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# Inverting Near-Surface Absorption Bodies with Full-Waveform Inversion: a Case Study from the North Viking Graben in the

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## Summary

Shallow absorptive bodies are an ongoing challenge in velocity model building due to the dispersion and attenuation they cause to seismic data: ignoring absorption in model building can lead to erroneous velocities and poor imaging. Ray-tracing-based tomographic inversions for attenuation can perform well, but typically provide lower resolution than a full waveform approach. Also, the method carries inherent drawbacks in the near surface, where absorptive bodies are often at their most influential, due to acquisition limitations. This work highlights visco-acoustic full-waveform inversion (Q-FWI) as a method for estimating high-resolution velocity and attenuation models. We present a very large, real data, case study where Q-FWI has been applied to ~36,000 km2 of 3D, narrow azimuth, variable-depth streamer data over the North Viking Graben region of the Norwegian North Sea. The results delineate both known and previously unknown absorptive bodies of varying size and strength. Our results show that Q-FWI can invert for high-resolution velocity and attenuation models, providing superior imaging using an attenuation compensating pre-stack depth migration.

## Introduction

Anelastic effects of the Earth, characterized by the well-known Quality Factor (Q), cause amplitude attenuation and phase dispersion in seismic data, distorting the wavelet and reducing the subsequent image resolution. Methods such as Q-tomography (Hung et al., 2008) estimate both background and localized Q, replacing the traditional constant Q approach. However, ray-based Q-tomography has drawbacks: 1) the updated Q models lack high spatial-resolution; 2) the method inherently struggles in shallow areas, where Q bodies can be most influential, due to limited near-offset data; 3) Q-tomography often enters at the later stages of the model building with the purpose of enhancing final imaging rather than velocity estimation, meaning systematic velocity errors could already exist.

Acoustic full-waveform inversion (FWI) is now widely adopted for building high-resolution velocity models in areas that are well-penetrated by diving waves. Zhou et al. (2013) discussed an evolution of the Q-tomography process by using an FWI-derived velocity model to guide the Q-tomography. However, inverting for Q in a pure FWI context (Q-FWI) is clearly the ultimate goal. This topic has been investigated over a decade or so, and a few successful examples exist of Q-FWI applied to surface-seismic field data, such as Stopin et al. (2016). The work presented here shows the application of Q-FWI to a large dataset (~36,000 km$^2$), delineating attenuating bodies of varying strength and scale throughout the whole survey and demonstrating a clear uplift in the subsequent imaging process.

## Attenuation in the North Viking Graben

The North Viking Graben area of the northern North Sea (Figure 1) has been among the world's most prolific hydrocarbon provinces. More than 40 BBOE have been discovered in the region, including giant fields such as Statfjord, Gullfaks, Oseberg and Troll, some of which are known to present strong absorptive Q bodies. Our survey area covers the Norwegian Channel Ice Stream where occurrences of very shallow spatially variable gas bodies are observed on a regional scale. These regional scale anomalies first raised the need for Q-FWI in this area, as a stable conventional FWI was difficult to obtain without honoring Q due to the strong absorption. Since a well-defined Q model is needed to accurately model the wavefield, we developed a workflow to invert for high-resolution Q by FWI.

