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**Sequence Stratigraphy Applied to Log Interpretation: Improving Methodology by Means of Signal Processing Techniques and Outcrop Calibration**

We present results from an investigation into the application of clustering and signal processing techniques to descriptions of geologic formation. The ultimate goal of this investigation is twofold. Firstly, it is intended to validate a methodology incorporating a chain of fast and easy to use algorithmic processes in order to speed up log data interpretations in terms of sequence stratigraphy and sedimentary bodies' architecture while improving their consistency by minimizing any possible operator bias. Secondly, it is meant at providing a "log simulator" producing pseudo logs from outcrop description; be it for educational purposes or for comparison between sub-surface reservoir and their outcropping analogs in the course of operational surveys. Up-scaling of HR data (either core or outcrop) to log and seismic resolution and calibration of log data on core data are more particularly addressed in this view. The proposed methodology is a low cost approach which can be transposed to core descriptions for core-log calibration.

A whole sedimentary system, such as a turbiditic event, can not be understood without a description of the interrelationship, at different scale, between its components. Quite expectedly, its description is made easier if it is first broken down into its elementary components which lend themselves to an easier characterization by quantitative attributes or properties, the latter being the best candidates to further algorithmic processing. The interrelationship between elementary components of a sedimentary system is intuitively perceived through the patterns defined by their characteristics displayed along a depth axis. Sequence stratigraphy provides with the set of rules to interpret such patterns. Application of signal processing techniques to the records of such attributes or properties transposes this phase of pattern perception from the realm of the expert intuition to that of "automated production line". Note that, so far, stratigraphic distribution of log responses is not taken into account in the currently available software meant at log interpretation, be it porosity saturation estimate or electrofacies (log type) analysis.

The HECHO Group (Eocene Turbidite systems of the South Central Pyrenees) is a reference for any geoscientist involved in the survey of turbiditic formations; they are used as analog of many subsurface reservoirs by several oil companies. Because they provide with ample continuous exposure to document stratigraphic facies evolutions, outcrops of the HECHO Group are used here as reference. Using outcrop obviates the difficulties inherent in limited core coverage and continuity.

**Modeling logs from outcrop descriptions.**

In order to compare outcrop data to well logs, it is mandatory that outcrop description is made at a sufficient resolution to appropriately document any feature of sedimentologic significance possibly affecting log signatures. However to ensure practicality of outcrop description and their transcription into pseudo logs, it is considered that the size of plugs cut for petrophysical measurements is the maximum resolution desirable. It is also conjectured that characterizing accurately the facies and their sequential genetic interrelationship is of greater significance than their perfect geo-referencing. Thus, in a first step, the cross sections are described at a resolution allowing generating pseudo logs with 1 inch sampling rate, and interpreted in term of sedimentary facies on the basis of the hydraulic processes controlling their deposition. By their size and characteristics, the smallest elements of description, termed

"unit layer", compare to lamina sets or beds. They are characterized, to some extent, by their grain size distribution, fabric and texture types and their volume proportion of each mineralogic class comprised by the surveyed outcropping formation and which can be easily identified by a field geologist.

In a second step, attributing petrophysic characteristics such as natural radioactivity, matrix density, photoelectric factor, to mineralogic classes, makes it possible to transcribe outcrop descriptions into pseudo logs of nuclear properties (GR, density, Pe...) by simply reversing the method commonly used to derive mineralogy from logs. Similarly, class characteristics can be derived, modeled or calibrated from lab measurements. Observations pertaining to grain size distribution (GSD) are encoded and displayed as histograms in a way made familiar to petrophysicists by the introduction of NMR logging. Should an analogy with photography be used, the GSD log would be the negative and the NMR T2 distribution the print or conversely. Observed GSD can then be used for modeling porosity and bulk density, Hydrogen Index and permeability. Up-scaling GSD at log resolution is performed by means of the so called "Histogram Up-scaling" procedure which consists in summing up, all the histograms comprised by the whole or portions of "unit layers" belonging to up-scaling interval. Histograms are clustered by MRGC algorithm, a procedure only constrained by data structure and thus devoid of any operator bias; clusters are assigned indices automatically ordered by a neural method. As a result the suite of histograms is labeled by a suite of ordinal values more suitable to further interpretative processes, be they color coding, cross-plotting, and further steps of clustering or application of signal processing techniques. The main advantage of the "Histogram Up-scaling" procedure lies in the fact that, contrary to one-dimensional logs, histograms bear the textural information so critical for facies identification. Indeed any log such as GR is interpreted with the totally unverified, implicit assumption that observations represent a homogeneous population. Instead histograms clearly show whether the formation is homogeneous (either due to deposition or intense reworking of laminations), or heterogeneous, made of either laminae or conglomeratic elements of contrasting mineralogy and grain size distribution. Comparison between modeled GSD logs and real NMR logs makes it possible to further investigate the advantage offered by the application of clustering technique to NMR logs in order to extract geological information that can not be recovered from conventional logs.

