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Title: Seismic travel-time and attenuation tomography to characterize the excavation damaged zone and the surrounding rock mass of a newly excavated ramp and chamber

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Highlights:

- 4D seismic tomography is able to resolve rock-mass changes due to excavation work.
- Attenuation tomography is more sensitive to changes than travel-time tomography.
- Changes of rock-mass are not restricted to the new excavation.

Keywords: mining, time-lapse tomography, excavation damaged zone, underground lab, attenuation

Abstract:

Seismic travel-time and attenuation tomography were applied to characterize the excavation damaged zone and the adjacent rock mass in the GFZ-Underground-Lab within the research and education mine *Reiche Zeche* of the Technical University Bergakademie Freiberg (Germany). The lab is situated in gneiss rocks at 150 m depth and comprises three galleries which enclose an area of approximately 50 m x 100 m. Along these galleries two seismic surveys were performed before and after the excavation of a new ramp and chamber. For both measurements, travel-time and attenuation tomographies for P-waves were performed with the ray-based inversion algorithm SIMULPS14. The seismic velocities were calculated from first-arrival travel times whereas a logarithmic-spectral-ratio approach was used to calculate the corresponding quality factors (Q) for attenuation tomography. A comparison of the tomograms reveals a decrease of average P-wave velocity values from 5.64 km/s to 5.54 km/s and of average Q -values from 29.8 to 26.5 in the whole area after the excavation of the new cavities. The maximum changes are located at already weakened zones either at the conjunction of two galleries or of a major fracture zone with a gallery. The attenuation tomography shows a higher sensitivity to rock mass changes than the travel-time tomography. However, the calculation of the Q -values demands a higher signal quality than the determination of the seismic travel times.

1. Introduction

Underground excavation inevitably causes an excavation damaged zone (EDZ) around the cavity. The EDZ is characterized by irreversible changes of the stress field due to the removal of rock mass. The dimension of the EDZ depends essentially on the rock mass under consideration (e.g. geology, mechanical properties), the excavation method (such as drilling and blasting, tunnel boring machine (TBM)) and the characterization method of the EDZ [1]. Information on the EDZ is important for the evaluation of construction stability. For example in nuclear waste disposal construction sites the hydraulic and thermal properties of the host rock within the EDZ are of great importance for the safety of the storage facility [2].

To investigate the EDZ, different techniques are applied either from the cavity surface or from boreholes. Optical devices can be used for fracture detection in boreholes [3]. Seismic borehole probes have been developed to measure the seismic amplitudes and velocities along the borehole walls [4]. If several boreholes are available, the probes can be combined for cross-hole measurements to determine the seismic properties in between the boreholes. Geophysical methods are also applied at the surface of the cavity. Similar to applications at Earth's surface, seismic sources and receivers are mounted on the cavity surface to investigate the EDZ by tomographic inversion methods [5]. These seismic approaches are based on the fact that the EDZ can be defined through a strong seismic velocity gradient [4, 5]. Cross-hole and surface seismic measurements consider the rock mass at different scales. Cross-hole approaches are able to characterize the rock mass between two boreholes with centimeter to decimeter resolution. Surface seismic measurements cover a larger area but with a resolution on the order of meters. For both approaches the seismic source and the corresponding signal bandwidth is the governing parameter to define the resolution. For borehole as well as surface seismic measurements travel-time-tomography methods are used to determine the spatial distribution of seismic velocities. Attenuation tomography approaches are based on the determination of the seismic amplitude decay described by the quality factor Q . In general, the travel-time tomographies show an increase of velocities with increasing distance from the underground cavity. A similar increase is also observed for the quality factor. This has been shown, for example, with a cross-hole-attenuation tomography by Nicollin [6] for the Opalinus clay in the Mont Terri Rock Laboratory.

