The responses of electrical resistivity tool to CO_2 dissolution in brine and carbon mineralization – Implication for Monitoring Underground CO_2 Sequestration.

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Abstract. Evaluation of the reliability of CO_2 monitoring techniques is a critical step in risk assessment of any CCS project. Electrical resistivity survey has an edge over seismic survey as a tool to monitor CO_2 plume migration, mainly due to the insensitivity of the latter to CO_2 saturation above 20%. However, the ability of electrical resistivity sensors to track CO_2 dissolution in aquifer brine and then carbon mineralization that occurs afterwards is still not very convincing as shown by the conflicting experimental and field data published in the literature. The objectives of this paper include a review of published experimental and field data, present more experimental data to clear some doubts and then use the knowledge gained therein to produce an electrical resistivity response model to the different geochemical processes that take place in the life cycle of CO_2 storage in underground aquifer formation. Here, three different types of laboratory experiments are presented to enhance our understanding of the responses of electrical resistivity to: (1) CO_2 plume migration in a saline aquifer, (2) CO_2 dissolution in aquifer brine, (3) CO_2 mineralization process in a carbonate rock. Laboratory flow and static experimental systems were set up, which consist of flow pumps, an industrial oven, pressure and temperature transducers, core (sample) holder, an electrical resistivity meter that is able to log electrical resistivity measurements at high pressure and high temperature, and a data logging computer for monitoring and storing the measured data. The three experiments showed that electrical resistivity: (1) is highly sensitive to CO_2 plume migration (2) is insensitive to CO_2 dissolution in aquifer brine, (3) is sensitive to rock dissolution and the subsequent mineralization process. An explanation is provided why electrical resistivity is insensitive to CO_2 dissolution in aquifer brine. Also, a validation experiment was conducted to validate the response of electrical resistivity to carbon mineralization. Finally, an electrical resistivity response model was developed to describe the behaviour of resistivity to the different geochemical processes during CO_2 underground storage process.

1 INTRODUCTION

Carbon dioxide (CO_2) plume, post injection into subsurface rocks such as deep saline aquifer, goes through both dynamic and static phases. Dynamic CO_2 flow occurs during CO_2 injection phase and the subsequent migration to the top of the storage reservoir (by buoyancy force), where the injected CO_2 exists as a gas phase at the top (below the cap rock) and above the aquifer brine. At this stage, the CO_2 remains there for decades or centuries where it gradually dissolves in the underlying aquifer brine for decades to centuries, depending on the amount of mixing with the formation water and the salinity of the water [1]. Mineralization process also occurs immediately as long as the dissolved CO_2 creates a solution capable of dissolving the carbonate rock minerals [2]. The dissolution and mineralization following the static state is the most significant process as it involves relatively much larger volume and takes longer time [3]. Investigating the effectiveness of a CO_2 monitoring tool in a storage site during residual, dissolution, and mineralization trapping is an important step to ensure the environmental sustainability of the CCS project. There are various geophysical monitoring techniques such as acoustics/seismic, gravity, and resistivity measurements. Seismic is the most extensively used technique but it becomes insensitive at CO_2 saturation above 20% [4], given electrical resistivity method an edge.

However, there are conflicting reports on the response of resistivity to CO_2 injection and dissolution in formation rocks. Forster et al. [5] and Zemke et al. [6] conducted laboratory tests on Stuttgart sandstone samples collected from the Ketzin field. They injected CO_2 solution into the brine saturated sample and observe no or insignificant change in core resistivity. They concluded that the effect of CO_2 injection on electrical resistivity and ultrasonic velocity can be relatively small, probably caused by a high amount of bound water. Some other researchers presented field data (Frio sandstone) that shows no change in the electric conductivity of the formation brine even when there is evidence of dissolved CO_2 as seen by low pH value [7]. The data from these two fields suggest that the electrical resistivity tomography (ERT) logs may not have captured the dissolved CO_2. However, the researchers working on Nagaoka field reported decrease in resistivity which they attributed to CO_2 dissolved in brine [8].

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Such interpretation can be negated if the reduction in electrical resistivity is due to water re-imbibition into the measurement zone or CO_2 leakage away from the measurement zone. The conflict in the published data can be resolved by carefully designed experimental works.

Other experimental data in the literature also showed some conflicting conclusions about the response of electrical resistivity to CO_2 injection in brine saturated rocks. Some experimental data showed that dissolved CO_2 does not change the conductivity of brine alone [8-7, 9]. Vialle et al. [9] reported a change in the conductivity of both the rock and the effluent fluid after a carbonate rock sample is injected with brine containing dissolved CO_2 and they also reported that the fluid conductivity is unchanged if it did not flow through the rock sample.

The disparity in either field data or experimental data can be due to several reasons. First, the conditions under which the electrical resistivity was measured in a reservoir rock/rock sample can differ. The electrical resistivity measurements can be taken (i) during CO_2 displacing brine (ii) after CO_2 dissolution in brine and (iii) during or after CO_2 mineralization process. Because these geochemical processes differ, the response of electrical resistivity measurements may also differ. Secondly, the electrical measurements taken on a bulk fluid (outside a reservoir rock or rock sample) can differ depending on the salinity and temperature of the brine and also depending on whether the fluid samples were taken before or after reaction with the rock minerals.

