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ERT monitoring of gas injection into water saturated sands: modelling and inversion of cross-hole laboratory data.

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Keywords: CO₂ and N₂ injection; electrical resistivity tomography; saturated sands; transport modeling; cellular automaton; electrode configuration.

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26 **ABSTRACT**

27 A set of laboratory experiments were performed in order to investigate the capacity of the
28 electrical resistivity tomography method to detect and monitor the circulation of gaseous CO₂
29 into geological media. The experiments consisted of injecting reactive (CO₂) or inert (N₂)
30 gases into reactive (carbonate) or inert (silica) sands saturated with water. The laboratory
31 setup was a metric-scale cylindrical tank instrumented with electrodes placed on vertical rods,
32 hence simulating a borehole to borehole monitoring network. The results demonstrated that
33 the ERT method can efficiently detect, locate and image gas circulation plumes. Two main
34 behaviors were identified: either an increase of the medium resistivity due to the invasion of
35 the porous space by an electrically insulating gas phase, or a resistivity decrease induced by
36 dissolution processes that enhance ionic concentrations in the saturating water. The observed
37 anomalies showed varying geometric shapes depending on which type of sand was used. A
38 3D cellular automaton model was built and managed to reproduce different gas plumes
39 circulation patterns and the electrical resistivity response associated. This modeling work
40 confirmed the link existing between the shapes of the resistivity anomalies, the gas plumes
41 geometry and the particle size distribution of the sand. Through a numerical sensitivity
42 analysis, several measuring protocols were tested and developed in order to improve the
43 imaging capacity of the electrical resistivity method. Results demonstrated that the most
44 efficient protocol was different depending on the shape of the gas plume, thus stressing the
45 importance of having a priori knowledge on the geological, lithological and hydraulic
46 characteristics of the subsurface, in order to correctly assess the most likely gas plume
47 geometry and hence design the most adapted monitoring protocol.

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51 **1. INTRODUCTION**

52 Since the beginning of the industrial era, anthropogenic activities such as combustion
53 of fossil resources and deforestation have resulted in a continuous increase of atmospheric
54 CO₂ concentrations (Neftel et al., 1985; Keeling et al., 2009), which have recently passed over
55 the symbolic threshold of 400 ppm (Showstack, 2013). It is very likely that these elevated
56 concentrations participate to major environmental impacts such as climate change (Manabe
57 and Stouffer, 1980; Cox et al., 2000) and ocean acidification (Doney et al., 2009). Carbon
58 capture and storage (CCS), which consists of capturing the CO₂ emitted by high emissions
59 industrial units and storing it in deep geological formations, is considered today as a viable
60 strategy to mitigate these impacts.

61 To ensure the long term efficiency of the process and prevent environmental impacts
62 associated with CO₂ leakage into nearby aquifers, it is vital to develop and utilize monitoring
63 tools that allow the detection and quantification of any CO₂ transfer out of the targeted
64 geological formation. Several approaches can be employed to achieve this goal. Some of them
65 focus on the monitoring of the CO₂ plume itself (generally in the supercritical state), and aim
66 to detect any change occurring in this area. Other strategies are directed toward the
67 monitoring of the geological formations located above the plume up to the surface, in which
68 case the goal is to detect a prospective CO₂ transfer within these structures (which would
69 likely happen under the gaseous state if the pressure and temperature conditions allow it). The
70 present study falls in the second category. Several approaches can be employed; in particular,
71 geophysical methods can be used to study in an indirect way various physical properties of the
72 subsurface, and detect possible variations of these properties due to the presence of leaking
73 CO₂. Among them, the electrical resistivity tomography (ERT) method is of particular interest
74 because the electrical resistivity of geologic materials is sensitive to the nature, the

composition and the distribution of fluids in the porous space. Furthermore, the costs of implementation are significantly lower than those of seismic methods (generally used by the oil and gas industry), thus providing a monitoring strategy with a higher temporal discretization.

To date, the ERT method has been successfully applied by numerous authors for CO₂ detection into water saturated geological media (Xue et al., 2006; Bergmann et al., 2017; Auken et al., 2014). Depending on the physico-chemical state of the studied medium, two main processes can affect the ERT response of the ground. In some cases, the gaseous CO₂ is observed to cause a global increase of the medium resistivity, as it acts as an electrically insulating phase within the porous space. Such effects have been observed and well documented through field experiments (Xue et al., 2006; Kiessling et al., 2010; Bergmann et al., 2017; Carrigan et al., 2013) and at the laboratory scale (Nakatsuka et al., 2010; Breen et al., 2012; Bosch et al., 2016). In other cases, it has been observed that the bulk resistivity of the ground can decrease when important dissolution processes are occurring (Peter et al., 2012; Vialle et al., 2014; Auken et al., 2014). The general sequence of events starts with the dissolution of some of the gaseous CO₂ into the saturating water, which becomes more acidic, thus enhancing the potential dissolution of minerals. All the newly dissolved ionic species lead to a more electrically conductive water and hence to a less resistive medium. In some cases, dissolution and desaturation effects can be observed simultaneously (Xue et al., 2006; Barrio et al., 2014, Yang et al., 2015).

In this paper, we present metric scale experiments which aim to simulate a gaseous CO₂ leakage through a relatively simple medium (well characterized sand saturated with water) and monitor the resistivity variations induced by the gas circulation. Although strong differences obviously exist, these experiments can be seen as an attempt to approach the conditions of a borehole-to-borehole ERT monitoring network through which a CO₂ leakage

path would form, in geological conditions close to those of a saturated aquifer with a relatively homogeneous structure. Two different sands were used in order to study in parallel carbonated environments (in which strong dissolution processes can occur) and silica based environments (in which dissolution processes are very weak). The experiments were performed using gaseous CO₂ and gaseous N₂ in order to study separately the “insulating phase” effect, when gas invades the porous space and no dissolution processes occur. Before the experiments, a preliminary study was conducted to investigate different ERT measuring protocols and choose an optimal one. Then, we present the results of the laboratory experiments. In view of the results, a model was designed under the form of a cellular automaton with stochastic behavior, in order to simulate gas injection and circulation through the medium. Coupling this model with the software R3t (Binley 2013), we were able to reproduce the ERT responses observed during the experiments and to infer the geometry of the gas plume, which changes depending on the grain size distribution of the sand. Finally, in a third phase, the cellular automaton model was used as a tool to study numerically the sensitivity of the electrodes configurations and to develop new, more efficient acquisition protocols.

