Correlation of internal salt structures with GPR amplitudes

V. Gundelach; N. Blindow; U. Buschmann; C. Salat
Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany
gundelach@bgr.de; norbert.blindow@bgr.de; ulrich.buschmann@bgr.de; christina.salat@bgr.de

***Abstract*—In salt deposits with low electric conductivity ground penetrating radar (GPR) is an efficient non destructive tool for the exploration of internal structures. Faulted salt layers, potassium, clay, and anhydrite can be mapped by measuring distance and direction of reflecting objects. Various antenna types help to enhance resolution or penetration depth. Additional information about the conductivity of reflecting structures is included in the attenuation of the direct and reflected signals. Within the last two decades unique results from a salt dome in Northern Germany with various GPR systems were achieved. With this information a classification of various salt structures can be made by studying the signal amplitudes of reflections and of the direct wave between transmitting and receiving antenna, especially with borehole measurements.**

Keywords—GPR, salt dome, borehole, signal attenuation, geological model

I. INTRODUCTION

In a low conducting environment such as rock salt, the non-destructive GPR method is able to reach several hundred meters of penetration depth. Therefore this method is used for geological investigations of the Gorleben salt dome in northern Germany.

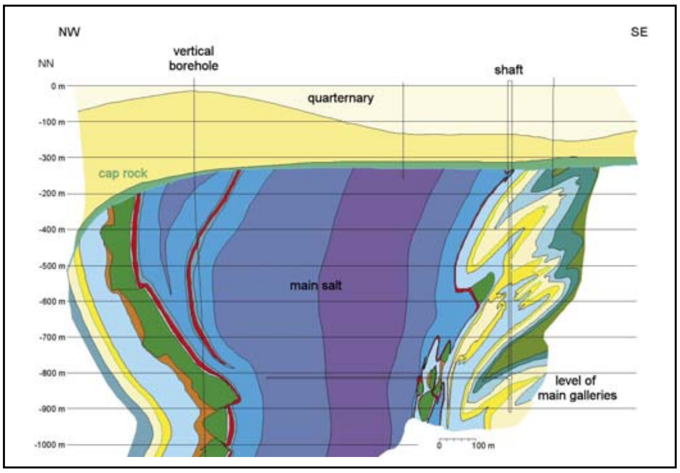

Figure 1. Vertical geological section across the Gorleben salt dome, (legend Fig. 3 explains colors)

A geological section [8] of the salt dome is shown in Fig. 1. The salt is covered by more than 200 m tertiary and quaternary sediments. The main salt in the center is flanked by faulted anhydrite and younger salt. First structural results with GPR were achieved by borehole systems in vertical boreholes drilled two kilometer deep from the surface. Inside the salt dome the method provides spatial information from direction sensitive antennae in exploration boreholes. During mining operations additional profiles towards all directions in the shaft and the drifts were measured. Typically clay layers or anhydrite are detected as reflections as well as galleries or moisture zones. Not only reflection travel times can provide information about the salt. The attenuation of the GPR signal can also help to classify the different chemical composition and moisture content of salt layers in general.

II. METHOD

A good method to estimate the amplitude of the direct pulse is taking the maximum of the Hilbert envelope (Fig. 2) which is independent from phase variations. This value can be picked for every trace of a profile and then interpreted in correlation with the salt geology. Another option would be time integration of the absolute amplitudes of the first onsets, but this method is more prone to disturbing effects.

