Introduction

Knowing petrophysical parameters and their contrasts is crucial to reliably monitoring CO₂ underground storage processes. The electrical conductivity turns out to be a sensitive indicator for a resistive gaseous or supercritical CO₂ (scCO₂) phase replacing a conductive pore fluid in a porous medium like a saline sandstone aquifer. A comfortable approach to relating rock properties with geoelectrical measurements is Archie's law. However, it only holds when the phases do not interact, but CO₂ is a reactive gas. Therefore, a systematic investigation of the impact of CO₂ on electrical rock properties is necessary before applying existing empirical formulas. This is essential because CO₂ is known to significantly dissolve into water. Furthermore, CO₂ is generally injected in a supercritical state, which changes the physical and chemical behaviour of CO₂. The presence of a CO₂ phase gives rise to a complex network of physical and chemical processes that all contribute to changing the bulk conductivity of rock [1].

Theory

At depths greater than approximately 800 m, pressure and temperature are generally sufficiently high to turn CO₂ into its supercritical state (critical point: 30.98°C, 7.38 MPa) [2][3]. ScCO₂ shows a fluid-like density, a gas-like viscosity and acts as a strong solvent. Unaccounted chemical reactions and interactions may therefore occur. As pressure builds up, CO₂ increasingly dissolves into water. This effect is diminished with rising temperatures and increasing water salinity. The unstable carbonic acid H₂CO₃ dissociates in two steps providing additional charges to the solution and changing its electrical conductivity:

\[
\text{CO}_2\text{aq} + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \\
\text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- \\
\text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-}
\]

Information about pore water conductivity \( \sigma_w \) and water saturation \( S(x,y,z,t) \) can be transformed into electrical formation conductivity \( \sigma \) using empirical conductivity models, e.g., Archie's law and its expansion by Waxman & Smits to account for both electrolytic conductivity \( \sigma_{\text{ar}} \) and interfacial conductivity \( \sigma_{\text{ws}} \) [4][5]. Both models only apply when gas and water do not interact. This requirement is not fulfilled for the system of water/CO₂.

Figure 1 Left: Sketch of the laboratory equipment used in this study. Right: Draft of the measuring cell used for our dissociation experiments (closed bottom) and flow experiments (permeable cell bottom, indicated by the dot patterned plate). A, B are current electrodes, M, N potential electrodes.

Apparatus and experimental procedures

An experimental set-up has been developed and implemented to simulate the sequestration process on the laboratory scale including its phase interactions. The apparatus, schematically outlined in Fig. 1, allows for monitoring the electrical conductivity of a water or sand sample at pressures up to 40 MPa and temperatures up to 80°C. Using the set-up described in Figure 1 three types of experiments have
been carried out at pressures up to 13 MPa and temperatures up to 40°C: Static dissociation experiments aiming at the electric impact of dissolving and dissociating CO₂, dynamic flow-through experiments aiming at the impact of CO₂ replacing the pore water, and combined experiments with static and flow-through periods to show the interaction of CO₂ and water within a real pore space.

Results

The pressure, temperature and salinity dependent dissociation processes can double the pore water conductivity (Figure 2). This is quantified by a dissolution adaptation of the models of Archie and Waxmann & Smits, respectively, that contains two adjustable parameters (see light gray curve in Figure 2). Our data and adaption formula can be confirmed by a geochemical simulation (see dark gray curve in Figure 2). The flow experiments achieved a reduction of the sample conductivity by a factor of up to 33. A combined experiment proved that the dissolution effect on conductivity can easily be measured at a sand sample.

![Figure 2 Increase of water conductivity with CO₂ pressure at 25°C for \( \sigma_{\text{base}}^{\text{base}} = 1.9e-2 \text{ S/m} \) (dots) and \( \sigma_{\text{base}}^{\text{base}} = 7e-1 \text{ S/m} \) (squares). The light gray curve represents the dissolution adaption; the dark gray curve shows the geochemical modelling result.](image)

Conclusions

The results of the presented laboratory experiments show that the electrical conductivity of water bearing porous media is highly sensitive to the presence of CO₂. We show that the presence of CO₂ in the pore space gives rise to a complex network of processes all of which contribute to the contrast in bulk rock conductivity. The dominating reduction of rock conductivity by CO₂ replacing the conductive pore water is damped by dissolution. The observations merge into a conceptual model of the electrical processes in the pore space. An addition to the laws of Archie and Waxman & Smits allows accounting for the dissociation. Further laboratory experiments will aim at further quantifying the influence of pressure, temperature, salinity and pH on the electrical conductivity. The conductivity reduction due to the CO₂ phase will be studied in more detail.

References