Characterizing intrinsic and stratigraphic Q in VSP data with information measures, Part II

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ABSTRACT

In an earlier report that has the same title as this, an information measure was devised and conducted on the synthetic vertical seismic profiling (VSP) data sets, with the ability to amplify small differences produced by the processes of intrinsic amplitude attenuation and stratigraphic filtering, aiming at discriminating between the two. The information measure was adapted to seismic records like this: for a discrete zero-offset VSP data set, each of its time snapshots was regarded as a "message"; we used Shannon entropy to measure the amount of information carried by the "message", which represents the degree of disorder of the wave field at the instants of time, and investigated the entropy variation with time. It was observed that the intrinsic Q and stratigraphic Q always tend to affect the measured entropy result in the opposite way. For the first-order entropy, wave fields including intrinsic Q tend to contribute to small entropy values while wave fields including stratigraphic Q tend to contribute to big entropy values. Making use of this attribute of entropy, this research investigates the relationship between: (a) the entropy peak increase from the wave field that associates with neither intrinsic Q nor stratigraphic Q to the wave field under simultaneous effects of intrinsic and stratigraphic Q, and (b) the strength of stratigraphic Q relative to total Q measured by the spectral ratio method. A seemingly positive relationship between them is found, implying that the entropy behavior may be used as an indicator of the relative strength of intrinsic Q and stratigraphic Q when they are both active. The speculation is supported by the result of the information measure on a field VSP data.

INTRODUCTION

Stratigraphic filtering and absorption have highly similar amplitude attenuating and dispersing effects on the seismic wave: decaying and spreading waveform, reducing the high-frequency content of the initial disturbance and appending an incoherent coda to the signal. Stratigraphic filtering can be regarded as an extrinsic Q factor since its mechanism lies in the subsurface stratification instead of intrinsic rock properties. Correspondingly, the absorption can be regarded as an intrinsic Q factor.

In a 2016 CREWES report (Lv and Innanen, 2016), an information measure was applied to synthetic VSP data sets to characterize absorption and stratigraphic filtering. From the information theory perspective, wave field containing complex reflecting events can be thought as carrying considerable amount of information in it, whereas wave field which excludes a complex train of reverberations might be said to have relatively small amount of information. Because stratigraphic filtering is associated with internal multiples, wave fields containing stratigraphic filtering effect were expected to carry larger amount of information than other wave fields.

The information measure used Shannon entropy to measure the amount of information, which is positively related to the degree of disorder, in the VSP wave fields. For a discrete

VSP data set, we assumed each of its time snapshots to be a "message", and data points of different receiver depths with amplitude u_i in the snapshot were regarded as the letters which constitute the message (figure 1). The calculated entropy is based on the amplitude probability distribution function (PDF) that reflects the chances that at any given receiver depth the data point will have a particular amplitude value.

Assume each time snapshot consists of N data points (i.e. responses from N receivers), and every data point takes an amplitude value $u_i (i = 1, 2, \ldots, m)$, which represents one of m possible amplitude values, by enumerating the occurrences of a particular u_i in the snapshot as $W(u_i)$, define probability of its occurrence (Innanen, 2012) as:

$$P(u_i) = \frac{W(u_i)}{\sum_{i=1}^{m} W(u_i)}, \tag{1}$$

providing a form of the probability distribution function (PDF). The entropy of a single data point is calculated as:

$$H' = -\sum_{i=1}^{m} P(u_i) \log_2 P(u_i). \tag{2}$$

The entropy of a snapshot is then, making use of the additivity attribute of H':

$$H = N * H'. \tag{3}$$

Equation 2 is the mathematical expression of the first-order entropy. The first-order entropy incorporates the statistical knowledge of different amplitude values in the wave field but does not take correlation of amplitudes of adjacent data points into consideration. Equation 2 implies that both more possible amplitude values and a more evenly distribution of their probabilities contribute to greater entropy. Overall, H is expected to go up when the disorder of the wave field increases.

The previous research showed that the time domain first-order entropy (was referred to as "initial entropy" in the 2016 report) behaves differently under effect of extrinsic Q and intrinsic Q in the wave field. The existence of extrinsic Q tends to enhance the amplitude scattering in the wave field and make its entropy variation curve to have a large peak value. On the contrary, the existence of intrinsic Q in the wave field tends to weaken the amplitude scattering and make the corresponding entropy variation curve to have a small peak value. In some sense, the two attenuation mechanisms affect the measured entropy result in the opposite way, given the premise that a proper amplitude bin was used to classify data points of the data set (Lv and Innanen, 2016). This gave promise in using information measure to distinguish between intrinsic Q and extrinsic Q.

In this research, we conjecture that the entropy variation curve of a wave field including attenuation of both absorption and stratigraphic filtering will reveal information regarding the relative strength of two Q in the wave field.

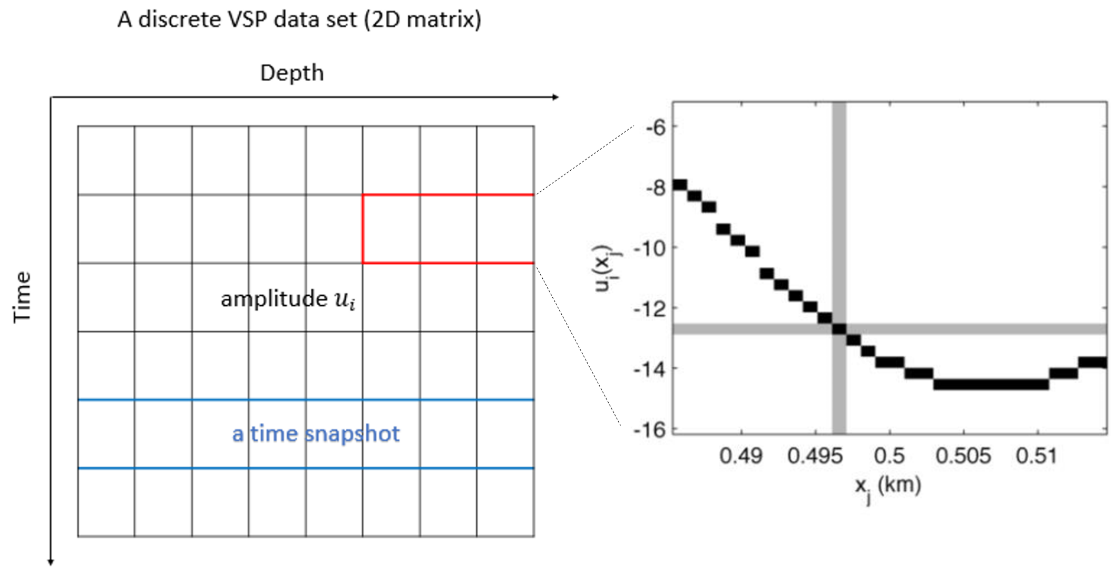

FIG. 1. An example of discrete VSP data set in 2D matrix form (each square represents a data point of the data set) (left) and a demonstration of part of the time snapshot (right) (*right plot from Innanen (2012)).

THE INFORMATION MEASURE WHEN BOTH INTRINSIC AND EXTRINSIC Q ARE ACTIVE

Research strategy

The previous research conducted the time domain entropy measure on seven wells collected from three working areas in North America. We designed a controlled trial to study the separated and combined effects of intrinsic Q and extrinsic Q on entropy. In which, four VSP wave fields having different attenuating condition were built from each well. The wave fields include respectively: (a) neither internal multiples nor absorption; (b) internal multiples only; (c) absorption only; (d) both internal multiples and absorption. Then, entropy variation with time of all the wave fields was measured (figure 2).

