Deriving a high-resolution regional scale Q model over the Northern Viking Graben

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Summary

Deriving an accurate high-resolution seismic quality factor (Q) model is necessary to both compensate for the phase dispersion and amplitude attenuation effects of the Earth's anelasticity during imaging, and to reduce parameter cross-talk during velocity model building (VMB). Various methods exist for deriving Q, each with potential inherent limitations that can restrict their suitability for scalable applications, such as over the ~14,000 km2 area presented here in the Norwegian North Sea. We describe a multi-process Q derivation workflow, including dual-azimuth Q full-waveform inversion (Q-FWI), time-lag FWI guided ray-based Q tomography, and well-synthetic validations using Q sensitive metrics to derive a regional high-resolution Q model. When incorporated into VMB and subsequent Q migrations, the regional Q model is shown to both locally and regionally compensate for amplitude attenuation and phase dispersion, and providing an associated improvement in imaging.

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Introduction

The seismic quality factor, Q, describes the Earth's anelastic effects which cause amplitude attenuation and phase dispersion of seismic waves. Incorrectly compensating for Q during seismic imaging can hinder resolution and focusing, and result in incorrect amplitude and frequency content, both spatially, and across offsets affecting structural interpretation, inversion and AVO. These issues are exacerbated if Q is not inverted and honored in velocity model building (VMB) due to parameter cross-talk (Hak and Mulder, 2011) causing erroneously derived velocities.

Accounting for the effects caused by Q through either 3D Pre-Stack Depth Migration (Q-PSDM; Xie et al., 2009) or other 3D pre-stack methods has become common practice. However, deriving an accurate high-resolution Q model across multiple stratigraphic intervals remains a challenge, especially in regional data sets. Numerous derivation and validation methods are explained in the literature each with their own benefits, but inherent limitations which hinder their suitability for scalable applications.

Here we adopt a workflow for achieving a high-resolution Q model over a regional 14,000 km^2 data set as part of a wider multi-parameter VMB sequence. This includes dual-azimuth (DAZ) Q full-waveform inversion (Q-FWI), a high-resolution time-lag FWI (TLFWI; Zhang et al., 2018) guided ray-based Q tomography, as well as an authentication process by analysing Q sensitive metrics against well data. This provides a reliable high-resolution regional Q model which, when utilized in VMB and subsequent Q migrations, is shown to enhance imaging at both local and regional levels.

Setting, surveys and challenges

The 14,000 km^2 survey area is in the Northern Viking Graben (NVG) area of the Norwegian North Sea (Figure 1a), where Q is a challenge with widespread attenuating bodies of various magnitudes, dimensions, and depths. It contains numerous hydrocarbon discoveries, some of which are themselves prolific Q bodies. The full area was surveyed by East-West orientated multi-sensor data from 2020 to 2022, with 12,000 km^2 covered by North-South orientated variable depth streamer data from 2014 to 2016. Both surveys had twelve 75 m separated, 8 km long, streamers providing diving wave penetration down to 2 km deep. The two surveys complimented each other in illumination and spectral content. The data sets employed a modern DAZ processing flow, explained by Latter et al. (2022) over a sub-area.

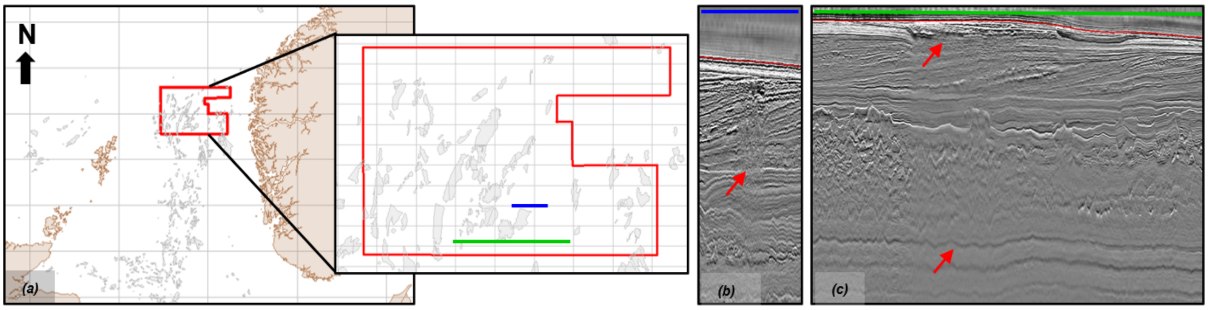

Figure 1 *(a) Survey location with established fields overlain. Cross-sections (b) and (c) show legacy migrated seismic with background only Q compensation, highlighting some Q imaging challenges.*

