DISTRIBUTION OF TRAPPED GAS SATURATION IN HETEROGENEOUS SANDSTONE RESERVOIRS

SUZANNE Karine (Ecole des Mines de Paris), HAMON Gérald (TotalFinaElf), BILLIOTTE Joël (Ecole des Mines de Paris), TROCME Vincent (GazDeFrance)

ABSTRACT

Maximum residual gas saturation (Sgrm) is known to be a key factor in evaluating gas recovery from a lean gas reservoir invaded by aquifer water. This work focuses on variations of Sgrm within heterogeneous gas-bearing sandstone reservoirs.

Three hundred Sgrm measurements were performed by capillary imbibition and supplemented by lithological description, thin sections, XRD analysis, porosity, permeability, grain density, formation factor and cementation factor. The core plugs were selected from three different sandstone gas reservoirs and from Fontainebleau Sandstone outcrops.

The main results are as follows:

1) Sgrm values are very scattered, from 5% to 85%, when porosity ranges from 6 to 24%.

2) Sgrm versus porosity plots show three major trends:

- Two very different but clear trends in the low to medium porosity range (below 14%). As porosity decreases, Sgrm increases for Fontainebleau sandstone whereas it decreases for the other sandstones.
- The third trend is in the high porosity region where the above two trends merge to an average of around 25-35%.

3) There is no clear relationship between Sgrm and grain density, formation factor, cementation factor, or clay type.

4) The amount of clay is the controlling factor in the Sgrm versus porosity relationship. In the low porosity region, the clay-free Fontainebleau sandstone traps much more gas than the shaly reservoir samples. For shaly sandstone, the greater the clay content, the lower the Sgrm.

INTRODUCTION

During depletion of gas fields, the aquifer often encroaches into the reservoir, and residual gas saturation (Sgr) is used to estimate microscopic recovery. Published values of Sgr vary between 15 and 80%. The economic impact of Sgr on gas reservoirs can be extremely high. This is even more crucial for heterogeneous reservoirs where assessing Sgr for different rock types is the key issue.

Many studies have attempted to understand gas-trapping mechanisms. First, Geffen (1952) established that residual gas saturation measured in the laboratory on core plugs is the same as in a gas reservoir. Crowell (1966) illustrated the effect of initial gas saturation (Sgi) on trapped gas saturation (see also MacKay, 1974 and Jerauld, 1996). Land (1971) first proposed a characteristic shape for the relationship between Sgi and Sgr:

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$$C = \frac{1}{S^*_{gr}} - \frac{1}{S^*_{gi}} = \frac{1}{Sgrm} - 1\,.$$

Parameters are: S^*_{gi} that is effective initial gas saturation, expressed as fraction of the pore volume excluding the pore volume occupied by the irreducible wetting phase, S^*_{gr} that is effective residual gas saturation, expressed as fraction of the pore volume excluding the pore volume occupied by the irreducible wetting phase, and C that is Land coefficient.

The effect of water flooding rates on Sgr was found to be negligible (Geffen, 1952; Crowell, 1966; Delclaud, 1991). Katz (1966) showed that the residual gas left behind the moving water front remains constant and equal to that obtained during the measurement of capillary pressure. Several authors demonstrated that Sgr obtained by water flooding and spontaneous imbibition are very close (Geffen, 1952; Crowell, 1966; MacKay, 1974), provided the reduction in Sgr due to diffusion is disregarded (Delclaud; 1991). The type of displacing liquid was also found to be negligible in effect (Geffen, 1952; Kyte, 1956; Jerauld, 1996). The same Sgr values were obtained whatever the pressure and temperature prevailing during the core test (Geffen, 1952; Chierici, 1963; MacKay, 1974; Delclaud, 1991).

The results mentioned above prove that simple experimental conditions may be representative of gas trapping in reservoirs. As the objectives of this study are to gather a large number of experimental results over a large range of rock characteristics, simple experimental conditions are preferable. In this work, trapped gas saturations are obtained by spontaneous imbibition at ambient conditions on dry samples.

Many studies have tried to correlate trapped gas saturation to reservoir characteristics.

Chierici (1963) presented Sgr results obtained on 251 small samples of different lithological type: sand, sandstone, and bioclastic limestone plugs. Sgrm values ranged from 10 to 31 percent. He failed to correlate Sgr values with porosity, permeability or irreducible water saturation. Attempts to correlate Sgr with distribution of pore entry radius and several combinations of porosity and permeability were also unsuccessful.

