# Borehole Radar Probing in Salt Deposits

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## ABSTRACT

*High-frequency electromagnetic radar methods have been used for about 10 years in salt mines to investigate exploitable salt structures. The boundaries of such deposits, as well as layers of anhydrite, basalt, dolomite and clay, and even brine cavities can be located and their direction and distance determined. The results are very important both for economic reasons and for mining safety.*

*Recently, radar sondes have been developed to explore the interior of salt deposits from deep boreholes. Detailed knowledge of the geology of a salt deposit is essential for the planning of mines, the construction of caverns and for underground storage of fuel and gas or disposal of radioactive material.*

*Standard borehole logs can contribute information only about the immediate vicinity of the hole, whereas electromagnetic radar waves are able to penetrate into the salt for several hundred meters. Discontinuities in the salt can be located by pulsed electromagnetic radiation and by measurement of the travel time and direction of the reflected pulses.*

*The radar sonde is constructed to withstand temperature and pressure in boreholes down to about 3,000 meters. Its diameter is only 88 mm. The operating frequency can be selected from between 20 and 100 MHz to achieve either deep penetration or high resolution. It is also possible, by separation of transmitter and receiver, to carry out measurements between two boreholes.*

*This paper explains the method and equipment, presents results of measurements in deep boreholes, and finally gives an overview of the interpretation, as well as of further developments in this field.*

## INTRODUCTION

A number of patents exist in which it is stated that the use of electromagnetic waves is suitable for investigating salt deposits. For example, it was suggested that in order to test for the presence of salt, or to find out whether the salt is dry or wet, measurements be carried out using radiation between boreholes, shafts or galleries. Moreover, electromagnetic reflection (EMR) and other similar methods were said to be able to help solve geological problems associated with mining.

All these patents were filed between 1910 and 1930, and although high-frequency em-technology underwent very rapid development, several decades went by before suitable electromagnetic methods became available for the recurring problems confronting mining geophysics.

At the Fifth International Symposium on Salt in Hamburg in 1978, a paper was presented on an EMR method that was jointly developed in the Federal Republic of Germany by the Federal Institute for Geosciences and Natural Resources (BGR) and the firm Kali und Salz AG. It is an exploration method for detecting structures in salt deposits, and the boundaries of salt bodies, and was specially designed for use in mines. The instrument functions on the same principle as conventional radar but uses longer wavelengths in the VHF range.

The working range of the instrument extends from about 5 m to over 1000 m. By using direction-finding aerials, the position of reflecting horizons and discontinuities can be determined in three dimensions.

In salt domes, the positions of anhydrite and claystone beds can be located, as well as the top and base of the salt structure itself. In the case of horizontally bedded salt, it is possible to locate cross-cutting basalt dykes, the base of the salt and individual clay beds. Similarly, moisture-bearing fractures and brine-filled cavities can be detected.

The system has been in routine use for 10 years. Every year, many kilometers of profiles are measured in the course of geological investigations for the planning of mining operations and prevention of hazards. The method is not only being applied in Germany but also in Canada.

An example of underground radar measurements in a horizontal salt deposit is shown in Figure 1. The instrument was set up in the Hessen Potash Bed gallery and was directed downward. The recorded time is 2 μs. The interpretation of the measurements shows a fault zone near the Thuringen Potash Bed and the base of the Werra Salt (Figure 2).

It was, in fact, the successful use of this method in mines which suggested to us that the instrument might be modified for use in boreholes.

Salt domes are potentially the most suitable sites for large-scale and economic storage of liquid and gaseous hydrocarbons. At present, they are also considered to be the most convenient disposal sites for radioactive waste. The storage of this material requires extremely safe conditions over long periods of time. For this reason, it is essential to have an accurate knowledge of the detailed structure of the salt dome around the planned disposal site.

The first step in the investigation of salt domes that have been earmarked for storage or disposal purposes, or for a new mine, is generally the drilling of boreholes. In this way the geologist can obtain first-hand information about the salt dome in the form of drill cores and cuttings. Drilling is followed by the running of logs. The standard borehole logs provide further information about the rocks in the immediate vicinity of the hole, but the

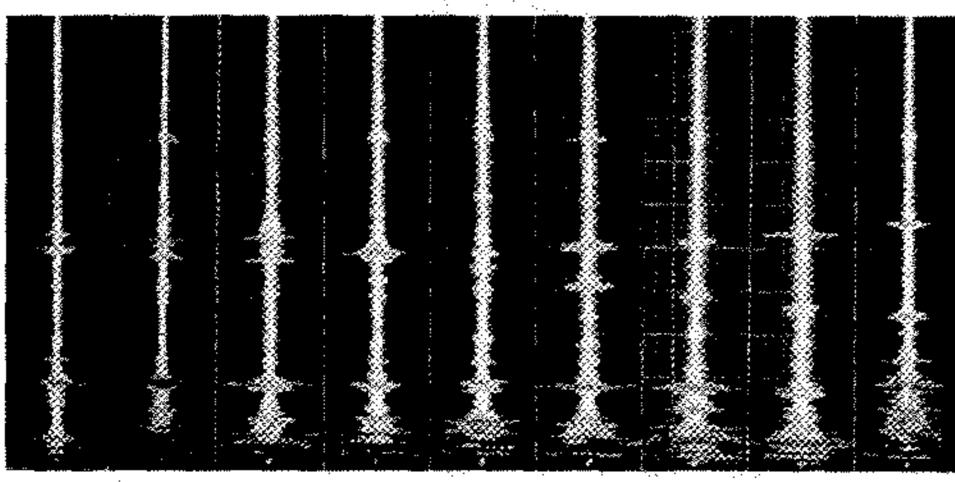

**Figure 1.** Record of high-frequency electromagnetic reflection measurements from inside a salt mine. Measurements were made every 10 m along the profile with a constant transmitter-receiver spacing of 10 m.

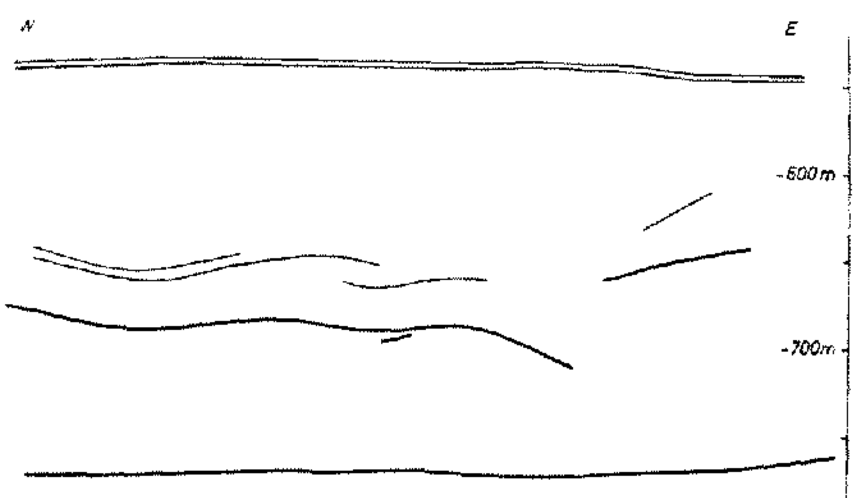


**Figure 2.** Interpretation of EMR-measurements, carried out in a salt mine.

structure of the bulk of the salt dome remains unknown. High-frequency electromagnetic waves, however, can be transmitted through rock salt for hundreds of meters and are reflected at discontinuities. If the directions of the reflected signals and their travel times are determined, then the locations of the discontinuities and their distances from the borehole can be calculated. Measurements are carried out at intervals down the borehole and permit a picture of the structure around the hole to be built up.

The electromagnetic reflection borehole system is based on the recording of ultrashort pulses generated by a special type of transmitter and reflected by characteristic rock layers (reflectors). Transmitter and receiver are situated in the same borehole. Figure 3 shows the basic arrangement. Initial problems were set by the conditions in the borehole and its small size, as well as by the necessity to provide effective wireline facilities for data transmission and power supply.