In wave field (d), both stratigraphic filtering and absorption contribute to the overall amplitude attenuation and dispersion, so that its entropy result is under the combined influence of intrinsic Q and extrinsic Q. Presumably, by comparing its entropy result with the entropy result of wave field (a) for the same well, which includes neither intrinsic Q nor extrinsic Q effect, it can be decided if the entropy behavior is sensitive to the relative strength of intrinsic Q and extrinsic Q when they are both active.

We use the entropy peak increase from wave field (a) to wave field (d) built from an identical well to quantify the entropy change. A positive entropy peak increase indicates that wave field (d) contributes to a larger entropy peak value than (a) and a negative number indicates a smaller entropy peak value of wave field (d) than (a). Also, the larger the number, the more entropy peak increases from (a) to (d). Based on existing knowledge of the first-order entropy, the stronger the strength of extrinsic Q relative to total Q is in a wave field, the larger its corresponding entropy peak increase should be. And if the statement is true, it may in turn serve as an approach to estimate the extrinsic Q strength in the desired

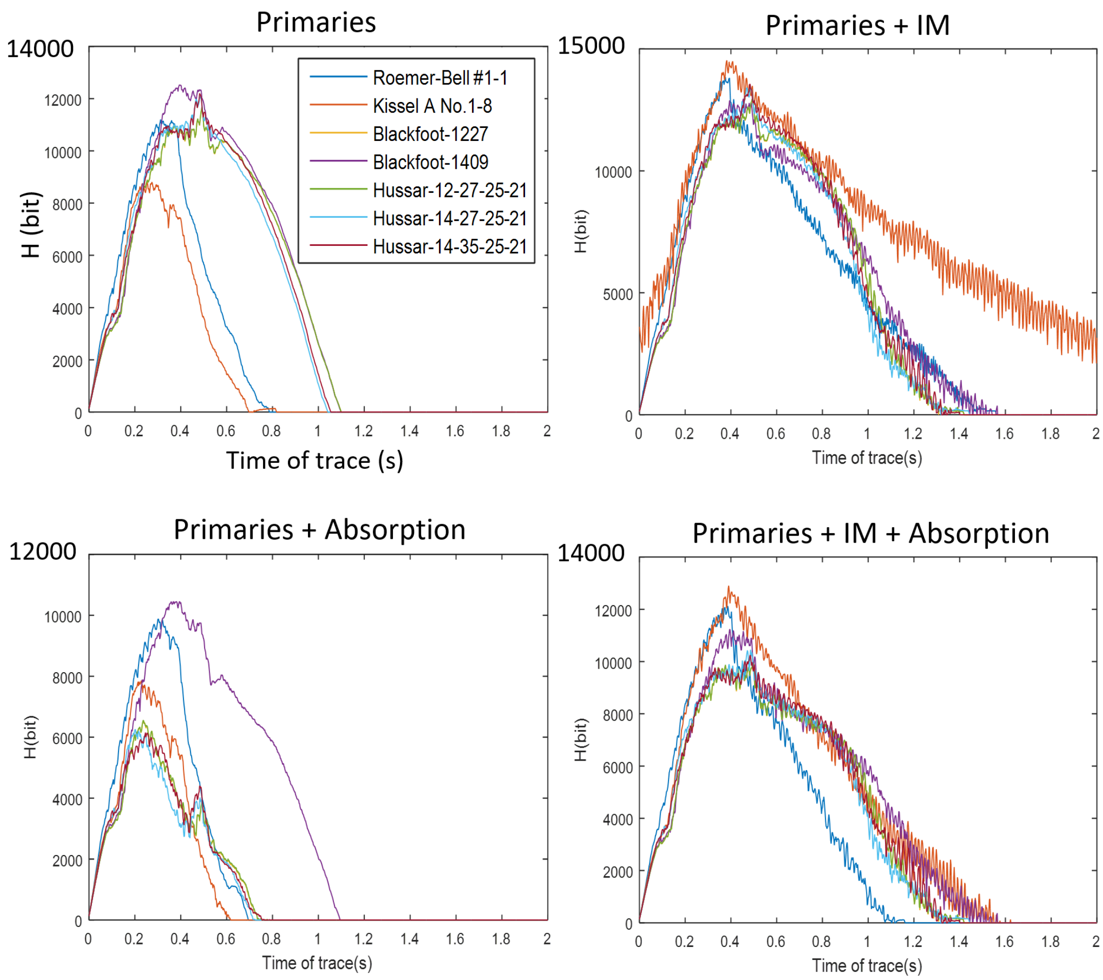

FIG. 2. The first-order entropy variation results of synthetic VSP data sets built separately from seven wells containing respectively: (a) neither internal multiples nor absorption; (b) internal multiples only; (c) absorption only; (d) both internal multiples and absorption.

region.

Q determination in seven wells by the spectral ratio method

Whether or not the above hypothesis is true is investigated by observing the relationship between entropy peak increase and the intrinsic and extrinsic Q estimated from the corresponding wave fields by the spectral ratio method.

In a VSP data set, let $A_x(f)$ be the amplitude spectrum of a downhole pulse recorded at depth x and $A_0(f)$ be the amplitude spectrum of the reference downhole pulse recorded at depth x_0; the relationship between the two amplitude spectra is:

$$A_x(f) = G_x A_0(f) e^{-B_x f}. \tag{4}$$

The equation describes the process of the pulse being attenuated in amplitude when it propagates from depth x_0 to depth x (generally $x > x_0$). G_x and B_x represent different aspects of the total attenuation. G_x stands for attenuation factors such as geometrical spreading, transmission loss, change of acquisition condition, etc.. And attenuation factors associated with B_x include absorption and stratigraphic filtering. B_x is usually referred to as the cumulative attenuation (CA) from depth x_0 to x.

To reflect the average attenuation level in this depth range, define an interval attenuation k_x as:

$$k_x = \frac{B_x}{x - x_0}, \tag{5}$$

and it is generalized to

$$k_x = \frac{\Delta B}{\Delta x} \tag{6}$$

in case of inconsistent Q distribution with depth.