Katz (1966) presented a very general relationship between gas saturation and porosity on sand and sandstone cores. Sgr decreased from 50 to 10% when porosity increased from 10 to 40%. He did not find any trend against permeability.

MacKay (1974) reported Sgr values ranging from 24 to 44% on sandstone cores. He showed a very weak relationship between porosity and Sgr.

Keelan (1975) presented Sgr results for various carbonate types. Values range from 20 to 70%. Correlations between Sgr and porosity, permeability, combination of the two, initial gas saturation, pore entry distribution, images of thin section, and photomicrograph were sought. He concluded that Sgr increased as porosity decreased but no relationship with permeability was found. In a sandstone reservoir study, Keelan (1976) presented Sgr values from three reservoirs ranging from to 32 to 45%, and concluded that Sgr increases slightly as permeability decreases.

Batycky (1981) presented a compilation of Sgr on carbonate rocks. The values vary from 40 to 70%.

Delclaud (1991) illustrated the wide variation of Sgr and its strong dependency on porosity for a North Sea gas field.

Jerauld (1996) studied Prudhoe Bay sandstone and conglomerate with porosity ranging from 13 to 25%. Maximum Sgr varies from 22 to 32%. He concluded that the maximum trapped gas saturation depends primarily on porosity, grain sorting, and microporosity. For sandstone, low porosity and poor sorting results in larger trapped gas levels. He also found a significant decrease in Sgrm with rising clay content. Conglomerates have, on average, a lower level of trapped gas at a given porosity level than sandstone. SEM photographs confirm the pore size to pore throat ratio as explanation of the gas trapping variation.

This short review shows that attempts to correlate Sgr with petrophysical characteristics have either failed or found a relationship against porosity. Figure 1 shows Sgrm versus porosity. It combines the results mentioned above and those of several other studies (Bousquié, 1979; Aissaoui, 1983; Fishlock, 1986). It illustrates a very general trend of increasing Sgr with decreasing porosity.

The present work studies relationships between maximum trapped gas saturation on the one hand and sandstone characteristics: porosity, permeability, grain density, formation factor, cementation factor, mineralogical data, clay contents and type on the other hand.

EXPERIMENTS

Core Samples

Samples were selected from three gas reservoirs, two from the Far East (M1 and M2) and one from West Africa (I3), and from Fontainebleau Sandstone outcrops (FTB). Their porosity and permeability range respectively from 6% to 25% and from 0.1 to 3 000 mD. Figure 2 illustrates porosity versus permeability. The samples' clay contents vary from 0 to 33%

Fontainebleau is 100% quartz, well-sorted sandstone, in which porosity is reduced due to quartz overgrowths around the grains as described by Bourbie (1985). The grain size is around 250 µm, with regular and plane surfaces and irregular geometric form. No noticeable variation in grain size is observed with porosity. The pores are of two main types: large, angular pores between quartz grains (radius of 10 to 30 µm), or very thin planar pores between two grains that represent an insignificant contribution to porosity. The SEM images show that decreasing porosity is directly related to decrease in relative volume of the large pores.

Reservoir sandstones contain primarily quartz grains, with variable amounts of cementation and other minerals (detrital clays, pyrites) along with bioclasts for some of the samples. Grain morphology varies from sub-angular to sub-rounded. Several types of grain surface are observed: planar and regular, altered, or irregular. The highest porosity values are those measured on samples composed of coarse-grained sand with little cementation. Porosity decreases as grain size decreases and cementation increases.

I3 sandstone contains clay laminations with bioturbation traces of varying intensity. Samples have a coarse pore structure, pores being located either between quartz grains, or as free space between cement and grains, or within interstratified minerals (illite,

illite/smectite, and smectite).

M1 and M2 sandstones have a grain size ranging from medium to very fine. Clays are scattered. Pore volume is either between quartz grains (radius of 5 µm), or as free space between cement and grains (radius about of 1 µm), as well as between cement minerals, or as space inside clays.

Cylindrical plugs of different lengths, and 23 mm or 40 mm in diameter were cut from whole core samples.

