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Q-compensation imaging in the local angle migrated domain for deep targets

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Introduction

We introduce an efficient inverse Q-filter implementation in the pre-stack depth migrated domain, referred as Q-ES360™, to compensate for seismic wave attenuation and dispersion effects. The filter is realized using Futterman's model in which these two phenomena are linked by the causality principle.

That answers the recent need to improve vertical resolution of seismic images. One of main reasons of depth-dependent vertical resolution is impact of inelastic rocks on traveling wavelet [2]. Amplitude of particular frequency components gets reduced. That is attenuation. The second physical phenomenon is dispersion of geological media, i.e. frequency-dependent speed of seismic waves. Both effects increase with increasing frequency. Amplitude spectrum becomes narrower, while changes in phase spectrum, much complex than simple phase rotation, cause essential deformations of wavelet.
Fig.1 illustrates these amplitude and phase changes of the propagating seismic wavelet in case of good quality VSP data. Decay of seismic signal with propagation distance and related non-stationarity are among fundamental troubles of geophysicist processing seismic data.

Proposed is a novel approach in which the filter is applied directly on the seismic events of the multi-dimensional migrated gathers. The implementation of the Q-compensation filter directly on the angle depth gathers introduces a tremendous advantage in terms of performance, with the ability to perform Q-corrections with different parameters in a post-migration processing option. Traditional processing technology offers application in time domain, and has some drawbacks. Usually excessive noise introduced by amplitude component at high frequencies. Tests of the new proposed method prove the problem is much reduced.
Synthetic results show spectrum enhancement and improved image recovery. We also demonstrate the method on real data emphasizing the improvement of amplitude recovery in deep targets, and improvement of wavelet shape.

Estimating Q model

The Q coefficient, better known as Q-factor, is the parameter characterizing attenuating properties of inelastic media. Widely accepted description of Q model [1] is the formula used to estimate Q model from decay of amplitude spectra at high frequencies:

$$A(x) = A(0) \cdot exp\,(-\pi f x / VQ\ ) \tag{1}$$

where f is frequency, V velocity, A_0 initial amplitude, and $A(x)$ amplitude of the wavelet after traveled distance x. That considers only attenuation.

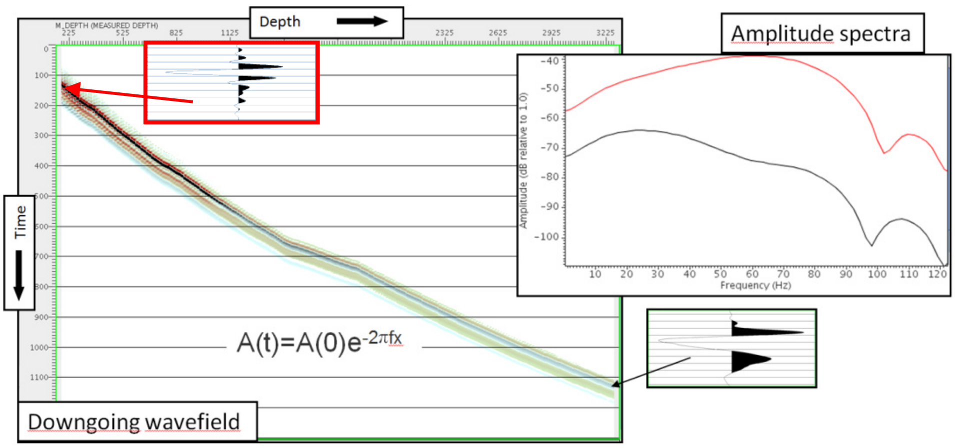

Fig. 1. Changes in wavelet measured from VSP downgoing wavefield in a well in Poland.

The well-known spectra ratio method was used to estimate Q model from the VSP data:

$$\ln\left(\frac{A(t,f)}{A_0(t_0,f)}\right) = \frac{\pi f(t-t_0)}{Q} \tag{2}$$

where the estimation consists of determination of slope in the assumed frequency range.

The method can be applied to surface or well seismic. Specific processing issues must be solved in practice. To get reliable estimations, some quality requirement should be met as to frequency band, and S-to-N ratio. Also, an impact of slope of the reflectivity series spectrum must be accounted for. Fig.2. provides example of how Q model is estimated from VSP data.

