DISTRIBUTION OF CLAYS IN SANDSTONES BY IMAGE ANALYSIS: QUANTIFICATION, REPRESENTATIVITY AND EFFECTS ON PETROPHYSICAL PROPERTIES.

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Abstract

Distribution of clays in sandstones was quantified using Scanning Electron Microscopy image analysis. Prior to estimation of mean values, representativity was checked using variograms, which gave the size of sample to be studied. Several parameters were calculated, either from granulometric or from geostatistical procedures. Attempt was made to correlate these parameters to permeability: straightforward use of well-known formalisms was likely to give acceptable values for model sandstones, but failed in the case of reservoir sandstones, where the spatial relationship between framework grains and clays is more complex.

Introduction

Whatever their abundance in oil-bearing sandstones, clays hinder fluid flow, by plugging the pore volume. The oil-brine distribution may depend on their nature. Heterogeneity of their distribution is a major factor affecting petrophysical properties of the sandstones. An attempt is made here to quantify this distribution through image analysis, in three dimensions, after having checked the representativity of sample. In a second part, examination of well known formalisms correlating permeability with measured parameters is performed.

Samples and methods

The study focussed on sandstones, with differing clay contents and heterogeneity:
- clean sandstones (from Fontainebleau), containing only quartz, but with different porosity and permeability values,
- model argillaceous sandstones, used for laboratory experiments,
- argillaceous reservoir rocks, from the North Sea.

The characteristics of the samples are given in Table I, and some images are shown Plate I,a,b,c.

Brine permeability measurements were performed, and wettability indices measured on some of the samples, according to usual procedures (Cuiec, 1991).

Scanning electron micrographs of polished sections were recorded on a Jeol 35CF fitted with an Energy Dispersive Spectrometer (EDS) Tracor 524 and an image analyser Tracor 5700-8500. For backscattered electron images, grey levels are associated with the chemical contrast: the higher the mean atomic number Z, ($Z = \Sigma C_i Z_i$, with C_i concentration of element i, Z_i atomic number of element i) the higher the grey level (0=black, 256=white). So, usually, pores are black, clays, often mixed with pores, are dark grey, quartz and albite are mean grey, K-feldspars, carbonates, some micas and chlorites are light grey, and heavy minerals, like pyrite, apatite or titanium oxide, appear white. Segmentation of images between two grey levels allows the building of binary

