Journal of Geoscience and Environment Protection, 2014, 2, 1-7
Published Online June 2014 in SciRes. http://www.scirp.org/journal/gep
http://dx.doi.org/10.4236/gep.2014.23001

An Experimental Study of the Effect of Rock/Fluid Interaction on Resistivity Logs during CO_2 Sequestration in Carbonate Rocks

Abdulrauf Adebayo, Mohammed Mahmoud

Petroleum Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia
Email: abdulrauf@kfupm.edu.sa

Received January 2014

Abstract

Accurate laboratory measurements and analysis of electrical properties of core samples are a prerequisite step to the evaluation of oil and gas reserves. In recent times, this evaluation technique has been adopted in carbon dioxide sequestration projects for estimating and monitoring carbon dioxide (CO_2) accumulation in saline aquifers. Several papers have reported laboratory success in the use of resistivity measurements to monitor the flow and also estimate the volume of CO_2 plume in geological formations. Such laboratory experiments did not capture the effect of CO_2 -brine-rock interaction (CBRI) on saturation estimation. The possibility of a change in value resistivity due to CO_2/brine/rock interactions, and the possible effect on CO_2 monitoring and estimation are of immediate interest here. Preliminary results of an ongoing research work showed that a much longer experiment time accommodates CO_2-brine-rock interaction which ultimately lead to change in rock resistivity. We hereby present the electrical behavior of carbonates to CO_2/brine/rock interaction during prolonged CO_2 sequestration and the effect on saturation estimation. This electrical behavior and its possible effect on CO_2 monitoring and estimation are discussed.

Keywords

Carbon Dioxide Sequestration and Monitoring, Resistivity Log, Rock Fluid Interaction, Archie Equation

1. Introduction

CO_2 is normally injected into underground formation at high pressure and temperature such that the CO_2 exists in a supercritical state. The supercritical state will reduce the volume of rock space occupied by injected CO_2 per unit volume of CO_2 existing at atmospheric condition. The pressure and temperature at which CO_2 exist in this state can be found in aquifers at depth of about 800 meters or more. Hence candidate formations for carbon cap-

How to cite this paper: Adebayo, A., & Mahmoud, M. (2014). An Experimental Study of the Effect of Rock/Fluid Interaction on Resistivity Logs during CO_2 Sequestration in Carbonate Rocks. *Journal of Geoscience and Environment Protection, 2,* 1-7. http://dx.doi.org/10.4236/gep.2014.23001

ture and sequestration (CCS) must be at this depth (Benson, 2008). While CO_2 is injected into a subsurface formation, four major trapping mechanisms ensue namely: 1) Physical/Structural trapping—a process whereby impermeable cap rock at the top of the formation prevent the CO_2 from escaping out of the formation, keeping it in place (Benson, 2008; Wang, 2010), 2) Solubility trapping—a process whereby injected CO_2 dissolves in formation pore water, 3) Mineral trapping—occurs when aqueous CO_2 reacts with formation rock minerals producing precipitates of carbonate minerals, and 4) Residual or Capillary trapping which occurs after CO_2 injection stops and water begins to imbibe into the aquifer displacing the CO_2 already in the aquifer. Not all the CO_2 is displaced but some are left behind as residual CO_2 (residual trapping). Dissolved CO_2 can acidify formation water and subsequently mobilize and transport trace metals as it migrates in the formation (Gaus, 2010). A storage formation with strong cap rock is thus crucial to avoid leakages of trace metals and compounds into overlying portable aquifers. There is also the need for proper monitoring of CO_2 migration so as to observe its behavior, distribution, and possible leakages. Hence, evaluation of the reliability of CO_2 monitoring techniques should be first step in risk assessment of any CCS project (Wang, 2004). Techniques required for monitoring CO_2 migration can be borrowed from a variety of other applications such as those used in the oil and gas industry, and those used in ground water monitoring (Benson, 2008). Examples of such techniques are seismic, gravity, and resistivity measurements. Seismic is the most extensively used technique. The use of resistivity measurements is also promising. Resistivity technique is applicable because rocks contain saline water and are thus conductive. The use of resistivity measurements to monitor and quantify CO_2 in underground geological formation depends on the fact that formation resistivity is higher at locations occupied by CO_2 compared to locations un-invaded by CO_2, and the resistivity increases as CO_2 saturation increases. The amount of resistivity changes depend on the volume of CO_2 present. With the use of Archie's equation or modified Archie's equation, CO_2 saturation distribution, migration, and volume can be estimated. Many experimental and field studies have successfully used resistivity measurements to monitor CO_2 migration (Ramirez, 2003; Wang, 2010; Giese, 2009; Christensen, 2006; Nakatsuka, 2010). Archie's equation is given in Equation (1).

