CHAPTER 3

THEORY AND METHOD

3.1 Orbital-forcing of climate change

At timescale of 10,000-100,000 years, global and regional climates change in a systematic way that can be predicted from detailed knowledge of the Earth's orbit, Milankovitch model (Nio *et al*., 2006). Because, changing of Earth's orbital parameters influence on changes in insolation, the flux of solar energy at the Earth's surface and its distribution with latitude and through the seasons. Translation of variable insolation into climate is complex, involving the linked circulation systems of the atmosphere and ocean, mediated by the changing distribution of land and sea. For this reason, climate is a major influence on the production and deposition of sediments, every stage in the cycle of weathering, erosion, transport, and deposition of sediments (De Jong *et al*., 2006). Climate change is registered in the stratigraphic record. Facies-sensitive wireline logs provide a near-continuous sampling of lithofacies change, and this record can be analyzed to provide time-significant information that can be used in classification and correlation of the stratigraphic succession (Figure 3.1).

3.1.1 Orbital control insolation

Insolation, or solar energy flux, is the ultimate control on climate. Milankovitch made extensive calculations and conclusively demonstrated that insolation does indeed vary as a result of changes in the three key parameters of orbital eccentricity, axial obliquity, and the precession of the equinoxes.

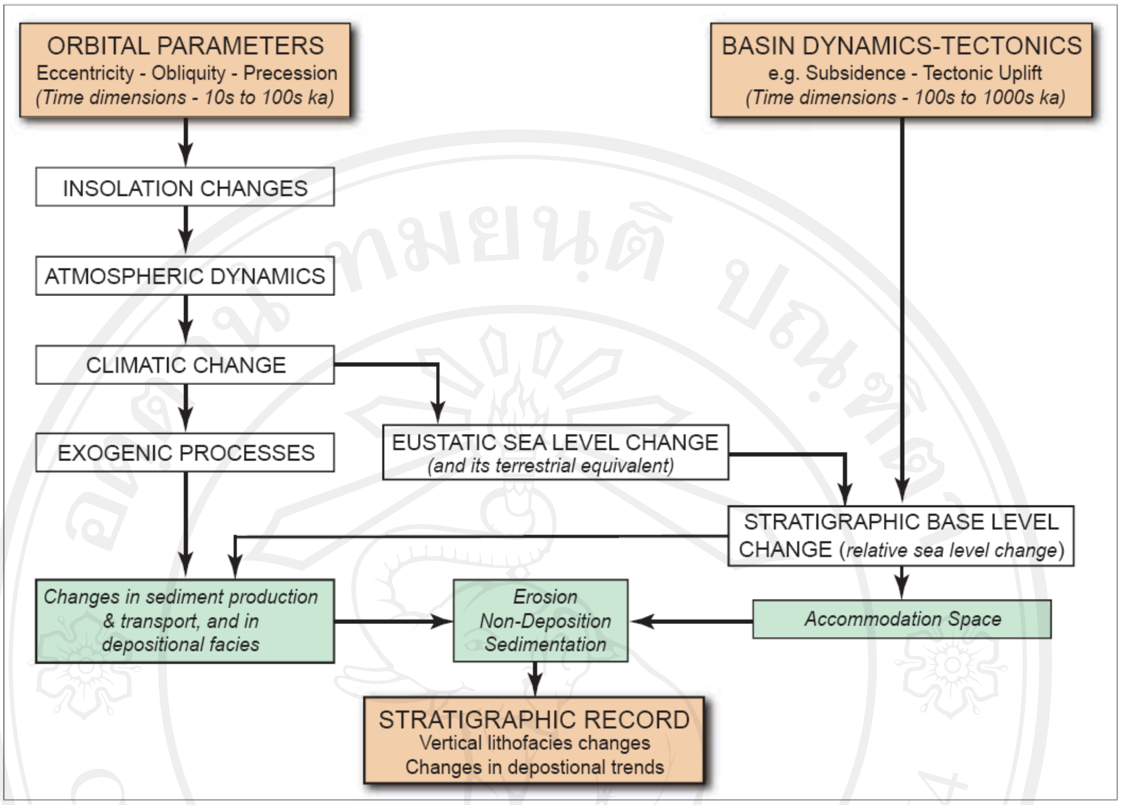

Figure 3.1 Connection between the orbital parameters (top left) and their record in strata (bottom). Climate change is, hence, a key control on vertical lithofacies change (De Jong *et al.*, 2007).