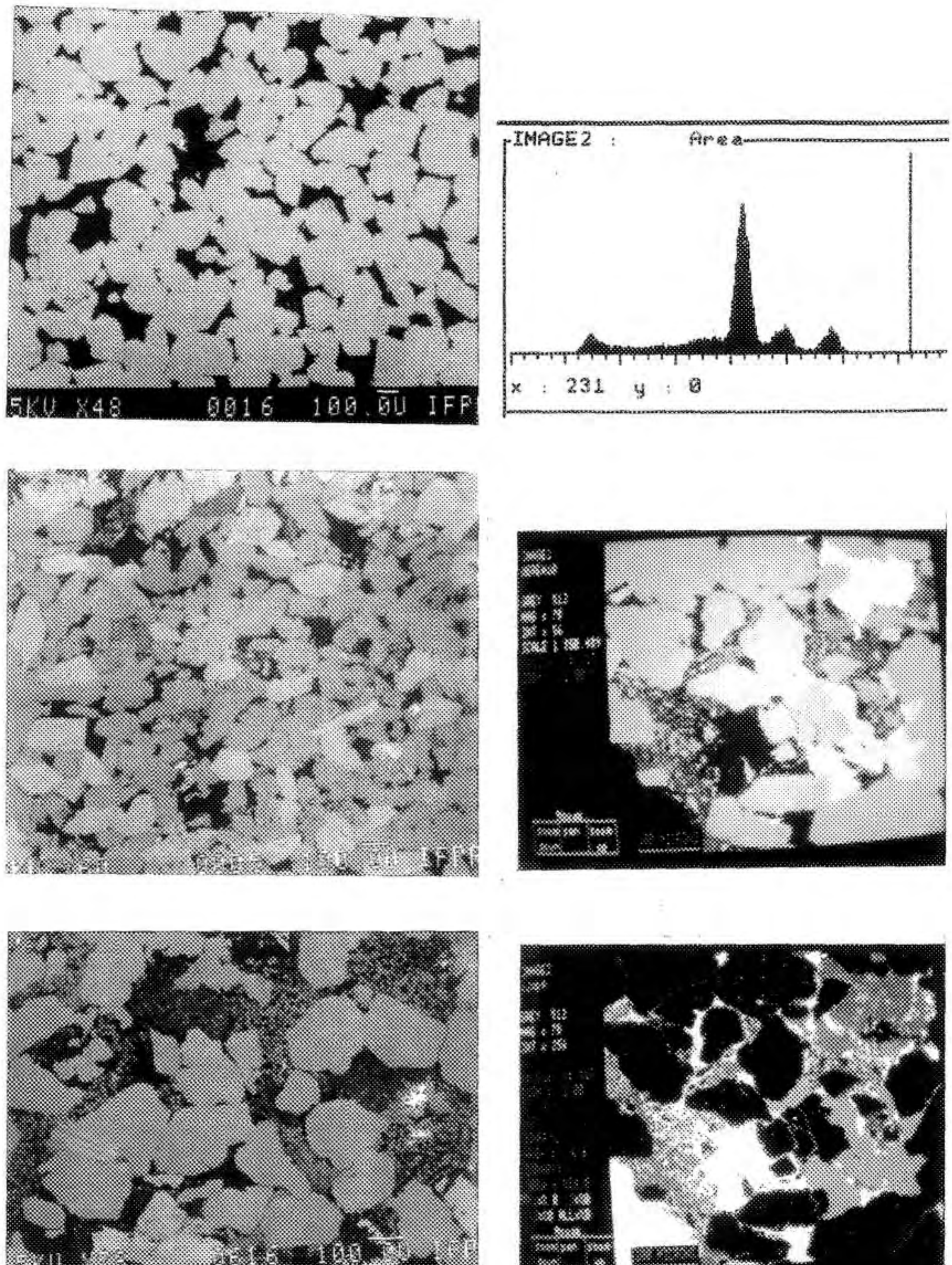

Plate I

images (Plate I, d,e,f)[1]. An EDS allows semi-quantitative elemental analysis of elements with Z>11, thus precise identification of minerals. Combination of both techniques with image analysis has already been used by Fens *et al.*, (1991).

Table I: Characteristics of sandstones

Fontainebleau sandstones					
name	H2	Z296	GAGV	GB3	F600
porosity (%)	25	18.5	16.6	15.6	12.9
permeability (md)	3300	2600	1600	1000	700
Model clayey sandstones					
name	GV	GMES	Berea	GAM	
porosity (%)	14	14	15	13	
permeability (md)	1400	82	150	82	
clay nature and content					
Illite	4 %	9.8%	0 %	9.8%	
Kaolinite	0.5 %	3.1 %	4.7 %	3.1 %	
Reservoir sandstones					
name	A6	A7	A8	Q	A92
porosity (%)	22	12	18	15	16
permeability (md)	470		156		412
clay nature and content					
Illite	6.5 %	2.5 %	6.2 %	5.5 %	4.5 %
Kaolinite	7.9 %	3 %	5 %	3.8 %	9.5 %

Before image acquisition, the problem of sampling representativity must be addressed. The range of variation of any property may show variations depending on the localisation of the image (Matheron, 1965). To make correlations between images, they must be recorded with a known pattern: usually, about ten adjacent images in two perpendicular directions of space on two polished sections, one parallel to the main direction of the core, the other perpendicular. Properties were measured on these images, and the variograms of these values calculated (see appendix for definitions). When a plateau was reached, an arithmetic mean value could be taken over at least the number of values needed to reach this level.

Magnification must be chosen carefully before acquisition. Using a magnification x 50, with a screen of 512 x 512 pixels (= picture element), for a 10 cm wide image, each pixel will be about (4 µm)^2, while if the magnification is x 200, the pixel will be 1 µm^2, thus allowing a better resolution of clays, but leading to much more images to cover the same surface area of sample: for one centimeter length, from 5 images to 20 !!! As some measurements will depend on the magnification, for a comparison purpose, the same order of magnification is required. The present work used values between x 48 and x 78.

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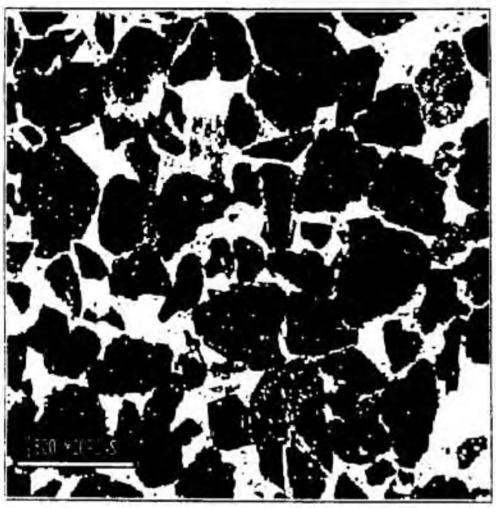
[1]Plate I, a,b,c: respectively Fontainebleau, model and reservoir sample backscattered electron images.
d,e,f: grey level histogram of a backscattered electron image of a model sandstone, and binary images (here in colors) drawn from the segmentation.