B_x and k_x are related to the commonly used attenuation factor α_x by

$$B_x = \frac{\pi \Delta t}{Q} \Rightarrow \frac{B_x}{\Delta t} = \frac{\pi}{Q} = \alpha_x, \tag{7}$$

and

$$k_x = \frac{\Delta B}{\Delta x} = \frac{\Delta B}{\Delta t v_x} = \frac{\alpha_x}{v_x}. \tag{8}$$

α_x is the reciprocal of Q, and it has unit $nepers/wavelength$. To calculate α_x, we need to know B_x. Taking logarithm on both sides of equation 4 and reorganize, we get:

$$\log \frac{A_x(f)}{A_0(f)} = -B_x f + \log G_x. \tag{9}$$

See that B_x is the negative of the slope of a linear function of spectral ratio in frequency. α_x can then be derived according to equation 7 or 8. In practice, the reference amplitude spectrum A_0 is usually chosen at a early traveltime where attenuation has not taken place,

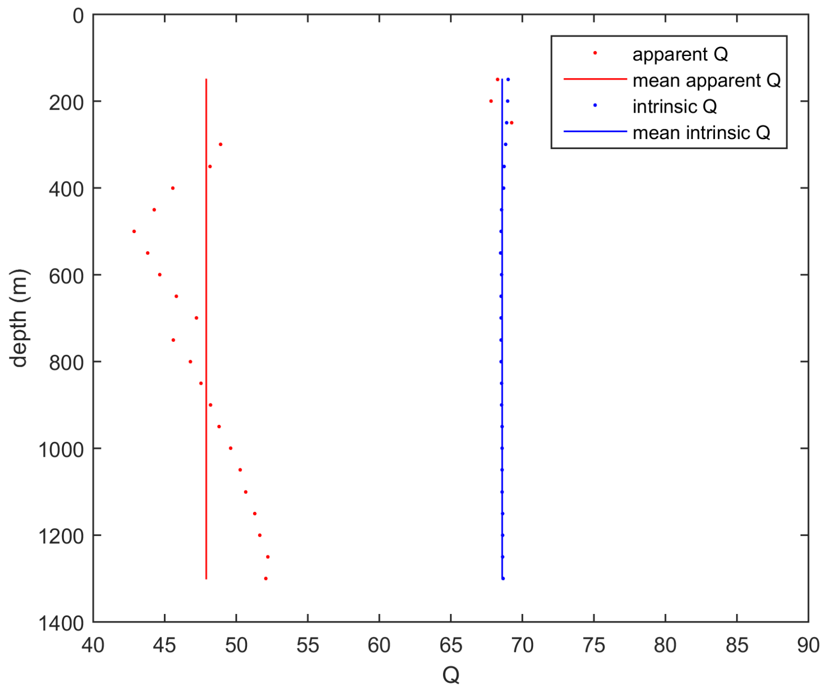

FIG. 3. Intrinsic Q and apparent Q distributions with depth measured respectively from the wave field including only absorption and the wave field including both absorption and internal multiples built from a Blackfoot well 1227 by the spectral ratio method.

so that α_x at any depth x in reference to this A_0 will be the true attenuation in situ, rather then a relative quantity.

We applied the spectral ratio method to wave field (c) and wave field (d) built from seven wells. For all wells, the calculation adopts the amplitude spectrum information in frequency range 10-100Hz to exclude noise at low and high ends of the spectra. And due to the resolution limit of the spectral ratio method (Hauge, 1981), B_x from different depths are linear fitted to get k_x and then get the Q information. Wave field (c) contains only internal attenuation, so the Q estimated from it is referred to as intrinsic Q. Wave field (d) contains both internal and external attenuation, thus the Q estimated from it is apparent Q. Since wave field (d) is identical to wave field (c) in every aspects except the additional inclusion of internal multiples, intrinsic Q estimated from wave field (c) is also the intrinsic Q in wave field (d). The extrinsic Q in wave field (d) is derived using relationship (Spencer et al., 1982):

$$\frac{1}{Q_{apparent}} = \frac{1}{Q_{intrinsic}} + \frac{1}{Q_{extrinsic}}. \tag{10}$$

Figure 3 presents the apparent Q and intrinsic Q distribution estimated from wave fields of well Blackfoot 1227 as an example. Estimated Q information of all wells is listed in table 1 and 2.

Seen in table 1 and 2, the measured intrinsic Q for all wells are very close to $Q = 70$ which was used in the forward modelling process. Indicating that the spectral ratio method is effective here. Considering that we are only trying to get a general idea of the relative strength of intrinsic and extrinsic Q in the well positions, and also that the information measure is applied to time snapshots, so that the measured entropy includes a mix of Q effects of all depths; the Q distribution at small depth intervals is not needed. Therefore, mean values of Q are adopted for the experiment.

Table 1. Q information in seven wells' positions (I)

	Roemer Bell No. 1-1	Kissel A No. 1-8	Blackfoot 1227	Blackfoot 1409
Intrinsic Q	68.6	68.6	68.7	68.5
Apparent Q	29.2	54.2	47.9	35.8
Percentage of extrinsic Q in total Q (%)	57	21	30	48

Table 2. Q information in seven wells' positions (II)

	Hussar 12-27-25-21	Hussar 14-27-25-21	Hussar 14-35-25-21
Intrinsic Q	68.6	68.6	68.7
Apparent Q	47.9	34.1	42.0
Percentage of extrinsic Q in total Q (%)	30	50	39

Relating the entropy behavior to the strength of extrinsic Q

The last row of table 1 and 2 lists how much of the total Q is contributed by the extrinsic Q. The comparison between it and the entropy peak increase from wave field (a) to wave field (d) of the corresponding wells is displayed in figure 4.

It is found in figure 4 that, Roemer Bell No. 1-1, the one having the strongest extrinsic Q of all wells, also has the largest entropy peak increase of all; in contrast, Kissel A No. 1-8 appears to have the weakest extrinsic Q and the smallest entropy peak increase. Similar positive relationship of extrinsic Q strength and the entropy peak increase are observed on well Blackfoot 1227 and three wells from Hussar working area as well. Despite that these six wells show good similarity, it is hard not to notice the abnormal behaviour of well Blackfoot 1409. It has the third strongest extrinsic Q but the smallest entropy peak increase (actually negative).

The abnormality of Blackfoot 1409 may be due to a poorly estimated extrinsic Q strength or an undiscovered character of entropy. To find the answer, we reviewed and compared the log data for the seven wells. Figure 5 displays the P-wave velocity and density logs of all wells, zooming on the depth region 400-600m. Obvious peculiarity can be found in (4)—log data of Blackfoot 1409. First, they seem to have a narrower frequency band than log data of other six wells. Figure 6 verifies this. We see that wave field (c) for Blackfoot 1409 has a narrower frequency band than that for Blackfoot 1227, with the partial loss of both high and low frequency components. This would almost certainly have affected the outcome of spectral ratio method, since there will be fewer points corresponding to signal when linear fitting the spectral ratio to frequency using equation 9.

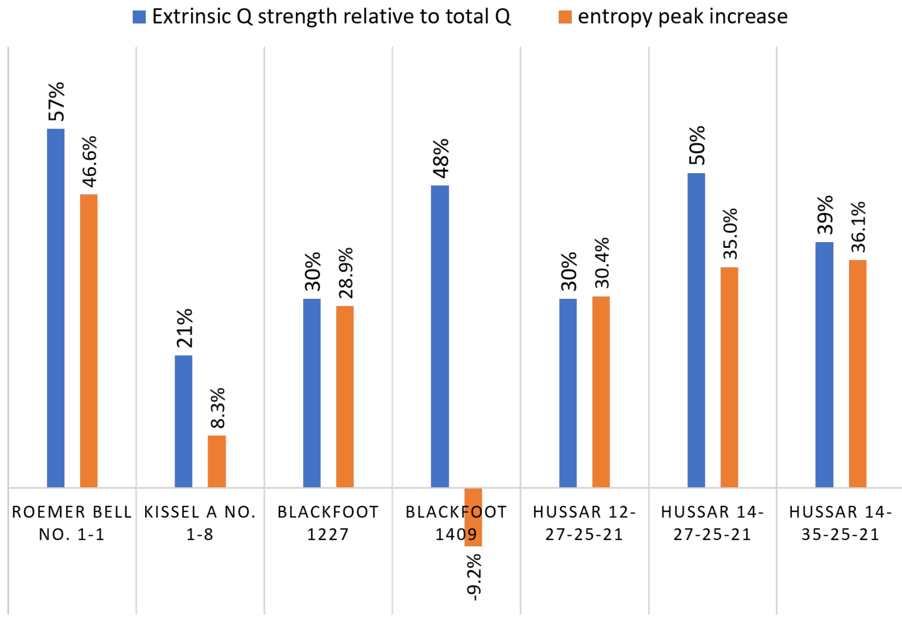

FIG. 4. Comparison between extrinsic Q strength relative to total Q and the entropy peak increase from the wave field including both absorption and internal multiples to the wave field including only absorption built from seven wells.

