CORE PETROPHYSICAL MEASUREMENTS ON UNCONSOLIDATED SANDS IN DEEP WATER RESERVOIR

B. Levallois –ELF EXPLORATION PRODUCTION

With the increase of the exploration in the deep offshore, the coring of unconsolidated formations is more and more frequent. Because of the economy of the project and the importance of the accumulations, the petrophysical measurements and their analysis are crucial for a better evaluation of these formations. This paper presents the main results obtained from the treatment of unconsolidated sands in such shaly sand formations.

The measurements of porosity, permeability, electrical properties and mineralogy made on 1000 unconsolidated samples are presented. All the measurements have been made at reservoir effective stress. A complete granulometric distribution by laser diffraction and whole rock X-Ray mineralogy have been acquired on all the samples. The synthesis of these measurements shows that contrary to the consolidated sandstone, there is no relationship between the porosity and the permeability. It presents how the porosity and the permeability behaviour can be explained by the granulometric parameters (median grain size and sorting).

A wide range of analysis (multisalinity formation factor, mineralogy, Cation Exchange Capacity and salts extraction) have been made on samples with an increasing clay content. These measurements can provide the variations of the formation exponent 'm*' and the cation Exchange Capacity in function of the clay content. These correlations are determinant for the water saturation interpretation with the JUHASZ technique that is used in shaly formations.

Finally, this paper presents the technique used for the construction of continuous 'core logs' of the basic core properties (porosity, permeability, grain density and clay content) all along the cored interval at the centimetric scale. It shows how is built the 'core logs' by extrapolation of the punctual measurements made on samples with the core imaging (CT scan and photographs) and the sedimentological description. It also presents how the 'core logs' improve the matching between the core measurements and the interpreted logs thanks to the upscaling. A field case demonstrates that on high frequency heterogeneous formations comparing the samples measurements at centimetric scale with the logs interpretation at decimetric scale is the classical pitfall in such heterogeneous formation.

INTRODUCTION

With the increase of the exploration in the deep offshore, the coring of unconsolidated formations is more and more frequent. Because of the economy of the project and the importance of the accumulations, the petrophysical measurements and their analysis are crucial for a better evaluation of these formations.

This paper presents:

1 – an analysis of the correlations that exist between the grain sizing and the petrophysical behaviours. The present analysis is based on a set of 1000 measurements (porosity-permeability-grain sizing) made at reservoir effective stress.

2 – how the resistivity measurements on the shaly sands samples can precise the electrical behaviour of the shaly formation in order to perform an accurate water saturation interpretation with the Juhash [4] technique.

3 – the construction of a continuous 'core log' in order to upscale the core measurements from the centimetric scale of the samples to the decimetric scale of the well logs. A field case in an heterogeneous shaly sands formation is presented to show how this technique improves the core log matching and avoid the classical pitfall of a matching without upscaling.

BASIC CORE MEASUREMENTS - EXPERIMENTS

For the rock basic properties evaluation, the measurements that are systematically performed are the brine and gas permeability, the porosity, the grain density, the formation factor, the mineralogy and the grain sizing. On all the samples, the permeability and the porosity are measured **at reservoir effective stress**.

Sampling:
Because of their unconsolidated state, as soon as they are plugged, the samples are immediately put into a viton sleeve. They will remain into the sleeve until the end of the measurements. In order to check the integrity and the homogeneity of the samples, as a direct visual control is impossible, a scanner of each sample is systematically done. Some samples are rejected because of heterogeneity, foam injection or destructuration. The scanner is a fundamental stage to eliminate the samples that would provide erroneous petrophysical properties to the formation.

Petrophysics:
The gas permeability is measured at effective stress and at 10 different pore pressures in order to correct the measurements from the Klinkenberg and Forscheimer effect. The pore volume is measured by nitrogen expansion into the sample at effective stress according to the Boyle's law. The solid volume is also measured by expansion of nitrogen in a chamber that contains the sample.

Mineralogy and grain sizing:
The mineralogy is determined by the technique of the X-ray diffraction. When the mineralogy is more complex, the X-ray diffraction is completed by the fluorescence technique. The granulometric distribution of the samples is acquired by the technique of the laser diffraction particle. It provides us 85 classes of grain size from 0.05 µm to 20 mm. In the correlations that will be presented, using all the 85 points that characterise the granulometric distribution is not realistic. Only 3 parameters that 'summarised' the grain size distribution are extracted:

- **median** : corresponds to the quartile Q50 on the cumulative size distribution.

- $$\text{sorting} = \sqrt{Q75/Q25} \qquad\qquad \text{skewness} = \frac{Q25 \times Q75}{Q50^2}$$

with Q75 and Q25 quartile at 75 and 25 % of the cumulative size

The sorting indicates if the grain size distribution is more or less scattered whereas the skewness characterises the asymmetry of the grain size distribution.

Results on several field cases:
Measurements following the previous procedures have been performed on 1300 unconsolidated core samples from 6 different fields on the tertiary deep offshore. Among these samples, we will focus only on the clean sands that contain less than 5% of mineral clay, namely 1000 samples. All the samples are uncemented.

Petrophysics
Contrary to the consolidated sandstone, there is no correlation between the porosity and the permeability (figure 1). Porosity is mainly comprised between 20 and 40 %. The permeability is high, between 100 mD and 5 Darcy. For a given porosity, we can find samples with several magnitudes of permeability and the highest permeability do not correspond to the highest porosity.

Petrophysics versus Grain sizing
The figure 2 shows that there is a good relationship between the porosity and the median grain size. The porosity increases when the median size decreases. If we observe all the plots, we can note that the correlations are very close. Some slight difference maybe explained by a difference in the effective stress applied during the pore volume measurements. In fact, the effective stress depends on the depth of the samples, so it can vary from one to an other.

On the same way, there is a correlation between the porosity and the sorting (figure 3). When the sorting is better (value going towards 1), the porosity is increasing. This confirms previous studies [1, 2] made on artificially mixed and packed sands that shows that the porosity was first influence by the sorting and at a second degree by the median grain size. If, on these field cases the two parameters seems to have a comparable influence, it is because contrary to artificial mixing of sands, there is a narrow relationship between the median grain size and the sorting ; **the finer is the grain size, the better is the sorting and then the higher is the porosity**.

