Improved field techniques and integrated case histories

Geoelectric exploration and monitoring in rock salt for the safety assessment of underground waste disposal sites

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Abstract

The safety of an underground waste disposal site depends to a large extent on the presence and migration of the water in the rock. Geoelectrics is the most suitable method particularly in underground mining conditions to explore and monitor the moist zones in many different rocks. Recent developments in hardware, inversion schemes and petrophysical interpretation of the resistivity enable reliable and useful measurements to be conducted with direct current geoelectrics for exploration and monitoring also in salt rock environment with rather high resistivities and resistivity changes. Examples are presented for resistivity exploration and monitoring in rock salt. The measurements are carried out in the research mine Asse in North Germany which is used for investigations into handling, storage, disposal and geological interaction of nuclear waste. A fully automated geoelectric system suitable for salt rock environment and long-term monitoring was used with a large number of electrodes installed permanently. Logistical conditions allow measurements only in profiles so that two-dimensional inversion schemes had to be used and their suitability and limitations are shown. At one site where the moisture is visible in a limited area at the wall the extension of the moist zone in the rock is explored and determined. This helps to estimate the possible changes that might occur in future and which measures have to be taken. At another site in a large area in the rock salt the resistivity has been monitored over several months. The resistivity distribution in the area shows local variations indicating changes in the state of rock salt which is otherwise usually homogeneous. The changes are related to disturbed rock zone at near surface around the voids due to the stress induced by the mining, to the neighbouring cavities and also disturbed zones in the deeper rock due to the stress redistribution in the last 30 years since the excavations took place. Also significant changes of resistivity with time are detected for which an estimate of water content can be given. These are attributed to fluctuations of the water content in the disturbed rock areas. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

An increasing importance is attached to rock salt as it is generally considered to be very suitable for the storage and disposal of high and medium level nuclear waste as well as of toxic chemical and industrial waste (Matula, 1981; Herrmann and Knipping, 1993). Presently many rock salt mines in Germany and around the world are already used for waste storage purposes and also for storage of oil, gas and pressurised air.
Geoscientific investigations of salt rocks, which are basically rock salt, anhydrite, carnallite and salt clay, are expected to yield information about the tightness and stability of the rocks and, hence, on the suitability of the rock to host hazardous material for a very long time. Apart from large scale geophysical surveying for geological site characterisation, there is an increased need for small scale, but high resolution investigations to assess the properties and the state of the rock in the surroundings of drifts, shafts and caverns in the mine. The disturbed rock zone around any void in the mine is a potential migration path for dangerous material to interact with the biosphere even after the void is sealed.

Many geophysical methods are suitable for the exploration of the structures in salt rocks. Main features like the boundaries of rock salt to anhydrite or salt clay may be found using seismics. Also disturbed rock zones can be characterised by their seismic velocities and attenuation. Ground Penetrating Radar (GPR) has been found very useful in the past to explore the geological structures. A high degree of resolution can be achieved using tomographic modus. It is even possible to distinguish between reflections from geological boundaries or from voids by using reflection characteristics. However, the main draw back with GPR is that in moist areas the electromagnetic waves are attenuated strongly, i.e., the depth of the investigation is rather limited. Further limitation is due to strong reflections from geological features such as even very thin moist clay layers, and transmission beyond these layers is not possible. Because the moist areas are not penetrated by GPR it is also not possible to estimate any water content with GPR in salt rocks. In order to overcome some of these problems in exploring rock salt geoelectrics is utilised and adopted.

Geoelectrics has not been used very often in salt rocks as these are generally highly resistive, so large layouts are only possible with an adequate power source. Usually there are problems concerning the electrode coupling. But the most important limitation is that a large number of measurements is needed for a reasonable degree of resolution and elaborate means are required for processing and interpretation of the data. These problems are gradually being overcome in the past ten years or so. Automatic multielectrode systems and also inversion algorithms for mass data at a high degree of resolution and accuracy are now available (Barker, 1992; Loke, 1995). As a result, geoelectrics is being increasingly used and it has turned out to be a valuable tool to assess various aspects of the salt rocks essential for the safety of a disposal site; for example, to explore and monitor the presence of natural and man injected brine to derive quantitative estimates of parameters like porosity and water (i.e., brine) content.