Eccentricity

As discovered by Kepler who was a German astronomer, the Earth's orbit is an ellipse, not a circle. The Earth-Sun distance therefore varies slightly through the annual cycle. However, the eccentricity of the orbit (its deviation from a circle) is not fixed, but varies over geologically significant periods of time. The primary period over which the eccentricity varies, from a minimum of near zero to a maximum of 0.06, is about 100,000 years (100 ky). Additional periods exist of 413 ky, 1300 ky, and around 2 My (Figure 3.2 a).

Obliquity

The tilt, or obliquity, of the Earth's rotational axis is also variable, between 22 and 24.5 degrees (where 0º means orthogonal to the plane of the Earth's orbit). The primary period over which this factor varies is 41 ky, with a secondary period of 54 ky. Obliquity (combined with precession) affects the angle of incidence of the Sun’s radiation, especially at high latitudes (Figure 3.2 b).

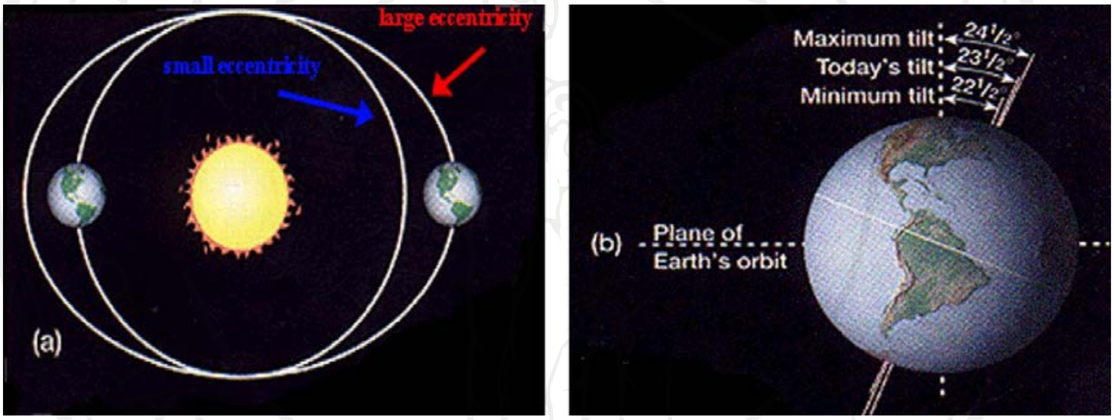

Figure 3.2 The basic orbital parameters that affect insolation and its latitudinal and seasonal distribution. Eccentricity is the departure of the orbit from a circle. Obliquity is the tilt of the Earth’s rotational axis (Missouri State University, 2005).

Precession

The third astronomical factor affecting insolation is the effect of precession. Although astronomers describe this factor in a more complex way, its effect is to move the incidence of the seasons around the Earth's elliptical orbit. Thus, for example, the northern hemisphere's winter solstice may occur when the Earth is either at perihelion (closest to the Sun) or at aphelion (furthest from the Sun). The result is that each hemisphere goes through the following succession of seasonal variations (but with the northern and southern hemispheres being 180° out of phase with each other):

1. Medium summer - medium winter
2. Short, hot summer - long, cool winter
3. Medium summer -medium winter
4. Long, warm summer - short, cold winter

The total insolation for the year is largely unaffected by the precession; it is its distribution through the seasons that is more important. The main periods associated with precession are 19 and 23 ky. Because these two periods are rather close together, it is rare for their separate effects to be recognized, and it is more usual to associate an average period of 21 ky with the precession (Figure 3.3).