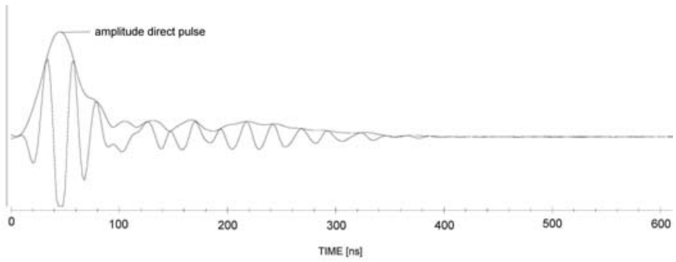

Figure 2. Amplitude estimation by picking the maximum of the envelope

III. SALT GEOLOGY

The salt geology at the area of interest in the Gorleben salt dome is well known because of extensive geological mapping in combination with geophysical and geotechnical working. It is dominated by the younger Leine-sequence and older Staßfurt sequence (see center of Fig. 1). The older salt has higher conductivity [13]. The salt of these sequences can be divided into different layers according to their varying properties (Fig. 3). At the boundary of these two sequences a clay layer (grauer Salzton z3GT) acts as a dominant reflector for GPR. This is accompanied by a potash layer (z2SF, red color) in the Staßfurt-sequence. Some layers are very thin or vanished whereas others show large extent. The main salt (z2HS) in the Staßfurt-sequence is divided into three sub-layers (z2HS1-3) which sometimes are not easy to discriminate by visual core analysis.

Figure 3. Part of the salt sequence in northern Germany and corresponding color codes

IV. Measurements in Galleries

The standard setting for profiles in the galleries is a 5 µs time record with 1 ns sampling rate, 32-fold stacking and 0.5 m steps with parallel 50 MHz dipole antenna at 5 m offset. The profiles are measured in sections depending on the accessibility of the gallery. The data processing includes band pass filtering and application of an amplitude gain function.

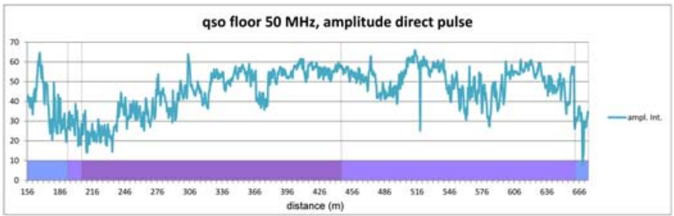

Figure 4. Direct pulse amplitude at the floor along gallery qso related to the salt geology

The best coupling of the antennae to the salt occurs on profiles along the floor of a gallery. The floor is relatively smooth and even compared to the rough and warped surfaces at the roof and the walls. Therefore an example from the floor in gallery "qso" is chosen (Fig. 4) which allows correlating higher and lower amplitudes with salt geology although the dataset shows some events which are caused by other influences. At most profiles in galleries these influences are covering the conductivity information. The amplitude values were extracted from data without corrections such as system calibration factors, material coupling, or gain values. Thus only relative values can be given. Absolute values depend on the used equipment and varying measurement conditions for the different radar systems.

V. Measurements in Boreholes

In boreholes, GPR systems with 50 MHz center frequency were used with an antenna separation of typically 10 m. The borehole diameter was only a few cm wider than the radar housing. At the beginning of the development of borehole radar tools [1] measurements were made in exploration boreholes with simple dipole antennae. The next step in evolution of borehole probes was to depict the complex internal structure of salt domes by measuring the direction as well [2-7, 9, 10]. The knowledge of distance and direction of reflecting structures from the borehole in addition to other geological information is a valuable help in creating the geological model. But also the information about the conductivity of the medium which is correlated to the signal amplitude of the direct wave from transmitting to receiving antenna can help to discriminate structures, especially if there are only few and poorly reflecting elements. The schematic sketch in figure 5 shows the expected area of influence from the rock on the direct wave travelling from the transmitting to the receiving antenna. The proportions of the sketch are chosen for a 50 MHz borehole system.

