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P-wave traveltime tomography for a seismic characterization of black shales at shallow depth on Bornholm, Denmark

Maria Baumann-Wilke*, Klaus Bauer*, Niels H. Schovsbo[†] and Manfred
Stiller*

* *GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam,
Germany. Email: maria.baumann-wilke@gfz-potsdam.de, klaus.bauer@gfz-potsdam.de,
manfred.stiller@gfz-potsdam.de*

[†] *Geological Survey of Denmark and Greenland GEUS, Øster Voldgade 10, 1350
Copenhagen K, Denmark. Email: nsc@geus.dk*

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Running head: **Seismic characterization of black shales**

ABSTRACT

Black shales are organic-rich rocks with the potential to contain oil or gas. On the Danish island Bornholm, Lower Palaeozoic black shales at shallow depth (< 50 m) have a high maturity and a high total organic carbon content. We carried out seismic measurements in the southern part of Bornholm in October 2010 along two profiles to study the seismic properties of the shallow-lying black shales. The profiles were located as near as possible to existing borehole locations for geologic control, and were arranged perpendicular to each other to allow an estimate of the 3D structure of the subsurface. We analyzed the data using P-wave traveltime tomography and obtained 2D P-wave velocity models with a good resolution up to a depth of 100 m. Based on borehole information and the geological setting three formations can be identified in the tomography models: (a) the Komstad Limestone

Formation with a thickness of about 4 m, (b) the Alum Shale Formation with a total thickness of 33 m and (c) the Læså Formation consisting of sandstones. The Alum Shale appears as a low velocity zone between the Komstad Limestone at the top and the Læså Sandstone Formation beneath. All layers dip south-westward. We observe good agreements between borehole-logging data, acoustic velocity measurements of Alum Shale samples in the laboratory and our P-wave velocity tomograms.

INTRODUCTION

Black shales are marine sedimentary rocks with a high content of organic matter which gives them a dark grayish to black color depending on the amount, type and maturity of the organic carbon (Arthur and Sageman, 1994). They contain between 1 and 30 % total organic carbon (TOC) (Weissert, 1981). Black shales are widespread geographically and were deposited throughout much of the earth's history.

The interest in black shales has increased in the last decades because of their potential to contain extractable oil or gas and thus to contribute to the worldwide energy supply. However, relatively little has been published concerning the physical properties of black shales (e.g. Sharma, 1974; Johnston, 1987; Vanorio et al., 2008; Prasad et al., 2009). In contrast, conventional hydrocarbon resources and their associated sedimentary rocks have been investigated to a much greater extent in the past, also with regard to their physical properties (e.g. Gregory, 1976; Domenico, 1977; Doyen, 2007).

On the Danish island Bornholm, Lower Palaeozoic black shales of the Alum Shale Formation are found in the southern and south-eastern parts of the island. The Alum Shale has TOC values of up to 10 % (Buchardt et al., 1986). It is thermally mature having a vitrinite reflectance of 2-3 %, and it is likely that hydrocarbons have been generated from this source rock (Buchardt et al., 1997). The Alum Shale layers on Bornholm have a thickness of about 33 m (Pedersen, 1989; Schovsbo et al., 2011). The shallow depth and the high TOC content of the Alum Shale makes Bornholm an ideal location for a shallow seismic investigation of black shales. Moreover, the location of shallow boreholes with extensive logs, and geochemical characterization of the rocks allowed us to combine the seismic results with detailed knowledge of the subsurface geology.

We derived 2D velocity models for two profiles using P-wave traveltimes tomography. The existing borehole information were compared with our traveltimes tomography results. We find the black shale layer is characterized by P-wave velocities of about 3 km/s with a thickness of 33 m dipping south-westward. In the southern part of the tomography profile, the black shale is overlain by limestone. At greater depth, sandstones are present. Comparison of velocity tomograms and borehole information shows a strong correlation and provide proof of the reliability of the used method.