Previous experiments for using direct current geoelectrics in rock salt have helped to recognise and to overcome the difficulties particularly concerning the hardware used (Kessels et al., 1985; Skokan et al., 1989). A special high power automated multielectrode geoelectric system was successfully put to operation at the salt mine Asse in North Germany (Yaramanci and Flach, 1989a,b). The system is used by a large scale multimethodical investigation to assess the stability and the tightness of an underground sealing in a drift (Flach and Yaramanci, 1989; Walter and Yaramanci, 1993; Walter et al., 1993). Using tomographic measurements around a sealing with a threedimensional (3D)-electrode array and 3D-resistivity modelling the moisture distribution in the disturbed rock zone around a sealing has been mapped. This and a large number of measurements in the drifts using profiles yield very useful information of the geometry and state of different salt rocks relevant to the safety assessment of an underground site (Yaramanci, 1994a; Kurz, 1997; Zimmer and Yaramanci, 1997). Large data sets collected for in situ resistivities of salt rock and corresponding laboratory measurements have made it possible to derive water contents from the resistivities (Kessels et al., 1985; Kern et al., 1992; Kulenkampff and Yaramanci, 1993;
In this paper, two case histories are presented which are representative of the exploration of moist zones and for monitoring large areas in rock salt. Also methodological and petrophysical aspects of geoelectrical exploration in rock salt are presented and the accuracy and resolution which can be achieved shown.

2. Equipment and processing

In order to be able to conduct repeated measurements in large numbers, a geoelectrical measurement system was designed (Yaramanci and Flach, 1989a). It consists of a commercially available measurement instrument for geoelectrics, SYSICAL R2 of IRIS Instruments (1993), which is controlled fully by a computer via the serial link. This instrument was specially modified for use in highly resistive salt rocks. The injection current range of the instrument is reduced from 1 A down to 200 mA as possible currents in salt rocks are usually around a few tens of milliamperes. The accuracy of the current measurement is also modified down to 10 μA. The range of the measured voltage is increased from 4 V up to 20 V as these are quite large in the resistive rock salt. The accuracy of the measured voltages is 50 μV which is still suitable for even very conductive moist areas. The instrument has an input impedance of 5 MΩ which is suitable even for measurements in high resistive media. Measurements are conducted using many cycles of direct current with alternating sign and stacking. Effects from natural self potential and electrode polarisation are taken care for as this are measured and corrected for.

The voltage supply for injection current is from the mains via the usual AC/DC converter in steps of 50, 100, 200, 400 and 800 V. As the converter can be set up manually for a certain value, measurements are organised in such a way that they are grouped to suitable voltage ranges. Meanwhile, experiments for automating the input voltage also have been successful using a computer controlled voltage supply so that by an over- or under-voltage the measurement will be repeated automatically with the next appropriate voltage.

A multielectrode switch box was built with special relays which also is directly controlled by the software via serial link or, if necessary, manually. It can accommodate up to 480 electrodes and is free programmable; it is also able to check electrode configurations for their correctness so short circuits and zero connections are avoided.

A special software is designed to conduct the measurements in arbitrary configurations and time periods. The basic parts of the software are: (1) the information about the measurements containing the numbers of the electrodes to be used, the duration of the measurement and number of cycles, (2) the information about the address of the electrodes at the multielectrode switch box and (3) coordinates of the electrodes. After the measurements, apart from the full information about the current and voltages, the apparent resistivity is also immediately available so that almost an online processing including the inversion is possible. The whole system can be used in remote control via modem or internet so large numbers of measurements with any kind of configurations can be started at any time and all-around continuous monitoring is possible.