Maximum residual gas saturation (Sgrm) measurement

The following sequence was performed. 1- Plugs were cleaned with chloroform by soxhlet extraction and dried at 80°C. 2- Matrix volume was measured either using helium picnometry, or by hydrostatic weighing on chloroform-saturated samples 3- Bulk volume was measured by mercury hydrostatic weighing. 4- Gas permeability measurements. 5- Formation factor was measured on brine-saturated samples. 6- Sgrm was measured as described in Figure 3.

Spontaneous imbibition of refined oil into a dry sample was used to obtain maximum trapped gas saturation. Isopar L was used as the invading wetting phase. Density, surface tension and viscosity at ambient laboratory conditions are 0.77 g/cm^3, 1.38 cP and 24 .10^{-3} N/m respectively. Isopar L is used in order to carry out imbibition with strongly wetting liquid for both outcrop and reservoir samples. Oil spontaneous imbibition was performed by immersing the lowermost tip of the sample into oil and measuring the change of weight versus time. The sample was suspended from a hook underneath a balance as illustrated by figure 3. The major part of the sample remains immersed in air. Air remains saturated with liquid vapour as both the oil tank and the sample are in a closed system.

Change in oil saturation is calculated by mass balance, accounting for both the effect of buoyancy forces on the fraction of the sample immersed in oil and the effect of capillary forces along the perimeter of cylindrical sample. Trapped gas saturation is calculated from change in oil saturation as described below.

Change in gas saturation during imbibition is plotted against the square root of time. Figure 3 shows that two straight-line segments are usually observed: an early capillary-dominated period, followed by a late diffusion-dominated period. The intersection of these two lines was selected as the trapped gas saturation. Throughout the experiments, these two regimes were always clearly observed regardless of the sample permeability, except for the very low porosity Fontainebleau samples (porosity = 4%). Results for these very tight Fontainebleau samples were discarded.

Measurements and observations

The different types of measurements are listed in table 1.

- Porosity, permeability, grain density, formation factor and cementation factor were measured on the same plugs as for Sgrm measurements.
- Mineral composition and clay type by XRD analysis were carried out on plug off-cuts for M1 and M2, and on part of the plugs for I3 and FTB sandstone. XRD analysis is

done on minerals and on the fines fraction.

Observations on thin sections and photomicrography supplemented the measurements.

Three mineralogical analyses were performed on Fontainebleau sandstone with various porosities. They confirm the sample composition as 100% of quartz.

RESULTS

Relationship between trapped gas saturation and porosity

There is a fair relationship between porosity and Sgrm for each sandstone belonging to the lower- or the uppermost Sgrm/porosity trend of this work, as illustrated by figure 4.

Figure 5 compares the Sgrm/porosity trends obtained by Aissaoui (1983), by Jerauld (1996) and in this work on Fontainebleau samples. Our results superimpose onto Jerauld's data. There is a slight discrepancy between our results and Aissaoui's data. This is ascribed to the procedure used by Aissaoui to measure Sgrm. Sgrm was achieved when saturation did not change over a 24 hours period. Consequently, Aissaoui's estimate of Sgrm partially includes the diffusion period and is consequently lower than our estimates. The overall agreement between our results and Jerauld's and Aissaoui's data is deemed to corroborate the reliability of our laboratory procedures.

Figure 6 shows the relationship between porosity and maximum trapped gas saturation on the Fontainebleau, I3, M1 and M2 sandstones. It illustrates that:

1) Sgrm values are very scattered: from 5% to 85%.

2) Sgrm versus porosity relationships present three major trends:

- Two very different but clear trends in the low and medium porosity range, i.e. below 14%. As porosity decreases, Sgrm increases for Fontainebleau sandstone whereas it decreases for other sandstone.
- Concerning the highest porosity values, i.e. above 14%, the two trends above merge around an average Sgrm of 25%.

Very similar behaviour was observed for Sgrm versus permeability trends (Figure 7). Figure 8 shows the comparison between literature and our porosity/Sgrm trends. This figure illustrates that our Fontainebleau results are in very good agreement with literature data. On the other hand, the lowermost Sgrm/porosity trend has never been clearly evidenced before.

In the following, we try to correlate Sgrm with a combination of porosity and mineralogical data.

Influence of clays

Macrolithological description shows that samples belonging to the lowermost Sgrm/porosity trend are very often shaly. Moreover, microphotographs (Figure 9) and mineralogical analysis (Figure 10 a) confirm that the Fontainebleau sandstone is effectively clay-free. The hypothesis was advanced that clay content controls the Sgrm versus porosity trends.