2. MATERIALS AND METHODS

2.1 Experimental set-up

To perform the experiments, an 80-cm-high, 48-cm-diameter cylindrical Plexiglas tank was used (Fig. 1a). Electrodes were arranged in 10 rings of 6 cylindrical electrodes fixed on plastic rods attached on the inner wall of the tank. The vertical ring spacing was 5 cm, and the lowest ring was located 18 cm above the bottom of the tank (Fig. 1b). The electrodes were not placed exactly on the wall of the tank due to the diameter of the rods (1 cm) and the space between each rod and the internal wall (3 mm). The electrodes (4 mm in diameter and 5 mm

in length) were made of stainless steel to prevent from corrosion. Gas injection was performed using a valve placed at the bottom center of the tank. The gas was injected through a cylindrical air diffuser (10 cm in height and 12 cm in diameter, Fig. 1c) placed on the axis of the tank, between the planes 10 and 8. A small pipe connects the diffuser to a valve placed at the bottom center of the tank, and linked to gas reserves. All these components were made of PVC to minimize electrical disturbances.

Fig. 1. Experimental set-up. Picture of the cylindrical tank equipped with the electrodes (a) and of the gas diffuser (c). Sketch of the tank and position of the electrodes (b).

2.2 Porous medium

Experiments were performed with two types of sand. The first one is a silica sand from Fontainebleau (France) and the second is a carbonate sand obtained from commercial aggregates. The porosity values of the sands were estimated using decimetric columns filled with sand, by measuring the mass difference between the unsaturated state and the water saturated state. The permeability estimates were obtained by applying different hydraulic heads values on the saturated columns and monitoring the hydraulic flow. The structural and

hydraulic characteristics of the sands are listed in Table 1, where errors were calculated as the standard deviation of the results obtained on 4 independent measurements.

Table 1. Characteristics of the sands

	Sand	
	Silica	Carbonate
Composition	98 % mass silica 2 % mass feldspars	98 % molal CaCO ₃ 2% molal MgCO ₃
Grain size	200–400 μm	50–2000 μm
Porosity (%)	39 ± 1	45 ± 1
Permeability (μm^2)	4.5 ± 0.5	16.5 ± 1.3

To create a homogeneous distribution in the tank and avoid bubble trapping, the sand was slowly, regularly poured into water using a sieve whose mesh size is slightly larger than the largest grain size. Sand and water were then added and stirred simultaneously so as to always keep a free water layer of a few centimeters thick at the top of the medium, which was removed once the filling procedure was completed. Such procedure ensured that no significant air bubbles remained compared to the volume of the tank and the amount of gas injected during the experiments. The air diffuser was placed after the lowest ring of electrodes was reached. We avoided the formation of unfilled cavities in the zones between the vertical plastic rods and the internal wall of the tank, since they could act as preferential gas migration pathways. No compaction process was applied during the filling procedure except in these zones.

2.3 Gas injection and dissolution processes

We employed dinitrogen (N₂) and carbon dioxide (CO₂) during the experiments. Dinitrogen (N₂) presents a very low solubility into water (about 0.016 volume per volume at a temperature $T = 0^\circ \text{C}$), and does not react with the solid phase, while carbon dioxide (CO₂)

has a solubility into water at 0° C of about 0.88 and can react with the solid matrix once dissolved in water. In the conditions of the experiments, these gases can be considered as perfect insulators (their resistivity is about 15 orders of magnitude higher than the resistivity of the water used during the experiments). It is important to note that we worked with an opened system, where the injected gas is allowed to pass through and flow out of the medium (the tank is not covered up). Gas injection is done according to the following protocol: a first injection phase is performed at a rate of about 200 L·h⁻¹ for at least 30 min, creating a steady state with multiple gas pockets spread in the tank and gas migration pathways that seem stable, as indicated by the observation of bubbles appearing continuously at the same locations at the surface of the medium. Then, the injection rate is increased to 400 L·h⁻¹. Once a steady-state is reached (about 30 min later) the ERT acquisition starts and the injection is sustained until the whole acquisition sequence is performed, which lasted about 1.5 hours.

Experiments involving N₂ injection allowed studying the case where changes of resistivity are solely induced by an increase of the gas saturation, and where no dissolution processes occur. On the other hand, during CO₂ injection, chemical reactions due to carbonic acid might occur depending upon mineralogy (Xu et al., 2005; Busch et al., 2009; Raistrick et al., 2009). When put in contact with water, part of the gaseous CO₂ dissolves and reacts with water forming carbonic acid, which will itself dissociates, providing additional ionic species into the water. Those processes can be summarized by the following equations.

In the case of a solid phase composed of calcium carbonate, the dissolved CO₂ will also enhance the dissolution of part of the solid matrix, further increasing the ionic concentrations in the saturating water.

CO₂ and minerals dissolution can hence generate an input of dissolved species which modify the water resistivity value. Therefore, in experiments involving CO₂ injection, two phenomena can possibly affect the effective resistivity of the media: 1) water saturation level variation due to gas invasion, which would provoke an increase of the effective media resistivity and 2) dissolution processes, which would result in a decrease of the media resistivity. In the following, we will refer to these two phenomena respectively as the “insulating phase” effect and the “dissolution processes” effect.

2.4 Data acquisition and processing

The acquisition device was a Terrameter SAS 1000 connected with a 64-electrode multiplexer ES-1064 by ABEM. Injected current consists of square waves of alternating polarity of 20 mA to avoid polarization and associated noise (Parasnis, 1997). The acquisition delay was set to 0.1 s and the acquisition time to 0.2 s.

To perform a tomography reconstruction, we measured the potential differences resulting from current injection for a large set of electrodes arrays. Finally, to obtain an estimation of the resistivity distributions from the measured resistances, inversions were carried out with the software R3t (Binley, 2013), as it is suitable to the medium geometry and experimental conditions. R3t is based on a regularized objective function with weighted least square. Neumann conditions are specified at the boundaries where no current flow is allowed (see Binley, 2013 for more details). The solution of the inverse problem is obtained through a

Gauss-Newton procedure, as described in Binley & Kemna (2005). In this study we used the background regularization scheme described in Binley (2013), where the regularization parameter is optimized each iteration by carrying out a line search. The convergence of the inversion process occurred only when the root-mean-square (RMS) error, as defined in Binley (2013), was below 1.

The electrodes were modeled as point sources. This was considered an acceptable hypothesis given the results from Rücker & Günther (2011). According to their study, the errors related to the point source assumption become important when the ratio between the electrode spacing and electrode length overcomes 0.2. In the present study this ratio never overcomes 0.1 for all measurements.

As explained in Binley et al., (1995, 1996a, 1996b), Binley & Kemna (2005) and, Daily et al., (2004), the characterization of the error is required for ERT modeling to assess its effect during reconstruction of the true resistivity distribution. The error can be inferred from repeatability and reciprocity. Repeatability is related to the precision at which measurements are obtained under identic conditions. Reciprocity is based on the principle that switching positions between injection electrodes A and B and measuring electrodes M and N should yield the same resistance value.