Vertical resolution of the two types of pseudo logs described above is then progressively degraded to simulate wire-line logs of conventional resolution and sampling rate.

### **Multi-scale sequence analysis by automated signal processing technique.**

In order to evidence sequence patterns, the one-dimensional logs modeled from outcrop data are subjected to a new signal processing technique called "SEDIWAVE", which emulates the way geologists interpret log curve shapes or topographic profiles by locating breaks, characterizing trends and identifying multi-scale sequential patterns. For the sake of simplicity and because of the obvious analogy between logs and signal, indexed with depth or time respectively, we will use here the term "frequency" although the term of "wave number" is more appropriate to our scope of work. The purpose of the comparison between process results and outcrop interpretation is twofold. Firstly, comparison is meant at validating the process itself and its results interpretation method; secondly it is intended at exploring the side effects of the limited resolution of conventional logs on the facies characterization. Thus it addresses the question of "how much logs are really representative of the formations?" and its consequences on both their interpretation in term of sequence stratigraphy and their use as extrapolator for data prediction.

SEDIWAVE is based on Wavelet transform. It is fully auto-optimized and only controlled by signal itself; this makes it easy to operate and totally devoid of any operator bias. Further, a fully automated process of signal reconstruction is embedded. It documents the pertinence of the signal characteristics extracted during the analytic phase and the validity of the algorithm itself. It is also used as an up-scaling tool and allows filtering out local irregularities.

The Wavelet Transform (WT) was developed by Morlet in 1982, to investigate in details the variations of amplitude, shape frequency and phase versus propagation time of seismic signal. Since then, its power for analysis of non stationary processes that contain multi-scale features, and detection of singularities has been well demonstrated. Compared to Fourier transform, WT offers the invaluable advantage of an accurate localization (along the time or depth axis) of any signal feature of interest. SEDIWAVE uses the Continuous Wavelet Transform algorithm with the "Morlet" Wavelet, which is complex valued (sine and cosine function modulated by a Gaussian envelope) enabling one to extract information about signal amplitude and phase.

WT expands a one-dimensional signal like GR log, into a two-dimensional depth-frequency image; as a consequence, a simplification process is needed to extract what we call "signal architecture" and interpret as multi-scale sequence patterns. Signal architecture can be viewed as the montage blueprint of the signal's building blocks: the "cells", defined by their top, bottom and order. Order characterizes the relative position, with respect to frequency range, of a cell within the multi-scale pattern. It is defined from signal "energy". A cell corresponds to a signal interval, either a break or a bed. Beds of lower order group to form beds of higher order and define increasing or decreasing upward trends. Breaks, at any given scale, do not show any internal organization.

The results of the analytic step are displayed with the "stacking patterns" conventions of sequence stratigraphy. Due to its limited "depth resolution" a log cannot give a full account of thin beds encased within strongly contrasting beds or bounding surfaces between contrasting beds; note that the contrast can only be seen if the considered rock property is within the sensitivity range of the logging tool. "Shoulder effect" is another term used to refer to this phenomenon. Breaks in the signal originate from strong contrasts; they are detected in the course of the analytic process. By their similarity with breaks, "unresolved" thin contrasting beds can also be detected. Thus we added two new codes to the "stacking pattern" display conventions; they account for these features specific to well logs: breaks and unresolved beds. Because log values associated to both types of features are not representative of the real formation, their detection (and filtering out) is a powerful tool for quality control and uncertainties evaluation ahead of any subsequent interpretation. Wherever strata are lithologically contrasting and their thickness is of the same magnitude than the logging tool resolution, the poor representativity of log readings explain the partial or total failure of supervised neural techniques to characterize facies identified on cores. The same apply to extrapolation of data such as permeability measured on plugs.

The wavelet coefficients corresponding to each cell allow the signal reconstruction; cells of same order are selected to reconstruct the signal at this order. The higher the order, the smoother the reconstructed log. Iterating this analysis-synthesis process makes it is possible to model the response in a frequency range comparable to that of seismic. Note that the signal processing technique described here apply to logs sampling either continuous variables (e.g.: GR) or ordinal variables (e.g.: electrofacies index).

