

Borehole Radar — An Efficient Geophysical Tool to Aid in the Planning of Salt Caverns and Mines

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ABSTRACT

The planning and design of caverns and mines in salt formations requires the early drilling of vertical boreholes from the surface. In the case of new mines, horizontal and inclined underground boreholes have to be drilled after the shaft has been sunk.

Radar measurements made from these drill-holes can detect claystone and anhydrite beds as well as boundaries of salt layers at distances of up to several hundred meters. With a newly developed direction-finding antenna, the spatial position of the geological anomalies recognized can also be determined. With this method, additional knowledge about shape, size and internal structure of the salt mass can be obtained, and decisions on the construction of the cavern or mine can be made. Moreover, radar investigations provide significant information on pockets of brine in the salt and therefore can contribute to mine safety.

INTRODUCTION

Reflection measurements using high-frequency electromagnetic waves, here called EMR measurements, are based on the well-known principle of radar. A pulse is transmitted from an antenna with a selectable frequency 10–100 MHz. This signal penetrates the surrounding rock and is reflected by various types of heterogeneity. The reflected signals are received by the receiving antenna. The travel time of the signals is a function of the distance between the transmitting antenna, the reflector, and the receiving antenna and the velocity of propagation of the electromagnetic waves in the penetrated medium. In rock salt, the wave velocity is about 42% of the speed of light.

Media with a low attenuation of electromagnetic waves, i.e. low electric conductivity, are most suitable for EMR measurements. Rock salt deposits, for example, show favorable properties (see Table 1). A range of several hundred meters can be attained using a frequency around 40 MHz. Owing to the fact that their electrical conductivity and dielectric constant (permittivity) show a very distinct contrast to the surrounding medium, as well as the consequently high reflectivity, heterogeneities are readily identifiable. Clay layers, anhydrite, basalt,

and dolomite as well as water-bearing rock zones and brine-filled fissures in the salt rock can be clearly recognized.

MEASUREMENT TECHNIQUES AND HARDWARE

Various antenna configurations are possible, depending on the problem (Fig. 1). For measurements carried out from a mine gallery, the transmitting and receiving antennae are arranged at a defined distance from each other and from the gallery wall. According to the type of measurement, the two antennae can be moved either simultaneously or individually; in the latter case, the distance between the antennae is steadily changed.

For reflection measurements in boreholes, the distance between the transmitting and receiving antennae is kept constant and the entire antenna array is moved stepwise from one measuring position to the next. If there are several boreholes, the antennae can also be moved separately. In this way, so-called penetration measurements are possible, which are very suitable for the approximate determination of the dip directions of reflecting horizons, as well as for the calibration of down-hole directing-finding antennae. This particular method, however,

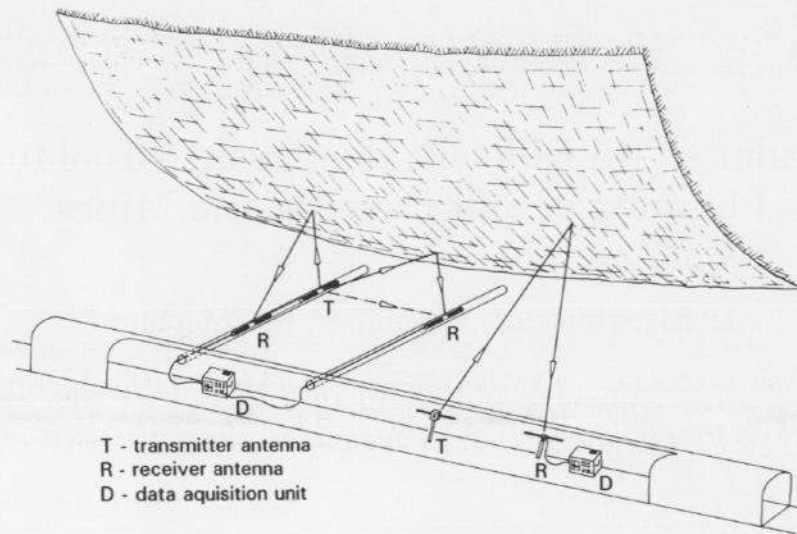


Fig. 1. Underground measurements in galleries and boreholes.

TABLE 1

Electrical properties of different evaporites from the Zechstein salt formation, taken from core samples. Measurements by H. Nickel

Rock type	Permittivity ϵ_r	Specific electric resistivity (Ωm)
Rock salt (Z2)	5.75	10^{10} – 10^{15}
Banded salt (coarse)	6.25	10^{12}
Kieserite (Z2)	6.35	2800
Brecciated carnallite rock (Z2)	6.1	3100
Leine carbonate (Z3)	22	40
Anhydrite (Z3)	7.8	3400
Red salt clay (T4)	30–45	400–700

is mainly used for attenuation measurements, tomographic studies and velocity measurements.