Figure 10 highlights the influence of clay presence and content on trapped gas saturation for low and medium porosity samples. It confirms that none of the samples belonging to the lowermost trend is clay-free. Figure 10 (b) shows a very clear relationship between the clay amounts and the trapped gas saturation for all the reservoir samples: the larger the clay fraction, the lower Sgrm.

Table 2 presents the regression coefficients between maximum trapped gas saturation on one hand, porosity, clay contents, illite and kaolinite content and combination of some of these factors on the other hand. It confirms that Sgrm is controlled by two keys: porosity and clay content.

Clay type influence

Presence, type, structure and location of clays within the porous network are known to influence petrophysical characteristics (Wilson, 1977), such as permeability and irreducible water saturation.

We observed different clay types: illite, smectite, illite/smectite, kaolinite and chlorite. Table 3 lists our main observations. No correlation was found between Sgrm and location or structure of clays.

Attempts to correlate Sgrm with any of the clay types were unsuccessful, as illustrated by regression coefficients in table 2 and figure 11 (a and b). A weak trend was obtained between Sgrm and kaolinite or interstratified clay contents for I3 sandstone: Sgrm values decrease if kaolinite contents decrease.

Relationship with other petrophysical parameters

We also tried to correlate Sgrm with other petrophysical characteristics such as grain density, formation factor, and cementation factor. Figure 12 does not present evidence of any clear trend between Sgrm and these parameters.

DISCUSSION

Our results on sandstone samples show that Sgrm varies from 5 to 85%, when porosity ranges from 6 to 24%. The very large scatter in Sgrm illustrated by our results explains why attempts to find a single relationship between porosity and Sgrm often failed in the past (Chierici, 1963). Clearly, Sgrm cannot be predicted *a priori* using porosity or permeability only, or any usual combination of the two.

Our uppermost Sgrm/porosity trend obtained on Fontainebleau sandstone is consistent with data in other literature as shown in figure 1. The lowermost Sgrm/porosity trend has never before been clearly reported for sandstone. However, it should be noted that such trends have occasionally been mentioned but often disregarded (Katz, 1966). Evidence of decreasing Sgr with decreasing porosity has also been published by Bousquié (1979) on outcrop carbonate samples.

Finally, porosity and clay content seem to control two-phase Sgrm. Our results show a decrease in trapped gas saturation with increasing clay content. This is consistent with Jerauld's results (1996), except that he reported an overall increasing trend of Sgrm when porosity decreases.

Our results suggest that the difference in Sgrm/porosity behaviour can be ascribed to clay presence. In the low porosity region, the clay-free Fontainebleau sandstone traps much more gas than the shaly reservoir samples. In the medium to high porosity region, Fontainebleau and clean reservoir samples trap nearly the same amount of gas. These observations suggest that trapping mechanisms differ in the high and low porosity regions depending on the amount of clay and the pore network geometry.

It is agreed that the main factors affecting trapping of the strongly non-wetting phase are pore-to-throat ratio, throat-to-pore coordination number, type and degree of heterogeneity and surface roughness (Wardlaw, 1978). The latter two mechanisms are deemed negligible for Fontainebleau: thin sections show that this sandstone is effectively very homogeneous and SEM observations do not show any surface roughness.

In Fontainebleau sandstone, variations in pore network topology with porosity are deemed to control gas-trapping. Aissaoui (1983) distinguished two types of pores, depending on pore throat dimension. Our own observations confirm this pore typing. He noticed that the pore throat sizes diminish with porosity. This suggests that the variation with porosity of the ratio between pore body and pore throat is responsible for gas trapping. This explanation is consistent with the trapping behaviour in individual pores obtained by Wardlaw on glass micro-models (1982). Further work is required to support this hypothesis on Fontainebleau sandstone.

In our reservoir sandstone, the presence of clay results in low Sgrm. This suggests that the microporosity within clay structures does not trap gas. The rationale behind this assumption is based on several mechanisms: low body-to-throat aspect ratio for most clay types, gas diffusion from microporosity to effective porosity due to the very high capillary pressure within the microporosity (Jerauld, 1996). Bousquié (1979) also concluded that microporosity does not trap gas on outcrop carbonate samples. He defined microporosity from mercury injection curves, as the fraction of the pore volume accessible by pore throats smaller than 1 μm.

However, it should be noted that this assumption has never before found clear corroboration. An extensive laboratory programme has recently been devoted to this issue and results are presented in a companion paper (Hamon, 2001).

