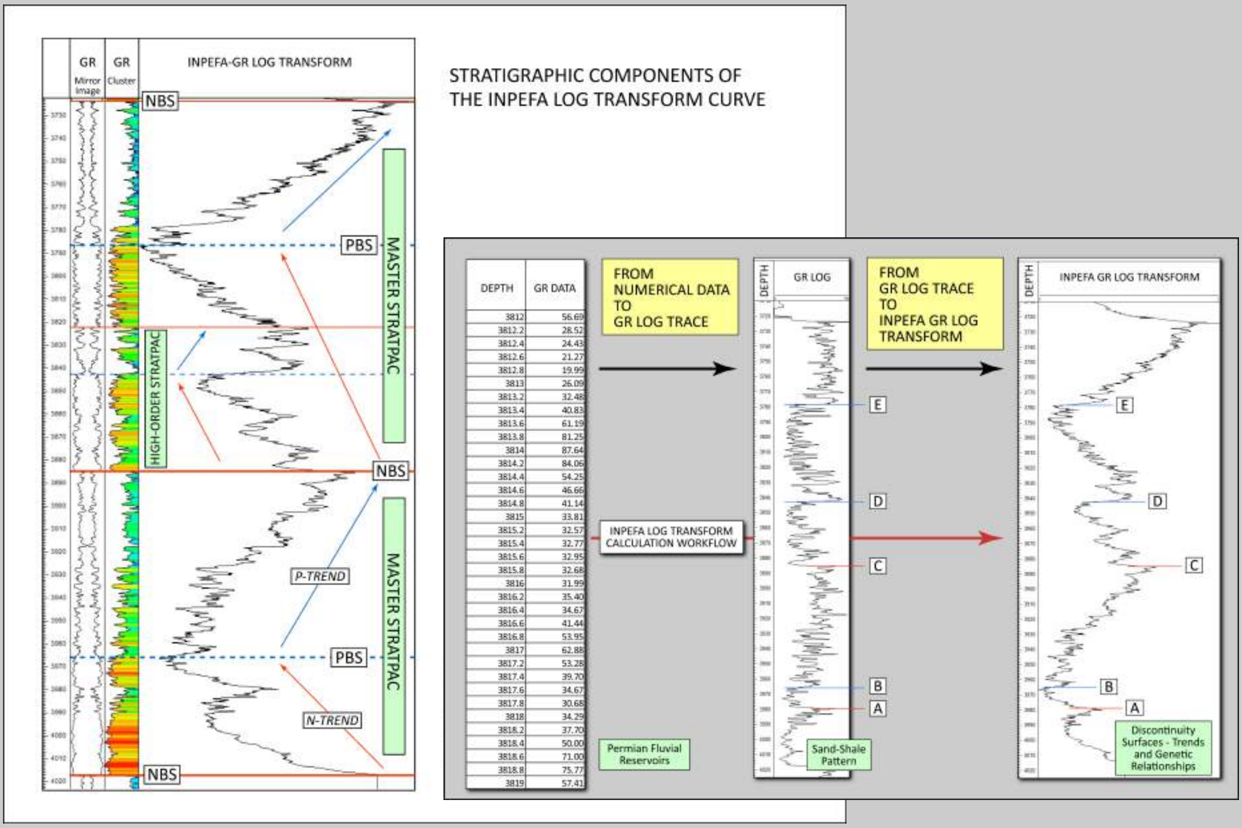
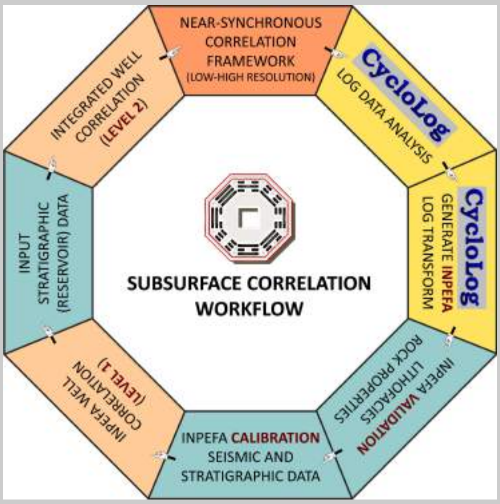
ENRES STRATIGRAPHIC METHODS AND WORKFLOW APPROACHES IN SUBSURFACE WELL CORRELATIONS

THE INPEFA LOG TRANSFORM AND STRATIGRAPHIC INTERPRETATION MODELS

OPEN FILE REPORT





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INTRODUCTION

Stratigraphy is the study of layered rocks and can be considered as the backbone of the geological science. Stratigraphy includes the deciphering and ordering of physical, biological and chemical events that affected the earth's atmosphere, hydrosphere and lithosphere (see e.g. Brenner and McHargue, 1988; Doyle and Bennet, 1998). Some of the effects of these events are recorded in a complex way in the sedimentary rock succession. The study of these events and their records help stratigraphers to develop methods to study ancient events.

In making stratigraphic correlations, we need to make use of all tools, methods and working concepts available. Subsurface well correlations using wireline logs have a number of specific features:

- Large amount of digital and objective data
- Machine-objective continuous sampling with data points at regular spaced interval
- Data over an extended vertical section covering whole or several stratigraphic intervals

This available dataset in the subsurface is in distinct contrast with outcrop datasets. The advantages of outcrop datasets are:

- Good access to the rocks (e.g. lithology, structure and texture, etc.)
- Depending on the outcrop exposures – good 2D and possible 3D overviews
- May serve as good analogues for the subsurface

Because of the specific character of the subsurface dataset, a different approach in the stratigraphic analysis is needed – the conventional approach to stratigraphy is basically ***descriptive*** and has been developed on outcrop data. Strata are observed and described, and are then classified according to available criteria, such as lithofacies, fossil content, or chemical composition. In ENRES, we start instead from the concept that a large part of the observed vertical variation in strata is controlled by known processes and is therefore ***predictable***.

In the subsurface, wireline logs are the perfect data source for mathematical analyses as mentioned above, and we can use these results for stratigraphic interpretations. For this purpose, ENRES has developed a unique tool for the analysis of vertical variations in the wireline log data – INPEFA Log Transform.

Global Cyclostratigraphy was introduced by Perlmutter and Matthews (1990) as the study of cyclic depositional patterns produced by climate and tectonic processes. The authors assumed that the theory of orbitally-forced (Milankovitch) climate change was sufficiently well-established that it could now be used to drive predictive models of the stratigraphic succession of lithofacies. ENRES has taken the approach a step further, by developing a method for recognising the predicted stratigraphic packaging in the subsurface, using a spectral analytic method to transform standard wireline log data.

The INPEFA Log Transform is part of the CycloLog software and consists of a mathematical-statistic analysis of the numerical log data. The analysis is based on recognizing the spectral structure in the log data. In this way normally unseen information from routine wireline log data can be extracted, and it allows the construction of a reservoir scale correlation framework.

The INPEFA Log Transform identifies discontinuities, depositional trends and a hierarchical pattern in the stratigraphic succession. We believe that these features are controlled by orbitally-forced climate changes, and that makes the INPEFA Log Transform a predictable tool instead of only descriptive. The results offer the geologists a unique approach for subsurface stratigraphic correlations and interpretations.

The vertical succession of the INPEFA Log Transform curve shows a unique stratigraphic pattern of discontinuity surfaces, depositional trends and a hierarchical pattern – the ***INPEFA stratigraphy***. ENRES is using the INPEFA stratigraphy as one of the primary tools in subsurface evaluations (see Figure 1)

INPEFA stratigraphy is together with lithostratigraphy, relative chronology and chemostratigraphy part of the sequencing tools. The important difference is that INPEFA stratigraphy is objectively (or data-driven) obtained from wireline log data.

