GPR Measurements for Determining 3-dimensional Structures within Salt Deposits

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1. Introduction

GPR (Ground Penetrating Radar) measurements have been used in German salt mines for over 25 years. This measuring technique has an excellent track record for geological exploration as well as in the planning and safety of underground mining activities.

GPR is a non-destructive measuring technique and is therefore the method of choice for the investigation of geological structures in planned salt mines and salt repositories for radioactive waste whose integrity must be confirmed and maintained.

GPR measurements are carried out in boreholes drilled from the surface or from drifts. GPR measurements are also carried out as standard practice in drifts, shafts and underground workings.

Because one is dealing in the subsurface with full space, directionally oriented measurement and evaluation is very important for the proper spatial determination of the results.

2. Measuring and evaluation methods

The radar measuring technique used by us is based on the principle of pulse radar. A transmitter sends periodic electromagnetic wave pulses via an antenna into the rock being investigated. When the waves encounter a rock horizon with different electrical properties, part of the electromagnetic energy is reflected from the boundary surface. The reflected wave is received after a certain time by the receiving antenna and is recorded and evaluated by the receiving equipment (fig. 1). If the wave velocity in the rock is already known, one can use the travel time to calculate the distance between the boundary surface and the measuring point.

The wave propagation velocity in salt was determined by irradiation measurements between boreholes and verified with velocity analysis. Almost without exception, zones investigated in salt deposits are multilayered, e.g. consisting of interbedded halite-anhydrite-claystones. The objective of the GPR measurements is to determine the distance and direction to mining engineering and geologically interesting rock formations from drifts or boreholes cut in halite. Almost every low-attenuation pure halite, e.g. in the Zechstein evaporites, can be penetrated by electromagnetic waves to depths of several hundred metres. In general, strong electrical property contrasts result in high reflectivity. Anhydrite beds, as well as claystones, are the most frequent reflection horizons in evaporites. This is due to the relatively high electrical conductivity and dielectric value of these materials compared to halite. The boundaries of water saturated layers and top salt are other prominent reflection horizons.

Evaporites also contain areas with relatively high conductivity capable of attenuating electromagnetic waves - in some cases totally. Virtually no wave propagation can take place in claystones so that no reflections can be received from subsequent boundary layers.

When they are saturated with liquids, anhydrite, and especially halite, also have similar attenuation properties. Water saturations of only a few percent considerably increase electrical conductivity and therefore also the attenuation of EM waves. Very strong reflections can occur at the boundaries between dry and liquid saturated layers because of the strong electrical contrast.

The precise position of reflectors picked in radargrams is generally determined on the basis of a numerical calculation method called migration. The "Kirchhoff" and F&K migration methods commonly used in seismic processing are not applicable here because they would result in the loss of directional information. If the distance and direction of a reflection is known one can use a relatively simple algorithm worked out by us [2] to determine the precise spatial position of the reflection points along a profile. This migration is based on the principle of wave front reconstruction. This allows determination of a spatially precisely oriented elementary plane at each reflection point. Merging these elementary plans along a profile creates a band in space that represents the spatial position of the reflection horizon.

3. The location of internal structures in salt by GPR drift surveys using a domal structure as an example.

Three-dimensional structures can be precisely determined if, in addition to successfully defining the distance of reflections during drift surveys, it is also possible to detect the direction from which they received.

The measurement example discussed describes a zone whose complex structure is of particular importance for the drifting of the salt mine. The zone in question is an updomed potash bed surrounded by drifts. Reflections from a strong marker (Mittleres Orangesalz, Zechstein - a thin anhydrite-rich bed) are measured from the wall and the floor as well. Repeated 360 degree measurements orthogonal to the drift (or logging profile) generates the directional data required. The updoming of the potash bed is indirectly verified by the key marker horizon.

3.1 Principle of drift measurements

Depending on the subject being investigated, GPR measurements in drifts are carried out along profiles along the roofs, walls or floors parallel to the drift axis. The dipole antennae generally used for this purpose only have omnidirectional orientation characteristics. This means that these antennae cannot be used to directly determine the spatial position of reflectors. When we undertake drift measurements we therefore also use an Adcock direction finder or carry out "radial or 360 degree" measurements. As shown in figure 1, the latter involves taking measurements along a drift cross-section orthogonal to the drift axis. This allows approximate determination of the direction from which the reflections were received on the basis of travel time and amplitude analysis.