The measurement error was estimated using both repeatability and reciprocity principles (Binley & Kemna, 2005 ; Daily et al., 2004) during a preliminary experiment (N₂ injection into saturated siliceous sand). One estimation was made before starting the gas injection and another one while gas injection was occurring but when gas migration pathways seemed stable. The error inferred from reciprocity was found to be always less than 1% in both cases. This value was considered low enough to be ignored and reciprocity was therefore not assessed during the experiments presented in this paper. Only the repeatability error was taken in account in the inversion process.

2.5 Optimal acquisition arrays

An important issue in ERT surveys relates to the sensitivity of the electrode configurations used for the acquisition and, by extension, to the sensitivity of the measuring protocol. The optimization of the electrode configurations on the surface of the soil (surface ERT) has been studied by several authors (Dahlin & Zhou, 2004; Christensen et al., 2006; Szalai et al., 2009). To our knowledge, most cross-well ERT monitoring strategies implement dipole-dipole or bipole-bipole arrays for acquisition (Pezard et al., 2016; Commer et al., 2016 ; Yang et al., 2015, Preignitz et al., 2013) sometimes mixing both arrays (Hermans et al., 2015). A review of pros and cons of some classical cross-borehole arrays are also presented in Bing & Greenhalgh (2000). In the case of measurements at the surface of a cylinder, Binley & Kemna (2005) recommend to use all linearly independent combinations. We chose to investigate this issue for our particular case, by testing several protocols on simple media with uniform resistivity distribution. The arrays bipole-bipole, dipole-dipole, Schlumberger and the protocol called *cross-rods* configuration (recommended by Binley & Kemna, 2005) were tested. For the bipole-bipole array (Fig. 2a), current adjacent electrodes are located in the same plane whilst potential electrodes are located on the same position in the upper or lower plane. In dipole-dipole (Fig. 2b) the current electrodes are placed in the same rod and the potential electrodes in the adjacent rod, but the separation between A and B and M and N covered all possible combinations. In the Schlumberger array (Fig. 2c) all the electrodes were placed in the same rod where the distance between A and M equals the distance between N and B. The *cross-rods* configuration consists of all possible 4-electrodes combinations located in the same plane (on the same ring), for each plane. All the possible 4-electrodes combinations are represented on Fig. 13. The main advantage of this protocol is that it forces the current lines to pass through the sand pack, enhancing the penetration depth.

Fig. 2. Scheme of the “classical” acquisition arrays: bipole-bipole (a), dipole-dipole (b) and Schlumberger (c). Letters A and B denote the positions of the current injection electrodes and M and N that of the potential measurement electrodes.

As a first test, for each protocol, the resistances measured on a medium composed of silica sand fully saturated with water were compared with the resistances values obtained through forward modelling of the same medium. The silica sand was saturated with a NaCl solution concentrated at 0.56 g.L^{-1} . The resistivity of such medium was measured thanks to a test cell, which yielded a value of $38 \text{ } \Omega \cdot \text{m}$. This resistivity value was then used to perform a forward modeling of the acquisition. Fig. 3 displays the results obtained with the different protocols tested. Concordance between measured and modeled resistances is much better when the *cross-roads* protocol is used than when the other “classical” configurations are used (bipole-bipole, dipole-dipole or Schlumberger). Given these results, we used exclusively the *cross-roads* protocol in the experiments described hereafter.

Fig. 3. Comparison between measured and modeled resistances. (a,b): Schlumberger protocol; (c,d): bipole-bipole; (e,f): dipole-dipole; (g,h): cross-rods configuration. *Left column:* measured (orange) and modeled (black) resistances values for each measurement. *Right column:* modeled vs measured resistances.

3. EXPERIMENTAL RESULTS

As explained in the previous section, two types of gas (N_2 and CO_2) and two types of sand (silica and carbonate) were used in this study, which resulted in the realization of four different experiments, one for each gas/sand combination. In the following, we will refer to each experiment using the initial of the sand type and the gas type formula. For example, C/ N_2 will be referring to the experiment involving the injection of dinitrogen into saturated carbonate sand.

3.1 ERT measurements on pure water

Fig. 4 shows the resistivity distribution obtained after inversion when applying the *cross-rods* protocol on a medium consisting of tap water with a resistivity of $21.3 \Omega \cdot m$ at $20^\circ C$. The values obtained after inversion are very close to the true water resistivity value, indicating the good performance of the measuring protocol and the inversion process. Only few artifacts can be observed toward the lateral zones of the tank, mainly located in the vicinity of the electrodes. The resistivity values associated with these artifacts deviate no more than 7 % from the real water resistivity value.

Fig. 4. Resistivity distribution obtained after inversion of ERT measurements performed on water only (water resistivity is $21.3 \Omega \cdot m$). a) Isometric view of the 3D model. b) 2D section between rods denoted A and B. The black square represents the gas diffuser position.

3.2 Gas injection into carbonate sand

Fig. 5 shows the resistivity distribution obtained for the experiments involving carbonate sand (C/N₂ and C/CO₂). For these experiments, the carbonate sand has been saturated with a NaCl solution whose initial concentration was 0.25 g.L⁻¹ ($\rho = 18.5 \Omega \cdot \text{m}$). During and after sand saturation, the resistivity of the water was found to decrease slowly, until reaching a stable value of about 14 $\Omega \cdot \text{m}$ at 17.5°C, which is most likely due to the dissolution of some carbonated particles during and immediately after the saturation process. Fig. 5a shows the resistivity distribution of the initial state, before gas injection, which is quite homogeneous except for some small artifacts in the vicinity of the electrodes. A slightly higher resistivity zone can also be observed in the central part of the tank, which might be a consequence of the plastic gas diffuser presence.

Fig. 5b and 5c show the results of experiments C/N₂ and C/CO₂, respectively. For both experiments, the resistivity distributions obtained are no longer uniform. The N₂ injection results in the formation of a high resistivity anomaly, likely to be induced by gas accumulation into the porous space. This anomaly exhibits a u-shape stretching from the gas diffuser to the surface of the tank and represents a significant resistivity increase of about 50 % compared to the initial state. The injection of gaseous CO₂ results, on the contrary, in a decrease of the resistivity values compared to the initial state. This anomaly is also u-shaped, centered with the axis of the tank, and stretching from the top of the diffuser to the surface of the sand pack. It is likely that the injection of gaseous CO₂ into a reactive medium such as carbonate sand leads to strong dissolution processes which increase the electrical conductivity of the saturating water and hence reduce the medium resistivity. In this case, even if gas accumulation is also occurring, the impact of dissolution processes is stronger and dominates the resistivity response of the medium.