Regarding the permeability, there is a generally weak relationship with the median grain size and the sorting (figure 4). The permeability tends to increase when the mean grain size is increasing but the cloud of points is a little bit scattered. One reason for the dispersion is that the permeability is not only influenced by the median grain size but also by the sorting. For a given median grain size, the permeability has tendency to increase when the sorting is better.

By a multivariable regression, we also tried to see if the skewness could improve the correlation between grain size and petrophysics but no relationship has been found. The skewness is quite less correlated to the petrophysics than the sorting or the median grain size.

The good correlation between the grain sizing and the petrophysics has two major interests. The first one is the possibility to predict the petrophysical behaviour only with the granulometric parameters.
The second one regards the characterisation of the geological reservoir model with petrophysics. The grain sizing will be the link between the geology and the petrophysics. In fact, on the tertiary formations, the lithological facies are mainly based on the grain size of the rocks. Thus, as we have a good correlation between grain size and petrophysics we will be able to petrophysically characterise each geological facies with a rather good accuracy.

ELECTRICAL PROPERTIES OF THE FORMATION

For the electrical log interpretation in the shaly sands from the tertiary formations, we use the Juhasz method. The Juhasz method is based on the Waxman&Smith formula in shaly sands [3] that gives the formation conductivity (Ct) in function of the total water saturation (Swt), the formation factor F*, the formation water conductivity (Cw) and the clay conductivity given by the term B.Qv:

$$Ct = \frac{Sw_t^{\,n}}{F^*}\left[Cw + \frac{B \cdot Qv}{Sw_t}\right] \quad (equ.\ 1)$$

In the term B.Qv :

- B corresponds to the conductance of the clay. An empirical formulation of B in function of the temperature and the resistivity of the formation water is given by Juhasz [4] :

$$B = (-1.28 + 0.225 \times T - 0.0004059 \times T^2)/(1 + (Rw^{1.23})*(0.045 \times T - 0.27)) \quad (equ.\ 2)$$

T: Temperature (°C) – Rw resistivity of the formation water (Ohm.m)

- Qv : quantity of cations that can be exchanged by volume of clay porosity:

$$Qv = \frac{\phi_{clay}}{\phi_t} \times V_{clay} \cdot Qv_{clay} = Qv_n \cdot Qv_{clay} \quad with \quad Qv_n = \frac{\phi_{clay}}{\phi_t} \times V_{clay}$$

ϕ_{clay} : clay porosity (frac) – ϕ_t : total porosity (frac)

V_{clay} : volumic clay fraction – Qv_{clay} :Qv of 100% clay sample

So, if we replace Qv in the equation 1, we have:

$$Ct = \frac{Sw_t^{\,n}}{F^*}\left[Cw + \frac{B \times Qv_n \times Qv_{clay}}{Sw_t}\right] (equ.\ 3)$$

The calculation of the water saturation by solving the equation 1 imply the knowledge of the $\mathbf{Qv_{clay}}$. The JUHASZ technique determines the Qv_{clay} only with the logs. In fact, in a water interval (Swt = 1), the equation (3) becomes: $\mathbf{F^* . Ct = Cw + B \cdot Qv_{clay} \cdot Qv_n}$, so Qv_{clay} can be calculated by a linear regression on the crossplot (called the 'JUHASZ crossplot) 'between F*.Ct and Qv_n. Nevertheless, when we try this method on field cases, most of the time, the linear correlation between F*.Ct and Qvn is not obvious or impossible to get. This is because **the formation exponent m* used to calculate F* (=1/$\mathbf{f^{m^*}}$) has been supposed constant with Qvn which is absolutely not the case**. As a consequence, in order to reduce the uncertainties on the determination of the Qv_{clay} by the JUHASZ method, core measurements are necessary to determine how m* varies.

Measurements:
For a sample 100% saturated with brine, if we consider a crossplot between the sample conductivity Co and the brine conductivity Cw (fig. 5), they are linearly correlated. F* corresponds to the inverse of the linear slope. On clean samples, if Cw = 0 then Co = 0 and F* = F. On the contrary, on shaly sample, at Cw=0, Co is superior to zero. This is because of the contribution of the clay to the sample conductivity. In this case, only one resistivity measurement is not enough to calculate F*. We need either at least 2 conductivity at 2 different salinity or one conductivity and the B.Qv of the sample.

The first solution (resistivity for several salinities) is hard to perform on shaly samples because it is long and difficult to circulate different brines in samples with a low permeability. In general we work with the second solution:

- We choose a set of samples with a different shaliness in order to be predictive on the whole interval of variation of the Qvn.

- On each sample, a mineralogical analysis by XRD and a Cation Exchange Capacity (CEC) measurements by cobaltihexamine titration [5] are performed. The CEC and the basic core measurements (porosity ϕ and grain density ρ_S) are used to calculate the Qv:

$$\mathbf{Qv = \frac{CEC \times r_S \times (1 - f)}{100 \times f}}$$ (equ 4)   CEC: Cation Exchange Capacity in meq/100g

ρ_s : grain density in g/cc - Φ : porosity in fraction

  B is given by the equation (2). So we have the B.Qv point.

- On the samples that are permeable to be flooded, we saturate them with a reconstituted brine equivalent to the formation water in order to get a resistivity measurement. Nevertheless, that can be performed only on samples that contains less than 25-30% of clay. In fact, above this limit, the samples are not permeable enough to be well saturated with brine. In that case, we measure their conductivity just after plugging. The samples are taken in the center of the core and immediately measured to be sure that the fluids (formation water) are still in place. The good saturation of such samples is controlled afterwards by comparing the pore volume measured by helium expansion

and the loss of water after drying. If there is a difference, that means that the sample was partially dessaturated so it is rejected. The conductivity of the formation water that saturated the sample is calculated according to the analysis of the salts that are removed from the dry sample.

So we have a resistivity measurement which is linearly correlated with the B.Qv in order to determine the F* of each sample .

