A MODIFIED HYSTERESIS RELATIVE PERMEABILITY INCLUDING A GAS REMOBILIZATION THRESHOLD FOR BETTER PRODUCTION FORECASTS OF GAS STORAGES

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Noordwijk, The Netherlands 27-30 September, 2009

ABSTRACT

The natural gas storage in deep aquifers is extensively used worldwide to meet the gas demand. The storages are subjected to annual gas cycling (gas injection in summer and gas withdrawal in winter) but recent years have seen the development of multi-cycling to optimize the value of the storages. These working conditions have stressed the need to improve the pressure history matching of the numerical models especially at the end of the gas withdrawal period which is critical to evaluate the gas storage deliverability. It is observed that the simulated pressure tends to systematically overestimate the measured pressure independent of the gas storage site considered. This systematic behavior suggests that the origin of this mismatch is due to one of the constitutive laws implemented in the model rather than inadequate parameters.

In the first part of the paper, the hysteresis relative permeability formalism is identified as the main error driver of the above mentioned mismatch. Using the standard formalism of hysteresis relative permeability curves (Carlson type), the mobilization of the trapped gas by depletion is effective once the reservoir pressure decreases during the withdrawal period. Using the modified formalism, anchored on core experiment observations which established the existence of a gas saturation threshold above the residual one to reconnect the gas phase, the gas transfer from the periphery to the center is delayed thus reducing the pressure support. The second part is dedicated to the implementation of the new formalism of gas-water relative permeabilities and the significant improvement of the history matching which was obtained for several aquifer gas storages.

The main conclusion of this study is that the constitutive laws introduced in our simulators (that may differ according to the recovery process, the displacement mode,) are a key step to set up the most relevant as possible forward modeling and increase the quality of the history matching process.

INTRODUCTION

The underground gas (UGS) storage activity is used worldwide to modulate the gas delivery rates according to the seasonal variation of the consumption (peak during the winter period). Most of the UGS have been setting up in former gas depleted fields (more than 300 actives sites in US-Canada). When such sites are not available, the UGS has also been considered in salt caverns and deep aquifers. This is exactly the context in France where 10 sites have been developed in aquifers during the last 50 years with a total working volume around 10 bcm. Comparing to E&P activity, the field development scheme is quite different (Figure 1 right). The number of the injection / production wells is larger to sustain high rates. These wells are concentrated in the vicinity of the top structure to delay the water production. There are also a large number of observation wells around and above in the control aquifer to monitor the extension and the confinement of gas in the structure.

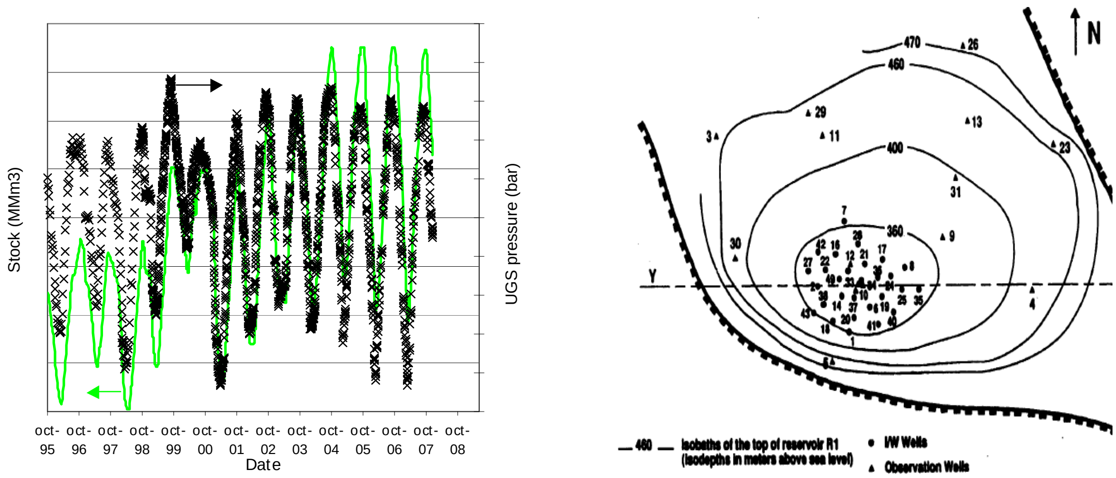


Figure 1: standard evolution of the pressure with the gas inventory (left) – example of well density and location for one UGS reservoir (De Moegen and Giouse, 1989)