For borehole measurements it is most important that the boreholes are not filled with brine, which, due to its high conductivity, impedes the transmission of high-frequency electromagnetic waves. Before EMR measurements are carried out, these boreholes must either be drained or filled with a non-conducting mud, e.g. diesel oil.

Several types of downhole probes have been developed to suit the requirements of different applications:

(a) For vertical boreholes, a probe is used which can withstand high pressures and can be used down to depths of several thousand meters. The probe uses a standard seven-wire borehole cable and works at frequencies of 20, 40, and 80 MHz.

(b) For investigations in mines a probe and data acquisition system are available. This probe is suitable for horizontal, inclined and vertical drill-holes up to 1000 m long. To extend the range of performance of underground probing, a completely flame-proof borehole radar system consisting of recording equipment and a hydraulically operated probe has been developed.

(c) Light-weight probes with a diameter of 40 mm have been specially designed for slim-hole investigations. These work at frequencies between 30 and 400 MHz. The higher frequency range covers close-range detection and has a very high resolution.

During the early stages of development of EMR probing methods, an analog recording technique was used. It consisted mainly of photographing an oscilloscope screen. In fact, on account of its simplicity and reliability, this method is still used in combination with portable probes. Modern data processing methods, which allow a more rapid and accurate evaluation of the raw data obtained, require digital recording devices. Therefore, digital recording units had to be developed that could withstand the conditions in mines and at drilling sites.

The transmitting and receiving antennae were previously exclusively slim dipole antennae. They allow accurate determination of the distance to the individual reflectors, but do not provide any information on their azimuthal position. A considerable step forward was achieved with the development of a new direction-finding receiving antenna (Fig. 2), which provides information on the direction of the signals received. A switch is installed in the middle of the antenna, which makes it possible to use the antennae as dipole as well. Figure 3 shows the typi-

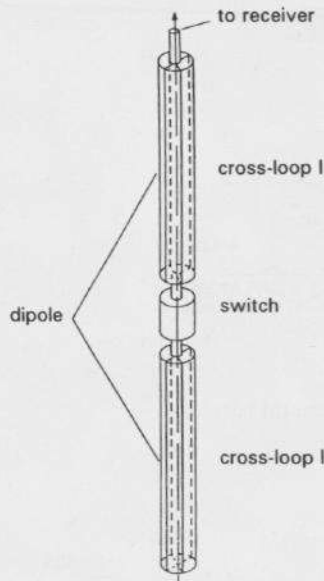


Fig. 2. Integrated cross-loop dipole antenna.

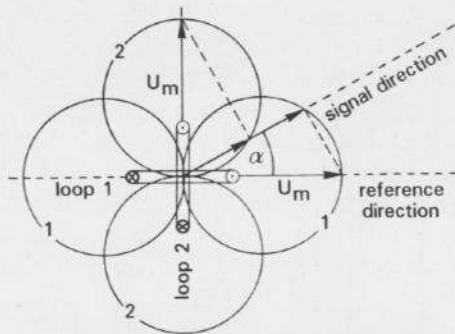


Fig. 3. Radiation pattern of a cross-loop antenna.

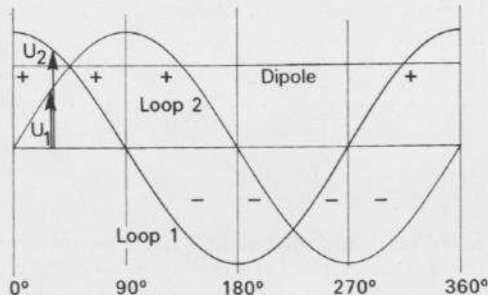


Fig. 4. Amplitude and phase relationships of the cross-loop antenna.

cal azimuth patterns of the two loop antennae. The dipole provides a rotationally symmetrical voltage pattern, whereas the loop antennae give a crossed pair of figures-of-eight; the phase changes by 180 degrees each time the zero axis is crossed. Calcula-