The electrodes are made of common steel with a length of 20 cm and a diameter of 2 cm. They are centred and cemented in holes of 3 cm diameter. Because the rock is usually very dry and the contact resistances are very high the electrodes had to be moistened occasionally. The electrodes are installed along profiles equidistantly and are usually 2 m apart.

For the measurements the usual four point configuration is used with two electrodes for the injection of the current and another two electrodes to measure the field. Several configurations were tested including pole–pole or dipole–dipole arrays (Kurz, 1997). As the cur-
rents are very small, reasonable measurements are only possible using linear arrays with the potential electrodes between the current electrodes. The most convenient array is that of Wenner layout which is also used in most of the work.

A serious problem encountered in underground measurements is that the electrodes are on profiles on the walls so that for small layouts half-space conditions can be assumed safely but after expanding to larger layouts full space conditions are valid. Usually, when profiles are in drifts, layouts larger than 5 times the diameter of the drift are to be considered in full space. In this work, the geometric factor is always calculated for half space also because of the requirements of the inversion scheme used. Consequently the apparent resistivities, as well as the inverted resistivities, for large layouts, are to be multiplied by a factor of 2.

The inversion of the apparent resistivities are calculated using the program RES2DINV (Barker, 1992; Loke, 1995) which is based on a least square iterative algorithm. It is comparable to other programs currently available and is therefore, representative. The merits of the inversion will be discussed in the last section along with other possible sources of errors.

### 3. Examples of exploration and monitoring

In this section, two field examples from the salt mine Asse in North Germany are given.

#### 3.1. Delineation of a highly moist zone

Although rock salt is supposed to be very dry, occasionally water (i.e., brine) might migrate and seep in to the voids. This is not unusual and experienced often in salt mining. In fact, many mines are lost that way in northern Germany. Generally the mining activity itself induces stress release around the openings and this favours the development of a disturbed rock zone in which brine may migrate easily. At one location (called A) prominent moisture was observed on the walls and ceiling of the cavern K3 (Fig. 1). In order to delineate the extension of the moist zone in the rock it was decided to conduct geoelectrical measurements. This was the only possible means of exploration, as, due to safety reasons, boreholes in highly moist zones are generally not allowed by mining laws.

The area is entirely in rock salt bounded to the South by almost vertical layers of anhydrite and sandstone which are not reached by the geoelectrical measurements. A profile consisting of 50 electrodes 2.5 m apart was installed in the caverns K2 and K3 over a length of approximately 140 m (Fig. 1). The caverns are 60 m in length and 40 m in width and 12–15 m in height. The electrodes along the profile are installed in K2 on the wall at a height of 1.5 m from the floor and in a borehole in the pillar between K2 and K3. As the cavern K3 was filled partly with backfill the profile had to be installed towards the east with increasing height.

![Map of the location A with 50 electrodes 2.5 m apart on the profile from 251 to 300. The electrodes are installed on the south face of the chambers, in a borehole between the chambers K2 and K3 and in the ceiling in chamber K3. The hatched area shows parties of rock salt creeped into the chamber. The location is entirely in the rock salt (Na) of different ages with minor differences in mineral content. At the south there is almost vertical dipping anhydrite (So1A) and sandstone (So).](image)
at the wall and at −30 m even it had to be continued at the ceiling.

The measurements are conducted with the conventional Wenner layout for every possible ‘a’ and shifted always for ‘a’ so the maximum coverage was possible. Starting with the smallest layout of \( a = 2.5 \) m this was systematically increased to be 5 m, 7.5 m, 10 m, etc., up to 40 m. The horizontal displacement of every layout for fixed ‘a’ has been \( \Delta x = 2.5 \) m so when layouts become larger also the overlapping area of neighbouring measurements increased.

The results of the two-dimensional (2D)-inversion are shown in Fig. 2. The depths here correspond to the horizontal distance from the wall of the cavern to the rock. There are basically two low resistivity features observed which are associated with the moist zones. The areas with \( 10^5 - 10^6 \) \( \Omega \text{m} \) correspond to the undisturbed rock salt which are found almost everywhere in the mine and are considered to be unmoistened.

