INTERPRETATION OF SEISMIC TOMOGRAPHY RESULTS USING DATA QUALITY AND RESIDUAL ERROR MAPS

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Abstract

In seismic borehole tomography, the interpretation of the results is commonly limited to the comparison of the velocity map, the ray coverage, and the global root-mean-square RMS residual. However, the quality of the seismic data has a significant influence on the accuracy of the arrival time picking, but is generally not considered in the inversion. This paper presents an enhancement of the inversion taking into account the data quality, based on the signal-to-noise ratio, by using it to weight the traveltime residuals in each iteration step. This implementation also calculates the spatial distribution of the data quality and the distribution of the residual remaining at the end of the inversion, which are used to support the evaluation of a velocity map. The effect of the data weighting is studied on a field data set. Quality and residual maps are given and their relevance for the interpretation is discussed. The results indicate that areas of exceptionally high signal attenuation can be identified by means of the quality information.

Introduction

Seismic borehole tomography is a well-established geophysical method providing high resolution information of the subsurface. Most commonly, the interpretation of the tomography results are limited to the evaluation of the seismic velocity map, the ray coverage, and the global RMS residual. The ray coverage is used to distinguish areas where the velocity map is trustworthy from zones of lower reliability. The global RMS is an important parameter for evaluating the general success of the inversion. Structural information about the subsurface are drawn from the seismic velocity map, which is the result of an inversion procedure using the first arrival times of the seismic signal.

Keywords: Borehole Seismic Tomography, Simultaneous Iterative Reconstruction Technique (SIRT) Inversion, Traveltime Residuals.

It is well known that the data quality of seismic signals varies greatly, not only from region to region but even inside one data set. The data quality can vary from excellent (Figure 1) to very low (Figure 2). It is obvious that in the case of excellent data quality the first arrival time picking is easier and more accurate (Figure 1) compared to the picking of seismic signals which are contaminated by much noise (Figure 2). Generally, the data quality of seismic signals is not considered in the tomographic inversion. The present tomography inversion scheme mixes traveltimes of seismic signals with low and excellent data quality but treats them equally weighted within the inversion.

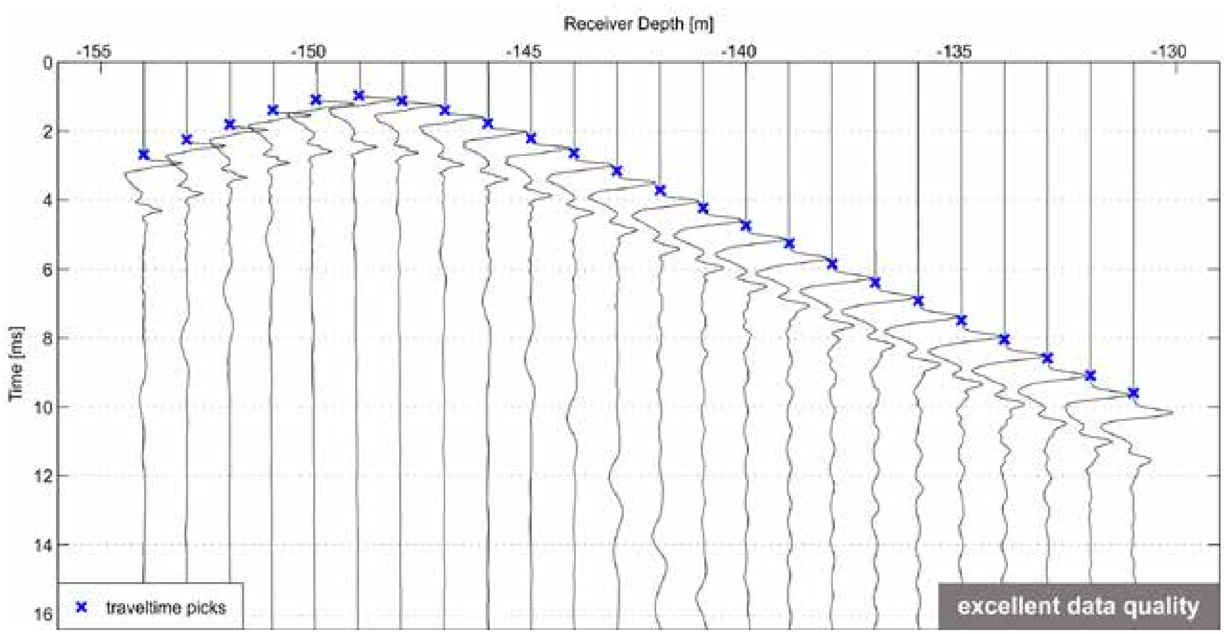

Figure 1: Seismic signals, gathered in saturated sand, showing excellent data quality.