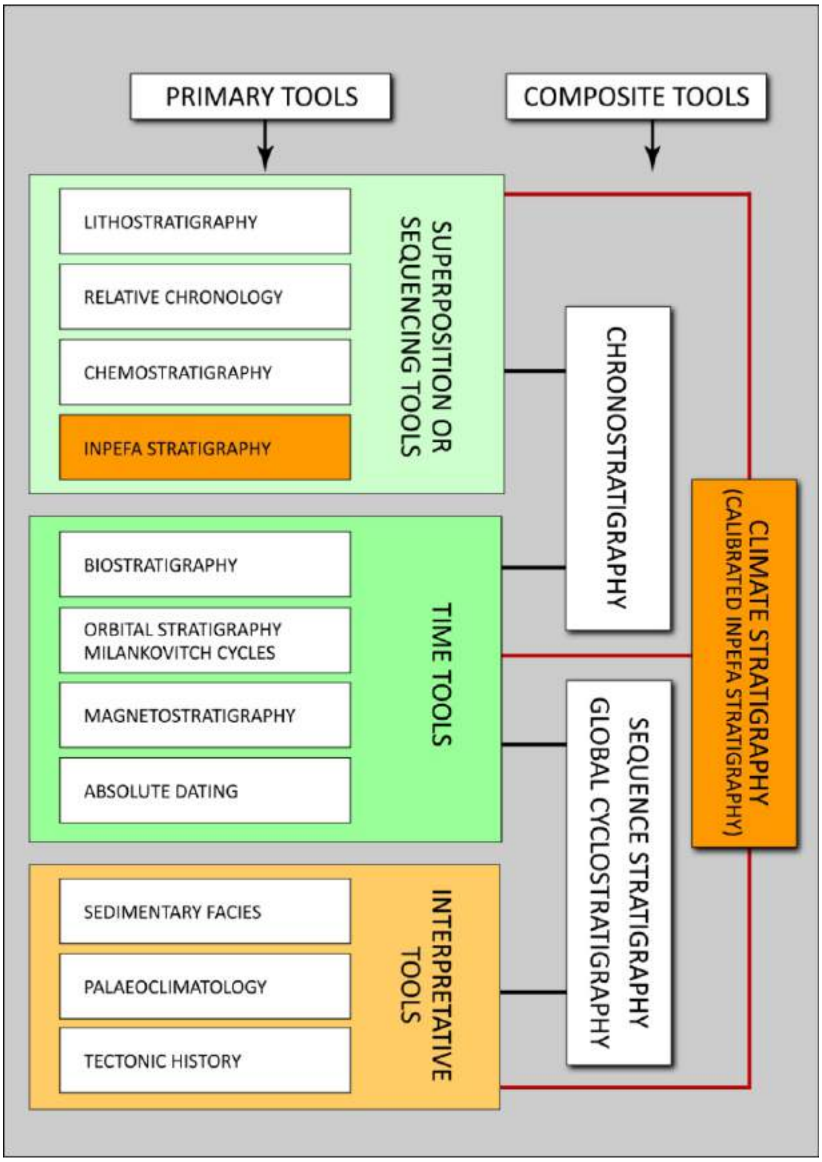

Figure 1: Schematic overview the principle tools within the stratigraphic toolkit (modified after Doyle and Bennet, 1998)

ENRES has developed a specific workflow for subsurface correlation which consists of a data-driven analysis followed by a model-driven interpretation. Briefly, the approach comprises the following key elements (Figure 2):

- A facies-sensitive log – usually the GR – is transformed to INPEFA. The curve shows uphole changes in the waveform properties concealed in the numerical log data, and displays discontinuity surfaces and trends.
- The INPEFA stratigraphy should be calibrated with the sequencing and time tools (see Figure 1)
- The INPEFA stratigraphy can be used for any stratigraphic interpretation (such as sequence stratigraphy or climate stratigraphy)

More details of the workflow and interpretation methods will be discussed in later sections.

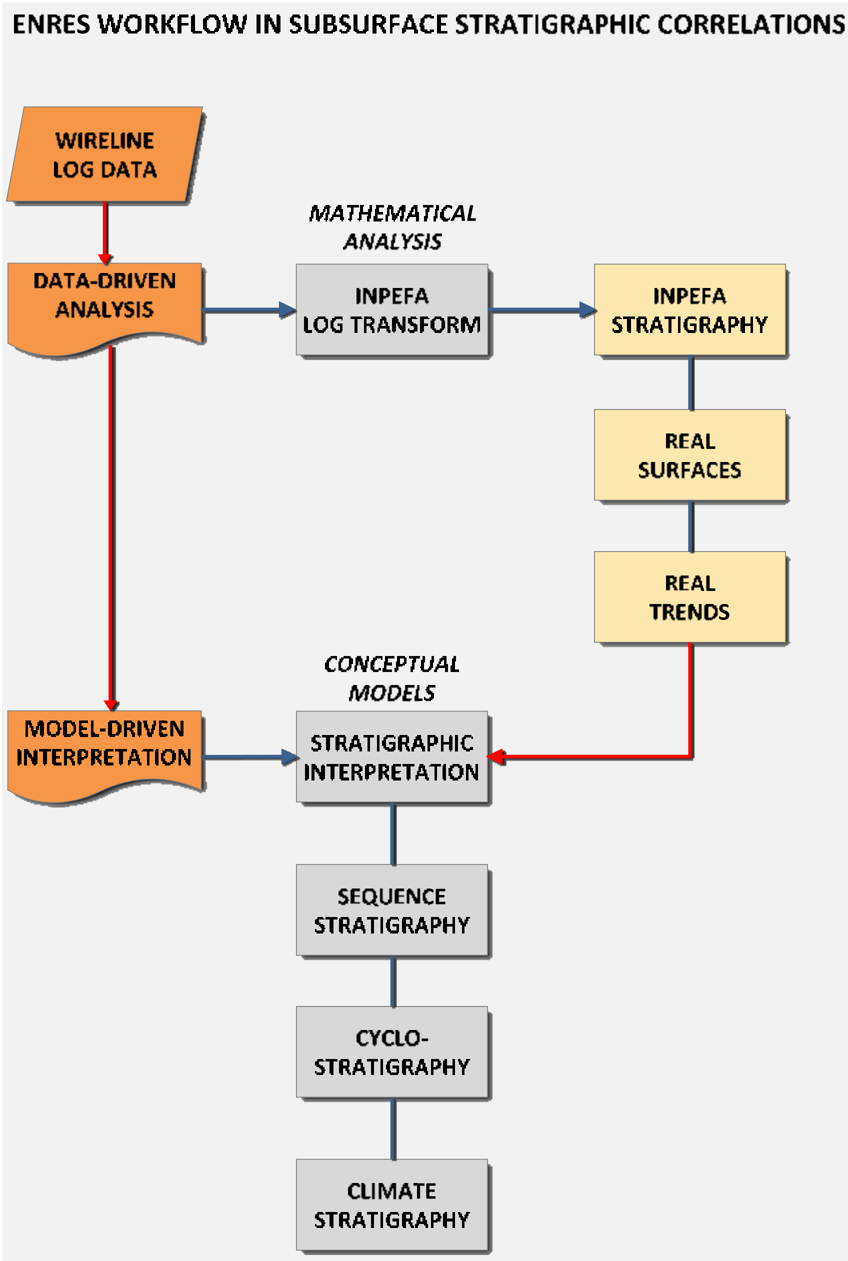

Figure 2: ENRES' workflow in subsurface stratigraphic correlations

CYCLOLOG INPEFA LOG TRANSFORM DATA-DRIVEN ANALYSIS

The INPEFA Log Transform is part of a set of log transformation routines within the CycloLog software (Figure 3).

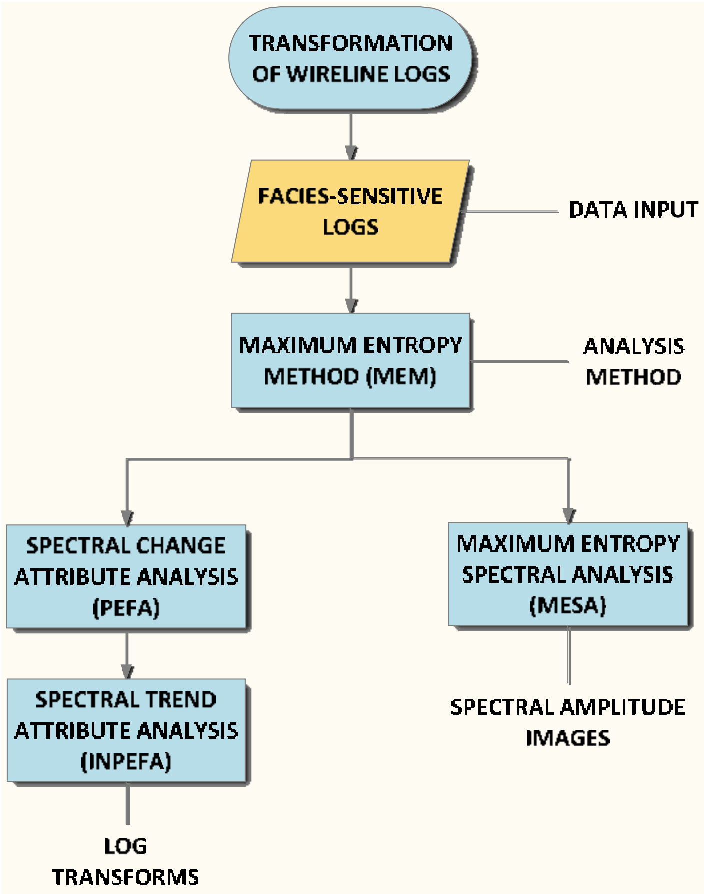

Figure 3: Interrelationship of log transformation routines in the CycloLog software

The log transformation treats wireline log data as a composite waveform, with properties of wavelength, amplitude and phase that vary uphole. As such, it can be analysed using the methods of spectral analysis; the mathematical method used in CycloLog is the ***Maximum Entropy Method (MEM)***. The interrelationship between the different analysis routines in this approach is shown in Figure 3.