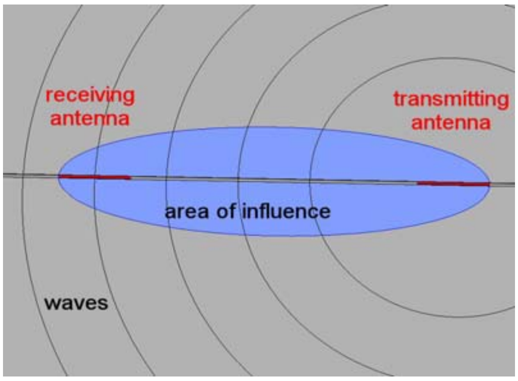

Figure 5. Schematic sketch: area of influence on the direct signal amplitude in a borehole

Figure 6. Plan view to a horizontal borehole in salt at the 840 m level with colour coded amplitudes (linear scale) of the direct wave signal

One example from the horizontal borehole 427 illustrates the result from the direct signal amplitude in comparison to the salt geology. The borehole is completely situated in the main salt area with a length of 480 m (Fig. 6). The color bar shows high amplitudes in red, which means high resistivity, and low amplitudes in blue. Along the east to west profile, from z2HS2 salt to z3 salt, the amplitude increases continuously.

Another example from horizontal borehole 254 shows an amplitude plot of the direct signal envelope in comparison to salt structures (Fig. 7) showing more details in variation. The borehole passes orthogonally through the geological structure (Fig. 9). This borehole has a length of more than 540 m. It starts at the center of the main salt and is cutting the younger Leine-sequence. There it is expected to measure higher amplitudes caused by lower conductivity of the salt. The moisture from the wet drilling process and the anhydrite layers might be the reason for higher conductivity. The lowest amplitude values correlate with clay (z3GT) at the beginning of the green areas (anhydrite, z3HA) (Fig. 7, 9).

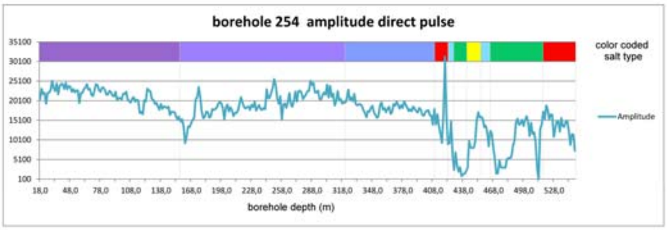

Figure 7. Direct pulse amplitude and salt geology in borehole 254

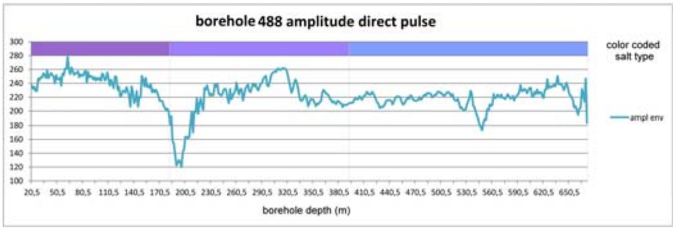

Figure 8. Direct pulse amplitude and salt geology in borehole 488

The next example from horizontal borehole 488 (Fig. 8) shows a similar amplitude plot of the direct signal envelope in comparison to main salt structures. The amplitude scale is independent from Fig. 4 and 7 because of different equipment, amplification, manually and measurement condition. Borehole 488 has a length of more than 670 m, starts at the same point as borehole 254 in the center of the main salt and unexpectedly does not reach the Leine-sequence (Fig. 8, 9). That means the salt structure is strongly faulted between borehole 254 and borehole 488. The information about direction and distances of the structures was found in the reflected signals. In the direct signal amplitude a good correlation can be seen at the boundary from z2HS1 to z2HS2. In both borehole profiles the low amplitude indicates the change of the salt structure. The major part of the main salt seems to be more or less low conductive.

The color scale for both boreholes in figure 9 is chosen by individual max-min interval independent from absolute values of the direct pulse amplitude. For comparability the starting point in the south of the boreholes was set to the identical color.