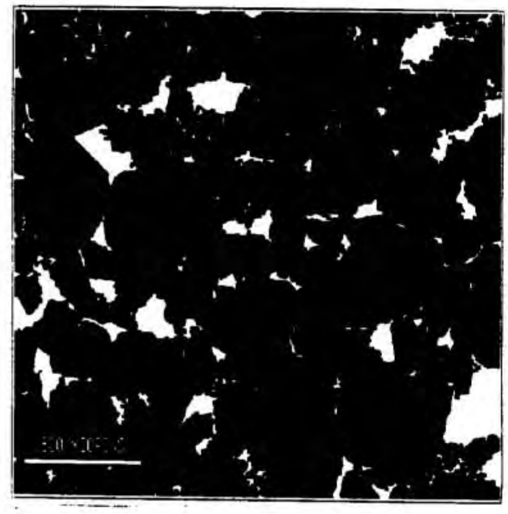
a

operation	porosity (%)	volumic surface area (μm^{-1})
none (a)	18.4	0.0232
erosion (b)	9.0	0.0088
dilation (c)	29.8	0.0212
opening (d) (erosion+dilation)	13.7	0.012
closing (e) (dilation+erosion)	21.1	0.0176

Effects of mathematical morphology operations on images parameters

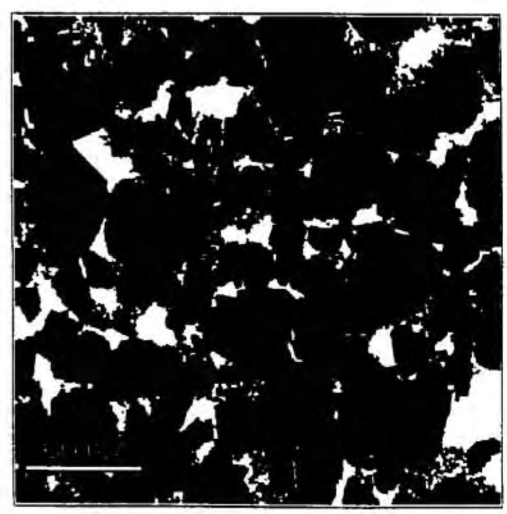


c



b

e



d

Plate II

These choices having been set, bi-dimensional SEM/image analysis have usually followed the path:

- backscattered electron image acquisition on polished sections,
- image processing (thresholding, segmentation, binarisation): binary images showing the distribution of pores, clays and framework minerals were built up,
- elemental analysis: minerals identification, semi-quantification,
- image analysis: granulometry (size and shape), covariance function calculations (volumic surface area, correlation distance).

Mathematical morphology operations are often used prior to image analysis, to smooth the images (Fens *et al.* 1991), or as a step of the process (Ehrlich *et al.* 1991). Definitions and effects of the main operations are given in Appendix. These operations affect the whole surface area, and may change the value by a large factor: this is particularly true when clays are looked for, because the size of the pixel may be of the same order as the size of the clay particles: erosion suppresses a large part of the clay particles, and they are not restored by a further dilation. These effects are illustrated on Plate II[2] . In the present study, none of these operations has been used on images before the following processes.

Many granulometric parameters can be calculated from binary images: the ones we have selected are listed and defined in the Appendix. Using a commercial software, some operations cannot be impeded, and smoothing and contouring are performed in the Tracor procedure, thus modifying to some extent the image. The result of such a granulometric analysis is a list of values for each particle, which are usually drawn as histograms of the number of particles having the same range of values. To improve the meaning of the drawing, the surface area has been used in place of the number of particles. Even this way, the representation is hard to sum up, and finally, the value of the property corresponding to half of the surface area has been retained for comparison purpose. Whatever the software, the determination of granulometric parameter needs that pores be defined as individuals in the frame of the image: depending on the scale and shape, this may be impossible.

Covariance function calculations provide a means to measure the volumic surface area, from the tangent at the origin of the function, which is expressed as $\mu m^2 / \mu m^3 = \mu m^{-1}$ and the range, which is the distance over which there is no more relation between the points. These calculations may be done on binary images of pores, but also, if needed, on the binary images of clays only. Rectangular functions, between e.g. pores and clays, may be calculated in a similar way. The calculations do not require that the pores (or other measured quantity) be defined as individual particles and is thus more general than granulometric procedures.