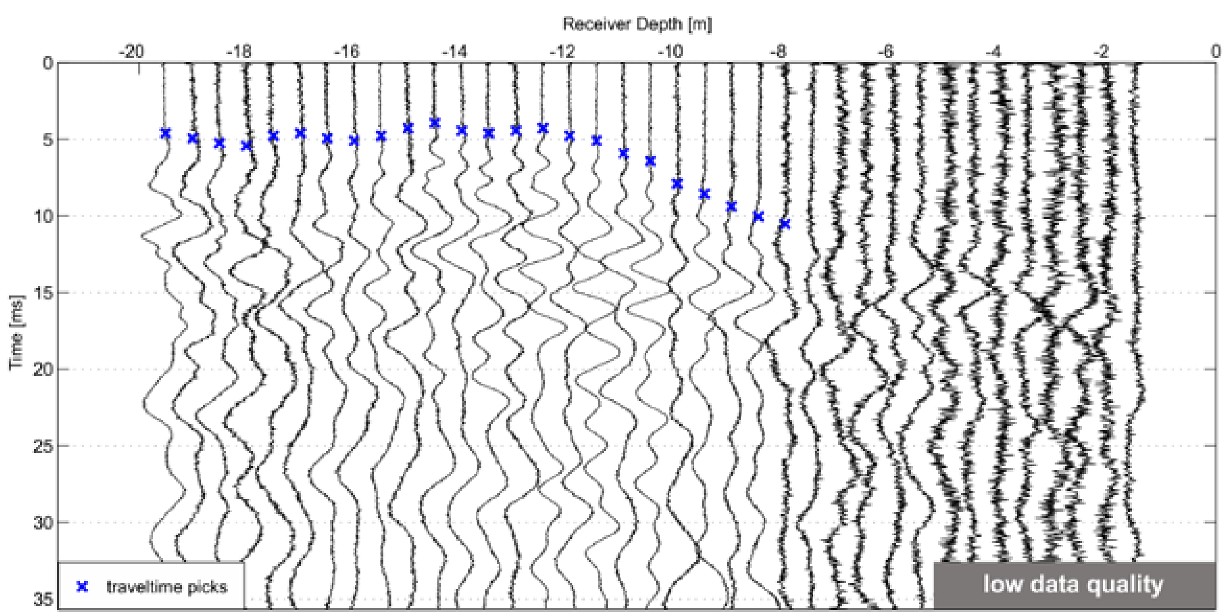

Figure 2: Seismic signals, gathered in weathered unsaturated limestone, showing low data quality.

This paper presents an enhancement of the inversion taking into account the data quality, based on the signal-to-noise ratio, by using it to weight the traveltime residuals in each iteration step. Furthermore, the implementation calculates the spatial distribution of the data quality and the distribution of the traveltime residual remaining at the end of the inversion. These two additional values are used to support the evaluation of a seismic tomography velocity map.

Data Quality Weighting

It is obvious that the signal-to-noise ratio influences the accuracy of a traveltime pick. Thus, the larger the noise, the lower the reliability of a traveltime pick. If the related uncertainty is not addressed within a tomographic inversion process, all picked traveltimes have the same weight and contribute equally to the determination of the seismic velocities within a seismic tomogram. In other words, a seismic velocity determined by a "perfect" traveltime pick competes with an uncertain velocity estimate of a poor traveltime pick. Therefore, equally weighted traveltimes are not the best assumption, as seismic field data are often contaminated by noise of different amplitude and the data quality ranges from perfect quality to useless.