Results on 2 field cases:
This approach has been fully applied on 2 sets of samples (21 samples on the well H and 16 samples on the well I). The samples are chosen so as to sweep the full range of clay content encountered on the cores.

First, the Cation Exchange Capacity has been measured on all the samples. There is a good linear correlation between the Cation Exchange Capacity and the Clay content on the two wells (fig. 6). Nevertheless, the correlations are not exactly the same. This is because of the nature of the clay assemblage. It is constant on each well but slightly different from each other. If the clay assemblage was variable on the same well, a multilinear correlation with the different clays would have been necessary to correlate the CEC.

In parallel, one resistivity measurement has been performed on each sample in order to calculate a F* as described before. The figure 7 presents $m^*(=-\log(F^*)/\log(\phi_t))$ in function of the clay content. It shows **that m* is not constant but that there is a good correlation between m* and the clay content**. In the two cases, m* increases with the clay content. We can also note that there is a continuity between the m* calculated on the permeable samples that have been ressaturated and the non permeable shaly samples that have been directly measured with their own formation water. The similarity of the laws obtained for these two cases can not be generalised. In fact, we are here in a very similar lithological environment. Other experiments made on consolidated formations have already shown very different behaviours.

In conclusion, for the utilisation of the JUHASZ technique which is one of the most appropriate approach in shaly sands, the assumption that m* is constant whatever the clay content is, makes that the resistivity log are more difficult to interpret. Electrical core measurements on samples chosen in the full range of shaliness can provide the true behaviour of m* and then reduce the uncertainty on the water saturation interpretation.

Core Log

One of the objective of the petrophysical measurements made on the cores is the calibration of the well logs interpretation in order to reduce the uncertainties on the reservoir properties. Classically, after depth matching, the core measurements are directly compared with the logs interpretation and the interpretation parameters are adjusted until having a satisfactory match between the logs and core measurements. On the tertiary reservoir, we note that the comparison is often difficult even after optimisation of the interpretation parameters.

The main reasons are :

- The scale of the logs (about 0.6 m) is larger than the scale of the petrophysical measurements (5 cm).

- The heterogeneity of the formation is so important that all the intervals have not been sampled and then, the laboratory measurements do not represent all the cored interval.

This problem of matching is illustrated on the figure 8 that represents the comparison of the blind logs interpretation and the core measurements on 20 meters. On these 20 meters we have extracted the photographs of 2 metres of cores to show the very high heterogeneity of the core and the difference of resolution between the logs and the samples.

In order to help the comparison, what we called a '*core log*' is built. It is a continuous log that provides the porosity, permeability, grain density and clay content all along the cored interval.

Methodology for the construction of the core logs [6]:
For the construction of the core log, we collect all the information available on the cored interval: conventional petrophysical measurements – Clay content from X-ray diffraction – core logs (core gamma-density and core gamma-ray) – sedimentary description – cores photographs (daylight, ultraviolet and X-ray scanner photographs).

The cored length is divided in several intervals. These intervals are defined so as to be petrophysically homogenous. Those subdivisions are done according to :

- Sedimentary description of the core. The different intervals determined by the sedimentologist are often homogenous and could have the same petrophysical properties.

- The observation of the core : it's a good mean to visually control its homogeneity.

- The logs recorded on the core. A seemingly homogenous interval could present serious variation of core gamma-density or core gamma-ray response. After controlling that those variations are not due to measurements conditions (loss of materials, failure, ...), we subdivide with a few more intervals which present a comparable core log response.

Once defined these intervals, a value of porosity, permeability, grain density and clay content is attributed to each one using the following method :

- if the interval contains one plug, the properties of the plug is affected to the interval.

- if there is more than one plug, we control that the measurements are close and affect the mean of each property.

- if there is no measurement, we look for the closest similar interval in petrophysical terms. After controlling that different parameters (gamma-ray, gamma-density, facies) are similar, we affect the same petrophysical properties to this interval.

- if there is no equivalent interval, the porosity is extrapolated from the core gamma-density corrected from residual fluids effects and the clay content is extrapolated from the core gamma-ray.

The figure 9 presents the 2 meters extracted on the figure 8 with the continuous logs in crenels. Each crenel corresponds to a petrophysically homogeneous interval. We can observe that the log go through all the sample measurements. We can also note that many intervals have no measurements. The value that has been attributed to these intervals comes from measurements made on a similar petrographic facies.

Upscaling and comparison with interpreted well logs
For the comparison with the interpreted logs we need to work at the same scale. Thus we have to put the core log which is at the sample resolution (5 cm) to the log resolution (~ 60cm). This transformation is done by the passage of a mobile window smoothing of 60 cm that do the mean of the values contained into the window. At this stage we are able to do the comparison with the interpreted well logs. The figure 9 illustrates the upscaling and the comparison between core and well log. The figure 10 presents the case of a core log on 150 meters of cores. We can note that in many intervals, even if the core log at the sample resolution go through the samples, the smoothed core log do not pass through the samples measurements but gives a good matching with the well log interpretation. In this case, it is clear that trying to match only the samples measurements will conduct to a completely erroneous interpretation.

CONCLUSION

In the field case, the unconsolidated formations, the grain sizing is fundamental to understand the basic petrophysical behaviours of the sands. The porosity increases when the grain size decreases and when the grains are better sorted. Even if the relation with permeability are not so good, there is a tendency that indicates that permeability increases when the grain size increase and when the grain are better sorted. Moreover, contrary to the consolidated sandstone, there is no correlation between the porosity and the permeability.

In the JUHASZ technique which is one of the most appropriate water saturation interpretation method in shaly sands, the assumption that the formation exponent m* is constant is erroneous. It could conduct to a false or an inaccurate interpretation. Laboratory measurements of resistivity on samples chosen in the full range of shaliness can provide the true behaviour of m* and then reduce the uncertainty on the water saturation interpretation.

The tertiary formation are often very heterogeneous, so the resolution of the samples is centimetric whereas the resolution of well logs is decimetric. As a consequence, trying to match the samples measurements with the interpreted log is difficult and can conduct to very erroneous interpretations. A solution to this problem requires the construction of a continuous core log of the main core properties (porosity, permeability, grains density and clay content) at a centimetric resolution. Afterwards, the core log is smoothed to be upcaled at the well log resolution. Thus, the well logs can then be compared with the

smoothed core log in order to adjust the interpretation parameters and obtain a real matching at an equivalent scale.