This study is a systematic design of well controlled experiments to separate and clearly explain the responses of resistivity at different stages of the geochemical processes in the life of CO_2 in an aquifer rock. Also, the validation of electrical resistivity response to dissolution and mineralization using a bulk fluid experiment is novel. All these responses are then presented as a response model for different stages of CO_2 transformative journey in the aquifer.

2 EXPERIMENTAL SETUP AND METHODOLOGY

The experiments are divided into three types representing three processes namely (1) CO_2 displacing brine (2) CO_2 dissolution in brine and (iii) CO_2 mineralization process. Rock samples (sandstone and limestone) in the form of core plugs which were properly saturated with a synthetic brine formulated in the laboratory were used to mimic aquifer rocks.

2.1 CO_2 displacing brine

In this experiment, the response of electrical resistivity to the process of CO_2 invading and displacing brine in a brine saturated aquifer rock is measured. The experimental setup for this is shown in Figure 1. An Indiana limestone (97% calcite, liquid permeability of 15 mD, porosity of 15%, diameter of 3.78cm and length of 9.85cm) was saturated with brine before placing in a core holder, after which a confining pressure of about 2000 psi was applied and a back pressure of about 1350 psi. The oven temperature was set to 40 ^{0}C while the salinity of the brine was about 58,000 ppm. Supercritical CO_2 which was stored in a cylinder inside the oven was then injected into the core sample following initial flow of brine at a constant flow rate of 0.5cc/min. About six pore volumes of CO_2 was injected at a constant rate while the pressure drop and the electrical resistivity across the sample was measured continuously throughout the displacement process.

2.2 CO_2 dissolution in brine

In this experiment, the response of electrical resistivity to the process of CO_2 dissolution in aquifer brine is measured. Here two types of measurements were carried out. The first is the flow of charged brine (brine with dissolved CO_2) in an aquifer where the charged brine displaced pure brine (without dissolved CO_2) from the aquifer rock. Secondly, the resistivity of the bulk brine (not in the core plug) is measured without dissolved CO_2 and then with dissolved CO_2. The experimental setup in Figure 1 was also used for the two experiments. In the first experiment under this category, a non-reactive rock sample was used to eliminate the effect of rock dissolution on the electrical resistivity measurements. Hence, a Berea sandstone with a liquid permeability of about 100 mD, porosity 20%, length 27 cm, diameter 3.8 cm was saturated with brine before placing in a core holder, after which a confining pressure of 3500 psi was applied with a backpressure of about 3000 psi. The oven temperature was set at 60°C while the salinity of the brine was about 58,000ppm. The pressure drop and the electrical resistivity across the sample was measured continuously throughout the displacement process.

In the second experiment under this category, the core holder in Figure 1 was replaced with a resistivity cell for fluid measurements. The electrical resistivity of the fluid was measured while flowing through the test cell at a constant flow rate and at a constant backpressure, confining pressure, and temperature. First, pure brine (without dissolved CO_2) was injected for approximately 30 minutes at a constant flow rate of about 0.5 cc/min. Supercritical CO_2 was then injected to displace the brine and allowed to flow for about 30 minutes at the same flow rate. This was followed by the injection of charged brine for about 45 minutes at the same flow rate.

2.3 CO_2 mineralization process

Here, the response of electrical resistivity to the mineralization process of CO_2 in a carbonate rock (porosity of 17.8% and gas permeability of 538mD) is evaluated. The experimental setup used for this experiment is shown in Figure 2. First, dry CO_2 was injected into a rock sample partially saturated with brine (i.e. water saturation was slightly less than 100%). CO_2 injection was from the top of the sample through a stainless tubing, such that the injected CO_2 occupies the top of the core plug and the steel tubing to form a gas cap (as indicated in Figure 2). The CO_2 was injected at a supercritical condition (Pressure > 1700 psi, Temperature > 42 ºC) while a confining pressure above 2500 psi was applied. A non-conductive mineral oil was used in the batch reactor to apply the confining pressure and the required temperature. The reactor was wrapped with a heat tape, which heated the mineral oil to the set temperature and the temperature regulated by a thermostat. The temperature around the core plug was measured by a thermocouple mounted near it. The electrical resistivity across the core sample was measured with an LCR (Inductance capacitance resistance) meter connected across it. The outlet of the core plug was closed so that the brine in the core plug was not displaced, and the gas cap would gradually dissolve into the brine in the pores of the underlying rock sample. The pressure, temperature, confining pressure, and electrical resistivity of the rock sample were all measured continuously for a period of 60 – 80 days at an interval of one hour. This process represents the gradual dissolution of the CO_2 plume at the top of the aquifer into the underlying brine zone in the pores.