GEOLOGICAL SETTING

Bornholm is a basement horst located within the Fennoscandian Border Zone (Vejbæk et al., 1994; Graversen, 2009) and is characterized by a mosaic of fault blocks. The northern part of Bornholm is dominated by Precambrian granites and gneisses, whereas in the southern part of the island Palaeozoic and Mesozoic sediments are present (Figure 1b). The Palaeozoic rocks are mainly composed of sand- and siltstone of Lower Cambrian age and black to gray shales in the Middle Cambrian to Silurian section.

The Cambrian sand- and siltstones on Bornholm comprise the Nexø, Hardeberga and Læså Formations. For a recent review of these formations see Nielsen and Schovsbo (2006). The Læså Formation is dominated by greenish gray siltstone with variable glauconite content. Phosphorite nodules occur at several levels and sandstone layers are common, especially in the upper part of the formation. The top member, the Rispebjerg Member, is a regionally widespread sandstone bed. The Alum Shale Formation of Cambrian and Lower Ordovician age consists of dark organic rich mudstone with abundant disseminated pyrite. On Bornholm and in southern Sweden (Scania) the formation has a low proportion of diagenetic carbonate beds. Ordovician shales and limestone formations on Bornholm above

the Alum Shale comprise the Komstad Limestone, Dicellograptus Shale and the Lindegård Formation (Stouge and Nielsen, 2003).

Borehole control in the study area is provided by Skelbro-1 (Buchardt et al., 1986; Pedersen, 1989; Pedersen and Klitten, 1990) and Skelbro-2 (Schovsbo et al., 2011). The Skelbro-1 hole was drilled in 1984 and the geologic description as well as the geochemical analyses was presented by Pedersen (1989). A detailed log stratigraphy based on core samples was reported by Pedersen and Klitten (1990). The Alum Shale in this well occurs between 4 and 37 m below the surface. In 2010 the Skelbro-2 well was drilled 300 m east of the Skelbro-1 location. The Alum Shale in the new area occurs between 8 and 42 m below the surface (Schovsbo et al., 2011).

DATA ACQUISITION

The shallow seismic experiment was carried out in the southern part of the Danish island Bornholm in October 2010 (Figure 1a) to determine the seismic properties of the Alum Shale Formation. The investigation area was located as near as possible to the drill sites Skelbro-1 and Skelbro-2. Two seismic profiles were acquired (Figure 1c), one N-S directed (Line-1) and the other W-E directed (Line-2). Line-1 almost crosses the well location Skelbro-2. The W-E profile had to be farther from the boreholes due to the presence of a main road and a lake. The acquisition parameters for both profiles are summarized in Table 1. We used the Geode system by Geometrics for the data acquisition. The single component geophones used had a natural frequency of 10 Hz. Additionally, stand-alone digital data recorders (GFZ-cubes) using single component geophones with a natural frequency of 4.5 Hz were positioned to reach the full extent of the profiles. The source was a Propelled Energy Generator with a 40 kg weight drop (PEG-40Kg). It was dropped ten times at

every shot location. All receivers were active for each shot. The sampling rate was 1 ms. With this configuration, a maximum penetration depth of 100 to 150 m was reached by the tomographic rays.

The collected data are of high quality. Restitution filtering (Astiz et al., 1991) was applied to equalize both geophone types (4.5 Hz and 10 Hz). To further improve the signal-to-noise ratio, all ten shots at each shot location were stacked. The first arrivals can be identified in the raw data up to maximum offsets of 300 to 500 m, depending on the noise level (Figure 2). The noise was mainly caused by heavy wind and traffic.