$$S_w = \left(\frac{aR_w}{\varnothing^m R_t}\right)^{1/n} \tag{1}$$

where "a" is a constant determined as the intercept passing through 100% porosity on a formation factor-porosity plot, while "m" and "n" are cementation factor and saturation exponent respectively and are obtained from laboratory resistivity measurements on core samples.

Kiessling et al. (2010) applied Archie's equation to estimate CO_2 saturation distribution in a CO_2 SINK test site close to Ketzin (Germany). Similarly, Nakatsuka et al. (2010) reported the use of Archie and modified Archie equation to estimate CO_2 distribution in the Nagaoka pilot CO_2 injection site. Time lapse resistivity measurements in both cases were used to monitor movement of CO_2 to and away from different zones of interest. Changing resistivity values were interpreted as change in CO_2 saturation. **Figure 1** shows the time lapse resistivity logs for both cases.

This study is new compared to previous works in the following sense: Many previous laboratory works have focused on the applicability of electrical resistivity measurements to track CO_2 migration by way of resistivity change as a function of CO_2 saturation changes during CO_2 sequestration. Such experiments were also conducted only within several hours or less. The fate of formation resistivity in the event that the CO_2 remained trapped in the pores for an extended period of time and the subsequent effect of the CO_2/brine/rock reactions on resistivity and on CO_2 monitoring and estimation has not been addressed. This paper investigates the effect of CO_2 brine rock reaction on resistivity and CO_2 saturation estimation.

2. Materials and Methods

All samples were collected from the same quarry rock of Indiana lime stone with recorded high level of homogeneity. Cylindrical samples with dimension of 3.74 cm diameter and length of 7 cm were cut and surface grinded to ensure very flat end faces. Samples were cleaned by solvent reflux method and vacuum dried in oven at 80˚C. Sample properties were then measured and tabulated in **Table 1**. De-aerated synthetic brine with composition and properties shown in **Table 2** were prepared and used to saturate core samples.

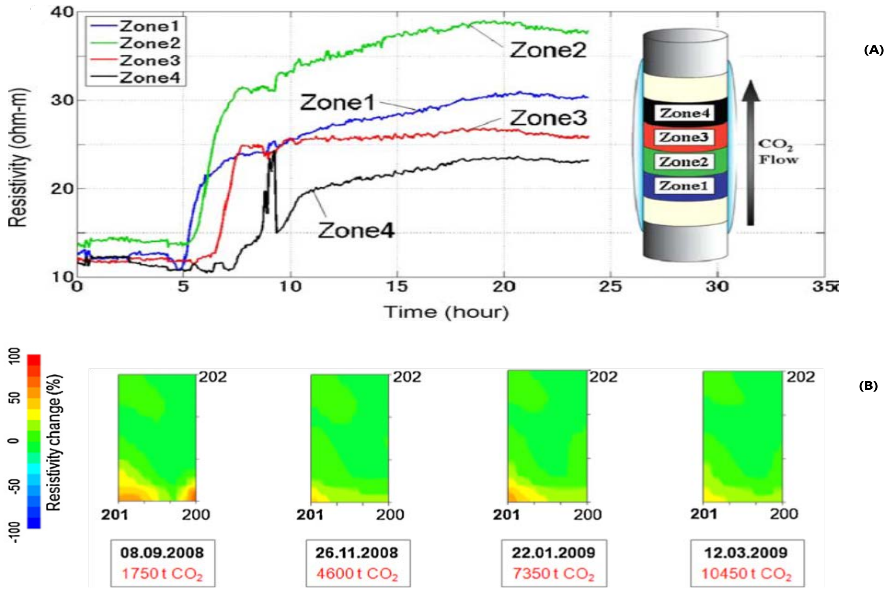


Figure 1. Time lapse resistivity logs: (A) laboratory data taken with permission from Nakatsuka et al. (2010) (B) field data taken with permission from Kiessling et al. (2010).