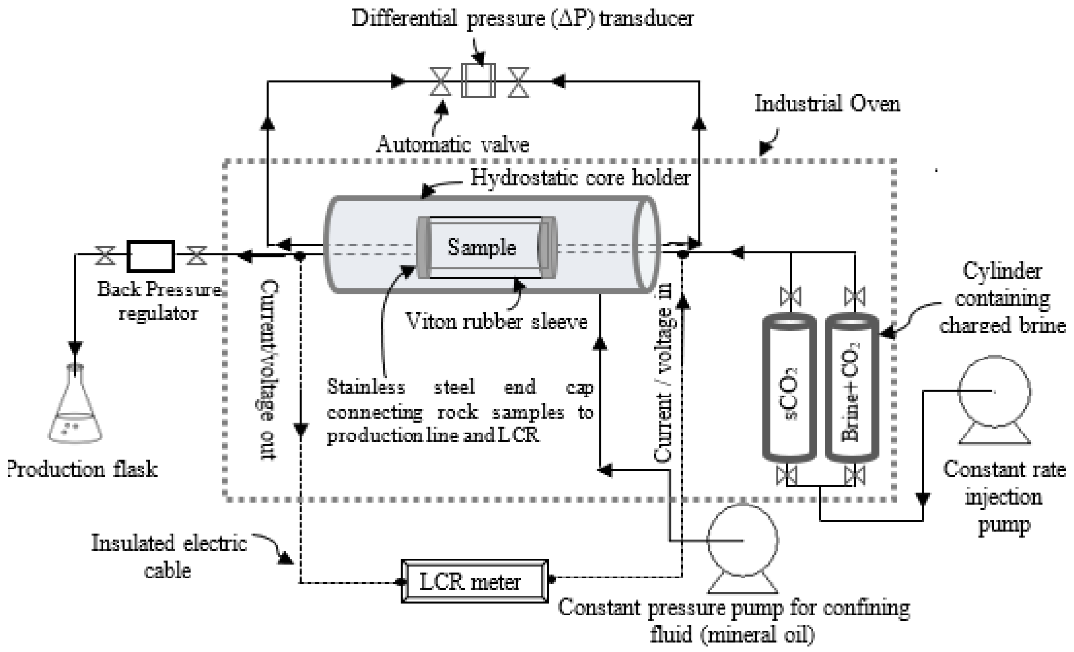

Fig. 1. Experimental setup for CO_2 displacing brine in pores containing brine in a dynamic (flow) system.

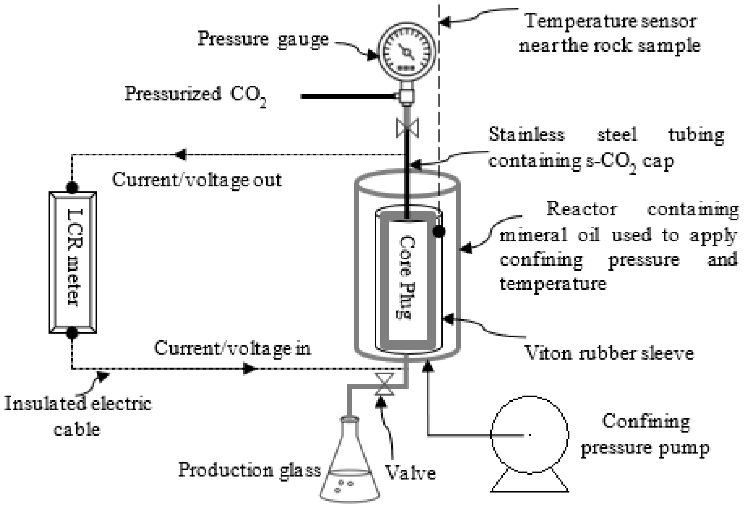

Fig. 2. Experimental setup for CO_2 dissolution in pores containing brine in a static (no flow) system

3 RESULTS AND DISCUSSIONS

Figure 3 shows both the electrical resistivity and pressure drop measurements during the displacement of brine by super critical CO_2. The resistivity of the rock at 100% brine saturation was about 5.3 ohm·m and this was maintained constant during constant brine flow in the sample. The pressure drop also remained fairly constant during this period. The two measurements (resistivity and pressure drop) increased after the start of CO_2 injection. Resistivity increase is due to the displacement of brine (the electrically conductive fluid) from the core and replacement by supercritical CO_2 (a non-conductive fluid). The resistivity continued to increase as more brine wass displaced until a steady state value when no more brine could be displaced (that is when the core reached an irreducible water saturation level). The pressure also increased during CO_2 injection until after about two pore volume of CO_2 injection when the pressure began to decline and then stabilized after four pore volumes of CO_2 injection. Pressure decline during coreflood is normally associated with breakthrough of the displacing phase (here CO_2), while the increase in pressure that occurred earlier was due to the resistance of the rock to the flow of gas and perhaps because of the dissolution of the CO_2 in brine at the interface as CO_2 enters the core face. When CO_2 dissolves in brine, a more viscous and denser brine phase is formed [10] and as a result, the pressure at the inlet may increase. The effect of the dissolution of CO_2 in brine on electrical resistivity measurements cannot be ascertained in this experiment since brine is also displaced in the process.