TRAVELTIME TOMOGRAPHY

Traveltime data

Traveltimes were picked manually. For Line-1 a total of 17369 traveltimes were picked, whereas 14622 arrival times for Line-2 could be determined. No traveltime data could be obtained where the noise level was too high. Figure 3 shows the distribution of the first arrival times for every source-receiver pair. The traveltimes in Figure 3 were reduced with a reduction velocity of 3 km/s. The diagonal traces indicate the zero offset traveltimes, where source and receiver locations are equal. Figure 3 gives a first impression of the velocity structure of the observed subsurface.

The traveltime distribution for both profiles shows an overall trend of linearly decreasing traveltimes with offset due to an increase of velocity with depth. The distribution for Line-2 (Figure 3b) is very even; therefore, a 1D velocity structure can be presumed. The traveltime distribution for Line-1 (Figure 3a) shows no clear 1D behavior. Decreasing traveltimes for larger source and receiver distances at near offsets (close to the diagonal) yield the

assumption of a high velocity structure at shallow depth.

We calculated the differences between the P-wave arrival times of reversed shot and receiver pairs. The absolute values of the differences are plotted in a histogram (Figure 4). They are normally distributed, which is an indication for the good quality of the traveltime picks. The pick uncertainty is estimated by fitting a Gaussian distribution to the histograms of both profiles. The Gaussian distribution is of the form

$$f(\Delta t) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-\Delta t^2}{2\sigma^2}\right), \quad (1)$$

where Δt is the time difference and σ the standard deviation, $\sigma = 1.2$ for Line-1 and $\sigma = 1.3$ for Line-2. These values were used as the pick uncertainties.

1D and 2D velocity modeling

The first step of the tomographic velocity modeling was to find a simple 1D P-wave velocity model which satisfies the traveltime data of all shots accurately. Although Figure 3a yields the assumption of Line-1 not having a 1D velocity structure, we used the same strategy for both profiles for better comparability. We calculated traveltimes by ray tracing (Zelt and Smith, 1992) for different models with linearly increasing velocity for increasing depth; hence, the models can simply be described by two parameters, the P-wave velocity at the surface and a constant velocity gradient. We tested a large number of 1D models, where both parameters were varied within a range of reasonable values. The range of values was estimated using the sonic log information of the Skelbro-2 well. We obtained the root mean square (rms) error for each model, which resulted in a function of both parameters. The optimal 1D velocity model is found, when the rms error is minimized (Bauer et al., 2003).

The 1D models were used as starting models for the 2D P-wave traveltime tomography.

We used the SIMUL2000 package (Thurber, 1983, 1993; Evans et al., 1994; Thurber and Eberhart-Phillips, 1999) because of its robustness and the advantage of calculating a full matrix solution with a formal resolution matrix and a covariance matrix. The analysis of such matrices is essential for the interpretation and reliability of the final velocity models. SIMUL2000 is a damped least-squares inversion algorithm based on ray tracing. To obtain the optimal damping value for the inversion, a trade-off analysis was carried out (Eberhart-Phillips, 1986): single-step inversions for the initial model were performed using different damping values. The error between the calculated and observed traveltimes (data variance) and the variance of the velocity model in relation to the starting model (model variance) were determined (Figure 5). The optimal damping value can then be found when both variances are minimized. This value amounts to 50 for both Line-1 and Line-2.

We developed the tomography models using a graded inversion strategy (Evans et al., 1994), where the grid point spacing was systematically decreased. This reduces the influence of the initial model on the final velocity models and also reduces inversion artefacts which may appear as hyperbolic shaped velocity anomalies. The first iterations were carried out with a horizontal spacing of 200 m and a vertical distance of 50 m between adjacent grid points. The subsequent inversion steps had grid spacings changing from 100×20 m to 50×10 m and finally to 20×5 m. The resulting tomography models (Figure 8) were derived with grid spacings of 10 m horizontally and 2 m vertically.