In this paper we report the application of tomographic seismic measurements to characterize the EDZ and the adjacent rock mass along the galleries of an underground laboratory run by the German Research Centre for Geosciences (GFZ) in the research and education mine *Reiche Zeche* of the Technical University Bergakademie Freiberg (Germany). The extension of the underground laboratory by a newly excavated ramp and chamber was used as a test case for time lapse measurements by performing the seismic surveys before and after the construction works. Travel-time and attenuation tomographic inversion methods have been applied to the P-wave of these two datasets to observe changes within the EDZ and the rock mass enclosed by the galleries.

2. Test site design

2.1 Location and infrastructure

The GFZ-Underground-Lab is located at 150 m depth, on the first floor of the mine *Reiche Zeche*, in which silver, lead and zinc ores were mined from the middle of the 14th century until 1969 [7]. During the 1980's the mine was reconstructed and prepared for research and educational purposes. The Technical University Bergakademie Freiberg runs the mine for student training and research projects of other institutions. Within *Reiche Zeche*, GFZ has run the GFZ-Underground-Lab since 1998 for testing new seismic exploration technologies for tunneling and borehole drilling. It comprises an approximately 50 m x 100 m mainly homogeneous high-grade gneissic block at the first floor of the mine, surrounded by galleries with a width of 2 m and a height of 2.5 m on three sides, which were excavated by drilling and blasting during the 1950s (Figure 1). Along the galleries, 35 three-component geophones can be installed in one and two meter deep boreholes with a spacing of 4 m to 9 m. In 2011, the GFZ-Underground-Lab was extended by a chamber 10 m above the galleries (Figure 1). In order to access the chamber, a ramp with a dip of 40° was excavated from the gallery

Richtstrecke by drilling and blasting. The ramp has a width and height of about 2.5 m and the chamber has an approximate cubic shape with 5 m edge length. To test newly developed seismic borehole devices, three 8 ½" boreholes were drilled. The two horizontal boreholes are 30 m (B1) and 20 m (B2) long. The vertical borehole, B3, is 70 m deep and extends from the newly excavated chamber perpendicular through the rock mass surrounded by the galleries.

Figure 1: a) Perspective view of the GFZ-Underground-Lab showing all galleries and boreholes with their denotations. b) The view up the ramp towards the chamber with the stair and the rail track for equipment transportation to the chamber.

2.2 Geology

The research and education mine *Reiche Zeche* is situated within the Erzgebirge Mountains which are part of the Erzgebirge-Fichtelgebirge Anticlinorium. The rocks of the Erzgebirge, formed during the Variscan orogenesis, were superimposed and afterwards lifted during the Alpine orogenesis as a north-west tilted fault block. The mine is located in the eastern part of the Erzgebirge Mountains within the *Innerer Freiberger Gneis* an augen-structured biotite gneiss [8].

Due to its genesis the gneiss exhibits two different fault systems that developed during the Variscan and the Alpine orogenesis. The first fault system has a NNE - SSW strike direction and a fault dip of 70-90°. The corresponding en échelon joints strike in a N-S direction. The second fault system has a strike of WNW-ESE and also a dip of 70-90°. The corresponding en échelon joints strike in an E-W direction. The rock fabric varies slightly between granitic to coarse foliated and up to augen gneiss with smooth changes. Geological mapping along the galleries has revealed three broad, altered zones with faults in the range of centimeters up to several decimeters. The altered zones show yellowish brownish coloring, which indicates Fe^{3+} deposition. Hence, these faults exhibited water paths, at least in the past.

2.3 Seismic datasets

Two different datasets were used for P-wave travel-time and attenuation tomography. The first survey took place in December 2009 (herein Dec09 dataset, available at <http://dx.doi.org/10.5880/GFZ.sd.2013.001>) and the second in April 2012 (Apr12 dataset). The excavation of the ramp and chamber above the galleries occurred in between these surveys. The survey layout was almost the same for both measurements (Fig. 2). In December 2009, 76 source points were excited along the gallery surfaces with a spacing of 2 m to 4 m. The wavefield was recorded at 30 three-component geophones with a spacing of 4 m to 9 m (a detailed description of the seismic source and receiver is given below). Due to the ramp and chamber excavation in 2011, three source points (SP 18-20) and one receiver (GP 10) were omitted from the Apr12 survey. Receivers GP 21 to 26 were located in a 5 m area. This small spacing can lead to numerical errors in the inversion. To achieve nearly equal geophone spacing, receivers 22 to 25 were not used in the further processing.

