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A Methodology to Rescale the Vertical Coordinate into Geological Time Using a Geostatistical Analysis of Log Data

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SUMMARY

The aim of this paper is to outline a methodology to transform depth intervals into geological time intervals. Working in a geochronological system aids in the understanding of the physical properties of rocks and to do very precise correlations between wells. To transform the present coordinates a high resolution tool is necessary : the FMI® (Fullbore Formation MicroImager, Schlumberger).
First, well log correlations are established between seven wells at different scales. Relative variations of sedimentation rate are observed locally. Second, FMI® images analysis are used to reveal clear carbonate – clay interbedding which display cycles. Third, to study these cycles, geostatistical tools are used. The variographic analysis of conventional log data shows cycles of one meter. With FMI® data, smaller cyles can be detected. Variogram modelling and factorial kriging analysis suggest that three spatial periods exist. They vary vertically and laterally in wells but cycle ratios are stable and similar to orbital cycle (Milankovitch cycle) ratios. The three periods correspond to eccentricity, obliquity and precession. If orbital cycles are known, depth intervals can be converted into geological time intervals and thus give real sedimentation rates and quantification of hiatus duration.

Introduction

The common practice for modelling the heterogeneity of the rock properties of reservoirs is to (1) produce a geometric model of the main formations, (2) transform the present coordinate system into a geochronological system, and (3) model the rock properties in that geochronological system. Step 2 is usually performed by using very abrupt transformations. The present work concerns a rather homogeneous argilaceous formation. The presence of hiatuses (lack of sedimentation, or erosion) and variations of sedimentation rate and compaction rate can modify the petrophysical properties and also change the rock mechanical properties locally. The study of clay heterogeneities thus requires a thorough quantification and modelling of sedimentological and stratigraphical data, and the definition of an accurate geochronological system.

One of the main lines of research of the National Radioactive Waste Management Agency (Andra) is deep geological disposal studies. Andra has conducted studies in its Meuse/Haute-Marne underground research laboratory located at a depth of about 490 m in an argilaceous rock (argilite) 155 million years old : the Callovo-Oxfordian formation. The geological environment is stable with a very low water flow, little deformation, good response to the perturbations due to mining excavation work and the chemical impact of the waste.

The study of variations and spatial variability of the Callovian-Oxfordian clay layer can be conducted from logs analysis and it is very useful to predict the clay properties behaviour in a 250 km² area around the actual laboratory site.

The first part of this paper briefly presents the data; the second part deals with logs to study precisely the log correlation between wells (the most common logs used for this purpose are the gamma ray, the resistivity and the acoustic log) and to determine homogeneous intervals; the third part is concerned with the geostatistical analysis of conventional and high resolution logs. Finally, we show how these results can be used to transform depth interval into geological time interval.

1.   Data presentation

Seven wells along two perpendicular axes (NE-SW: 37 km and NW-SE: 15 km) are studied. Core and log data are available for nearly all the clay layer.

In this study, we use: (1) conventional logs : caliper, gamma ray, resistivities and sonic; and (2) a high resolution tool which provides an electrical borehole image: FMI® Fullbore Formation MicroImager (Schlumberger). The rock texture can be extracted, from dipmeter and image logs, with a texture classification software: BorTex® (Schlumberger), which provides 1D data: 'Background Conductivity' (BC) and 'Residuals'.
Carbonate content and BC are linked. When the carbonate content increases, the conductivity decreases, which makes it possible to follow the evolution of the carbonate content on the BC curve (Figure 1).

On the FMI® images and on BorTex® results (Figure 1), resistive and conductive alternations are present. These carbonate-clay interbeddings have a periodic organisation. Geostatistical tools are used to identify these cycles.

2.   Correlations between wells

Precise log correlation is established between wells from gamma ray, resistivities, sonic and 'background conductivity'. Biostratigraphical data (Marchand & Thierry, 2005) analysis confirms that, at this scale, the correlations are chronostratigraphic. Local relative sedimentation rate variations or even sedimentation stop (hiatus) can be observed.

Cycles have been shown in the Callovo-Oxfordian formation (Brégoin, 2003). If the whole clay layer is considered, cyclicity does not have a uniform organization; homogeneous intervals with a thickness larger than 10 m and correlable between different wells are selected.