At every inversion step we calculated three iterations. The resulting intermediate model was resampled and served as input model for the next inversion step. The velocity models for both profiles after every three iterations are plotted in Figure 6. The models are clipped according to their resolution. The left part of Figure 6 shows the evolution of the tomography model for Line-1. After a total of six iterations (Figure 6c) the 1D structure of the

initial model (Figure 6a) vanishes and a low velocity zone emerges at the southern part of the profile. When the grid spacing gets finer, the low velocity layer becomes more obvious. Near the surface at the southern end of Line-1 a thin southward dipping high-velocity structure appears. At greater depths a solid, likewise southward dipping layer with velocities of more than 4 km/s remains quite stable during the last iteration steps (Figures 6c-6e). The rms error plotted to the right of the models rapidly decreases from 5.6 ms to 3.3 ms during the first six iterations, and more gradually during the last iteration steps until it reaches its final value of 2.1 ms. (Figures 6d and 6e).

The right part of Figure 6 shows the development of the graded inversion of the W-E directed Line-2. The 1D behavior of the initial model (Figure 6f) is scarcely modified during all of the shown inversion steps. Only a narrow, slightly westward dipping low velocity layer appears at shallow depths at the western part of the profile. As for Line-1, a homogeneous high velocity structure emerges at greater depths. The small modifications in the velocity models can also be seen in the evolution of the rms error. Starting at a relatively low value of 3.9 ms, the error changes only slightly and gets to the value of 1.6 ms after a total of 12 iterations.

Resolution analysis

Both profiles were analyzed to estimate the lateral and spatial velocity resolution. The results of this analysis for Line-1 are shown in Figure 7. To determine the lateral resolution we designed checkerboard patterns (e.g. Zelt, 1998) with alternating positive and negative velocity perturbations of ± 0.05 km/s superimposed on the starting model used for the tomographic inversion. Three different pattern sizes were applied: 70×10 m, 140×20

m and 180×25 m (Figures 7a, 7b and 7c, respectively), for which the aspect ratio was chosen equal to the ratio of horizontal and vertical extension of the tomography model. We calculated synthetic traveltimes for each checkerboard model using the source-receiver configuration of the real measurement. Gaussian noise was added to the synthetic data with a standard deviation similar to the pick uncertainty. Three iterations were carried out using the synthetic traveltimes and the same inversion parameters as for the traveltime tomography. As expected, the recovered checkerboard patterns (Figure 7) show a good resolution for shallow depths. The resolving capability decreases with increasing depths.

To further estimate the resolution, we calculated the resolution matrix during the first iteration step using the starting model with source and receiver configurations of the picked data. The spread value (Toomey and Foulger, 1989), which is a measure of the spatial resolution of the model, was determined. For Line-1 it ranges from 0 to 10 (Figure 7d). High spread values correspond to a low resolution indicated by dark blue colors. A contour line for the spread value of 4 is added to the plot. The final tomography models (Figure 8) are clipped at this value to eliminate areas with insufficient resolution.

Anisotropy

Most sedimentary rocks, especially shales, are anisotropic. Horizontally layered sedimentary rocks are characterized by faster wave propagation in the horizontal and slower wave propagation in the vertical direction. The anisotropy of these rocks can be approximated by transverse isotropic (TI) media with a vertical symmetry axis (Johnston and Christensen, 1995). Anisotropy of shales is caused by the preferred alignment of clay minerals and organic material (e.g. Vernik and Liu, 1997), fine layering (Backus, 1962), cracks and fractures

(e.g. Sayers and van Munster, 1991), and stress anisotropy (e.g. Nur and Simmons, 1969). Depending on porosity, compaction history and the types of clay, the anisotropy for P-wave velocity in shales can be up to more than 30 % (Wang, 2002). Nevertheless, we neglected anisotropy in our modeling and used an isotropic tomography algorithm. As the isotropic inversion is easier to approach and handle compared to anisotropic tomography, the isotropic inversion is widely used for traveltime data, although the target is known to be anisotropic (e.g. Bleibinhaus and Gebrande, 2006). For crosswell data, Bauer et al. (2005) found a good correlation between velocity models derived by isotropic and anisotropic tomography, respectively. The isotropic velocities approximately corresponded to the average of the horizontal and vertical velocities of the anisotropic model. By comparison with borehole data, Bauer et al. (2005) showed that it is acceptable to assume isotropy for the ray-based velocity tomography of layered sediments. In our study we obtained a similar result with reasonable agreement between isotropic tomography velocities and borehole sonic logs (next section). For this reason, we consider isotropic tomography as an acceptable approach. The comparison of isotropic and anisotropic tomography will be a subject for future studies.