From the east end of the profile up to the −60 m position there is a zone with extremely low resistivity. The center of this zone is along the profile between −15 m to −35 m and about 6 m depth. The resistivity in this central zone is as low as 10 \( \Omega \text{m} \) and corresponds to a very large moisture content. The boundary of the moist zone to the west at −60 m is unusually sharp. The depth extension of the zone is around 10 m to 15 m at the east part but at the location around −60 m to −50 m even deeper. This area is therefore considered to be the migrating path of the brine from the levels above. The extension of the moist zone found by the geoelectric measurements shows that it is much larger in the rock than it might had been assumed from the few moist zones visible on the wall and ceiling.

Another low resistivity anomaly is found at the profile location from −80 m to −90 m having a center at a depth of about 4 m to 6 m. The resistivity is slightly lower than \( 10^4 \) \( \Omega \text{m} \),

![Resistivity section at location A (Fig. 1) with 0 m corresponding to electrode 251.](image-url)
indicating only a small increase in water content. It is a rather confined anomaly which explains why no moisture is observed on the wall at this location. This is an unexpected moist location which might be a recently opened path for brine migration and in process of progressing into the cavern.

It should be noted that the investigated area is no longer accessible as the cavern K3 is closed down by strongly creeping moist rock salt from the ceiling and South wall. The cavern K2 was backfilled recently in order to increase the stability and avoid large breakings (i.e., cracks). The electrode profile is still operating and is used for further monitoring.

3.2. Monitoring of resistivity change at a large area

At a location (called B) in the rock salt (Fig. 3) which is very close to the neighbouring sandstone it was decided to investigate the state of rock, i.e., the moisture content and stability over a long range of time. The area is typical of those encountered in salt mining where openings are very close to the non salt rock which behaves differently mechanically, i.e., as salt creeps into the openings the rather stiff rocks behind may crack and create potential migration paths for water. This might cause serious problems especially when the water paths are in some way connected to the aquifers. The measurements are also the very first large-scale geoelectric monitoring in the rock salt so that methodical aspects for the suitability of the method had to be considered.

The profile is located at the south wall of the openings along the whole length available at this location (Fig. 3). It consists of 249 electrodes with a separation of 2 m to cover a range of approximately 500 m. The openings along the profile are different so local conditions at the profile are to be taken into account in the interpretation. At this level only the caverns K4 and K8 are of standard size with 60 m × 40 m groundfloor and 15 m height. Along the whole profile the electrodes are installed on the wall at a height of 1.5 m except in the cavern K3 at the west end where the height is at 10 m because the cavern is backfilled up to that height. The drift between K3 and K4 was also backfilled so that the electrodes in this area are installed in a borehole connecting the caverns and has a slight gradient to connect the different heights in K3 and K4. Between K4 and K7 the profile is in the drift of an approximately 4 m × 3 m cross-section. K7 is a cavern with a height of only 4 m but extends into the lower level for 18 m. K9

![Fig. 3. Map of location B with 249 electrodes 2 m apart on a profile. The electrodes are installed in the chambers and drifts as well as in a borehole connecting K3 and K4. The location is entirely in rock salt (Na). At the south there is almost vertical dipping anhydrite (So1A) and sandstone (So).](image)
is similar to the standard size except that the width is 20 m instead of 40 m as in K8.

The south wall of the openings where the profile was installed runs parallel to the strike of the geology. To the north there is solely rock salt to a large extent. To the south there is anhydrite (So1A) approximately 20 m thick with an almost vertical dip and parallel to the wall in a distance varying from 10 m to 30 m. Further south there is sandstone (So) with rather larger thickness. There are further caverns just below this level in a similar geometry. Above this level, there is only pure rock salt.