Results

Representativity of images

Segmentation of images provide estimations, on each image, of the amounts of minerals defined above. These amounts show a range of variations, and the problem is to see if these variations are random or not: the range of variations can be, for a reservoir sample, among eighteen images, between *e.g.*: 9 and 24 % for pores, 7 and 21 % for clays, 56 and 67 % for quartz, 4 and 16 % for feldspars. This is illustrated on figure I,

[2]Plate II . Illustration of the effects of mathematical morphology operations on a binary image of pores of a model sandstone.

which shows the variations of minerals amounts for two sets of images, one in the vertical plane of the sample, the other in the horizontal plane. Figure II shows the variograms calculated starting from this values.

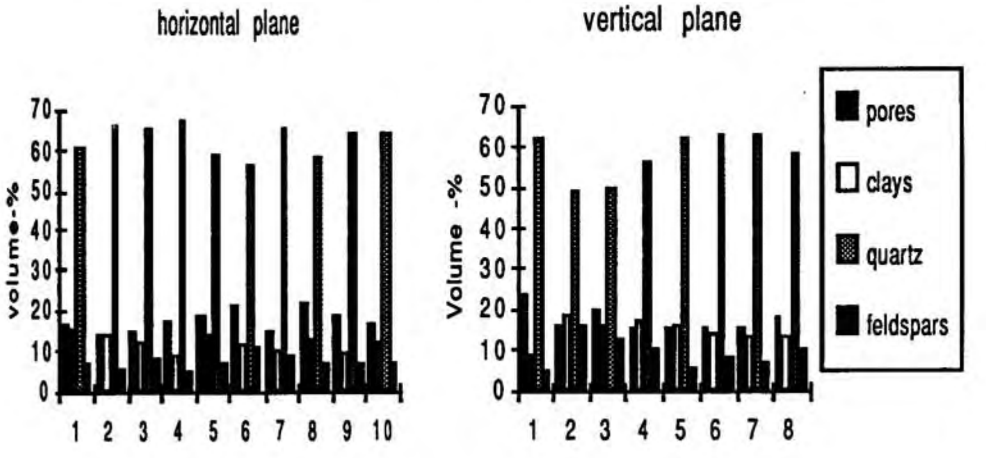


Figure I: *Histograms of the amounts of pores, clays, quartz and feldspars in two perpendicular planes of a reservoir rock.*