Table 1. Sample properties.

ID	L (cm)	D (cm)	Bulk Vol. (cc)	He. Pore Vol. 500psi (cc)	He Porosity (500psi) (%)	K (mD)
209	7.03	3.741	77.37	14.70	19.002	324
206	7.06	3.736	77.43	13.78	17.790	423

Table 2. Synthetic formation brine.

Saline Aquifer	
Composition	**Weight (g/l)**
Sodium Chloride (NaCl)	44.5
Calcium Chloride ($CaCl_2 \cdot 2H_2O$)	9.65
Magnesium Chloride ($MgCl_2 \cdot 6H_2O$)	3.41
Sodium Bicarbonate ($NaHCO_3$)	0.15
Sodium phosphate (Na_2SO_4)	0.28
TDS (g/l)	**57.99**
Density, g/cc	**1.02**
Resistivity @ 22.5˚C, (ohm-m)	**0.401**

3. CO_2 Injection Apparatus and Procedure

Figure 1 is the CO_2 injection set up. The setup is designed to store supercritical CO_2 in a brine saturated core sample at a typical reservoir condition of 40˚C and 2000 psi overburden pressure. It consists of a CO_2 source, a core resistivity assembly, a test cell, pressure system, a heater, gauges, a LCR meter, and a data acquisition system to record resistivity measurement as a function of time as CO_2 aging lasts. A 3.7 cm diameter by 7 cm long carbonate core was placed in a Viton sleeve embedded with two electric current potential electrodes. A Teflon tape was wrapped along the circumference of the core (except the portion that would be in contact with the electric potential electrodes) prior to placing it inside the Viton sleeve so as to delay the breakthrough of CO_2 through the sleeve. The core together with the sleeve was then coupled with the pore inlet and outlet tubing which doubled as current inlet and outlet electrodes respectively. The core assembly was placed into a test cell and then subjected to overburden pressure of 500 psi after which the core was circulated with brine to remove trapped air from the core's pore space. An inlet valve and outlet valve attached to the core assembly served as means of either closing up the core after CO_2 injection or for fluid sampling at the end of storage. At the end of brine circulation, cell temperature was raised to 45˚C, the overburden pressure too was raised to 2000 psi and the system left for over 24 hours for the core to equilibrate with the surrounding temperature and pressure. At this point, the outlet valve was closed and CO_2 was applied at the inlet tubing at a pressure of 2000 psi making the CO_2 to exist in a supercritical state in the core. After few hours, the inlet valve was closed. CO_2 inlet was from the bottom of the core and the outlet tubing was at the top. The outlet tubing was also connected to a pressure gauge used to monitor CO_2 pressure (**Figure 2**). The same procedure applied for the second core. Core sample IL-206 was aged for 3 weeks (46 days) and IL-209 was aged for (90 days). During these aging times, the DAQ system recorded measurements of resistivity, pressure, and temperature of the core as a function of time.

3. Results and Discussions

Results after prolonged storage showed that rock electrical signature was constant prior to CO_2 injection and later increased in response to CO_2 influx and remained constant again around this resistivity value until after quite a number of days when constant resistivity pattern changed to a more turbulent pattern suggesting the onset of chemical reactions between the three phases—CO_2, brine, and carbonate grains. Considering the first 300 hours of CO_2 storage (between 200th hour marking the beginning of CO_2 storage till 500th hour) in sample IL-206 (**Figure 3(a)**). It can be seen that although CO_2 pressure is fairly the same during this period but the formation resistivity dropped at about 150 hours after CO_2 storage and later increased to the CO_2 base line. Estimating CO_2 saturation within this period using Equation (1) would give different saturation profile whereas in the true sense the brine saturation is the same since no outflow was allowed. The same phenomenon can be seen