The forecast of reliable reservoir pressures is very important to predict the maximum rates that can be achieved according to the installed compression capacities. This is particularly important at the end of the withdrawal period (march-april) when pressures tends to reach their lowest values whereas cold temperature events can still occur (Figure 1 left). Numerical models (3D and 1D radial) have been set up for each site in order to anticipate these evolutions. Nevertheless, a comparison between the simulated and observed pressure data indicates that the most important error occurs exactly during this crucial period as indicated in Figure 2. This behavior is observed in a systematic manner (overestimation of the models) and several attempts were conducted to improve the reservoir parameter values using an assisted history matching tool with poor success (objective function build to minimize the average field pressure, the water production and the pressure evolution of observation wells in the peripherical water zone). It therefore suggests that the origin of this mismatch is due to one of the constitutive laws implemented in the model rather than inadequate parameters.

In the first part of the paper, the hysteresis relative permeability formalism is identified as the main error driver of the above mentioned mismatch. Using the standard formalism of hysteresis relative permeability curves (Carlson type), the mobilization of trapped gas by depletion is effective once the reservoir pressure decreases during the withdrawal period. Using the modified formalism which includes the existence of a gas saturation threshold before remobilization, the gas transfer from the periphery to the center is delayed thus reducing the pressure support. The second part is dedicated to the implementation of the new formalism of gas-water relative permeabilities and the significant improvement of the history matching which was obtained for several aquifer gas storages.

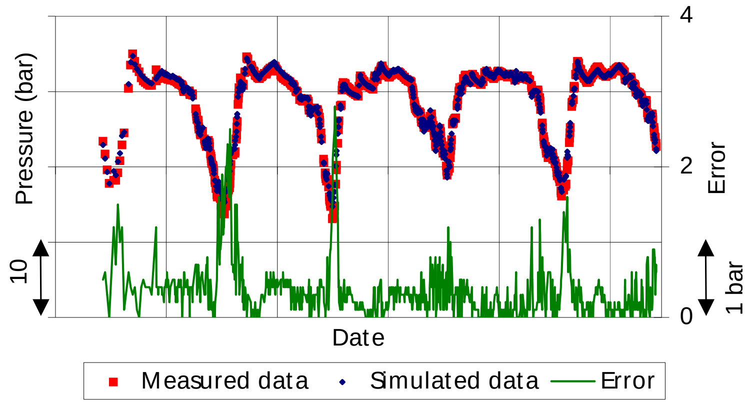


Figure 2: Example of the mismatch observed at the end of the withdrawal period for one UGS site

IDENTIFICATION OF THE GOVERNING MECHANISMS

The particular case of UGS comparing to standard gas field depletion

Annually the UGS reservoirs are submitted to very pronounced fluid movements due to the high depletion / repressurizing rate values (typically between 0.2 to 0.5 bar/d). It leads to the establishment of an intermediate region between the free gas zone and the virgin aquifer which is drained and re-imbibed every year as indicated in Figure 3.

During the gas withdrawal period, the gas is first trapped by the aquifer at the edge of the UGS and at high pressure. The high depletion rates tends to increase this local trapped gas saturation to higher values by expansion. With the standard relative permeability hysteresis curves, this additional saturation is immediately mobilized as soon its value becomes higher than the local S_{gr} value which depends on the value of the initial gas saturation : Land's formalism (1968). Using such formalism, most of the gas mobilized by expansion is therefore available for the pressure support in the free gas region of the UGS (central part). This behavior corresponds exactly to the mismatch observed between observed and simulated pressure data.