Acknowledgements:

Reference:

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4 - Juhasz, I – "The key to shaly sand evaluation using the Waxman-Smiths equation in the absence of core data". *SPWLA Second Annual Logging Symposium*, June 23-26, 1981.

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7 – O. Serra – "Diagraphies Differée", *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine*, 1979, Vol 1 – p43
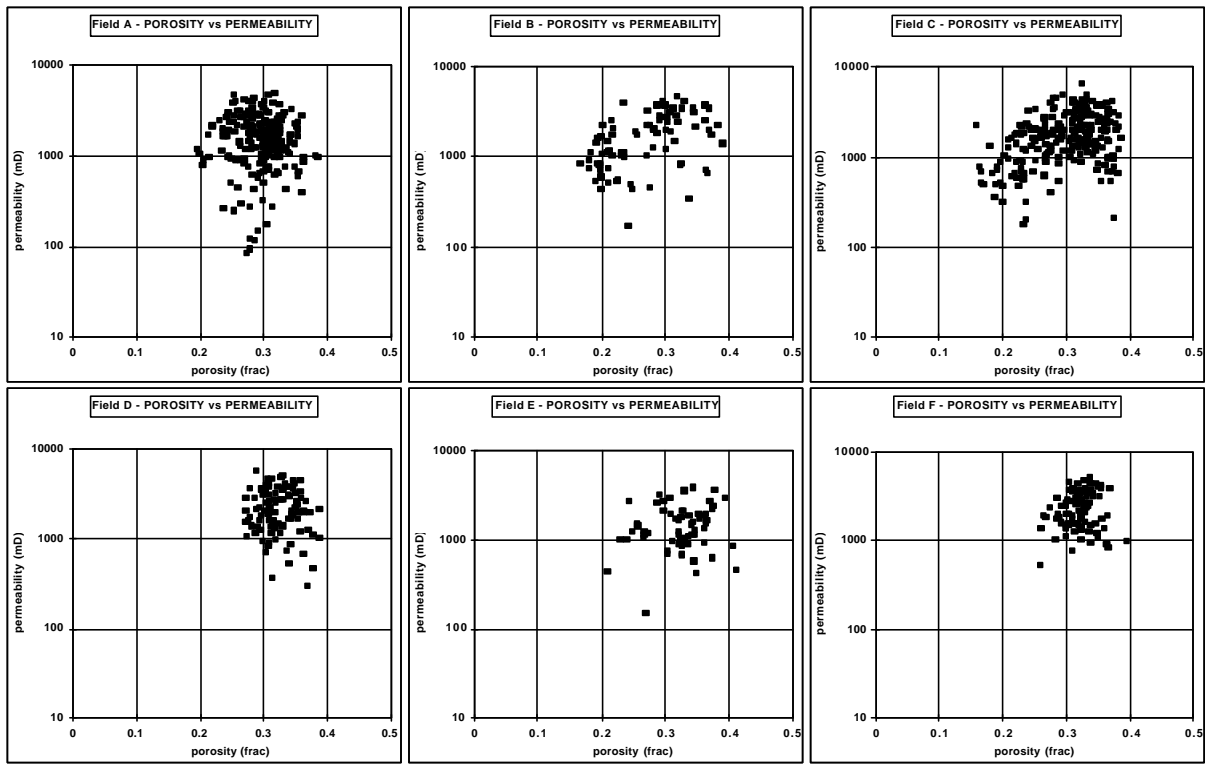
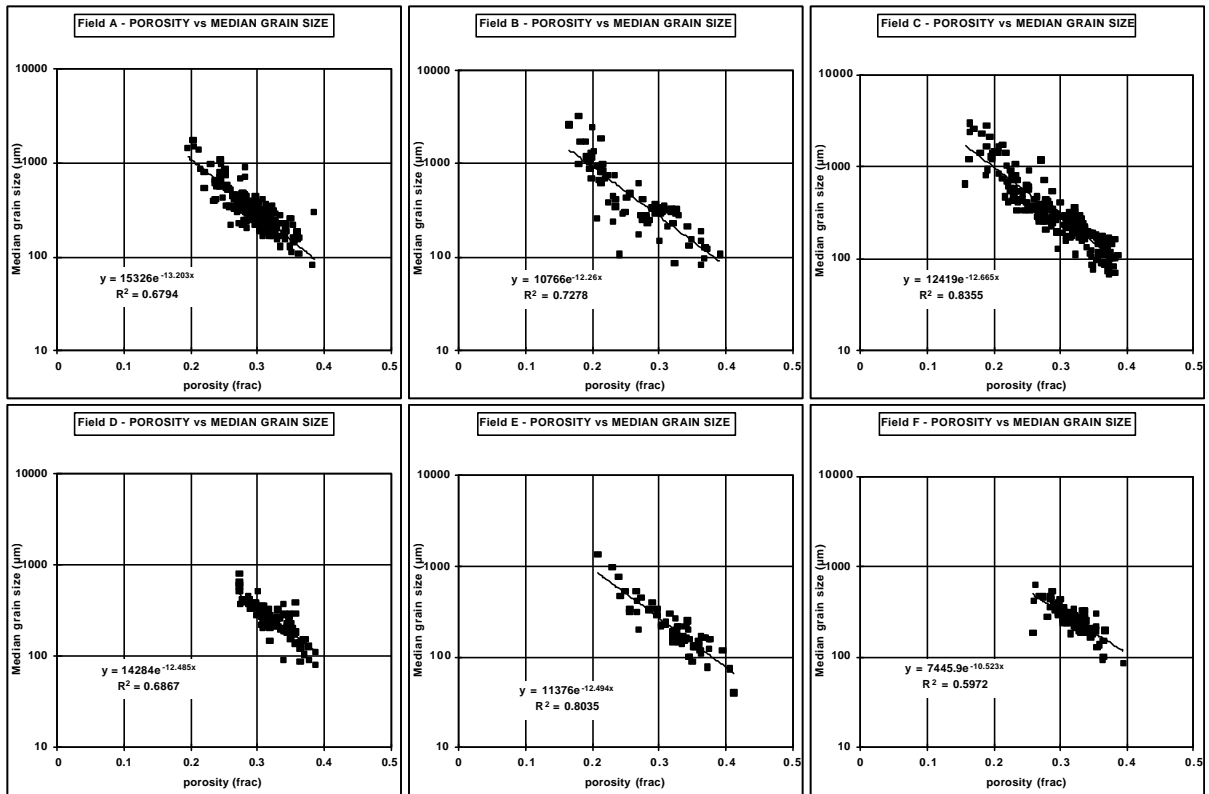*figure 1 – porosity vs permeability on clean (clay<5%) and unconsolidated samples*