Figure 2: Top view of the survey geometry. The encircled source and receiver locations were removed due to the excavation work. The dashed line marks the projection of ramp and chamber into the measuring plane and the filled dot depicts the penetration point of the vertical borehole B3.

The seismic source was a magnetostrictive vibrator source, comprising two actuators with a spacing of 28 cm. To ensure good source coupling, the housing is pressed to the side wall (Figure 3a). The source signal was a linear sweep with a length of 2.9 s. The signal frequencies ranged from 300 Hz to 3000 Hz in the Dec12 dataset and 150 Hz to 3000 Hz in the Apr12 dataset. To improve the signal-to-noise ratio by vertical stacking, three to five sweeps were excited at each source point. For each sweep, the source signal (pilot signal) given by the control device, was stored and later used for correlation of the raw data. To ensure the constructive interference of both actuators, a real time control system steered the amplitudes and phases of the source signals by a feedback loop using the registrations of accelerometer sensors integrated in the coupling stamps. The two actuators of the seismic source can be repositioned with an accuracy of about a decimeter because of the high side wall topography which complicates the mounting of the coupling stamps.

The receivers were installed in one or two meter deep boreholes. To ensure repeatable measurements, the patent ISIS-geophone anchors (patent number DE 10 2006 007 474.2) were used (Figure 3b). The tubing is glued into each borehole and this tubing has an internal thread into which the geophone anchor can be screwed (Figure 3c). This ensures equal coupling and correct orientation of the three individual geophones. In addition, the geophone anchor is always installed within the same borehole. GS14-L3 geophones are used as seismic sensors for the ISIS-geophone anchors. The applied source and receiver system enabled highly reproducible seismic measurements.

Both datasets were recorded with a sampling interval of 1/16 ms and had a length of 3072 ms (Dec09) or 3008 ms (Apr12), respectively. Figure 4 shows an example of a correlated and stacked shot gather from the Apr12 data set.

Figure 3: a) Double-vibrator source. b) Geophone anchor (top) and its tubing (bottom). c) Detailed diagram of the threaded anchor head and the three 1C-geophones in normal, vertical and horizontal direction. The normal direction is always oriented perpendicular to the galleries surface.

Figure 4: Shot gather of source point 68 from the Apr12-dataset. The wigggleplots show the channels of the vertical (a), horizontal (b) and normal (c) component with respect to the gallery surface. The black triangle marks the receiver shown in Figure 5.

3. Theory

3.1. Calculation of Q -values

The quality factor Q can be used to describe seismic attenuation. This Q -value is defined as the loss of wave energy (ΔE) per cycle of a harmonic excitation related to the peak elastic energy E [9].

$$(2\pi)/Q = \Delta E/E \quad (1)$$

The Q -value is inversely proportional to attenuation, i.e. low Q -values indicate high attenuation and *vice versa*. To calculate Q , a wide range of approaches are available [10]. In seismology, methods which calculate Q simultaneously with other seismological parameters are often used [11]. However, controlled-source seismic methods estimate Q individually, particularly in the frequency domain. One

of the most common approaches is the logarithmic-spectral-ratio method (LSR) [12, 13]. LSR defines the attenuation as the ratio of two frequency spectra. The frequency spectrum of a seismic wave can be obtained from the wave amplitude, $A(f,x)$ with