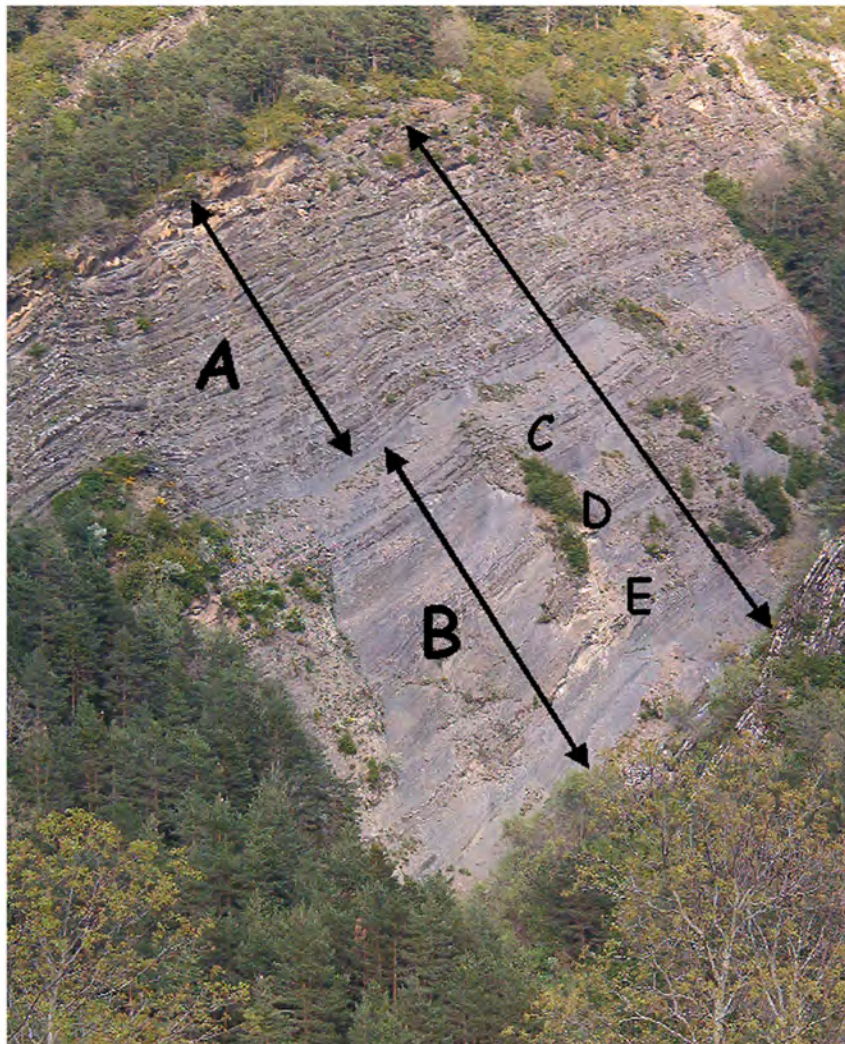
### **Interpretation of logs modeled from the Broto outcrop.**

Figure 1 shows the interval (40 m. to 125 m.) displayed on figure 2; note that, the formation is tectonically overturned, so the base of the turbiditic event is seen on top of the picture.

Figure 2 displays the description of outcrop (track 1) using Mutti's interpretation model, Mutti's facies 9 is detailed using Bouma's interpretation model. Facies codes are increasing from right to left. Modeled Pseudo GR and GSD logs and their interpretation are displayed; GR is on the left of the figure (track 3 to 5); GSD is on the right (Track 7 to 10).

The GSD log (track 6) is displayed using the NMR T2 distribution conventions : finer grain size are on the left of the histograms, poor sorting or lamination of different grain size appear as multimode histograms, the wider the mode the poorer the sorting. Conglomeratic facies whose clasts are made of detrital material would also appear with multimodal histogram. The result of MRGC clustering applied to GSD is displayed (track 8) as a color coded electrofacies column (red for facies with coarse material, green for shaliest facies). Reconstructed curve of GSD facies is superimposed both on 8 and 9. For easier comparison with outcrop description it is also superimposed on track 2.

Overall shape similitude between GSD electrofacies log and pseudo GR curve is obvious. However a quick comparison between GSD and GR logs in front of the two main sandstone bodies is sufficient to illustrate the limitations of GR to sort out sedimentary facies in sandstone material. Also it is clear that clean well sorted sandstone material may exhibit different grain size, hence comparable porosity and bulk density while their permeability will strongly differ. This again exemplifies how inefficient is a curve formed of single values to convey information about the structure of a population (formation) formed of groups (facieses). Signal architectures of both pseudo GR (tracks 3 and 5) and GSD (tracks 9 and 10) are displayed. Note the similar architecture of both signal and similar location of breaks (red color code) indicating bounding surfaces or trend inversion (dark green color code). Facies "relative" evolution is clearly



General view of the Broto Outcrop section.  
The formation is tectonically overturned.  
Arrow refers to fig 2

Fig 1

shown by both signal, however only GSD (or its counterpart, the NMR log) can provide with the information needed to identify the absolute position in the turbidite interpretation model.



