Lithological interpretation of the spectral dielectric properties of limestone

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ABSTRACT
Limestone is a raw material used in the building and chemical industries. To guarantee good quality, it is important to investigate the limestone before mining to get information about the lithology and the mineral content. The chemical properties of rock cannot be measured directly by geophysical methods. Therefore extensive laboratory work was carried out to find relationships between the chemical, mineralogical, petrophysical and spectral dielectric properties of artificially mixed and natural limestone rock samples. A comprehensive interpretation is possible by using a complex dielectric parameter model. An interpretation scheme was developed based on the fact that the specific internal surface area and the water saturation have the most influence on the spectral properties of rock at constant water salinities. These results were applied to field data measured with a borehole radar system. In order to interpret the field data directly using the results of the laboratory investigations, a new spectral interpretation method was developed. The method is focused on in-hole and cross-hole measurements with one receiving and one transmitting antenna. It was shown that all impurities causing an increase in the specific internal surface area compared to that of pure limestone could be detected by spectral dielectric measurements.

INTRODUCTION
The dielectric properties have been used for many years to investigate karst phenomena in limestone in the range of radar frequencies. Kaspar and Percen (1975) used electromagnetic transmission between boreholes to find the borders of karsts in limestone. Dubois (1995) performed borehole radar reflection tests in a limestone quarry. Corin \textit{et al.} (1997) carried out radar tomographies to analyse the degree of karstification in the area of future bridge foundations. Fechner \textit{et al.} (1998) carried out the same task in a limestone deposit using radar cross-hole and radar reflection measurements. They showed that the attenuation coefficient of the transmitted electromagnetic wave is a very decisive parameter in the detection of karstified zones. Apart from the information about karst occurrence, an estimation of the quality of limestone can be derived from radar measurements.

The frequency dependence of the dielectric properties is strongly related to processes occurring at the interface between the internal surface area of the rock material and its saturating water (Knight and Endres 1990; Knight and Abad 1995; Kulenkampff 1994).

The link between the chemical composition of the rock material and the dielectric properties can only be found by investigations into the mineral content. The general method of interpretation leads from the chemical via the mineralogical, petrophysical and spectral dielectric properties of artificially mixed and natural limestone rock samples. A comprehensive interpretation is possible by using a complex dielectric parameter model. An interpretation scheme was developed based on the fact that the specific internal surface area and the water saturation have the most influence on the spectral properties of rock at constant water salinities. These results were applied to field data measured with a borehole radar system. In order to interpret the field data directly using the results of the laboratory investigations, a new spectral interpretation method was developed. The method is focused on in-hole and cross-hole measurements with one receiving and one transmitting antenna. It was shown that all impurities causing an increase in the specific internal surface area compared to that of pure limestone could be detected by spectral dielectric measurements.

LABORATORY MEASUREMENTS
Materials and methods
The complex dielectric spectra between 0.3 MHz and 1 GHz were measured with a laboratory dielectric measurement system (DEMS) from Hewlett Packard. The rock sample with a diameter of about 12 mm and a height of 2–3 mm was laid between
two capacitor plates. Analysis of the reflected and transmitted electromagnetic wave enabled the complex spectra of the dielectric constant to be calculated. A detailed description of the measurement method can be found in Pelster (1995). The samples were characterized by their porosity, specific surface area, water content and mineralogical composition.

The specific internal surface area $S_n$ is defined as the internal surface area $S$ of the mass $m$ of the rock sample and was measured by nitrogen adsorption and desorption with the BET one-point method using the FlowSorb 2300 II from Micromeritics. It is given by

$$ S_n = \frac{S}{m} \quad (1) $$

The porosity $\Phi$, the water saturation $S_w$ and the water content $\theta_w$ were calculated from the weight of the dry and wet rock sample (plug) with known geometry. They are given by

$$ \Phi = \frac{V_{por}}{V_{tot}} \quad (2) $$

$$ S_w = \frac{m_w - m_d}{\rho_w \cdot V_{por}} \quad (3) $$

$$ \theta_w = \frac{m_w - m_d}{\rho_w \cdot V_{tot}} \quad (4) $$

where $V_{por}$ denotes pore volume, $V_{tot}$ denotes total volume, $m_w$ denotes wet weight, $m_d$ denotes dry weight and $\rho_w$ denotes the water density (1 g/cm$^3$).