An example of measured apparent resistivity section is given in Fig. 4. The results of the inverted measurements are shown in Fig. 5. These are for 13 time points over 7.5 months selected from a lot more measurements to demonstrate the main features in the changes. The successive measurements are not equidistant in time, the time lapse is between 3 to 20 days except for the last two measurements for which the time difference was 2.5 months.

The measurements consist of Wenner sections for the ranges of ‘a’ starting with 2 m with a maximum of 48 m. For fixed ‘a’ the measurement location is displaced for ‘a’ along the profile so that the coverage of neighbouring points is about 1/3. In every section there are 878 measurement points in all which had also to be kept to this size to fit the needs of the inversion schemes.

The main features of the resistivity distribution do remain slightly similar in time and can be easily followed through all the sections in Fig. 5. In general, the resistivity is within a range $10^5 - 10^6 \, \Omega\text{m}$. As this range is considered to correspond to the normal state of the rock salt, the deviations from these values are to be investigated closely. There is no resistivity below $5 \times 10^4 \, \Omega\text{m}$ so that extreme moist zones like in location A in the previous example are not present. At the higher end, the largest resistivities are slightly above $10^7 \, \Omega\text{m}$.

The resistivity change in the near surface area is about a factor of 10 with some prominent higher resistivity zones around $-435 \, m$, $-390 \, m$, $-340 \, m$, $-310 \, m$. These are very shallow but rather confined anomalies and are attributed to the near surface disturbed rock zone. It is well known that the creeping of the salt into the openings is usually very high in the immediate vicinity of the surface because of the additional moisture adsorbed from the air circulating in the mine favouring the creep. The zone behind has a moderate rate of creep so the rock may crack in these areas. The size and extent of these zones depend on the local conditions, on actual creep rates, surrounding geometry of openings and, therefore, the actual stress distribution. To the east of the profile, the variation of the resistivity in the near surface area is moderate with no significant extreme values so that it can be concluded that the rock here is not disturbed.

There are two further prominent high resistivity areas which are too deep (6 to 8 m) to be considered near surface. The first area is located

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Fig. 4. Example of the measured apparent resistivity section along the profile at the location B (Fig. 3) with 0 m corresponding to electrode 1.
at −220 m. It is present in all measurements over the whole time and changes slightly, the size extending into deeper regions. The other area is about from −150 m to 0 m with a rather large change in size and resistivity in time. These areas, obviously also disturbed rock zones, are not directly the result of the differential creeping at the near surface area but due to some other mechanism occurring in the deeper range. The reason is not very clear yet. Modelling of stress and creep behaviour with the real geometries of different geological layers here may give some indication on the mechanical behaviour.

Fig. 5. Inverted resistivity sections at location B for different times. Note the section is exaggerated for a factor of approximately 4 in the depth axis.
Although the resistivity distribution seems to remain stationary with respect to time, significant changes can be revealed by examining the differences of measurements in time. For this the ratio relating the resistivity to that of the previous measurement is very useful and shown in Fig. 6. Basically the results for resistivity changes are more accurate than the resistivity distribution itself because systematic errors are eliminated to a great extent by taking the ratio. In general, there is a change of about a factor of 2 to 3 which is not systematic locally and
temporally. The changes are larger for measurements taken over large time intervals.

One very prominent change occurs in the time to 18.2.97 between $-350$ m to $-300$ m in a depth of about 26 m in a rather large area and probably with an extension to deeper regions. These changes developed within a few days and continued further at least till 28.2.97 as it could be followed in the measurements not shown here. The range of the resistivity decrease is quite large at about a factor of 100. The area in fact has previously a rather high resistivity indicating a possible disturbed rock zone (Fig. 5) with higher porosity. The large decrease of re-

![Diagram](image)