The next experimental result (Figure 4) looks into the response of electrical resistivity to brine with dissolved CO_2. As observed in Figure 4, the electrical resistivity and pressure drop values are stable during injection of dead brine (brine without dissolved CO_2) in a 27 cm long Berea sandstone for over 10 pore volumes. The pressure drop increased during injection of charged brine (brine with dissolved CO_2) apparently because the charged brine is denser and more viscous. The pressure drop later became slightly stable at about 12 pore volume after which it fluctuated between 0.5 – 1 psi. The fluctuation may be attributed to either the compressibility of the live brine or dissolution of rock minerals and then plugging of pores. As seen in Figure 4, the electrical resistivity of the rock during the flow of charged brine reduced slightly by ≈ 3% of the resistivity when dead brine was flowing. However, Kharaka et al. [7] and Vialle et al. [9] earlier showed that the conductivity of brine did not change after dissolving CO_2, even when the pH of the brine reduced after dissolving CO_2. Hence, the reduction in resistivity (or increased electrical conductivity) observed in Figure 4 could be rock-induced, as extra conductivity is derived from the extra ions leached from the rock minerals during flow of charged brine. Fluid analysis like Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) on the fluid effluents from the rock after flow of charged brine can confirm this but unfortunately this is not available in this specific experiment. It is therefore difficult to conclude that the slight reduction in resistivity during the charged brine measurements in Fig. 4 is due to experimental uncertainties or due to extra conductivity by leached ions during flow of charged brine since fluid analysis were not conducted. But based on similar results published by Vialle et al. [9], it is likely due to extra conductivity of dissolved ions from the rock. Vialle et al. [9] showed that conductivity of the effluent brine (from a rock sample during flow of live brine) increased and that the increase was due to extra conductivity from the free calcium ions (Ca^{2+}) leached from the rock minerals during flow of charged brine. The results of Forster et al. [5] and Zemke et al. [6] on Stuttgart sandstone samples (collected from the Ketzin field) also showed that the electrical resistivity of a sandstone rock sample decreased after storing charged brine for hours and that the reduction in resistivity was due to the interaction between the live brine and rock minerals.

The reduction in electrical resistivity in an aquifer rock in the Nagaoka field several years post CO_2 injection as published by Mito and Xue [8] is likely due to the interaction of the rock with the charged brine in it and not necessarily due to CO_2 dissolved in brine as they reported [8]. It may also be due to imbibition of brine into the aquifer leading to displacement of the CO_2 plume from the point of measurements, though they argued that water imbibition was insignificant based on neutron porosity logs obtained during the resistivity measurements. The possible imbibition of brine into an underground aquifer rock following CO_2 injection and the corresponding reduction in resistivity of the rock then makes it difficult to attribute the reduced resistivity of the storage reservoir rock to rock-fluid interaction. Unless, water imbibition is ruled out, resistivity measurements cannot differentiate between resistivity change due to rock-fluid interaction (i.e. CO_2 dissolution and interaction of the charged brine with host rock) and CO_2 plume migrating away from the depth of measurement (i.e. water imbibing and displacing the CO_2 plume). Since the densification of the aquifer brine following CO_2 dissolution can cause a corresponding increase in viscosity as observed in Figure 4 and as reported by other researchers [11-13], time lapse density measurements could be helpful in detecting and accounting for CO_2 loss to dissolution in aquifer brine.

One would argue that the reason for lack of change in electrical conductivity of brine after dissolving CO_2 may be because the salinity of the brine (high ionic strength) may have dampened the effect of the little ions from the weak carbonic acid formed after CO_2 dissolution and dissociation in the brine. In other words, the aquifer salinity (in this case about 58,000 ppm salts) is high such that the effect of CO_2 dissolution/dissociation is not significant. A separate experiment involving only the fluids (brine with dissolved CO_2) was also conducted to fully understand the response of electrical resistivity to CO_2 dissolution in brine. The results of the bulk fluid experiments are shown in Figure 5.

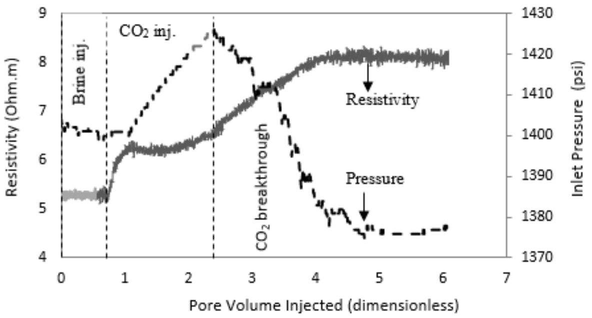

Fig. 3. Electrical resistivity and pressure during displacement of brine by supercritical CO_2 in an Indiana limestone.