The chemical content of the samples was determined by X-ray fluorescence and the mineral content was determined by X-ray diffraction (e.g. Neff 1962). The measured parameters are shown in Table 1. The CaCO$_3$, Al$_2$O$_3$, MgCO$_3$, Fe$_2$O$_3$, S, SiO$_2$ contents were determined as a result of the chemical analysis. They can be correlated to minerals for the investigation described here. The investigated compacted limestone is very pure and dense with a CaCO$_3$ content of more than 97%. It has hardly any layering and contains a very small amount of impurities. The disturbances are caused by a higher content of clay (increased Al$_2$O$_3$ content), dolomite (increased MgCO$_3$ content), ankerite (increased Fe$_2$O$_3$ content), pyrite (increased Fe$_2$O$_3$ and S content), quartz (increased SiO$_2$ content) or calcspar (increased CaCO$_3$ content). The impurities content amounts to some parts per million. Different types of karsts and weathering can also be observed.

Artificial samples of ground powders were investigated to establish a methodology. The pure limestone powder was mixed with 0, 1, 3, 6, 10, 30, 60 and 100% of clay or quartz powder. The laboratory program included the determination of the grain-size distribution, the specific surface area and the complex dielectric spectrum at three levels of saturation. The dielectric measurements were performed using an especially developed sample carrier for loose material. Table 2 gives a summary of the parameters that were varied.

Maxwell’s equations describe the fundamental dependences in electromagnetics. They define an effective current density that

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**TABLE 1**
Overview of the measurement program

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Method</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complex dielectric spectra</td>
<td>Dielectric measurements</td>
<td>0.3 – 3000 MHz</td>
</tr>
<tr>
<td>Specific surface area</td>
<td>BET one-point method</td>
<td></td>
</tr>
<tr>
<td>Weights of dry and water-saturated sample</td>
<td>Porosity</td>
<td></td>
</tr>
<tr>
<td>Mineral content</td>
<td>X-ray fluorescence</td>
<td>Clay, dolomite, quartz, calc spar, pyrite, ankerite</td>
</tr>
<tr>
<td>X-ray diffraction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2**
Overview of systematic laboratory measurements

<table>
<thead>
<tr>
<th>Parameter varied</th>
<th>Natural rock sample (46)</th>
<th>Artificial powder sample (16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impurity</td>
<td>Clay, dolomite, quartz, calc spar, pyrite, ankerite, weathering, karstification</td>
<td>Clay-schist, quartz (sand)</td>
</tr>
<tr>
<td>Water saturation</td>
<td>Dry, two states of partially saturation and maximum saturation</td>
<td>Varied due to the content of clay and quartz powder</td>
</tr>
<tr>
<td>Internal specific surface area</td>
<td>Varied due to impurities</td>
<td>Varied due to the content of clay and quartz powder</td>
</tr>
</tbody>
</table>
relates the electrical conductance current $j$ and the electric displacement current $\frac{\partial D}{\partial t}$, where $t$ denotes the time, as

$$V \times H = j + \frac{\partial D}{\partial t}$$

(5)

The electric material properties are described by the electrical conductivity $\sigma$ (charge transport) and the dielectric constant $\varepsilon$ (charge separation). These material constants influence the electric field strength $E$. The resulting parameters are the electric displacement $D$ and the current density $j$, given by

$$j = \sigma E$$

and

$$D = \varepsilon_0 E$$

(6)