We recall that the gas injection sequence consists of a first 30 min duration injection at a rate of $200 \text{ L} \cdot \text{h}^{-1}$ followed by a second 30 min duration injection at a rate of $400 \text{ L} \cdot \text{h}^{-1}$. At that point the “steady-state” has been reached (gas circulation patterns seem stable through visual inspection of the surface of the medium) and the ERT acquisition starts and lasts for about 1.5 hours. We note that the “steady-state” assumption is valid for experiment C/N₂ but not necessarily for experiment C/CO₂, where dissolution processes might still be occurring while the ERT acquisition is still in progress, thus leading to a kind of average resistivity distribution over the duration of the ERT acquisition (even though most dissolution processes are likely to occur before the beginning of ERT acquisition, given the fast kinetics of these reactions).

Fig. 5. Resistivity distribution obtained after inversion of ERT data acquired on carbonate sand saturated with water of resistivity $14 \text{ } \Omega \cdot \text{m}$: at the initial state (*left*), during N₂ injection of (*middle*), and during CO₂ injection (*right*). The black rectangle indicates the position of the diffuser.

We applied another inversion method in order to better extract the changes due to gas injection only, and remove the effects induced by the presence of the gas diffuser. This method is called the ratio-inversion. As explained in Miller et al., (2008) and Daily et al., (2004), a common approach for detecting changes from a background image is to normalize the data according to the following equation:

$$d_n = \frac{d_t}{d_0} \quad (6)$$

where d_t is the post-injection data, d_0 is the zero state data, and f_h is the data obtained through forward modeling of a homogeneous medium. The inversion process is then applied using this normalized data set (in our case a set of resistances values).

Fig. 6. Resistivity distribution obtained after application of ratio inversion on the data from experiments C/N₂ (*left*) and C/CO₂ (*right*). The resistivity anomalies remain u-shaped, stretching from the top of the diffuser to the top of the tank, and are centred with respect to the axis of the tank.

Fig. 6 show the results obtained with the ratio inversion method for experiment C/N₂ and C/CO₂. The shapes of the anomalies are globally very similar to those obtained with a “simple” inversion, i.e u-shaped, centered with respect to the tank’s vertical axis and stretching from the top of the diffuser to the surface of the sand pack. Based on these results, the ratio inversion method does not seem to provide significantly more accurate results, since the same shapes can be observed with a simple inversion. However, if one would intent to use these results in order to quantify the quantity of N₂ or CO₂ injected, it should be done with the ratio inversion results, which are supposed to take in account only the resistivity structures induced by gas injection, and exclude those present in the background resistivity distribution (like the gas diffuser).

3.3 Gas injection into silica sand

Fig. 7 shows the resistivity distribution obtained for the experiments involving silica sand (S/N₂ and S/CO₂). For these experiments, the sand was saturated with an electrolyte whose resistivity was 21 Ω·m at 18.5°C, which resulted in a higher background resistivity than for the carbonate experiments. As for the carbonate sand experiments, the initial state resistivity distribution (not shown here) was again quite homogeneous, exhibiting values mainly between 40 and 50 Ω·m and only few artifacts in the vicinity of the electrodes. Fig 7a shows the resistivity results obtained with a simple inversion. The injection of gaseous N₂ induces again the formation of a high resistivity anomaly, with values above 70 Ω·m, that we can attribute to the invasion of the porous space by the insulating gaseous phase. However, the shape of the anomaly is quite different since it does not seem to reach the upper part of the tank, as if most of the gas was being trapped in the lower part. The ratio-inversion method (Fig. 7b) manages to reduce some part of the anomaly that was likely due to the presence of the diffuser, indicating that gas accumulation in the lowest part of the tank might not be as

significant as the simple inversion results might suggest. However, the shape of the anomaly remain mainly horizontal, not stretching toward the top of the sand pack and hence being quite different from the results obtained with carbonate sand. Fig. 7c shows the results of the ratio inversion for experiment S/CO₂. Again, we observe a high resistivity anomaly, with values even higher than for experiment S/N₂. Even though it is likely that some of the CO₂ has been dissolving into the water, the “insulating phase” effect seems to be dominating in this case. In this case, the zone around the diffuser still exhibits high resistivity values after ratio inversion, which might be attributed to significant gas accumulation around the diffuser itself. Also, the anomaly again seems restricted to the lower part of the tank, showing horizontal components rather than the u-shape observed with carbonate sand. These different shapes suggest that the gas circulation patterns might be different depending on the type of sand used for the experiment.

Fig. 7. Inverted resistivity distribution for gas injection in saturated silica sand. a: N₂ injection, simple inversion. b: N₂ injection, ratio inversion. c: CO₂ injection, ratio inversion. The position of the air diffuser is given by the open rectangle.

3.4 Summary

These results confirm that the ERT method is a suitable monitoring technique to detect gas injection into geological media. Yet, the shape and the magnitude of the resistivity anomalies seem to depend on the nature of the sand, the type of gas injected and probably on the initial electrical conductivity of the saturating water. When the silica sand is involved, the anomaly seems to be restricted to the lower part of the tank, as if gas could not reach or accumulate in the upper volume. When the carbonate sand is used, the anomaly exhibits a u-shape centered with the axis of the tank, and spreading from the top of the diffuser to the surface of the tank. Also, for a highly reactive system such as carbonate sand and gaseous CO_2 (C/CO_2) the dominant physico-chemical processes are linked to the dissolution of the gas and of the solid matrix, leading to a decrease of the resistivity, as observed for example by Peter et al. (2012) or Vialle et al. (2014). Yet, for non-reactive or slightly reactive systems (S/N_2 , S/CO_2 , C/N_2), dissolution processes are weak and the dominant mechanism is the desaturation of the porous space, which increases the resistivity of the medium, as observed for example in the studies conducted by Nakatsuka et al. (2010), Breen et al. (2012) or Bosch et al., (2016).

In the following discussion, we want to address two main questions raised in view of these experimental results. 1) In the case of slightly reactive systems, why does the increase in resistivity exhibits different anomaly shapes depending on the type of sand involved. 2) Is it possible to develop new measuring protocols that will further improve the ability of the method to capture the shape and magnitude of these anomalies?

Note that these two questions seem to overlook the case where dissolution processes dominate the electrical response of the system whereas it is relevant in many scenarios of CO₂ leakage in the subsurface. We justify this choice because these particular cases have important temporal and kinetic aspects that are not addressed nor captured by the experiments presented previously, which rather focus on steady-state situations. However, they can both still bring pertinent answers to some of the possible CO₂ leakage scenarios, as well as to any other problems involving gas circulation in the subsurface or which demand the detection and delimitation of a resistivity anomaly.

In the next section, we will address question 1) and discuss how the sand grain size and the gas injection rate might be important factors controlling the geometry of the gas circulation plume, which results in varying resistivity anomaly shapes. We present a numerical model that was developed to challenge this hypothesis. It is structured as a stochastic cellular automaton and allows to simulating the injection of gas into saturated sands and computing the resulting electrical resistivity distribution of the medium. Finally, in section 5, we use this model to address question 2) and investigate the development of new measuring protocols that would improve the detection of these anomalies.