3.2 Spatial mapping of a salt structure on the basis of selected GPR drift profiles

The logging example discussed exclusively involves radargrams from profile sections along the floor and the southern wall of the main extraction drift. The survey point spacing along the profile is 1 m (see fig 1) and the transmitter-receiver separation

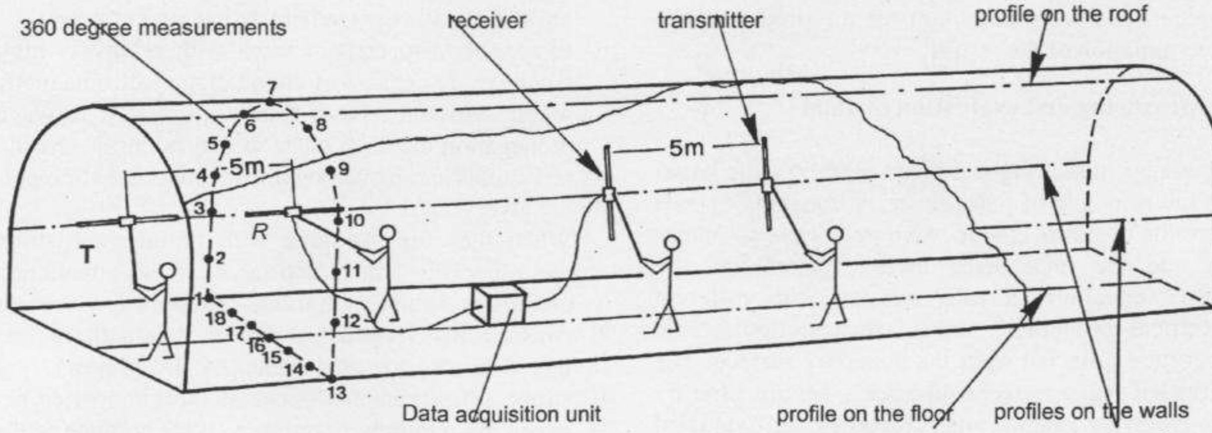

Figure 1. GPR measurements made at intervals radially around a cross-section through the tunnel and along profiles along the tunnel.

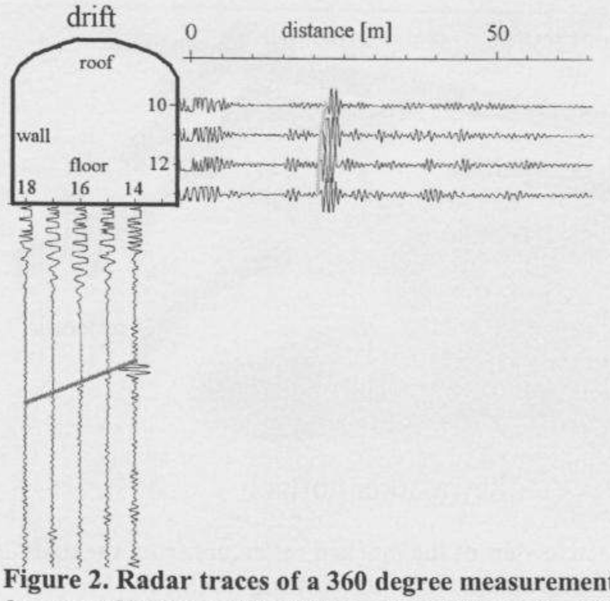

Figure 2. Radar traces of a 360 degree measurement from profile metre 100 at the wall and floor of a drift survey.