Ray coverage as a measure of ray density per volume is a common criterion to decide if a seismic velocity and the related velocity structure are trustworthy. Lehmann (2007), describes those and other factors affecting quality, resolution, and uncertainty. Guiding the tomographic Simultaneous Iterative Reconstruction Technique (SIRT) inversion of seismic traveltime data with respect to geometrical weighting factors is described by several authors (Krajewski, and others, 1989; Lehmann, 1992; Tinti and Ugolini, 1990). For instance, such weighting schemes take the different geometrical ray density or the ray azimuth into account, i.e., less weight will be applied to areas of lower ray density or to those areas with less azimuthal coverage. However, the weighting is only related to geometrical parameters and does not consider the data quality itself.

To evaluate directly the dependency between signal-to-noise ratio and traveltime picking accuracy, we performed a statistical analysis by generating synthetic wavelets. The signal-to-noise ratio is calculated by the ratio of the maximum first arrival amplitude and the average noise amplitude before the first arrival. This factor is called quality factor (QF) within our numerical implementation. QF values are normalized to the highest QF value in a data set. An example plot of the synthetic seismic signals is shown in Figure 3.

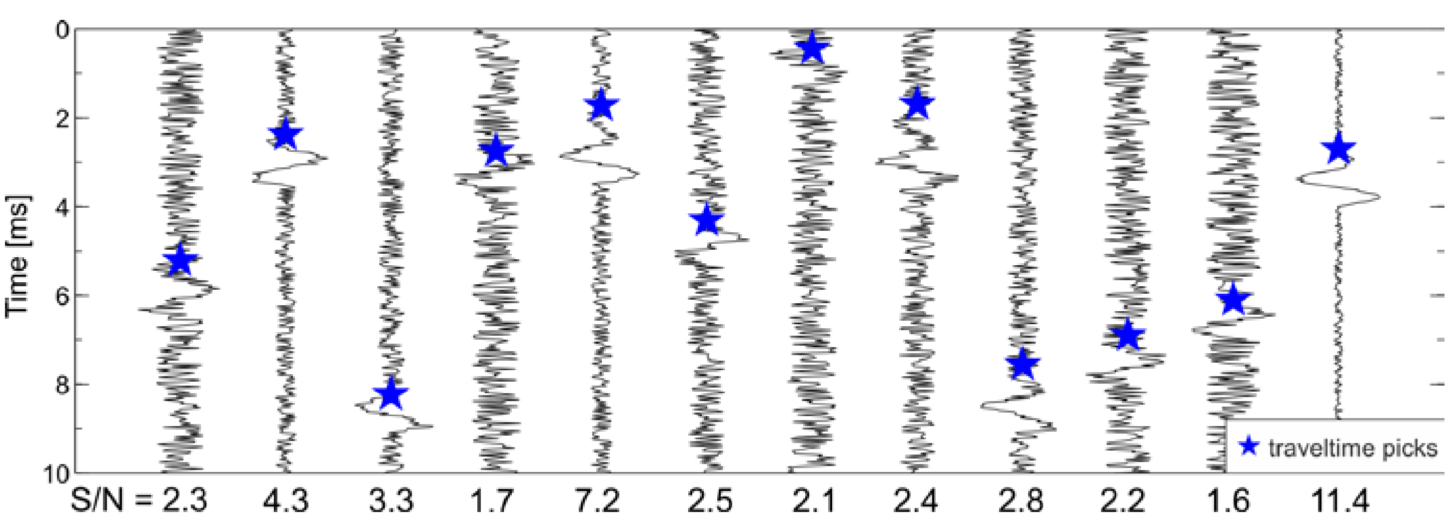

Figure 3: Synthetic seismic signals showing different signal-to-noise ratios and picked traveltimes (blue stars).

First arrival times were picked from modelled seismic signals to allow a basic statistical analysis. Traveltime errors were plotted versus the signal-to-noise ratio and an appropriate trend line was fitted to the mean traveltime picking errors as well as to the standard deviations of the traveltime picks. The results of the analysis are shown in Figures 4 and 5. The plots show how the average traveltime picking error and the standard deviation of the picking error decrease with increasing signal strength.

