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On baseline determination and gas saturation derivation from downhole electrical monitoring of shallow biogenic gas production

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Abstract

Adequate hydrogeophysical monitoring of CO_2 geological storage remains a challenge as different parameters might be modified during storage. That implies to compare real-time measurements to an adequate baseline. At the Maguelone shallow experimental site a representative baseline for electrical resistivity was built from a large number of downhole geophysical measurements. At this coastal site this issue is particularly important due to the production of biogenic gas from the subsurface sediments. For this, a modified petrophysical model based on the Waxman-Smits model is proposed to estimate gas saturation found to vary from 2 to 7% within shallow sand layers.

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Keywords: baseline; CO_2; biogenic gas; monitoring; petrophysical model

1. Introduction

The controllability and reliability of the CCS operations require precise monitoring of reservoir fluid and geophysical properties, either before or during CO_2 injection, and also in the long run to control storage stability over time. In this context, access to deep saline aquifers data from geophysical and chemical monitoring systems

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constitutes an important challenge preceding any industrial deployment. Therefore, controllable shallow depth injection provides a means to study at small scale and thereby reasonable cost the response of saline reservoirs during and after CO_2 injection.

Understanding the potential impact of CO_2 migration into shallow groundwater systems requires the development of an adequate monitoring strategy to follow gas plume dynamics and possible geochemical changes in the subsurface. The monitoring methods usually deployed combined surface deployment for large scale assessments, and downhole methods for near-field and more precise boundary conditions recording. Either at surface or downhole, hydrological, geophysical, mechanical and geochemical parameters are recorded to follow the complex processes associated with gas injection and long-term storage. Recently, shallow field experiments conducted by Dafflon et al. [1], Denchik et al. [2], Spangler et al. [3] and Pezard et al. [4] (*submitted*), demonstrate the feasibility of shallow gas injection and CO_2 plume propagation monitoring over time. In particular, these studies explore the sensitivity of time lapse resistivity measurements to gas injection and long-term storage. For instance, Denchik et al. [2] and Pezard et al. [4] show at the Svelvik (Norway) and Maguelone (Languedoc, France) sites, respectively, how a set of coordinated monitoring methods responds to gas injection (either N_2 or CO_2), inducing changes to host formation physical and chemical properties.

For all methods, adequate monitoring requires the determination of a baseline representative of the site dedicated to long-term CO_2 storage (Jones et al. [5]). This baseline cannot just be the average of measurements made over the few days preceding the injection. The Maguelone shallow experimental site provides the opportunity to study the accuracy of hydrogeophysical monitoring methods. The geology, petrophysical framework and hydrology of this site have been studied in details in previous studies, revealing the presence of a thin saline aquifer at 13-16 m depth surrounded by impermeable clay-rich materials. The monitoring setup is composed of a series of hydrogeophysical and geochemical methods, offering measurements of fluid pore pressure, electrical resistivity, acoustic velocities as well as pH and fluid properties including chemistry. After a series of gas injection experiments at the Maguelone site conducted, for the latest, in January 2013 [4], fluctuations overtime of reservoir fluids chemistry and properties (such as pore fluid pH) were in fact observed after steady state conditions were restored, demonstrating the natural variability of the site in terms of biogenic gas (such as H_2S, CH_4, CO_2) production and transfer from the sedimentary pile toward the surface.

This study is aimed to assess the response of the reservoir during CO_2 injection, by quantifying the produced natural gas and its transfer between the main reservoir located about 15 m depth and a secondary storage reservoir located at 8 m depth. To achieve a representative monitoring of gas storage and flow in the subsurface, all measurements need to be compared to a representative baseline, constructed for all geophysical and geochemical data recorded from surface and downhole observatories. In order to achieve this objective, high frequency measurements were made months after any gas injection at the site. This paper focuses on high frequency logging of electrical properties constrained with several geophysical and geochemical measurements covering the 20 m depth where the targeted saline aquifers are surrounded by clay-rich materials.

2. Experimental setup

2.1. Site characteristics

The Maguelone experimental site has been described in great details in geological, petrophysical and hydrogeological terms (Lofi et al. [6], Pezard et al. [4]).

In brief, the experimental site (Fig. 1) for gas injection hydrogeophysical and geochemical monitoring is constituted with two main saline aquifers located, respectively, between 8 and 9 m depth for the shallower one, and between 13 to 16 m depth for the deeper one (Fig. 2). The shallow reservoir consists in lagoonal sandy sediments deposited in recent Holocene times and topped by impermeable argillaceous materials.