To define these intervals, gradient variations and changes in the signal amplitudes of

gamma ray, resistivities and sonic, are considered. Three intervals are defined in the Lower Oxfordian (interval '**1**' at the base to interval '**3**' at the top).
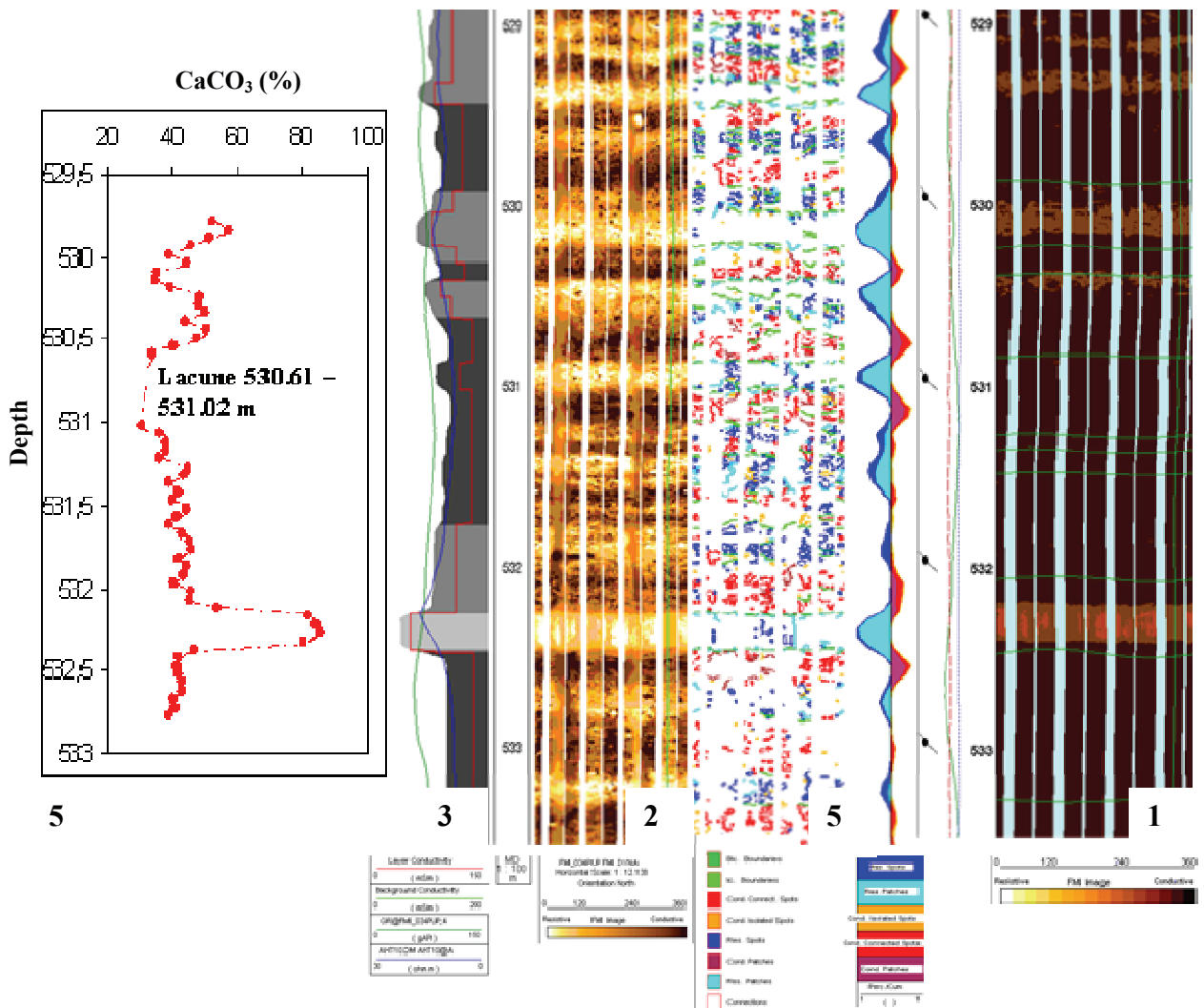
1 : *EID image : a same color represents the same resistivity range. Bright beds are resistive (carbonate) and dark beds are conductive (clay).*

2 : *Dynamic image: a same color does not correspond exactly to the same resistivity range. Contrasts are increased to obtain details. It is necessary to work with image 1 and image 2.*

3 : *'Background Conductivity' : it represents the main beds.*

4 : *'Residuals': it is the result of initial images minus 'background conductivity'.*