Here (Figure 5), the electrical resistivity of the following fluids was measured as they flow in sequence through a 1⁄8- inch nonconductive Teflon pipe: dead brine, supercritical CO_2, charged brine, diluted HCl acid. As seen in Figure 5, the resistivity of brine at 40 ^{0}C is 0.2 ohm·m and was stable for about 30 minutes. The resistivity of supercritical CO_2 is 14 ohm·m and was stable for over 30 minutes of continuous flow. This was followed by the flow of charged brine whose resistivity was also 0.2 ohm·m and stable for about 45 minutes of continuous flow. The last fluid is brine containing diluted hydrochloric acid. This was done to ensure that the experimental setup was sensitive to lower resistivity values. This bulk fluid experiment clearly shows that the electrical resistivity of charged brine and dead brine are very similar (≈0.2 ohm·m).

Based on the discussions above, it is important to point out that electrical resistivity may not be able to detect dissolution of CO_2 in aquifer brine but may detect the effect of the corresponding interaction between the rock and fluids that occurs afterwards, which could be a decrease in electrical resistivity (or increase in electrical conductivity) of the aquifer and vice versa. Also, resistivity of aquifer brine samples before and after CO_2 may or may not change depending on the time it was taken and whether a geochemical interaction had occurred between the charged brine and the host rock at the time of collection. The long-term interaction between host rock and CO_2/brine system under a static condition is investigated in Figures 6 and 7.

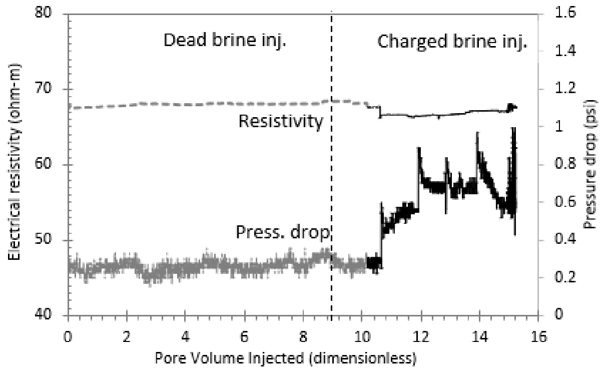

Fig. 4. Electrical resistivity and pressure drop during displacement of brine by charged brine in a Berea Sandstone. Note: inj. means injection.

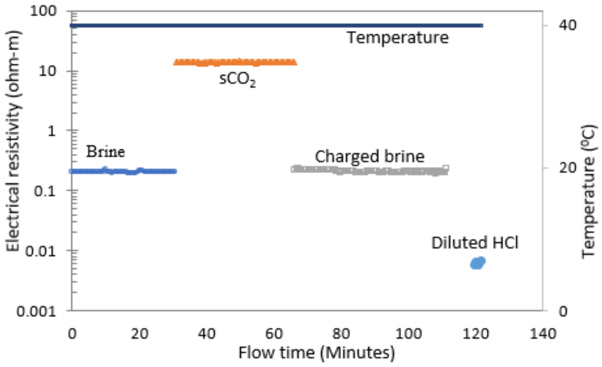

Fig. 5. Electrical resistivity of dead brine, charged brine, super critical CO_2, and dead brine with a drop of HCl. All at a flowing pressure of 1350 psi and a constant oven temperature of 40^{0}C.

Figure 6 represents the electrical resistivity profile of a limestone rock under static condition. Unlike experimental results in Figure 3 to Figure 4, here, there is no displacement of the brine from the rock sample. Rather both CO_2 and brine co-exist in the pores of the core at supercritical CO_2 conditions, allowing both dissolution of CO_2 in brine and rock – fluid interaction to take place over time. This type of experiment is rare and first presented by Adebayo et al. [14]). Figure 6 shows the trend in resistivity starting from when CO_2 was first forcefully injected in a limestone core plug containing brine. As shown in Figure 6(A), dry CO_2 was injected on the 7th day and the pressure of the CO_2 plume at the top of the sample was 1700 psi while the sample was under confining pressure of 2500 psi and the outlet was closed. Prior to CO_2 injection, the sample resistivity was maintained constant with a baseline value of approximately 3.2 ohm·m.

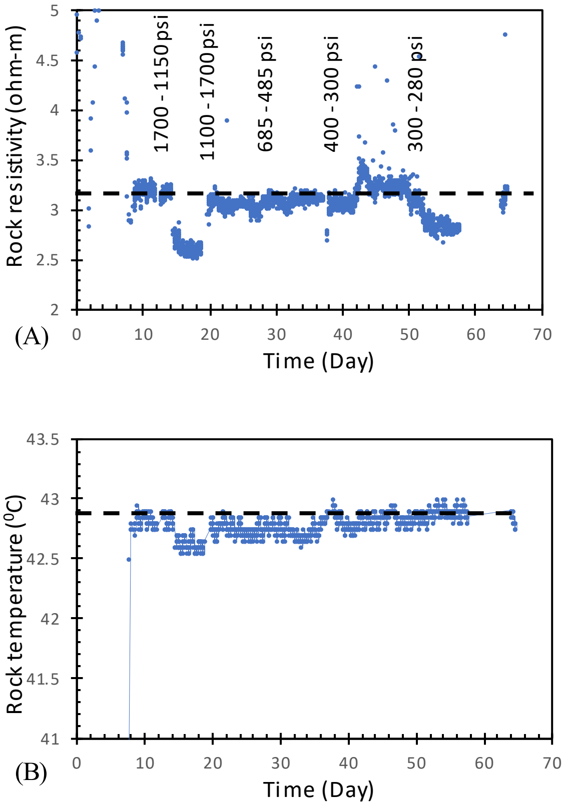

Fig. 6. Electrical resistivity of an Indiana limestone at a static storage condition.