The deeper reservoir consists in porous and permeable layer made of polygenic gravels and pebbles variable in grain size, locally cemented. It is surrounded by clay and silt horizons above and dark organic-rich clay materials below (Fig. 2). The description of the geological setting is supported by downhole geophysical data (natural gamma, electrical resistivity and seismic velocity logs in each of the holes penetrating it). From a hydrological point of view, the electrical conductivity logs indicated that the sedimentary column is saturated with saline water (34 $g.l^{-1}$) to

brackish water from surface down to 32 m depth. Reservoir permeability was also measured to 3.10^{-3} m.s^{-1} from downhole hydrogeological testing. During coring, hydrogen sulphide (H_2S) was encountered near 15 m depth in each of the holes crossing this reservoir, denoting the presence of the so-called biogenic gas within it.

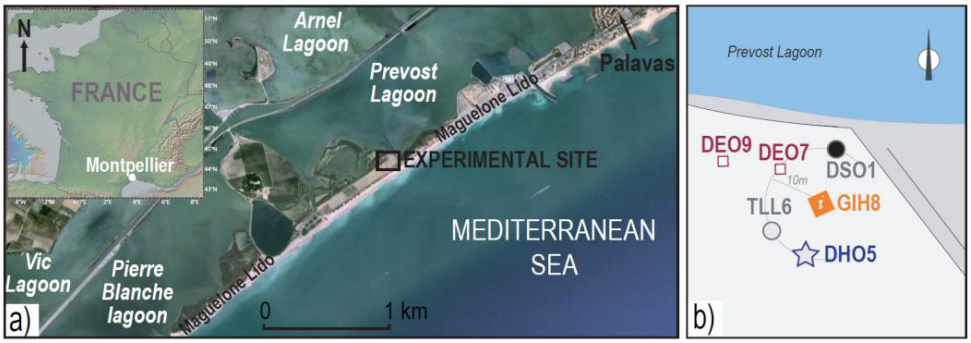

Fig. 1. Geographical location (a) of the Maguelone experimental site along the Gulf of Lion margin. Field spread (b). The monitoring system includes the TLL6 hole for time-lapse induction and sonic logging, downhole electrical resistivity observatories (in DEO7 and DEO9 holes), a downhole hydrochemical observatory (DHO5), a downhole seismic observatory (DSO1), a gas injection hole (GIH8).

2.2. Experimental field spread and data acquisition

Downhole geophysical data were recorded with wire logging sensors in a time-lapse logging (TLL) mode, with induction electrical resistivity and sonic P-waves logs. While natural gamma logs are used to estimate the shale fraction of the penetrated formations. TLL electrical data were acquired on July the 2nd, 2014 with induction tools. While the investigation range of these tools is on the order of 0.80 m, the sampling frequency in depth was set to 0.05 m. The subsurface electrical observatories (DEO7 and DEO9) are equipped by imaGeau™ SMD (for Subsurface Monitoring Devices) technologies described by Pezard et al. [4]. They use downhole electrodes located along the external surface of a PVC pipe to ensure a good contact between electrodes and the unconsolidated formation. The electrodes are made of gold plated copper to reduce corrosion over time. The technical specificities of the DEO7 are: 0.70 m electrode spacing from surface to the base, at 18.1 m depth, and a higher frequency sampling with 0.10 m electrode spacing from 13.0 m to 16.4 m depth, opposite to R1 reservoir. DEO7 was drilled and equipped in September 2012, and the measurements are made over time once a day in an automatic mode. In the following, only higher frequency data recorded from time lapse logging (in TLL6 and DSO1) and with the SMD in front of reservoir R1 (DEO7) are presented and analyzed.

2.3. Petrophysical model

The downhole electrical monitoring measurements are used to identify the sediments porosity structure, clay content, and the composition of the pore fluid. In a porous formation, the rock matrix is considered as non conducting material and the electrical conductivity depends mostly upon the nature of the electrolyte filling the pore space. As a consequence, a conductivity contrast appears when the brine contains, or is replaced with a non-conductive phase such as gas, and the porosity is a key parameter to study this petrophysical problem. In such a context, the computation of water saturation (S_w) in the pore space becomes the objective of this petrophysical modeling to derive gas saturation, that is (S_g = 1-S_w). Several models have been used in the past to reach this objective.