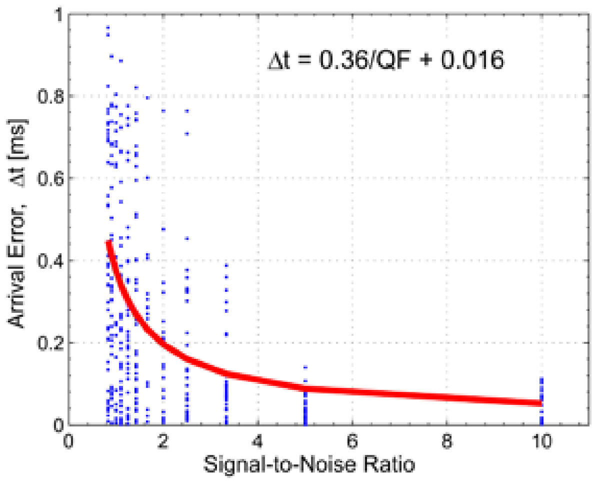

Figure 4: Average picking error.

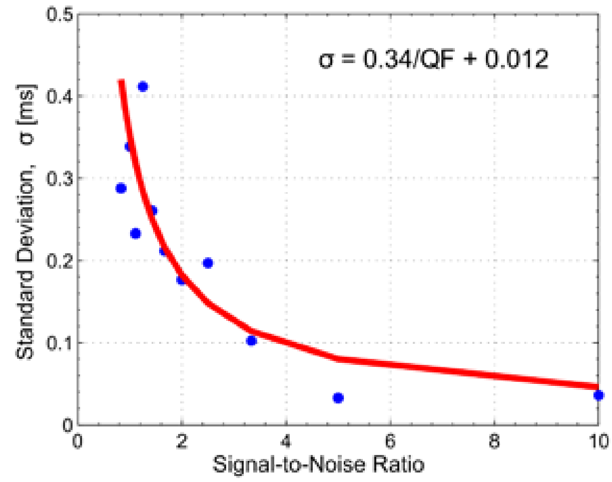

Figure 5: Standard deviation of picking error.

The plots show further that the improvement in accuracy of picking times tends to level off as the signal-to-noise ratio continues to improve, so the QF values assigned to represent data quality should reach a maximum at some threshold instead of continuing to increase with increasing signal-to-noise ratio. To account for the traveltime picking error, we introduce a data quality dependent weighting into the well-known SIRT tomography inversion procedure. Within this procedure, we assign a QF value to each seismic ray "k" calculated from the signal-to-noise ratio of the seismic trace. The QF value (normalized signal-to-noise ratio) is implemented in the SIRT slowness correction scheme (see Equation 1):

$$\Delta s_n = \frac{1}{\sum_k QF_k} \cdot \sum_k \frac{QF_k \cdot \Delta t_k \cdot r_{n,k}}{\sum_m r_{m,k}^2} \qquad (1)$$

where

Δt_k is the traveltime residual of ray "k",
$r_{n,k}$ is the length of the raypath segment (ray "k") in voxel "n",
m is the index of raypath segments belonging to ray "k",
QF_k is the quality factor of ray "k", and
Δs_n is the slowness residual in voxel "n".

If all QF values are equal, equation 1 reduces to the SIRT slowness correction scheme. The implementation of the QF value in the inversion procedure will give higher weight to rays with higher QF value. As a consequence, seismic velocities of rays with higher QF will be have greater influence in a cell than those with lower QF, i.e., the averaged velocity comes closer to the seismic velocity of higher weighted rays. After the final iteration, the distribution of the average QF value in each cell or voxel can be plotted next to the seismic velocity distribution. The QF value distribution shows areas with low and high QF value, thus with lower or higher reliability of the seismic velocity. In this way, the QF value distribution supports the interpretation and evaluation of a seismic tomogram. An example is shown in Figure 6.