The formalism retained to remobilize the gas by expansion from the edge of the UGS is therefore a key point to properly reproduce the end of the withdrawal period. As shown in Figure 3, the implementation of a gas remobilization threshold could modify completely the shape of the gas saturation profiles and reduce the pressure support. With a higher effective trapped gas saturation (S_{gr}+S_{gmob}), the brine saturation front would move faster, lead to lower free gas available for a given volume of gas withdrawn and therefore provide better forecast. An interesting point is that such formalism will modify only the pressure evolution where the mismatch is significant. Therefore keeping all the other adjusted reservoir parameters, it seems possible to improve the history simply by tuning the S_{gmob} value.

A literature review has been done to verify the validity of this formalism before its implementation in our reservoir codes.

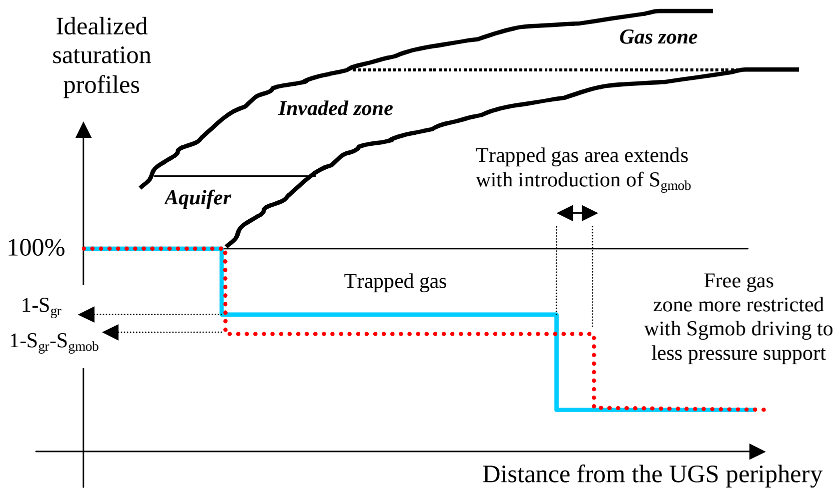


Figure 3: Expected impact of S_{gmob} on the saturation profiles within the UGS (solid blue line: profile obtained with standard formalism – dotted red line: profile obtained with the revised formalism)

Literature review on the gas remobilization process from Sgr by expansion

The literature associated to the relative permeability curves under depletion is mainly related to cases where no gas is initially present and immobile within the porous medium. It concerns applications related to late field depressurization (at S_{wi} or after waterflooding) and the heavy oil cold production (Maini, 1999; Braithwaite and Schulte, 1992; Scherpenisse et al., 1994, Naylor et al., 2000; Egermann et al, 2004). Experimental investigations on the trapped gas behavior under depletion are more scarce but fortunately of high quality and well documented.

The oldest reference was published by Fishlock et al. (1988). A comparative study between secondary drainage relative permeability obtained under injection and depletion is proposed in order to get more insight on the production of waterflooded gas condensate reservoirs by blowdown. The gas/brine relative permeability curves were measured on companion plugs using two different protocols. The reference relative permeability curves (i.e. under injection) obtained were standards and in agreement with other works (Braun and Holland, 1995) and also the formalisms widely implemented in the reservoir codes which state a reversibility between imbibition and secondary drainage krg curve (Killough, 1976; Carlson, 1981). The depletion experiments were conducted after establishment of a trapped gas saturation using two different core permeabilities and two depletion rates and all exhibit the existence of a remobilization threshold (S_{gmob}). The ISSM were used (In Situ Saturation Monitoring) which enabled to cross check the mass balance and also plot the saturation profiles. The main conclusions were that the rock fabric plays a major role on the S_{gmob} value, independent of the depletion rate (at least in the range investigated). All the results are gathered in Table 1 which shows S_{gmob} values ranged between 0.07 and 0.15 (fraction).