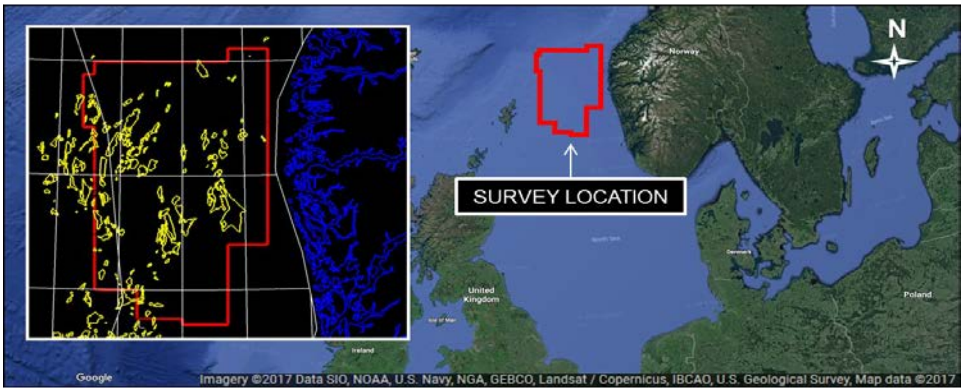


***Figure 1** Survey location (~36,000 km$^2$) in the North Viking Graben area of the northern North Sea.*

## FWI and attenuation

Our time-domain least-squares-based FWI scheme (Xiao et al., 2016) has been adapted to both honour and invert for Q. We use the standard linear solid (SLS) model to represent the absorption effects of the Earth (Robertsson et al., 1994), with the desired constant Q behaviour over a given frequency band approximated by a set of parallel SLSs. Our implementation to solve the visco-acoustic wave equation has been discussed in the context of a reverse time migration by Xie et al. (2015) and the details for the FWI case will be published elsewhere.

Inverting for more than one Earth model parameter with FWI is known to be challenging. This is also true for velocity and attenuation, often resulting in ambiguity between parameters (for example, Hak and Mulder, 2011). However, Malinowski et al. (2011) have shown that, for strong anomalies, FWI can discriminate between velocity and attenuation effects when using a non-linear inversion and wide-aperture surface seismic acquisitions. Use of inverse Hessian information, inverting wide bandwidths, incorporating a priori knowledge and performing simultaneous velocity and Q inversion all help to reduce cross-talk (Plessix et al., 2016, and references therein). However, we acknowledge cross-talk remains a concern even with some of these mitigation methods in place. In observations of synthetic control tests (A. Ratcliffe, pers. comm., 2017), we find certain combinations of velocity and Q anomaly are easier to invert than others. Specifically, we can effectively invert low velocity and low Q (strong absorption), whereas we struggle to invert high velocity and low Q. For typical seismic frequencies and bandwidths used in industrial FWI, the kinematic effects mainly drive the results. Hence, for the typical reference frequency used in Q models in the North Sea, in the high velocity/low Q case, these kinematics work in opposite directions in the data domain, meaning they partially cancel each other, making separation difficult. In the low velocity/low Q case, the kinematics work in the same direction meaning an iterative approach has more scope to separate them. This is fortunate as the low velocity/low Q case is the one most usually encountered with Q anomalies in our seismic data.

**Survey, pre-processing and Q-FWI details**

The survey was acquired offshore Norway in 2014-2016 using a variable-depth streamer and source acquisition (Figure 1). The nominal survey has an 18.75 m dual-source with a sail-line separation of 450 m. The streamer length is 7950 m, with 12 cables in total, each 75 m apart and a hydrophone group spacing of 12.5 m. FWI data pre-processing consisted principally of swell noise removal and sparse tau-p noise attenuation to enhance the low frequency S/N ratio, and a mute to keep the diving waves. As part of the ongoing velocity model building flow, a Q-FWI update up to 4 Hz has been run in production over the entire survey, using a simple starting velocity and anisotropy model derived from tomography and well-tie analysis. In selected regions we pushed this to 12 Hz to study the effect of higher frequencies on the results. Velocity was updated down to the diving-wave penetration (~2.0-3.0 km) and Q was updated down to shallower depths (~1 km). This approach is similar to the observed behavior in the checkerboard velocity and attenuation results shown in Malinowski et al. (2011). In addition, this strategy ties with the observation that the shallower section contains the most prominent absorptive anomalies, and acknowledges that, at this initial stage of the modeling build, the likelihood of cross-talk is increased in the deep (the deeper Q model will be revisited at a later stage).

**Data example: the Peon gas field**

The Peon gas field was discovered in 2005 at a depth of ~600 m beneath the sea surface. It is ~250 km$^2$ in size and contains an estimated recoverable resource of 15-30 billion standard cubic meters of gas. Figure 2 shows depth slices at 595 m of the inverted velocity and Q models overlain on a migrated image. Starting from a smooth background, both updated models correlate nicely with the underlying geology. Figure 3 shows the imaging uplift brought by this high-resolution Q model. There is an obvious flat spot, i.e. the gas/water contact at the base of the reservoir (indicated by the green arrows). This event appears flatter after imaging with the Q-FWI model when compared to the migrations with either the starting or conventional FWI models. In addition, the images beneath the gas field are improved (yellow arrows) with better focusing, higher resolution, stronger stack response and improved structural continuity. Also amplitudes of events across the section show better consistency and importantly, geological structures appear simpler with reduced undulations.