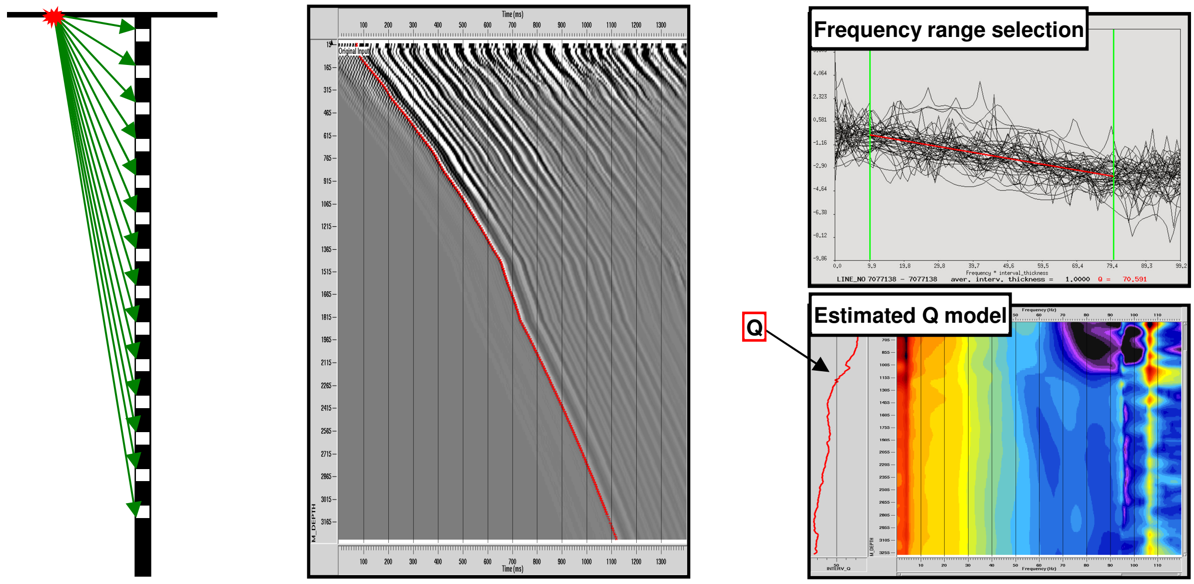

Fig. 2. Estimation of the Q model from VSP data.

The model of Q factor can be estimated from surface seismic as well. In that case, reliability and precision of estimation depend on quality of seismic data. Fig.4 provides an example of estimating Q poststack from seismic.

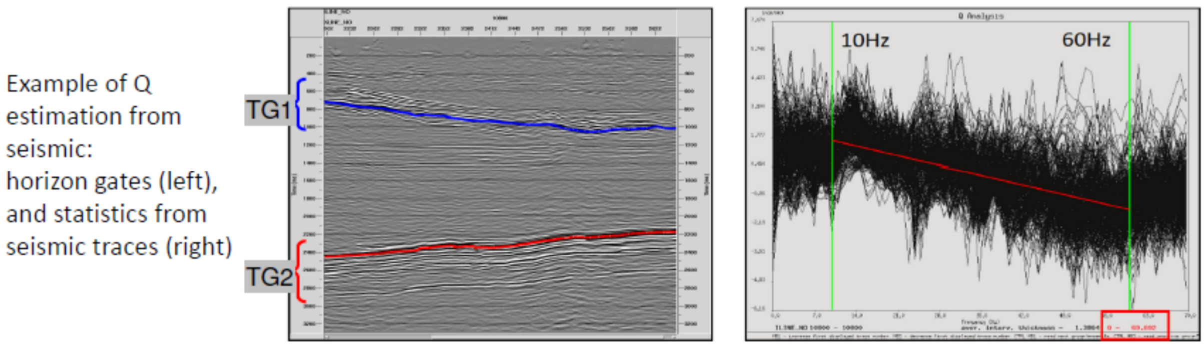

Fig. 3. Estimation of Q for the interval between two horizons TG1 and TG2. Spectra are reviewed (right panel) to select frequency interval of stable spectrum slope (here: 10 – 60 Hz), then Q is computed.