Fig. 6. Relation of resistivity to that of at previous measurement (Ratios between successive measurements in Fig. 5). The ratio is in logarithmic scale so that 0 means no change and an increase in resistivity is shown by positive values.
Sistivity suggests that this area might be filled with migrating brine. This area is also prominent later on at 3.5.97 and 16.7.97, characterised by a higher resistivity. This would support the idea of oscillating brine migrations in the rock salt due to continuously changing stress and strain by relatively high creep rates. It is not clear yet if these kind of changes can be attributed to the usual behaviour before some brine approach the openings.
4. Discussion

4.1. Accuracy of the observations and inversion

The accuracy of geoelectrical measurements depends on many factors. A knowledge of the reliability of the estimates of the resistivity distribution calculated by inversion is important by assigning structural elements to changing resistivities. Here, errors might be tolerated to a certain degree and the interpretation will be reduced only to significant changes over large areas associated with geological boundaries or moisture changes. Moreover, a precise determination of resistivity is important if some petrophysical meaning is to be attached to these values. Hence, some estimates are needed for the degree of accuracies.

A large number of inversions has been calculated for simulated structures and measurements by the means of forward modelling using standard geometries of dike like structures perpendicular and parallel to profiles at different depths as well as for normal layering and local inhomogeneities with rather large volumes. Generally structures parallel to the profile (i.e., in line with the main current direction) are mapped better than otherwise (Kurz, 1997). It is also well known that finite difference type of inversions cannot cope with sharp and large changes in the resistivities and the distribution is somewhat smeared or smoothed. Furthermore systematic investigations show that by inversion of apparent resistivities occasionally the model misfit can even increase when data misfit decreases. For that the rms-data error by inversions might not be an appropriate indicator for the fit; moreover, it is an integral measure of the misfit (Olayinka and Yaramanci, 1998).

Additional problems arise because the structure is actually 3D but the measurements are only suitable for 2D inversion as they can only be conducted along profiles in the drift. Apart from that, some parts of the profiles are in large caverns rather than in drifts and some other parts are in boreholes so that the estimation of the errors introduced by the geometry of the profiles and surroundings is quite complicated. Numerical simulations using 3D finite difference resistivity modelling (Fan, 1998) show that these effects may introduce errors as large as a factor of 2 or 3. However, by investigating changes, as is done by monitoring, it can safely be assumed that some of the errors due to the different factors discussed above are eliminated.

The error on the measurement, i.e., apparent resistivity is maximum a factor of 2. It is reasonable to assume that the error on the model section is of the same order of magnitude. But since the resistivity contrast between dry and wet rock salt is extremely high a factor of 2 is not great importance in the geological interpretation of the inversion results.

In all, it is realistic and rather on the safe side to assume that resistivities are mapped with an maximum error of a factor of 5. But the resistivity changes are certainly better in maximum error which might be around a factor of 2. These are presently the limits of resistivity measurements concerning the possible layouts and locations in the mining environment and can only be improved when measurements are conducted and also inverted for 3D which, however, is very time consuming and not affordable yet.

4.2. Petrophysical aspects of resistivity in rock salt

In order to interpret the resistivity and its changes in salt rocks, the physical cause of resistivity and the influencing factors must be well understood. A model used widely for a variety of rocks can be adopted for salt rocks which in its simplest form is based on the well-known equation of Archie (1942). The general model can be considered in terms of rock conductivity $\sigma$ as the sum of two conductivities, $\sigma_v$ and $\sigma_q$, in a parallel circuit (Schopper, 1982; Gueguen and Paliciauskas, 1994).

$$\sigma = \sigma_v + \sigma_q.$$ (1)
\( \sigma_v \) is the volume conductivity caused by the ohmic conductivity of the free electrolyte in the pores and \( \sigma_q \) the capacitive interlayer conductivity due to adsorbed water and cations at the internal surface of the pores. \( \sigma_q \) is, in contrast to \( \sigma_v \), strongly frequency dependent, being very small for zero frequency and becoming large with increasing frequency. For rocks with large internal surface for example containing a great deal of clay, \( \sigma_q \) might be very high and it is therefore called the clay term. For salt rocks, particularly at low frequencies, \( \sigma_q \) is much larger than \( \sigma_v \) and therefore \( \sigma \approx \sigma_v \). Going back to the more familiar expression in terms of resistivity, with \( \rho = 1/\sigma \), the ohmic resistivity of rock is