figure 2 – porosity vs median grain size on clean (clay<5%) and unconsolidated samples
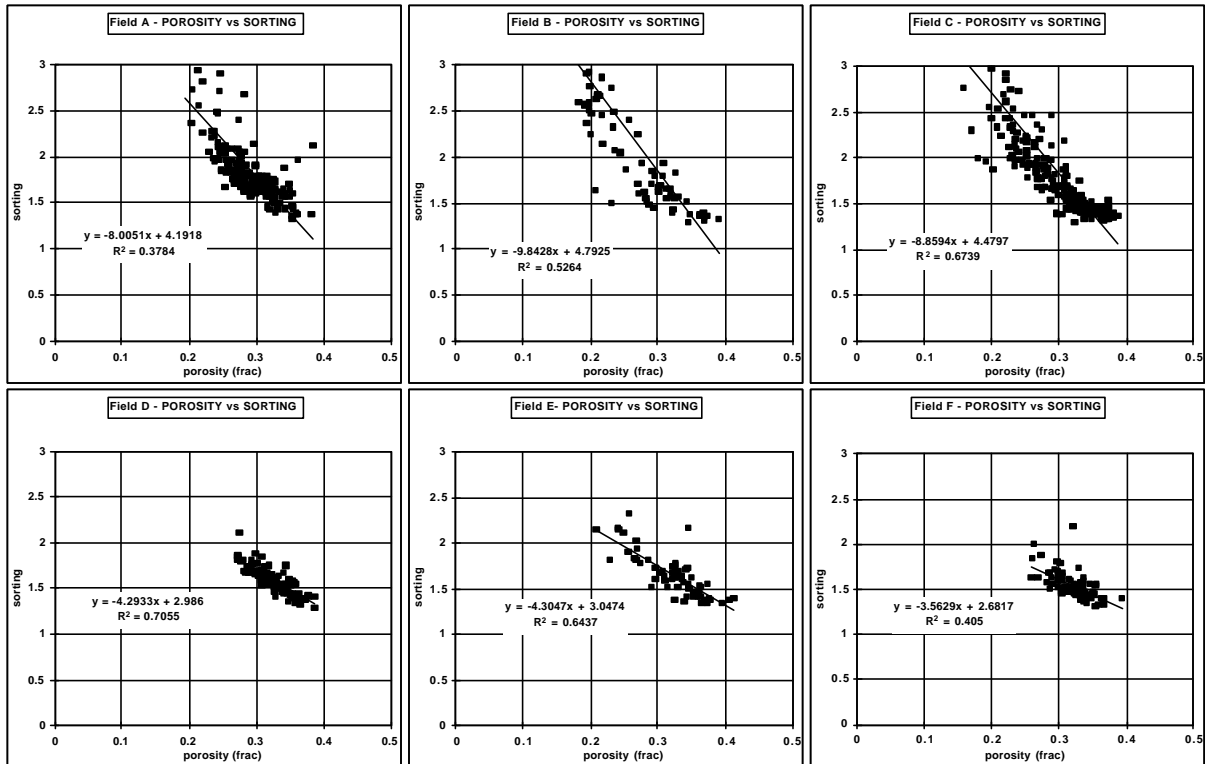
figure 3 – porosity vs sorting on clean (clay<5%) and unconsolidated samples
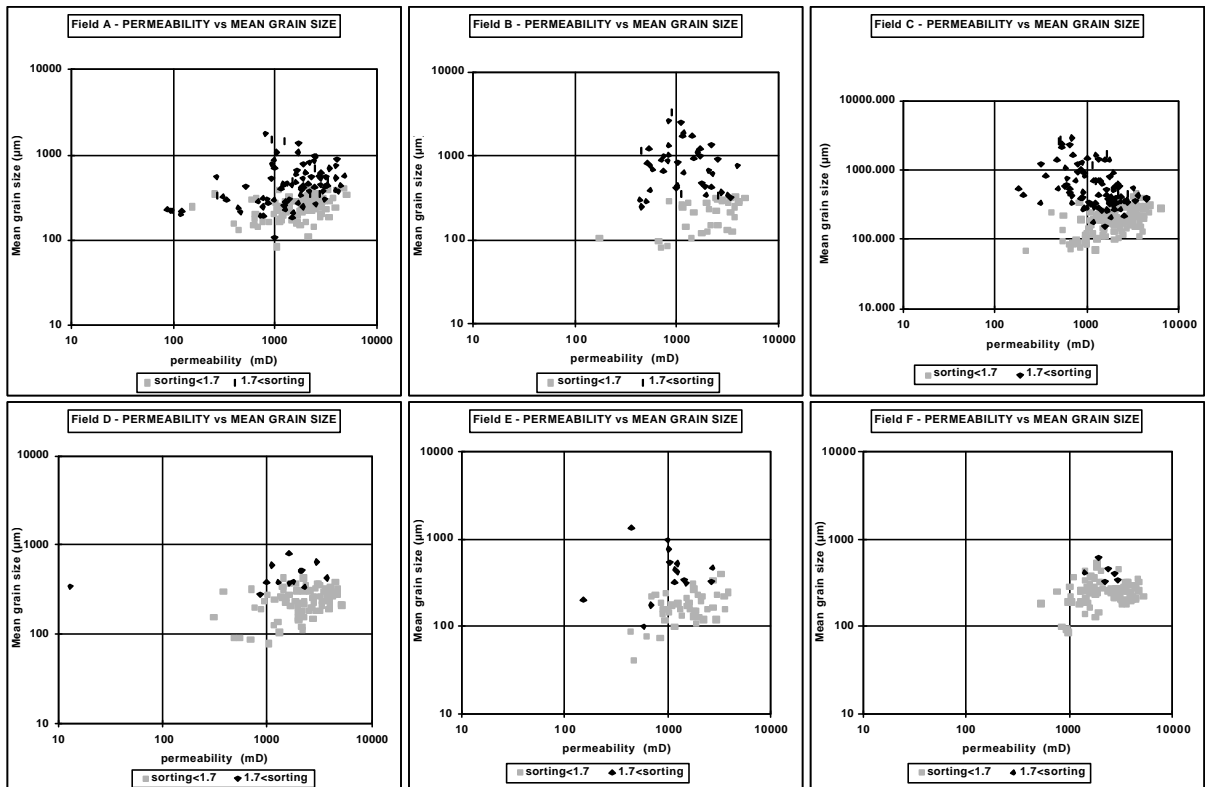
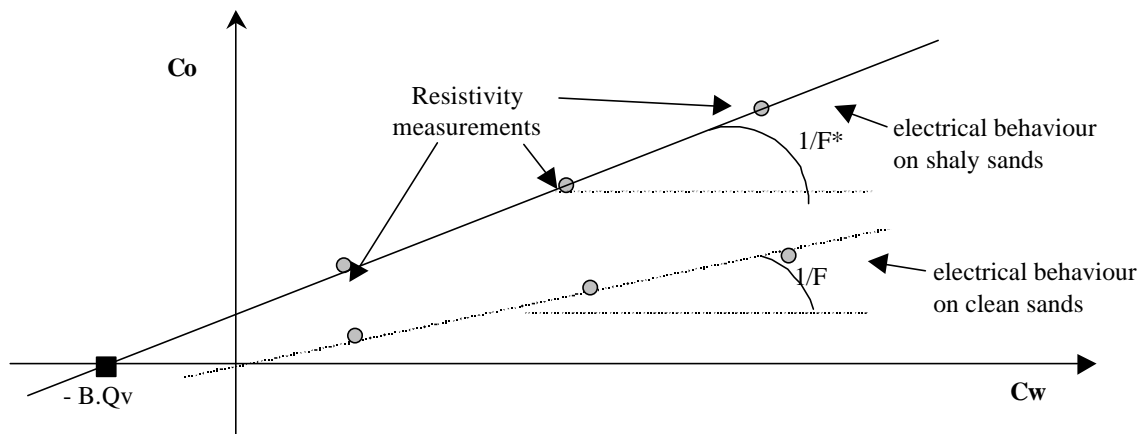*figure 4 – permeability vs median grain size and sorting on clean (clay<5%) and unconsolidated samples*