$$A(f,x) = A(x) \exp[-\alpha(f)l] \exp[i(kx-\omega T)] \quad (2)$$

where $A(x)$ defines the amplitude, $\alpha(f)$ is the frequency dependent attenuation coefficient, l is the length of the travel path, k is the wave number, ω the angular frequency ($\omega = 2\pi f$) and T the travel time of the seismic wave. The amplitude $A(x)$ includes geometrical spreading and is assumed to be frequency independent. Since the source spectrum is known, its travel path l_S is zero. The source attenuation term $\exp[-\alpha_S(f)l_S]$ can be set to one and only the attenuation term of the receiver spectrum $\exp[-\alpha_R(f)l_R]$ is considered. This assumption is valid when using the pilot signal. The logarithmic ratio of receiver spectrum $R(x,f)$ and source spectrum $S(x,f)$ yields

$$\ln(R(x,f)/S(x,f)) = -\alpha_R(f) l_R + \ln(R(x)/S(x)). \quad (3)$$

The attenuation coefficient α can be expressed by

$$\alpha = (\pi f) / (Q v) \quad (4)$$

with frequency f and seismic velocity v [13]. Rewriting equation (3) with this assumption yields

$$\ln(R(x,f)/S(x,f)) = -(\pi l_R) / (Q v) f + \ln(R(x)/S(x)). \quad (5)$$

Equation (5) has the form of a linear equation, with the slope $(-\pi l_R) / (Q v)$. Thus, the Q -value can be determined by the slope of this linear equation, plotting the logarithmic ratio ($\ln(R(x,f)/S(x,f))$) over frequency (Figure 5). The Q -value obtained by equation (5) describes the attenuation of the wave along its travel path from the source to the receiver. As a prerequisite for the attenuation tomography, the Q -values were calculated for every source-receiver pair of the measurement.

Figure 5 visualizes the applied processing steps to get the Q -values from the data. First, the P-wave is extracted by using a Hann-taper at each component (normal (1), horizontal (2) and vertical (3)) (Figure 5a). Second, the summed frequency spectrum of the receiver components is calculated (Figure 5b). Now, the LSR-approach can be applied to the data and with a linear regression the slope can be calculated using equation (5) (Figure 5c).

Q -values, calculated with the LSR approach as shown in Figure 5 comprise intrinsic attenuation and attenuation caused by scattering.

Figure 5: LSR data processing example. a) Components for the trace marked in Figure 4 with applied Hann-taper (dashed line) and first arrivals of the P- and S-wave. b) The frequency spectrum of the sweep (solid line) and the summed frequency

spectrum of the receiver components (dashed line), both normalized to their maximum. c) Result of the LSR (dashed line) and the corresponding linear regression (solid line).

3.2. Tomography

The applied tomography algorithm, SIMULPS14, is a ray based, damped least square approach [14]. In this local earthquake tomography (LET) algorithm, the considered waves are approximated by rays passing through the medium. LET algorithms are designed for seismological problems, where the sources (earthquakes) lie within the inverted volume. The source location depends on the velocity model and thus, the source location has to be estimated. However, SIMULPS14 allows the input of known source coordinates and has been successfully applied to seismic problems, such as cross-well seismic [15]. For an appropriate processing of the presented data, all software routines were modified to accommodate Cartesian coordinates. To prohibit gridding problems, the input parameters are described in units of meters and milliseconds, which hold the same ratio as the algorithm internal units of kilometers and seconds.

The iterative inversion of SIMULPS14 requires a numerical damping parameter, which stabilizes the least squares inversion. This numerical damping parameter is estimated by a trade-off analysis in which the data misfit is plotted against the model variance for a series of single-iteration inversions with a large range of damping values [16]. To calculate a seismic attenuation distribution, SIMULPS14 requires a known velocity model. Therefore, travel-time tomography is calculated first. The travel time T_{ij} along a ray path from source i to receiver j is related to the velocity v by

$$T_{ij} = \int_{ray\ path} 1/v\ dl, \quad (6)$$

in which dl represents a ray path segment. The F-test is applied as stop criterion, which compares the change of data variance of two iterations [17]. In attenuation tomography, the ratio of the travel time T to the quality factor Q is the main parameter. This ratio is called the t^* -operator.

$$t^* = T/Q = \int_{ray\ path} 1/(Q \cdot v)\ dl \quad (7)$$

SIMULPS14 provides several parameters which can aide in the evaluation of the inversion result, e.g. ray coverage and the root-mean-square (rms) value. The rms-value quantifies the quadratic difference of the synthetic data to the input data. Thus, the rms-value has the same unit as the input data, which is for both, travel time and attenuation tomography, milliseconds.