CONCLUSION

1) Sgrm values are very scattered, from 5% to 85%.

2) Sgrm versus porosity plots show three major trends:

- Two very different but clear trends in the low to medium porosity range, i.e. below 14%. As porosity increases, Sgrm decreases for Fontainebleau sandstone whereas it increases for other sandstones.
- Concerning the highest porosity values, i.e. above 14%, the two trends above merge around an average Sgrm of 25%.

3) Sgrm cannot be predicted a priori using porosity or permeability only, or any usual combination of the two.

4) There is no clear relationship between Sgrm and grain density, or formation factor, or

cementation factor.

5) The amount of clay controls the Sgrm versus porosity relationship. SgrM decreases as the clay content increases. No relationship was found between Sgrm and the type of clay or location within the porous network.

NOMENCLATURE

C: Land coefficient

clays: clay contents (weight fraction)

FTB: Fontainebleau sandstone

illite: illite fraction of clays (percent)

kaolinite: kaolinite fraction of clays (percent)

Kg: gas permeability (mD)

Phi: porosity (fraction of bulk volume)

S^*_{gi}: effective initial gas saturation.

S^*_{gr}: effective residual gas saturation.

Sgi: initial gas saturation

Sgr: residual gas saturation

Sgrm: maximum residual gas saturation

ACKNOWLEDGEMENTS

This paper is published with the permission of TotalFinaElf, Gaz De France and the Ecole des Mines de Paris. We thank S. Bouzida, J.B. Vignal and L. Menard for their contribution.

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TABLES

Sandstone	**Petrophysical and Sgrm measurement**	**XRD analysis**	**Thin sections**	**Photo micrography**
FTB	63	3	10	4
I3	54	31		2
M1	145	51	38	6
M2	100	47		3
total	362	129	48	15

Table 1: Number of measurements

R²	**Phi**		**Clays**	**Illite**	**Kaolinite**	**Formula**	**R²**
	parabolic	**linear**					
I3	0.49	0.32	0.68	0	0.3	1.18 Phi – 0.86 Clays + 0.22	0.74
M1	0.76	0.56	0.68	0.1	0	0.97 Phi – 1.39 Clays + 0.27	0.74
M2	0.69	0.68	0.37	0.1	0.1	1.83 Phi –0.12 Clays – 0.03	0.70
I3 + M1+ M2	0.52	0.40	0.61	0.25	0.21	1.02 Phi –1.04 Clays +0.24	0.70

Table 2: Correlation between Sgrm and petrophysical and mineralogical parameters on plug with XRD analysis

clays – type	Structure // Microporosity	Location within pore network I3	M1	M2
Illite, illite-smectite, smectite	Sheet of elongate spines (+++)	Pore filling	Pore lining and filling	Pore lining and filling
Kaolinite	Stacked plates (+)	Pore filling	Pore filling	Pore filling
Chlorite	Honeycomb (+++)	None	-	Pore lining