RESULTS AND DISCUSSION

After a total number of 15 iterations we obtained the final tomography models shown in Figure 8. The grid size is 10×2 m and the final rms error 2.1 ms for Line-1 and 1.5 ms for Line-2.

Included in the tomography result for Line-1 (Figure 8a) is the position and depth of the well Skelbro-2. We use the sonic log and stratigraphic information of the borehole to mark the area with black shale velocities in our final models. The top and bottom depth of the black shale formation is located at 8.5 m and 41 m, respectively (Schovsbo et al.,

2011). Using the range of velocities of the black shale extracted from the sonic log, we included contour lines in the final tomography models where the top and bottom of the isolated layer correspond to velocity values at the top and bottom of the localized black shale formation in the borehole. The top of the black shale is indicated by velocities of 2.8 km/s and the bottom shows velocities of 3.5 km/s. The contour lines clearly separate parts with black shale velocities from overburden with low velocities and the high-velocity structure in greater depth. At the southern edge of the model, border effects lead to higher velocities for the black shales. Therefore, we included dotted lines where we suppose the black shale layer continues in the southern direction. The contour lines are also inserted in the final tomography model of Line-2 (Figure 8b). The area with black shale velocities is smaller for Line-2 as it is for Line-1 and it thins out to the eastern part of the model.

With respect to the borehole information (Figure 9), the tomography model of Line-1 can be interpreted in the following way: The solid Læså Formation is found throughout the model below the 3.5 km/s contour line. The Alum Shale Formation, which is the black shale layer, is confined by the two contour lines and is dipping southward with a dipping angle of 7° up to a depth of 50 m. The Komstad Limestone is a high-velocity layer which covers the Alum Shale in the southern part of the model. It is also dipping to the south and appears at a distance of 520 m and down to a depth of 20 m. In the result of Line-2 (Figure 8b) no Limestone Formation is visible, but the Alum Shale can be identified in the western part of the model as a 20 m thick, with an angle of 1.5° westward dipping layer. The Læså Formation with high velocities is found below the black shale horizon.

In Figure 8c both final models are shown in a combined plot. Although the two velocity models were derived independently, both profiles match very well at the crossline. This is a good indication of the reliability of the tomographic results. With the shown results and

the stratigraphy of the Skelbro-1 well (Figure 1c) the 3D structure of the subsurface can be estimated: All layers are dipping south-westward which is proven by the Skelbro-1 well located to the north-west of the Skelbro-2 well. There, the top of the Alum Shale is in a depth of 4 m and the bottom is in a depth of 37 m. Thus, the layers are rising by 4 m from the location of Skelbro-2 to the location of Skelbro-1.

Figure 9 shows a vertical velocity profile through the final tomography model at the borehole location (black line). It is compared to sonic log data (light-gray line in the left panel) and velocities which were obtained by laboratory measurements of core samples extracted during the drilling of the Skelbro-2 well (stars). The sample velocities were derived by ultrasonic measurements with a wave propagation direction perpendicular to the bedding plane of the black shale. Although all velocities were obtained at different scales, they match well. The thin structures with high velocities in the sonic log and low gamma values (21 m, 26 m and 36 m depth, respectively) cannot be resolved by the tomography model. Our investigation of the samples shows, that these are inclusions of diagenetic limestone. The high velocities of the Limestone Formation are not reached due to the smoothness of the tomography model. The vertical velocity profile is only a part of the 2D tomography model, so it is influenced by the adjacent velocities north- and southward of the profile.

