the QVO algorithm (Dasgupta and Clark 1998). At azimuths parallel to fractures, the QVO-derived result should be a true zero-offset result. However, for any azimuth oblique to fractures, the QVO-derived result will *not* be a true zero-offset result (the latter should be azimuth-invariant for *any* model) but a 'smeared' average of results at all offsets. Chicinina *et al.* (2006) propose a fracture-derived $\sin^2\phi$ dependence of $Q^{-1/2}$, whereas the path effect used in our algorithm is approximately a Q^{-1}:$\tan^2\phi$ dependence. For our data, signal-to-noise ratios in the spectral ratios (Figures 2i-2p) suggest that any more sophisticated fitting of the data is probably unjustified. To show that this more complex offset dependence does not obscure our QVO-derived estimate of fracture direction, we break the data from a representative CMP (the closest to the geographic intersection of all lines) into near-, mid-, and far-offset subsets. The magnitude of the azimuthal variation does indeed increase with offset: the coefficient of the "cos(2[$\phi+\alpha$])" term is 60%, 90%, and 163%, for near-, mid-, and far-offsets respectively, of the value given by all offsets combined. Equivalent results for the constant "α" (where the fracture azimuth is 180-α) are 65°, 39°, and 20°, compared to 34° for all offsets combined. These imply a fracture direction of 159±11°, again probably representing a realistic bound on our estimates. Our 'all offsets' result is therefore roughly equivalent to

our mid-offset result, and we feel our fracture direction estimate in Figure 3 is therefore robust. This investigation of one CMP suggests that, to find fracture orientation, we should use just far-offset data, where the signature of attenuation anisotropy is largest; however, at long offsets, the signal-to-noise ratios are usually poorest. Instead, and preferably, we should capture both offset and azimuth dependence of attenuation (QVOA) in a single 'surface-fitting' analysis of the variation of spectral ratio slopes from MAZ datasets: we are under way with such work at present. We note, though, that the 'surface' to fit to such data may be rather complex. In anelastically attenuating, and hence dispersive, media, reflectivity must be frequency-dependent. This, combined with the frequency-dependent Q predicted for transmission through fractured media (Chapman 2003), implies a complicated spectral behaviour as a function of azimuth and offset (Chapman and Liu, 2005). Studies that hope to infer detailed fracture characteristics in settings such as low-Q fractured reservoirs may need to be set in such a framework (e.g. Odebaetu *et al.* 2006).

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