4. MODELLING

4.1 The effect of grain size and gas injection rate on gas plume geometry.

Apart from issues related to the geological storage of CO₂, the way that gas spreads into a saturated geological medium has also been studied during the development of the “air sparging” method (Böhler et al., 1990; Johnson et al., 1993), a remediation technique which consists of injecting air into or below a shallow contaminated area. While the air flows towards the surface, the contact with the pollutant triggers biodegradation processes and volatilization, allowing some of the pollutant to flow toward the surface under gaseous form,

513 along with the injected air. The context of air-sparging is relevant here because it involves the
514 circulation of a nearly non-reactive gas (air), which is why many studies dealt with laboratory
515 experiments very similar to those described in this study, especially those involving N₂
516 injection.

517 At the end of the 1990s, most of the authors working on the air-sparging method
518 agreed that, in a saturated medium, the air circulates according to two main patterns. The
519 “bubble flow” consists of a discontinuous circulation under the form of bubbles (Wehrle,
520 1990; Sellers and Schreiber, 1992); while the “channel flow” describes a circulation through
521 continuous pathways, often called channels, which evolve independently from each other and
522 are separated by zones fully saturated with water (Clayton, 1998; Elder and Benson, 1999).
523 The laboratory studies from Ji et al., (1993), Baker & Benson (1996) and Brooks et al., (1999)
524 have shown that the main discriminating factor between these two flow modes is the grain
525 size of the porous medium. Brooks et al., (1999) gathered from several studies the different
526 kind of flow that can be observed depending on the mean grain size of the studied medium.
527 This comparison (see their figure 1) suggests that for a grain size below 1 mm, the air
528 circulation follows the channel flow type, and for a grain size above 2 mm only the bubble
529 flow is observed. In between, a transition behavior is observed which consists of
530 discontinuous channels, and that later authors have been calling “mixed flow” or “slug flow”.

531 For thin sands ($d < 0.21$ mm), Peterson et al., (2001) identify a third type of gas flow
532 that they call “chamber flow”. It involves the existence of continuous channels, which will
533 accumulate in some location of the porous medium, following mainly horizontal components,
534 hence forming gas accumulation “chambers” connected between each other through
535 continuous channels that are essentially vertically oriented.

536 Brooks et al., (1999) have also studied the influence of the gas injection rate upon the
537 type of flow encountered. Their observations suggest that low injection rates favor the “slug

flow” or “mixed flow” type, whereas high injection rates allow the gas to form continuous channels. The different kind of flow observed depending on grain size and injection rate are summarized in their table 1. Regarding the experiments described in this paper, the silica sand and the carbonate sand maximum grain size are respectively 400 μm and 2 mm, and the injection rate is high with respect to the references from Brooks et al., (1999). We can therefore safely assume that the gas circulation during the experiments followed a “channel flow” type or at the very least a “slug flow”, and this assumption has been considered throughout the following modeling work.

4.2 Modelling gas injection into saturated sands

The model developed in this paper has been built as a cellular automaton using Matlab. A 3D parallelepiped matrix is generated, whose dimension is $d \times d \times h$, d being the diameter of the cylindrical tank used during the experiments (Fig. 8). With this model, each term of the 3D matrix corresponds to a 1 cm^3 volume of the tank that we refer to as a cell. The model consists of simulating gas circulation patterns through the cells, then defining an effective water saturation value for each cell and finally estimating the associated resistivity value using Archie’s law (Archie 1942).

Fig. 8. Isometric view of the parallelepiped matrix. Green cells have been assigned the value 1 and represent the studied medium, while transparent cells have been assigned the value NaN and correspond to the outside of the tank.

4.2.1 Modelling gas circulation patterns

As explained previously, based the grain size of the sand used during the experiments, it can be considered that gas circulation follows the “channel flow” type. The first step of the modeling process is hence to define the number of gas channels created during the injection, their dimensions and their respective trajectory. Selker et al., (2007) describe the formation of gas channels as a competition between restriction forces imposed by the capillary pressure and buoyant forces produced by the density difference between gas and water. Assuming that channels are cylindrical and that their extremity is hemispheric, Selker et al., (2007) define the channels radius value to be

$$R = \sqrt{\frac{3\sigma}{\Delta\rho g}} \quad (7)$$

where σ is the interfacial tension between gas and water (N/m), $\Delta\rho$ is the density difference between gas and water, and g is the gravity acceleration (m.s^{-2}). The computation of R in the case of N_2 into water saturated sands yields a value of approximately 0.5 cm. This implies that the channel diameter scale is similar to the scale of one cell of our cellular automaton grid. Selker et al., (2007) also propose an estimate of the number of gas channels created, that depends on the injection rate and on the physical and hydraulic properties of the gas and granular medium, respectively:

$$N \approx \frac{Q\mu}{3\pi\sigma\kappa} \quad (8)$$

where Q is the gas injection rate ($\text{m}^3 \cdot \text{s}^{-1}$), μ is the dynamic viscosity of the gas ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) and κ is the permeability to gas (μm^2) of the medium, that we estimate using the permeability to water values given in Table 1. Equation 9 yields about 300 channels for the silica sand and about 100 channels for the carbonate sand.

4.2.2 Stochastic evolution of channel trajectory

Once the number and dimensions of gas channels have been estimated, the next step is to define the geometry of the gas plume, *i.e* the trajectory of the gas channels. Looking back at Fig. 5b, the resistivity anomaly suggests that the gas spreads following a parabolic shape or “u-shape”, which has indeed been observed in several studies (Ji et al., 1993; Semer et al., 1998; Selker et al., 2007). Fig. 7, however, suggests that the gas is mainly concentrated in the lower part of the tank. This kind of behavior has been less frequently reported, but we assume in the following that it can be related to the “chamber flow” described by Peterson et al., (2001). Indeed, the chamber flow pattern has been reported for fine grain sands ($d < 210 \mu\text{m}$), which is approximately consistent with the grain size of the silica sand used in the experiment ($210 \mu\text{m} < d < 400 \mu\text{m}$). It is therefore possible that the gas accumulation in the lower part of the tank consists of one “chamber” spreading laterally, and that gas is flowing toward the surface through vertical channels whose concentration is not high enough to produce significant resistivity anomalies. This hypothesis is supported by visual observations that were made during similar gas injection experiments using the same silica sand (see Kremer et al., 2016a and their Figure. 9b).

Our first objective in this modeling work is to implement the parabolic shape gas circulation mode and the “chamber” flow mode, to see if they can respectively explain the resistivity anomalies observed during experiments C/N₂ and S/N₂. For Selker et al., (2007),

the parabolic circulation pattern can be explained by the fact that in a relatively isotropic medium, the probability that a gas channel moves toward one lateral direction or another is the same. Therefore, the probability distribution associated with the position of a gas channel in the horizontal plane follows a Gaussian law, and the channel concentration is maximal at the injection point.