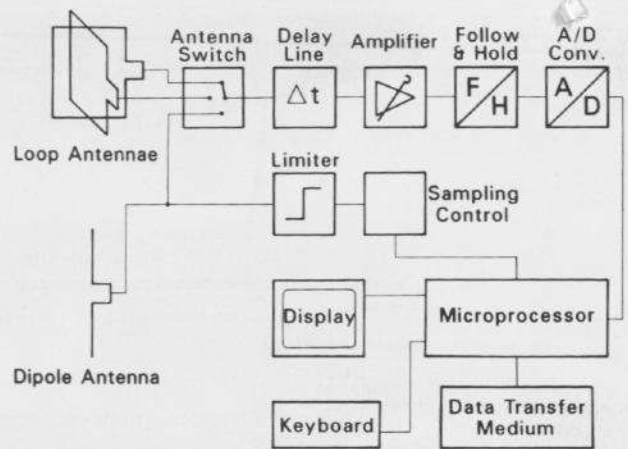


Fig. 5. Radar receiver unit, schematic.

tion of the bearing or angle of inclination is based on the amplitude and phase relationship of the antenna signals shown in Fig. 4 as a function of the azimuth or angle of dip, respectively. To be able to determine directions, the antenna must be fitted with an angle sensor for horizontal boreholes and a compass for vertical boreholes.

The block diagram shown in Fig. 5 represents an EMR receiving system for this type of antenna. The three types of information provided by the antennae, i.e. from the dipole, loop 1 and loop 2, are transmitted one after the other via an antenna switch to the recording unit. The recording unit must fulfil three functions: monitor the signal records and digitalize and store the signals. Analog presentation of the signals would allow them to be checked on the spot. All records can be transferred to a digital storage unit which permits transmission to a computer installed at the surface. Exchangeable semi-conductor storage bases with a capacity of up to 5 MBytes per unit have proved successful.

In the case of the light-weight, non-flame-proof types of borehole equipment, the high-frequency analog signals are transmitted from the borehole probe (antenna system) via a coaxial cable to the recording unit and only then digitized. In the case of the larger flame-proof types of equipment, they are digitized in the probe itself. Figure 6 shows the components of a flame-proof probe. The transmitter at the tip of the probe consists of an antenna tube with an integrated impulse generator. This tube is inserted into the borehole first. Next, to effectively isolate the transmitter from the receiving antenna, five insulating tubes are inserted. The next tube contains the receiving antenna system. Three further insulating tubes are then introduced, followed by the electronic unit. All tubes except the last have a standard length of 2 m. The electronic tube

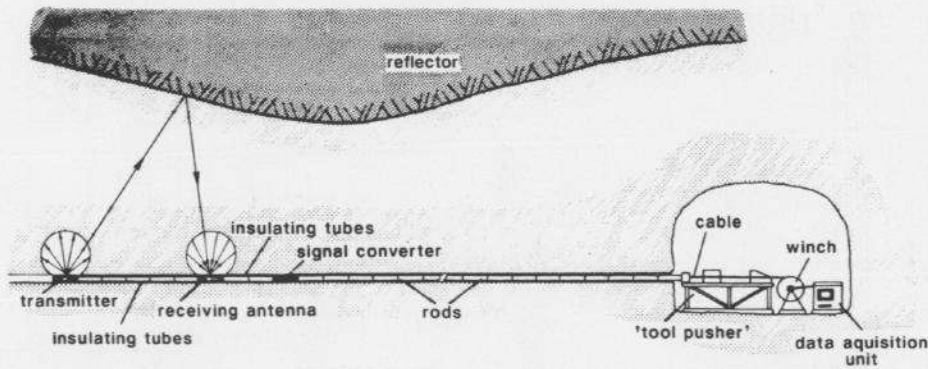


Fig. 6. Electromagnetic reflection measurements in horizontal boreholes.

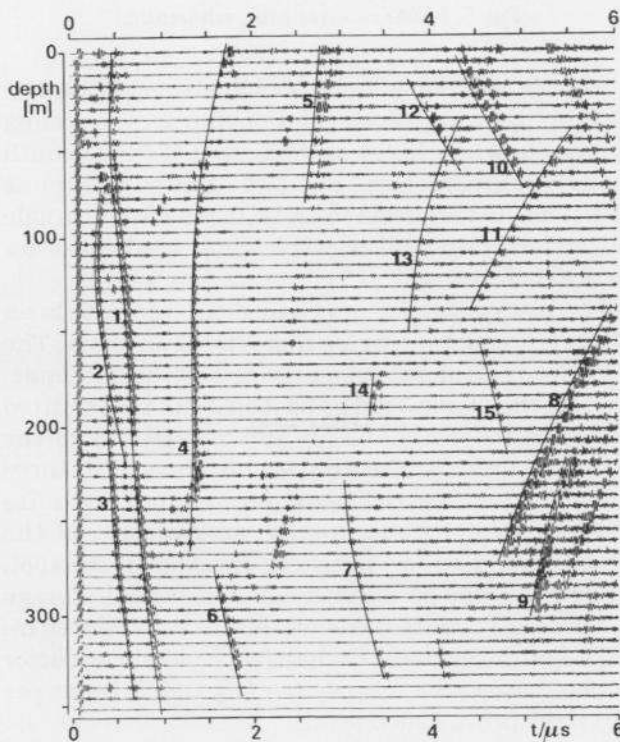


Fig. 7. Borehole radar record.