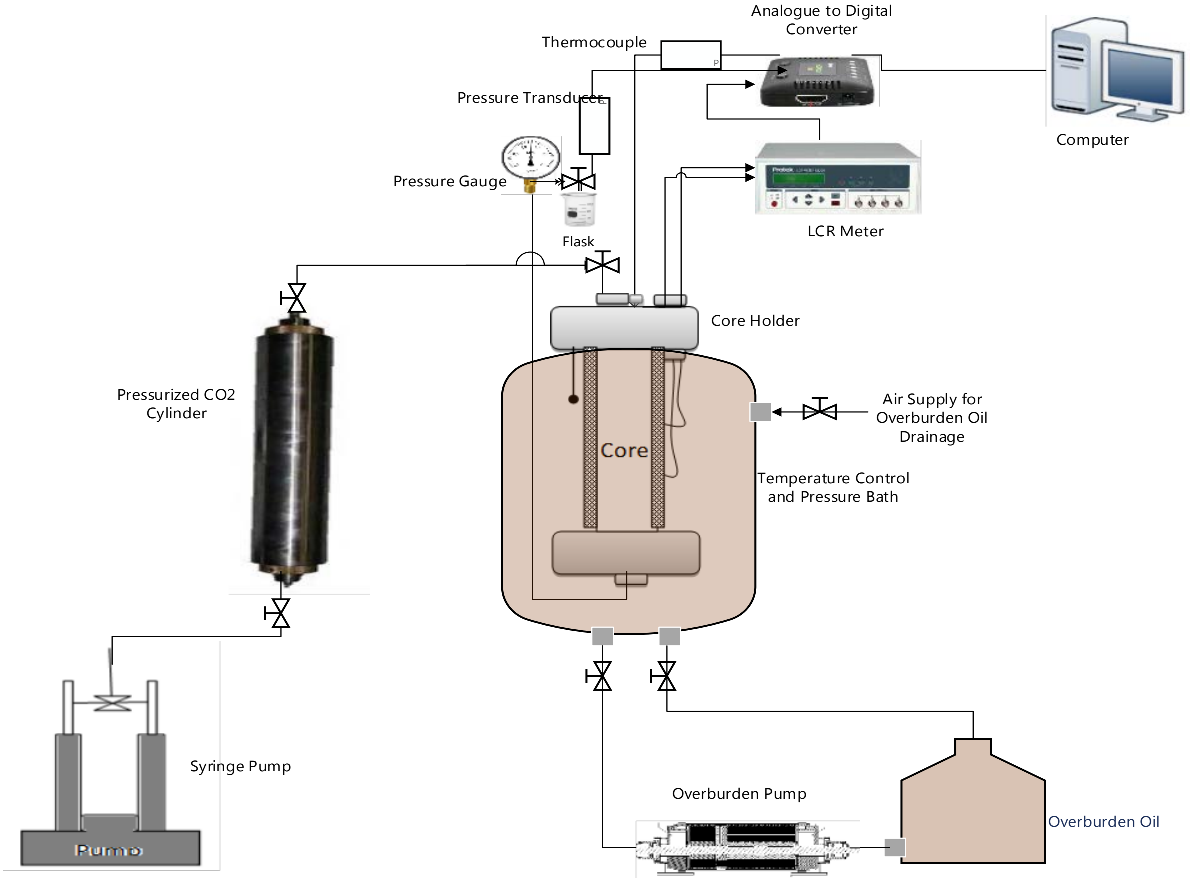
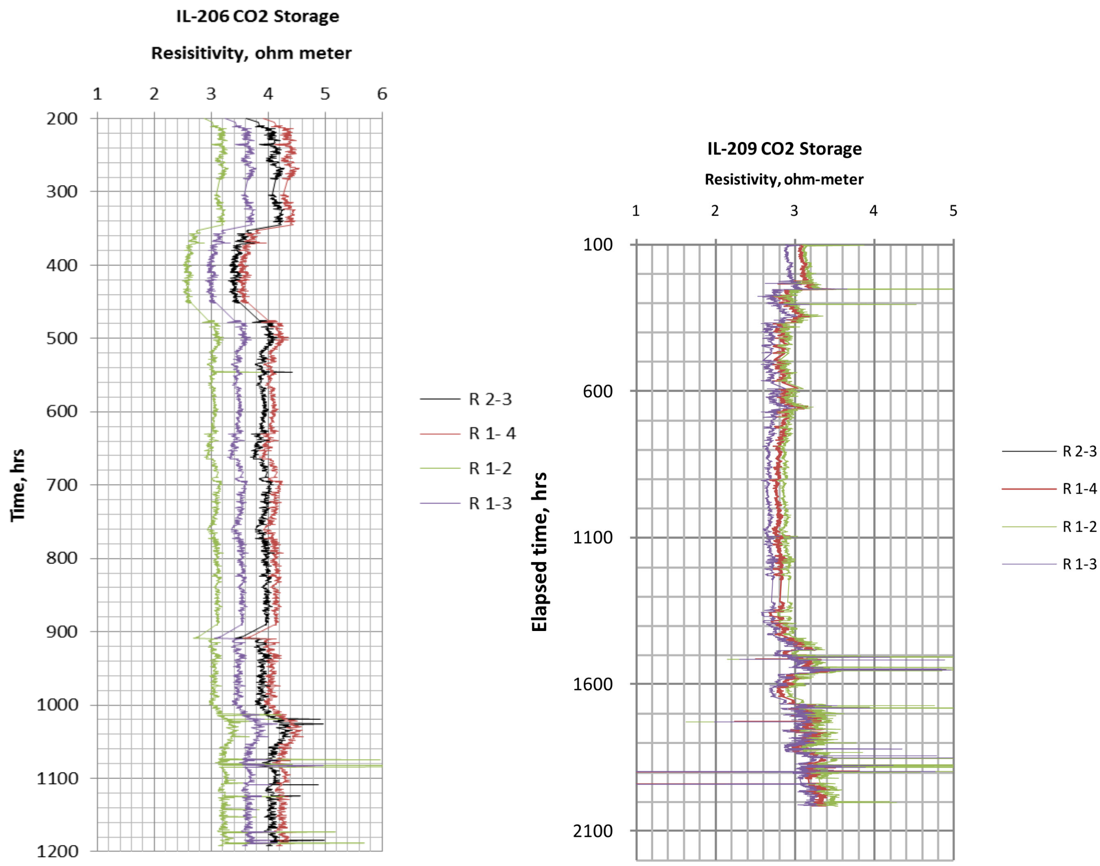