(7)

where $\varepsilon_0$ denotes the vacuum permittivity equal to $8.854 \times 10^{-12} \text{ F/m}$. Substituting (6) and (7) in (5), the following relationship is obtained:

$$j = \varepsilon_0 E + \varepsilon_0 \sigma \frac{\partial E}{\partial t}$$

(8)

Using the time-harmonic solution approach, $E = E_0 e^{i\omega t}$ where $\omega$ is the angular frequency and $i$ is the imaginary unit and having carried out the time derivation, the result is

$$j(\omega) = (\sigma(\omega) + i\omega\varepsilon(\omega)\varepsilon_0)E$$

(9)

Analogously to Ohm’s Law, a complex conductivity $\sigma^*$ can be formulated as

$$\sigma^*(\omega) = \sigma(\omega) + i\omega\varepsilon(\omega)\varepsilon_0$$

(10)

A model of a complex transfer function describes the frequency dependence of $\sigma(\omega)$ and $\varepsilon(\omega)$. Special parameter models that relate basic dielectric and limestone properties describe the rock composition. The conductivity model (Kulenkampff 1994) was chosen to approximate (10) because it needs the least number of model parameters compared to other models (e.g. Cole and Cole 1941; Taherian et al. 1990) to describe the measured complex dielectric spectra completely. It is given by

$$\sigma^*(\omega) = \sigma_0 (1 + (i\alpha\omega)^\alpha)^{-1} + i\omega\varepsilon_\infty$$

(11)

Comparing (11) with (10), we have

$$\sigma(\omega) = \sigma_0 (1 + (i\omega\tau)^\alpha)$$

(12)

and

$$\varepsilon(\omega) = \varepsilon_\infty$$

(13)

The transfer model containing the real part of the dielectric constant,

$$\varepsilon^* = \varepsilon_\infty + \frac{\sigma_0}{\varepsilon_\infty} (i\alpha\omega)^\alpha \cos \left( \frac{\pi\alpha}{2} \right)$$

(14)

and the real part of the electrical conductivity,

$$\sigma^* = \sigma_0 + \sigma_0 (i\alpha\omega)^\alpha \sin \left( \frac{\pi\alpha}{2} \right)$$

(15)

has four free parameters: the DC-conductivity $\sigma_0$, the exponent $\alpha$, the dielectric constant at infinity $\varepsilon_\infty$, and the relaxation time $\tau$. The parameter $\tau$ was set at a fixed time of $1 \mu s$ which corresponds to standardizing the frequency to $1 \text{ MHz}$. The remaining three free parameters are sufficient to describe the limestone properties. $\sigma_0$ and $\alpha$ are sufficient to model the frequency dependence of the real and imaginary parts of the permittivity completely; they are closely connected to the characteristics of the dielectric attenuation spectrum $\alpha(\omega)$. $\varepsilon_\infty$ determines the high-frequency limit of the real part of the dielectric permittivity, whereas $\sigma_0$ is the low-frequency limit of the real part of conductivity.

**Results**

The data obtained from the artificial samples was chosen to demonstrate the influence of the specific surface area and the pore-water content on the model parameters $\sigma_0$, $\alpha$ and $\varepsilon_\infty$ of the conductivity model (11). The water content of the sample is described by the parameters, porosity and saturation. All the investigated porosities of the artificially mixed samples vary only between 43% and 56%. Therefore the assumption can be made that the changes in the water content are mainly due to variations in the saturation. The estimated water saturations are calculated assuming a porosity of 50%.

In Fig. 2 the specific surface areas of the artificial samples are

![Figure 2](https://example.com/figure2.png)

**FIGURE 2**

Internal specific surface areas $S_m$ of artificial samples plotted against their limestone content.
plotted against their limestone content. The squares (limestone-schist probes) and circles (limestone-sand probes) mark the values measured on the samples with the BET one-point method. The solid and dashed lines show the theoretically expected values of, given by

$$S_{w,tot} = \sum \frac{m_i}{m_{tot}} S_i$$  \hspace{1cm} (16)$$

where $S_i$ is the specific surface area of the pure powder, $m_i$ is the mass of the component and $m_{tot}$ is the total mass. The measured specific surface area of a sample increases linearly with the clay content and decreases linearly with the quartz content of the sample.