contains the high-frequency amplifier, the monitoring and digitization unit, as well as the angle sensor and the compass. The electric power supply, the monitoring and data transmission between the probe and the recording unit are effected via a 7-wire standard borehole cable. The hydraulic winch for the borehole cable is equipped with a depth gauge which is connected to the recording unit. In vertical boreholes, the probe can be lowered using the borehole cable. In horizontal boreholes, the probe is inserted using rods and a hydraulic tool pusher. The borehole cable is carried along in the free space between the borehole wall and the rods.

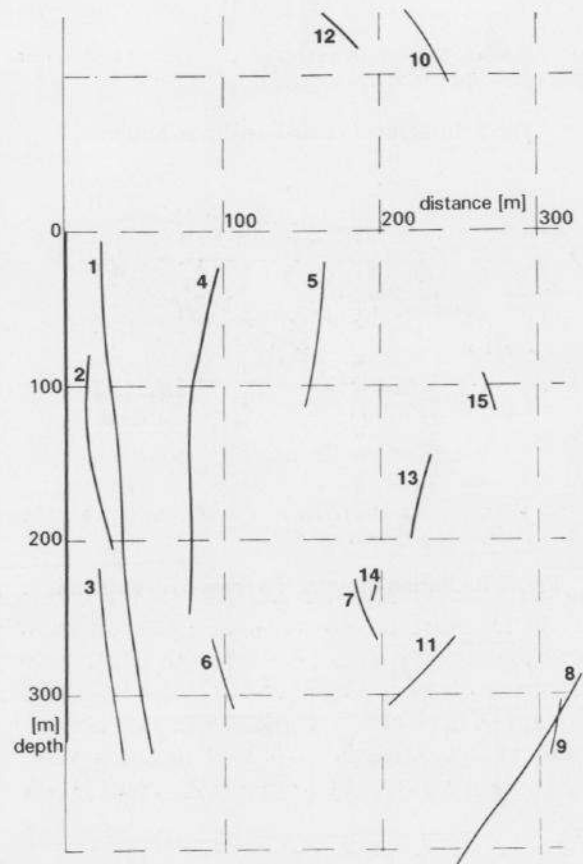


Fig. 8. Interpretation of the borehole radar record as shown in Fig. 7.

Using the EMR equipment described above, data from each measuring position are provided by the dipole antenna and the two loop antennae. Data from a profile provided by the dipole antenna are presented in a cross section. The cross section provides a clear picture of the reflections within the time range. The angle of dip of each individual reflection recorded at each measuring position is derived from the data provided by the loop antennae.

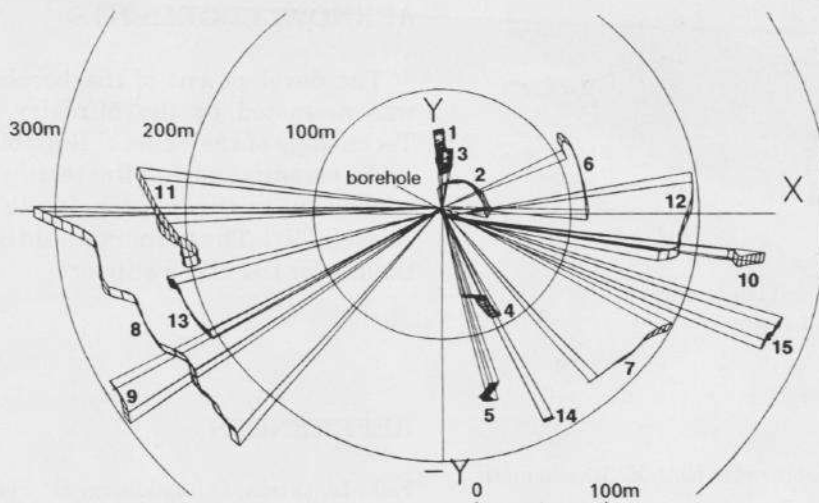


Fig. 9. Three-dimensional interpretation of borehole radar data. Horizontal borehole drilled in a salt mine. Representation is in the x - y plane (perpendicular to borehole axis).