The right panel of the figure shows the gamma ray log. The signal in the shale results from thorium in clay, potassium feldspar and from uranium. The uranium content in the Alum Shale is known to be related to the TOC content (Schovsbo, 2002) and is due to precipitation of uranium from the seawater together with organic carbon. Hence, the variation in gamma ray is an indication of the TOC content. In Figure 9, the black shale can be localized from a depth of about 8 m and below. From 30 m downwards there is a decrease of the gamma value due to both an overall lower TOC content in this part of the

formation and due to the presence of limestone beds (Pedersen, 1989; Pedersen and Klitten, 1990; Schovsbo et al., 2011).

Schovsbo et al. (2011) localized three different layers which can also be seen in the tomography model: (1) After 4 m of overburden the Komstad Limestone Formation marked by high velocities and a low gamma value can be found. It reaches a depth of 8.5 m below the surface. (2) The Alum Shale Formation has a total thickness of about 33 m and is characterized by lower velocities (about 3 km/s) and high values in the gamma ray log. (3) It changes over into the Rispebjerg Sandstone Member (upper part of the Læså Formation) after a total depth of 41 m. The drilling was stopped in the Rispebjerg Sandstone.

CONCLUSIONS

We carried out seismic measurements on the Danish island Bornholm at a location, where the occurrence of black shales at shallow depth was known from two boreholes. The aim of our work was to locate the black shale layers and characterize their seismic properties applying tomographic methods. In our resulting 2D P-wave traveltime tomography models for the two crossing profiles, the black shale layers can be clearly identified and separated from the adjacent formations.

Up to now, it was assumed that the black shales were in horizontal bedding. However, we found the black shale layers dipping south-westward. They are thinning out to the north-east of the study area. To avoid misinterpretation of borehole (1D) and seismic tomography data (2D) we will apply 3D geophysical methods to our data in the future.

For a classical characterization of hydrocarbon source rocks, the S-wave velocity, ratio of P-wave velocity and S-wave velocity v_P/v_S and Poisson's ratio are needed as well. With

further investigation of the data it might be possible to estimate these values and, therefore, classify black shales according to their potential to contain oil or gas.

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2 Raw shot gathers of Line-1 (a) and Line-2 (b) for two selected shot locations. For better visualization the traces are normalized by dividing the rms amplitude over the full trace length. The first arrival traveltimes (red dashes) were obtained by manually picking of the data.

3 Traveltimes for Line-1 (a) and Line-2 (b) as a function of source and receiver distance. The traveltimes were reduced with a reduction velocity of 3 km/s. The diagonal trace (equal source and receiver location) indicates zero offset traveltimes.

4 Histogram of the pick uncertainties for (a) Line-1 and (b) Line-2. The uncertainties were calculated by comparing the first-arrival times of reversed shot and receiver pairs. The inserted lines correspond to the best fit curves for a Gaussian distribution.

5 To select the optimal damping parameter for the first arrival tomography, the data variance and the model variance were calculated for a one-step inversion and damping values between 10 and 1000. The trade-off curve is plotted for Line-1 (a) and Line-2 (b), respectively. The preferred damping value of 50 is highlighted by a square.

6 (a) and (f) show the starting models for Line-1 and Line-2, respectively. (b)-(e) (Line-1) and (g)-(j) (Line-2) give the evolution of the models during the graded inversion, where the models were resampled (coarse to fine) after every three iterations. The small plots show the changes of the rms error for the inversion steps.

7 Resolution tests for Line-1. The recovered anomaly patterns for the checkerboard

tests after Zelt (1998) were obtained for three pattern sizes: (a) 70×10 m, (b) 140×20 m and (c) 180×25 m. Velocity variations of ± 0.05 km/s were added to the starting model used for the traveltime tomography (Figure 7a). (d) Distribution of the spread value derived from the resolution matrix. Low spread values correspond to a high resolution. The contour line for a value of 4 was used to clip the final tomography model (Figure 8a).