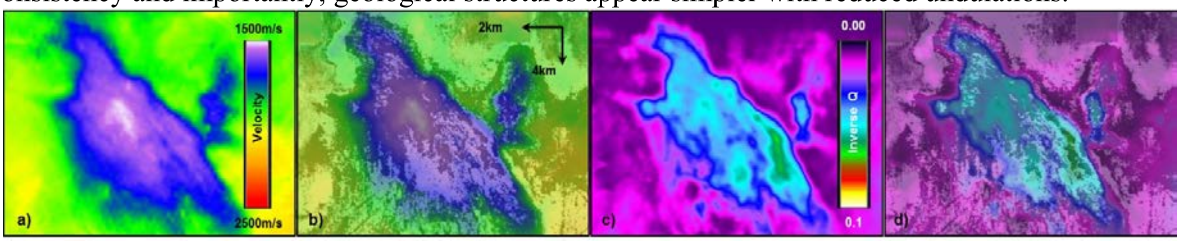


***Figure 2*** *Depth slices at 595 m of output Q-FWI velocity model through the Peon gas field: (a) without, and (b) with seismic overlay. Output 1/Q model: (c) without, and (d) with seismic overlay.*

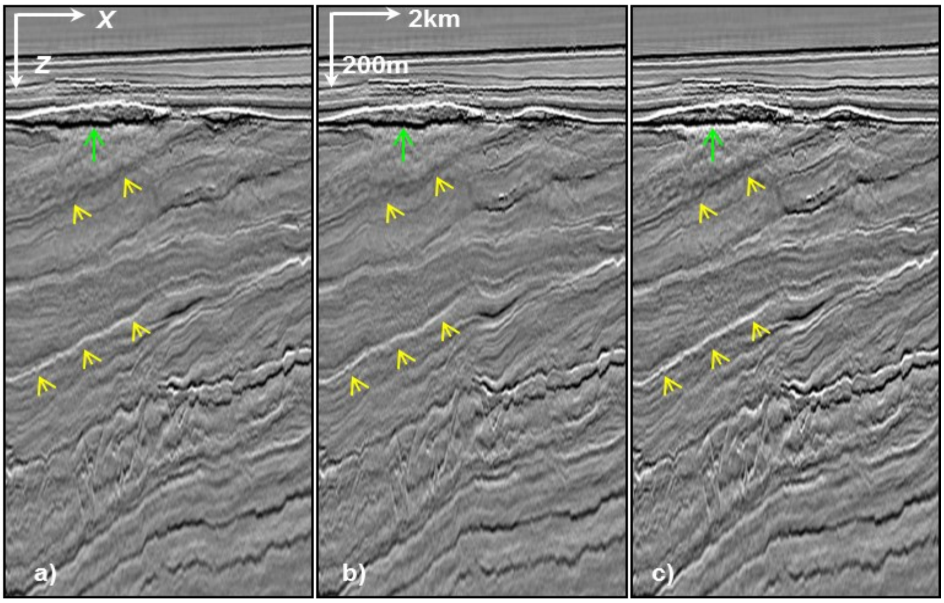


***Figure 3*** *Comparison of Q-compensating pre-stack depth migrated sections through the Peon gas field imaged with: (a) starting velocity model (Q=150), (b) conventional FWI output velocity model (Q=150), and (c) Q-FWI output model, Q-migrated with the high-resolution velocity and Q models. Green arrow indicates the flat spot, which shows a better response after Q-FWI than a conventional FWI approach; yellow arrows indicate better focused sediments with simpler structure after Q-FWI.*

**Data example: higher frequency Q-FWI over small-scale gas pockets**

The Q-FWI production at 4 Hz captured the dominant Q bodies in the shallow section and has largely resolved their associated imaging problems. However, to further investigate even higher-resolution Q models and their uplift on velocity model building and interpretation, Q-FWI up to 12 Hz has been run on a smaller test area (~230 km$^2$). Figure 4 shows these results over a region containing a previously unknown set of small-scale Q bodies that are potential drilling hazards. Here the lateral and vertical extent of the Q anomalies correlate highly with the reflection anomaly and are seen to clearly solve the image distortion, as indicated by the orange rectangles in Figure 4i and 4j.