The parameters $\sigma_0$, $\alpha$ and $\varepsilon_\infty$ of the conductivity model (11) were determined for each of the mixed samples by fitting the complex dielectric spectra measured at varying water saturations. Figure 3 shows the dependence of these parameters on the specific surface area, based on two states of partial saturation. $\sigma_0$ increases with the water content and with the specific surface area. $\varepsilon_\infty$ shows a slight increase with the water content but a decrease with the specific surface area. $\varepsilon_\infty$ increases with the water content and shows no dependence on the specific surface area.

Figure 4 shows a detailed view of the mineral content of the artificially mixed samples. The model parameter $\sigma_0$ increases linearly with increasing water content to an estimated water saturation of 35%. An approximation above a linear approximation fits the data best at higher water contents. The pure quartz samples show the smallest increase and the pure clay schist samples the greatest increase with increasing water content. $\alpha$ increases with increasing water content and the increase is highest for low water contents. Pure quartz samples show the highest values and pure clay schist samples the lowest values. $\varepsilon_\infty$ shows a slightly non-linear behaviour and increases with the water content. It exhibits no dependence on the clay or sand content.

Figure 5 shows an interpretation scheme to differentiate types of limestone using the dielectric parameters $\alpha$ and $\sigma_0$ of the conductivity model. It is possible to distinguish if the high $\sigma_0$-value of a sample is caused by high water saturation or by a large specific surface area. Partially saturated samples have small or intermediate $\alpha$-values; a completely saturated rock has higher values of $\alpha$. A sample moves from a lower-left to an upper-right position on the plot when its pore-water content rises, while samples with a higher value of the specific surface area lie more to the left. Two arrows mark these basic influences. Different classes of limestone are defined by the areas I, II, III and IV. Area I contains all the samples with a small specific surface area, such as pure limestone, limestone with quartz or limestone with only a very small amount of impurities. Area II contains the calc spar samples. Area III contains limestone samples with a high or very high MgCO$_3$ content and a dolomite content, as they have a higher specific surface area than pure limestone. Area IV contains all samples that have a significantly higher specific surface area.
Matrix for determining the composition of limestone using the model parameters $\sigma$ and $\alpha$. It shows the possible differentiation of pure limestone or limestone with quartz (I) from calc spar (II), from limestone with dolomite (III) and from limestone with clay or limestone with clay and dolomite (IV). The data base consists of the whole data set of hard rock samples, completely and partially saturated.

FIELD MEASUREMENTS

Technical equipment and measurement procedure

In the development of a methodology, in-hole transmission or transit-time measurements (Fig. 6a) have the advantage that the core material of the rock under investigation is well known. The transmitting and the receiving antennae are moved simultaneously along the borehole with a fixed offset. The emitted signal travels directly from the transmitter to the receiver in the immediate vicinity of the borehole as indicated by the arrows (Fig. 6).

The originally emitted signal must be either known or detected for interpretation. Two measurements with different offsets (long-path and short-path) between the antennae are carried out. Both have the same emitted signal and are influenced identically on the common path. The difference between these two recorded signals is caused by the dielectric properties of the area investigated (marked bold).