Table 3: Structure and location of clays

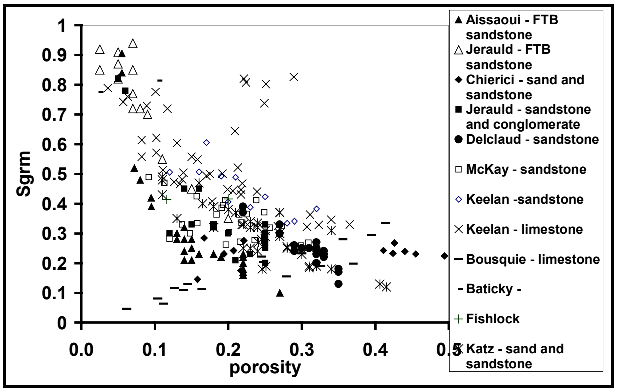

Figure 1: Literature data on maximum trapped gas saturation versus porosity

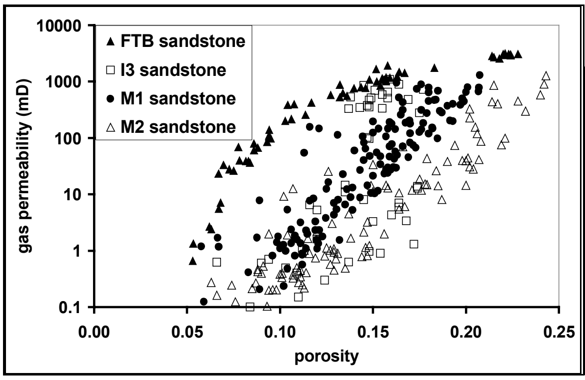

Figure 2: Porosity against permeability

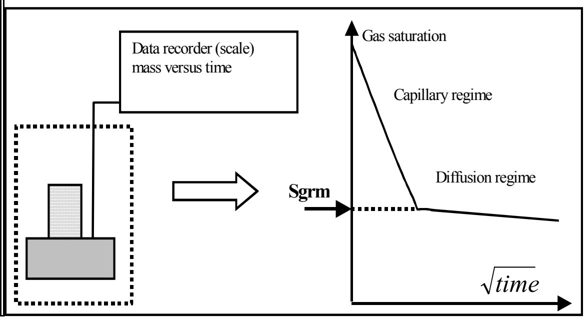

Figure 3: Principle of measurement of Sgr

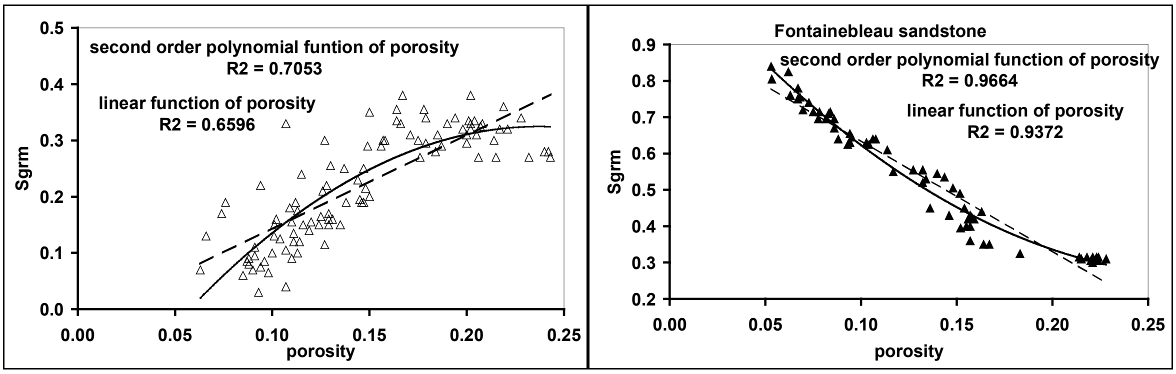

Figure 4: Sgrm versus porosity for M2 (4a) and Fontainebleau sandstone (4b)

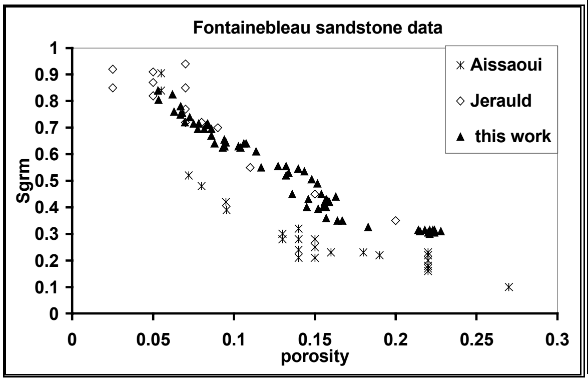

Figure 5: Sgrm versus porosity for Fontainebleau sandstone, literature and our data

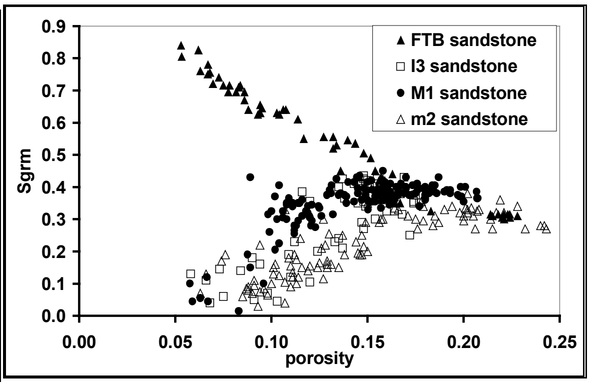

Figure 6: Sgrm versus porosity for Fontainebleau sandstone and all samples.