Figure 2. CO_2 sequestration and online resistivity measurement system.

later at about 1000th hour to 1100th hour. The same phenomenon was observed in another experiment done on a different sample (IL-209) confirming repeatability (**Figure 3(b)**). The effect of such variation in resistivity measurements is best described in **Table 3**. This behavior showed that drop in formation resistivity does not necessarily mean migration of CO_2 away from the location but can be due to CO_2/brine/rock interaction. To be able to explain the reason for such electrical behavior in **Figure 3**, we carried out elemental analysis (XRFD) on precipitates seen at the bottom of brine effluents taken from samples at the end of storage (**Figure 4**). The precipitates were identified to be carbonate grains which confirm carbonate grain dissolution (**Figure 5**). Samples' permeability also reduced from 423mD to 201mD in IL-206 and from 324mD to 297mD in IL-209 (**Figure 6**). However, porosity remains either the same or a bit lower.

4. Conclusions

1) Resistivity logging in sequestration project can give information on fluid rock interaction.



(a) (b)

Figure 3. Resistivity versus time while CO_2 reacts with brine saturated carbonate (A) IL-206 (B) IL-209.

Table 3. The effect of Archie's parameters on saturation estimation (Bennion et al., 96).

	Effect on S_x (If Under Estimated)	Effect on S_w (If Over Estimated)	Effect of Small Error
Satnration Exponent (n)	Value too low	Value too high	Strong
Archie Constant (a)	Value too low	Value too high	Moderate
Water Resistivity (R_w)	Value too low	Value too high	Strong
Cementation Exponent (m)	Value too low	Value too high	Moderate
Total Resistivity (R_r)	Value too low	Value too high	Strong

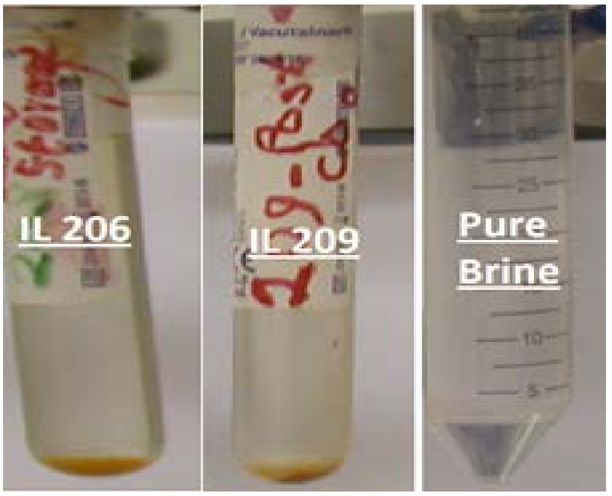


Figure 4. Brine effluent after CO_2 storage. Sediments seen at the bottom.