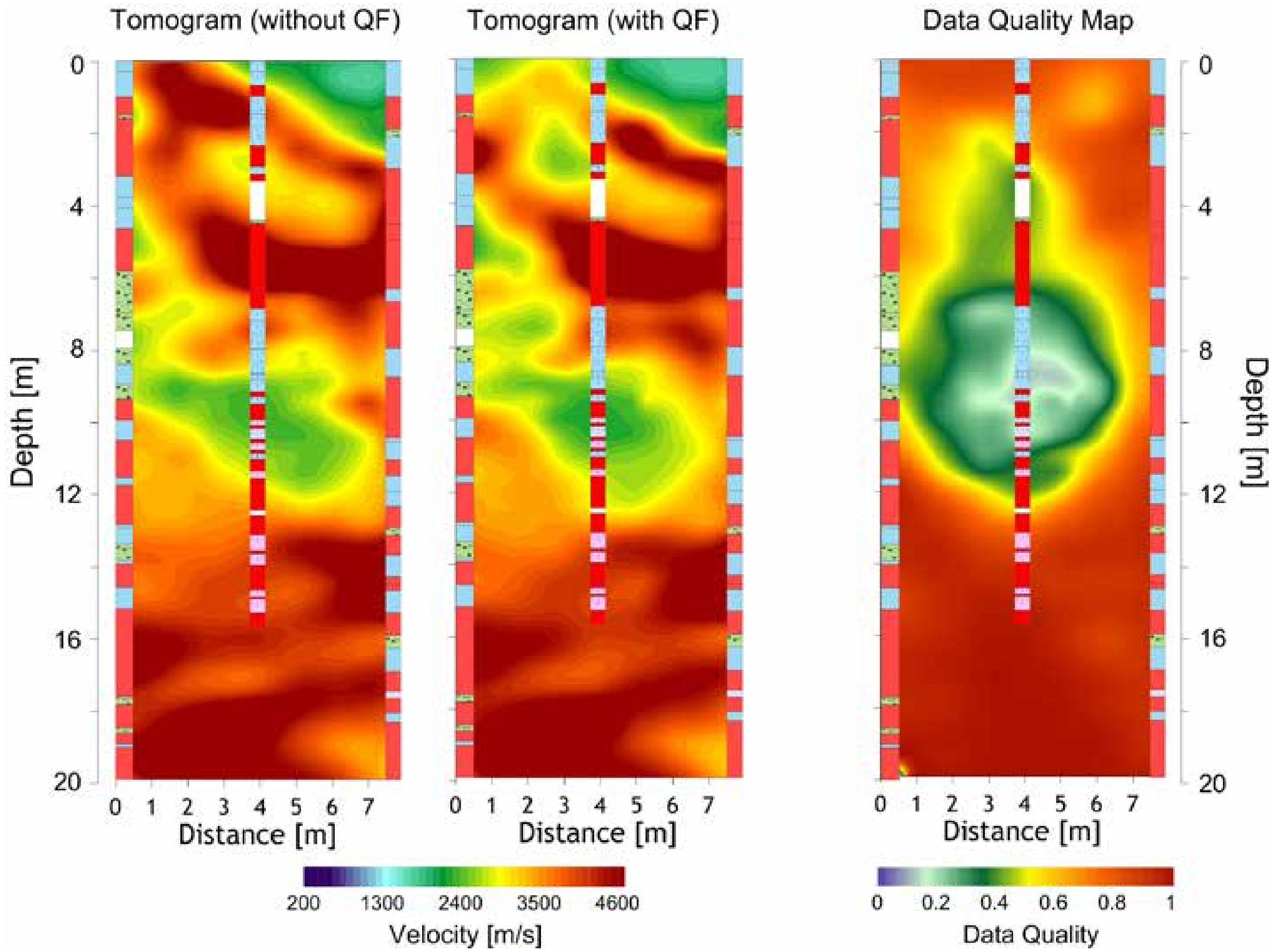

Figure 6: Seismic tomogram without QF (left), seismic tomogram with QF (middle) and related QF value map (right). Coring information is displayed for three boreholes (red – hard rock, blue – weathered rock, green – soft rock, white – cavity).

In general, the seismic tomograms displayed in Figure 6 do not show large differences. The main zonation, such as the high and low velocity areas at the top, the middle and the bottom of the tomograms is similar, as is as the velocity range. However, there are small changes visible in the tomogram inverted using the QF values leading to better differentiation, i.e., less smooth structures. For example, the center area with lower seismic velocities shows a higher resolution especially between the left and middle boreholes. Furthermore, the area around the cavity found at 4 m depth in the middle borehole is sharpened and shows a better resolution. The distribution of the QF values is shown on the right side of Figure 6. Areas with low QF values are in general areas where the velocity determination is less reliable, whereas higher QF values point to a more reliable velocity estimate. Low QF values may correspond to material with higher absorption. Within the QF value distribution, a large area with low QF values is shown in the center part, pointing to material with higher absorption than in other areas. Moreover, the area around the cavity in the middle borehole also shows very low QF values, supporting the seismic tomogram interpretation of the existing cavity. Material of excellent rock quality shows typically higher QF values. This pattern is in agreement with the coring information, especially for the section below 12 m. Thus, we conclude that the implementation of the QF values for seismic inversions offers additional and valuable information for the interpretation of a seismic tomogram.