4. Results

The same data pre-processing sequence, including the correlation with the pilot signal, was applied to both datasets (Dec09 and Apr12).

Shot points SP18-20 and receiver GP10 from the Dec09 dataset were not used for the tomographic inversion to ensure the same geometry for both surveys. Source and receiver offsets less than 15 m were generally omitted for the Q -value determination since P- and S-waves are not separated sufficiently within this offset range. Q -values from seismic traces with poor signal-to-noise ratio were also not taken into account for the later attenuation tomography. In total 1617 shot-receiver combinations were used for travel-time tomography and 772 combinations for the attenuation tomography of the Dec09 dataset. For the Apr12 dataset 1590 combinations for travel-time tomography and 705 combinations for attenuation tomography were used.

The grid size for the travel-time and attenuation tomographies was defined along 5 m intervals in the x - and y -directions. The bounding nodes (first and last defined node in the inversion grid) are set to -500 m and 500 m for both directions to ensure a stable inversion. For the z -direction only three nodes at -10 m, 0 m and 10 m are defined, with bounding nodes -10 m and 10 m. Thus, the problem is quasi two-dimensional. All inversions were calculated with homogeneous starting models of $v_{start} = 5.75$ km/s or $Q_{start} = 33$. The numerical stability of this grid size and the resulting model resolution were determined by checkerboard tests.

First, the travel-time tomography was calculated using the picked first onsets of the direct P-waves (Figure 6). The resulting v_p -values range from 5.1 km/s to 6 km/s for the Dec09 dataset and from 4.7 km/s to 6.6 km/s for the Apr12 dataset with a mean value of 5.64 km/s (Dec09) and 5.54 km/s (Apr12). The mean values are calculated by averaging of those grid nodes for which the ray coverage is nonzero. Both tomograms reveal an approximately 10 m wide low velocity zone ($v \leq 5$ km/s) at about $y = 25$ m. At the Dec09 tomogram, another area with lower velocities ($v < 5.5$ km/s) can be seen parallel to the *Richtstrecke* gallery at $y \geq 45$ m and at the corner of the *Richtstrecke* and *Quergang* galleries. At the Apr12 tomogram the velocities at these zones decrease further. Additionally, low velocities are observable south of the newly excavated ramp and chamber up to the low velocity zone at about $y = 25$ m.

The attenuation tomographic inversions for P-waves of both datasets are shown in Figure 7. The Q_p -values range from 13 to 56 for the Dec09 dataset and from 13 to 43 for the Apr12 dataset. The average Q_p -values are 29.8 (Dec09) and 26.5 (Apr12). Both Q_p -models show low values ($Q_p < 20$) along the galleries and in the area of the low velocity zone at $y = 25$ m.

Figure 8 shows the differences of the velocity and attenuation models calculated by subtracting the Dec09 from corresponding nodes of the Apr12. In the velocity model changes are clustered close to the new excavation and on the opposite site at the *Wilhelm Stehender Süd* gallery (Figure 8a). Figure 8b reveals changes of the Q -model in the majority of the ray covered area. Both figures are dominated by lowered v - and Q -value nodes.

Figure 6: P-wave travel-time tomography models. The Dec09 dataset is displayed in a) and the Apr12 dataset in b). Besides infrastructure and survey geometry (as in Figure 2), mapped fracture zones are numbered and marked with bold dashed lines.

Figure 7: P-wave attenuation tomography models. The Dec09 dataset is displayed in a) and the Apr12 dataset in b). Besides infrastructure and survey geometry (as in Figure 2), mapped fracture zones are numbered and marked with bold dashed lines.