First, let us consider the case of fully saturated clay free or so-called "clean" formation. In this case, Sundberg [7] defined the ratio of the porous media conductivity (C_t) to that of the saturating fluid (C_w) as the electrical formation factor (F). Archie [8] later found empirically that (F) is related to porosity ($\varnothing$) in "clean" clastic sediments through a connectivity term (m).

$$F = \phi^{-m} \tag{1}$$

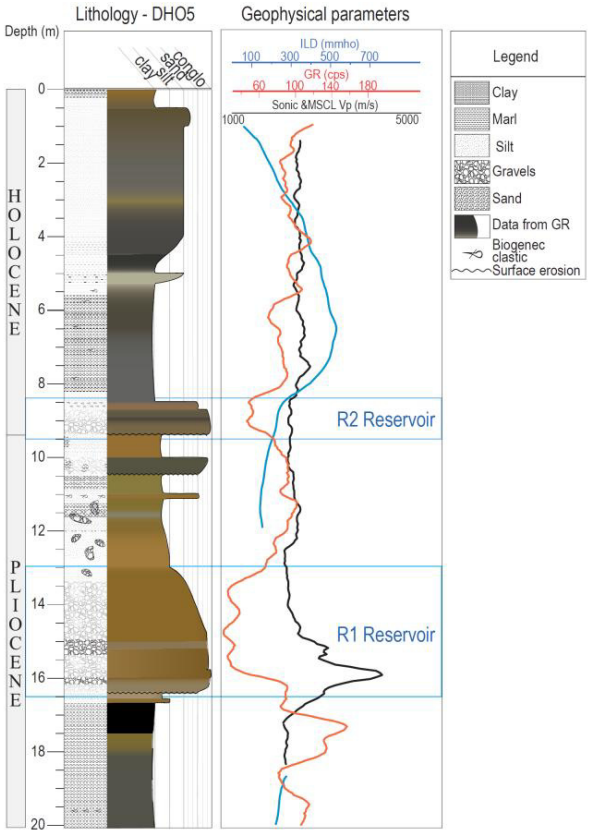

Fig. 2. Compilation of downhole geological and geophysical data from borehole DHO5. The lithological log (left) is constituted with Holocene deposit at the top and Pliocene sediments underneath. Petrophysical properties (right) include a natural gamma ray curve (*GR*; red colour), a P-wave velocity curve (V_p; black colour) and an electrical conductivity curve (C_i; blue curve).

In all, *F* becomes a scalar representation of the pore space topology in 3D. The exponent m, also called "cementation exponent" in oil and gas exploration, ranges overall from 1.3 to 2.5 in sedimentary rocks and is generally close to 2.0 in sandstone. A second Archie equation for non saturated rock ($S_w < 1.0$) proposes to evaluate the water saturation term (S_w) in the presence of a non conductive phase such as gas. The saturation consequently relates to bulk electrical conductivity, of partially saturated rocks and sediments, to the brine saturation (S_w) and to porosity ($\varnothing$) with:

$$C_t = (S_w^n . \phi^m) . C_w \tag{2}$$

The saturation exponent (n) is traditionally derived empirically and often found to be close to 2.0 [8] in clastic sediments, depending mostly on the pore fluid nature. For example, the value of n is higher for oil-wet rock ($n > 2.5$) than in a brine-wet media. It was set to 2.0 in the following. From this, the pore space gas saturation (S_g) might be derived from:

$$S_g = 1 - \sqrt{\frac{1}{\phi^m} \frac{C_t}{C_w}} \tag{3}$$

However, Archie's derivation assumes that the bulk conductivity is a linear function of electrolytical conductivity. While this model is applied with success to a remarkably wide range of rocks [9], it was found not to match in shaly sandstone (Waxman and Smits, [10]).

In the following, the presence of clay minerals was observed to increase the overall electrical conductivity of the rock. It was later shown to be related to an excess in cations located near the mineral-pore interface in a diffuse water layer, inducing a current pathways along the mineral surfaces, hence a parallel conductor to that of the

electrolyte within the bulk of the pore volume. Various models were proposed over the years to explain the origin of this additional conductivity, generally named surface conductivity as described by the diffuse double layer hypothesis. Simandoux [11] described for the first time this parameter in terms of shale volume (V_{sh}) associated to the conductivity (C_{sh}) of the clay phase, leading to

$$C_t = \frac{1}{F}.C_w + V_{sh}.C_{sh} \tag{4}$$

with simply

$$V_{sh} = \frac{GR - GR_{\min}}{GR_{\max} - GR_{\min}} \tag{5}$$

computed locally for a given reservoir from gamma ray (GR) logs.

Several models were developed to take into account the clay effect in saturation estimation from resistivity measurements. That formulated by De Witte [12] derived from Archie's model, considering clay contribution as an equivalent parallel circuit for gas saturation results. It was modified later by Poupon et al. [13] based on local field observations. These models were recently used by Nakatsuka et al. [14, 15] to derive gas saturation from porosity, shale volume fraction, pore fluid and bulk electrical resistivity (R_w and R_t , respectively). These two models produce high estimates of CO_2 saturation (S_g) with values above 50% in places, which does not fit with field observations.