8 Final tomography models after a total of 15 iterations for Line-1 (a) and Line-2 (b), respectively. The data are clipped by the resolution of the model. Included in the pictures are contour lines for the top and bottom of the black shale formation for 2.8 and 3.5 km/s, respectively. (c) The combined plot of both models shows a good agreement, although the results were obtained independently.

9 Comparison of a vertical P-wave velocity profile (black line) with borehole (gray lines) and sample information (stars). The velocities were tracked from the final tomography model at the position of the well location. The left sketch shows the interpretation as mentioned in the text (Lmst - Limestone, Sst - Sandstone).

	Line-1	Line-2
number of shots	58	61
shot spacing (m)	12	12
number of receivers	340	359
receiver spacing (m)	2	2
profile length (m)	689	716

Table 1: Acquisition parameters of the seismic experiment on Bornholm.

Figure 1: (a) The study area is located on the Danish island Bornholm in the Baltic Sea. (b) The geological setting of Bornholm (after Graversen, 2009) is dominated by faulting. (c) Geology at the area of the geophysical study; the two measured seismic lines and the well locations Skelbro-1 and Skelbro-2 are inserted.

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Figure 2: Raw shot gathers of Line-1 (a) and Line-2 (b) for two selected shot locations. For better visualization the traces are normalized by dividing the rms amplitude over the full trace length. The first arrival traveltimes (red dashes) were obtained by manually picking of the data.

Figure 3: Traveltimes for Line-1 (a) and Line-2 (b) as a function of source and receiver distance. The traveltimes were reduced with a reduction velocity of 3 km/s. The diagonal trace (equal source and receiver location) indicates zero offset traveltimes.

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Figure 4: Histogram of the pick uncertainties for (a) Line-1 and (b) Line-2. The uncertainties were calculated by comparing the first-arrival times of reversed shot and receiver pairs. The inserted lines correspond to the best fit curves for a Gaussian distribution.

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Figure 5: To select the optimal damping parameter for the first arrival tomography, the data variance and the model variance were calculated for a one-step inversion and damping values between 10 and 1000. The trade-off curve is plotted for Line-1 (a) and Line-2 (b), respectively. The preferred damping value of 50 is highlighted by a square.

Figure 6: (a) and (f) show the starting models for Line-1 and Line-2, respectively. (b)-(e) (Line-1) and (g)-(j) (Line-2) give the evolution of the models during the graded inversion, where the models were resampled (coarse to fine) after every three iterations. The small plots show the changes of the rms error for the inversion steps.

Figure 7: Resolution tests for Line-1. The recovered anomaly patterns for the checkerboard tests after Zelt (1998) were obtained for three pattern sizes: (a) 70×10 m, (b) 140×20 m and (c) 180×25 m. Velocity variations of ± 0.05 km/s were added to the starting model used for the traveltime tomography (Figure 7a). (d) Distribution of the spread value derived from the resolution matrix. Low spread values correspond to a high resolution. The contour line for a value of 4 was used to clip the final tomography model (Figure 8a).

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Figure 8: Final tomography models after a total of 15 iterations for Line-1 (a) and Line-2 (b), respectively. The data are clipped by the resolution of the model. Included in the pictures are contour lines for the top and bottom of the black shale formation for 2.8 and 3.5 km/s, respectively. (c) The combined plot of both models shows a good agreement, although the results were obtained independently.

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Figure 9: Comparison of a vertical P-wave velocity profile (black line) with borehole (gray lines) and sample information (stars). The velocities were tracked from the final tomography model at the position of the well location. The left sketch shows the interpretation as mentioned in the text (Lmst - Limestone, Sst - Sandstone).

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