A brief summary on the analysis procedures is give here:

- ***Maximum Entropy Spectral Analysis (MESA***) analyses and calculates the spectral content in the numerical log data which results in an uphole display of spectral amplitude images
- To examine changes in the waveform properties of the data, MESA computes a ***Prediction Error Filter (PEFA)***, a mathematical model of the data, with which the actual data is compared ot all at once but using a sliding window of (usually) 10 meters (30 feet) in length. The resulting PEFA Log Transform function represents

the errors arising from using the mathematical model to predict the data from one window to the other. PEFA thus is an expression of the continuity (or otherwise) of the spectral (waveform) properties of the data.

- The ***INPEFA Log Transform*** is the integral of PEFA; it shows the cumulative error in predicting from model to data as the sliding window is moved up the log from bottom to top.

In practice, the INPEFA Log Transform (or INPEFA) is calculated from the numerical dataset of any wireline log. Commonly, we choose the GR log, because the GR log is a typically shaling log representing a typical sand-shale pattern. The calculation consists of a complex mathematical routine including the MESA and PEFA (see Figure 4)

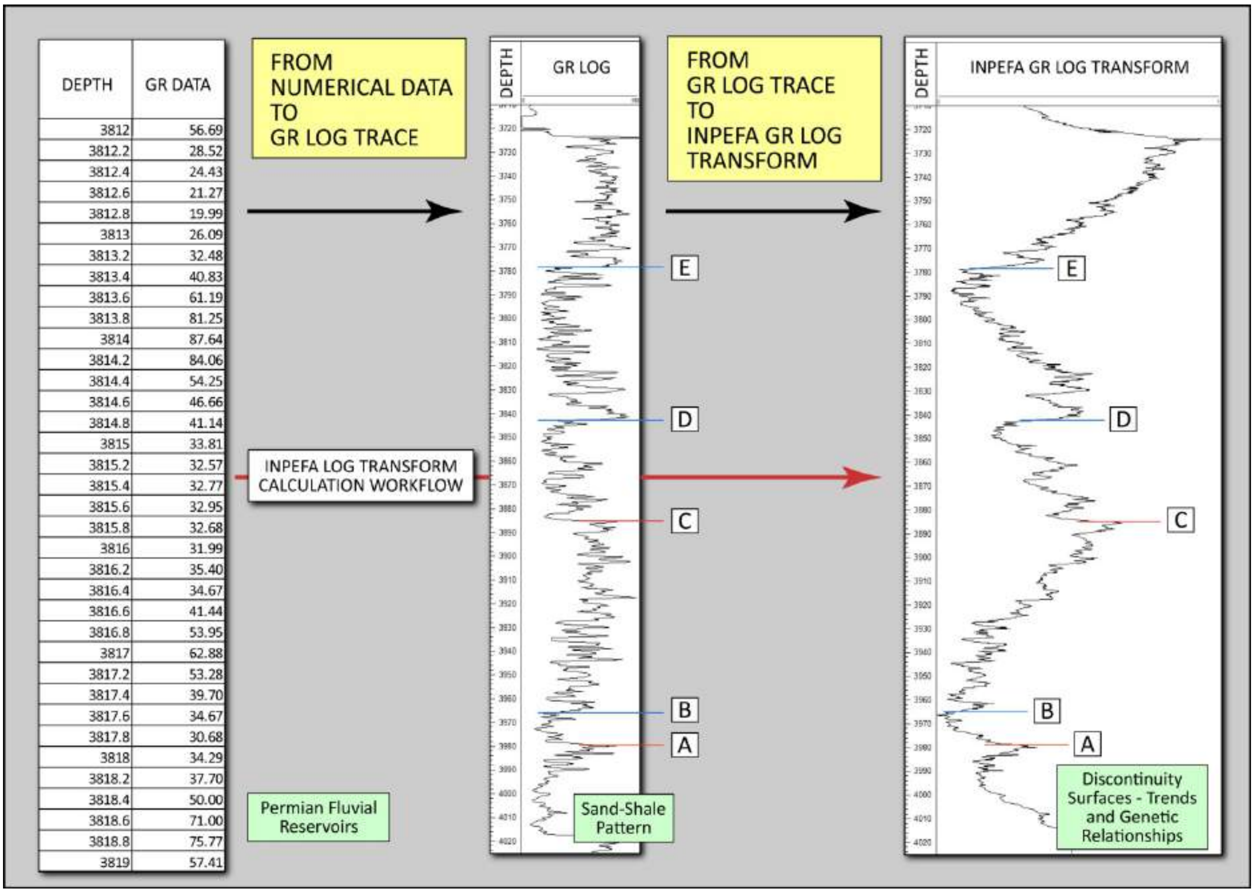

Figure 4: Flowchart showing the calculation routine of the INPEFA Log Transform. Note the position the breaks which can clearly be observed in the INPEFA, and the position in the GR log.

The shown example is from the Permian of the North Sea and is interpreted as an alternation of stacked fluvial channels and floodbasins. Note the sand-shale pattern as displayed in the GR log, and the INPEFA curve which shows distinct depositional trends separated by discontinuity surfaces (indicated as A, B, etc.). It also shows a clear hierarchical pattern.

SOME NOTES ON THE MATHEMATICS OF THE INPEFA LOG TRANSFORM

Some basics of the mathematics can be summarised as follows:

1. Linear prediction is a mathematical method for using successive values in a data series to predict the next value in the series. It is closely linked to the above-mentioned Maximum Entropy Method (MEM.
   As applied to a wireline log, linear prediction takes all of the values in a ***window*** – a relatively short interval – of data. CycloLog uses 10 meters or 30 feet as the default window length. It uses the information in this window to make its best prediction of the next data value above the window. The window is then moved up (typically, by 1 meter) and the information in the new window is used to predict the next data point, and so on.

2. Error calculation is the subtraction of each of the predicted values from the corresponding actual value. The resulting error curve is known as the ***PEFA*** curve (PEFA = Prediction Error Filter Analysis).

3. Integration of the errors is the mathematical integration of the PEFA curve, to yield what is effectively a ***cumulative error*** curve (***INPEFA = Integrated PEFA***).

Some more detail about the mathematics of the INPEFA Log Transform might be helpful for some of the users:

1. The INPEFA Log Transform can also be thought of as a ***spectral trend*** curve, i.e. a curve that shows changes in the spectral, or waveform properties of the original log (i.e***. its properties of wavelength, amplitude and phase***).
2. The INPEFA Log Transform of a random data set is identical to the original data series. The trends that the INPEFA curve adds to the original data therefore represent the ***existence of underlying non-random patterns***. This information, being contained in the waveform properties of the data, is not normally apparent to the eye; the INPEFA Log Transform provides a way of making this information available in a visually attractive form.
3. While the PEFA curve is scaled in the identical units of the original data, the process of calculating INPEFA standardizes the data such than an INPEFA curve is always scaled from zero to one.
4. The shape of an INPEFA curve (the length and slope of ots trends) is influenced by the range of the values in the original data. Outlying data values, by increasing the range, reduce the local variance in the INPEFA curve, making it less informative. Reducing the interval over which INPEFA is calculated usually results in reducing the range of the input data values, thereby increasing the variance in the INPEFA curve and enhancing its features.

COMPONENTS OF INPEFA STRATIGRAPHY

As mentioned before, INPEFA shows interval with distinct depositional trends which are separated by turning points representing discontinuity surfaces (Figure 5).