## BOREHOLE DATA-TRANSMISSION AND POWER-SUPPLY SYSTEM

Standard borehole cables are seven-wire structures with limited band width for linear high-frequency data transfer. Preference was therefore given to a newly developed, completely digital, two-way, data transmission system. This system is directly compatible with standard serial computer output modules (RS 232-C). The data rate is 9600 Baud, thus 960 words of eight bits each per second can be transferred in either direction (Figure 4).

The system needs only four wires, two for downhole data transmission and two for uphole. The same four

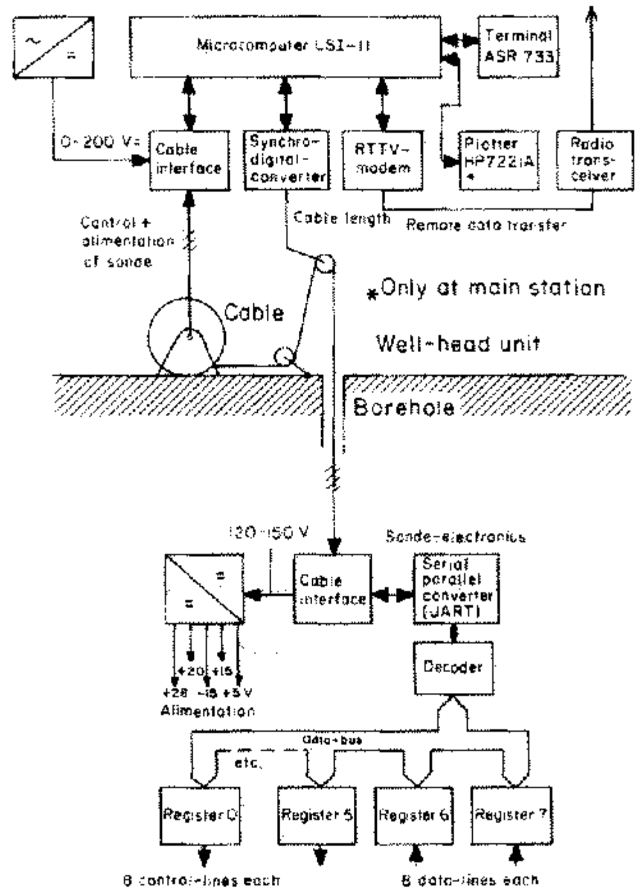


**Figure 4.** Control and data-processing system of the EMR-borehole-radar equipment.

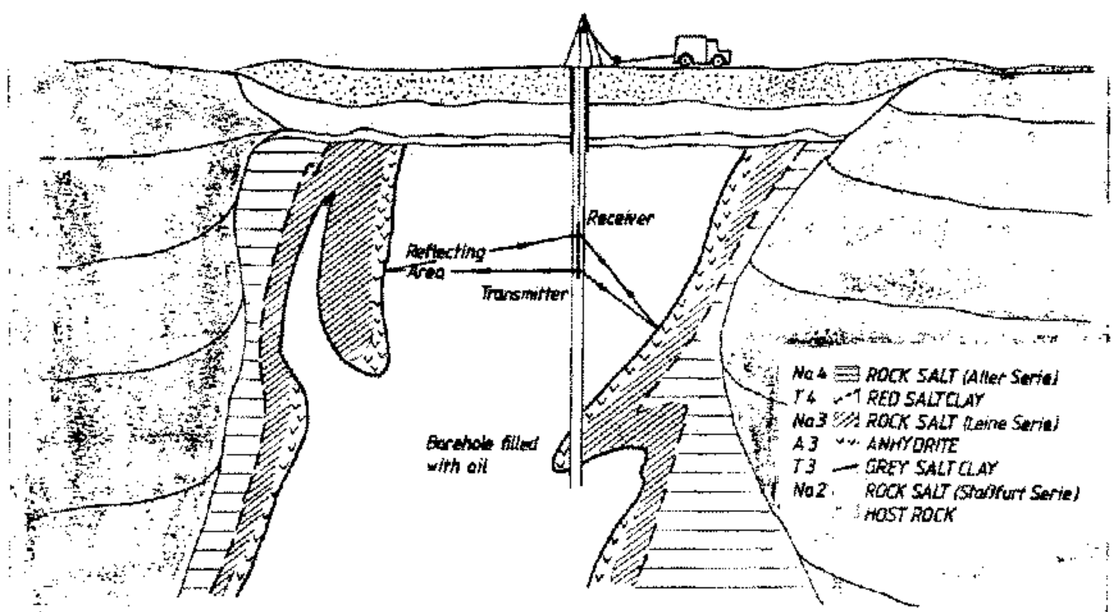


**Figure 3.** High-frequency electromagnetic reflection investigations in a salt dome carried out from a borehole.

wires are also used for the sonde power supply. The power supply is 100 to 160 volts DC; the two downhole leads are positive and the uphole ones negative. Power-conversion modules provide a separate power supply for the sonde electronics. Complete electrical isolation of digital-data transfer is achieved by the use of opto-couplers.

The control and recording equipment at the wellhead consists of the following units:

- microprocessor, for example, the LSI-11 made by the Digital Equipment Corporation
- terminal, e.g., the Silent ASR-733 made by Texas Instruments
- data-display unit, e.g., the 7221A plotter made by Hewlett Packard or an optical recording device, or a profilograph
- additional data-recording equipment such as a cassette or discette recorder.

The sonde has its own control and data-recording units which can accept standard software commands in the same way as any commercial instrument, such as a data terminal.

The system control software may be selected as required. For instance, the initial programs were run both in "hand-made" formats and in interpreter languages such as BASIC and FOCAL. For rapid operational programs, a combination of FORTRAN and a hand-made language proved to be most effective—at least for the PDP-11 compatible DEC system used in the equipment described here (Figure 5).

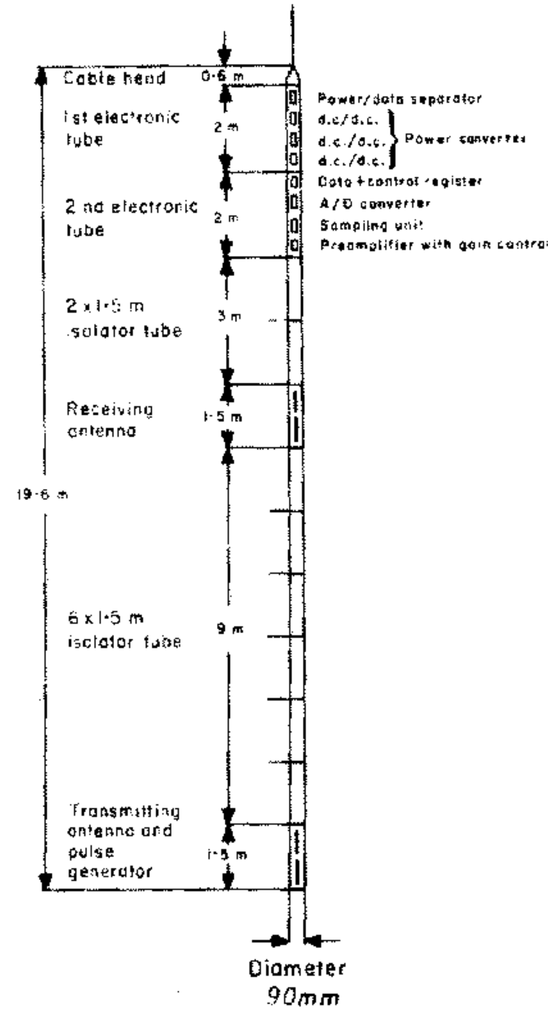


**Figure 5.** The EMR-sonde.

## THE RADAR REFLECTION SYSTEM

The reflection sonde has a total length of almost 20 m and a diameter of 88 mm. The transmitting and receiving antennas are individual units, arranged vertically one above the other and separated by 9 m of insulating material. From bottom to top, the arrangement is as follows:

- transmitter antenna 0.75, 1.5 or 3 m long
- up to 9 m of insulating spacers
- receiving antenna the same size as the other antenna,
- 3 m of insulating spacers with coaxial cable
- electronic unit in two metal tubes each 2 m long.