Figure 8: Differences between travel-time and attenuation tomography. a) Changes of the velocity model ($v_{\text{Apr12}} - v_{\text{Dec09}}$). b) Changes of the Q-model ($Q_{\text{Apr12}} - Q_{\text{Dec09}}$).

Figure 9: Checkerboard test for attenuation tomography of the Apr12 dataset. a) Synthetic model which was used for forward calculation. b) Inversion result of the synthetic data.

In order to assess the model resolution, we conducted classical checkerboard tests for the velocity and attenuation model calculation. Figure 9 shows the checkerboard test for the Apr12 attenuation tomography. The checkerboard test was calculated with a homogeneous velocity model of $v = 5.75$ km/s and a 5×5 m Q -checkerboard with $Q_{\text{low}} = 29.7$ and $Q_{\text{high}} = 36.3$ (Figure 9a). The forward calculation was done on a grid with 2.5 m spacing in x - and y -direction with all theoretically possible source-receiver combinations. Afterwards the synthetic dataset was reduced to the actually used combinations and inverted with a homogeneous start model of $Q_{\text{start}} = 33$ on 5 m grid interval.

The inversion of the checkerboard model in Figure 9b shows a clear pattern in the northern part of the model and beneath the ramp. South of the horizontal borehole B2, the homogeneous starting model dominates and the checkerboard pattern is less pronounced. This is due to a lack of receivers in the southern part of the investigation area. The ray coverage is mostly provided by rays between the *Richtstrecke* and *Wilhelm Stehender Süd* galleries. Only a minor portion of the ray coverage is provided by source or receiver positions of the *Quergang* gallery. Furthermore, the possibility of the inversion algorithm SIMULPS14 is very limited for forward calculation on small grids. The grid cannot be chosen arbitrarily small, because the forward calculation is also ray based and hence, poor ray coverage will affect the forward calculation, too.

Figure 10 summarizes the trade-off analysis for the four tomographic inversions. For each tomography, a series of single-iteration inversions were done with different damping values and the resulting data variance was plotted against the model variance. The chosen damping values (filled circle/triangle) are a compromise between data misfit and a large model variance.

In general the calculated P-wave velocities and Q -values are in good agreement with previously published values for granitic gneiss [18].

Figure 10: Determination of numerical damping for travel-time tomography (a) and attenuation tomography (b). In both plots the Apr12 data is indicated by triangles and the Dec09 data by circles. The filled symbols indicate the applied numerical damping values for the inversion calculation.

5. Discussion

The comparison of the tomographic results before and after excavation of the ramp and chamber reveals a decrease of the average P-wave velocity and average Q -value of the whole rock mass enclosed by the galleries. The change of mean P-wave velocities from before the excavation (mean $v = 5.64$ km/s) to after the excavation (mean $v = 5.54$ km/s) corresponds to a decrease of approximately 2%, which is quite low. Nonetheless, the visual impression is a significant decrease of the velocity along the galleries. This impression is confirmed, considering the changes of the single grid nodes. 105 grid nodes were covered by rays. Assuming a sensitivity threshold of $\Delta v \pm 0.1$ km/s, about one third of the nodes did not change (38 nodes), 21 of the nodes increased and 46 nodes decreased more than 0.1 km/s. These significant changes are also visible in Figure 8. Subtracting the v_{Dec09} -model from the v_{Apr12} -model reveals two areas with a significant velocity decrease of more than 0.5 km/s at the new excavation and on the opposite side at the *Wilhelm Stehender Süd* gallery (Figure 8a). The decrease of Q -values from $Q_{Dec09} = 29.8$ to $Q_{Apr12} = 26.5$ corresponds to a decrease of approximately 10%, which is significantly more than the decrease of the P-wave velocity. The decrease is also recognizable comparing the changes at each grid node. Assuming a threshold of $\Delta Q \pm 0.6$, which is relatively the same as for v , 65 of 105 cells decreased, 8 nodes did not change and 32 nodes increased. Considering Figure 8b, the difference in Q , $Q_{Apr12} - Q_{Dec09}$, a stronger decrease of Q -values in a wider area is observable, than for the velocity changes. The decrease of Q_P - and v_P -values is most prominent in the area along the galleries, e.g. along the *Quergang* and *Wilhelm Stehender Süd* galleries. Comparing v_P -results, areas of low velocities in the Dec09 dataset are further lowered and broadened in the Apr12 dataset. Furthermore, a lowering of Q_P - and v_P -values is visible in the direct surrounding of the ramp, especially between the *Richtstrecke* gallery and the projection of the ramp to the