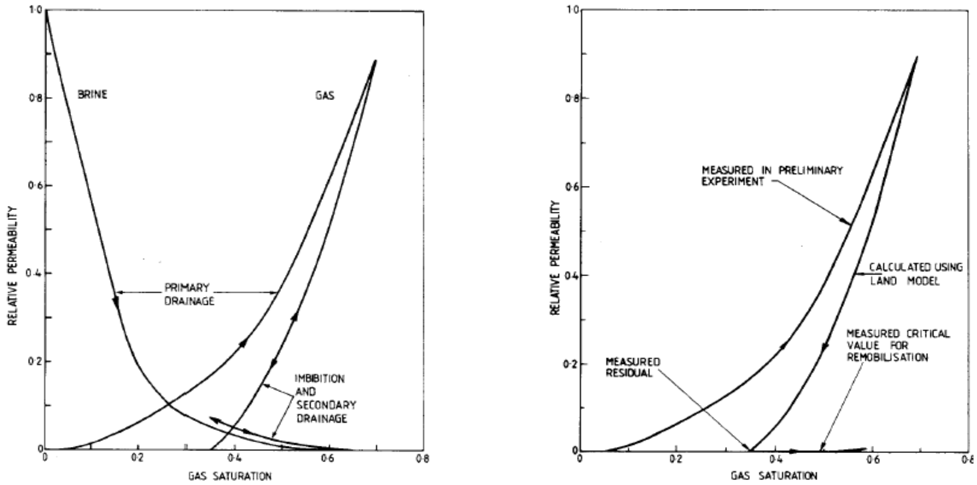


Figure 4: Gas/brine relative permeability curves shape according to the manner Sg varies: injection (left) or depletion from Sgrm (right) (Fishlock et al., 1988)

The second reference was published by Cable et al. (2003) in the context of the production potential of a transition zone containing trapped gas at elevated saturation values (Table 1). The experiments were conducted on reservoir cores in a very careful manner and with a high resolution ISSM (Figure 5). The results indicated that even with high trapped saturation values, a mobility threshold around 0.03 exists and needs to be overcome before gas can be mobilized.

Table 1: Summary of the results available in the literature concerning Sgmob

	Rock type	K mD	Phi %	DP/dt bar/hr	S_{gr} fraction	S_g @ mobilization fraction	S_{gmob} fraction
Fishlock et al.	Clashach	1280	20.0	34	0.35	0.5	0.15
	Sandstone	1280	20.0	3.4	0.35	0.49	0.14
	Low clay	240	11.6	4	0.39	0.46	0.07
Cable et al.	Res. Sands	3.2	20.4	0.5	0.47	0.5	0.03
	High clay	3.2	20.4	0.5	0.41	0.44	0.03

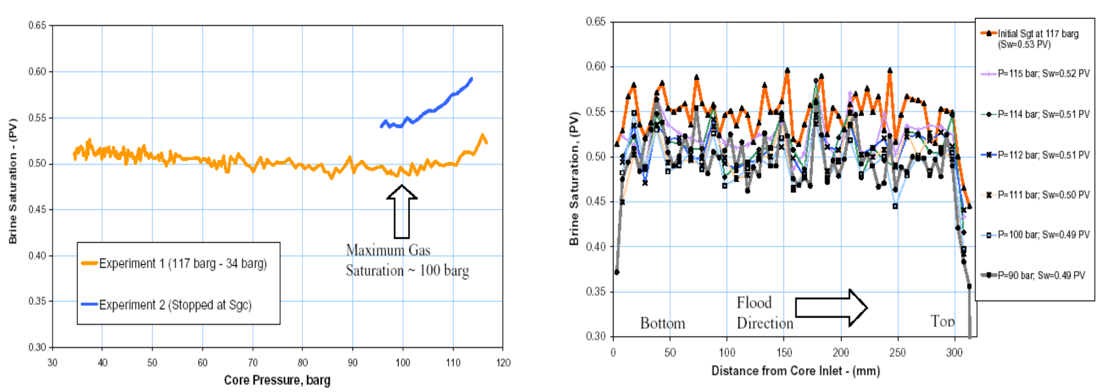


Figure 5 : illustration through ISSM measurements of the secondary mobility threshold under depletion (Cable et al., 2004)

Origin of the mechanism of secondary mobilization threshold

The origin of this onset of gas mobility above the S_{gr} value have been discussed by Fishlock et al. (1988). When gas is injected for a secondary drainage process (standard curves), it tends to follow the preferential pathways in terms of hydraulic resistance leading to a very efficient reconnection process of the residual gas (viscous forces overcome the capillary forces). When gas saturation is growing by expansion, there is a local quasi equilibrium between viscous and capillary forces that leads to the saturation of pores which are not involved in the reconnection process. It makes the relative permeability curves to be process dependent parameters, which is now well admitted for the recovery processes based on depletion.