To model this behavior, a stochastic approach has been adopted. It consists of simulating the trajectory of each gas channel independently as the successive invasion of neighboring cells. Each channel begins at a cell chosen randomly just above the gas diffuser. The trajectory of the channel is then constrained to 2 possibilities: 1) move up in one of the cells located above which share at least one edge with the present cell (9 possibilities); 2) move laterally in one of the cells sharing at least on edge with the present cell (8 possibilities). The first probabilistic event “gas moves vertically” is named V, of probability P_V , while the second probabilistic event “gas moves horizontally” is named H, of probability P_H . As the universe is restricted to these two events we have

$$P_V = 1 - P_H \quad (9)$$

For a given value of P_H (or P_V), a selection with equal probability is performed to determine whether the channel moves vertically or horizontally. Then another selection is done to determine which of the 8 (or 9) cells will be invaded. This is repeated until a cell at the top of the tank is reached. After that, we consider that the channel is stable and that gas is flowing out of the tank. This stochastic process is applied independently to each gas channel created. At the end of the simulation, the number of channels passing through each cell is recorded. The shape of the gas plume is then controlled by the value of P_H , as shown on Fig. 9 where, as expected, high P_H values result in a wider gas plume, with a higher number of channels in the middle part.

Fig. 9. Vertical cross-sections of the parabolic shape circulation model, for several values of probability P_H . The color code represents the total number of channels passing through each cell.

This way of simulating gas channel evolution preserves the Gaussian distribution of pathways described by Selker et al., (2007), as shown in Fig. 10a. To model the chamber flow accumulation describe by Peterson et al., (2001), the same stochastic approach is used, except that the probability P_H is no longer fixed, but is a function of the vertical position of the current cell.

$$P_H = \left(1 - \frac{z - z_{diff}}{h - z_{diff}}\right) \cdot e^{\frac{z - z_{diff}}{z_{max} - z_{diff}}} \quad (10)$$

where z is the actual position of the channel extremity, z_{diff} is the diffuser vertical location and h denotes the height of the surface. Such a definition implies that the probability of horizontal movement is high close to the diffuser location and decreases exponentially as the channel evolves toward the surface. It results in channel accumulation in the lower part of the tank, while the channel density is lower in the upper part (see Fig. 10b and 10c), thus reproducing the concept of “chamber flow accumulation”.

Fig. 10. a) Histogram representing the lateral distribution of channels in the parabolic shape model. The distribution is globally Gaussian. b) Vertical cross-section of the accumulation chamber model, and c) corresponding vertical distribution of channels.

4.2.3 Defining saturation level and resistivity values

As explained previously, given the definition of gas channel dimensions (equation 6), the channel diameter is approximately of the same order as the model cell size. Therefore, we consider in the following that several channels passing through the same cell only result in one channel passing through the cell. A fixed gas saturation value S_g is then attributed to all cells invaded by gas. This value is chosen randomly between 0.4 and 0.5, as observed by Chen et al., (1996). The saturation values distribution is then smoothed by averaging the value

of each cell with the value of its closest neighbors. Finally, the resistivity value of each cell is calculated using Archie's law (Archie, 1942). The porosity values of the sands are known, and the cementation exponent m was chosen to be 1.3 (unconsolidated sands). Note that surface conduction is not taken in account with Archie's law, which is acceptable given the conductivity value of the fluid which is in the range where surface conduction is negligible compared to bulk conduction (Glover, 2010). Fig. 11 displays the vertical sections of the saturation values obtained with the model and the associated resistivity distribution for the “parabolic” circulation case and for the “chamber accumulation” case.

Fig. 11. Vertical and horizontal cross-sections representing the distribution of channels, saturation values and resistivity values, respectively, for the parabolic circulation model (a,b,c) and the chamber accumulation model (d,e,f).

The gas circulation patterns are modeled assuming that they follow a “channel flow” type, as discussed previously. We parametrize their geometry and density based on the study conducted by Selker et al. (2007) which describes the formation of gas plumes into saturated sands. The way these channels circulate within the tank is controlled by probabilistic laws,

described in appendix A. They are key parameters that allow modelling different gas plume geometries and reproduce those observed during the experiments. In order to model the injection of N₂ into the carbonate sand, we use probabilistic parameters that produce a u-shape (or parabolic) gas plume (Fig. 11a), as suggested by the experimental results (Fig. 5 and 6), and as observed in several studies about gas injection into sands with similar characteristics (Ji et al., 1993; Semer et al., 1998; Selker et al., 2007). In the case of N₂ injection into silica sands, the resistivity shape observed in the experiments reminds the “chamber flow” geometry observed by Peterson et al. (2001) on similar fine grain sands. The probabilistic parameters are therefore adapted to reproduce this specific geometry (Fig. 11d). Then, gas saturation values are assigned based on Chen et al., (1996), smoothed by averaging with the neighboring cells (Fig. 11b and 11e), and resistivity values are finally computed using Archie’s law (more detail in appendix A). The results are 3D representations of the resistivity distribution within the tank, as shown on Fig. 11c and 11f.

4.2.4 Comparing model and experimental results.

The software R3t was then used to: 1) calculate the forward model associated with these two synthetic resistivity distributions, considering the same electrodes locations and measuring protocol (*cross-rods*) as during the experiments; 2) calculate the inverse model using the so computed synthetic resistances. Fig. 12 compares the inversion results obtained based on the synthetic models (b and d) with those obtained based on experimental measurements (a and c). The resistivity range is very similar in both cases (between 60 and 90 Ω·m), and the shapes of the high resistivity anomalies also match, thus confirming that in silica sands, the gas is likely to be circulating following the chamber accumulation flow type whereas in carbonate sands, the parabolic gas plume is a plausible description of the gas circulation patterns.

Fig. 12. Comparison between the inversion results obtained from the experimental data and from the cellular model, for the accumulation chamber (a, b) and the parabolic cases (c, d), respectively.

These results suggest that, in saturated sands, the grain size distribution is likely to be the main factor controlling the shape of the gas circulation patterns, and hence of the resistivity anomaly that is observed. The differences between the observed shapes are quite significant. Grain size distributions that result in high permeability values (e.g. $16.5 \mu m^2$ for carbonate sand) will favor the occurrence of u-shaped gas plumes that have a strong vertical component. For lower permeability values (e.g. $4.5 \mu m^2$ for silica sand), the gas plume takes the form of an accumulation chamber with dominating horizontal components. One could therefore expect that grain size variation within an aquifer will produce specific resistivity anomaly shapes alternatively dominated by vertical and horizontal orientations. These observations highlight the fact that knowing the grain size distribution of sandy aquifers is very important if one wants to anticipate the shape of the gas circulation patterns, and hence of the prospective resistivity anomaly that would be observed through ERT monitoring of the aquifer.