In this study, we deal with the observation of natural gas production from the sediment column below the site, without additional gas being injected. As a consequence, low (S_g) values are expected and a new model including a comprehensive petrophysical approach similar to that of Waxman and Smits [10] is required. The latter is based on a description of the surface conductivity within the pore space by taking into account the physics of the diffuse ion double layer surrounding clay minerals. The model was modified and later completed by Clavier et al. [16], and more recently by Revil and Glover [17]. While the former is more empirical, the latter is based on the pore space micro-geometry and determines the ratio between the surface conductivity and that within pore volumes, electrolytic in nature. The authors determined the ionic mobility from a database including 129 samples with different type of clay (β_s = 5.14 10^{-9} $m^2s^{-1}V^{-1}$ for a monovalent solute with Na^+ at 25°C). Similarly, Idelfonse and Pezard [18] applied the Waxman and Smits (W-S) model to alterated crystalline rocks.

In all, these models link the surface conductivity C_s with the cation exchange capacity (CEC) of the rock or sediment sample, representing the number of mobile cations that might be adsorbed per weight unit (meq/100g or cmol/kg) along pore surfaces. Normalized by unit of volume, the CEC is noted Q_v (meq/mL of total PV) and expressed :

$$Q_v = \frac{CEC.(1-\phi).\rho_m}{\phi} \tag{6}$$

The W-S formula becomes then:

$$C_t = \frac{1}{F}.(C_w + B.Q_v) \tag{7}$$

where B is the average mobility of the cations along pore surfaces which depends on salinity according to $B = B_0\left[1 - 0.6\exp(C_w / 0.13)\right]$, with B_0 = 4.78 10^{-8} $m^2s^{-1}V^{-1}$ as the maximum counter ion mobility.

We propose here a modified model based on the W-S formula. This model integrates the fact that part of the accessible pore space can be saturated by a variable gas fraction (S_g) taken into account in terms of water saturation (S_w = 1- S_g). In terms of porous media electrical conductivity, we then subtract the case of porous media assumed to be fully saturated (S_w = 1.0) where formation conductivity is noted Cmax to an hypothetical situation where the pore space is partially saturated (S_w < 1.0) noted C_t, using n = 2.0 as water saturation exponent in a first order approach :

$$C_{\max} = \frac{C_w}{F} + C_s \tag{8}$$

$$C_t = \frac{C_w}{F} S_w^2 + C_s \tag{9}$$

Solving the equation obtained after subtracting (eq. 8) and (eq. 9) leads to a second degree expression. The solution of the equation provides the expression (10) used to compute gas saturation (S_g) in this study:

$$S_g = 1 - \sqrt{1 - \left(\frac{C_{\max} - C_t}{(C_w / F)}\right)} \tag{10}$$

Due to the low amount of biogenic gas produced by the sedimentary pile at Maguelone, as demonstrated by the small changes in electrical resistivity recorded over time (Fig. 4), the ratio $\chi = \frac{C_{\max} - C_t}{2(C_w / F)}$ is assumed to be low enough, so that ($1 - \chi$) is close to unity. The gas saturation equation is then simplified to obtain:

$$S_g = \frac{C_{\max} - C_t}{2(C_w) / F} \tag{11}$$

In order to determine the gas saturation (S_g), several parameters (C_w, C_{max}, C_t, F) are then needed according to W-S equation. Most of those parameters are invariant over small periods of time and can be determined using log interpretation methods and petrophysical measurements on core. The electrical formation factor is extracted from a porosity log which is derived from sonic data based on Wyllie et al. [19]. The cementation factor m was determined from shale fraction volume (V_{sh}) and the ratio between electrical surface conductivity (derived from the potassium profile derived from spectral gamma logging) and ions mobility [18] using:

$$m = m_0 + \frac{3}{2}\alpha V_{sh}\frac{Cs_e}{\beta s} \tag{12}$$

α is a coefficient relating the cementation factor with *CEC* and is expressed in ml/meq and β_s is the surface ionic mobility of sodium (Na^+).

A linear function between the potassium contents (K) in clay minerals (kaolinite and illite) and K-feldspar and maximal surface conductivity (C_s) was obtained experimentally. This linear relation noted (C_s = 0.48·K-31.74), enables to determine the downhole surface electrical conductivity (C_s). The maximum conductivity C_{max} used in the following as monitoring baseline was derived versus depth for a given borehole from the maximum conductivity values measured by a series of repeated logs (over 80 induction resistivity profiles recorded over a period of several months in the same borehole). This hypothetic baseline is chosen in this study to be representative of the steady state where the system is considered to be saturated by brine only.