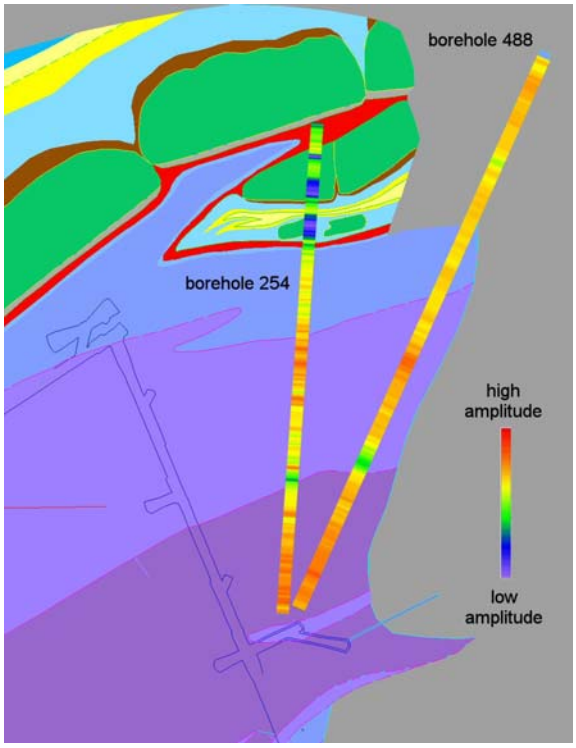

Figure 9. Plan view of horizontal boreholes in salt at the 840 m level with colour coded amplitudes (linear scale) of the direct wave pulse amplitude and salt geology

VI. RESULTS FROM LOW FREQUENCY ANTENNAE

In underground mines there is limited space for large antennae. Adapted to proper proportions for a handling in the galleries we constructed a pair of shielded 40 MHz antennae. The basis for that development was a low frequency antenna [11] normally carried by helicopter used for ice thickness measurements [12]. The data records of this system are measured continuously with 256-fold stacking at an antenna speed of 1-2 m/s. A trace consists of 8192 samples with 2.5 ns sampling interval. Mounted on a transport vehicle with a constant transmitter-receiver distance of 10 m, measurements on profiles in all directions are possible. Best conditions for a homogenous coupling of the antenna to the salt are given for profiles on the floor. An example profile (Fig. 10) through the main salt up to the Leine-sequence shows the possible range of reflections. In the lower conducting southern part the range with good reflections is more than 300 m instead of 80 m in the northern part where it is limited due to the higher conductivity. The direct wave from transmitter to receiver is without information about conductivity because the signal is overdriven.

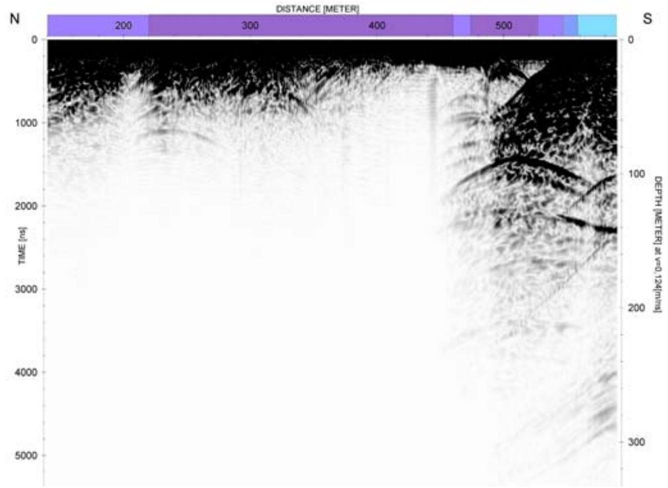

Figure 10. Part of a radargram from a profile on the floor along a gallery from northern to southern direction

SUMMARY

For the investigation of salt domes, GPR is the only non-destructive method which offers spatial information on a large volume to be obtained from few accessible spaces such as shafts, boreholes and drifts. During the investigations of the Gorleben mine, GPR profiles were measured in all directions at different frequencies, with different tools and antenna polarizations. The large data set offers the chance to examine many signal amplitudes in order to get a relative measure of the conductivity distribution within the salt dome. The best conditions for such an interpretation are given for borehole measurements. The detailed knowledge of internal salt structures allows correlating the attenuation of GPR signals with geological structures. Layers of the main salt can be distinguished by high conductivity anomalies, which are also typical for clay and anhydrite.

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