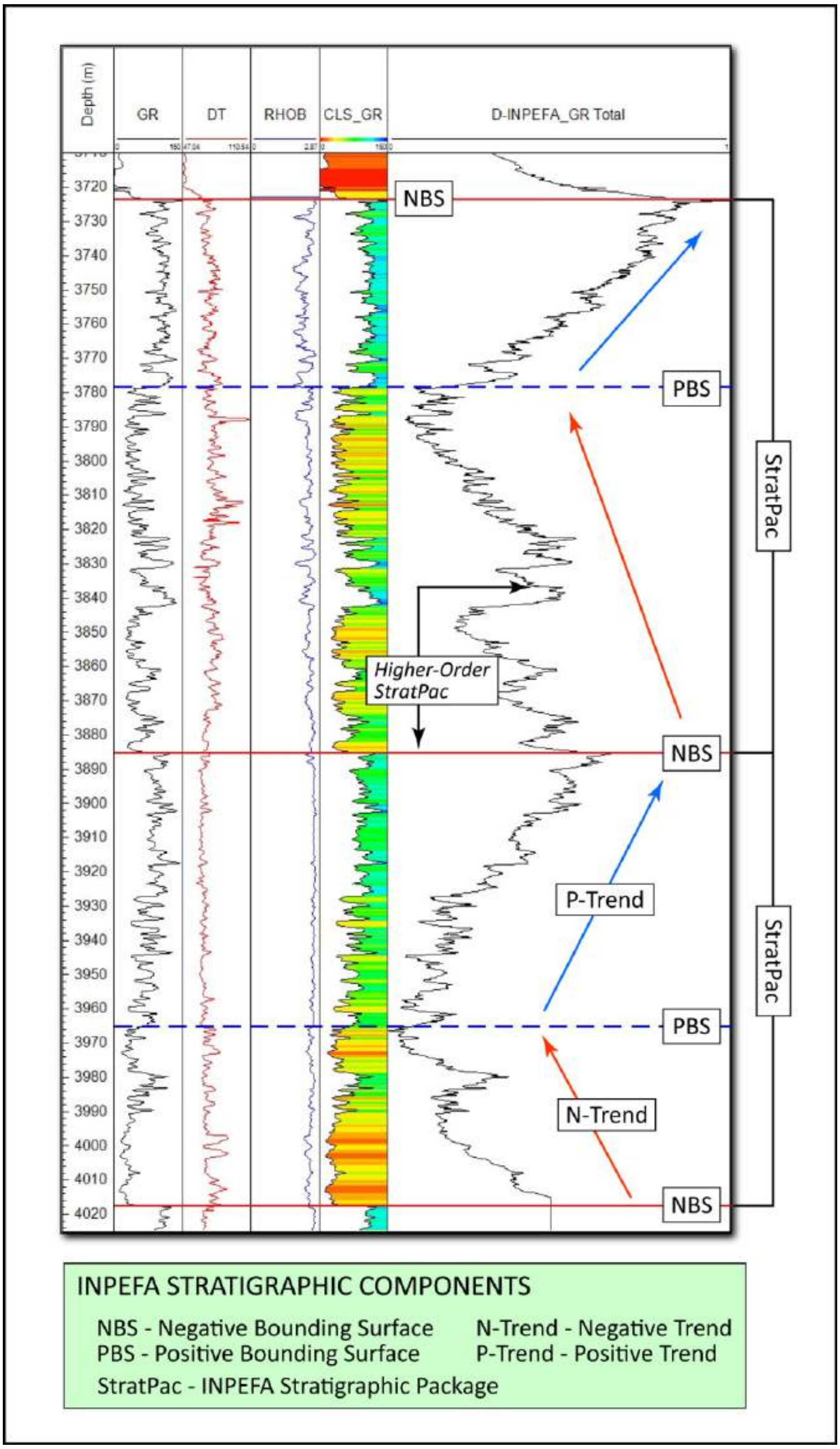

Figure 5: Components of INPEFA stratigraphy.

In order to keep the terminology neutral (avoiding any interpretative names), we use the following names (see Figure 5):

<u>INPEFA turning points or discontinuity surfaces</u>

- A negative turning point (NBS) is a point at which the depositional trend (in an upward direction) changes from positive to negative (or counter clockwise, CCW).
- A positive turning point (PBS) is a point at which the depositional trend (in an upward direction) changes from negative to positive (or clockwise, CW).

<u>INPEFA depositional trends</u>

- The depositional trend between NBS and PBS shows a CCW direction in an upward direction and is named the negative trend or N-Trend.
- The deposition trend between PBS and NBS shows a CW direction in an upward direction and is named the positive trend or P-Trend

<u>INPEFA stratigraphic intervals</u>

The interval between a two main NBS is called the INPEFA stratigraphic package or StratPac. It has ideally a C-shape with a PBS separating the interval in an N-Trend lower part and a P-Trend upper part.

LONG-TERM AND SHORT-TERM INPEFA CALCULATIONS

INPEFA Log Transform calculated for long intervals may lack enough character to achieve a confident stratigraphic breakdown. Recalculating INPEFA within shorter intervals of the data – so-called "Short-Term INPEFA" – can reveal much addition details (see Figure 6)

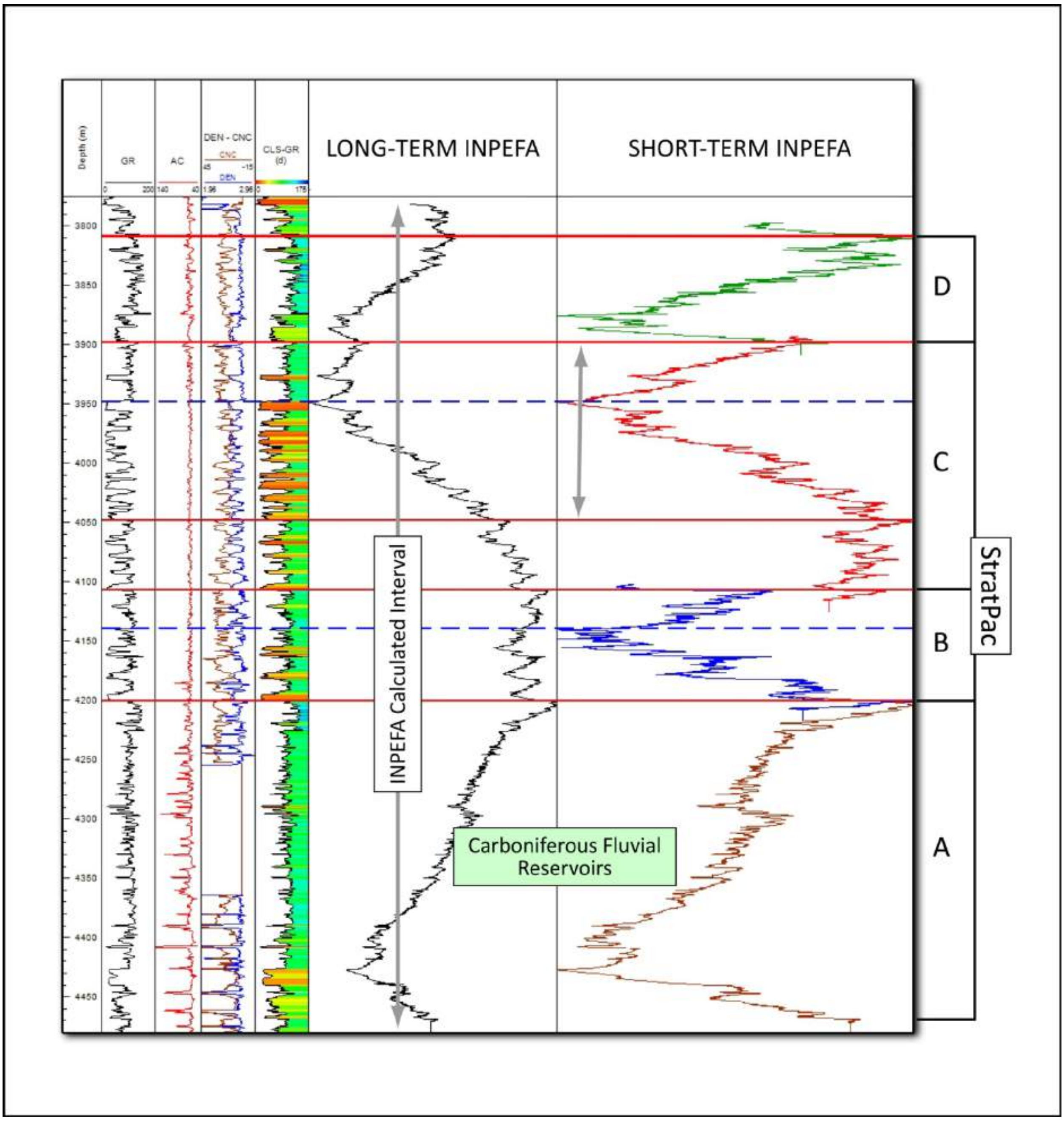

Figure 6: Long-Term and Short-Term INPEFA calculations.

Calculating INPEFA for a long interval tends to have a kind of averaging effect on the data – the amount of variation in the resulting INPEFA curve may be reduced. Shortening the interval analysed has the effect of increasing the (relative) variation within that inreval, with the results that the details of the INPEFA curve become much clearer.

THE WORKFLOW IN SUBSURFACE WELL CORRELATIONS

The ENRES workflow procedures in subsurface well correlations can be summarised as follows (Figure 7):

1. Generate a Long-Term INPEFA of the GR log for each individual well
2. Determine the main turning points (i.e. NBS and PBS). Note that these turning point and related trends are part of the INPEFA stratigraphy and are not yet calibrated. These turning point are so-called Stratigraphic Anchor Points (SAP)
3. Validate the INPEFA trends with the uphole lithofacies development by using the classified colour analysis of the GR (CLS-GR)