3. Results

As identified in spectral natural gamma data and lithology from core (Fig. 2), a dark organic matter rich clay is located about 17 m depth in the basis of the reservoir R1. Hydrogen sulphide (H_2S) encountered during drilling at 15 m depth in most of the shallow holes denotes the presence of biogenic activity in the Maguelone sedimentary piles, due to organic matter decomposition below the coastal lagoons encountered at the site and along most of the coast of the Gulf of Lion. When recorded, repeated induction logs in some of the Maguelone shallow holes, small changes in resistivity were measured (up to 7%) in less than a few hours. What initiated this study is the fact that these small changes were restricted to sand-rich layer such as reservoirs R1 and R2 (Fig. 3). In the clay layers, changes in resistivity over time can be smaller than 0.1%, here somewhat quantifying the error introduced by the logging tool sensor and electronics.

In the following, the modified W-S model is used to determine gas saturation changes over time in the two main reservoirs. Repeated high frequency logging in the TLL6 borehole produced a database of over 80 logs from which a maximum conductivity envelope was to obtain C_{max} in this hole and for this monitoring period.

3.1. Quantification of biogenic gas saturation

A first estimate of gas saturation was computed from the recent model by Nakatsuka et al. [14]:

$$Sg = \left\{ 1 - \left(\frac{1}{RI} \right)^{1/n} \right\} \times \frac{1}{V_{sh}} \tag{13}$$

However, values between 2 to 4% were obtained for the shallow reservoir (R2), and generally above 30% in the deeper one (R1), with values above 100% in places. These unrealistic results appear to arise from the inverse correlation between S_g and V_{sh}, providing too large values in the case of very low clay fractions such as a few percents.

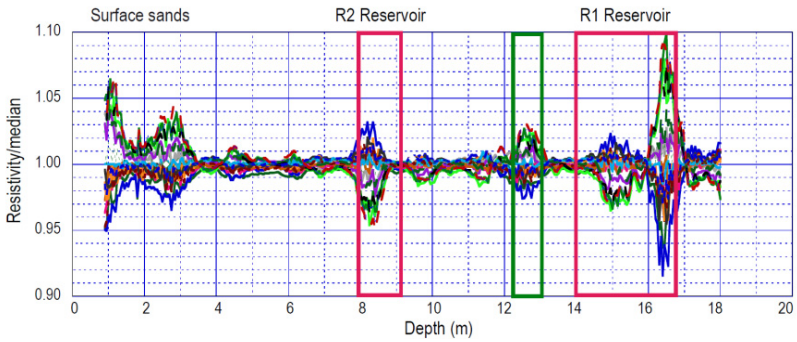

Fig. 3. High frequency induction logging recorded in a time-lapse mode every 15 minutes for 3 hours in the TLL6 borehole. Resistivity values (R_t) divided by resistivity median were computed to identify changes over time in these profiles, and found to be mainly located in sand-rich layers (R1 and R2 reservoirs).

On the basis of the modified W-S model (eq. 11), changes in biogenic gas saturation were derived and found to rise up to 7% (Fig. 4a-b) in the deeper aquifer (R1). Higher gas saturation values were derived for reservoir R1 in the TLL6 borehole while lower values (up to a maximum of 4%) in the nearby DSO1 borehole (Fig. 1b). Even lower saturation values were obtained for other layers down to 20 m depth, with maximum gas saturation values up to 2% derived for the shallower R2 reservoir (8 m depth), both in DSO1 and TLL6.

The model is in agreement with the sedimentological structure, as high saturations are obtained only in sand-rich layers, and mostly at the base of reservoirs R1. As expected also, saturation values close to zero are obtained in the surrounding clay-rich zones. These results are confirmed from downhole electrical data recorded in a dipole-dipole mode using electrical data from an automatic observatory called SMD for "Subsurface Monitoring Device" deployed by imaGeau® in DEO7. This observatory provides several advantages, including the possibility to validate nearby time-lapse induction measurements and to compute gas saturation on the basis of the modified W-S model (Fig. 4c).

Gas saturation values are only obtained for reservoir R1 where the SMD probing electrodes have been located. As obtained previously from induction data in TLL6, maximum gas saturation values of up to 7% are derived from SMD data for the bottom part of R1 (Fig. 4b-c).

These results are also in agreement with numerical simulations of CO_2 injection experiments at the Maguelone site by Bassirat et al. [20]. These simulations indicate a decrease in gas saturation from 20% a few minutes after CO_2 injection down to about 6 % five days later, denoting the steady state gas content values reached a few days after injection and in spite of partial CO_2 dissolution into the porous fluid. The natural gamma ray logs records recorded in all boreholes at Maguelone show a prominent uranium peak just below the base of R1 associated with clayey layer enriched in organic matter identified in cores. Natural gas could be produced from similar organic-rich layers located at depth, throughout the shallow sedimentary pile.