Second, the velocity and density distributions of Blackfoot 1409 show little detail in small depth ranges due to the lack of high frequency information; the log data do not have the cyclic features that log data of other wells have. So it is likely that the interbed reverberations in wave fields built from these logs are not as strongly developed as in other wells and thus have a weaker extrinsic Q.

To demonstrate the point, we computed the transmission loss (TL) exhibited by the wells. Transmission loss and external cumulative attenuation are usually positively related (Schoenberger and Levin, 1978), so if Blackfoot 1409 has a smaller transmission loss than others, is should also has a weaker extrinsic Q. We calculated the one-way transmission loss of the direct arrival recorded by the bottom receiver (at 1300m), according to:

$$one-way\ transmission\ loss = 1 - \prod_{k=0}^{N}(1-R_k), \tag{11}$$

in which N is the total number of layers through which the wave has transmitted, R is the reflection coefficient of the kth interface.

The one-way transmission loss at 1300m for seven wells are listed in table 3. We realize that the value for Blackfoot 1409 is significantly smaller than others, being only half of the largest value. Thus it is reasonable to infer that this well has the weakest extrinsic Q among all. As a result, it should have the smallest entropy peak increase among all.

To sum up, the reason that Blackfoot 1409 failed to show the positive relation between extrinsic Q strength and entropy peak increase as other wells did is very likely that its Q was poorly estimated by the spectral ratio method.

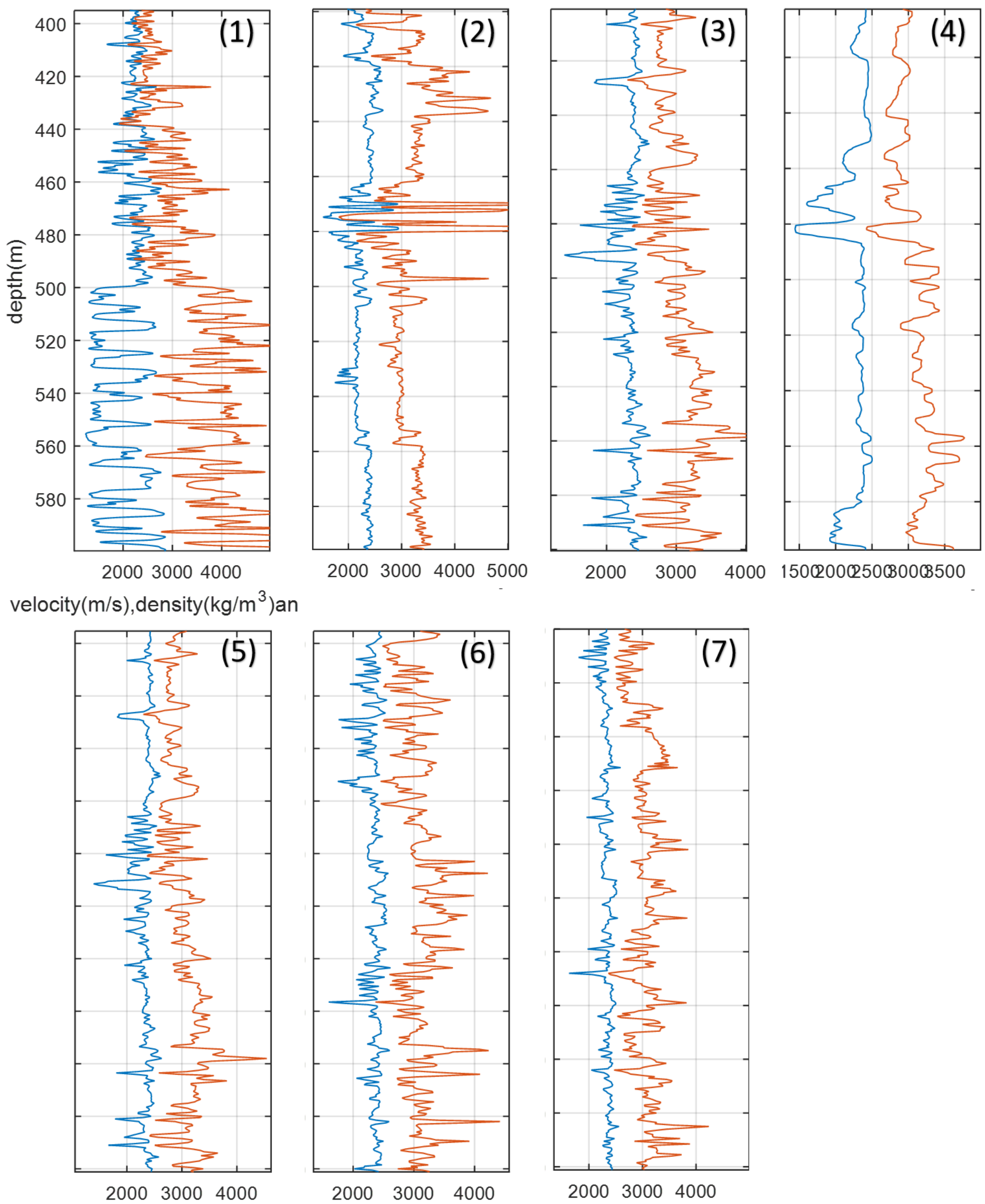

FIG. 5. P-wave velocity and density logs in depth range 400-600m of wells: (1) Roemer Bell No. 1-1; (2) Kissel A No. 1-8; (3) Blackfoot 1227; (4) Blackfoot 1409; (5) Hussar 12-27-25-21; (6) Hussar 14-27-25-21; (7) Hussar 14-35-25-21.