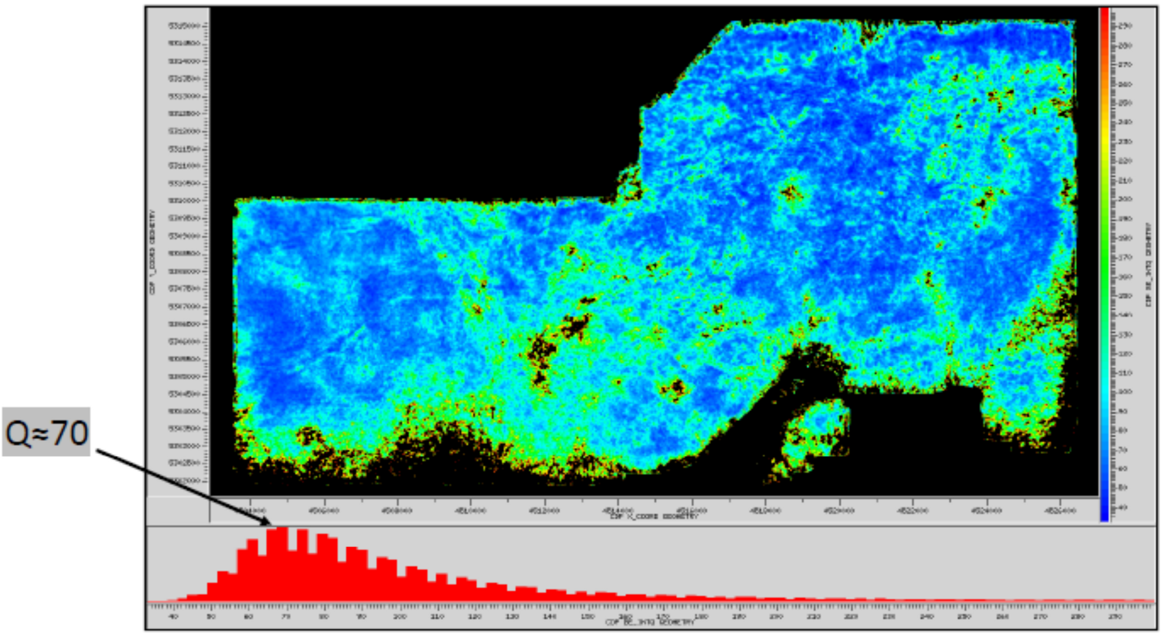

Fig. 4. Map of effective Q estimated along , and between, given pair of horizons, proves stability of the estimation procedure.

Q-compensation built into seismic depth migration

Impact of rocks' inelasticity causes decay of propagating seismic signal and distortion of its shape. That can be recovered with the inverse Q filtering. Recent development of seismic processing and imaging technology, e.g. [3], [4], [5], or [6] allows to apply Q-compensation directly in depth-angle domain, what is natural, geological system of coordinates. Such an approach brings several advantages. Unification of compensations for: wavelet stretch, spherical divergence, and the Earth attenuation, is directly related to the nature of seismic waves propagating through rocks. It is only in depth-angle domain where complex ray paths through the media model can be correctly described. Realistic correction of several physical phenomena has become feasible.

The enlargement of seismic section seen in Fig. 5 and 6 is a piece of Ordovician interval where vertical resolution plays key role in assessment of quality of seismic data processing. First results of Q-compensation implemented inside prestack depth migration ES360™ (common reflection angle migration) can be seen in Fig.6. Comparison of Fig.6 to Fig.5 proves evident improvement in resolution brought by inverse Q filtering to the seismic image. Prestack application of the Q compensation provides big improvement actually to the prestack seismic, so can be used for interpretation: simultaneous inversion and AVO / AVAZ analyses. The full Q-compensation formula, accounting also for dispersion reads:

$$D\,(\text{Ray Pair}, \omega) = e^{-\frac{i\omega T^*}{\pi}\ln\left(\frac{\omega}{\omega r}\right)}\; e^{\frac{\omega T^*}{2}} \qquad (3)$$

where $\omega = 2\pi f$, f_r stands for reference frequency, and T* denotes travel time integrated along the particular seismic ray traced from source to a depth point, then back to receiver (actually, because of ES360 philosophy of tracing rays only one way: down-top. It is a pair of rays: depth point to source, and depth point to receiver).