3.2. Gas saturation error evaluation

Gas saturation values computed here from the modified W-S model can be considered as noise to gas content evaluation during gas injection, and could constitute an obstacle to gas leak detection in the context of geological

storage. While the gas saturations values appear to be low and could be challenged in terms of absolute value, possibly underestimated, a need for an error computation arose to validate the petrophysical model. This computation was carried out based on Arrhenius law, linking conductivity changes with temperature. For temperatures lower than 100°C, the Arrhenius model is considered as linear ($C_w = 3 + T/10$) in the case of sea water, for example. A temperature change ΔT thus introduces changes in pore fluid electrical conductivity and therefore in gas saturation values. Recent downhole temperature records at Maguelone from Bragg sensors installed along an optical fiber show temperature changes over time on the order of 0.10 °C, hence a ΔT value on the order of 0.5 %, and an associated fluid conductivity change ΔC_w on the order of 0.05 %. As a consequence, the error in gas saturation ΔS_g can be determined from :

$$\Delta S_g = \frac{F.\Delta C_t}{2.\Delta C_w} \tag{14}$$

yielding ΔS_g values up to ± 3.3 %. As a consequence, induction resistivity logging data are little influenced by temperature changes in the media and derived gas saturation values can be trusted on that basis. Concerning tool electronics, changes over time in induction resistivity values lower than 0.5 % are obtained in front of clay layers (Fig. 3), underlining the very low error introduced by the double coil system and associated electronics of the induction logging tool.

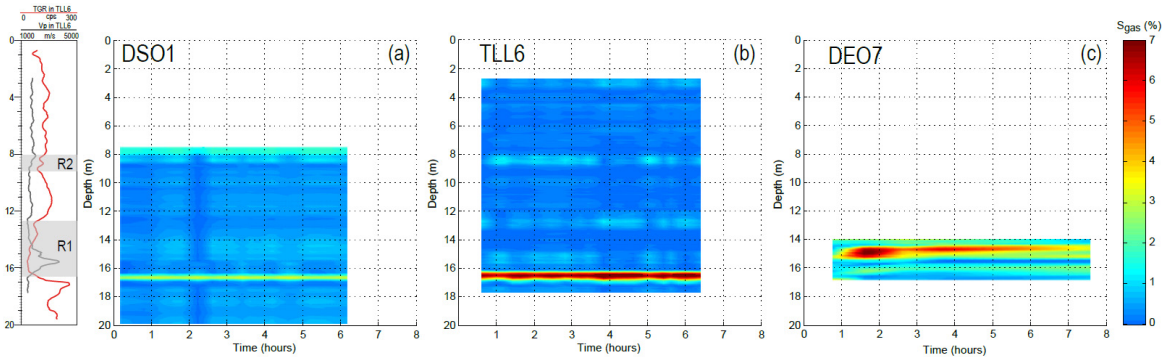

Fig. 4. Computed biogenic gas saturation at the Maguelone experimental site based on the modified W-S model from time-lapse induction logging in the DSO1 (a), TLL6 (b) boreholes and permanent SMD electrical observatory DEO7 (c). These saturation results are supported by downhole geophysical data.

4. Discussion

Gas dynamics in the Maguelone shallow subsurface has also been studied by looking at gas saturation changes over time at a given depth (16 m and 8 m, respectively) chosen within reservoirs R1 and R2. A mirror effect illustrating the gas transfer by gravity from R2 to R1is obtained (Fig. 5). This gas transfer is confirmed by a gas saturation cross plot of R2 (8 m) versus that of R1 (16 m) in both holes (DSO1 and TLL6), with an inverse correlation demonstrating that the overall mass budget is constant over very short periods of time between R1 and R2 (Fig. 6). Organic-rich layers are also here inferred to be the source of subsurface gas production to explain this process.

Because of biologic activity within such layers, gases (H_2S, CH_4 and CO_2, in unknown relative proportions at this point of the study) are irregularly released toward the surface and into sand-rich reservoirs located at shallower depth. At the Maguelone experimental site, the gases appear to rise with gravity up to reservoir R1, then slides along the gentle slope of the reservoir top ($\alpha \leq 2°$), moving upward through impermeable layers along poorly cemented tubings to reach reservoir R2, and later toward the surface. During upward migration from source, portion of the gas might be dissolved inside the pore fluid then diffuses in all directions. This process can explain why gas saturation decreases at 16 m depth, while it simultaneously increases at 8 m. When arriving at 8 m depth, a portion of the visiting gas remains inside the reservoir and a portion continues its upward migration following a gentle slope of 1°.

Gas presence at 15 m depth was reported previously by Lofi et al. [5], associated with a decrease in fluid conductivity in this reservoir.