Q derivation methodology

Q can be derived from surface seismic and well data by various methods. Ray-based Q-tomography can be used (Gamar et al., 2015) but does not achieve the same resolution as FWI and may break down in shallow water settings due to limited offset information. Q-FWI (Xiao et al., 2018) can mitigate these issues by honoring and inverting for Q in FWI. However, Q-FWI can suffer with multi-parameter cross-talk and, compared with velocity inversions, the inverted Q can be limited in terms of resolution at deeper depths (this observation was also made by Malinowski et al., 2011). We see this more in areas of reduced wavefield illumination, especially below the diving wave penetration. Well-based derivation methods using either VSP or check-shot data have been utilized, some locally over the NVG area (Carter et al., 2020), but these cannot be used to derive a high-resolution field as they are inherently limited in spatial sampling and are often missing near surface sampling where shallow attenuating bodies are rife.

Hence, we adopt a workflow for achieving a high-resolution Q model over this regional area, drawing on the merits of each method and combining them where necessary as part of a wider multi-parameter VMB sequence. First, diving wave DAZ Q-FWI is performed for the shallower sections aided by the illumination afforded by the diving waves of the two perpendicular 8 km streamers, to obtain the first velocity and attenuation models. Then a DAZ TLFWI guided Q-tomography is performed to derive deeper Q bodies where reflection sampling is more plentiful. This extends the work done by Zhou et al. (2014) to incorporate the full wavefield with TLFWI, including reflections, diving waves, ghosts and multiples to help derive significantly higher-resolution deeper Q bodies than could be achieved by just using ray-based tomographic methods alone.

Finally, the Q model was then validated using well-based metrics. These included analyzing phase shifts of data migrated using the legacy and updated models against computed well synthetic seismograms spread over the regional area. Phase shifts were computed using a cross-correlation method based on a Hilbert transform. These also facilitated fine tuning to the background Q field to improve the phase match. Finally, subsequent velocity and anisotropy inversions were performed honoring the high-resolution Q model with DAZ TLFWI, and DAZ reflection tomography.

Results and Discussion

To first appreciate the impact deriving a regional high resolution Q model can have on a local scale, in Figure 2 we review the Q-PSDM results imaged using the updated Q and velocity models compared to the legacy models (Xiao et al., 2018). We observe that directly beneath the most prominent attenuating bodies (blue arrows) the reflectors are more spatially continuous as amplitude attenuation and dispersion have been locally compensated. Deeper, comparing the red and green arrows, we see the crestal unconformities are now visible and, in the Jurassic, minor fault blocks and internal reflections are now more clearly defined. Sub-Jurassic, the basement reflections are more structurally continuous, with some smaller antithetic faults coming into focus. While the dominant imaging improvements are due to the locally improved amplitude and phase compensation with the high-resolution Q model, indirect effects of the multi-parameter inversions also contribute, since the velocity inversion converges more accurately with reduced parameter cross-talk when the Q is both inverted and honoured.

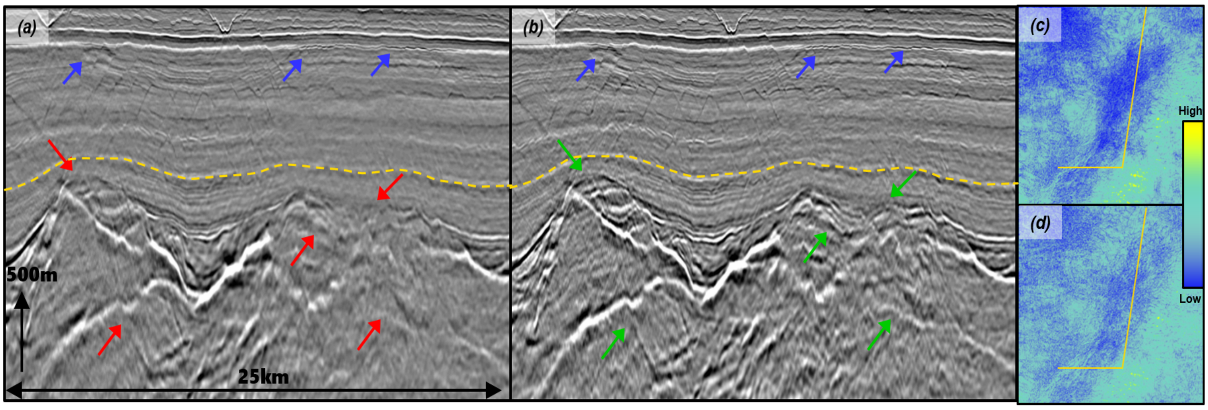

***Figure 2** Q-PSDMs beneath gas bodies at 2000 m (blue arrows) using: (a) legacy, and (b) updated velocity and Q models. The corresponding RMS amplitudes >20 Hz are extracted along the yellow horizon and displayed in (c) and (d), respectively. Note despite spatial reflectivity variations, the improved structural continuity, focusing and amplitude balancing when migrating with the new models.*