Fig 5 – Conductivity crossplot for the calculation of F*. On shaly sands, 2 possibilities : at least 2 resistivity or one resistivity and the 'B.Qv' point. On clean sands, F*=F [ref 7].
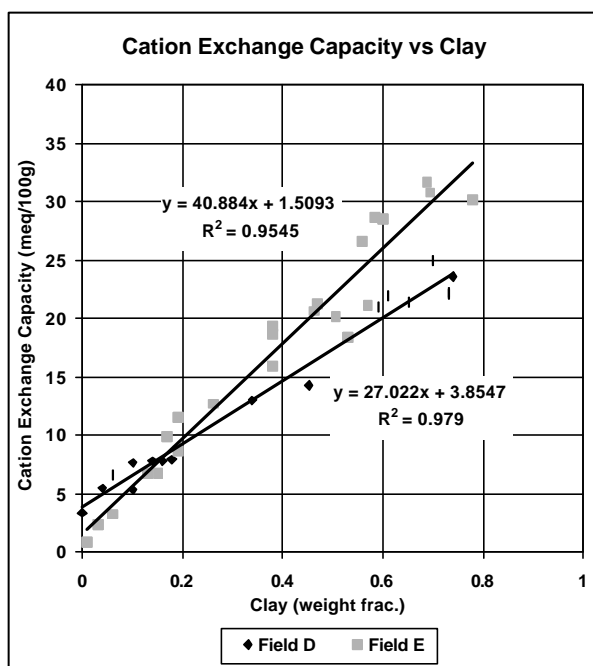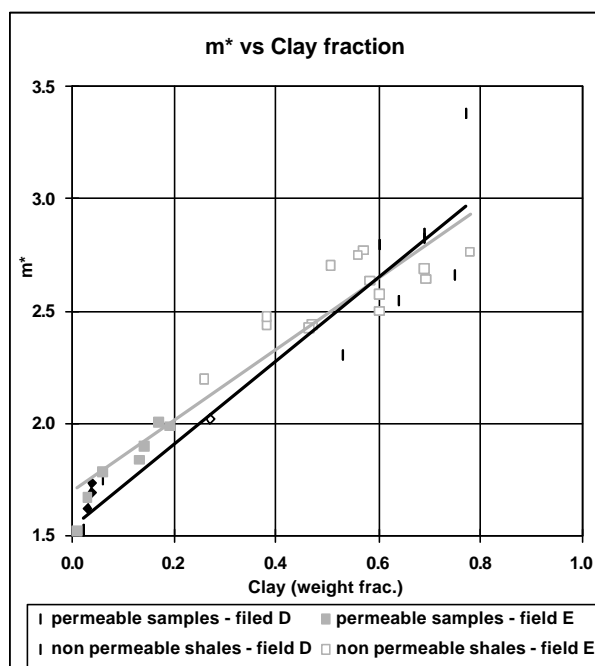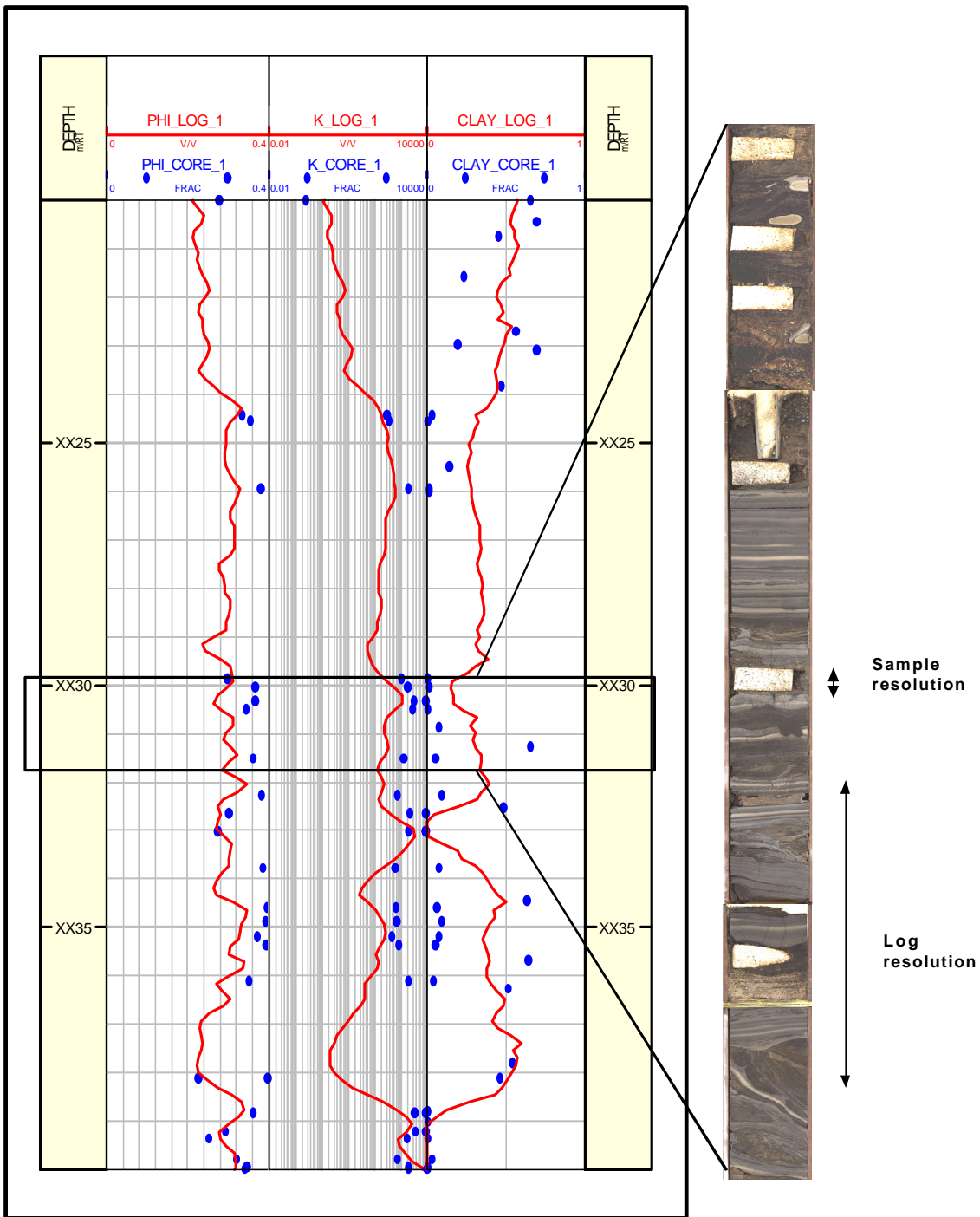