Using profile metre 100 as an example, radar traces of the 360 degree measurement of the wall and the floor are shown in relation to the survey points marked in figure 1. The direction can be deduced from the amplitude and the reflection travel time differences. In this case, the reflector in the direc tion of the wall can be correlated with the floor level and is identical to the reflector on the floor. Figures 3 and 4 show profile sections of the floor and the wall which show the course of the reflectors in the 360 degree measurement. The radar traces are treated with an automatic gain control to compen sate the attenuation of the electromagnetic wave propagation. The radargram of the floor profile (fig. 3) clearly shows that the reflector shown at profile metre 100 in the 360 degree measurement does no appear under the floor until profile meter 130, and that the distance increases further along the profile. This is a reflection of the key marker horizon. A reflection hyperbola is present immediately

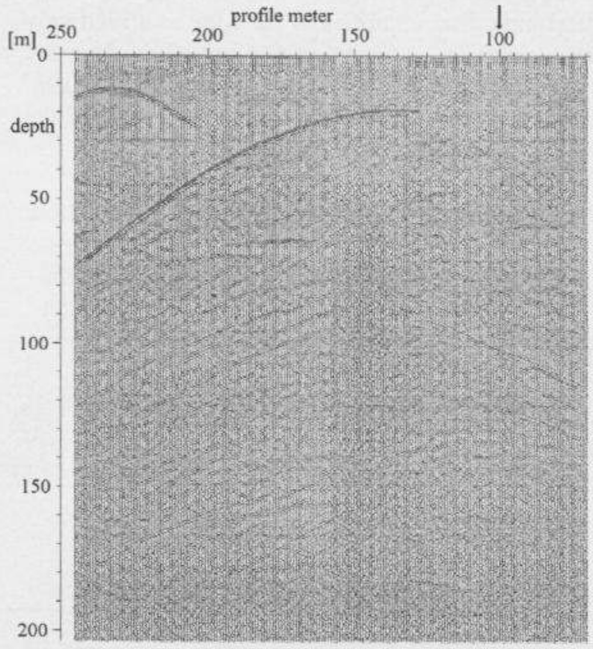

Figure 3. Radar cross-section of the floor of the drift profile

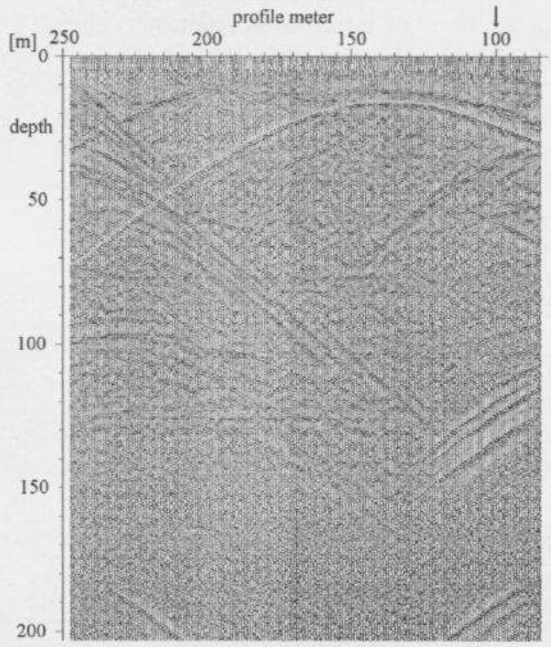

Figure 4. Radar cross-section of the southern wall of the drift

is 5 m. The effective logging frequency is around 50 MHz. The 360 degree surveying is carried out every 15 to 20 m (fig. 1). The interpretation of the 360 degree measurement is hampered by the non-rotation symmetrical cross-section of the drift and the variable coupling of the antennae and the rock. The cross-section of the drift is sketched in figure 2.

underneath the floor at profile metre 235. This is attributable to a borehole which runs beneath the floor. The radargram of the wall profile depicted in figure 4 shows a striking reflector which echoes the course of the key marker horizon in the context of the radar profile. The reflector moves closer to the drift and then moves farther away down the profile.

Numerous other reflectors are identi fied in the radargram, some of which are attributable to drifting and bore holes, while others are attributed to salt structures. Figure 5 shows a perspective view of the underground workings with the horizon of the geological section at the drifting level. The intersection of the potash bed lying beneath the marker hori zon marks the dome structure. The small lines show the reflecting key marker horizon. The measurement profiles on the wall and the floor are shown above with the associated reflectors. The reflectors highlights the dip along the flanks of the dome while others reveals the kinked boundary of the dome to the north.