Switching to a regional view, the new Q model is compared to the legacy Q model in Figure 3, with the legacy result derived by single-azimuth Q-FWI alone. The resolution obtained by DAZ Q-FWI is clear in the shallow. Different scales of absorbing geological bodies are delineated better than legacy, from localized gas clouds (Figure 3e), to the regional Norwegian Channel (Figure 3d). Variation of Q within these features has also been well captured. Below the diving wave penetration at 2 km, a spatially varying attenuation layer is inverted by DAZ TLFWI guided Q-tomography. While harder to appreciate while zoomed out, the regional imaging improvement over the legacy is portrayed in Figure 3b. While natural reflectivity variations along reflectors are expected, the spatial continuity of amplitudes beneath the attenuating features is clearly enhanced, after dispersion and amplitude attenuation effects have been compensated with new Q-PSDM using the updated Q and velocity models.

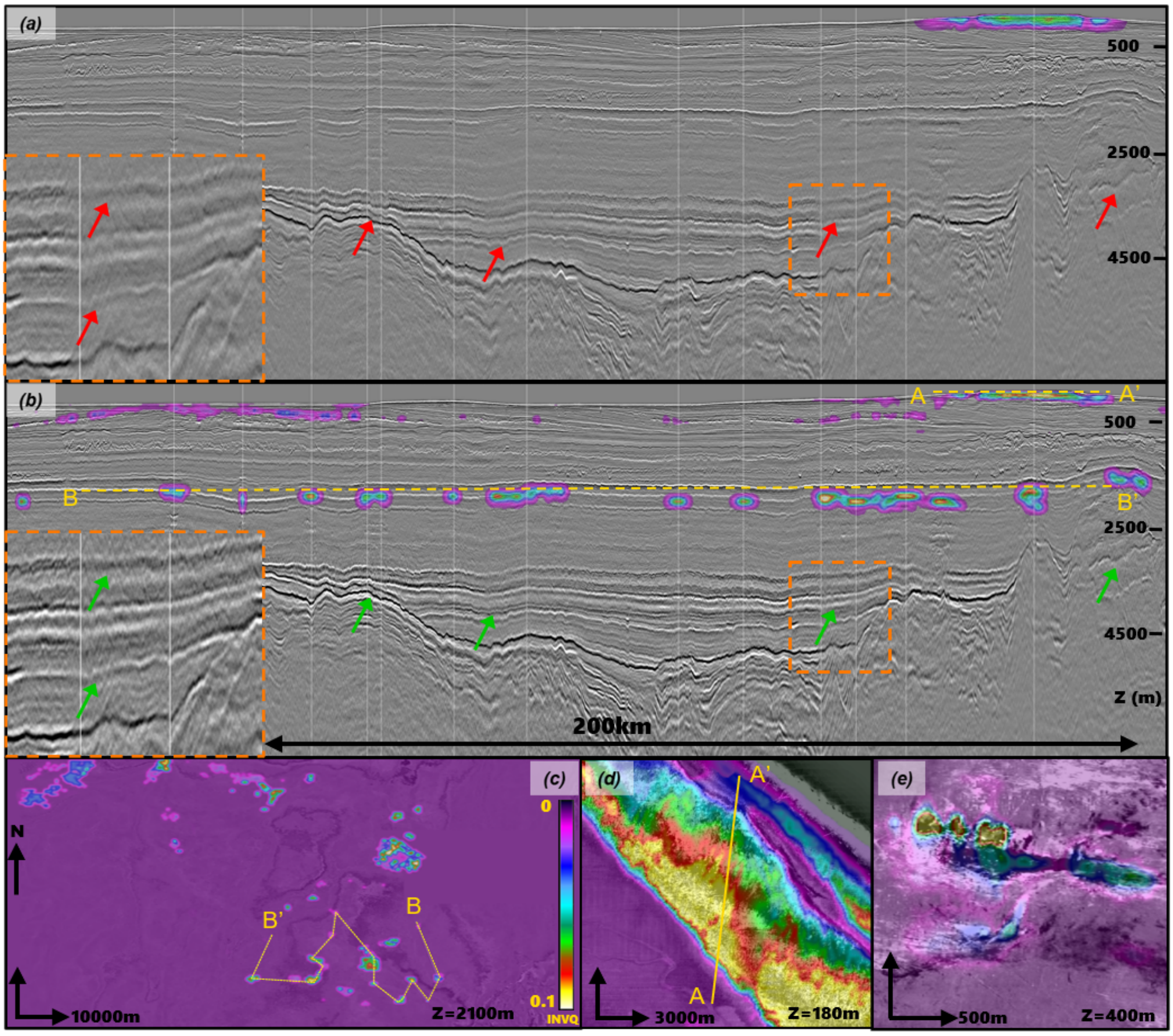

Figure 3 *Fence images of: (a) legacy, (b) updated Q models with associated Q-PSDMs. (c) deeper depth slice through new Q model, along with shallower depth slices in (d) and (e). Note on the vertical cross-sections, inverse Q values beneath 0.01 are set to transparent to highlight localised bodies.*