### Pulse Transmitter

The pulse generator and transmitting antennas are an integrated and fully self-contained unit. The transmitter consists of a gas-discharge tube situated in the center of a dipole antenna. In practice it operates like a carrierless pulse transmitter where the shape of the radiated wavelet is essentially controlled by the characteristics of the dipole antenna.

The pulse-repetition frequency is free running and ranges around 1000 Hz. The power is supplied by self-contained mercury or lithium cells, which have a capacity of 8 to 30 hours, depending on the type of battery. The batteries drive a high-voltage generator matched to the characteristics of the gas-discharge tube.

The transmitted frequency spectrum depends on the antenna length. At present, three types of antenna are used:

- a 0.75 m antenna transmitting in the 80 MHz region
- a 1.5 m antenna transmitting in the 40 MHz region
- a 3.0 m antenna transmitting in the 20 MHz region.

Since the antenna has no electrical connection to the upper electronic units, the radiation pattern and tuning are completely free of disturbance.

### Receiving Antenna

The prototype sonde was fitted out with a dipole receiving antenna that had exactly the same dimensions as the transmitter antenna. With this arrangement, optimum transmission conditions and high sensitivity could be attained but no information about direction. It soon became clear that it was just as important to determine the direction of the reflections as their distance from the borehole. A direction-finding antenna was thus developed; this proved to be somewhat difficult, owing to the small size of the borehole in comparison with the wavelength used.

The newly developed antenna system is a combination of 1 dipole and 2 loop antennas. This permits excellent resolution of the direction of the received signal. The system functions without the necessity of mechanical rotation of the antenna. It produces three components for each signal, from which the azimuthal direction is calculated with reference to a compass built into the sonde.

## SIGNAL CONVERSION AND RECORDING

The main feature of the reflection sonde is an ultrafast follow-and-hold (F/H) system which is capable of sampling discrete signal-amplitude values at 2 ns intervals. One sample is taken at each transmitter pulse. One sampling period is equivalent to an interval of 2.048 $\mu$s, or 1024 samples.

Up to 10 sampling periods of 2 $\mu$s each may be run consecutively. This means that reflections arriving during the 20 $\mu$s after the arrival of the triggering pulse can be recorded in 10 sampling periods with slight overlap. The resolution of the analog/digital converter is eight bits, which is equivalent to 256 discrete steps.

The amplitude samples are forwarded to the wellhead electronic unit by the data-transfer system described above and are stored in the computer memory for processing. Each amplitude word is followed by a timing word provided by a 500 MHz counter which is started by the triggering pulse and stopped by the sampling action. Since only eight bits can be transferred at a time, any overflow is eliminated by computer program. A preamplifier-attenuator combination permits the gain between the antenna and the F/H unit to be set at any value between +80 and −63 dB.

The triggering pulse can be picked up either from the antenna output or from the preamplifier output.

## DATA PRESENTATION

Data and time samples are stored in the computer memory and may be monitored in real-time by an oscilloscope or, preferably, recorded on a direct-writing galvanometric recorder. The latter has the advantage of internally filtering the point characteristics of the sampled signal, without the aid of any software, by means of the cut-off frequency of the galvanometer. Data-output rate can be matched to any recording device simply by using a suitable computer program.

Cross-sections can be produced using seismic cross-section cameras, either on-line or from recorded data in data centers. The raw data is currently recorded on 3M-cassettes of the DC-300 type.

## BOREHOLE CONDITIONS

Electromagnetic waves cannot be transmitted through a highly conducting medium. Thus the sonde cannot work inside the casing or in salt water muds. It is necessary to fill the borehole with oil before starting the measurement procedure. This is not only inconvenient but also costly. At present, work is being done to develop a way of avoiding this step. Should it not be required to measure the whole length of the borehole, then it is technically possible, and cheaper, to only partially replace the drilling mud by oil.

## MEASUREMENT PROCEDURE

The sonde starts to send useable data when both antennas have passed the well casing and are only surrounded

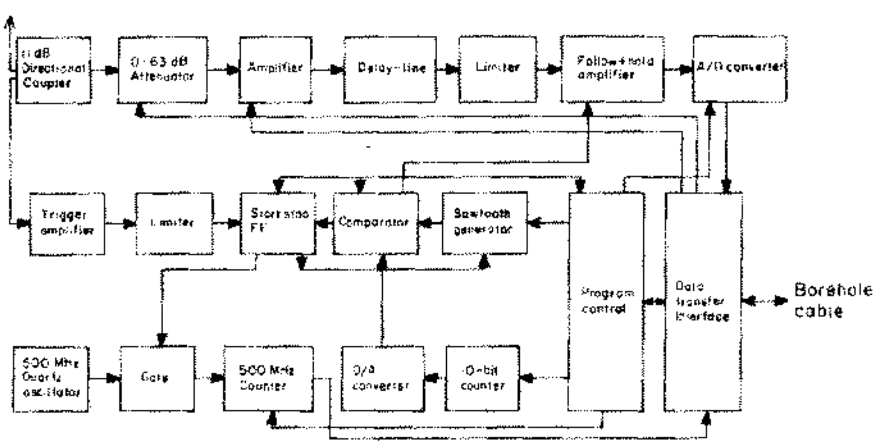


**Figure 6.** Flow diagram of the EMR-sonde electronic unit.

by salt. Data sampling and transfer is in discrete time blocks each 2 μs in length. The gain can be selected separately for each time block.

After transfer of the complete record, which normally consists of 5 time blocks or a total of 10 μs, a monitor record can be displayed on an oscilloscope or automatically plotted on paper. In order to obtain better close-range resolution, an additional recording is made of the first 2 μs block, at low amplification, before the normal record starts.

Part of a typical well radar survey is displayed in Figure 7. The distance between successive traces is 10 m. The displayed time is 4 μs. Each trace starts with the high-amplitude pulse which has travelled from the transmitter via the direct route. This is followed by characteristic reflections with different travel time. It can be clearly seen that the reflected signals have very different amplitudes; to achieve satisfactory resolution, the amplification must be chosen to suit each individual record.

The same section as shown in Figure 7 but over a displayed time of 10 μs appears in Figure 8. As mentioned above, the first 2 μs block is recorded twice, first with low amplification to prevent overloading by relatively strong signals. Thereafter, gain is increased by program control. After each 2 μs block, the gain can be modified to compensate for the decaying reflection amplitudes.

Switching transients during gain modification may look like true reflections but can easily be recognized because of their time coincidence in all traces. The record also shows typical reflections of long travel time.

The digital data structure and storage on magnetic tape permits data processing to be carried out subsequently as in seismic work. A section is shown as a variable-area representation in Figure 9. The similarity to seismic cross-sections is evident. The quality of the signal display may be enhanced by using conventional seismic processing procedures.

## INTERPRETATION OF THE DATA

Interpretation of the data is performed in several steps. First, travel times are converted into distances. The velocity of propagation of electromagnetic waves in rock salt is 125 m/μs, that is about 40% of the speed of light. In other words, a travel time of 1 μs corresponds to a distance of about 62 m between the reflector and the borehole. The actual positions of the reflectors are constructed by a method involving migration (Figure 10). A picture is obtained of the reflectors, their correct dip and their distance from the borehole, but with no azimuthal information. Thus the reflectors may lie in any direction. The next step depends on the availability of existing information on direction or orientation.

Before the direction-finding antenna was developed, the only available information which could be used was that from the borehole, in particular that from oriented cores. The dip values measured on the drill cores help in determining the direction of those reflectors which are cut by the borehole, or lie near it.