\[
\rho = \rho_w \phi^{-m} S^{-n} = \rho_w F I \tag{2}
\]

where \( \rho_w \) the resistivity of water, \( \phi \) the porosity, \( m \) the Archie exponent (or cementation factor), \( S \) the degree of saturation, \( n \) the saturation exponent. Sometimes a constant called ‘\( a \)’ is introduced in Eq. (2) in order to get a better fit of experimental data. The porosity is defined as \( \phi = V_p/V \) and the degree of saturation as \( S = V_w/V_p \) with \( V \), \( V_p \) and \( V_w \) being the volumes of the rock, pores and the water, respectively. The actual dependence of the resistivity on the pores is expressed with the formation factor \( F = \phi^{-m} \) and saturation index \( I = S^{-n} \).

For a rock with full saturation (i.e., \( S = 1 \)) the resistivity in Eq. (2) becomes

\[
\rho = \rho_w F \tag{3}
\]

where the index 0 stands for fully saturated rock. This is the well-known equation of Archie (1942) and is widely used particularly in interpretation of resistivity well logs. For rock salt the formation water (i.e., brine) is chemically fully saturated by NaCl and has a resistivity of \( \rho_w = 0.035 \, \Omega m \). For different type of salt rocks where the chemical constitution of the brine is different including also partly MgCl and KCl, \( \rho_w \) might be lower by a factor of 2. The Archie exponent for salt rocks has been determined to be \( m = 1.9 \) based on an extensive program of combined laboratory and in situ measurements (Yaramanci, 1994b).

Laboratory measurements have shown that the rock salt is usually not fully saturated, and the degree of saturation might be between 10% to 50% (Kulenkampff and Yaramanci, 1993). The effect of saturation on resistivity might be understood better by introducing the water content directly into the resistivity equation. The relative water content is given with

\[
G = V_w/V = \phi S \tag{4}
\]

By combining Eqs. (2) and (4):

\[
\rho = \rho_w G^{-m} S^{m-n} \tag{5}
\]

For full saturation (i.e., \( S = 1 \)) and therefore \( G = \phi \) the expression in Eq. (5) reduces to the Eq. (3). In Eq. (5) the term \( G^{-m} \) describes directly the effect of decreasing \( \rho \) as water content \( G \) becomes larger. The term \( S^{m-n} \) describes basically the effect of redistribution of water. However, even for large values of \( m-n \) and low values of \( S \) the effect is not greater than a factor of 2. There are only few own laboratory measurements for \( n \) of rock salt yet but they suggest that \( n \) is in the same range as \( m \) so that it can be assumed that \( m-n \approx 0 \) and consequently \( S^{m-n} \approx 1 \). However, measurements on individual samples especially from locations with recent deformations such as from the disturbed rock zone around the shifts showed some significant departures from \( m = n \) so the effect of \( S^{m-n} \) cannot be ignored a priori.

The common value of resistivity of \( 5 \times 10^5 \, \Omega m \) associated with the undisturbed rock salt corresponds to a water content of approximately 0.02%. This means for average porosities for rock salt of 0.1% to 0.5% a degree of saturation lower than 20% as has been verified many times with controlled laboratory measurements. An increase of resistivity to a value of \( 10^4 \, \Omega m \) can be associated with a decrease of average water content from 0.02% down to 0.004%. A small decrease of the usual resistivity to \( 10^5 \, \Omega m \) might mean that the water content is increased by a factor 2. This certainly is just at the limit of significant detectability. To explain changes
of resistivity down to 10 $\Omega\cdot m$ as encountered in the location A, the water content must be about 5% which in fact might be as large as that in highly disturbed and flooded rock salt. In general, the estimation of water content is only possible within certain limits as the resistivity also depends on the pore network. The geometry of the pore structures, that open during stress build-up, and the pore network properties are not satisfactorily known.