figure 6

figure 7

figure 8: Comparison between blind well logs interpretation and core petrophysical measurements on a very heterogeneous shaly sand tertiary reservoir. The difficulty to match the two sets of data is because of the difference of resolution between the samples (5 cm) and logs (60 cm).
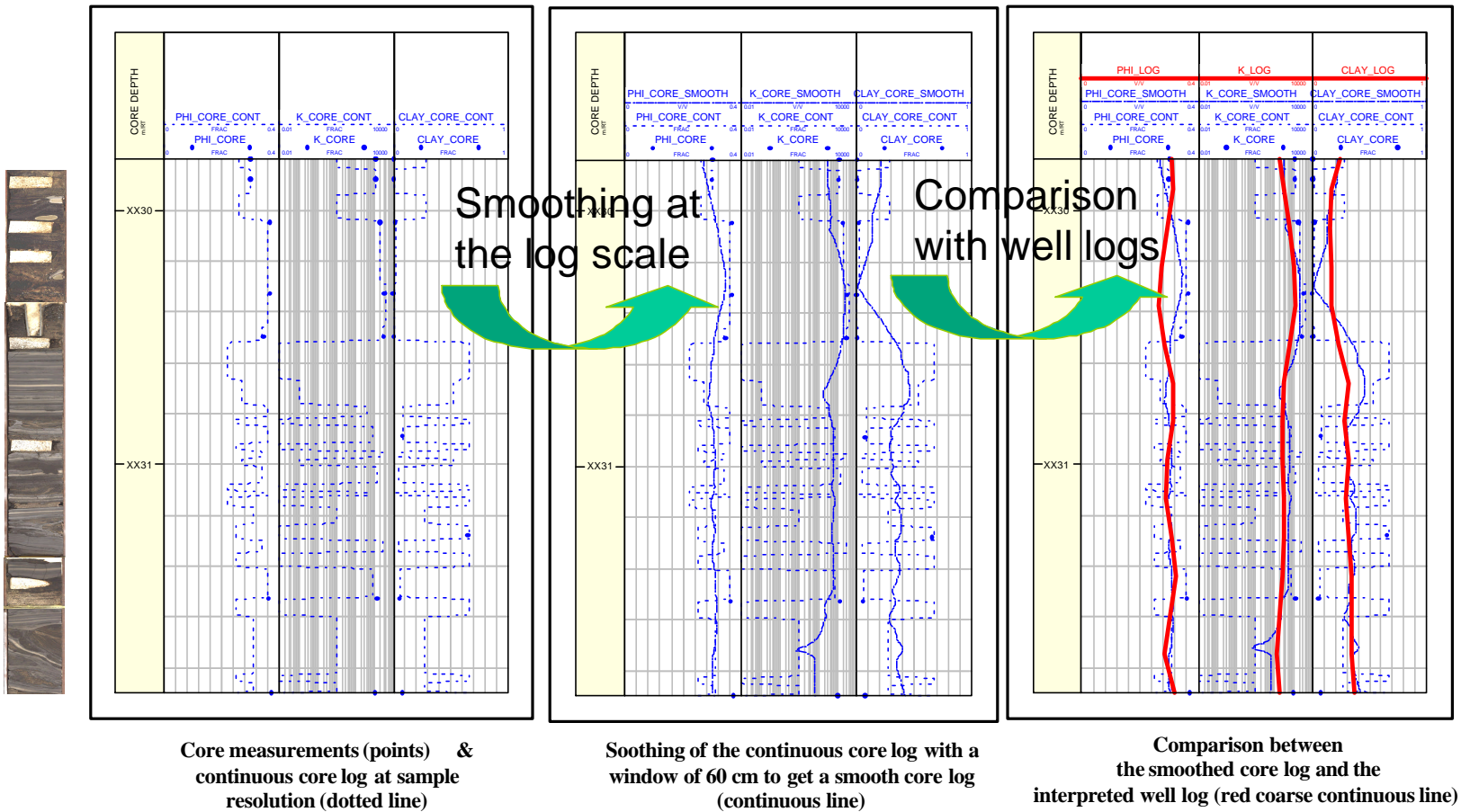
Core measurements (points) &
continuous core log at sample
resolution (dotted line)