Cross-hole borehole radar measurements (Figs 6b and c) are commonly used for the exploration of limestone deposits. The transmitting and receiving antennae are located in two different boreholes during the measurements. This is advantageous when investigating larger rock volumes. The distance between the boreholes that receive the signal is dependent on the dielectric properties of the rock. Borehole distances of 100 m or more can be investigated in very pure limestone (low $\sigma_0$). Two types of cross-hole measurement are mainly used in economic investigation programs: horizontal and tomographic transmission. Since the emitted signal cannot be measured directly, it has to be calculated using reference values. These reference values or signals are obtained from transmission measurements in a formation with well-known dielectric properties, such as very pure limestone. The attenuation should be very low for these reference measurements, otherwise high-frequency information will be lost.

For horizontal transmission (Fig. 6b), the transmitting and receiving antennae are moved along the two boreholes simultaneously. They are always situated at the same depth level. The results make it possible to separate depth intervals with pure limestone from depth intervals with inhomogeneities or anomalies. They produce significant information about the vertical extent of a zone containing disturbed limestone.

To investigate the horizontal extent of the anomalies, further investigations, such as expensive borehole radar tomographic transmissions (Fig. 6c), are necessary. The antennae are moved to various positions to obtain both horizontal and inclined raypath patterns.

A four-scan technique (Fig. 6d) is performed only in the depth intervals identified as being anomalous in order to avoid the expense of a full tomography survey (Fechner 2000). Four additional scans are measured in the relevant depth interval. One antenna is held on one edge of the depth interval of interest while the other antenna is moved along the depth interval in the other borehole. This is performed at the four edges of the area under investigation.
The field measurements were carried out with the RAMAC/Borehole equipment using 60 MHz (in-hole) and 22 MHz (cross-hole) dipole antennae. A detailed description of the RAMAC system can be found in Olsson et al. (1992).

**Interpretation methods**

The registered signal \( S_r \) can be described as a function of the emitted signal \( S_e \), a function \( G \) accounting for geometric losses, a function \( R \) describing reflection losses and the dielectric transfer function \( E \). It is given by

\[
S_r = f(S_e) G R E .
\]  

(17)

Reflection losses can be neglected for the measurements presented here since no material changes with significant changes in the dielectric constant occur in the limestone investigated.

\( G \) accounts for the decrease in energy density with distance from the emitting antenna. It can be determined by comparison with measurements in homogeneous media with known dielectric properties. The wavelet is measured at two different distances from the emitting antenna. Assuming that the emitted signal \( S_e \) is constant, the difference in the signals refers to \( G \) in the case of negligible \( R \).

While the emitted signal \( S_e \) can be measured directly for in-hole measurements as described above, cross-hole measurements must be treated differently. The same spectral forwarding technique used for the determination of the ground function is applied (Fig. 7). In this case, it is not the ground function that is changed but the emitted signal. The ground function is known from measurements in media with known dielectric properties.

From the theory of electromagnetic wave radiation (Ward and Hohmann 1987, \( E \) is given by

\[
E = e^{-\alpha \omega} e^{-\frac{\omega}{c_0}} \tag{18}
\]

with the velocity \( v(\omega) \) and the attenuation \( a(\omega) \) of electromagnetic waves given by

\[
v(\omega) = \frac{\mu_0 \varepsilon'(\omega) \varepsilon_0}{2} \sqrt{1 + \left( \frac{\sigma'(\omega)}{\varepsilon'(\omega) \varepsilon_0} \right)^2 + 1},
\]  

(19)

\[
a(\omega) = \omega \frac{\mu_0 \varepsilon'(\omega) \varepsilon_0}{2} \sqrt{1 + \left( \frac{\sigma'(\omega)}{\varepsilon'(\omega) \varepsilon_0} \right)^2 - 1},
\]  

(20)

where \( \omega \) denotes angular frequency, \( \mu \) denotes magnetic permeability, \( \varepsilon' \) denotes the real part of the dielectric constant, \( \sigma' \) denotes the real part of the electric conductivity, \( \mu_0 \) denotes the magnetic field constant \((4\pi*10^7 \text{ Vs/Am})\) and \( \varepsilon_0 \) denotes the vacuum permittivity \((8.854*10^{-12} \text{ F/m})\).