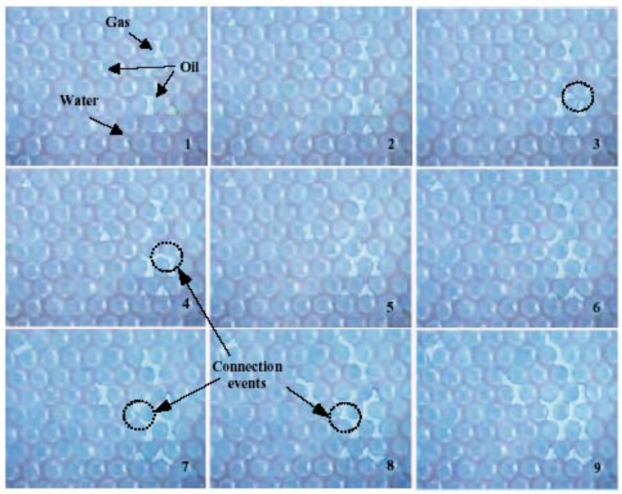


Figure 6 : Visualization of trapped gas in oil blob reconnection process during depletion during a micromodel experiment

The Figure 6 gives an illustration of this mechanism in the context of the connection of gas by blowdown of a live residual oil (Egermann et al., 2004). The mobility of the gas was found extremely low due to a double reconnection process (oil and gas).

ADDED VALUE ON THE PRESSURE FORECAST

Implementation on the new relative permeability formalism

The standard calculation of the gas relative permeability under hysteresis was slightly modified to incorporate the secondary mobility threshold (S_{gmob}). When the first imbibition cycle is followed, the code is still using the Carlson formalism where the trapped gas is calculated using the Land equation (1968):

$$K_{rg}^{I}(S_g) = K_{rg}^{D}(S_{gf}(S_{gr})) = K_{rg}^{D}(1 - S_{gt}(S_{gr})) \qquad \text{(Eq. 1)}$$

with

$$S_{gr} = S_{gt} + \frac{S_{gf}}{1 + CS_{gf}} \qquad \text{(Eq. 2)}$$

where C is the trapping constant which depends on the rock fabric, S_{gf} the free gas saturation, S_{gt} the trapped gas saturation.

In conventional simulators, the secondary drainage is accounted for using the equations that prevail during imbibition (i.e. reversibility :Eq. 1 and Eq. 2), which do not enable to simulate gas remobilization threshold (non reversibility).

In the new formalism, two cases have be distinguished for a secondary drainage:

- If $S_{gr} < S_g < S_{gr} + S_{gmob}$ then $K_{rg}=0$
- If $S_{gr} + S_{gmob} < S_g < S_{gma}$ (gas saturation value at the departure of the first drainage curve) then Krg is still calculated from Eq. 1 using

$$S_{gr} + S_{gmob} = S_{gt} + \frac{S_{gf}}{1 + CS_{gf}} \quad \text{(Eq. 3)}$$

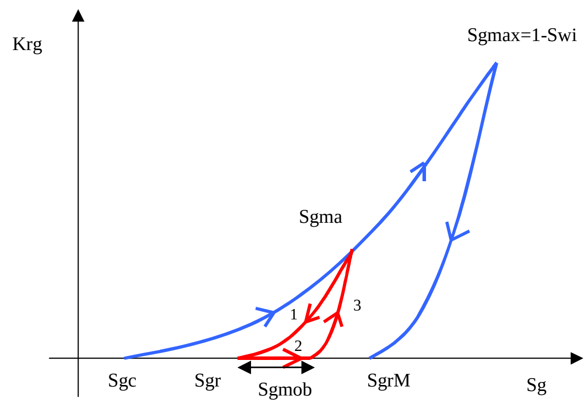


Figure 7 : Shape of the krg curve using the new formalism (SgrM: the maximum residual gas saturation)

The output of the new formalism is illustrated in Figure 7 with the scanning curves in red (first drainage and imbibition at Swi in blue). Three parts have been numbered to make the link with the reservoir behavior:

- 1 : corresponds to the gas trapping by the aquifer due to the depletion and the aquifer activity.
- 2 : the trapped gas remained immobile until the second mobility threshold is reached by depletion. Once mobile, the high mobility of gas makes the saturation remain close to Sgr + Sgmob during the end of the withdrawal.
- 3 : gas is reinjected and can eventually go further on the first drainage curve.