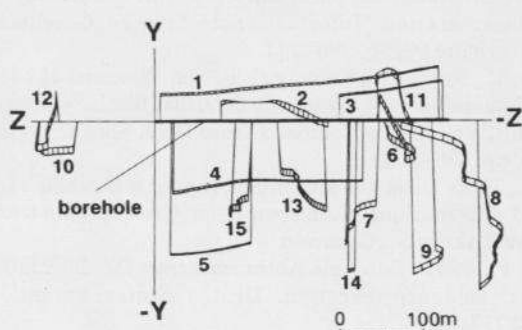


Fig. 10. 3D interpretation of borehole radar data. Same borehole as in Fig. 9. x - z plane (vertical).

Figure 7 shows a typical cross section displaying the reflector horizons. They are marked interactively on the screen. For each position, the depth, travel time and angle of dip are recorded and assigned to the relevant horizon. Next, the distances are calculated from the travel times and, using the migration process, the position of the reflection point is determined.

Figure 8 shows the horizons after migration neglecting the angle data. Before the direction-finding antenna had been developed, this represented the final result. A 3-dimensional picture could only be obtained on the basis of geological data. Now that the angle of dip can be determined, a 3-dimensional evaluation is possible.

Figure 9 shows a 3-dimensional representation as a projection on a vertical plane at right angles to the borehole axis. The horizons, which so far could only be represented as lines, are now shown as ribbons so that a better 3-dimensional picture is obtained. Lines running from the ends of the horizons perpen-

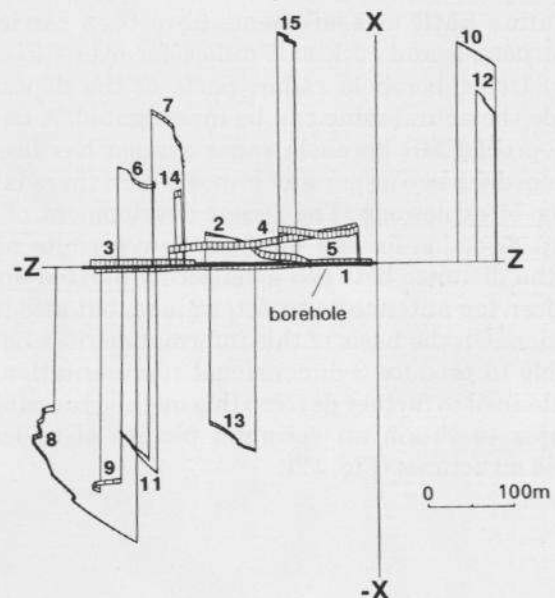


Fig. 11. 3D interpretation of borehole radar data. Same borehole as in Fig. 9. x - z plane (horizontal).

dicular to the borehole facilitate assignment to a certain depth. The projection of the horizons on a vertical plane parallel to the borehole axis is shown in Fig. 10 and the projection on the horizontal plane is shown in Fig. 11. Using these three representations, it is possible to determine the position of the reflecting horizons in space. A 3D graphic computer program can provide a 3-dimensional representation from various angles. After geological interpretation, it will provide important information which will prove useful in planning the exploitation of the deposit.

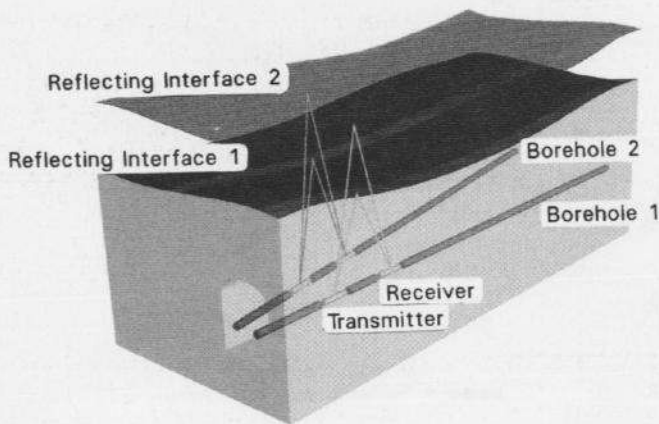


Fig. 12. Principle of the borehole radar method. 3D schematic representation.

CONCLUSIONS

Routine EMR measurements have been carried out in potash and rock salt mines for over fifteen years. Using borehole radar, parts of the deposit outside the actual mine can be investigated. A new flame-proof EMR borehole radar system has been developed for use in parts of mines where there is a danger of explosions. The recent development of a special direction-finding antenna now permits not only the distance between a reflecting horizon and the receiving antenna to be determined, but also its direction. On the basis of this information, it is now possible to produce 3-dimensional representations. It is planned to further develop this method to enable the user to obtain an optimum picture of underground structures (Fig. 12).

ACKNOWLEDGEMENTS

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