The temperature profile around the core sample is shown in Figure 6 (B), which represents the average of two measurements from two temperature sensors around the sample. The baseline temperature was also about 43°C. At day 15 (i.e. eight days after CO_2 injection), the resistivity dropped to about 2.5 ohm·m, representing about 19% drop in resistivity. CO_2 pressure also dropped during this period, likely due to dissolution in brine. Coincidentally, the temperature around the sample decreased during the same period. The resistivity and temperature rose back to the baseline values after few days. It is known that electrical resistivity has an inverse relationship with temperature. Hence, it can be ruled out that the decrease in resistivity was not due to external change in temperature around the sample (since both decrease at the same time). The decrease in resistivity (increase in conductivity) is thus likely due to dissolution of rock minerals causing significant increase in ions concentration sufficient to cause such an increase in the conductivity of the rock. Based on previous results (Figure 4 and Figure 5), CO_2 dissolution alone cannot cause such a decrease in the resistivity unless it is accompanied by rock dissolution and sufficient free moving ions. The accompanied reduction in temperature around the rock during the dissolution process may be an indication that such dissolution is an endothermic process (unless a contrary evidence exists to suggest otherwise). The subsequent increase in both resistivity and temperature back to the baseline values in Figure 6(A) is interesting. This may be attributed to mineralization process since CO_2 source is gradually depleted (lower CO_2 pressure) and pH value (not measured here) may have dropped. Mineralization or precipitation results in removal of the extra ions formed after mineral dissolution. Hence, the rock conductivity will reverse to the baseline value if all the extra ions precipitated into solution. The resistivity and temperature remained on the baseline for over 20 days while CO_2 pressure continue to drop. The drop in CO_2 pressure is likely due to gradual dissolution in brine. There was a slight increase above the baseline followed by another decrease in resistivity after 50 days, while the average temperature remained at the baseline. Evidence of dissolution and precipitation in this experiment is based on visual observation of precipitates in the fluid collected at the end of the experiment. The solid particles in the fluid were filtered, dried, and X-ray fluorescence (XRF) analysis conducted on them. The XRF result showed 67% calcium, 19% Silicon, 9% Chlorine, and traces of Iron and Sulphur. This indicates that the precipitates were predominantly from the rock minerals. The permeability of the sample also reduced significantly by about 37% (from 540mD to 335mD) due to pore throats blockage by the precipitates. The porosity remained unchanged. Ion chromatography (IC) and inductively coupled plasma optical emission spectroscopy (ICP-OES) analysis conducted on the brine (after filtering out the solid components) revealed the presence of extra dissolved ions as summarized in Table 1. The trend in the resistivity profile during CO_2 storage at static condition was reproducible as shown from several other experiments conducted on different samples as reported in Adebayo et al. [14].

Table 1. Fluid analysis

	Pure Brine (mg/l)	**Brine after CO_2 Storage (mg/l)**
Na	17462	19002
Mg	317	344
Ca	3570	3866
Cl	35879	37801
SO_4	365.5	319
HCO_3	34.5	58
CO_3	4434	8946
TDS	62062	70336

To verify the interpretation of the resistivity response, another experiment was conducted as reported in Figure 7. Ethylenediaminetetraacetic acid (EDTA) is a chemical solution (a chelating agent), when dissolved in brine can adsorb/chelate any newly generated or added metal ions (such as calcium) onto its chemical structure, hence preventing it from free movement. So, in the repeated experiment, the brine saturating the core sample contained 3% EDTA. The purpose was for the chelating agent to adsorb the calcium ions that is generated during the rock dissolution process and bind them to itself, such that they (the ions) do not contribute to electrical conductivity. As observed in in Figure 7(A), the same mechanism that is suspected to be the rock dissolution process occurred after about 10 days post CO_2 injection (CO_2 pressure was 2000 psi). Like in Figure 6, the temperature dropped at this time and then increased back to the base line (black dotted horizontal line) after some days. Interestingly, here, the resistivity increases during the same period (as opposed to the decrease observed in Figure 6 in this period). The increase in resistivity is apparently because the chelating agent immediately adsorbs the dissolved calcium ions as they are leached from the limestone minerals rendering them immobile and hence not able to contribute to electric conductivity as was the case in Figure 6. As observed, the resistivity increased above the base line. Perhaps, the chelating agent adsorbed some pre-existing ions from the brine during this period. However, after about 20 days, the resistivity dropped below the base line values indicating that there may have been some more ions in the brine. Such is possible if the chelating agent is saturated and cannot bind more ions or released some of the adsorbed ions (which can be driven by pH change). There is a need for further studies to understand these mechanisms.