This information enables the geologist to obtain a more distinct picture of the structure in the vicinity of the borehole. The results of such a survey are shown in Figure 11. The borehole is situated in the folded boundary layer between Zechstein 2 and 3. The located discontinuities are anhydrite and clay layers. The bold lines represent the reflectors detected by the EMR sonde. The reflectors on the left, above the top of the salt dome, are probably best interpreted as part of the Main Anhydrite that has penetrated into the cap rock.

In some instances, uncontorted strata with a relatively constant dip are encountered in salt domes; an example is shown in Figure 12. This structure is reasonably simple to interpret with a high degree of certainty: a single measurement of the strike would be sufficient to enable the attitude of the whole structure to be determined.

However, this is by no means the general rule; most of the structures met with during EMR surveys in Northern Germany and Jutland were found to involve more or less strongly folded strata. In addition, most of the reflectors located with the borehole-radar technique are not only generally steep or vertical, but they are relatively short—normally less than 100 m.

This shows that originally continuous beds of clay and anhydrite suffer considerable dislocation during the rise of a salt dome. This particular borehole penetrated Zechstein 1 and 2 strata (Figure 13). The reflectors are dolomite beds near 1100 m and 2100 m, and anhydrite and clay beds which occur near the boundary between Zechstein 2 and 3.

The corresponding geological model constructed from the results of the radar survey and data from the drill cores is shown in Figure 14. It can be seen that the direction of dip changes with depth. One cannot safely assume that the dip direction as measured in the borehole remains constant 50 or 100 m away from the borehole. Thus it is essential to determine the direction or azimuth of the reflectors if gross inaccuracy is to be avoided during interpretation.

## DIRECTION FINDING

As mentioned above, a special antenna system, which has been developed recently, allows directional resolution of the signals. The necessary directional data is obtained by using a combination of two loop antennas and a dipole antenna.

The two loop antennas, set at right angles, eliminate the necessity of mechanical rotation of the direction-finding antenna during measurement. However, since the two loop antennas give two possible directions, a dipole

