H003

Deriving 3D Q Models from Surface Seismic Data Using Attenuated Traveltime Tomography

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SUMMARY

Estimation of the intrinsic attenuation of the Earth, conveniently described by the quality factor Q, is of great importance in seismic processing and rock physics interpretation. However, deriving a Q Earth model from seismic data is quite challenging, as anelastic and elastic attenuation effects on propagated waves can be difficult to dissociate. In this paper, we propose to derive 3D Q Earth models from prestack surface data by applying an inversion of the attenuated traveltimes of selected seismic events (first arrivals, reflections). Attenuated traveltime is defined as the traveltime of the propagated signal weighted by its effective-Q factor. This factor is obtained from a preliminary effective-Q mapping based on a suitable amplitude analysis and assumed to provide "intrinsic enough" effective-Q estimates. An estimate of the velocity is only required for a kinematic ray tracing during the inversion. This technique can be applied, for instance, to first-arrival events. A first-arrival tomography is implemented to derive both a near-surface velocity model (traveltime inversion) and a near-surface Q model (attenuated traveltime inversion). This approach is illustrated here on a synthetic dataset. Reflection attenuated traveltime tomography can be considered in a similar manner.
Introduction

Compensation for the effects of the intrinsic attenuation of the Earth (conveniently described by the quality factor Q) is of great importance in surface seismic data processing. It can improve image quality and amplitude analysis (such as AVO), as propagated waves can be strongly affected by these effects. Seismic processing applications that use advanced inverse-Q filtering or Q-migration (Yu et al., 2002; Mittet, 2007) require reliable Q Earth models. Q Earth models can also be of great help in rock physics interpretation. However, the determination of such models is far from obvious, mainly because anelastic and elastic attenuation effects on the propagated waves can be difficult to dissociate. Over the past years a few inversion schemes have been proposed to derive space-consistent 2D or 3D Q models from prestack surface data. These are based either on a full waveform estimation (Malinowski et al., 2007), on a pulse broadening analysis (Rossi, 2007) or on amplitude observations (Brzostowski and McMechan, 1992). While pulse broadening measurements may be less affected by spurious elastic effects, their analysis relies on simplified assumptions about the source wavelet spectra. On the other hand, to derive reliable intrinsic attenuation models, any amplitude inversion of prestack data requires a carefully designed scheme to remove, as far as possible, elastic effects that contribute to amplitude attenuation (such as geometrical spreading, transmission/reflection losses or scattering). This can be done by removing elastic features from the data using some preliminary modeling, although this significantly increases the cost of the process and requires a very accurate estimation of the velocity model. Another approach can be to invert for both elastic and anelastic factors, as proposed by Rickett (2006) for the determination of 1D Q models. Alternatively, we propose a two-step process in which we first derive a space-and-time-varying effective-Q map using an appropriate amplitude analysis that should provide “intrinsic enough” effective-Q estimates, without specific additional data preprocessing. A 3D Q model is then obtained by means of an attenuated traveltime tomography (aTTT) scheme based on the inversion of the attenuated traveltimes derived from the effective-Q map.

Effective-Q mapping

The intrinsic amplitude attenuation of a wave propagating through a medium can be expressed in terms of effective-Q ($Q_{\text{eff}}$), defined as the integration of the Q-effects along the propagation path. Assuming that amplitude attenuation varies linearly with frequency and that $Q_{\text{eff}}$ is independent of frequency in the bandwidth of interest, the log spectral ratio (LSR) between a propagated signal and the reference signal may be approximated as:

$$\log \left( \frac{A(f)}{A_0(f)} \right) = \frac{\pi}{Q_{\text{eff}}} f + c,$$

where $f$ is the frequency; $A_i$ and $t$ are the spectral amplitude and the propagation time of the event, respectively; $A_0$ is the reference spectral amplitude (source); and $c$ contains remaining elastic effects such as geometrical spreading or transmission/reflection losses and is assumed independent of frequency. Following the traditional LSR slope analysis technique applied, in particular, on VSP data (Tonn, 1991), the effective-Q value of a propagated event can be derived using a linear regression of its LSR as a function of frequency. Performing a linear regression for each event to derive a space-and-time-varying effective-Q map can be expensive. When considering a whole reflection dataset, we propose to use cost-effective extensions of the LSR method such as the one introduced by Lancaster and Tanis (2004) using smoothed spectral amplitudes, which allows a rapid estimation of a dense effective-Q map while removing the local reflectivity overprint. Alternatively, the Bachrach et al. (2006) approach, based on a low-order polynomial fitting technique of a time-frequency representation of the amplitude, can be used. This method should intrinsically allow the
separation of the elastic effects from the anelastic contribution, and has the great advantage of not requiring an explicit estimate of the reference amplitude. However, while smooth effective-Q mapping techniques may be appropriate for large-scale heterogeneities, a local LSR slope analysis of selected events may be more suitable when fine detail is required.