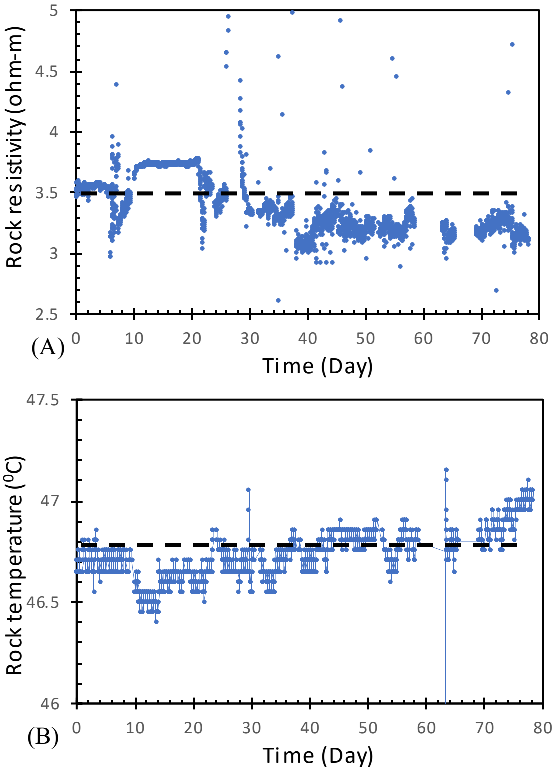

Fig. 7. Electrical resistivity of an Indiana limestone at a static storage condition. Here, a chelating agent is present to bind with the dissolved ions.

An attempt was made to study the response of electrical resistivity to the mechanism of chelation of Ca^{2+} ions by the chelating agent (EDTA). In Figure 8, the electrical resistivity of only the fluids in the pores of the samples in Figure 6 and Figure 7 was measured. First the resistivity of brine is shown by the black data points (representing the state of the sample in Figure 6 before reaction with the rock). This was followed by that of brine with more dissolved ions (2000ppm $CaCl_2$) to mimic addition of Ca^{2+} ions that occurred during rock dissolution in Figure 6. The orange data point represents the resistivity of the solution (Brine + EDTA) present in the sample in Figure 7 before rock reaction with the rock. This is followed by the resistivity of another solution (brine + EDTA + $CaCl_2$) representing the chelation process after reaction with rock minerals – that is the increase in resistivity above the base line, shown as the black dotted line, as in Figure 7). The $CaCl_2$ represents the additional calcium leached from the rock after reaction. It is thus obvious that the resistivity pattern in Figure 8 represents those observed in Figures 6 and 7.

Vialle et al. [9] conducted a continuous flow of brine and then CO_2-charged brine in a 99.9% calcite rock sample for several days. During flow, they measured pH, electrical conductivity, ion concentration of the flowing liquid and sonic velocity of pure brine and CO_2 saturated brine under room temperature and atmospheric pressure. They reported that there was no difference between the conductivity of the pure brine and charged brine. However, the conductivity of the charged brine and that of the rock sample (through which the charged brine was flowing) changed as soon as interaction between the rock and charged brine started. There was no precipitation reported in their flow experiment since the dissolved ions were consistently transported out of the rock and new charged brine was continuously injected at a steady state. The pH (H^+ content), and Ca^{2+} ions concentration in the produced fluid were maintained at steady state since there was consistent supply of charged brine.

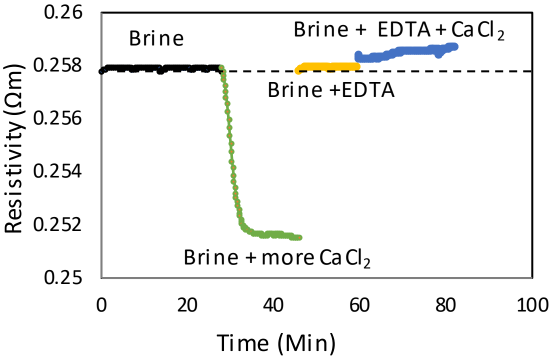

Fig. 8. Electrical resistivity of brine, brine with more dissolved $CaCl_2$ salt, brine with only EDTA and then brine with EDTA and more dissolved $CaCl_2$.

Based on the results presented above and the results reported in the literature (field and lab data), the chart presented in Figure 9 is a representation of the responses of electrical resistivity of rock and that of the pore fluid alone as CO_2 is stored and goes through different geochemical process in the storage aquifer. The behaviour of reservoir pressure, pH and ions are also presented.