Validating a Q model, especially on a regional scale, can be challenging. Figures 4a-4b show the phase error from cross-correlating the Q-PSDM using the legacy and updated models, respectively, to synthetic seismograms derived from 16 wells spread over the 14,000 km^2 area. The rationale being that with a more accurate Q model and dispersion effects compensated, the phase error with the synthetic seismograms should be lower. While over specific intervals this result was difficult to interpret due to localized noise and tuning issues, globally there was an improvement with the updated model with no bulk phase rotation error (green dotted line), while the legacy Q result carried a 3 degree mean error (pink dotted line). Furthermore, after modelling synthetic data with both the legacy (Figure 4e) and new (Figure 4f) Q models, the tie between the observed and synthetic data was closer with the new Q model.

Conclusion

We show that limitations associated with individual Q-derivation methods can be mitigated by using a combined approach. This results in a high-resolution regional scale attenuation model, delineating attenuating bodies of varying scales, intervals and depths. After Q-PSDM the new Q model was shown to correct for dispersion and amplitude attenuation regionally, improve ties to well based QCs, and materially improve imaging locally under attenuating bodies when used in a multi-parameter VMB workflow. Further work can include increasing the well coverage to reduce remaining ambiguity in the QC. Furthermore, maximising the imaging benefits of the high-resolution Q model could be achieved with Q-compensating least-squares migration (Latter et al., 2018) or FWI Imaging, and incorporating more physics into the inversion algorithms, for example, including elastic effects in the Q-FWI.

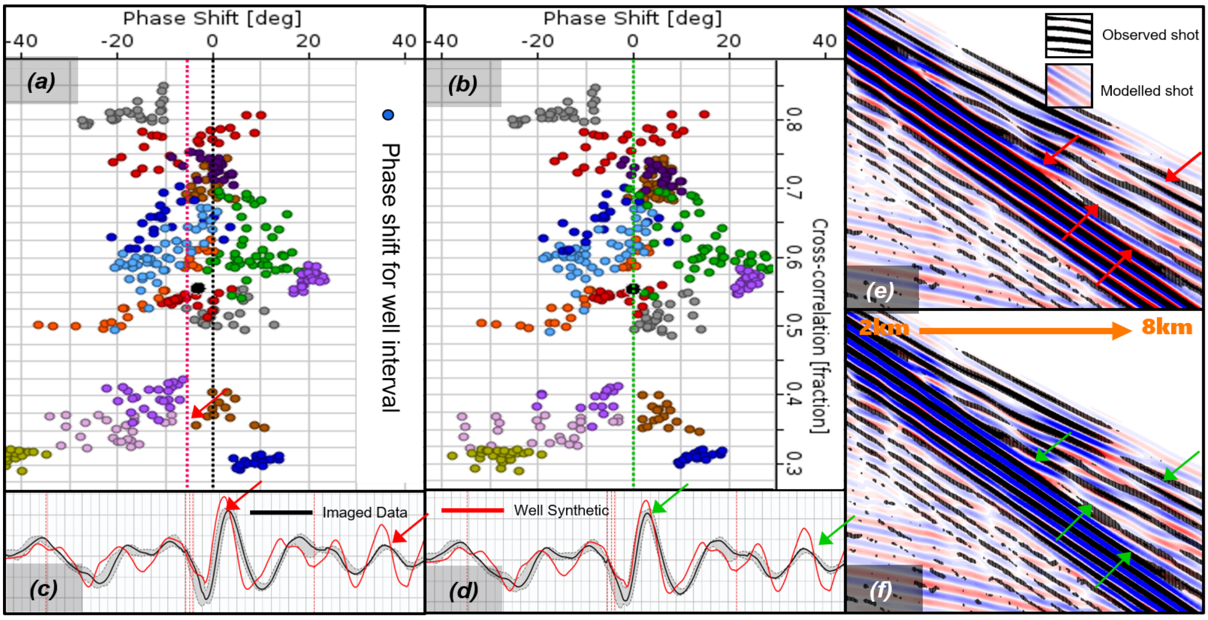

***Figure 4** Calculated phase shifts of synthetic seismograms vs Q-PSDM of: (a) legacy, and (b) updated Q models, with examples for one well interval in (c) and (d), respectively. Each colour represents a well and each dot represents a sample range for each well. An example of a visco-acoustically modelled shot using the (e) legacy Q, and (f) the new Q model overlaid against the observed data.*

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