5 : *Carbonate content measured on cores*

Figure 1 : FMI® Images and BorTex results for the well EST 322, and comparison with carbonate content measured on cores.
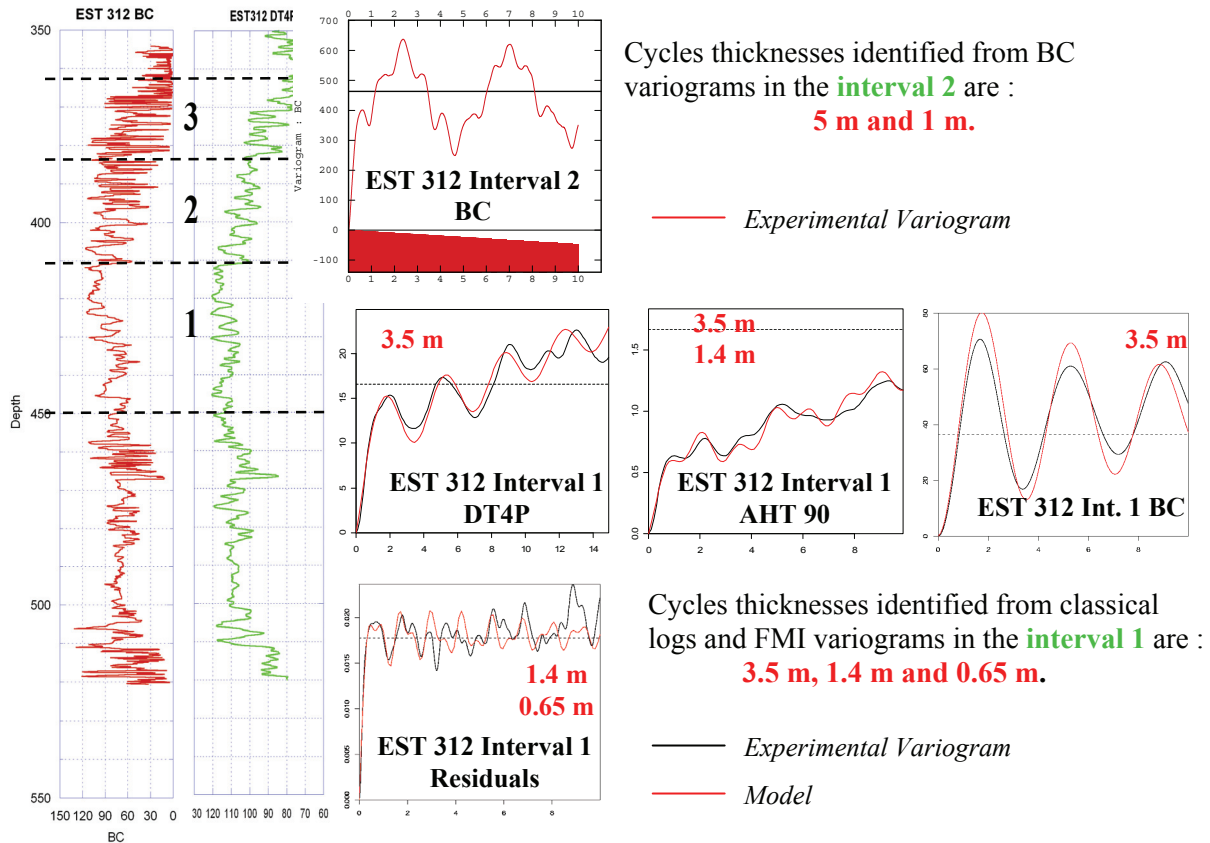
3. Geostatistical analysis

The variographic analysis of classical log data, in homogeneous intervals, shows distinct periods (Figure 2), whatever the studied log. Similar results are obtained by spectral analysis of magnetic susceptibility (Huret, 2006)

In order to get a better resolution, the FMI® images are analysed, particularly the 'background conductivity' and the 'conductive inclusion proportion' (BorTex® results). Three periods are observed on the calculated variograms. FMI® thickest cycles are similar to periods given by classical log analysis. A better resolution is obtained with the conductive inclusion proportion : cycles 30 cm thick can be observed on variograms. To verify these thinnest

cycles, a variographic analysis of gamma ray with 1 cm sampling rate (in wells drilled from the ANDRA underground laboratory) is then carried out.

As a result three main periods of log data are identified; these periods vary vertically in a given well and laterally between different wells.


Cycles thicknesses identified from BC variograms in the **interval 2** are :
5 m and 1 m.

——— *Experimental Variogram*

Cycles thicknesses identified from classical logs and FMI variograms in the **interval 1** are :
3.5 m, 1.4 m and 0.65 m.

——— *Experimental Variogram*
——— *Model*

Figure 2 : Geostatistical analysis of intervals 1 and 2 of the well EST 312 (Bure, France).
DT4P : Sonic, AHT 90 : Resistivity, BC : Background Conductivity.

4.   Geochronological reference system

Cycles ratios are similar to the orbital cycles ratios from the Upper Jurassic (Berger & Loutre, 1994); the three main cycles given by log data correspond to eccentricity (95000 years), obliquity (37700 years) and precession (about 20000 years). The periodic impact of eccentricity can be observed on both classical log data and FMI[®] data analysis while precession is only seen on FMI[®] geostatistical analysis. Obliquity can be given by conventional log data and is often detected while fitting a variogram model.