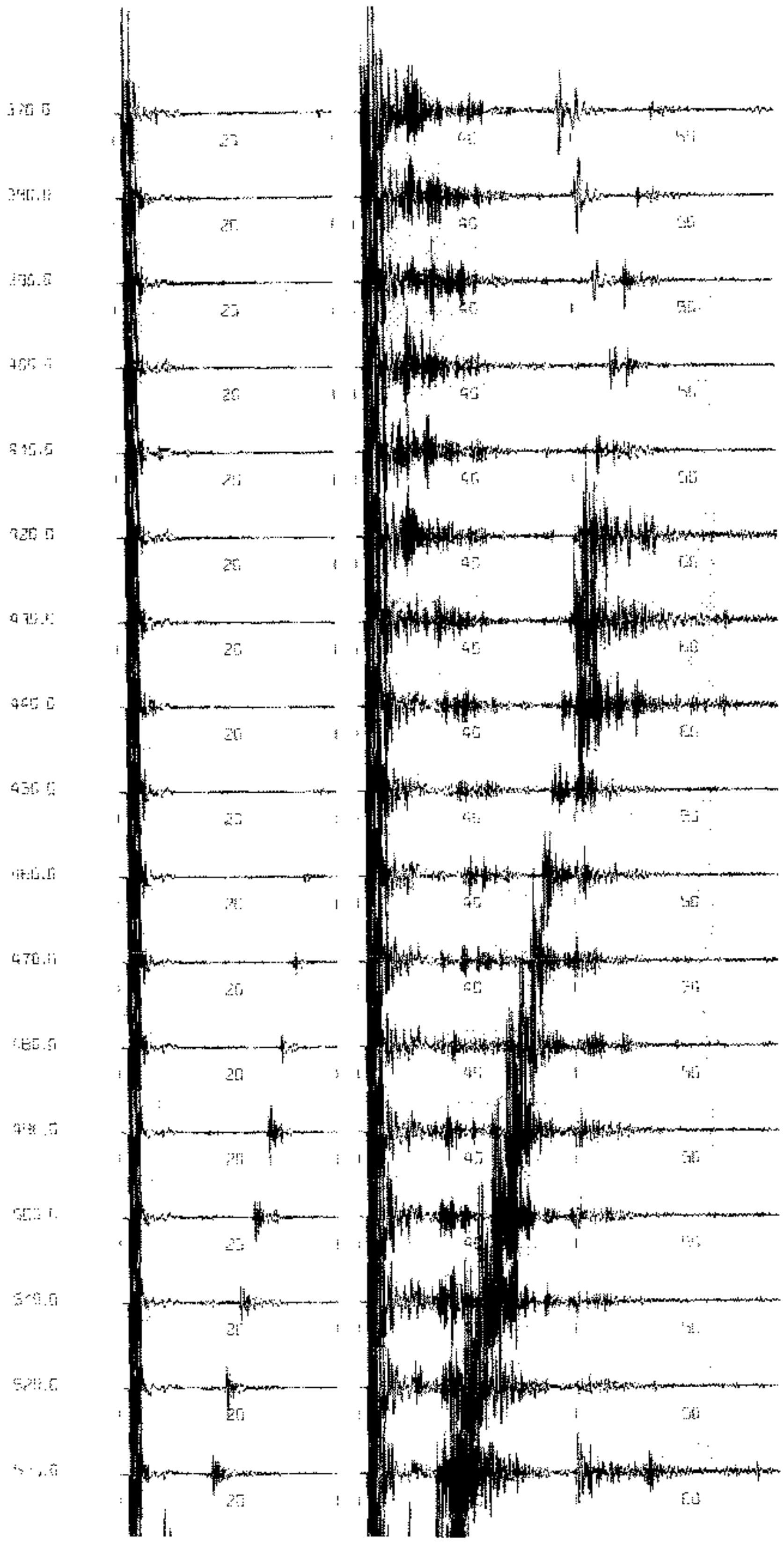

**Figure 7.** Part of a typical borehole record; recorded time 2 + 4 $\mu$s.

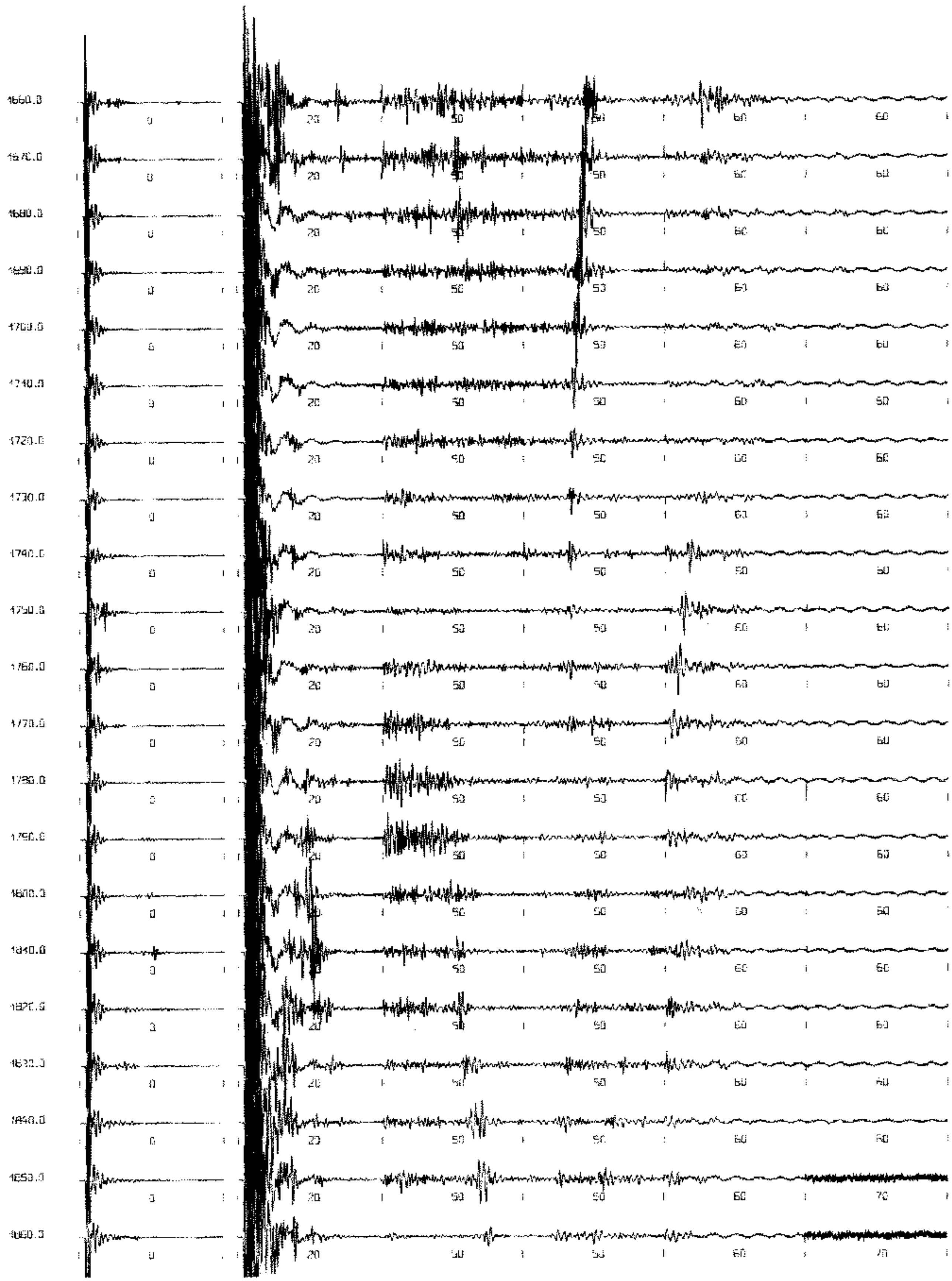

**Figure 8.** Part of a borehole-EMR record, 2 ÷ 10 μs.

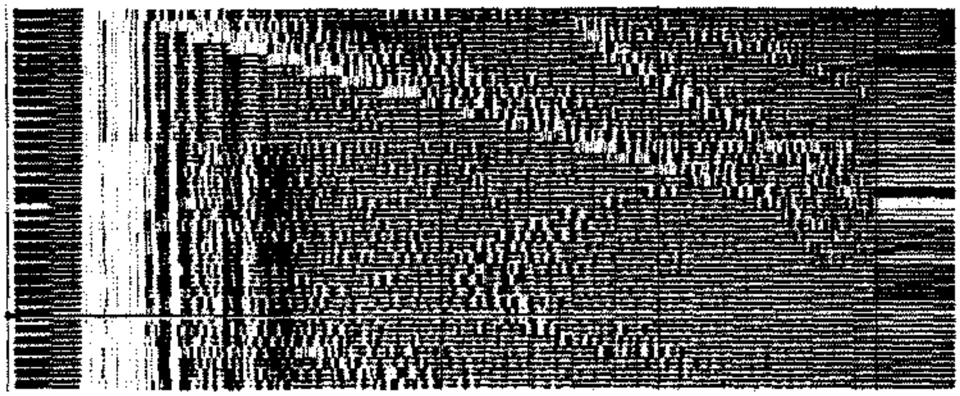

**Figure 9.** Variable-area display of borehole-EMR measurements.

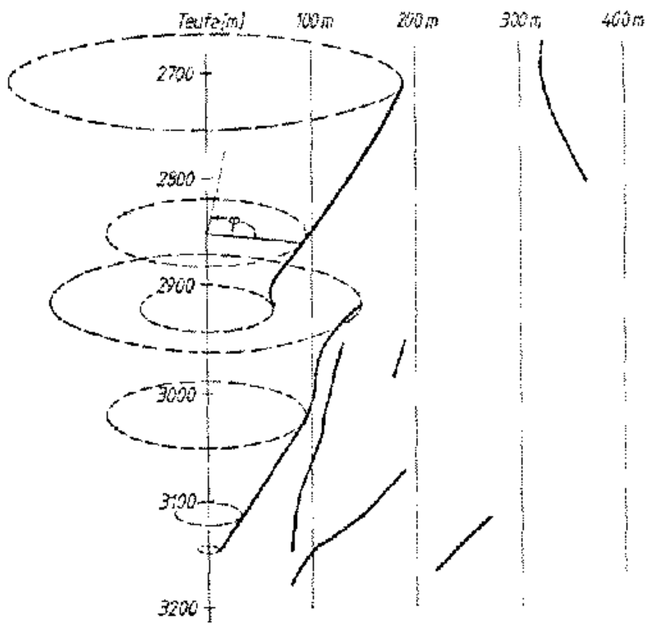


**Figure 10.** Construction of reflectors from travel times of radar reflections.

antenna is also necessary to enable the true direction to be determined.

The direction pattern, shown in Figure 15, is given for:

- the loop antenna (the dash-dot curve in the diagram) with two broad maxima and two sharp minima, and
- the dipole antenna (the dashed curve), a circle.

Thus, at each measuring point, three signals, two from the loop antennas and one from the dipole antenna, are recorded in order to obtain all the necessary information.

Part of a record using loop-antenna signals is given in Figure 16 as an example. The two loop antennas are rotated by computer simulation in 15-degree steps in the polar plane, relative to magnetic north as determined by a compass. Each reflection shows two definite maximum and minimum positions. The direction of dip can therefore be either to the north or to the south. The true direction is determined by comparison of the polarity of the signals with that of the dipole signal. The true direction of incidence is given when the phases of the signals are the same.

Another example of direction finding is shown in Figure 17. Between each trace and the next, there is again a simulated rotation of the loop antennas of 15°. Both maximum values (30° and 210°) and minimum values (90° from the maxima) can be seen. Therefore, the reflections come from the direction 30° or (30 + 180°). The lowest trace is the signal from the omnidirectional dipole antenna. Comparing the polarities of the two signals, it can be seen that the phases are the same for the 30-degree trace. The direction 30° is therefore the correct bearing of the reflector.

Thus, the directions of all detectable reflectors can now be determined by borehole radar. The enormous amount of data makes it essential to improve the interpretation technique, in particular to make it less time consuming. Currently, therefore, the work in this field is concerned primarily with development of the software.

## CURRENT DEVELOPMENT WORK

### Determination of Physical Properties using Amplitude Analysis

Work is being done to investigate the possibility of determining some petrologic properties of the reflecting material from the amplitude and from the distortion of the electromagnetic pulse.

A discontinuity between two types of nonconducting salt with different dielectric constants should theoretically produce no change in the form of the reflected pulse. The situation is quite different for conducting reflectors such as clay beds.

Some results from model calculations are shown in Figure 18, assuming an original pulse of the type shown at the top. If the resistivity of the reflecting half-space is low