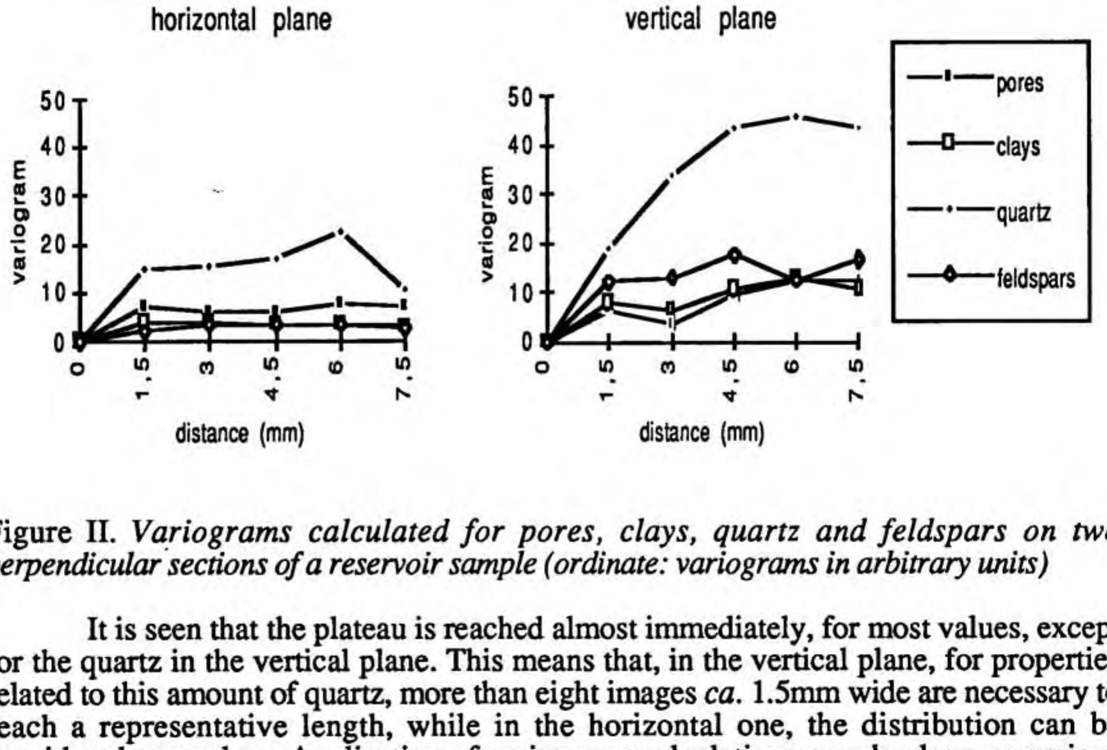


Figure II. *Variograms calculated for pores, clays, quartz and feldspars on two perpendicular sections of a reservoir sample (ordinate: variograms in arbitrary units)*

It is seen that the plateau is reached almost immediately, for most values, except for the quartz in the vertical plane. This means that, in the vertical plane, for properties related to this amount of quartz, more than eight images *ca.* 1.5mm wide are necessary to reach a representative length, while in the horizontal one, the distribution can be considered as random. Application of variograms calculations may be done on various properties.

When the plateau is reached, it is considered that a mean can be taken over all the images needed to reach this plateau: the number of images may be a few ones (in Fontainebleau, or in model sandstones), but can reach about twenty, at the magnifications used in the present study, if the size of grains or pores is large compared to the field of the image: in some cases, it was not possible, for the size of the available sample in polished section, to reach this plateau.

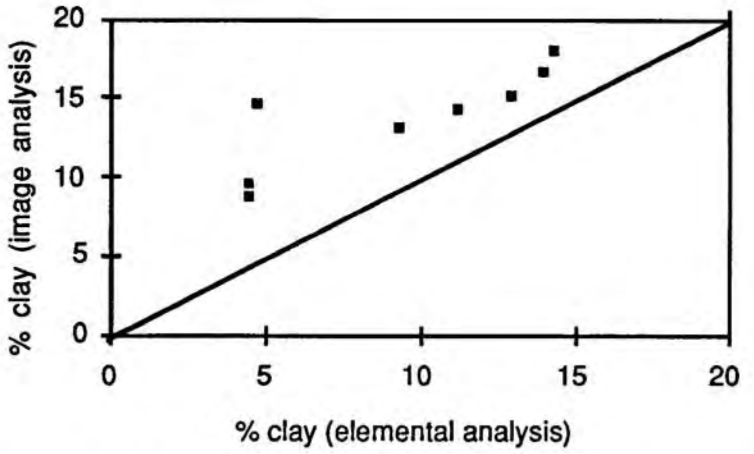


Figure III. *Comparison of evaluation of clay content of the studied samples by two methods*

Comparison of porosity calculated from these measurements, with the value measured on a plug with brine gives a good agreement. For the estimation of minerals content, comparison can be done from results found respectively :

- by elemental analysis, starting from about one gram of powder, and processing the experimental values using a DATREC software (Durand *et al.*, 1991) ,
- by segmentation of images taking the average over the so-determined number of images (a correction for porosity must be done).

This shows a fair agreement of the two determinations, with only a slight overestimation of clay content, due to edge effects (Figure III). Provided the representativity has been checked by this method, images are a good representation of the composition of the rocks, and spatial relations found hereafter are significant.

Granulometry

Granulometric parameters were easily measured on the Fontainebleau and the model sandstones. But it was not possible to obtain values on all reservoir samples images, because in some cases the pores extended through the images in such a way that individualisation was not possible, or was possible for only a small part of the pores. External perimeter and maximal projection were positively correlated, as well as the shape factor. In contrast, the aspect ratio did not show any systematic variations.

Spatial relationships

Spatial relationships between the different mineral phases found in the samples are given by the covariance functions, calculated from pores only, or for clays. The volumic surface area for pores only is about half the volumic surface area of clays only, but this ratio depends on the distribution of clays, which may be more or less compacted, and thus seen as individual particles, or as packets. The ranges are still more difficult to interpret: in some cases, the range is not reached for one image, meaning that it should be calculated on a larger image. The range of pores and the range of clay distribution may be different, the latter being larger, but this is not always true. Ranges are usually between hundred and several hundred micrometers.

Discussion

The results obtained by image analysis are shown as a function of the total porosity in Figure IV, with the permeability measurements. The values are mean ones, taken over the whole set of images, when the asymptotic level was reached. When a plateau was not reached, the values are not reported.