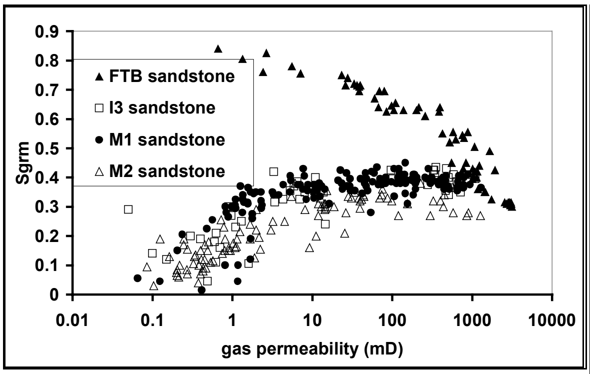

Figure 7: Gas permeability versus Sgrm

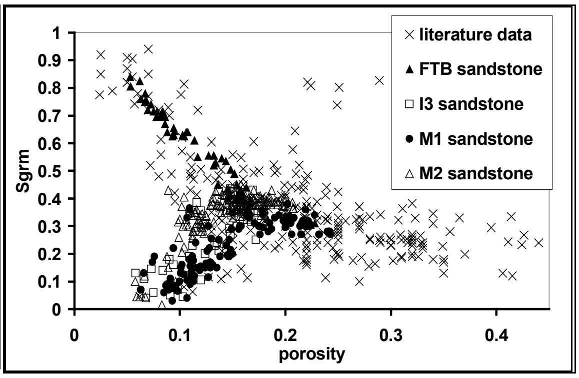

Figure 8: Porosity versus Sgrm, literature and our data

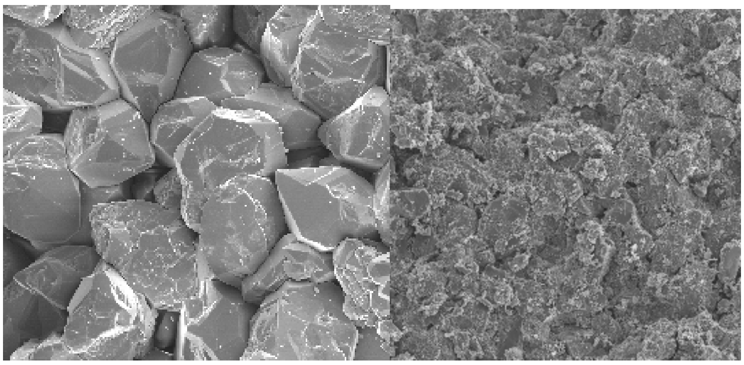

Figure 9: SEM images of Fontainebleau sandstone and reservoir sandstone (Phi = 9% - *100)

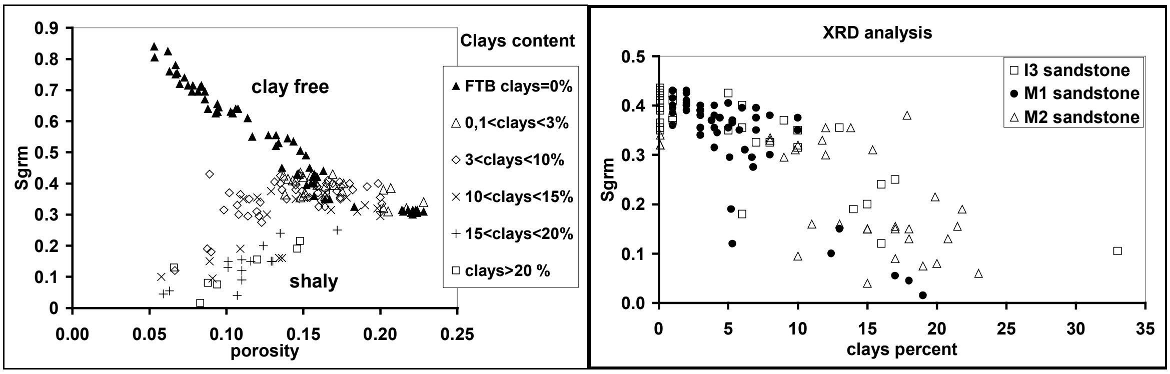

Figure 10: Influence of clay presence (10a) and Sgrm versus clay content (10b)