The run time or the peak-to-peak amplitude in the time domain is usually used for interpretation of borehole data. The whole distortion of a radar wavelet gives additional spectral dielectric information. A spectral forward-modelling technique is used for the interpretation of measured radar wavelets in this investigation (Fechner 2000).

Using a standard FFT, the emitted signal is transformed into the frequency domain where a synthetic ground-response function is applied to it (Fig. 7). The resulting signal is re-transformed by an inverse FFT (IFFT) and compared to the recorded signal in the time domain. The synthetic ground function is manipulated and the synthetic wavelet is fitted to the measured wavelet by changing the model parameters \( \sigma_o, \alpha \) and \( \varepsilon_{ss} \). The decisive parameters \( \sigma_o \) and \( \alpha \) of the ground can be found when the best fit between the synthetic and the measured wavelet is achieved. The synthetic ground function is calculated with the help of frequency-dependent spectra, which are calculated using the conductivity model in equation (13) with \( \varepsilon'(14) \) and \( \sigma'(15) \). The parameters used are the velocity \( v(\omega) \) and the attenuation \( a(\omega) \) of the electromagnetic wave underground.

**Results**

The method was applied to an in-hole transmission data set measured in pure limestone and in limestone with different quantities of clay, with karstified and weathered zones (Fig. 8). The investigated rockmass investigated had a reduced water content due to drainage. The \( \sigma_o \)-values are extracted from the field data and compared with the drill-core and its chemical parame-
clay, which was lost due to mud circulation or washing before the chemical analysis. The $\sigma_0$-values extracted from the in-hole measurements detect depth intervals with higher clay content, karsts or weathering. The range of $\sigma_0$-values for pure limestone, limestone with higher clay content and karsts coincide with values obtained from laboratory investigations (Fig. 5). This allows a direct interpretation of the field data with the help of the laboratory results.

Figure 9 shows the $\sigma_0$-values from a horizontal transmission survey. The depth scale is standardized to sea-level elevation to take the topography into account. The geological profiles of the two participating boreholes are shown with a depth scale referring to below top ground surface. The rockmass between the boreholes consisted of drained pure limestone with two layers of disturbed limestone at a depth of about 30–35 m and 60 m below top ground surface. It contains clayey, very clayey and weathered limestone. Clay-filled karst cavities of roughly 7 m thickness were detected only in borehole 1 between 136m and 143 m below top ground surface. The measurements were carried out with a step interval of 1 m (solid lines) and 4 m (cross-bars). Both data sets match very well.

The laboratory result indicated that $\sigma_0$-values smaller than 0.07 S/m refer to pure limestone between the boreholes. In the depth intervals with higher $\sigma_0$-values the limestone is disturbed.
The degree and the horizontal extent of the disturbances in these depth intervals cannot be detected by horizontal transmission.

Four scans were measured on the edges of the depth interval for further investigation of the horizontal structure of disturbed zones at depth intervals, A and B. First the $\sigma_0$-values for every trace of the four scans were obtained. The radiation pattern of the antenna (e.g. angles, raypaths) has to be considered for tomographic measurements. The influence of the angle between the radiation and the dipole axis is considered by measuring a reference wavelet radiating at the same angle as the measured data. In this way the radiation pattern of the antennae is already taken into consideration within the reference wavelets used as input for the modelling. The reference scan of traces is measured in pure limestone.

The four-scan data set in Fig. 10 consists of scans measured within the two depth intervals with higher $\sigma_0$-values. The ray patterns are also displayed. Several ground models were calculated for each depth interval to interpret the $\sigma_0$-curves. Transparent areas mark pure limestone; bodies with anomalous $\sigma_0$-values are shown in grey. The dashed curves refer to measured data and the solid lines to the data calculated with the ground models. They show good conformity in interval B. The deviation in interval A might be caused by the complicated geological situation, which cannot be taken into account completely. Table 3 shows the $\sigma_0$-values for the different sections of the final ground models.