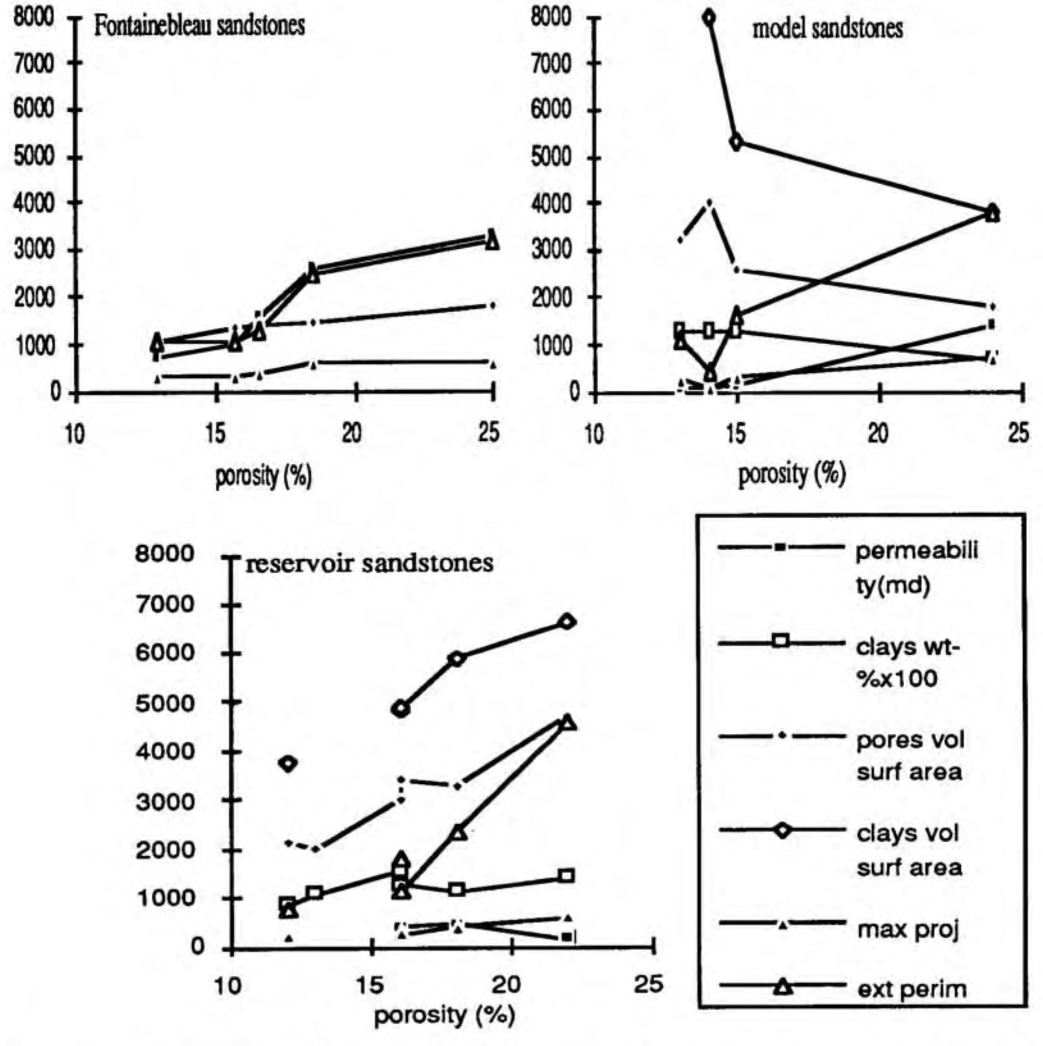


Figure IV. *Correlation between permeability, clay content, geostatistical parameters (volumic surface area of pores and of clays, expressed in 10^{-4} μm^{-1}) and granulometric parameters (external perimeter and maximal projection, expressed in μm) and the total porosity of the samples.*

For Fontainebleau sandstone samples, which are quite homogeneous, the arithmetic mean can be taken over a few images (less than 10). The trend of variation of all parameters, size and surface of pores, is the same: surface area of pores is related to their extension. So finding relationships between any parameter and the porosity seems likely.

For model sandstone samples, a plateau is reached for a small number of images (less than 10), indicating a good homogeneity of the sandstones, except for Berea, because the sample used was bedded, and in the vertical plane, the plateau was reached only for a high number of images (about 20 in this plane). In the same range of porosity as for Fontainebleau, the permeabilities are far smaller, and increase with total porosity, but decrease with increasing clay content.