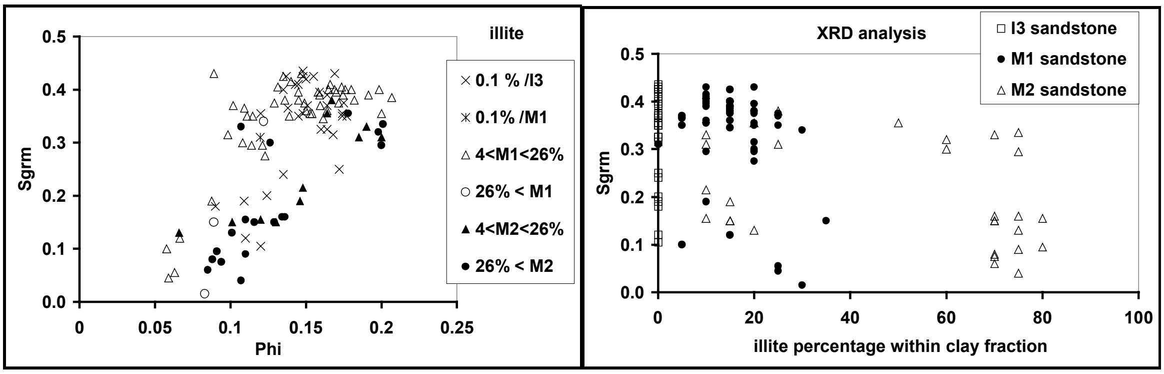

Figure 11: Influence of illite percentage (within clay fraction) on trapped gas (11a) and Sgrm versus illite contents (11b)

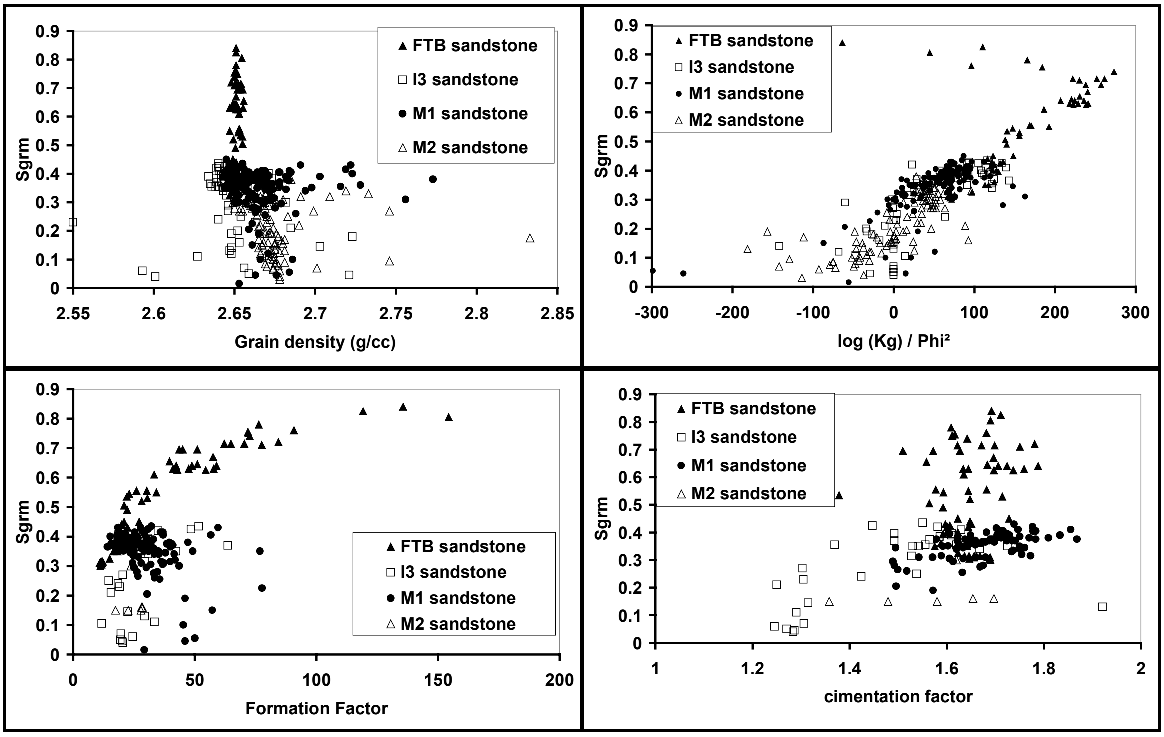

Figure 12: Trapped gas as a function of petrophysical parameters.

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