Formula for travel time T* integrated along the seismic ray is:

$$T^* = \int \frac{dl}{\upsilon \; Re(\omega_r) \; Q(\omega_r)} \qquad (4)$$

where ω_r stands for reference frequency, for which the model of Q is defined. The first exponent in formula (3) describes phase correction, while the second one – amplitude correction in the whole inverse Q filter.

This novelty method turned out to produce stable, noise-free results. Seismic images produced with this application match template data derived from well logs. Both synthetic and real data tests prove the stabilization mechanisms, built into depth migration, works very well, and better than existing available other implementations.

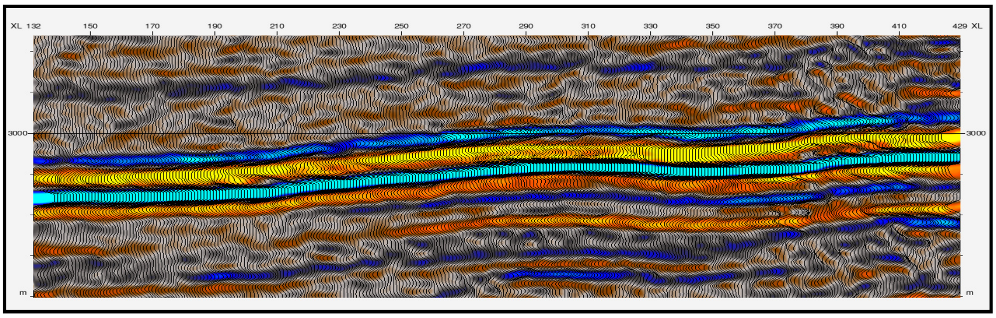

Fig. 5. Depth section before application of the inverse Q filter.

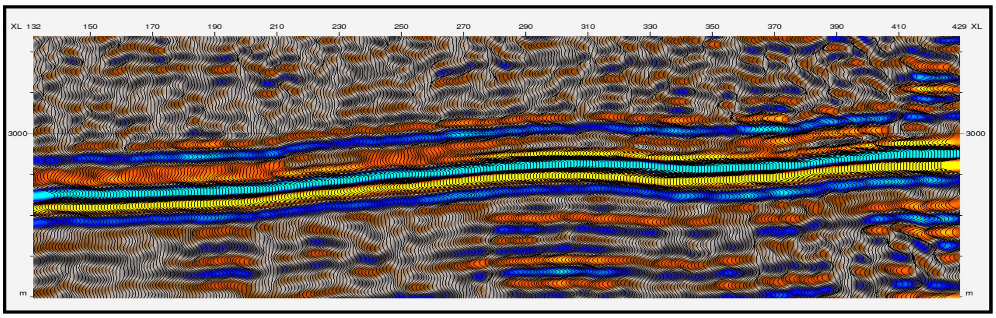

Fig. 6. Depth section after Q filter has been applied.

The Fig.7. documents mathematical test performed on synthetic traces to make sure what are relations between today's routine statistical deconvolution, and performance of the new tool. Examination of Fig.7 (no. 2) reveals not only superiority of Q compensation, but also some drawback of statistical spiking deconvolution: potential of creating false events because of statistical approach to separate wavelet spectrum from reflectivity spectrum.

More realistic illustration is provided in Figures 8 to 10: false reflection marked with black arrow in Fig.9, and recovery of weak reflection in Fig.10 – seen in the yellow rectangle.