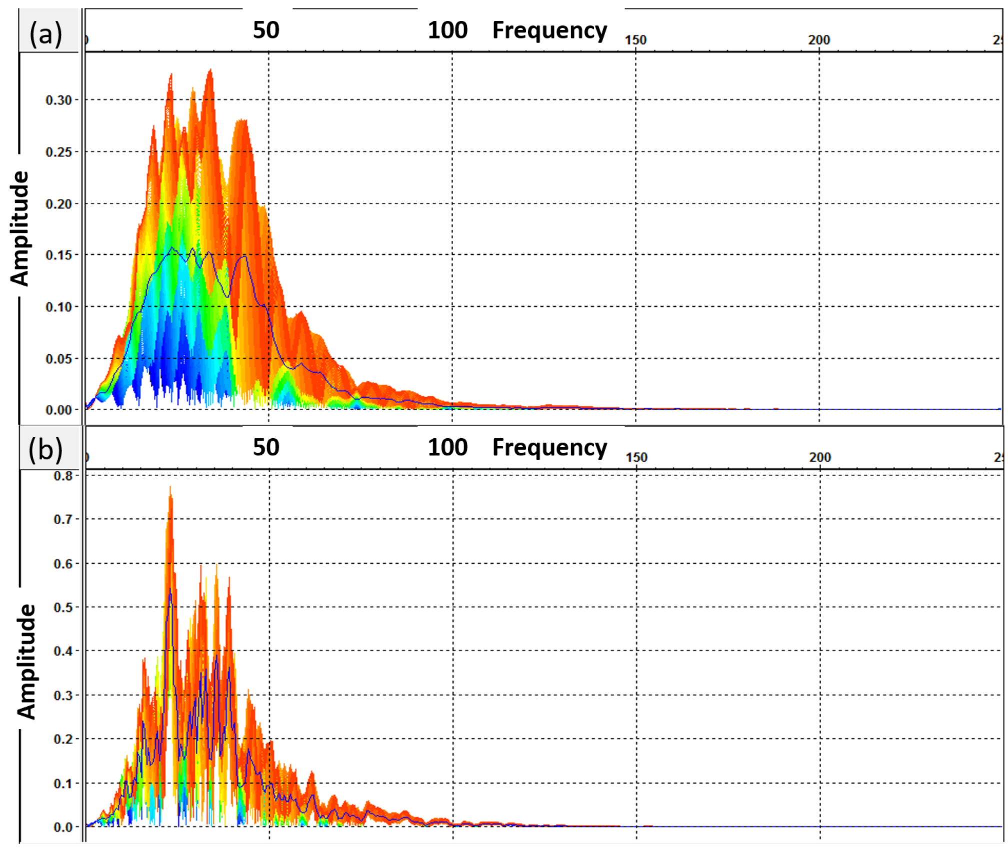

FIG. 6. Frequency bands of a wave field built from well Blackfoot 1227 (a) and Blackfoot 1409 (b).

Table 3. One-way transmission loss of seven wells

	Roemer Bell No. 1-1	Kissel A No. 1-8	Blackfoot 1227	Blackfoot 1409	Hussar 12-27-25-21	Hussar 14-27-25-21	Hussar 14-35-25-21
TL	0.99	0.97	0.86	0.51	0.86	0.88	0.86

Regardless of the Blackfoot 1409 result, the result of other six wells supports the hypothesis, that the stronger extrinsic Q is relative to total Q, the larger the entropy peak increase would be. In figure 4, all wells except Blackfoot 1409 appear to have positive entropy peak increase, when their corresponding extrinsic Q strength range from 20% to 60%. It indicates that the impact of extrinsic Q on entropy is more influential than that of intrinsic Q. When both Q take 50% of total attenuation, the entropy peak increase is positive, instead of being approximately zero. Therefore, whenever the entropy peak increase is negative, it could mean that the extrinsic Q strength over the depth interval of interest is rather weak, likely to take less than 20% of total attenuation.

INFORMATION MEASURE ON A FIELD VSP DATA SET

As a supplement of the information measure study, we applied the first-order entropy measure to a field VSP data set, which is the zero-offset record of a multicomponent walkaway VSP dataset (Hall et al., 2012). Data from this area is suitable for the stratigraphic filtering study because well logs acquired at a nearby position reveal good layering character, and comparison between log data and the simulated wavelet implies that the stratification of the area is nonresolvable (figure 7). CREWES participated in the data acquisition in 2011. The location and the identity of the company are not disclosed by request.

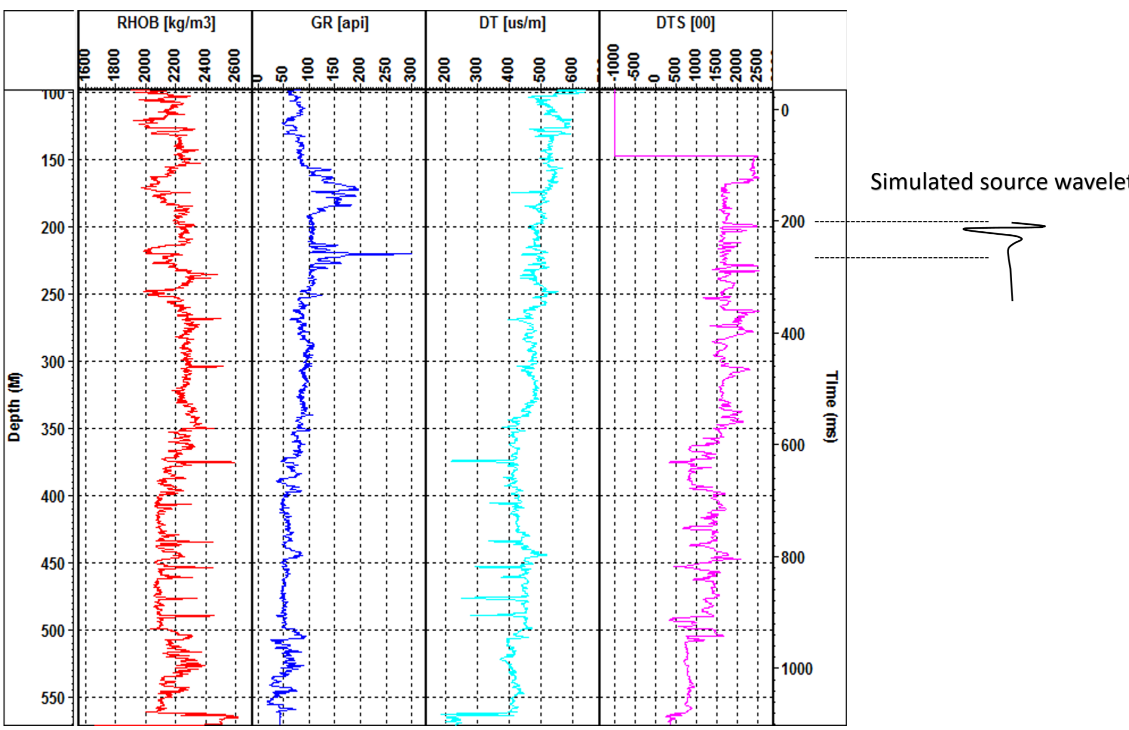

FIG. 7. Log data from a nearby well position of the VSP data used in the research, and its comparison with the simulated source wavelet.

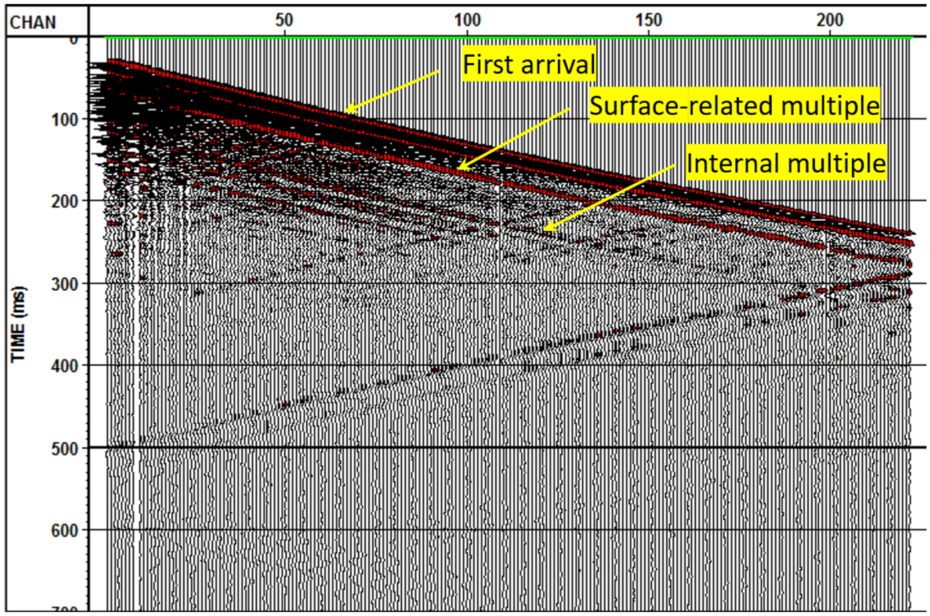

FIG. 8. The zero-offset VSP record of an anonymous multicomponent walkaway VSP data set.