Variographic analysis gives the mean thickness corresponding to the eccentricity, obliquity and precession cycles in each homogeneous interval. Factorial kriging is then used to estimate the influence of each orbital cycle. Factorial kriging also shows the local variations of cycles thickness.

To improve the search for sedimentation rate variations, it is useful to transform depth intervals into geological time intervals (Figure 3). Working with log correlations, biotratigraphic correlations, orbital cycles and factorial kriging analysis results makes it possible to estimate the stratigraphic interval duration as well as the hiatus duration.
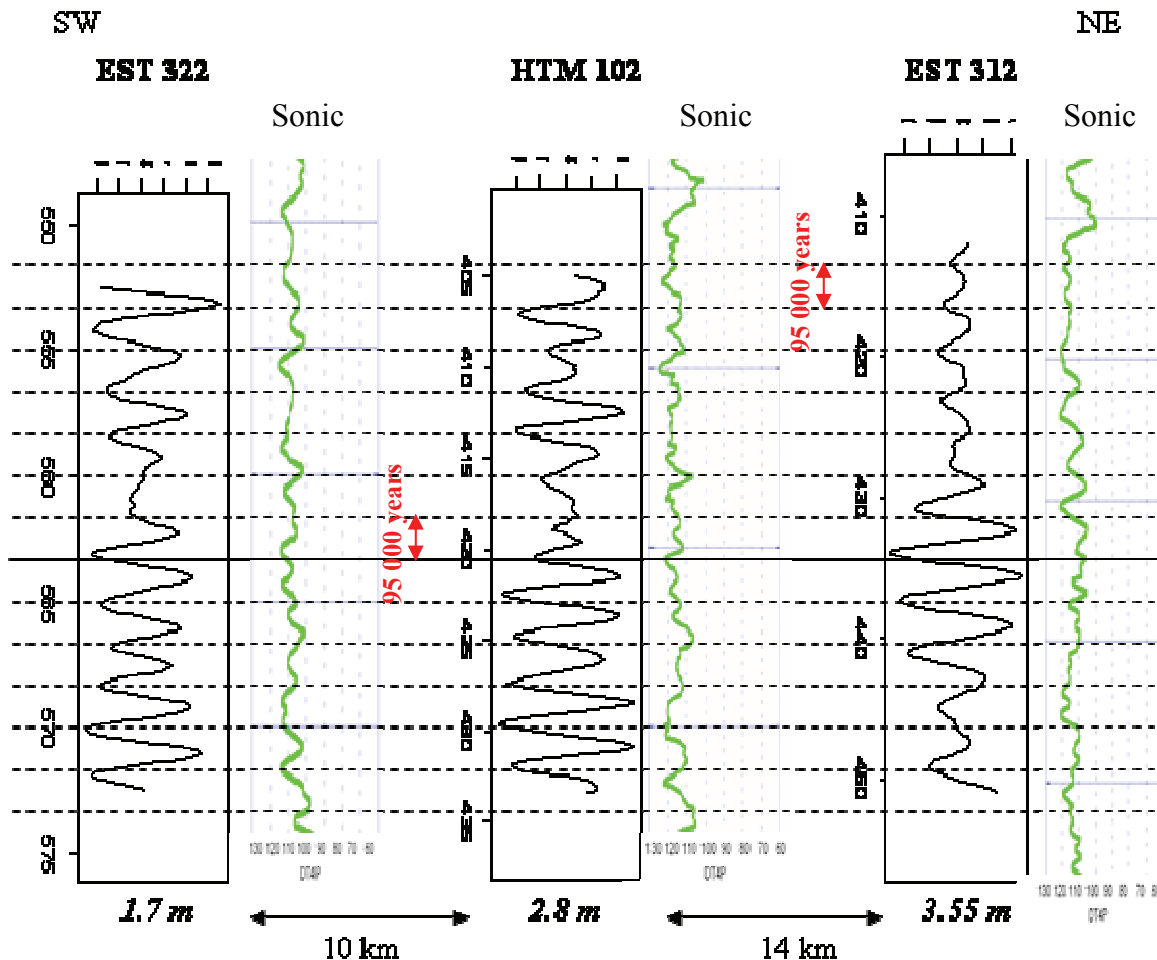
Each interval between dotted lines represents 95 000 years (Eccentricity). So this interval can correspond to 3.55 m in EST 312, 2.8 m in HTM 102 and 1.7 m in EST 322.

Figure 3 : Sonic and estimation of the component linked to the eccentricity (Interval 1) in EST 312, HTM 102 and EST 322.

Conclusion and perspectives

The aim of this work is to optimize the use of logs and images data in order to characterize Callovo-Oxfordian formation variations and spatial variability. The next step, according to Andra aims, will be to predict and simulate the geometry and the properties of the clay massif on a 250 km² area around the laboratory site.

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