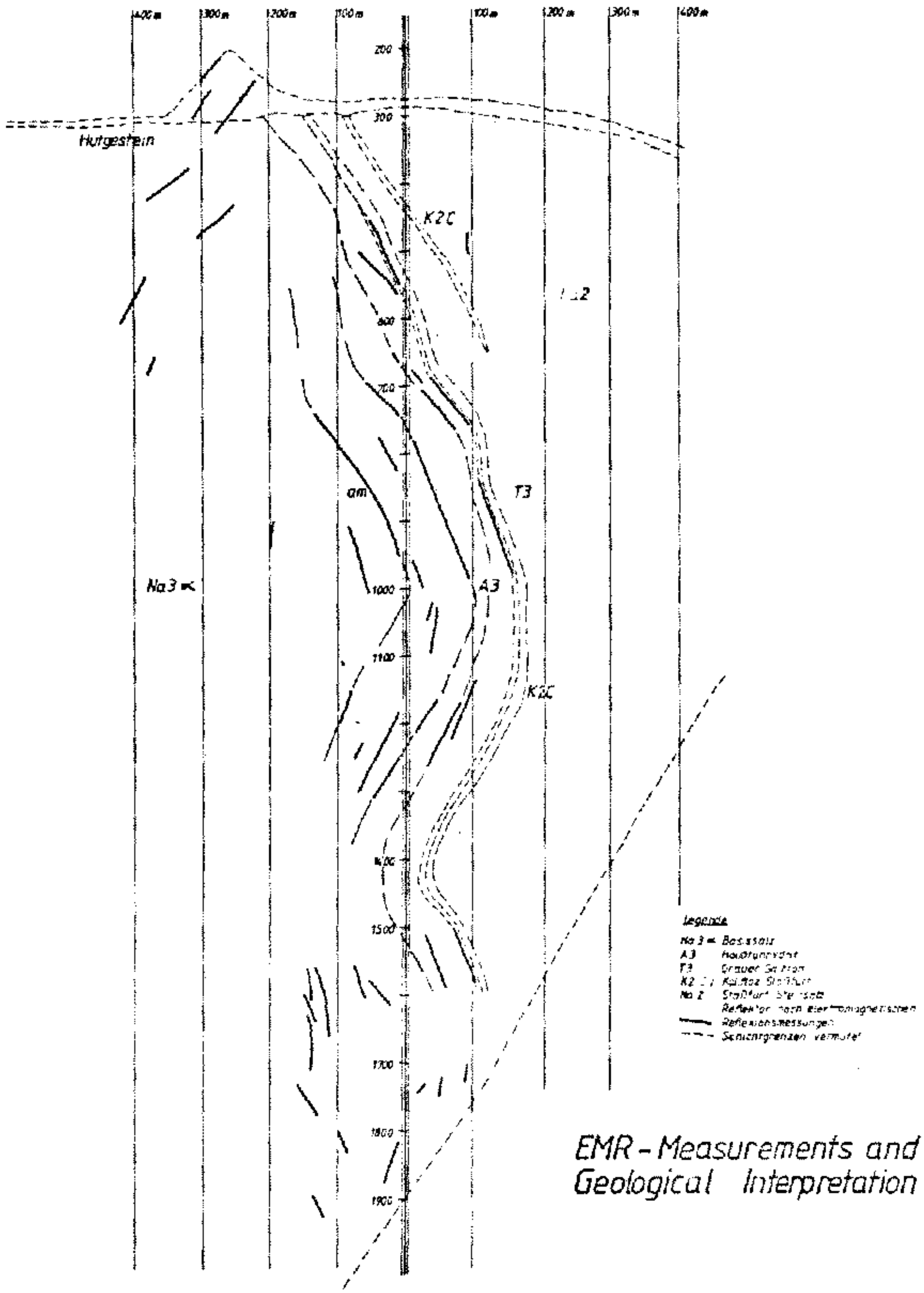


**Figure 11.** Geological interpretation based on borehole-EMR measurements in a salt dome.

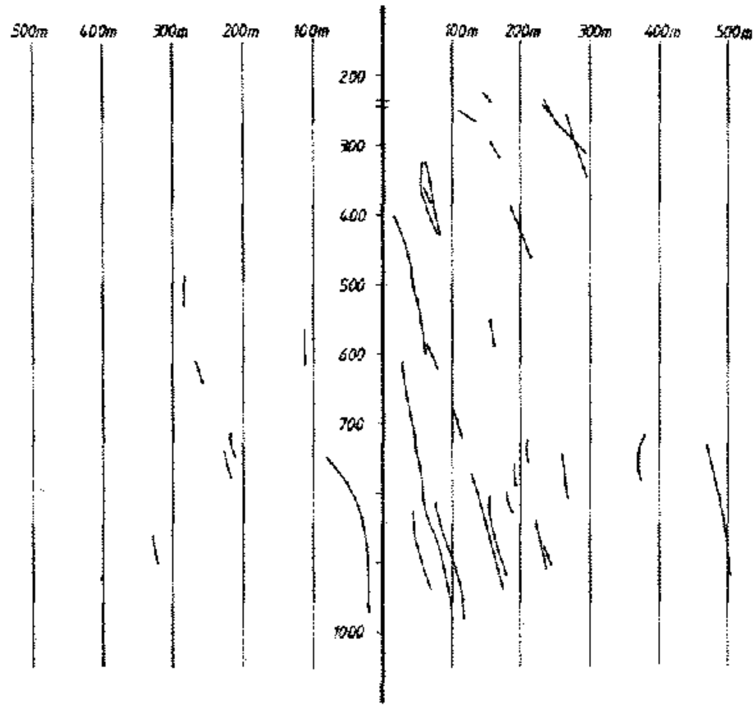


**Figure 12.** Relatively constantly dipping strata in a salt dome, located by borehole-EMR measurements.

(in this case less than about 1 or 3 ohm.m), then the half-space acts as a mirror; there is a phase shift of 180° (bottom of the figure). With increasing resistivity, not only does damping take place, but also a distortion of the original pulse can be seen, in particular, a broadening of the first half-wave. For these calculations, the dielectric constants were assumed to be equal.

As these simple model calculations show, it may be possible to obtain some idea of the physical characteristics of the reflector by analysis of the shape of the reflected signal.

### The Radar Sonde in Horizontal Boreholes

Underground reconnaissance work in mines mainly involves the drilling of horizontal boreholes. If the radar method were employed in these boreholes, then much useful information could be obtained about the structure of the deposit. A radar sonde is currently being developed for use in horizontal, small caliber, drill holes.

### Acoustic Methods

Additional information about the internal structure of salt domes can be supplied by acoustic methods, preferably using a similar wavelength to that employed by the radar method. Electromagnetic waves are reflected at discontinuities between rocks differing in their electrical properties; similarly, acoustic waves are reflected at discontinuities in elastic properties. Successful acoustic experiments have been carried out with a pulse transmitter and triaxial accelerometers held in contact with the borehole wall. The pulse used was shorter than 1 ms, and the mean frequency about 5 kHz.

Briefly, some of the results are as follows:

a. The penetration in transmission mode was over 500 m.
b. The direction-finding capacity of the accelerometer was found to be excellent in transmission mode, where azimuthal reference was provided by a compass.
c. In single-borehole experiments, reflections could be recognized, but the "seismogram" is much more complex than with electromagnetic waves. In addition to pressure (P) waves shear (S) waves arise. However, these two types of waves can be helpful for interpretation in special cases.

## CONCLUSIONS

To date, the radar reflection method has been successfully employed in 10 deep boreholes in salt domes involving a total of 13 profile-kilometers.

The equipment is designed for frequencies of 20, 40 and 80 MHz. The 80 MHz sonde is used for close-range investigation, near the borehole, and where higher resolution is required, in particular for cavern projects. The