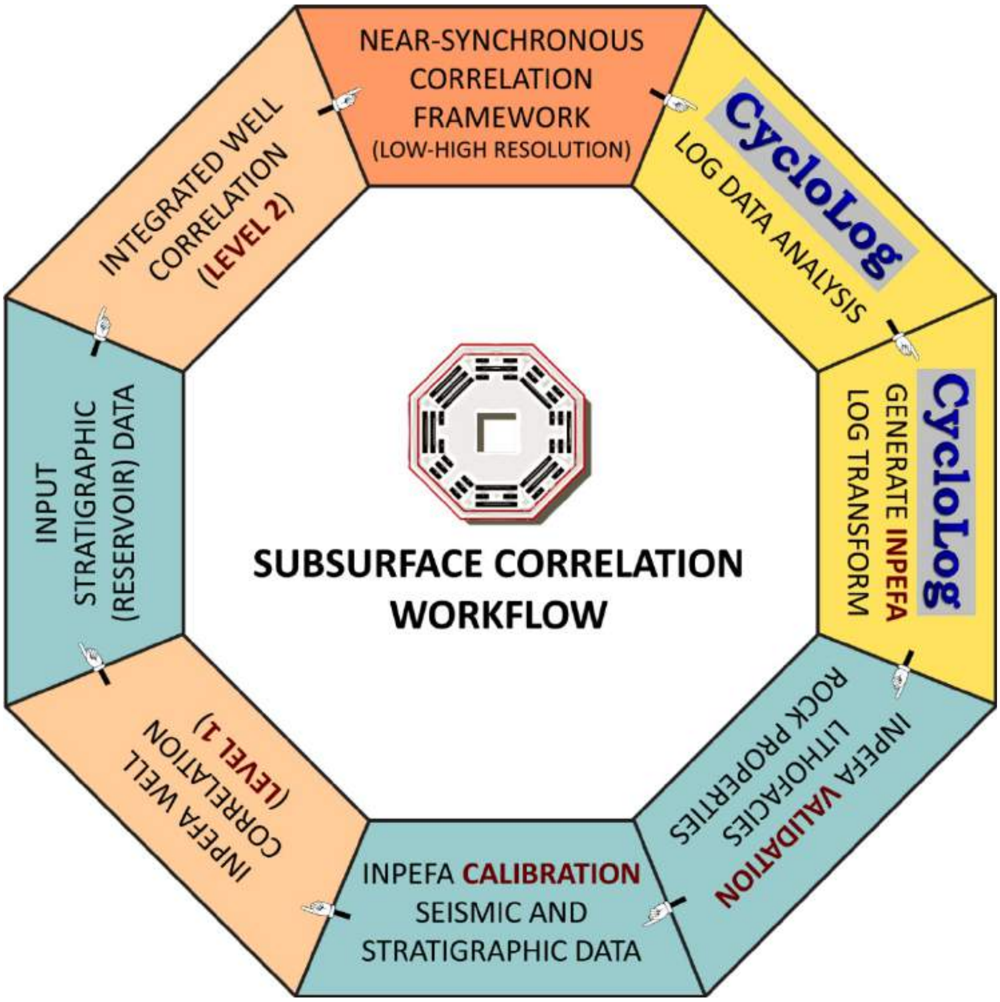

Figure 7: ENRES workflow in subsurface well correlation.

4. Calibrate SAP with formation tips, seismic and biostratigraphic data. The large-scale INPEFA stratigraphy has now been calibrated and its general chronostratigraphic position has been defined
5. Generate Short-Term INPEFA. Note that the Short-Term INPEFA intervals are chosen in an iterative calibration with the Formation tops, seismic picks and biostratigraphic data

6. Define new NBS and PBS breaks using the Short-Term INPEFA patterns. Define the INPEFA Stratigraphic Packages (StratPac)
7. Generate a LEVEL 1 correlation
8. Input additional geological and stratigraphic data (if available)
9. Carry out a pattern correlation of the Short-Term INPEFA and if needed carry out an iterative change of the Short-Term INPEFA
10. Generate a LEVEL 2 correlation and the consistency of the StratPac correlation

STRATIGRAPHIC INTERPRETATION MODELS

GLOBAL CYCLOSTRATIGRAPHY

Global Cyclostratigraphy (Perlmutter and others, 1990, 1998) develops the idea that climate change goes through recognizable and predictable patterns, and that lithofacies variation can be predicted from these patterns. There is therefore a deterministic component to lithofacies development. Global Cyclostratigraphy uses this fact to drive a procedure for modelling 3-D basin-fill, at the scale of seismic data. The methodology does not attempt to resolve specific stratigraphic events or to correlate them; this is the domain of Sequence Stratigraphy and Climate Stratigraphy.

The model accepts the control of global climate by changes in the Earth's orbital parameters, through their influence on insolation: this is the ***Milankovitch model of orbitally-forced climate change***.

The phases of a climate cycle

In order to consider the implications of the Global Cyclostratigraphic model in more detail, we first introduce a descriptive framework that allows referring to the successive phases of a climatic cycle. For simplicity, we follow Perlmutter and Matthews (1990) by modelling a single cycle as a cosine wave, as in Figure 8. The "cycle" here is meant to represent the climatic expression of any insolation cycle, from precession (~20 ka) to eccentricity (100 or 400 ka), or longer. "Climatic maximum" implies the warmest phase of the cycle, and "climatic minimum" the coolest.

The single climatic cycle is also displayed as a succession of several cycles. An important feature is the C-shape during the D2-C-B1 phases of the cycle. It represents generally a cooling and a warming phase which (if the section is preserved) can be observed in the INPEFA pattern (Figure 13) and outcrop (Figure 9).

To summarise, Global Cyclostratigraphy give us the following key principles:

- The Milankovitch theory predicts climate change with periods in the order of 104 to 106 years; depositional processes in this part of the geologic time spectrum can be expected to be resolved in wireline log data.
- The range of climatic variation generated by orbitally-forced insolation change depends on latitude and is predictable. Climate can vary from warmer to cooler and/or from arid to humid over a typical climatic cycle.
- Lithofacies succession is controlled by climate succession, operating through the variables of weathering and erosion, sediment transport, sea level (or base-level), and depositional environment.

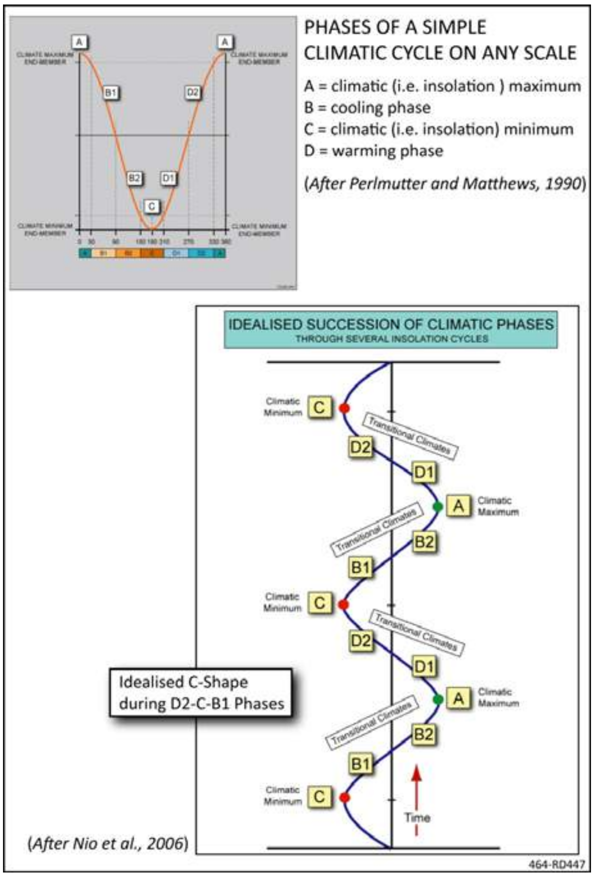

Figure8: The phases of a climate cycle

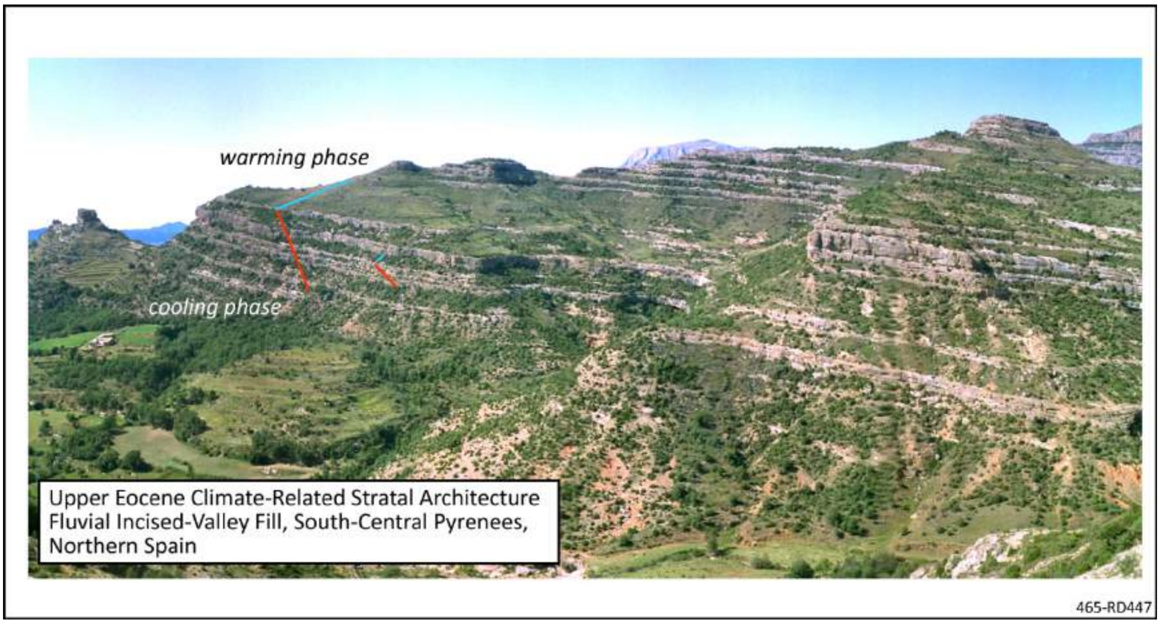

Figure 9: Cooling (red) and warming (blue) phases in alluvial-fluvial incised-valley fill. Note the low-order and high-order cycles.