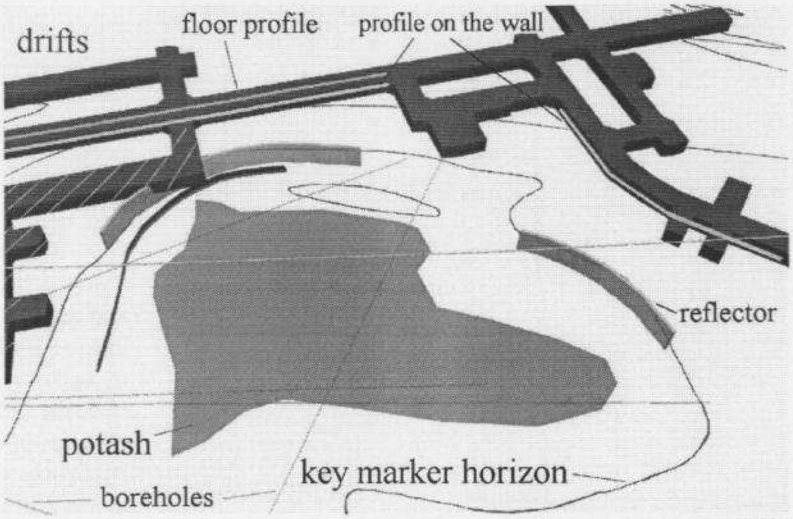

Figure 5. Perspective view of the marked reflectors from the drift profiles and a geological section at the drifting level.

Another reflector from a wall profile in the eastern part of the drift openings is shown to confirm the dome on the basis of information from other drift sections.
Numerous additional reflectors from profiles in other drifts as well as from other depths allow al most complete verification of the domal structure in this area. They were left out of the diagrams to avoid confusion.
Geologists can model detailed 3D structures on the basis of the 3D reflectors, drift exposures, and borehole information.

4. Exploring an anhydrite flank in the salt dome by GPR borehole surveys

Information on the geological structure of the surrounding rock is required to plan drift cutting as reliably as possible.GPR borehole surveys can determine discontinuities in the rock at a relatively large depth of penetration by surveying laterally along boreholes in a non-destructive way. The prin ciple of the technique and the arrangement of the antennae are shown in figure 6.

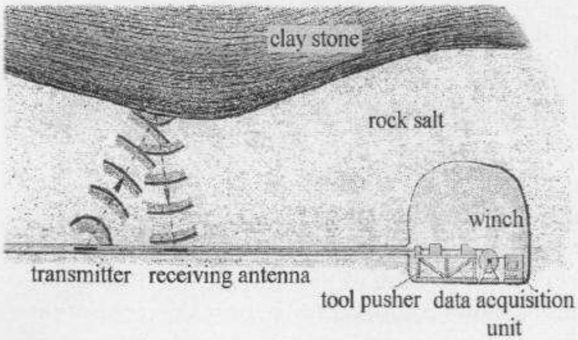

Figure 6. Principle of GPR borehole surveying in a horizontal borehole.

4.1 Principle of direction-sensitive GPR borehole surveys

Combined cross-frame antennae which can be converted into a dipole are used as the reception antennae for direction-sensitive GPR borehole surveys. The transmission antennae consist of a dipole.

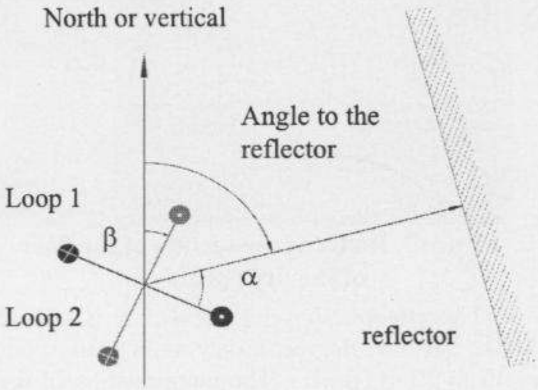

Figure 7. Determining the absolute direction orientation of the reflector from the loop angle α and system rotation β.