Residual Error Maps

Iteration progress is measured by the RMS value of the seismic traveltime residual, i.e., measured minus calculated traveltime. The RMS value in most cases remains non-zero, pointing to a non-perfect fit. The small misfit of each traveltime residual can be transformed into a slowness error per voxel. One calculates the slowness residual for each voxel as in Equation 1 and divides it by the slowness in that voxel calculated during the final iteration. One then obtains a relative slowness residual error, as displayed in Figure 7. Areas with relative slowness residual errors close to 0 indicate good estimates of the local seismic velocity. Negative or positive relative slowness residual errors are a sign of underestimated or overestimated velocities, respectively.

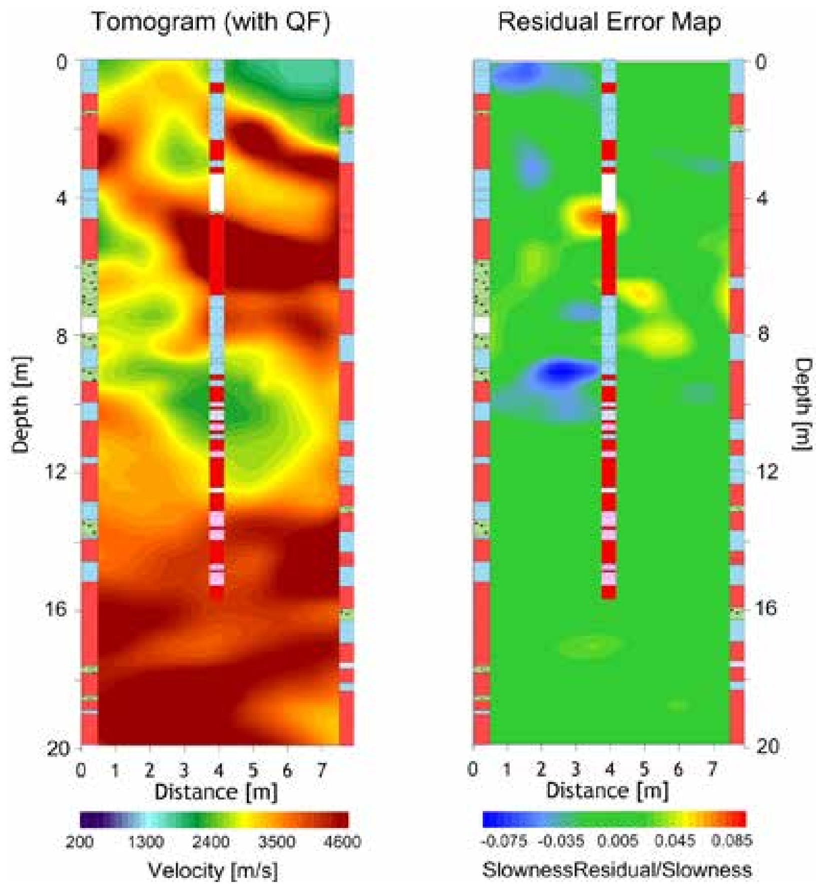

Figure 7: Seismic tomogram with QF (left) and residual error map (right).

Implementation

The procedure has been implemented in GeoTom software. The time-picking software TomTime calculates data quality factors from signal-to-noise ratios. The tomographic inversion software GeoTomCG allows those and other data quality factors to be part of the input data. Thus, the data quality factors can be based entirely on the signal-to-noise ratio or can also take into account other factors judged to affect reliability.

Conclusions

A new data quality weighted seismic traveltime inversion scheme has been presented. The weighting scheme was implemented into the well-known SIRT procedure. Data quality was calculated based on the signal-to-noise ratio of the seismic data. In principle, the data quality weighting allows any individual data quality criteria to influence the inversion procedure. The data quality weighting allows the reliability of the resulting seismic tomogram to be interpreted in terms of the chosen quality criteria. In addition, a procedure to access remaining relative slowness errors after the final iteration is described. The data quality weighted inversion has been successfully tested on field data.

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