- "Climatic succession is … mappable, and is a function of global position" (Perlmutter et al 1998). Patterns of lithofacies succession are similar within any one climatic belt.

- Climatic succession controls depositional rates as well as lithofacies. Through its influence on energy conditions and base-level, it will also control the balance between deposition, non-deposition and erosion within the basin; therefore the vertical pattern of hiatuses and erosion surfaces must also reflect climatic succession.

The vertical stratigraphic succession in a basin is therefore directly related to climatic change, albeit in the form of a filtered and incomplete record.

Because climate change is an influence over stratigraphy that is external to the basin, we predict that the pattern of vertical lithofacies change (including any hiatuses and erosion surfaces) will be similar, at least within any latitude-related climatic belt.

Vertical succession is exactly what is sampled by wireline logs. Therefore, an analytical tool that looks at the pattern of vertical change (and is also sensitive to breaks in the succession) can potentially reveal the pattern imposed on the depositional system by the succession of climate change.

The CycloLog INPEFA Log Transform was developed based on the principles of Global Cyclostratigraphy. The following diagram (Figure 10) summarizes the relationship between the principles of Global Cyclostratigraphy and the development of CycloLog.

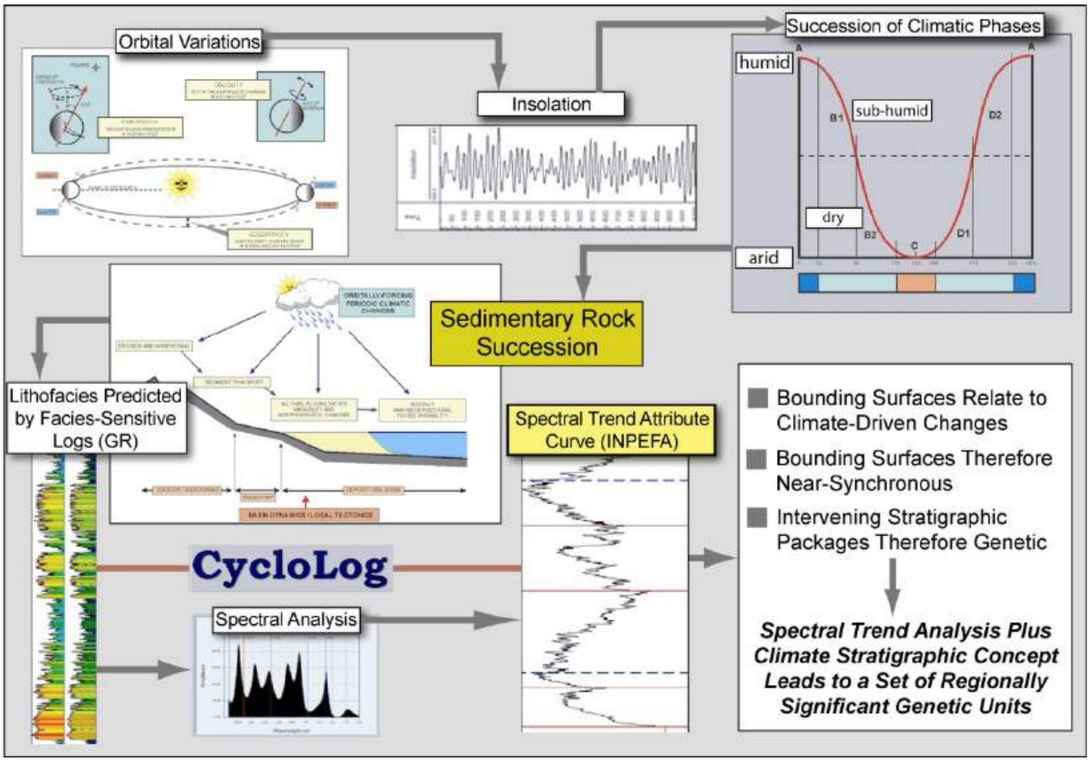

Figure10: Global Cyclostratigraphy principles and the development of CycloLog INPEFA

SEQUENCE STRATIGRAPHY

We do not want to present an extensive discussion on sequence stratigraphy as extensive references are available on the principles and applications. More important is the application of sequence stratigraphic concepts in the interpretation of the INPEFA log transform.

Catuneanu and others (2009) have recently updated this concept. They have re-phrased the background and rationale of sequence stratigraphy which is relevant for our approach:

"Sequence stratigraphy is uniquely focused on analyzing changes in facies and geometric character of strata and identification of key surfaces to determine the chronological order of basin filling and erosional events. Stratal stacking patterns respond to the interplay of changes in rates of sedimentation and base level, and reflect combinations of depositional trend that include progradation, aggradation and downcutting. Each stratal stacking pattern defines a particular genetic type of deposit (i.e. transgressive, normal regressive, etc.) with a distinct geometry and facies preservation style".

The INPEFA Log Transform contains all aspects stated in this statement and the INPEFA curve can be used in defining the different stratal stacking patterns.

Figure 11 shows an example of a sequence stratigraphic interpretation of the INPEFA Log Transform. A new subdivision of the sequences has been proposed by Catuneanu and others (2009), which is used in continental alluvial-fluvial systems.

New subdivision nomenclature:
LAST – Low-Accommodation Systems Tract with amalgamated channel fills
HAST – High-Accommodation Systems Tracts, dominantly fine-grained alluvial floodbasin deposits

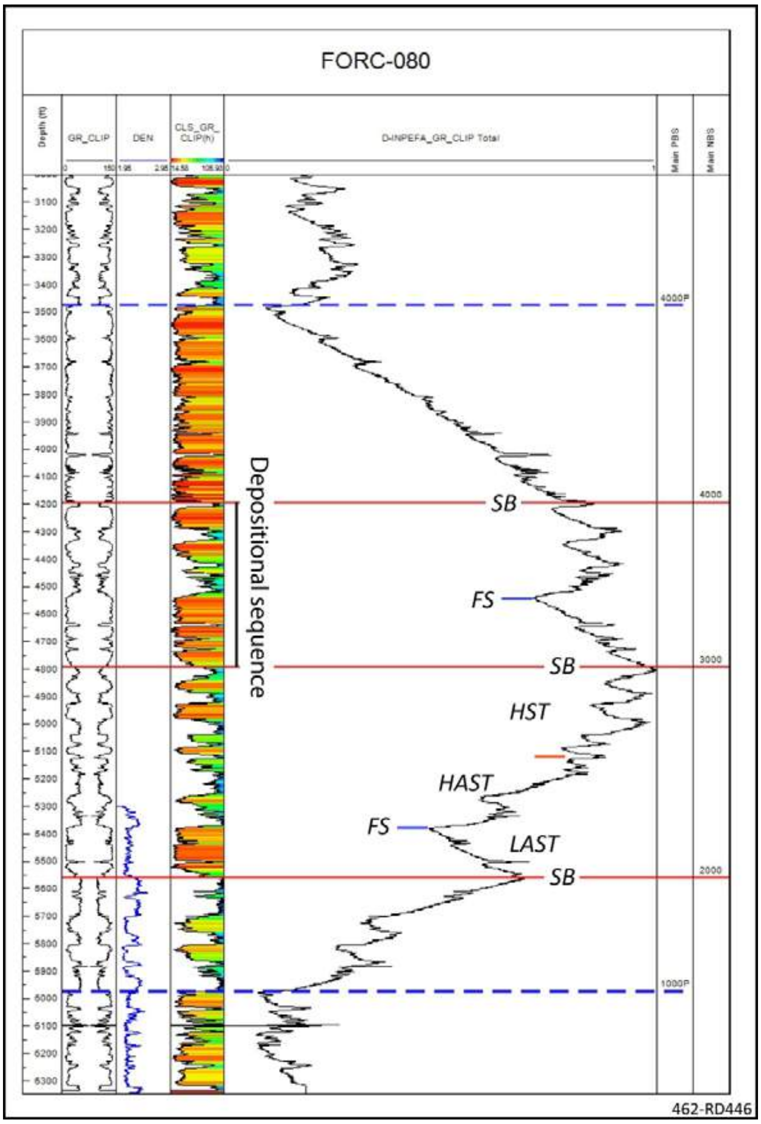

Figure 11: An example of sequence stratigraphic interpretation of the INPEFA log transform. SB – sequence boundary; FS – "flooding" surface; LAST – low-accommodation systems tract; HAST – high-accommodation systems tract; HST – high-stand systems tract. Alluvial-fluvial systems of the delta plain, onshore Nigeria (data courtesy JOA).

CLIMATE STRATIGRAPHY

Climate Stratigraphy is using the fundamental findings of Global Cyclostratigraphy as the basis of a method of stratigraphic analysis and correlation.

Sequence stratigraphy has proven to be an effective tool for subsurface correlation in both local and regional scale. The method is considered as the modern approach to integrated stratigraphic analysis.