Soothing of the continuous core log with a
window of 60 cm to get a smooth core log
(continuous line)

Comparison between
the smoothed core log and the
interpreted well log (red coarse continuous line)

figure 9: Example of core log : construction at the sample resolution – upscaling to the well log resolution - comparison with well logs

Figure 10 :
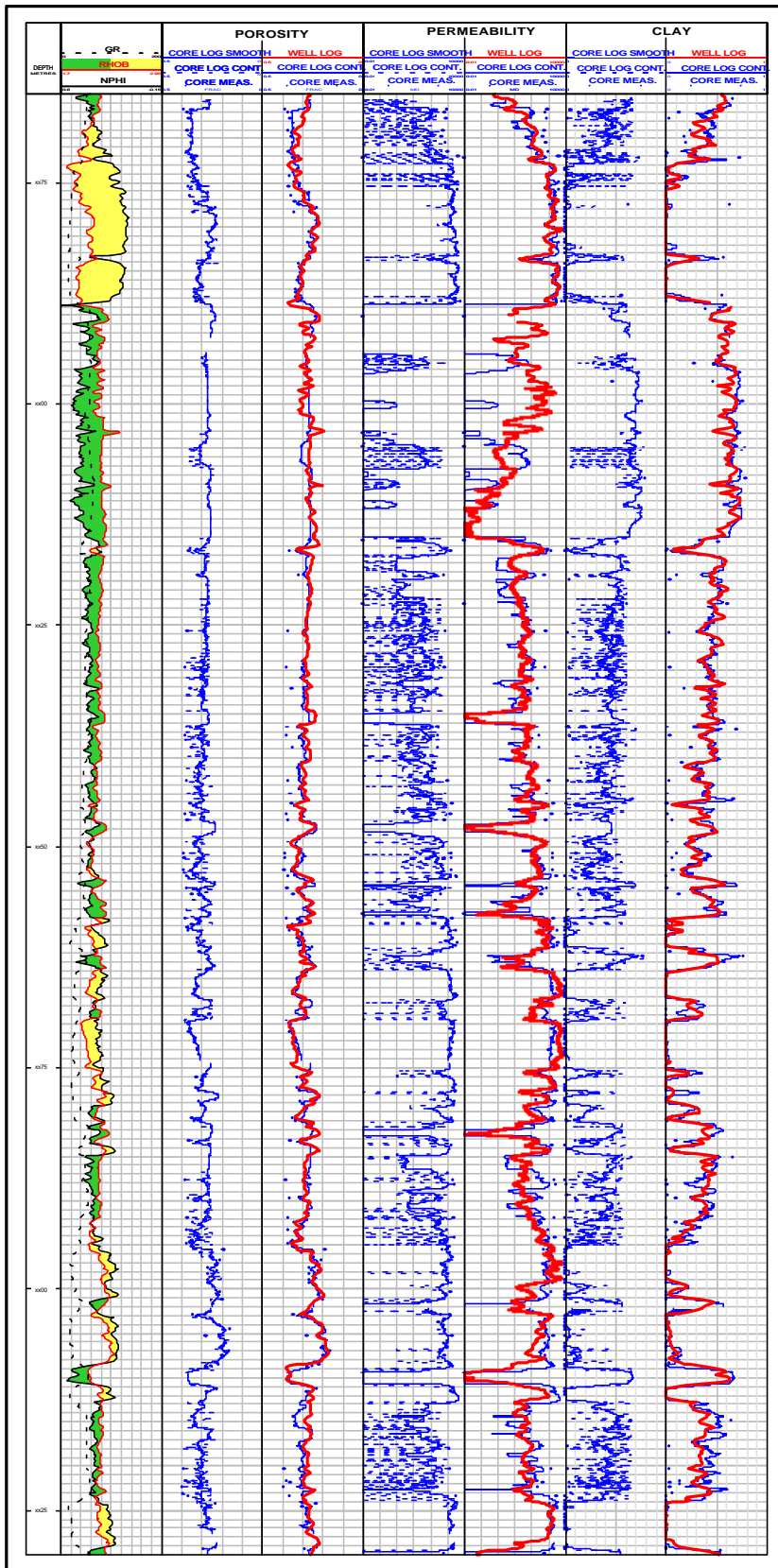
Example of core log (porosity – permeability and clay) on 150 meters.

There are 2 tracks by properties :

• The first track represent the samples measurements (points), the continuous core log at sample resolution (dotted line) and the smoothed core log at the well log scale (line).

• The second track represents the samples measurements (points), the smoothed core log (fine line) and the well log interpretation (red coarse line).