**Conclusions**

We have applied Q-FWI to a ~36,000 km$^2$ area in the North Viking Graben, Norwegian North Sea. The high-resolution velocity and Q models were inverted at an early stage in an ongoing velocity model building. Q-FWI is a challenging process, with parameter cross-talk being a concern. However, we show strong evidence of a convincing Q-FWI result through the geological conformability of the estimated models, as well as uplift in the resulting Q-compensated migrated images that could not be obtained from conventional FWI alone. More advanced imaging methods (least-squares Q-migration) could be utilized to maximize the benefit of the high-resolution Q model. We believe that including better physics in the inversion has led to a better velocity model and a superior subsurface image.

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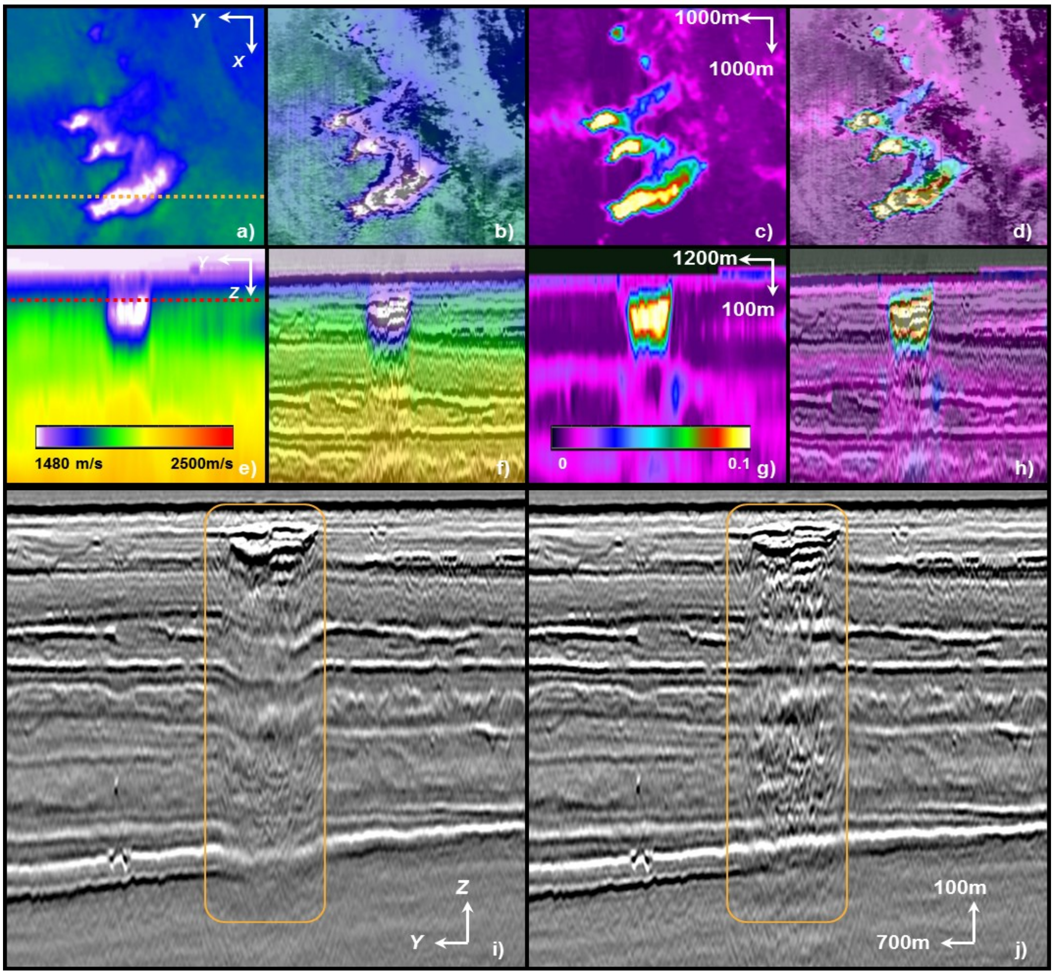


***Figure 4*** *Q-FWI results for a small-scale set of gas pockets: depth slice of updated velocity and 1/Q models (a and c) without, and (b and d) with seismic overlay. The crossline section is shown in (e)-(h) and the dotted lines on these panels indicate the location of the extracted data. Comparison of Q-compensating pre-stack depth migrated crossline sections imaged with: (i) starting velocity model (Q=150), and (j) Q-FWI output model, Q-migrated with the 12 Hz velocity and Q models. The orange rectangle shows the correction to the distorted image through the gas pocket with the Q-FWI model.*