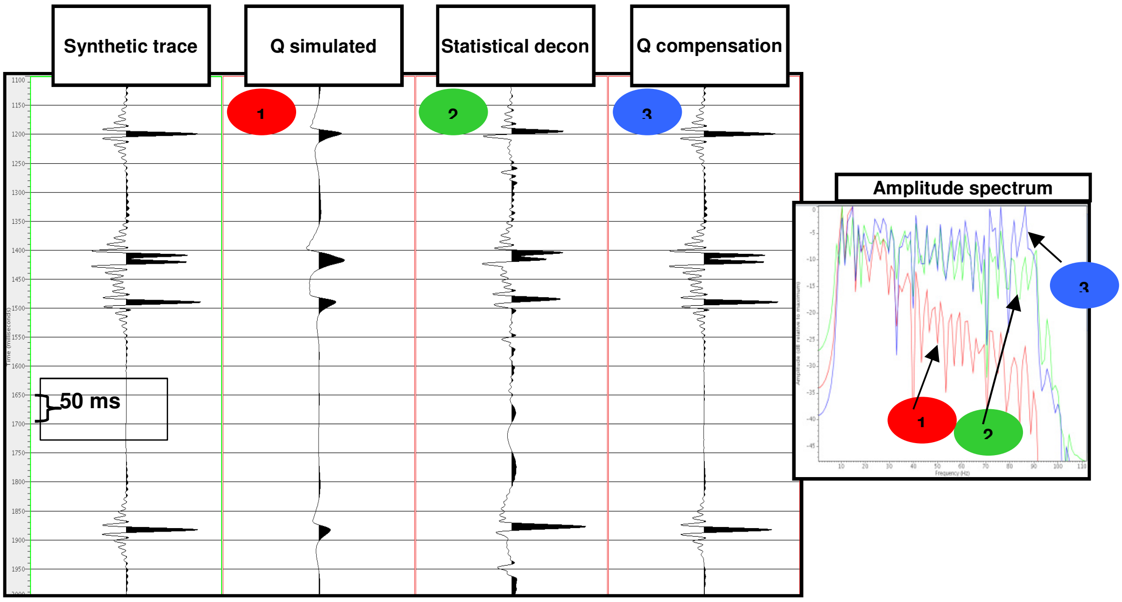

Fig.7. Verification on synthetic: routine spike deconvolution (2) vs Q-compensation (3).

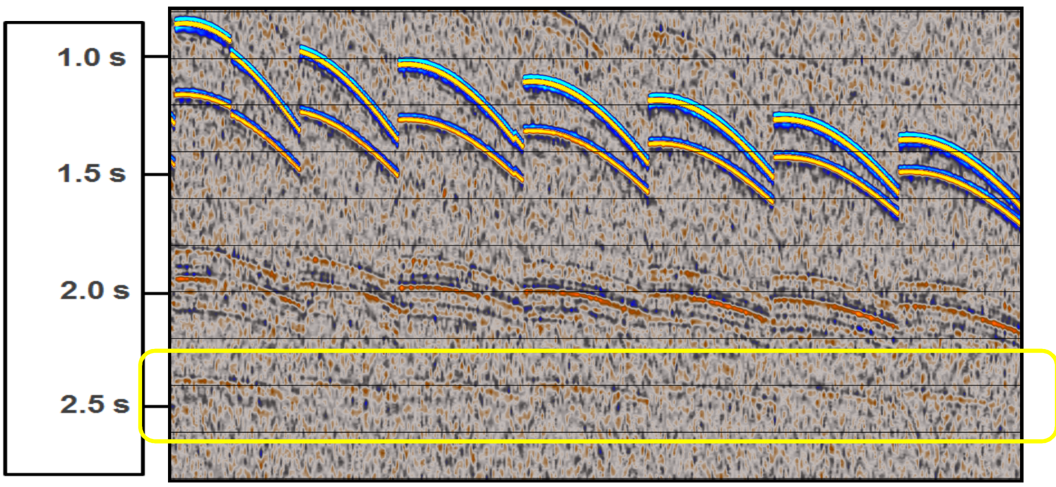

Fig.8. Synthetic CMP gathers. Forward Q filter simulates the Earth filtering.