Volumic surface area of the pores varies in the same way as volumic surface area of the clays only. This correlation indicates that both the framework grains and the clays are distributed in the same way, which is consistent with detrital clays widespread during deposition. Maximal projections and external perimeters are in the same order of magnitude than Fontainebleau ones, but they are negatively correlated to the surface areas, meaning that this surface area is mainly due to clays and no more related to the size of the pores. However, the maximal projection and perimeter vary in the same way as permeability. Thus, for these model samples, permeability depends mainly on the pore size, is reduced by the clays, but is relatively little affected by the clays localisation in the porous space.

For reservoir sandstone samples, the plateau was not reached in some cases: either in one direction only, for bedding reasons, or in both directions, meaning that the observation scale used was too small, owing to *e.g.* a large grain size and pore size.

Volumic surface areas of pores and of clays vary also in the same way, but increase with the total porosity, for a similar clay content. This suggests first that the clays are also equally distributed, at the scale of the sample studied, but second that the dispersion of the clays is better when the porosity is higher, which is consistent with diagenetic clays, growing in the porous space, while detrital ones (in the model sandstones) more frequently line the pores. Permeability is also quite small, but is not related to the external perimeter nor to the maximal projection, indicating that in this case presence of clays not only decreases the total permeability, but also modifies the geometry of pores in a way that is not accounted for by the used parameters.

This analysis provided quantitative data for choosing the observation scale, and comparing the geometrical distribution of the pores and the clays in different sandstones. For the samples studied here, the distribution of clays has not the same effect on the permeability for reservoir and for model sandstones.

More precisely, the effect of the measured parameters, when applied to relationships established to predict permeability values have been tested on:

* the Poiseuillé relationship:

$$K = \phi \frac{r^2}{8}$$

with ϕ the porosity, and r the radius of pores.

* the Kozeny-Carman relationship:

$$K = \frac{\phi^3}{k_o(L_e - L)(1 - \phi)^2 S_s^2}$$

with ϕ the porosity, k_0 the Kozeny constant, (L-Le) the tortuosity (the product of these two factors being usually taken as 5), S_s the specific surface area,

* and also the Jacquin (1964) relationship for Fontainebleau sandstones,

$$K = A\,\phi^{4.5}$$

with A being a constant and ϕ the porosity.

Application of these laws to the above measured values, taking for S_s the volumic surface of pores, and for r half of the value of the maximal projection, gives nearly always excess values for permeability. As an example, the values found by Kozeny-Carman formula are shown in Figure V.

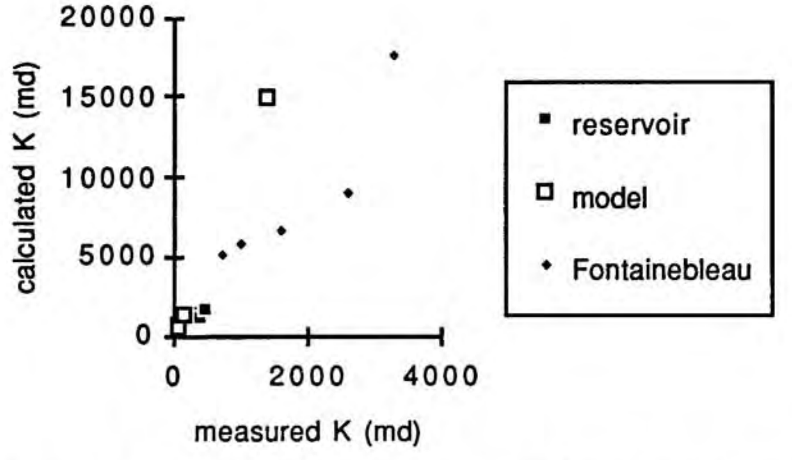


Figure V. *Comparison between the measured values of permeability, and the values calculated by the Kozeny-Carman formula, using the parameters drawn from image analysis, for the different sandstones.*

Several reasons may be invoked to explain this discrepancy. First, the surface area of pores may be underestimated, but even taking the value for the clay surface area to calculate K also gives values that are too high, and the values are in excess also for Fontainebleau, where there are no clays. Second, taking values determined by gas adsorption, which are far higher, neglects the fact that these values are obtained on powdered samples, in which crushing has created new surfaces. The radius of pores may also be too high. The maximal projection is indeed a high estimation of size, but is must be remembered that we took the value corresponding to half of the surface of the pores. However, the values for model sandstones vary in the same way, and could thus be ajusted, using some tortuosity factor.

