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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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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 × 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.

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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 1980s 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 $\times$ 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 (Fig. 1). Along the galleries, 35 three-component geophones can be installed in one and two meter deep boreholes with a spacing of 4–9 m. In 2011, the GFZ-Underground-Lab was extended by a chamber 10 m above the galleries (Fig. 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 $8\frac{1}{2}''$ 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.

2.2. Geology

The research and education mine *Reiche Zeche* is situated within the Erzgebirge Mountains which are part of the Erzgebirge–Fichtelgebirge Anticlinorum. 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.

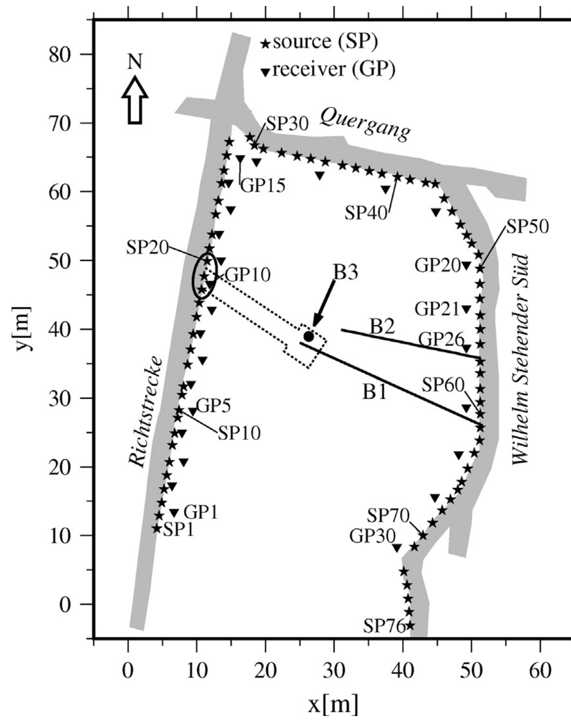

Fig. 2. Top view of the survey geometry. The encircled source and receiver locations were removed due to the excavation work. The dashed line marks the projection of ramp and chamber into the measuring plane and the filled dot depicts the penetration point of the vertical borehole B3.

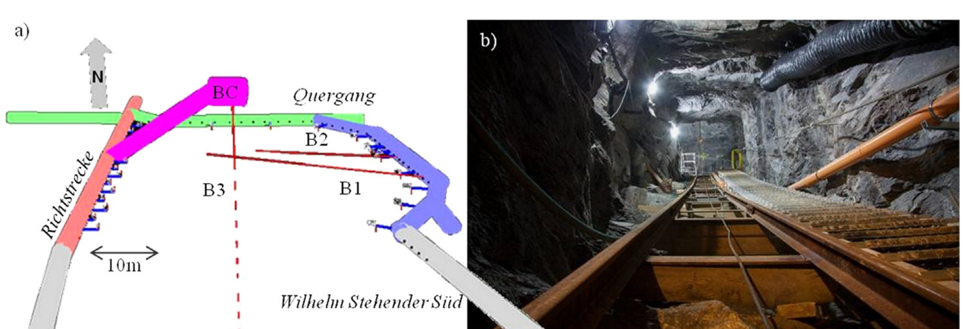

Fig. 1. (a) Perspective view of the GFZ-Underground-Lab showing all galleries and boreholes with their denotations. (b) The view up the ramp towards the chamber with the stair and the rail track for equipment transportation to the chamber.