Depending on the position of the borehole - hori zontal or vertical - the borehole logging tool is oriented to north or vertical (angle β in fig. 7) by using a compass or an angle of rotation sensor. Sequential surveying of the two loop signals and the dipole signal allow time series to be derived for each survey point, which in turn are used to deter mine the travel time and location of reflection sour ces. The amplitudes of the loop signal are added u via a window range and mutually correlated to determine the direction (figure 8) [1].
An absolute direction angle can assigned to each

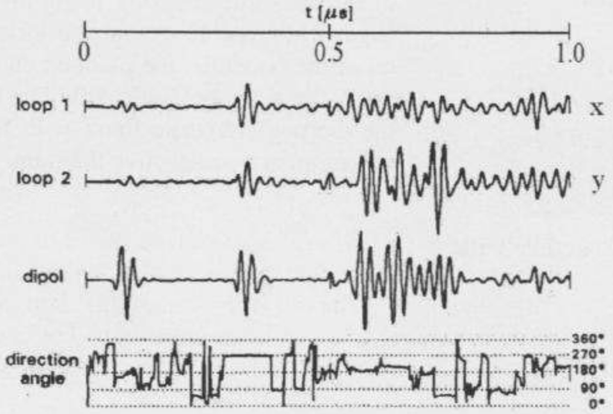

Figure 8. Calculation of the direction orientation from the loop amplitudes and the dipole signal at each sample.

time point of the measurement series by phase comparison with the dipole signal and taking into consideration the system rotation β. A simple migration method (wave front reconstruction) allows the precise 3D position of each reflection point or reflection surface to be determined.

4.2 Example of a GPR borehole measurement with directional antennae in borehole RB427

Borehole RB427 was drilled almost horizontally for a length of approximately 470 metres to explore northerly located anhydrite flank for the purposes of planning new drifting. Because brine was used to drill the hole, this needed to be carefully removed and blown away prior to carrying out the GPR survey. The survey was carried out in 1.5 m steps with a measurement frequency of around 50 MHz and a recording length of 5 µs. Assuming a propagation velocity in salt of 124 m/µs, the lateral depth of penetration of the survey was around 300 m.

The dipole measurement radargram (fig. 9) clearly shows mutually parallel reflections which approach the borehole at increasing depth. The dynamics of the radar traces are equalised in this case by an ini tially exponentially increasing and then logarithmi cally increasing attenuation equalisation function. The advantage of this function is that amplitud differences and thus reflectivity changes remain

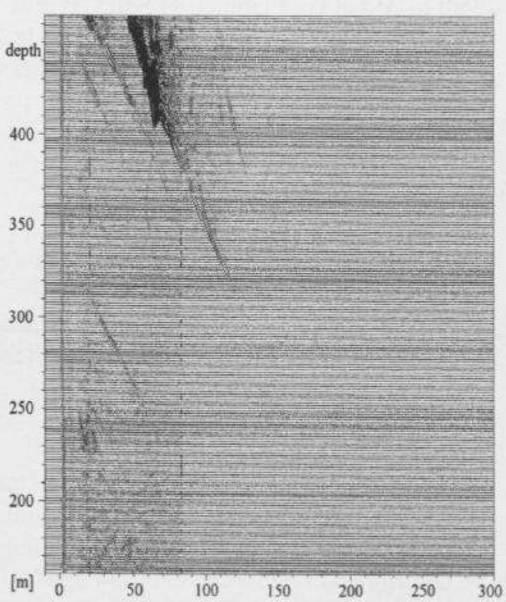

Figure 9. Radargram of a GPR survey in borehole RB427.