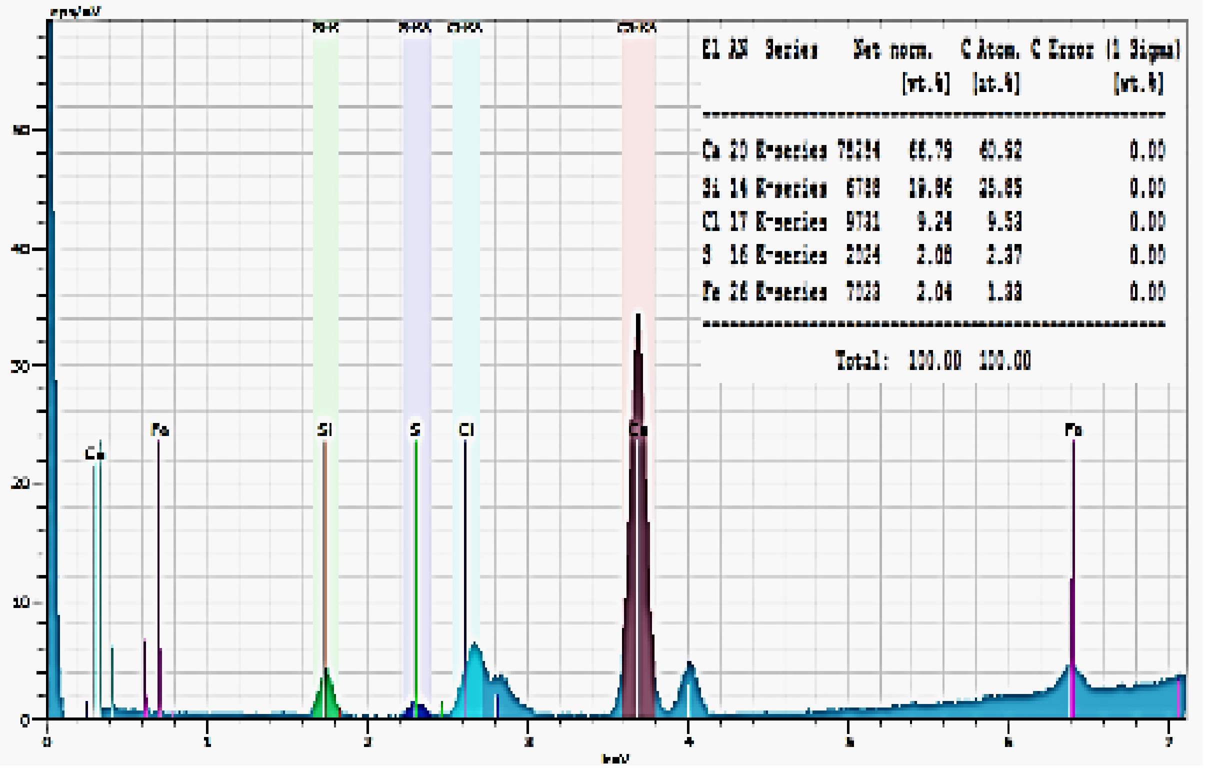


Figure 5. XRFD analysis on precipitates.

2) Successful interpretation of this electrical signature can be a breakthrough in the understanding of mineralization process in CO_2 sequestration projects.

3) Results showed that drop in formation resistivity does not necessarily mean migration of CO_2 away from the location but can be due to CO_2/brine/rock interaction

4) Collected brine effluents from storage showed carbon dioxide-rock fluid-rock interaction while XRFD analysis on precipitates showed that carbonate minerals and cementing materials dissolved in brine solution.

5) Rock permeability have also been found to be significantly impaired by formation damage while porosity seems to be slightly improved or remained unchanged.