Figure 8 shows the raw zero-offset VSP record. It has good S/N ratio, so that the P-wave events such as primaries, surface-related multiples and internal multiples can be recognized. S-wave events also exist in the record, but they are ignored because the wave type does not really matter in the information measure and that the S-wave energy is quite weak comparing to the P-wave energy.

First-order entropy calculation on the real VSP data

Same as the synthetic data experiment, a controlled trial consists of four wave fields including various attenuation factors was designated for the information measure on field data. The wave fields contain, respectively, attenuating effects of: a) neither absorption nor stratigraphic filtering ; b) stratigraphic filtering only; c) absorption only; and d) both absorption and stratigraphic filtering.

To get the wave fields, the raw zero-offset VSP record was processed so that the undesired attenuation factors in it could be preferentially eliminated. We used a 3.2 exponential gain to compensate the absorptive attenuation based on the record's intrinsic Q estimated by the spectral ratio method (detail is in the following section), this way the absorption will not be overly or insufficiently compensated in general. We used the predictive deconvolution to remove surface-related multiples and internal multiples in the record. The pre-processing went like this: a predictive deconvolution was first applied to the raw record to remove source ghost. This generated wave field (d). Then we applied a 3.2 exponential gain to (d) to get wave field (b). Meanwhile we applied another predictive deconvolution to wave field (d) to eliminate the internal multiples in the wave field to get (c). To get wave field (a), both the exponential gain and the internal-multiple-eliminating predictive deconvolution were applied to wave field (d). Figure 9 and 10 show the processed wave fields. Most parts of the four wave fields hold decent S/R ratio except the near surface zone, thus data from the first 30 traces were discarded in the information measure.

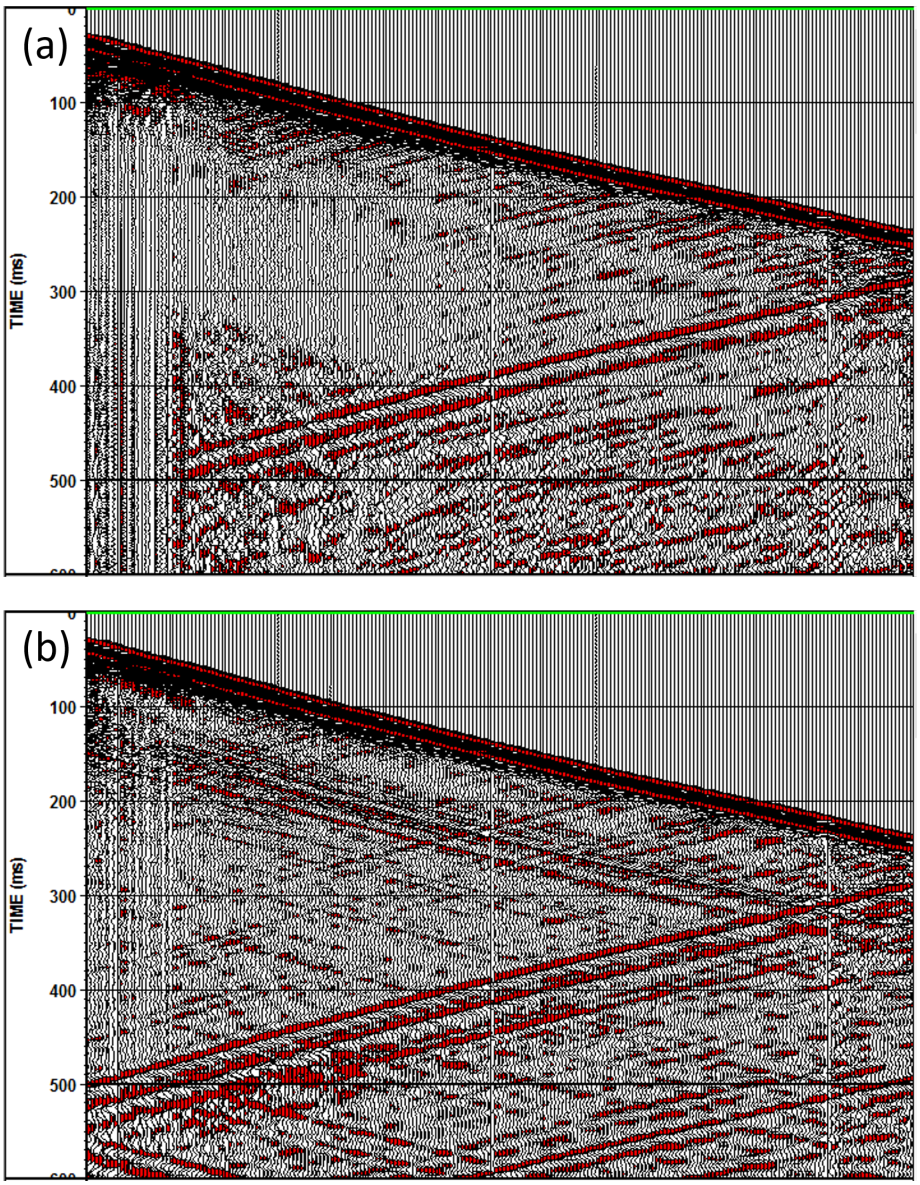

FIG. 9. Processed zero-offset VSP records. (a) is derive by applying a 3.2 exponential gain and two times of predictive deconvolution (aiming at removing source ghost and internal multiples) to figure 8 record; (b) is derive by applying a 3.2 exponential gain and one time of predictive deconvolution (aiming at removing source ghost) to figure 8 record.