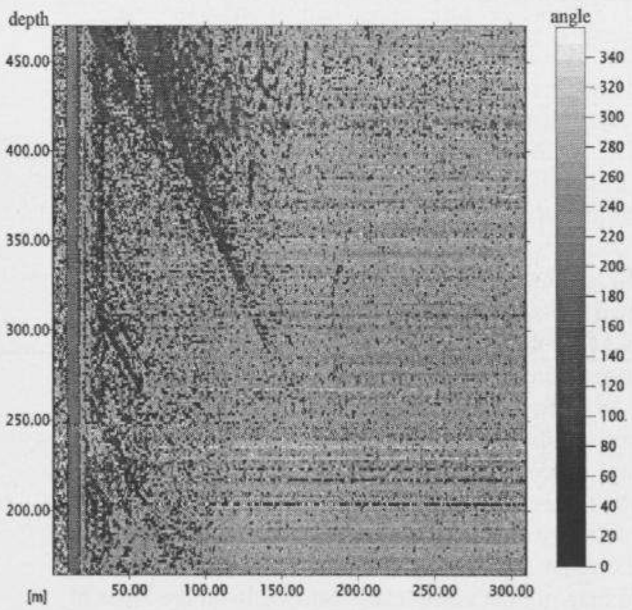

Figure 10. Greyscale coded diagram of the calculated directional orientation in borehole RB427.

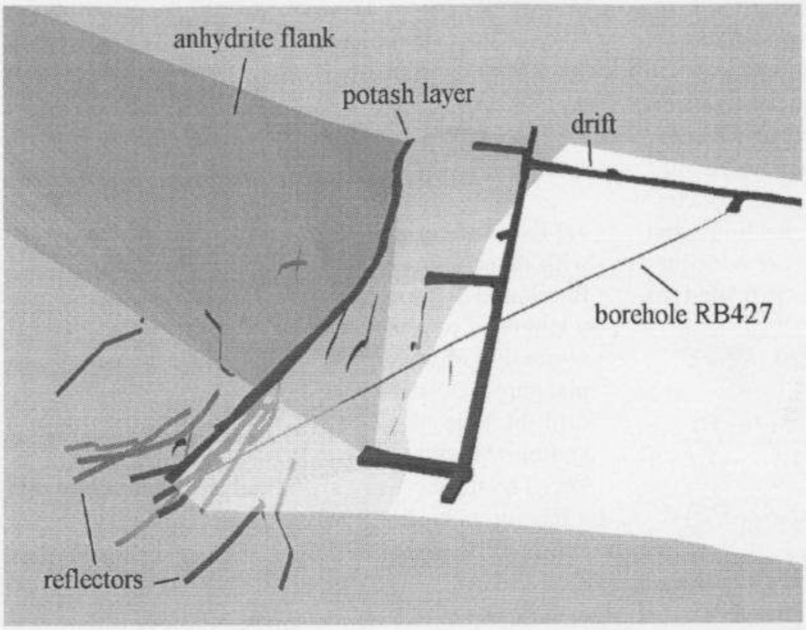

Figure 11. Perspective view of the geological flank structure with some reflectors from borehole RB427.

identifiable. With the angle calculation method described above, an angle can be assigned to every survey point in the radargram. The calculated angles are greyscale coded in figure 10. In this case the angle 0 means up and angle 90 is north. The greyscale coded reflections reveal that the structures are reflecting from below from a northerly direction. Detailed evaluation of the radargram allows reflectors to be configured three-dimensionally to reveal the position of the anhydrite structure being investigated. Figure 11 shows the location of the borehole, the planned course of the drift, borehole RB427 and the dipping anhydrite flank with the reflectors in a perspective diagram.

5. Conclusions

Because underground GPR surveys are carried out in full space, it is essential to be able to determine the position of the reflections in three dimensions. In addition to determining the distance, it is there fore also important to determine the direction from which a reflection has been received by using di rectional antennae or special surveying techniques. The reflectivity, i.e. the detectability of disconti nuities within the stratigraphic sequence, depends on differences in the electrical rock parameters, conductivity and dielectric value (permittivity) of the geologically and/or mineralogically differenti ated units. The depth of penetration of this method is particularly good in salt because of the low electrical conductivity of the propagation medium.
The three-dimensionally determined reflectors derived from GPR surveys are a valuable tool for the three-dimensional modelling of geological structures. Given a dense profile grid, and a favou rable orientation of the objects being investigated to the radar signal propagation direction, it is possible to map almost completely with GPR on the basis of non-destructive techniques.

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