The resistivities of the major salt rocks can be attributed directly to their water content. In large scale surveys the mean resistivities for different undisturbed salt rocks are found to be $5 \times 10^5$ $\Omega\cdot m$ for rock salt, $5 \times 10^4$ $\Omega\cdot m$ for anhydrite, $10^4$ $\Omega\cdot m$ for carnallitite and less than $10^2$ $\Omega\cdot m$ for salt clay (Yaramanci, 1994b; Zimmer and Yaramanci, 1997). Laboratory measurements show that these resistivities are mainly due to the amount of the pore electrolyte. Lower values of resistivity are ascribed to increased amount of water. Higher values of resistivity are attributed in general either to closed pores under high stress and water is squeezed out or to disturbed rock with increased porosity or openings as some of the current paths get disrupted.

The knowledge about the explicit relationship of resistivity to water content in rock salt, as discussed above, allows some more insight into the nature of anomalies encountered. At location B the minimum resistivity of about $5 \times 10^4$ $\Omega\cdot m$ corresponds to a water content of 0.06% and the maximum resistivity of about $10^7$ $\Omega\cdot m$ corresponds to a water content of 0.004%. This a significant variation with a factor 15. The minimum water content is somewhat higher than the usual porosity indicating that these areas might have enlarged pore space because they are subjected to a stress decrease.

The most prominent change at 18.2.97 between $-350$ m to $-300$ m in a depth of 26 m with a resistivity decrease of about 100 times within few days corresponds to a water content increase of an factor 10. This somewhat significant as the area is in anhydrite and it cannot be ruled out that in this area some migration paths have opened. However, this happened temporarily as the area got resistive in following days.

In general the differences changes in resistivities and water contents show that the disturbed rock zone is significantly not homogeneous and changing continuously probably due to different creeping rate into openings depending on the size of openings itself.

A major difficulty in interpreting the resistivity in terms of water content is that no explicit information is available on the degree of saturation and therefore also on the porosity. The only limit to porosity is that it cannot be smaller than water content.

The capacitive interlayer conductivity $\sigma_q$ in Eq. (1) is often neglected in rock salt. However extensive laboratory measurements show that when rock salt is drained the volume conductivity $\sigma_v$ will decrease and the frequency dependent interlayer conductivity will dominate (Kulenkampff and Yaramanci, 1993). This means that repeated frequency dependent measurements in situ may give an indication on the changing degree of saturation. Measurements in that respect carried out in the presented case studies, however, are somewhat ambiguous and did not give any significant clues probably due to technical problems as the electromagnetic coupling between in cables could not completely avoided.

5. Conclusions

Geoelectrics is a valuable and probably the most suitable tool to explore the geological structure and particularly to monitor changes due to water migration. With respect to exploration the salt rocks like rock salt, anhydrite, carnallitite and salt clay have quite different resistivities and are, therefore, distinguishable. With respect to the monitoring particularly for water presence and migration, small changes in water content might cause large resistivity changes. Not only qualitative exploration but also some
quantification of the brine is possible. This is very important because the amount of brine is essential to estimate the porosity and the degree of saturation which influence relative and absolute permeability, storage capacity, creep properties, nuclide transport properties, etc.

A combination of geoelectrics especially with radar is a promising tool as one method may compensate the drawbacks of the other. Many investigations show that some boundaries in the salt can be detected by radar even for thin layers which would not be resolved with geoelectrics. In contrast, the penetration of radar is limited by strong reflectors and only with geoelectrics is it possible to look behind the reflector.

It is necessary to increase efforts to evaluate the capability of geoelectrics for salt rock environment and investigate the improvements possible. The major draw back presently is that due to logistical conditions only 2D measurements are possible so the location of anomalies are often not unique. 3D measurements should be used wherever possible, appropriate and affordable.

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