The final ground model for depth interval A shows that the whole investigated zone between the two boreholes consists of slightly disturbed limestone. The detected $\sigma_0$-value of that body suggests that these impurities are probably caused by higher clay content or by slight weathering of the limestone. A very high dolomite or calc spar content can be excluded since these impurities do not exist in this limestone quarry to this extent.

The final ground model for depth interval B shows karst and rock with cracks and areas with higher clay contents. The extent of three bodies with higher $\sigma_0$-values can be defined from sections with pure limestone within the investigated area. The middle body shows the highest $\sigma_0$-value and, in its altitude and vertical extent, corresponds very well with the loam-filled karst cavities found in the drill-core. The upper body corresponds very well with the hanging rock section in the drill-core. The $\sigma_0$-values of these two bodies match the laboratory results of comparable materials very well. The lower body with a $\sigma_0$-value of 0.05 mS/m cannot be distinguished in the drill-core.

**CONCLUSIONS**

Pore water interacting with the internal specific surface area is found to be the main influence on the dispersive behaviour of the dielectric properties of limestone. This can be estimated by spectral investigation of the high-frequency dielectric properties of the rock material. The spectral dielectric properties in the MHz-range with the so-called conductivity model have three free parameters $\sigma_0$, $\alpha$ and $\varepsilon_\infty$. Whereas $\varepsilon_\infty$ is significantly influenced

<table>
<thead>
<tr>
<th>Depth interval</th>
<th>Classification</th>
<th>Limestone quality</th>
<th>$\sigma_0$-values [mS/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Disturbed body, impurities</td>
<td>Low</td>
<td>0.09</td>
</tr>
<tr>
<td>B1</td>
<td>Pure limestone</td>
<td>High</td>
<td>0.003</td>
</tr>
<tr>
<td>B2</td>
<td>Upper disturbed body, impurities</td>
<td>Low</td>
<td>0.13</td>
</tr>
<tr>
<td>B3</td>
<td>Middle disturbed body, impurities</td>
<td>Very low</td>
<td>0.3</td>
</tr>
<tr>
<td>B4</td>
<td>Lower disturbed body, impurities</td>
<td>Low</td>
<td>0.05</td>
</tr>
</tbody>
</table>
only by the pore-water content, $\sigma_0$ and $\alpha$ are dependent on both the pore-water content and the internal specific surface area. With the help of these two parameters a matrix can be formed, which makes it possible to differentiate between the influence of the pore-water content and the influence of the specific surface area. For practical use in limestone exploration, pure limestone can be distinguished from rock types with a higher specific surface area caused by clay or a higher dolomite content, karstified zones and weathering.

The laboratory investigation program showed that the same specific dependence of the complex dielectric properties upon pore filling and matrix characteristics is detected for artificial loose material samples and hard rock samples.

A method for the derivation of the complex and spectral dielectric properties of rock material from transmission borehole radar data has been developed and applied to data measured in a limestone quarry. The determining parameter $\sigma_0$ can be detected in laboratory data as well as in in-hole or cross-hole data. Impurities such as weathering, karsts, higher clay content or a very high dolomite content cause a higher specific surface area and can be detected with the help of the field data. Calc spar can also be detected. The clay content indicated by high Al$_2$O$_3$ and MgCO$_3$ contents in the chemical analysis is found to have the most significant influence within the investigated rock.

A combination of horizontal transmission and a scanning method offers a comparatively fast and cheap alternative to an expensive full tomography survey in the case of cross-hole investigations. With these measurements and the interpretation technique based on laboratory investigations, it is possible to obtain an adequate picture of the structure and the rock composition for limestone deposits.

This technique can be used to investigate other lithologies with similar lithological and petrophysical properties. Nevertheless, it must first be checked that neglecting reflection losses and the assumption of straight rays is permissible.

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