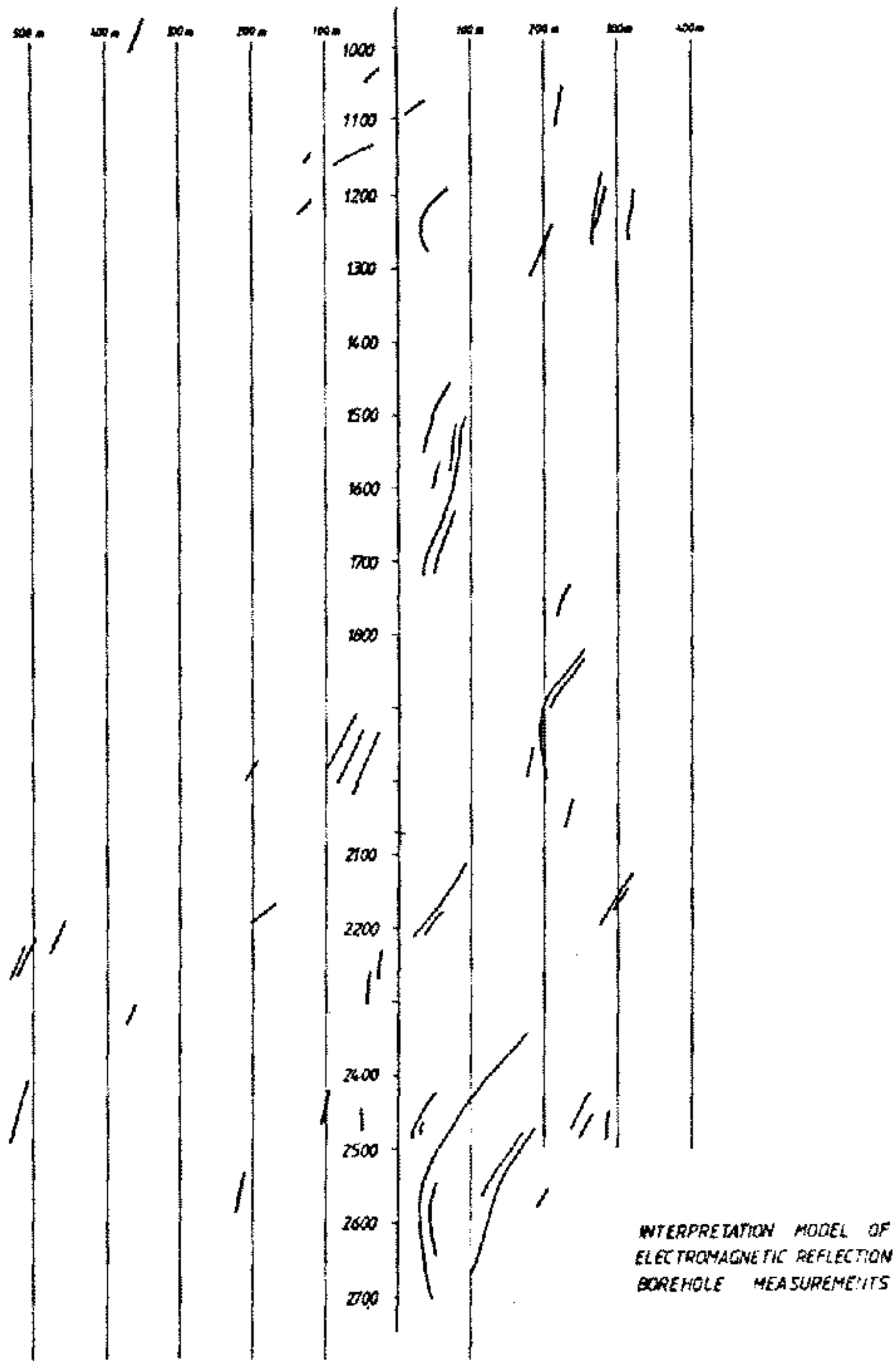


**Figure 13.** Internal salt dome structure showing more contorted strata.

40 MHz instrument is most suitable for intermediate distances up to 300 m, and over 300 m, measurements are carried out at 20 MHz. Thus, the range from 10 m from the borehole to over 600 m can be covered.

If two or more boreholes are available, then radar measurements can be carried out from two boreholes; this may provide additional information about the structure of the salt dome.

Transmitter and receiver are lowered into separate boreholes. Because of the large distance between the transmitter and receiver, excellent wide-angle reflections can be obtained from reflecting interfaces or surfaces which are not perpendicular to the incident ray. With this method the flanks of a salt dome were located at distances of about 800 m from the boreholes.

Using the equipment as described, measurements were

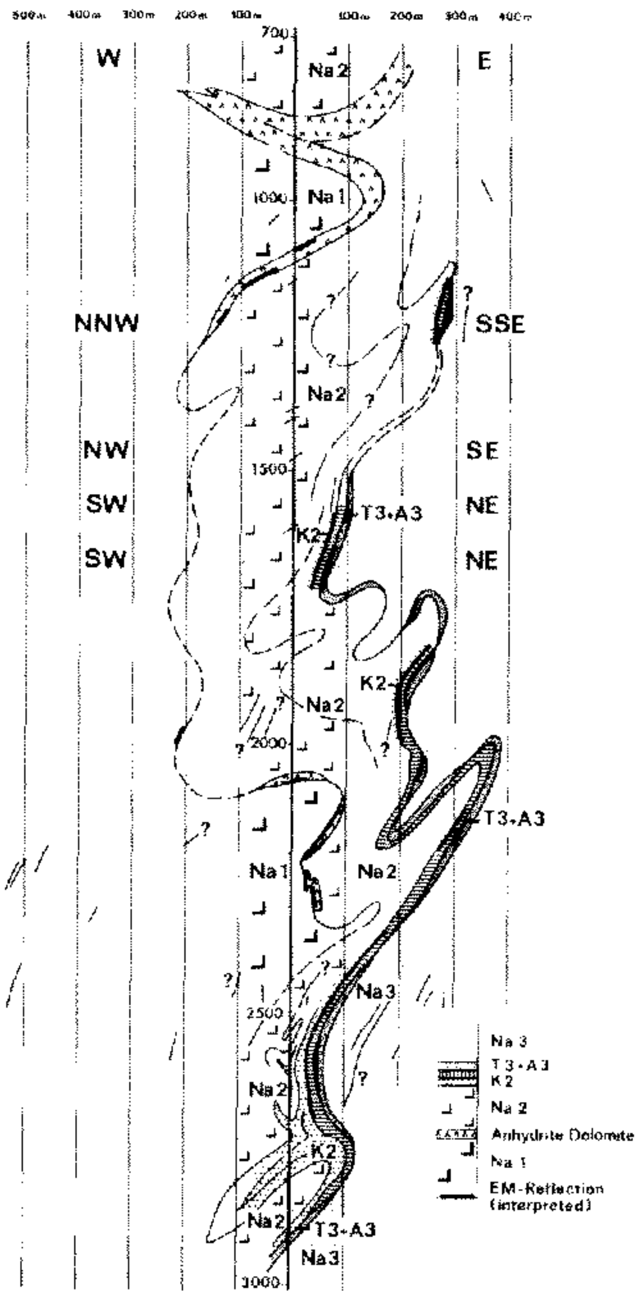


**Figure 14.** Geological model, constructed from results of the radar survey and data from drill cores.

carried out in boreholes in salt domes down to depths of 3200 m. At this depth the sonde must withstand a pressure of 450 bars. The depth at which the sonde can be used is limited by the maximum operating temperature of 85°C. The equipment has been employed under a wide range of operating conditions and has proved to be very reliable; it has good resolution and permits an accurate interpretation of underground structures to be made.

One great advantage of the system is that the recorded data can be subsequently processed in seismic data cen-