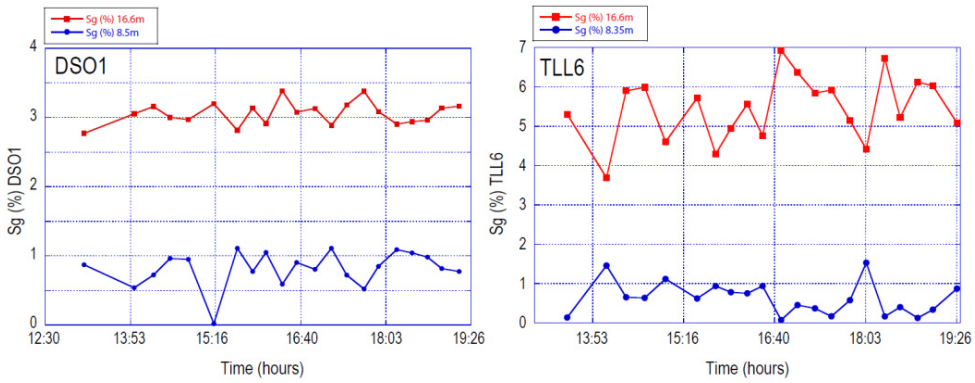

Fig. 5. Gas saturation as function of logging time. The two curves representing gas saturation at 8 m and 16 m evolve following a mirror pattern (when S_g decreases at 16 m, it simultaneously increases at 8 m).

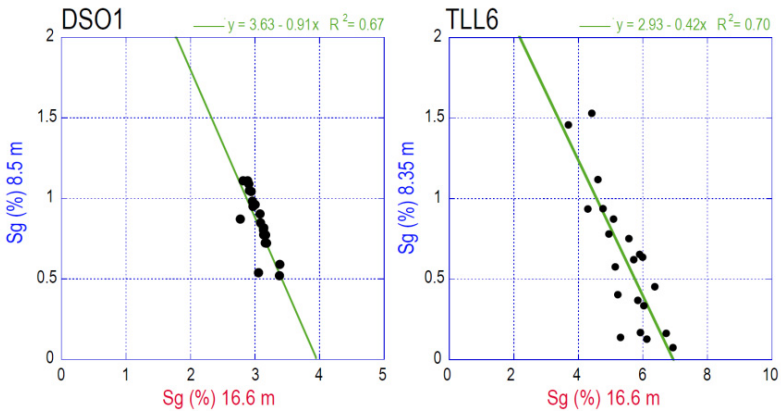

Fig. 6. Inverse correlation of gas saturation (S_g) between the two sand-rich layers located respectively at 8 m and 16 m depth (R2 and R1 reservoirs). In both cases, the correlation coefficient is on the order of 0.7.

This rapid gas dynamic response denotes a local gas production, and an average cycle of charge-discharge of about 30 minutes is measured. Despite the rapidity of the mass transfer, the gas displacement velocity cannot be related directly to the sampling rate of the downhole sensors, as a full measurement cycle in a time-lapse mode takes less than 10 minutes. This observation contrasts with a common hypothesis proposing that subsurface dynamic below coastal lagoons is controlled by tides.

5. Conclusion

Gas saturation was quantified at the Maguelone shallow site using a simple model taking into account the presence of clays on the basis of the Waxman-Smits equation [11]. This indicated that natural gas production within the sedimentary pile from biological activity cannot be neglected during gas injection experiments [4]. In the two main reservoirs located at shallow depth (R1 and R2), a variable gas content of 7% and 4% was obtained over short periods of time in the TLL6 and DSO1 boreholes, respectively. The difference might be due to the gentle stratigraphic slope identified from cross hole log and core analyses, TLL6 being located upslope from DSO1. This study also revealed a rapid dynamic mechanism resulting in transfer of biogenic gas from the bottom reservoir (R1)

to the top one (R2), possibly due to gas leaking along some of the monitoring boreholes. These sand-rich layers constitute buffer reservoirs for biogenic gases before being released to the atmosphere. Future studies at Maguelone will first focus on biogenic gas sampling from a downhole multi-packer completion in order to identify and quantify the different gas phases produced over time by the sedimentary pile.

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References

[1] Dafflon B, Wu Y, Hubbard SS, Birkholzer JT, Daley TM., Pugh JD, Peterson JE, Trautz RC, Monitoring CO_2 Intrusion and Associated Geochemical Transformations in a Shallow Groundwater System Using Complex Electrical Methods. Environ. Sci. Technol 2013 ; 47; 314–321. doi:10.1021/es301260e

[2] Denchik N, Pezard PA, Neyens D, Lofi J, Gal F, Girard J-F, Levannier A. Near-surface CO_2 leak detection monitoring from downhole electrical resistivity at the CO_2 Field Laboratory, Svelvik Ridge (Norway). Intl. J. Greenhouse Gas Control 2014 ; 28, 275-282.