Presentation of the numerical code used in this study

In this work, the hydrodynamics of an aquifer gas storage is modeled through a two-phase water/gas fluid flow simulator (including gravity). This fully implicit in-house simulator has a 1D radial geometry (Figure 8) taking into account the structural shape of the reservoir (Schaaf et al., 2008) which enables to reproduce the stabilizing effect of gravity on the gas/water interface position. The main advantage of this code is its simplicity (fast calculation time) and its ability to include all the parameters that rule the behavior of the saturation profile and the pressure. This code is used on a routine basis for operational purposes to obtain the average field reservoir pressure (namely) evolution with respect to the gas cycling. As the pressure support from the associated aquifer is the driving process of the gas storage, the aquifer is fully part of the grid (right part, larger cells).

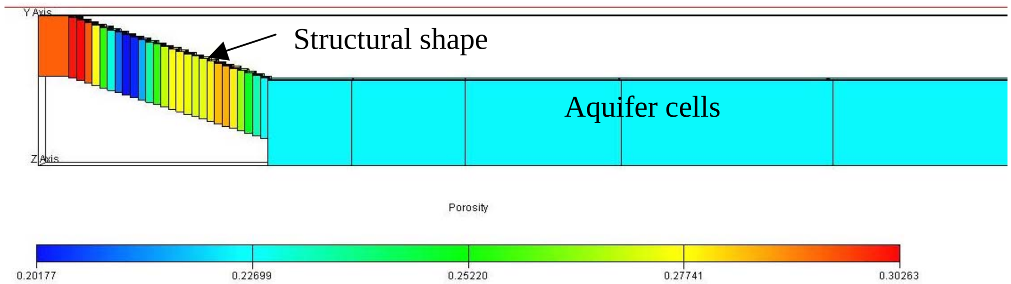


Figure 8: Example of the 1D code grid system

Improvements of the history matching quality

An assisted history matching tool has been used to come up with the optimized value of the reservoir parameters with and without the new formalism. Figure 9 illustrates how the addition of S_{gmob} contributes to the significant reduction of the objective function (OF) during the optimization process. This OF represents the overall mismatch between the observed and simulated average reservoir pressure data: $OF = \frac{1}{2}\sum_{j=1}^{m} w_j \left(P_j^{obs} - P_j^{sim}\right)^2$. Figure 10 illustrates how new formalism tremendously improves the history matching at low pressure for two different sites for several consecutive years. Such improvement was observed for all the sites investigated (6 in total).