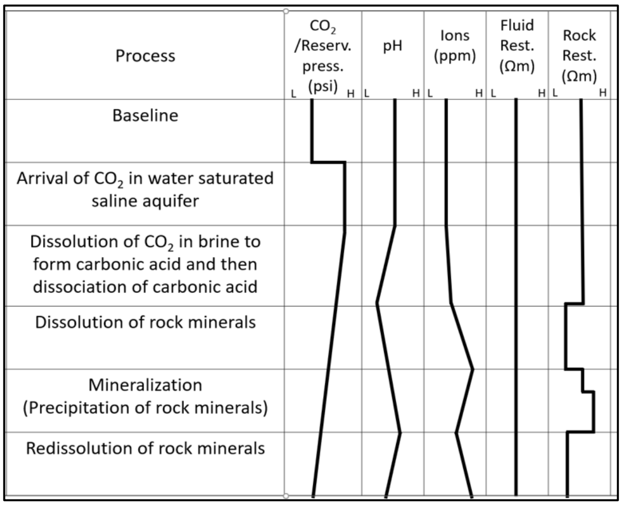

Fig. 9. Proposed flow chart of the response of electrical resistivity of an aquifer rock initially saturated with brine and later dissolved CO_2 brine, and other geochemical processes that follow. Note: L means low value and H means high value.

3 CONCLUSIONS

The following main conclusions are derived from the results presented in this study.

1. CO_2 dissolution in brine does not cause change in the electrical resistivity/conductivity of the brine. However, the resistivity of rock increases if the injected CO_2 displaces the brine out of the rock or out of the region of the rock being measured,

2. In a static/closed reservoir system, the resistivity of rock decreases if there is rock dissolution and increases again following precipitation/mineralization.

3. Dissolution of CO_2 in brine causes higher viscosity of the charged brine and a resultant increase in pressure (inlet and differential pressure) during flow in aquifer rock.

4. Electrical resistivity measurements can be used for monitoring the following processes: CO_2 plume migration, dissolution of rock minerals, and mineralization of CO_2, provided the baseline values are properly recorded and the conditions under which resistivity measurements are made are clearly identified and used accordingly in their interpretation.

5. The inability of electrical resistivity measurements to clearly detect CO_2 dissolution in brine means it cannot account or differentiate between CO_2 lost due to dissolution into brine, and the CO_2 lost due to leakage (through fractures or other pathways).

6. Time lapse density measurement is required to account for CO_2 dissolved in aquifer brine.

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References

1. M. Bentham and G. Kirby. Oil & Gas Science and Technology – Rev. IFP 60 (3), 559-567 (2005).
2. S. Bachu. International Journal of Greenhouse Gas Control 40, 188-202 (2015). https://doi.org/10.1016/j.ijggc.2015.01.007.
3. IPCC (Inter governmental Panel on Climate Change), Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge, UK, New York, NY, USA. (2005).
4. Y. Nakatsuka, Z. Xue, H. Garcia, T. Matsuoka. International Journal of Greenhouse Gas Control **4** (2) 209-216 (2010) https://doi.org/10.1016/j.ijggc.2010.01.001.
5. A. Förster, B. Norden, K. Zinck-Jørgensen, P. Frykman, J. Kulenkampff, E. Spangenberg, J. Erzinger, M. Zimmer, J. Kopp, G. Borm, C. Juhlin, C. Cosma, S. Hurter. Environmental Geosciences **13** (3), 145-161 (2006). https://doi.org/10.1306/eg.02080605016.
6. K. Zemke, A. Liebscher, M. Wandrey. International Journal of Greenhouse Gas Control, **4**, 6, 990-999 (2010), https://doi.org/10.1016/j.ijggc.2010.04.008.
7. Y.K. Kharaka, D.R. Cole, S.D. Hovorka, W.D. Gunter, K.G. Knauss, B.M. Freifeld. Geology, **34,** 7, 577- 580 (2006). https://doi.org/10.1130/G22357.1.
8. S. Mito and Z. Xue. Energy Procedia **4**, 3284–3289 (2011). https://doi.org/10.1016/j.egypro.2011.02.248.
9. S. Vialle, S. Contraires, B. Zinzsner, J-B. Clavaud, K. Mahiouz, P. Zuddas, and M. Zamora, J. Geophys. Res. Solid Earth, **119**, 2828–2847, (2014). https://doi.org/10.1002/2013JB010656.
10. J. Ennis-King, L. Paterson. In Proceedings of the Greenhouse Gas Control Technologies-6th International Conference, 1–4 October 2002; Kyoto, Japan; Elsevier: Amsterdam, The Netherlands, (2002).
11. S. Bando, F. Takemura, M. Nishio, E. Hihara, and M. Akai 2004. J. Chem. Eng. Data, **49** (5), 1328-1332, (2004). https://doi.org/10.1021/je049940f
12. M. Fleury and H. Deschamps. J. Chem. Eng. Data, **53** (11), 2505-2509, (2008). https://doi.org/10.1021/je8002628
13. A. Kumagai and C. Yokoyama. J. Chem. Eng. Data, **44** (2), 227-229, (1999). https://doi.org/10.1021/je980178p
14. A. R. Adebayo, H. Y. Al-Yousef, M. Mahmoud. J. Energy Resour. Technol., **137**(3) (2015). https://doi.org/10.1115/1.4028772