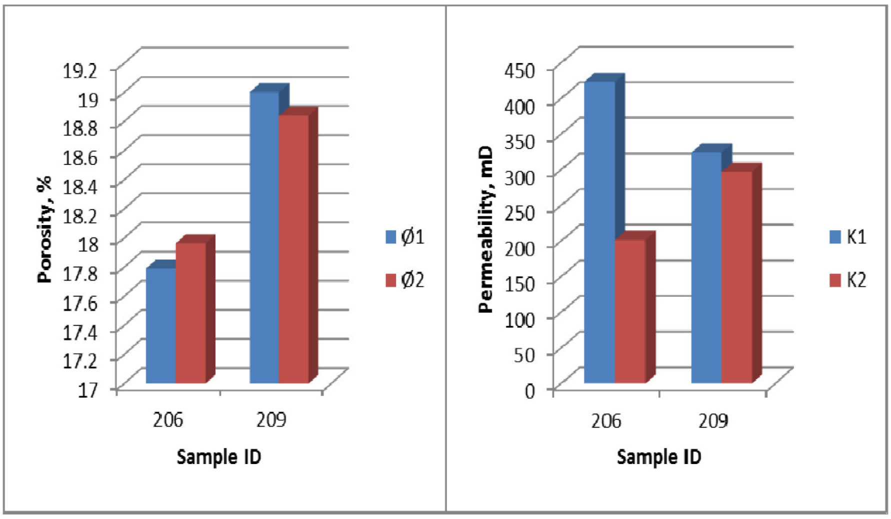


Figure 6. Porosity and permeability for IL-206 and IL-209.

Acknowledgements

The authors are grateful to the King Fahd University of Petroleum & Minerals and the King Abdul-Aziz Center for Science and Technology-Technology Innovation Center on Carbon Capture and Sequestration (KACST-TIC-CCS) for their support under project number KACST-TIC-CCS-6.

References

Bennion, D. B., Thomas, F. B., & Bietz, R. F. (P0003-96). Determination of Initial Fluid Saturations—A Key Factor in By-passed Pay Determination.

Benson, S. M., & Cole, D. R. (2008). CO_2 Sequestration in Deep Sedimentary Formations. *Elements, 4,* 325-331. http://dx.doi.org/10.2113/gselements.4.5.325

Christensen, N. B., Sherlock, D., & Dodds, K. (2006). Monitoring CO_2 Injection with Cross Hole Electrical Resistivity Tomography. *Exploration Geophysics, 37,* 44-49. http://dx.doi.org/10.1071/EG06044

Gaus, I. (2010). Role and Impact of CO_2 Rock Interactions during CO_2 Storage in Sedimentary Rocks. *International Journal of Greenhouse Gas Control, 4,* 73-89. http://dx.doi.org/10.1016/j.ijggc.2009.09.015

Giese, R., Henninges, J., Lüth, S., Morozova, D., Schmidt-Hattenberger, C., Würdemann, H., Zimmer, M., Cosma, C., Juhlin, C., & CO_2 SINK Group (2009). Monitoring at the CO_2 Sink Site: A Concept Integrating Geophysics, Geochemistry and Microbiology. *Energy Procedia, 1,* 2251-2259. http://dx.doi.org/10.1016/j.egypro.2009.01.293

Kiessling, D., Schmidt-hattenberger, C., Schuett, H., Schilling, F., Krueger, K., Schoebel, B., Danckwardt, & Kummerow, E. J. (2010). Geoelectrical Methods for Monitoring Geological CO_2 Storage: First Results from Cross-Hole and Surface-Downhole Measurements from the CO_2 SINK Tests It Eat Ketzin (Germany). *International Journal of Greenhouse Gas Control, 4,* 816-826. http://dx.doi.org/10.1016/j.ijggc.2010.05.001

Nakatsuka, Y., Xue, Z., Garcia, H., & Matsuoka, T (2010). Experimental Study on Monitoring and Quantification of Stored CO_2 in Saline Formation Using Resistivity Measurements. *International Journal of Greenhouse Gas Control, 4,* 209-216. http://dx.doi.org/10.1016/j.ijggc.2010.01.001

Wang, S., & Jaffe, P. R. (2004). Dissolution of a Mineral Phase in Potable Aquifers Due to CO_2 Releases from Deep Formations; Effect of Dissolution Kinetics. *Energy Conversion and Management, 45,* 2833-2848. http://dx.doi.org/10.1016/j.enconman.2004.01.002

Wang, S., Lee, M., Park, M.K., & Kim, J (2010). Box Experiments on Monitoring the CO2 Migration in a Homogeneous Medium Using Electrical Resistivity Survey. *Geoscience Journal, 14,* 77-85. http://dx.doi.org/10.1007/s12303-010-0009-1