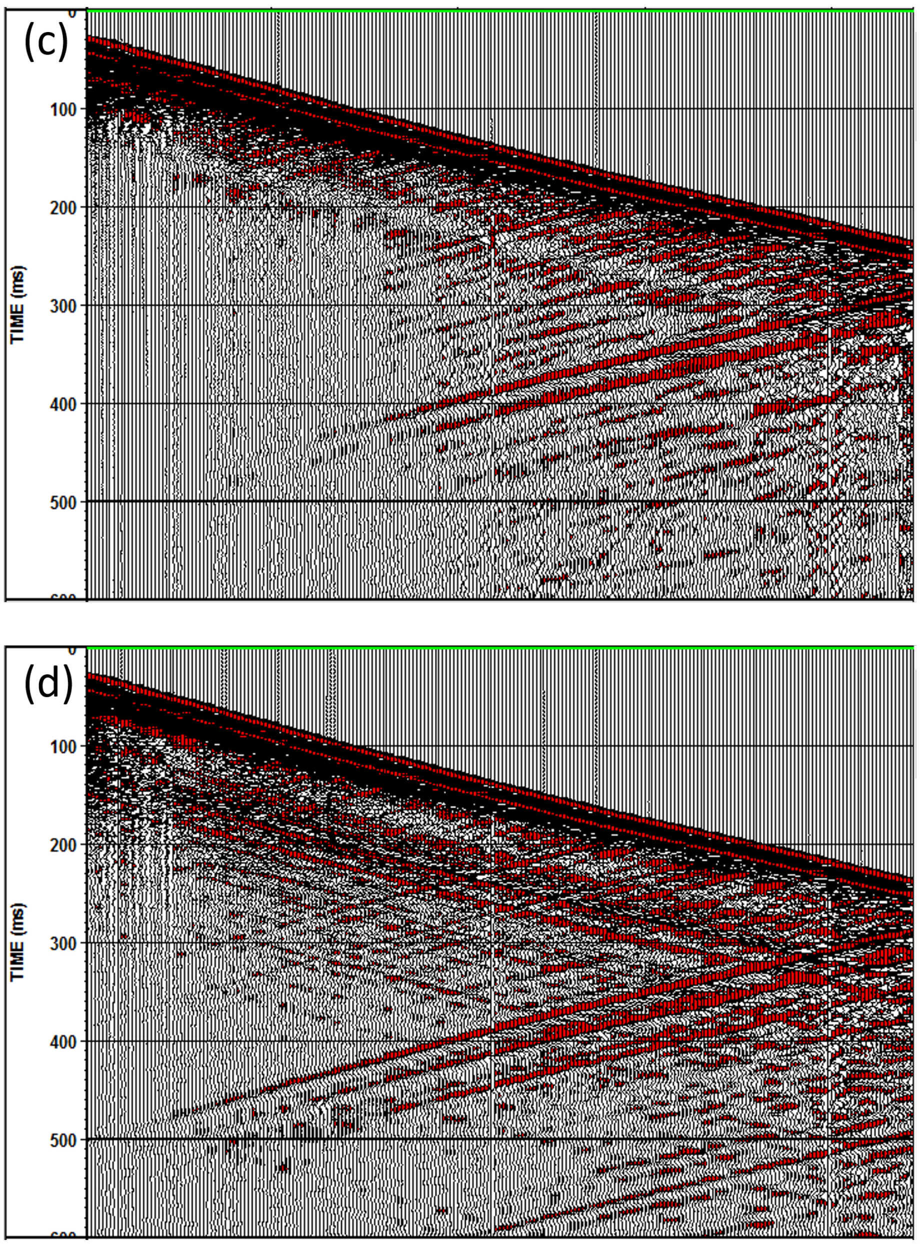

FIG. 10. Processed zero-offset VSP records. (c) is derive by applying two times of predictive deconvolution (aiming at removing source ghost and internal multiples) to figure 8 record; (d) is derive by applying one time of predictive deconvolution (aiming at removing source ghost) to figure 8 record.

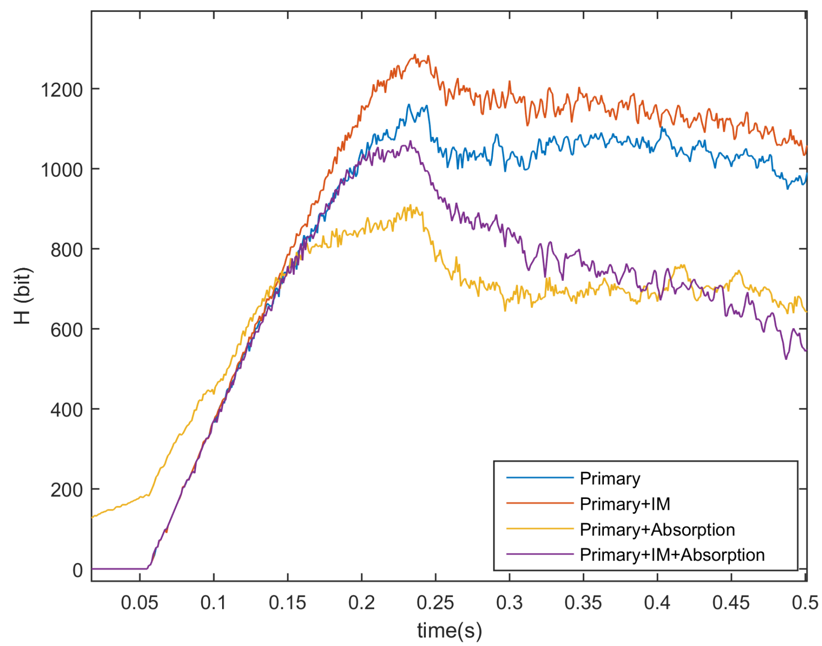

FIG. 11. The first-order entropy variation result for wave fields in figure 9 and 10 (zooming on time 0-0.5s).

The first-order entropy variation results of the four wave fields are displayed in figure 11. The entropy calculation used amplitude bin size 0.001. It can be seen in figure 11 that:

(1) Wave fields including internal multiples contribute to entropies with larger peaks than entropies derived from wave fields excluding internal multiples, seen by comparing red and purple curves to the blue and yellow ones respectively;

(2) Derived from wave fields which include absorption, the yellow and purple entropy curves have smaller peaks than red and blue ones;

(3)The wave field including only internal multiples has the largest entropy (red curve) and the wave field including only absorption has the smallest entropy (yellow curve).

Intrinsic Q and extrinsic Q have opposite effects on the entropy variation result, just like in the synthetic data experiment. It manifests that when data set has a good S/N ratio, the behavior of its entropy measure is consistent with that of synthetic data. We then tried to use this measured entropy result to predict the extrinsic Q strength relative to total Q in this region.

Estimation of extrinsic Q strength of the region

A negative entropy peak increase from wave field (a) entropy to wave field (d) entropy can be derived from figure 11. According to the earlier hypothesis on the connection between the entropy peak increase and the extrinsic Q strength, the number being negative implies that extrinsic Q strength of the region is considerably weak, accounting for less than 20% of the total attenuation strength.

We measured the Q strength in wave field (c) and (d) of figure 10 with the spectral ratio method as a reference. Amplitude spectrum information of 10-250Hz was utilized because the raw VSP record has a broad frequency band (figure 12). Figure 13 and 14 show the measured intrinsic and apparent cumulative attenuation (CA) B_x from wave field (c) and (d) respectively. The final α_x is displayed in figure 15, with detailed information listed in table 4. See in table 4 that extrinsic Q accounts for approximately 15% of the total Q in this region. The extrinsic Q strength, implied by the entropy behavior or calculated from the attenuation determination method, agrees with each other.

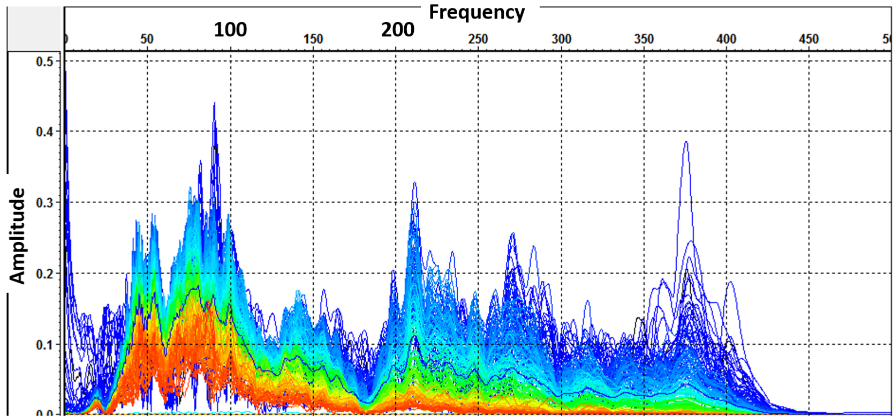

FIG. 12. Frequency band of the VSP record in figure 8.