Climate stratigraphy is using these aspects in its concept and has also made a further development with the support of the analysis tool, CycloLog.

All three conceptual interpretation models are related to each other (Figure 12). Despite many common aspects, some important differences are present:

- Global Cyclostratigraphy is mainly dealing with large-scale basin fill pattern
- Sequence Stratigraphy and Climate Stratigraphy are both dealing with reservoir-scale correlations
- Global Cyclostratigraphy and Sequence Stratigraphy have achieved their insights by conceptual modelling
- Climate Stratigraphy has based their insights for an important part by deterministic modelling of the subsurface with its specially designed software tool, CycloLog. Results have subsequently been integrated in conceptual models generated in the subsurface as well as in outcrop analogues.

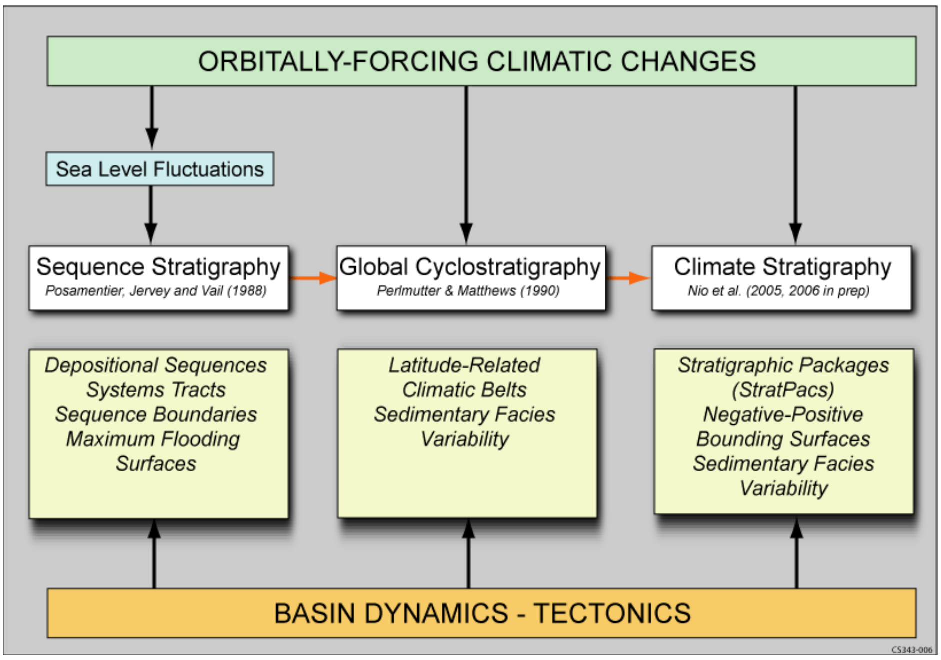

Figure 12: The relationship between Sequence stratigraphy, Global Cyclostratigraphy and Climate Stratigraphy (after Nio, 1995)

The deterministic approach in Climate Stratigraphy is the use of its analysis tool, CycloLog. The INPEFA log transform generated from facies-sensitive logs (commonly the GR log) shows the relationship with the basic principle in Global Cyclostratigraphy. It shows the cooling and warming phases on (see Figure 8) in the INPEFA pattern as well as in an outcrop analogue (see Figure 13).

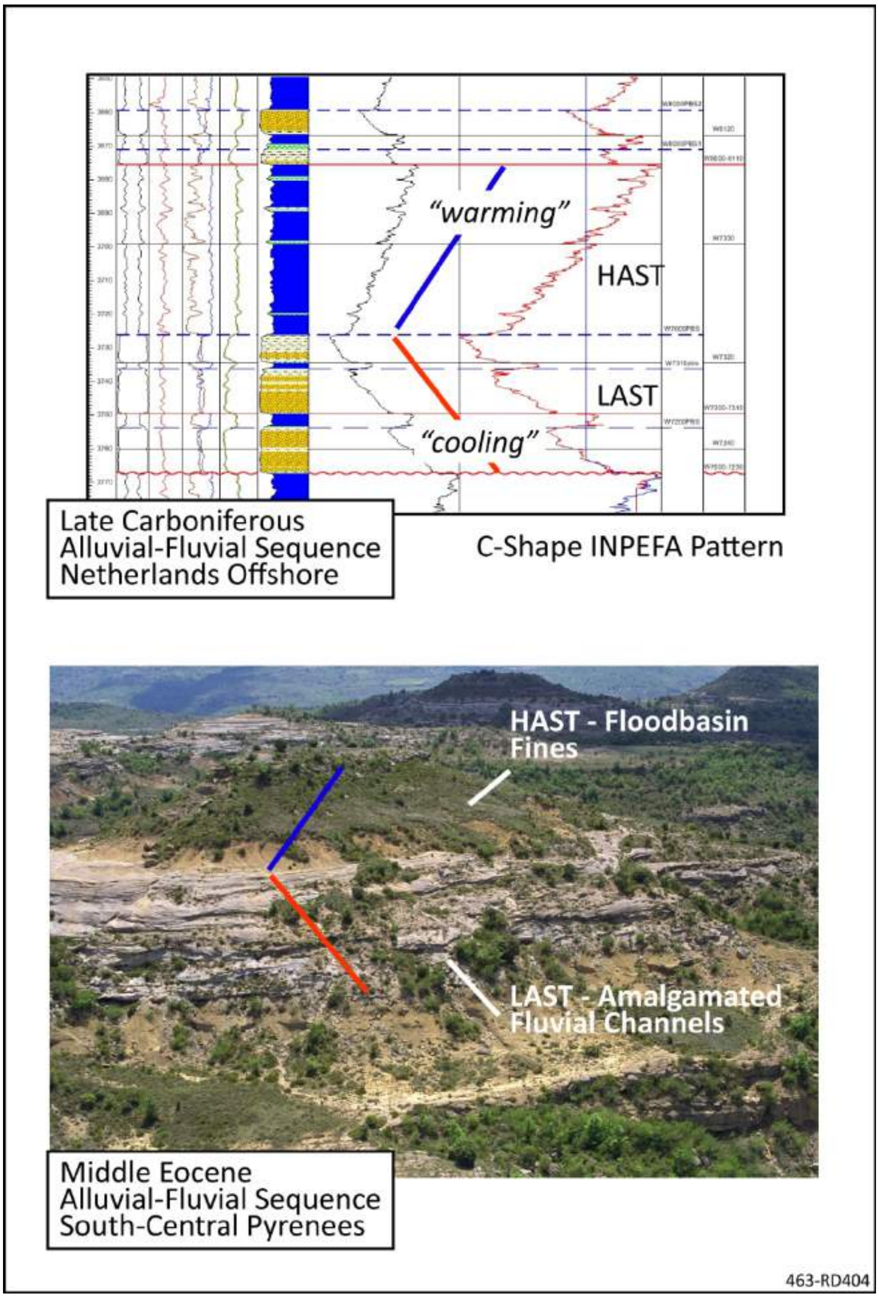

Figure 13: C-shape INPEFA pattern is according to climatic phases as defined by Global Cyclostratigraphy

Climate Stratigraphy consists of a two-fold approach, (1) the deterministic modelling and analysis of facies-sensitive wireline logs using CycloLog, and (2) the interpretation of the INPEFA log transform using Climate Stratigraphy concepts. In developing the ideas on Climate Stratigraphy and defining its principles, results from CycloLog analyses and comparisons with outcrop analogues were extensively used.

Essential principles of Climate Stratigraphy can be summarised as follows:

- Climate Stratigraphy uses the fundamental findings of Global Cyclostratigraphy as the basis of a method of reservoir-scale stratigraphic analysis and correlation. It includes the principle that climate change is quasi-cyclic as a result of primary orbital control.
- Climate Stratigraphy uses an important part of the insights of Sequence Stratigraphy which emphasizes facies relationship and stratal architecture within a chronological framework, the recognition of genetic units that result from the interplay of accommodation and sedimentation.
- Specific aspects of Climate Stratigraphy include the recognition of vertical lithofacies patterns which retain a (partly distorted and incomplete) record of the nested orbital periodicities which is accessible through the spectral (wavelength, amplitude, phase) properties of facies-sensitive logs.

THE ROLE OF TECTONIC PROCESSES

CLIMATE CHANGE OSCILLATION AND BASIN DYNAMICS

The preserved sedimentary rock succession in a stratigraphic profile was formed in an interaction between sedimentary depositional process, climate change cycles, basin dynamics, and various post-depositional processes. Despite the complexity of the interaction of these processes, a certain order can be observed. It is important to recognize the time frame in which these processes are active (Figure 14). We have divided the recurrence time interval in the Calendar, Solar, Milankovitch, Sequence Stratigraphy and Tectonic Bands. In this scheme, sedimentary processes for instance are active within the Calendar Band. Cyclic sedimentation within this band is for instance related to tidal depositional processes. The making of sedimentary facies basically takes place in the time frame of the Calendar and Solar Bands. In petroleum geological terms, the processes within this time frame are primarily responsible for the reservoir quality.