5. DISCUSSION

In light of these results, we investigated the possibility to develop new measuring protocols that would improve the capacity of the ERT method to detect and capture the shape

and magnitude of the resistivity anomalies produced by gas circulation into saturated sands. Indeed, even if some information is available to help anticipate the shape of the expected resistivity anomaly, it is possible that different cross-hole protocols would not be equally efficient into detecting and retrieving the gas plume geometry because of their different sensitivity characteristics.

As a reminder, the *cross-rods* protocol was initially chosen to perform the experiments because it was proven to be more efficient than the bipole-bipole, dipole-dipole and Schlumberger protocols (see section 2). Here we attempt to design even more efficient protocols than the *cross-rods*. To do so, our approach consists of analyzing the sensitivity distribution of all the electrode configurations that composed the *cross-rods* protocol, so as to combine them in a new, more optimal organization. The respective efficiency of these new protocols is then tested using the cellular automaton model, by simulating rough synthetic resistivity distributions as well as realistic gas circulation patterns.

5.1 Electrode configurations families.

The *cross-rods* protocol consists of performing all possible electrode combinations for current injection and voltage measurement, in each of the 10 planes (rings) of electrodes instrumenting the tank. Electrodes from different planes are never used together for a single measurement. This protocol hence results in several electrode geometric combinations. To be more specific, as a plane contains 6 electrodes, the number of combinations possible for 4 electrodes measurements yields 45 possibilities (not including reciprocals). Among these 45 possibilities, one can distinguish 8 different geometric families, which are represented in Fig. 13 and that we name “classes” 1 to 8.

Fig. 13. Schematic representation of the different electrodes arrays families encountered in the *cross-rods* protocol.

5.2 Sensitivity distribution of the different families.

Given the different geometries of these electrodes combinations, they present different sensitivity distributions that we chose to estimate using the following procedure. The objective is to perform forward modeling using the *cross-rods* protocol on two cylindrical media (representing the cylindrical tank) to which a different resistivity distribution is applied. We attributed to the first medium a homogeneous resistivity distribution of $25 \Omega \cdot \text{m}$ (same order of magnitude than the saturated sand). The second medium has the same background

resistivity value in which is included a more resistive cylinder ($100 \Omega \cdot m$) whose axis is identical or parallel to the cylindrical tank axis. For each electrode configuration class, the resistances obtained through forward modeling are then compared by computing the relative resistance variation percentage between the “cylindrical intrusion” model and the homogeneous model:

$$\partial R_{\%} = \frac{|R_{cyl}| - |R_{hom}|}{|R_{hom}|} \quad (11)$$

where R_{cyl} and R_{hom} are the resistances values obtained through forward modeling on the cylindrical intrusion model and the homogeneous model, respectively. Generally speaking, the sensitivity distribution quantifies how much a given resistance measurement is affected by a change of resistivity in the medium. Here, the parameter $\partial R_{\%}$ can be seen as a “macroscopic” estimation of the sensitivity since it quantifies how much the resistance measured is affected by the presence of a resistive cylinder. Then, by displacing the cylindrical intrusion into the (xy) plane, and repeating this forward modeling comparison, one can quickly obtain a 2D mapping estimation of the sensitivity distribution in the (xy) plane. These sensitivity distributions were estimated for each electrode geometric configurations and regrouped in Fig. 14, where high relative variations values denote a higher sensitivity area. The resolution of this mapping is relatively poor (resolution equivalent to the cylindrical intrusion diameter), but was very quick to implement, and nevertheless yields quantifiable and valuable information regarding the sensitivity behavior of the different electrodes configurations used in the *cross-rods* protocol.

Fig. 14. Sensitivity distributions obtained for each class of electrode array geometry. Letters C-, C+ and P+, P-, denote the current injection electrodes and potential measurement electrodes locations, respectively.

Fig. 14 shows that the geometries can be separated into two different groups. Geometries n°1, 4, 6 and 7 have a relatively high sensitivity distribution, rather homogenously distributed and

842 symmetrical with respect to the center of the tank (excepting n°4). Among them, geometry
843 n°6 is of particular interest since it presents the highest sensitivity values at the center of the
844 tank, and high values ($> 10\%$) on a diametrically symmetrical fringe. Another group
845 composed of geometries n°2, 3, 5 and 8, rather show high sensitivity values at the lateral areas
846 of the tank. In particular, geometry n°3 has the highest values distributed over approximately
847 a third of the tank circular surface. This suggests that, taken together, the 3 electrode arrays
848 that possess geometry n°3 provide a high sensitivity scan of the entire tank surface, except in
849 the center.

850 Another electrode configuration which deserves special attention is geometry
851 n°8. This specific set-up yields extremely high relative variations compared to the others (in
852 the order of $10^4\%$). This is due to the numerical nature of the study, and is directly related to
853 the fact that the injection and measuring dipoles are perpendicular. Because of this, in a
854 perfectly homogeneous medium, perpendicular dipoles imply that the current lines and the
855 equipotential lines are perpendicular, yielding a null potential difference and therefore a null
856 resistance. In our case, the obtained resistance is not exactly 0 because of the irregularities of
857 the mesh (the tank is not perfectly cylindrical), but remains very small (of the order of 10^{-3}
858 Ohm). Then, including a different resistivity object in the environment still leads to the
859 measurement of small resistances, in the order of 1 Ohm, which results in a relative variation
860 of several order of magnitude. Even though these considerations depend on the numerical
861 nature of this study, it has also been observed in the real case that the relative variations
862 induced by gas injection in a relatively homogeneous medium are higher for the
863 measurements associated with this perpendicular electrode geometry. In the following
864 sections, we investigated further this specific configuration (and others), to verify if this
865 specific behavior could play an important role in the reconstruction of resistivity contrasts and
866 anomalies.

5.3 Designing new protocols

In this section we present several numerical tests performed in order to explore the behavior of some specific electrodes geometries and assess their influence on the quality of the inversion results. We also aim at creating new protocols that may possess an improved sensitivity and resolution compared to the *cross-rods* protocol. To do so, we performed a series of tests, which consisted of applying different protocols for the computation of the forward and then inverse problem, on specific resistivity distributions composed of a high resistivity object ($100 \text{ } \Omega \cdot \text{m}$) included into a lower resistivity background ($25 \text{ } \Omega \cdot \text{m}$) and comparing the quality of the inversion problem results between each protocol. The high resistivity object was chosen as a cross, composed of two perpendicular parallelepipeds (Fig. 15), so as to assess the capacity of the tested protocol to retrieve both horizontal and vertical structures.

Fig. 15. Representation of the cross-shape resistivity intrusion embedded into the homogeneous resistivity cylindrical medium.