measuring plane. Lower velocities and accordingly longer travel times of the seismic waves in the area of excavation works can be caused by the enlargement of the travel paths. This enlargement is caused by the removal of rock mass within the measuring plane and the newly created EDZ around the new cavities, which also influences the rock mass within the measuring plane below the ramp and borehole chamber. Furthermore, the cavities act as scattering bodies, leading to additional attenuation and therefore lower Q -values. These effects are not limited to the extent of the cavities but are enlarged by its new EDZ, especially when the ramp is already above the measuring plane. The overall lowering of the seismic velocities and Q -values demonstrates the distant effect of the newly excavated ramp and chamber. This distant effect is most pronounced in areas of already fractured rock mass, either through pre-existing cavities and/or geological reasons such as faulted rocks. One of these zones is the aforementioned low velocity zone which correlates well with fracture zones 24 and 109/112 mapped at the gallery surfaces (see Figure 6 for locations). Figure 11 shows the exposures of fracture zones 24 and 112 at the gallery surfaces. After the excavation of the ramp this zone appears to be expanded in particular in the vicinity of the galleries – an example of the combined effect of EDZ and pre-existing higher fracture density within the rock mentioned above. The low P-wave velocity and low Q -value zone at the corner area of the *Richtstrecke* and *Quergang* galleries is probably caused by intensive weakening of the rock mass, caused by the conjunction of galleries and their related EDZs. The further lowering of the P-wave velocities and Q -values in Figure 7 (b) and 8 (b) are signs of an intensified weakening in the area close to the galleries caused by the excavation process of the ramp.

Based on the variations in seismic velocity and Q -value, the extension of the EDZ along the galleries, except the area of fracture zones, can be roughly estimated to 10 m. When comparing the Q -value and P-wave travel-time tomography results, it is evident that the Q -value resolves a larger EDZ. This may be an indication that the Q -value is more sensitive to changes in the rock mass caused by an increase in fractures. This result is surprising as the Q -value calculation demands data with a high signal-to-noise ratio, resulting in a limited number of source and receiver combinations, particularly in areas with already low Q -values. In contrast, it is often possible to pick the first break in seismic wavelets with a lower signal-to-noise ratio, resulting in a larger dataset for the velocity calculation. This can be seen in Figure 7 (b). In the southern part ($y < \sim 10$), several areas of the model grid are not resolved since some of the formerly used source and receiver data pairs were omitted. Thus, the quality of attenuation tomography in this part is clearly reduced.

Figure 11: Exposure of fracture zone 24 at the gallery surface of the *Richtstrecke* gallery (top) and of fracture zone 112 at the surface of the Wilhelm Stehender Süd gallery (bottom). The yellowish brownish color (Fe^{3+} deposition) marks the altered zones.

6. Conclusions & Outlook

The seismic measurements obtained during the expansion of the GFZ-Underground-Lab demonstrates that rock mass changes due the excavation of a ramp and chamber can be determined by seismic P-

wave travel-time tomography as well as Q -value tomography. The excavation works lead to a significant decrease of P-wave velocities and Q -values which are not restricted to the area of the new cavity but are also observed around all pre-existing galleries. Maximum changes are observed in the conjunction areas of two galleries and at major fracture zones within the galleries.

In a next step, tomographic inversions for the S-waves will be calculated. In addition, borehole measurements with an optical televiewer system within the two horizontal observation holes are intended to identify the extension of the EDZ by measuring the fracture density with respect to distance from the gallery surface.

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