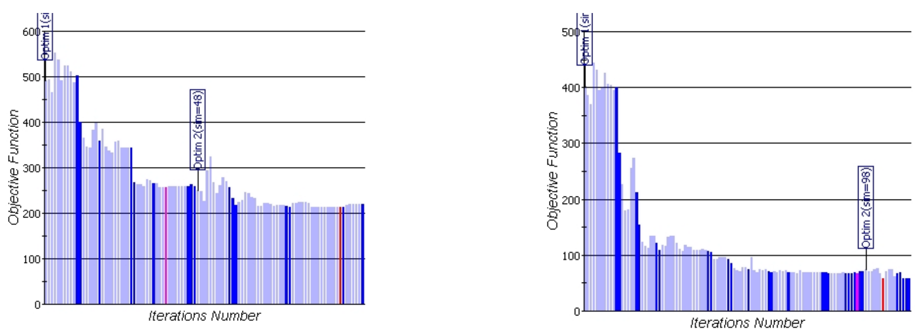
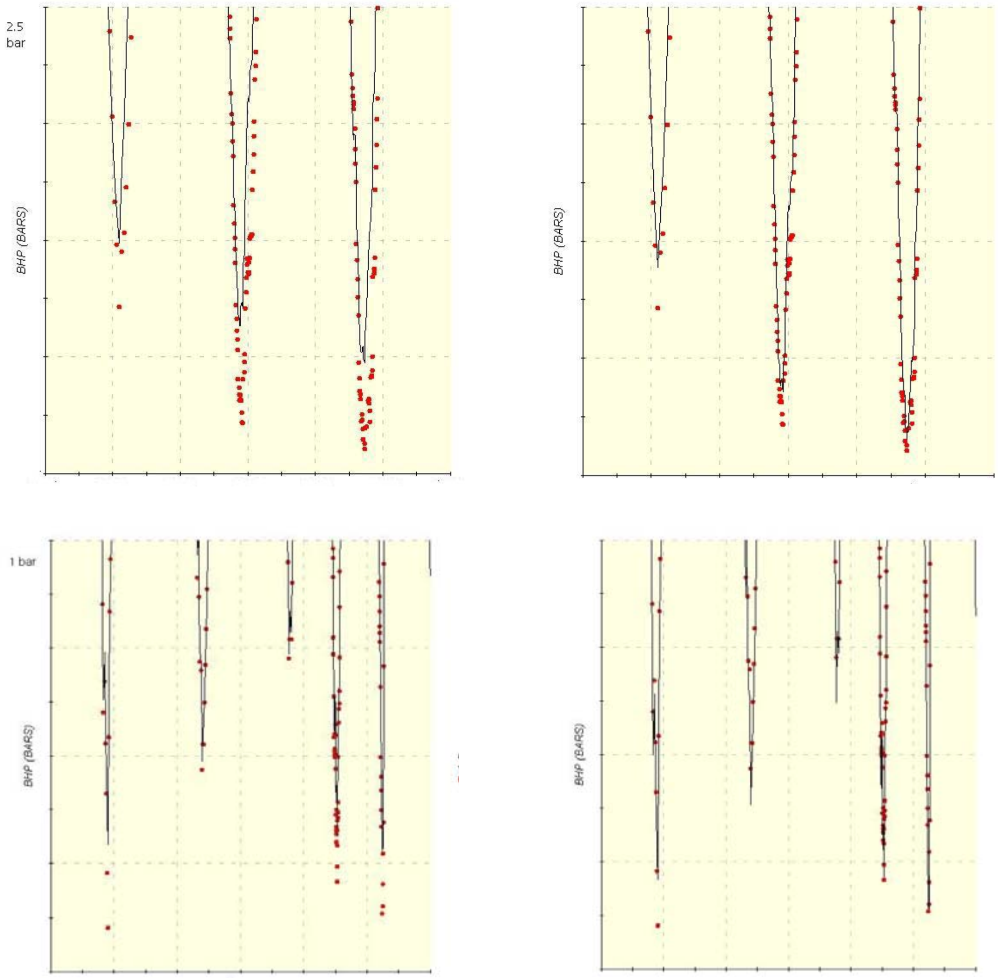


Figure 9: Comparison of the decrease of the objective function without (left) and with S_{gmob}



without S_{gmob} with S_{gmob}

Figure 10: Two examples showing the improvement in accuracy using Sgmob (curves on right)

DISCUSSION

The implementation of the new formalism has effectively improved significantly the quality of the pressure history matching but are the corresponding values of S_{gmob} representative ? The raw data and results related to the 6 sites investigated are gathered in Table 2.

Table 2: Results obtained on 6 different UGS sites

	Rock type	Av. K (mD)	Av dip (°)	S_{gr} (end point)	Opt. S_{gmob}
Site 1	Clastic – low clay	1200	0.9	0.25	0.037
Site 2	Clastic – low clay	1500	1.7	0.21	0.044
Site 3	Clastic – low clay	500	1.8	0.3	0.034
Site 4	Clastic – low clay	1700	0.4	0.25	0.03
Site 5	Clastic – low clay	700	1.2	0.15	0.048
Site 6	Clastic – low clay	1000	3.8	0.19	0.027