[3] Spangler LH, Dobeck LM, Repasky K.S, Nehrir AR, Humphries S.D, Barr JL, Keith CJ, Shaw J.A, Rouse JH, Cunningham AB, Benson SM, Oldenburg CM, Lewicki JL, Wells AW, Diehl JR, Strazisar BR, Fessenden JE, Rahn TA, Amonette JE, Barr Jon L, Pickles WL, Jacobson JD, Silver EA, Male EJ, Rauch HW, Gullickson KS, Trautz R, Kharaka Y, Birkholzer J, Wielopolski L, A shallow subsurface controlled release facility in Bozeman, Montana, USA, for testing near surface CO_2 detection techniques and transport models. Environ. Earth Sci. 2010; 60: 227–239. doi:10.1007/s12665-009-0400-2

[4] Pezard PA, Denchik N, Lofi J, Luquot L, Neyens D, Jaafar O, Perroud H, Henry G, Levannier A. (submitted). SIMEx at Maguelone (Languedoc coastline, France): a shallow integrated, multi-method hydrogeophysical monitoring experimental site for CO_2 storage. Time-lapse monitoring from downhole electrical resistivity. Submitted to the Intl J. Greenhouse Gas Control.

[5] Jones DG, Beaubien SE, Barlow T S, Barkwith A K A P, Hannis S D, Lister T R, Strutt M H, Bellomo T, Annunziatellis A, Graziani S, Lombardi S, Ruggiero L, Braibant G, Gal F, Joublin F, Michel K. Baseline variability in onshore near surface gases and implications for monitoring at CO_2 storage sites. Energy Procedia 2014; 63: 4155-4162. doi:10.1016/j.egypro.2014.11.447

[6] Lofi J, Pezard, PA., Bouchette F, Raynal O, Sabatier P, Denchik N, Levannier A, Dezileau L, Certain R. Integrated Onshore-Offshore Investigation of a Mediterranean Layered Coastal Aquifer. Groundwater 2013; 51, 550–561. doi:10.1111/j.1745-6584.2012.01011.x

[7] Sundberg, K. Effects of impregnating waters on elec- trical conductivity of soils and rocks: Transactions of the American Institute of Mining and Metallurgical Engi- neers 1932; v. 97, p. 367–391.

[8] Archie GE. The electrical resistivity log as an aid in determining some reservoir characteristics. J. Petrol. Technol.1942. v. 5, p. 1–8.

[9] Brace FW, Orange AS, Madden TR. The effect of pressure in electrical resistivity of Water-Saturated Crystalline Rocks. J. Geophys. Res. 1965, 70, 5669-5678

[10] Waxman MH, and Smits LJM. Electrical conductivities in oil bearing sands. SPE fall annual meeting, Houston, Texas, October, 1-4, 1968.

[11] Simandoux P. Dielectric measurements on porous media: Application to the measurements of water saturation: Study of the behavior of argillaceous formations. Revue de l'Inst. Français du Pétr. 1963; 18, 193-215.

[12] De Witte L. Relation between resistivities and fluid content of porous rocks. Oil and Gas J. 1950; 24.

[13] Poupon A, Loy ME,Tixier MP. SPE, J. of Petrol. Technol. 1954. pp.27-34

[14] Nakatsuka Y, Xue Z, Yamada Y, Matsuoka T. Experimental study on monitoring and quantifying of injected CO_2 from resistivity measurement in saline aquifer storage. Energy Procedia 2009 ; 1, 2211-2218.

[15] Nakatsuka Y., Xue Z., Garcia H., Matsuoka T. Experimental study on CO_2 monitoring and quantification of stored CO_2 in saline formations using resistivity measurements Intl. J. Greenhouse Gas Control 2010; 4, 209-2016.

[16] Clavier C., Coates G., Dumanoir J. The theoretical and experimental bases for the dual-water model for the interpretation of shaly sands, Soc. Pet. Eng. J. 1984; 24, 153-169.

[17] Revil A, Cathles LM, Losh S, Nuun JA. Electrical conductivity in shaly sands with geophysical applications. J. Geophys. Res. 1998; 103, 923-936.

[18] Idelfonse B, Pezard PA. Electrical properties of slow-spreading ridge gabbro from ODP Site 735, Southwest Indian Ridge. Tectonophysics 2001; 330, 69–92.

[19] Wyllie M.R.J., Gregory, A.R., and Gardner, L.W., 1956. Elastic wave velocities in heterogeneous and porous media: Geophysics, 21, 41-70.

[20] Bassirat F, Niemi A, Perroud H, Lofi J, Denchik N, Lods G, Pezard PA, Sharma P, and Fagerlund F. Modeling Gas Transport in the Shallow Subsurface in Maguelone Field Experiment. Energy Procedia 2013; 40, 337 – 345.