Test 1: influence of each electrode geometry on the *cross-rods* protocol performance

In order to investigate the importance of each of the 8 electrode geometries on the global performance of the *cross-rods* protocol, we performed a first test consisting of removing all measurements associated to a specific electrode geometry and compare the ability of these “truncated” protocols to retrieve the cross shaped object. The results are presented on Fig. 16. As expected, removing some measurements from the protocol deteriorates the quality of the inversion results. However, the degree of deterioration varies depending on which electrode geometry is excluded. Geometries n° 1, 2 and 3 seem to play an important role since their removal results in a strong weakening of the results quality compared to the full *cross-rods* protocol. The worst result seems to be obtained when geometry n°3 is absent from the protocol. Geometry n°6 may be the most important one, since without the associated measurement the inversion process cannot converge.

Test 2: measurements with electrodes in different planes.

The purpose of this test is to analyze the contribution of measurements involving electrodes from different planes. Given the results from the previous test, we chose to develop these *inter-planes* protocols using electrode configuration geometries n°3 and n°6. We define an *inter-plane* measurement as an electrode configuration where one current injection electrode and one potential measurement electrode are located in a different plane from the two other electrodes. Fig. 17a illustrates this definition. It shows that one electrode geometry can be derived in 9 additional measurements (without considering reciprocals). A protocol was designed which included all the *inter-planes* measurements possible using geometries n°3 and n°6. However this protocol gathered 900 measurements, when the initial *cross-rods* protocol has only 450 measurements. In order to have a comparable number of measurements and thus truly compare the global efficiency of the protocol, we designed a *split inter-planes* protocol, for which each initial geometry is not derived in 9 additional measurements but in 4, depending on the plane position of the initial measurement (Fig. 17b). By doing so the *split inter-planes* protocol is composed of 576 measurements, which is closer to the number of protocols composing the *cross-rods* protocol.

Fig. 18 compares the results of the “cross shape” test for the *cross-rods*, the *inter-planes*, and the *split inter-planes* protocols. We clearly observe that the *inter-plane* protocol gives the best results. The resistivity values are higher where the cross shape is supposed to be reconstructed, and the horizontal part of the shape is better retrieved with *inter-planes* protocols than with the *cross-rods* one. For a smaller amount of measurements (*split inter-plane protocol*), the results are slightly worse but still remain much better than the *cross-rods* protocol.

Fig. 18. Results from test 2. Comparison between the cross-shape test using a) the *cross-rods* protocol (450 measurements), b) the *inter-planes* protocol (900 measurements) and c) the *split inter-planes* protocol (576 measurements).

Test 3: random construction of protocols

Based on these results, we worked on building protocols using measurements from the *cross-rods* protocol and from the *inter-planes* protocols associated with geometry 6 and 8. As it is quite difficult to identify which specific configuration brings the most information, we chose as a first step to build protocols with 450 measurements by randomly selecting 150 electrodes configurations in the *cross-rods* and in the *6 and 8 inter-planes* protocols. We generated 10 different protocols and compared their results to the cross-shape test. Only 3 over 10 produced better results than the cross-rods protocol, among which one showed particularly good results that we named *Random*. By studying which electrode geometries were picked-up initially, we noticed that these 3 protocols have in common a high amount of measurements from geometry 2, 3, 4, 5, 6 and 8, and a low amount from geometry 1 and 7. Considering that the random pick-up from *6 and 8 inter-planes* protocol already bring a sufficient amount of geometries 6 and 8, we chose to restrict our random pick up in the *cross-rods* protocol to geometries 2, 3, 4 and 5, in proportions of 30, 60, 30 and 30 measurements, respectively. Among the 10 protocols generated with this method, 8 demonstrated a superior behavior at the cross-shape test than the *cross-rods* protocol, and one called the *Random Constrained* was selected as the most efficient.

Test on new geometries and realistic resistivity distribution

From the three tests previously described, three protocols emerged which showed a better capacity than the *cross-rods* protocol to reconstruct the cross-shape object: the *split inter-planes*, the *Random*, and the *Random constrained* protocols. Fig. 19 compares the ability of these protocols to reconstruct other geometries such as a non-centered cross (Fig. 19a) and a diagonal rod (Fig. 19b). In these two cases, the three new protocols still produce a better restitution of the initial resistivity distribution, and the highest resistivity values are reached

with protocol *Random constrained*. Fig. 19c and 19d compare the results of forward modeling and inversion processes performed on resistivity distributions that represent the “chamber flow” and “u-shape” gas plumes simulated with the cellular automaton model. In these cases, results are not anymore so consistent. The *Random constrained* protocol still demonstrates a satisfying behavior (2nd best for both distributions), but is not anymore the most efficient. For the chamber flow distribution, the *Random* protocol is superior, whereas for the u-shape distribution the *cross-rods* protocol is the most efficient protocol. These results demonstrate that the efficiency of the protocol to detect a gaseous plume greatly depend on the geometry of the plume. Here we found that *Random constrained* seems to be quite polyvalent whereas *Random* and *cross-rods* are respectively the best choices to image a “chamber flow” or a “u-shape” geometry.

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1024 **CONCLUSION**

1025 The laboratory experiments confirmed the ability of the ERT method to detect, locate
1026 and image CO₂ and N₂ plumes into water saturated sands. The experiments validated the
1027 occurrence of two different effects leading to opposite resistivity variations compared to the
1028 background distribution: the “insulating phase” effect and the “dissolution processes” effect.
1029 Also, the resistivity anomalies produced by N₂ injection exhibit different shapes depending on
1030 the type of sand used during the experiments. Parabolic shapes are observed with carbonate
1031 sands, whereas more flattened shapes are observed with silica sand.

1032 Using a gas circulation model designed as a cellular automaton with stochastic
1033 behavior, we managed to reproduce the resistivity distributions observed during the
1034 experiments involving N₂ injection and hence infer the geometry of the gas circulation
1035 plumes. The interpretation of these results with respect to existing literature on two-phase
1036 flow into granular media strongly support the hypothesis that the particle size distribution of
1037 the sand is an important factor controlling the geometry of gas circulation plumes, and hence
1038 of the resistivity anomalies obtained during the ERT monitoring. Sands with larger grain
1039 diameter ($d > 500 \mu m$) will tend to produce u-shape or parabolic anomalies, whereas in

smaller grain distributions ($d < 400 \mu m$), gas can accumulate within horizontal chambers which will produce flattened anomalies.

Finally, we developed new acquisition protocols and produced a variety of tests to study their characteristics and performances. These investigations demonstrated that the capacity of one acquisition protocol to retrieve the true resistivity distribution after data inversion can vary significantly depending on the shape of the resistivity anomaly that is to be detected. Therefore, in order to optimize the measuring arrays for the monitoring of CO₂ or any other gas transfer through the subsurface, one must carefully assess the prospective geometry of the gas circulation plume, and hence must gather relevant information on the geological structures composing the subsurface.

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