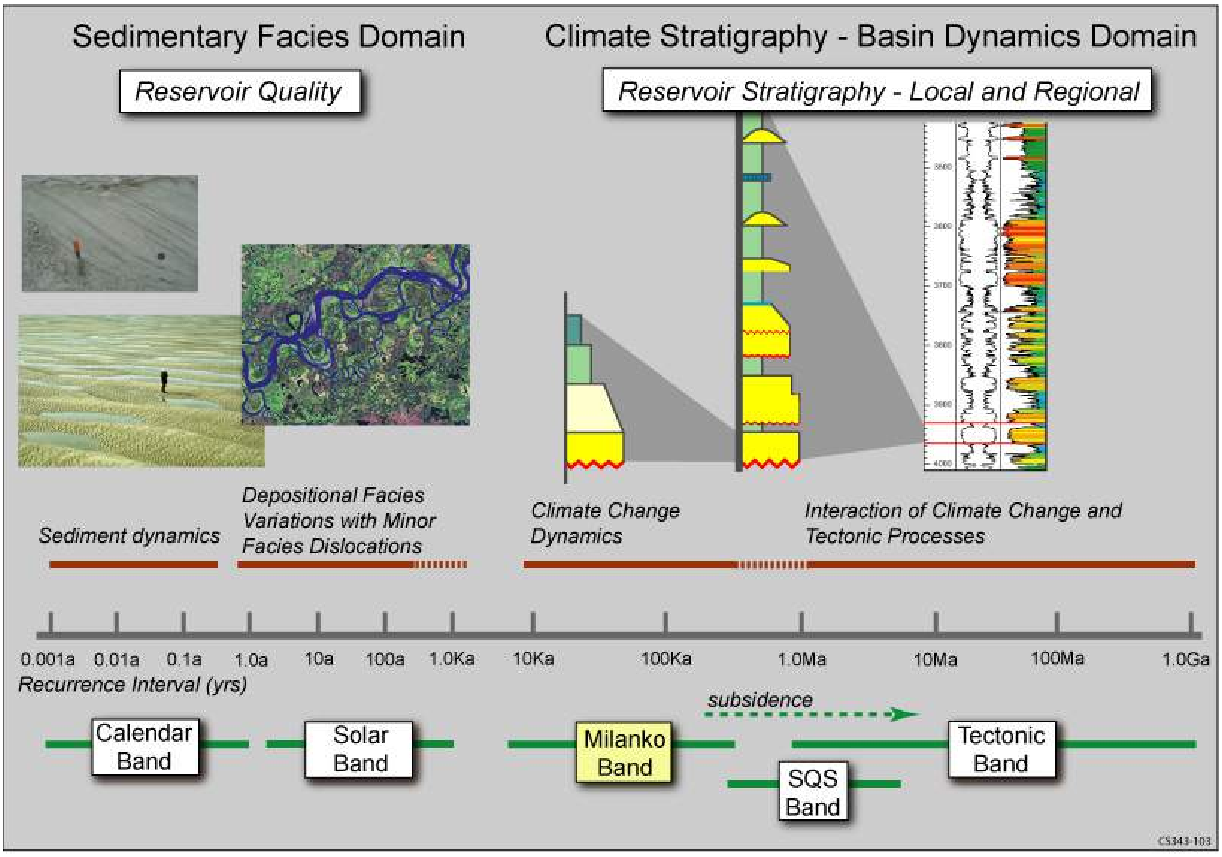

Figure 14: Time frame of processes that are responsible for the construction of the stratigraphic framework (after Nio et al., 2006)

Processes related to climate stratigraphy are dominantly present during the Milankovitch Band. Note that the resolution of climate stratigraphy is in the scale of 10 ka to around 500 ka. It is important to realize that we are looking to stratigraphic processes and not to sedimentary depositional processes. Stratal patterns which can be observed in outcrop, or sometimes in high-resolution seismic in the subsurface and also in near-synchronous stratigraphic correlations are related to stratigraphic processes within the Milankovitch Band.

An interaction between processes of the Milankovitch and Tectonic Band will initially take place during the 100 ka. Tectonics and basin dynamic processes such as basin subsidence are becoming more important in the time frame of 500 ka and later. The Sequence Stratigraphic (SQS) Band for instance is for a large part influenced by climate change processes and basin dynamics or tectonics.

The building blocks of a stratigraphic profile is the result of climatic changes within the 100 ka and if basin accommodation is large enough, these blocks build up the stratal sequences and finally the stratal architecture.

CLIMATE STRATIGRAPHIC PACKAGES (StratPac) AND BASIN ACCOMMODATION

The preservation of the climate stratigraphic package in the rock record is depending on the available accommodation. Accommodation is the space available for sediment to accumulate at any point in time (Jervey, 1988). We will not discuss in detail the interaction of base level fluctuations and sediment supply, as there are many references for this matter (see e.g. Jervey, 1988, Emery and Myers, 1996). What we want to bring forward here is the preservation of a stratigraphic package deposited during a eccentricity and long eccentricity Milankovitch cycle in relation to basin subsidence or basin accommodation (Figure 15).

Let us take an example where the eccentricity 100 ka cycle has a wavelength of 5 m. If the basin subsidence creates an accommodation of 0.05 m/ka, the whole stratigraphic package of 100 ka will be preserved. However, if the subsidence only creates an accommodation of 0.03 m/ka, only part of the 100 ka stratigraphic package will be preserved.

When interpreting the INPEFA curve, these aspects are important and should be included in the interpretation or correlation.

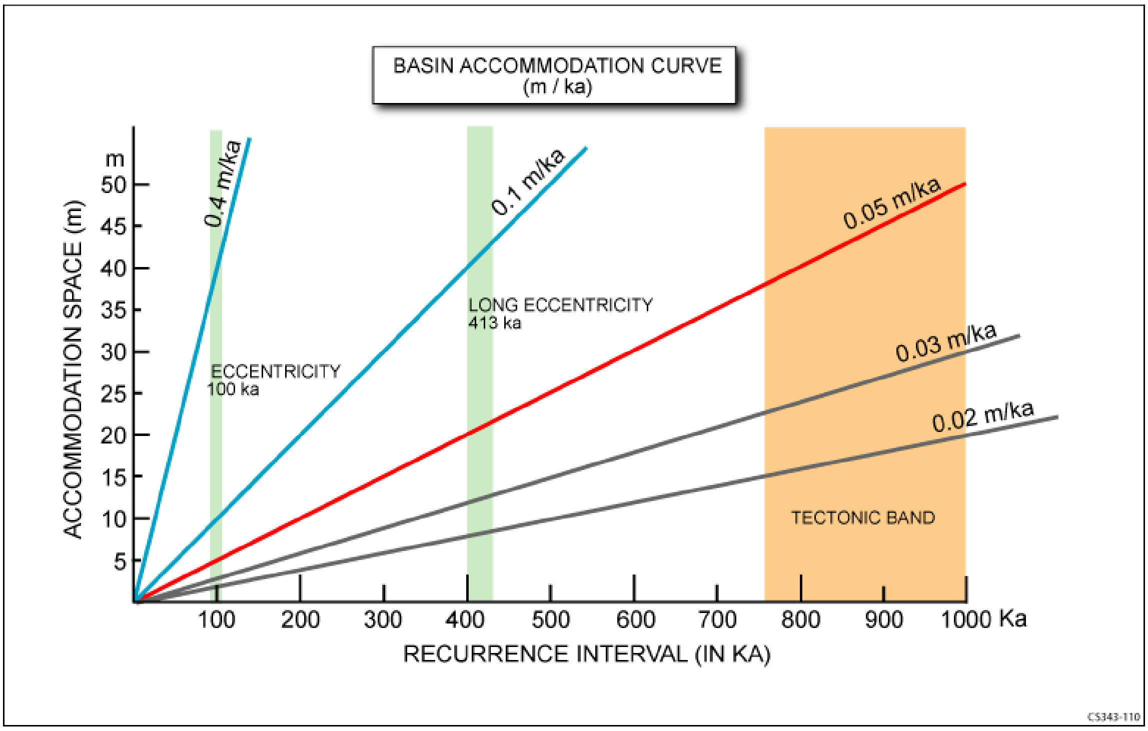

Figure 15: Preservation of Milankovitch cycle stratigraphic packages versus basin subsidence rates and/or basin accommodation (after Nio et al., 2006)

SOME IMPORTANT CONCLUSIONS

Given our emphasis on climate as the key driver of stratigraphic succession, it might be assumed that we ignore the effects of tectonics. Tectonic processes are, however, not discounted in our approach. The effects of climate change on the lithofacies succession - and the link with wireline logs - are in the 10,000s to 100,000s years part of the time-spectrum.

Tectonic processes act on a longer time-scale than insolation-driven climatic changes. In terms of their effect on stratigraphy, climate-driven patterns can be considered as superimposed on tectonically controlled patterns that are of longer duration. For instance, an overall increase in sediment-calibre in a given area (as the area becomes more sand-rich) may well be the result of increased tectonic activity, but the shorter term vertical lithofacies variations (as expressed in the changes and patterns of the INPEFA curves) are primarily controlled by climatic variations.