**Attenuated traveltime tomography**

Once a reliable effective-Q map is available (as a function of offset $h$, CMP $X$, and time $t$), spatial 3D Q models can be tomographically derived by inverting the attenuated traveltime $t^*$ of selected seismic events recorded at $(X, h, t)$ where $t^*$ is defined as the traveltime $t$ of the propagated wave (estimated by ray tracing) weighted by its effective-Q factor,

$$t^* (X, h, t) = \frac{t}{Q_{\text{eff}} (X, h, t)},$$

and is expressed as an integration of both velocity and Q effects along the propagation path (raypath) of the wave

$$t^* = \int_{\text{ray}} \frac{Q_{\text{eff}}^{-1}(s)}{v(s)} ds \approx \sum_{(i,j,k)} \delta t_{jk} Q_{ij}^{-1}.$$

In the above expression, $v$ is the velocity distribution of the medium. Assuming a 3D gridded Q model, $Q_{ij}^{-1}$ is the inverse of the Q element at grid cell $(i,j,k)$ crossed by the ray and $\delta t_{jk}$ is the traveltime component of the ray in the grid cell. An estimate of a 3D Q model can thus be obtained by performing a kinematic two-point ray tracing within the velocity model (determined beforehand) for each of the considered events $(X, h, t)$, and then solving the linear system formed from the above equation (in its discrete form).

**First-arrival attenuated traveltime tomography**

As a first application of the aTTT process, we restrict the inversion to first-arrival attenuated traveltimes. Of course, the deeper the diving waves (or any other first arrivals), the deeper the estimated Q model will be. Ray tracing is performed using an efficient Eikonal solver and the effective-Q mapping is restricted here to a LSR slope analysis of the first arrivals. Because this approach is closely related to first-arrival traveltime tomography for velocity model building, first-arrival aTTT is integrated in a first-arrival tomography process that consists first of a linearized (iterative) inversion of the traveltimes for velocity model building and then in a linear inversion of the attenuated traveltimes computed from the estimated effective-Q map. In this way, near-surface Q models are derived in addition to velocity models at a minimal additional cost. First-arrival tomography has been successfully applied to both synthetic and real data (Tanis et al., 2006) to build near-surface velocity models. Provided that the effective-Q mapping is accurate enough, we can expect the first-arrival aTTT performed with these models to provide near-surface Q models helpful for rock physics interpretation and/or Q-migration to correct, in particular, for shallow gas anomalies effects.

**Application**

In this paper first-arrival aTTT is illustrated with a simple 2D synthetic example. Data are computed from finite-difference visco-acoustic modeling in a model with a vertical velocity gradient and a low Q anomaly (strongly attenuative), as illustrated in Figures 1(a) and 1(b). Shots are simulated every 50 m, with a receiver spacing of 12.5 m and a maximum offset of 2.5 km (to the left of each source). Attenuation is clearly visible on the common offset section displayed in Figure 1(c). First-arrival traveltimes are picked as input to our first-arrival tomography scheme to derive both a velocity model and a Q model. The initial velocity model used as input is homogenous. Figure 2(a) shows the effective-Q values derived from the LSR slope analysis of the first arrivals. The direct arrival associated with the nearest
offset (12.5 m) is used as the reference wavelet and the linear regression of the LSR is performed from 10 to 90 Hz (input wavelet centered at 50 Hz). About 1200 effective-Q values are estimated (from 1 km to 2.5 km offset) and used to compute attenuated traveltimes to invert for Q. Inversions are performed with a 10-m by 10-m grid for the velocity model and a slightly coarser grid for the Q model (50 m by 50 m). The estimated velocity and Q models are illustrated in Figures 2(b) and 2(c). They both provide relatively good matches to the true models in the illuminated area. The Q anomaly is well recovered, although some low Q values are wrongly spread along the border of the illuminated area due to the lack of coverage (c.f. bottom left corner of the anomaly and artifact visible on the right side). However, the computed Q model suffers from a lack of vertical resolution in the shallow part above the anomaly because no first arrivals corresponding to events that turn at these very shallow depths exist to help to vertically constrain the model.

Discussion

By considering the application of aTTT to first arrivals, we derive a fast process to obtain 3D near-surface Q models. Although Q inversion is linear and does not depend on any initial assumption about Q, the whole process may require some a priori information about the velocity, as any traveltome tomography scheme. Of course the accuracy of the resulting Q
model will be dependent on the accuracy of the estimated attenuated traveltimes (and thus, of the effective-Q mapping) together with the accuracy of the velocity model from which raypaths are determined. For these reasons, it may be sensible to look for a coarser Q model than the velocity model. However, aTTT should be much less dependent than amplitude tomography on the knowledge we have of the velocity field. Provided that a depth velocity model is available, the application of aTTT to other prestack events such as reflections can be carried out in a similar manner with adequate two-point ray tracing of specific ray signatures. This, of course, requires some interpretation of the events to be inverted. The attenuated traveltimes can then be computed using the traveltimes provided by the ray tracer (no picking involved) together with the effective-Q map. Similarly to first-arrival tomography, both velocity and Q models can be derived using a general process of reflection traveltime and reflection attenuated traveltime tomography.

References