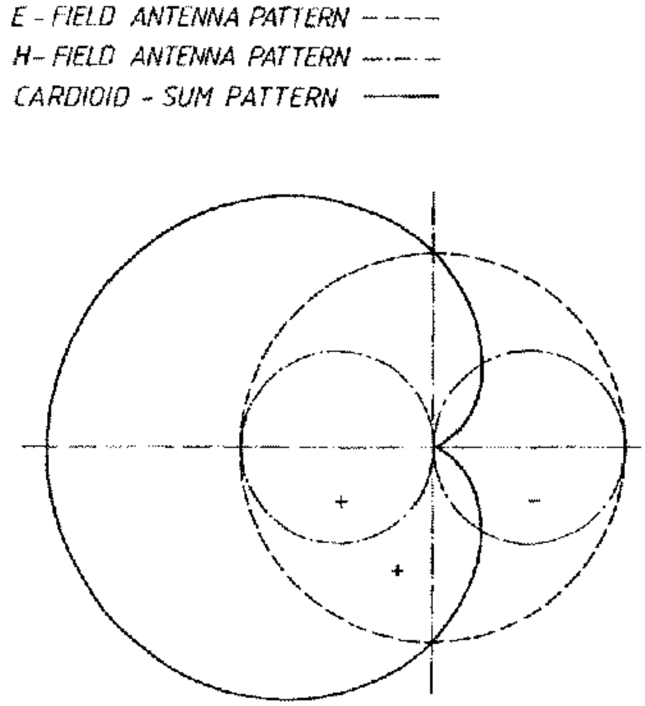


**Figure 15.** Radiation pattern of a dipole antenna (E-field) and a loop antenna (H-field).

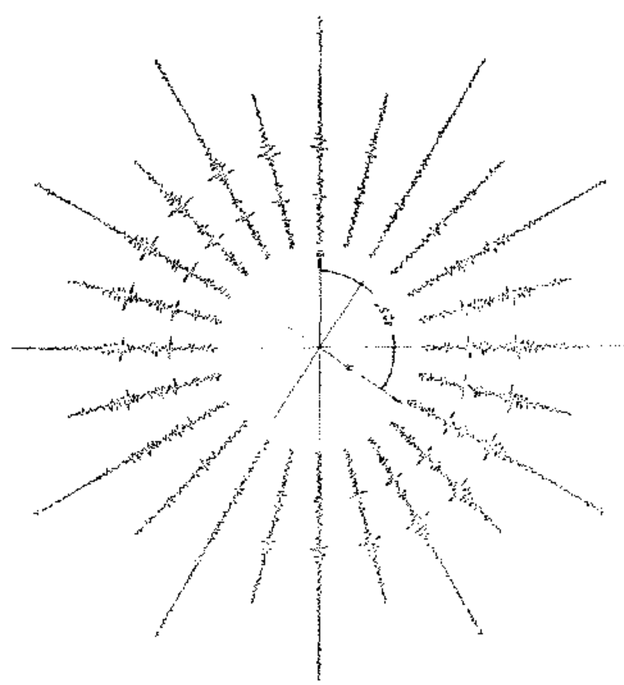

**Figure 16.** Direction finding using the cross-loop antenna. Polar representation of a time section.

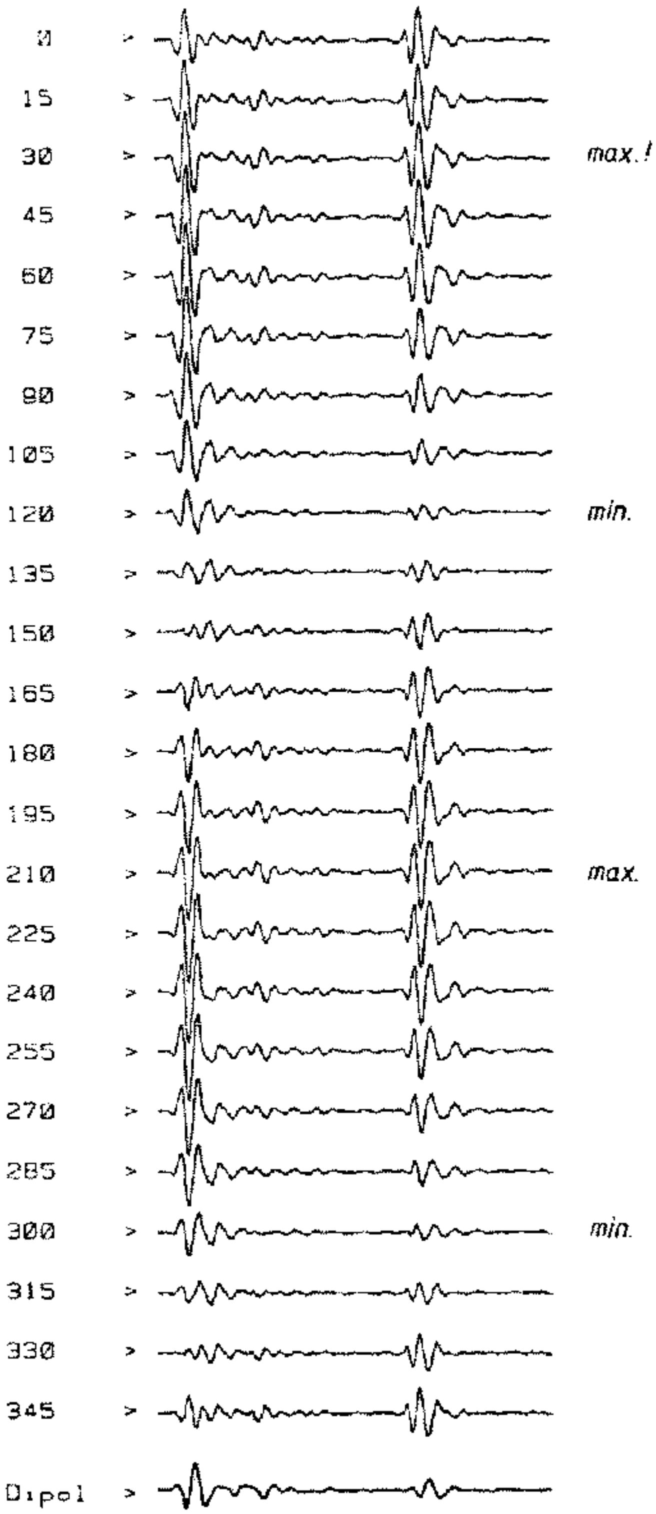


**Figure 17.** Directional record with vertically stacked traces.

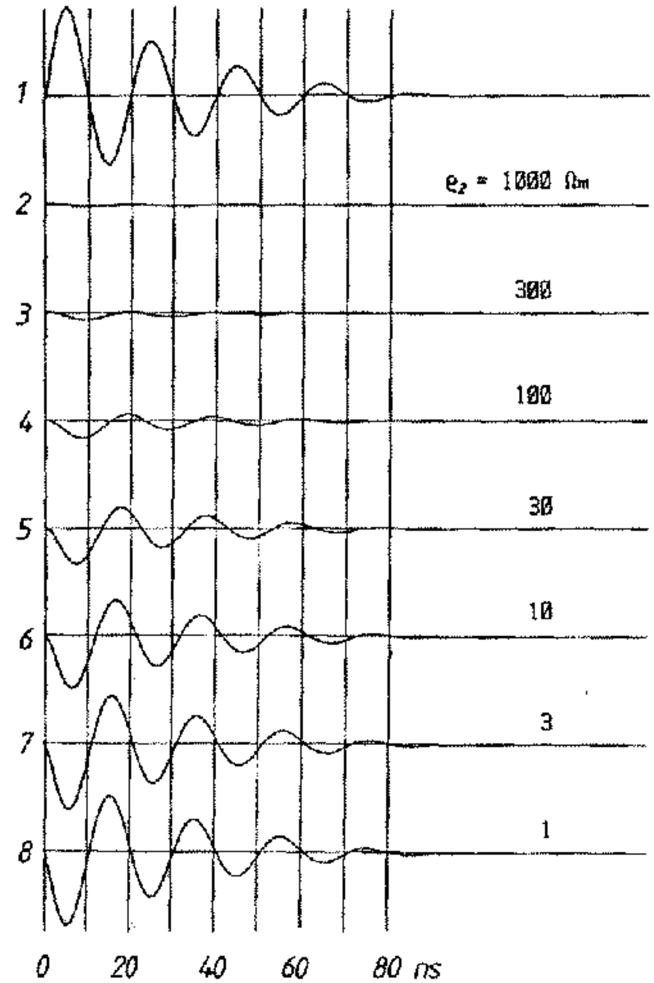


**Figure 18.** Distortion of a transmitted em pulse with f = 50 MHz (top) by reflection at a conducting half-space with different resistivities (1 to 1000 Ωm). Dielectric constant of both media $\epsilon_r = 5.8$. (model calculation).

ters using conventional techniques and equipment. The observed reflections enable a more detailed survey of the salt dome structure surrounding the well to be made. Areas with numerous discontinuities have been found, but there are also areas of homogeneous salt producing no perceptible reflections. This information is very important for any subsequent exploitation.

Acoustic methods can provide additional information and are in some ways complementary to electromagnetic methods. Some advantage can be expected if P-waves as well as S-waves are taken into account. In addition, the well may be filled with brine.

## ACKNOWLEDGEMENTS

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