But for argillaceous reservoir rocks, we have shown that extension of pores and surface area are not directly related, so simple geometrical relationships are likely to fail, and more sophisticated ones should be looked for. This is the case for permeability, which has been widely studied, but also for other properties, like wettability, for which the relationships are poorly known.

Conclusions

I. Processing of images has a great influence on the measured values, and should be performed very carefully to preserve the required resolution.

II. Variograms are a practical tool to test the representativity of the sampling of reservoir rock at the cm scale. Depending on the size of grains and pores and on the magnification, they give the minimum number of images to process in order to get representative measures. The number of images to take into account has to be increased until a plateau is reached in the variograms. This happens more often for reservoir sandstones than for laboratory models.

III. Representativity having been checked, it is possible, from SEM measures, to get significant values for porosity and amounts of minerals.

IV. Granulometric and geostatistical parameters provide quantitative tools to compare sandstone geometry, and distribution of clays inside the pores. Geostatistical, i.e. surface areas may be calculated for any kind of rock, whereas granulometric parameters are sometimes impossible to determine on reservoir sandstones.

V. Distribution of clays can be different for model and for reservoir sandstones. Lining and pore-filling clays induce specific effects on the size and surface area of pores, thus impeding direct application of well known formalisms to relate geometry to permeability. Distribution of diagenetic clays, as it occurs within the porous space, is more difficult to relate to the framework geometry, and thus to take into account in models using simplistic formalisms.

Further work is needed to take into account the effect of the available parameters on different petrophysical properties.

ACKNOWLEDGEMENTS

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Appendix

***Mathematical morphology and geostatistic definitions** (Matheron, 1965, 1967, Serra 1982, Coster and Chermant, 1985)*

Mathematical morphology allows quantification of intuition by the means of structuring elements. When using these tools, assumption is made that the objects are: (Serra, Coster & Chermant): invariant by translation, compatible with a scale modification, known through a measure mask, i.e. locally, semi-continuous. The main operations are:
erosion: :rubs out lines irregularities, suppresses particles small related to the structuring element,
dilation: :can connect separate particles
opening :erosion, then dilation: separates the particles, suppresses the small ones, cuts the large ones, smoothes the outlines,
closing :dilation, then erosion: connects the particles, by suppressing the small spaces between them.
Most used structuring elements are the square and octagon, the latter being more isotropic, but larger.

Classical statistics assumes that it is possible to repeat indefinitely a measure, and that these measures are independant, which obviously is not always true. A regionalized variable does not take the same value at any point of the field: it is linked to its support, and depends on the localization on this support, on the continuity of the phenomenon, it can be anisotropic and can show transition phenomena.

Variogram

To evaluate the dependance between two values f(x) measured in two points whose distance is a vector h, a variogram g (h) can be calculated, according to:

$$g(h) = 1/2\, E[(f(x) - f(x+h)]^2$$

with E the mathematical expectation of the expression between brackets. If the support of the value is not a point, but a field of measure, the so calculated variogram is called regularized

Properties of the variogram

* The form of the variogram is characteristic of the spatial relationship between the points (or the fields).
* Usually, in the simplest case, after a continuous growing, the variogram reaches an asymptote, for a value of h, h_p which is called the geostatistic range, *i.e.* the distance from where there is no more correlation between two measurements, in other words, the measurements can be considered as independant.
* The variogram has a directional meaning.
* Sometimes the ordinate at origin is high, this is called a "nugget" effect.

Covariance function

If the measure field is small referring to the object, the covariance function $C(X;h,\alpha)$ is defined as the probability that the structuring element $\vec{h}$ implemented in every point x of set X be contained in X, thus that x belongs to the eroded of X by $\vec{h}$, in the measure mask Z.

Properties of the covariance function:

* ordinate at the origin equals amount (e.g. of porosity)
* asymptote value equals the square of the amount
* directional meaning: isotropic or anisotropic

* derivative at the origin with respect to h is related to the specific perimeter, and thus to the specific surface area.
* first minimum: mean size of objects (e.g. pores)
* first maximum: mean distance between objects
* range: point of crossing of curve and asymptote. If a macrostructure exists, the asymptote is not reached.

Granulometric definitions

Particle: here, a pore, limited by an outline.

Area: the number of all pixels in the particle, converted to appropriate units, here μm^2.
External perimeter: particle perimeter, from pixel center to pixel center. Here converted to µm.
Maximal projection: defined by the points the farther belonging to the convex perimeter.
Shape: (external perimeter)^2 / (4π * area)
Aspect ratio: (maximal projection)/ (width)
Width: minimum Feret diameter along x (=projection of feature on x-axis)