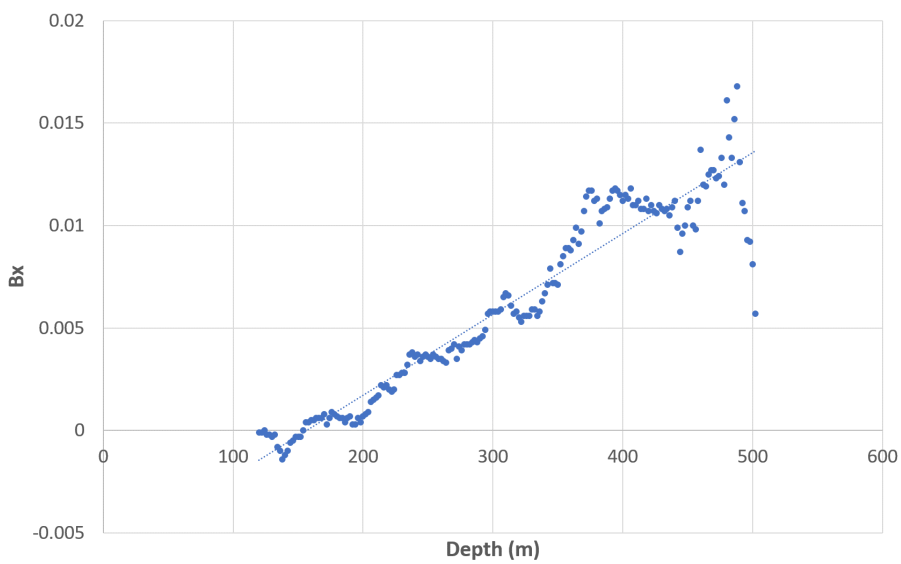

FIG. 13. CA distribution with depth of wave field (c) in figure 10.

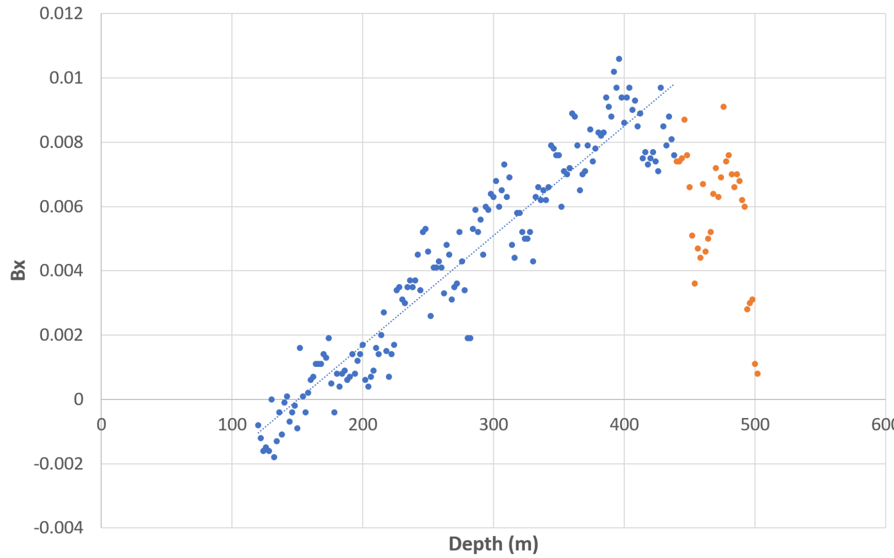

FIG. 14. CA distribution with depth of wave field (d) in figure 10. Orange points are abandoned when linear fitting B_x for k_x.

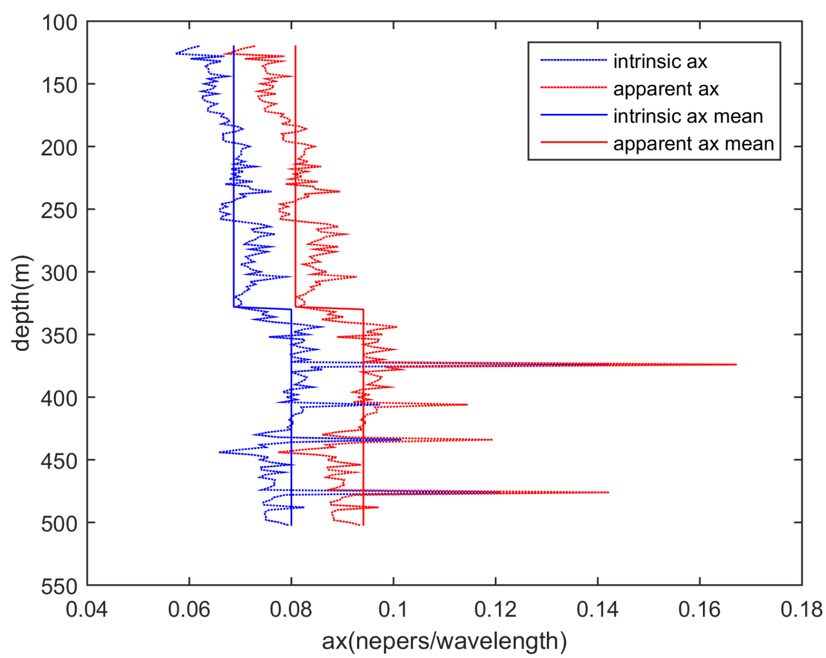

FIG. 15. α_x distribution with depth of of wave field (c) in figure 10 (blue) and of wave field (d) in figure 10 (red). Solid lines show their mean values.

CONCLUSION

Taking advantage of the opposite entropy behavior under effects of intrinsic Q and extrinsic Q, we investigated the possibility to use the measured first-order entropy result of a VSP wave field to estimated the relative strength of intrinsic Q and extrinsic Q in it and got positive response from the tests on synthetic data and field data. The collection of

Table 4. α_x distribution information for the field VSP data

Depth range (m)	120-328	330-502
Intrinsic α_x $(nepers/wavelength)$	0.069	0.080
Apparent α_x $(nepers/wavelength)$	0.080	0.094
Percentage of extrinsic α_x in total α_x (%)	15	15

seven wells and a field record is by no means large but it gave us an overall idea of how the measured entropy behavior is related to the relative Q strength. Generally, the more the entropy peak increases from the case which is associated with no frequency-dependent attenuation to the case which is associated with both intrinsic and extrinsic Q, the stronger the extrinsic Q is in the region being studied.

Although, since the entropy is not calculated from any definite wave field parameters, we were only able to decide which one of the two wave fields has the stronger extrinsic Q strength by comparing their entropy results, but could not say what the value of the extrinsic Q exactly is. Which brings up the thought that, because the entropy result of a wave field is affected by the quality of the data (for example, noise exists in a wave field may increase the disorder and make a larger entropy than it should contribute to), if different data sets are uneven in quality (ie. S/N ratio), the comparison among their information measure results will be unreliable.

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