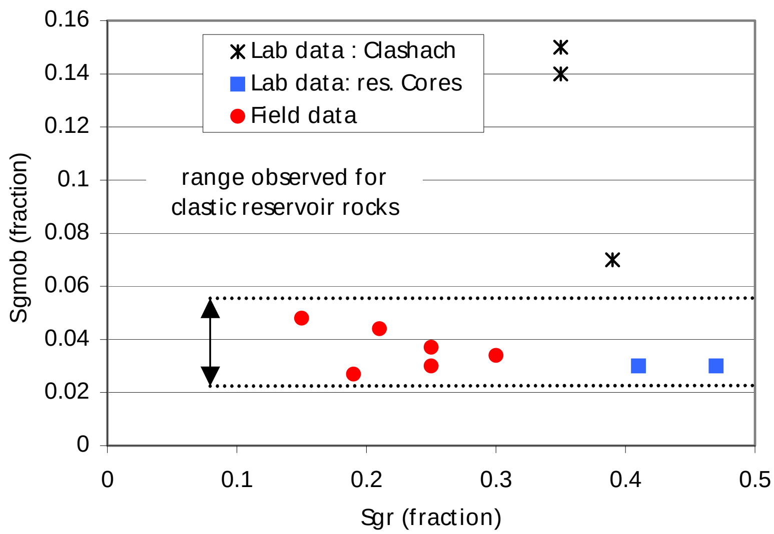


Figure 11: S_{gmob} trend as a function of the S_{gr} values (lab and field data)

It was not possible to obtain a correlation between S_{gmob} and the rock fabric or the depletion rate since these parameters are very similar whatever the sites considered in this study. No correlation neither appears when the average permeability or the dip (rules the contact surface between the gas and the aquifer) of the reservoir is considered. Better results are obtained when S_{gmob} is plotted according to the trapped gas saturation. Except for the data collected on the Clashach outcrop cores (Fishlock et al.), all the data obtained on reservoir clastic type rock data fall in the same range.

The specific behavior of the Chashach sandstone has been already observed in other works and is certainly associated to a particular pore structure in terms of phase trapping (Eleri et al., 1995; Suzanne et al., 2003).

Although this is not supported by data, it is likely S_{gmob} does not depend on the depletion rate but only on the expansion. In depressurization experiments with live oil, the nucleation sites are activated below the bubble pressure and their number is directly dependent on the depletion rate. In the process considered in this work, they are already existing and active sites during blowdown of trapped gas, therefore the kinetics of the gas growth should not be dependent on the manner the pressure is decreased (depletion rate).

The results obtained with the Clashach cores suggests that the S_{gmob} is very dependent on the pore topology. As additional experiments with other types of pore / throat size distribution (sandstone or carbonate) are not available, the pore network model could be designed in an appropriate manner to investigate this issue.

CONCLUSIONS AND PERSPECTIVES

A modified hysteresis model was successfully developed , implemented and tested to improve the forecast of the pressure regime during the withdrawal period of several UGS reservoirs in aquifer. It permits to better reproduce the remobilization of the trapped gas by expansion during the production and therefore better predict the pressure support by free gas.

From a reservoir engineering point of view, the main learning of this work is the importance that should be attributed to a preliminary study of the effective physical mechanisms taking place in the reservoir. In recent years, with the fast development of the calculation capacities, the history matching process turns out to reduce more and more to an inverse mathematical problem to solve using sophisticated workflows. This work illustrates that it is also worth looking carefully at the forward model and especially at the formalisms implemented to make sure they are relevant enough to simulate the physical mechanisms taking place in the reservoir. To this end, SCAL remains a unique way to understand and quantify the associated mechanisms under consideration as illustrated in the literature review.

Following these promising results, the formalism is on the way to be implemented in the in-house 3D code used to perform reservoir studies of UGS.

ACKNOWLEDGEMENTS

We are grateful to GDF Suez and Storengy for permission to publish these results.

NOMENCLATURE

C: trapping constant (Land's formalism)

K_{rg}^I, K_{rg}^D: imbibition and drainage K_{rg}

UGS: Underground Gas Storage

S_{gc}: critical gas saturation

S_{gr}: residual gas saturation

S_{gmob}: secondary mobility threshold

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