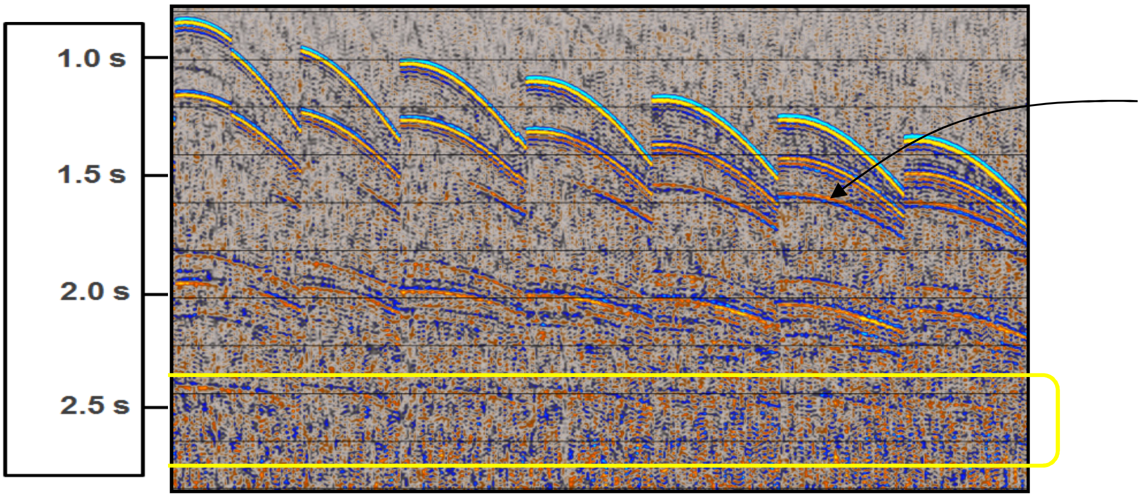

Fig.9. Statistical deconvolution applied to data seen in Fig.6. False reflection created.

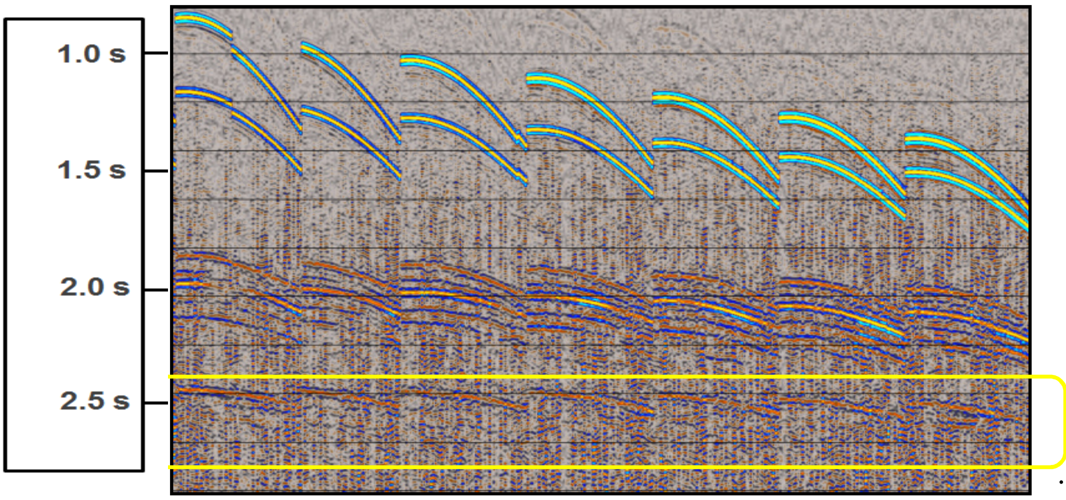

Fig.10. Result of the deterministic inverse Q filter. The weak reflection at 2.4 s is recovered.

Conclusions

Estimation of dynamic and inelastic properties of rocks has became as important as estimation of kinematic parameters: velocity or VTI.

Presented results of the tests on synthetics and first production-scale implementation of the Q-ES360™ technology give reason to expect this innovation in seismic wavelet processing can bring essential improvement in vertical resolution. Moreover, the inverse Q filtering in CRAM brings both corrections: for amplitude attenuation and for dispersion. That makes wavelet stationary, hence improves consistency of interpretation not only structural, but true amplitude relations as well.

Invaluable profit from the deterministic Q-compensation is independency of estimated Q model from the data. For that, it is recommended to build and cumulate regional-scale database of Q models and other inelastic parameters of rocks.

Q-ES360™ enables AVO analysis under complex overburdens, like thrust zones, salt tectonics, gas chimneys, complex unconformities, and simply allows for high resolution seismic. In some cases just identification at all, and interpretation of deep reflectors, as shown in Fig.10, is great benefit.

Acknowledgements

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