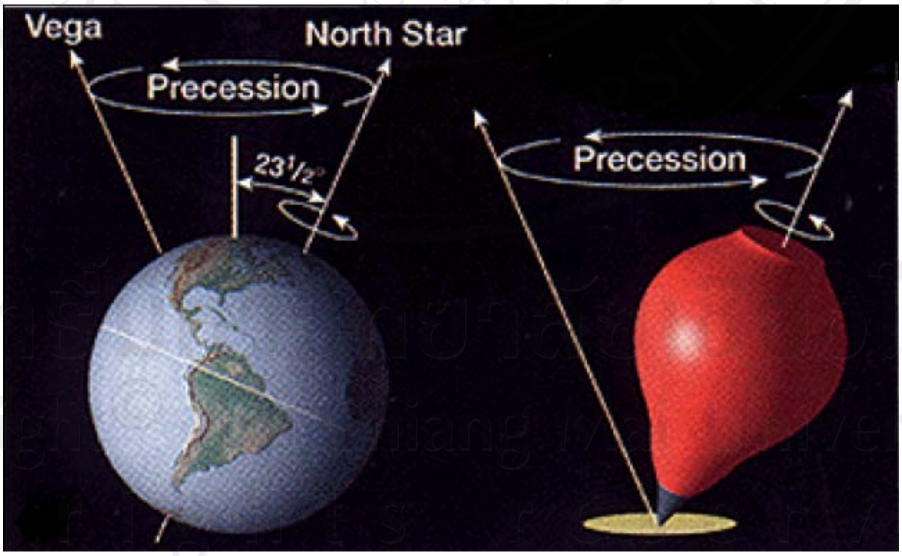

Figure 3.3 One of the basic orbital parameters. Precession is the rotation of the axis itself, which causes the seasons to precess around the elliptical orbit (Missouri State University, 2005).

3.1.2 Insolation and circulation of the atmosphere

The sun provides virtually all of the energy that drives the circulation of the Earth's atmosphere. The flux of solar energy received at the top of the atmosphere is called insolation, and this is the parameter that is under orbital control. The curvature of the Earth controls the angle of incidence of solar energy, and more energy per unit area therefore arrives at the tropics (high angle of incidence) than at the poles (low angle of incidence in summer; zero insolation in winter). The air at the tropics therefore receives more heat and warms up relative to the air at the poles. This sets up a basic pole to equator convection cell in each hemisphere. The equator is characterized by low pressure, caused by ascending air currents, while the poles are areas of high pressure, caused by descending air currents.

Regional temperature is primarily a function of latitude – temperatures are warmer at the equator than at the poles, because of the unequal distribution of insolation. Temperature distribution is then modified by the atmospheric circulation, taking warmer air towards the poles and colder air towards the equator, depending on location (Figure 3.4).

Atmospheric circulation also controls the distribution of humidity – a parameter of major importance to geological processes. Upward convection draws water from the oceans into the atmosphere by evaporation, making water available for precipitation. The high pressure zones, where convective currents are downward, are characterized by low humidity.

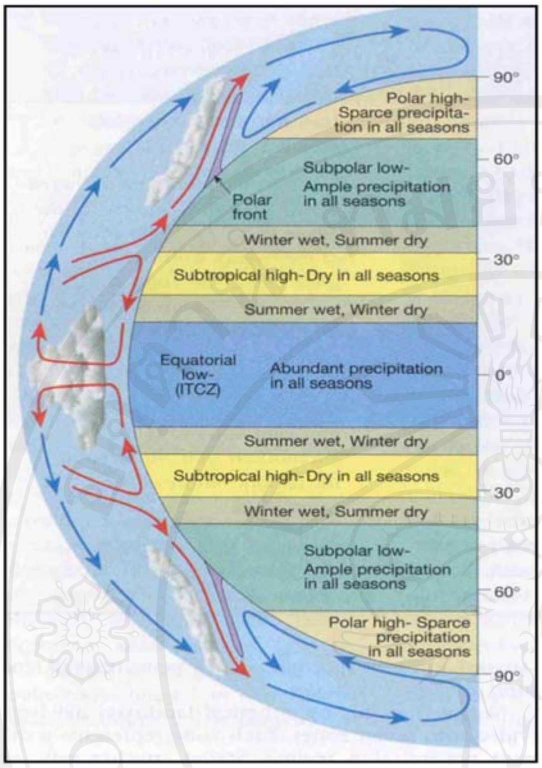

Figure 3.4 Latitude-parallel zonation of humidity and its seasonal distribution (Nio *et al*., 2006).

3.2 Cyclic sedimentation, Cyclostratigraphy and Global Cyclostratigraphy

The approach and concept of Climate Stratigraphy, arises from, and depends on, the concepts of Global Cyclostratigraphy, as proposed and practiced by Perlmutter and Matthews, 1990. Global cyclostratigraphy is a particular application of the more general concepts of Cyclostratigraphy, which in turn has a more specific connotation than the much older term "cyclic sedimentation". The progression of ideas is represented by these terms.

Cyclic sedimentation implies repetition of lithofacies in the rock record. Such repetition may involve two or more different lithologies, and may or not be rhythmic in the sense of showing more or less constant thickness of successive packages. Cyclic sediments have attracted interest and speculation for centuries. Modern studies of the causes of cyclic sedimentation probably started with the work of Sander in the 1930s. Sander's most important contribution was his proposal that:

(1) Cycles that are periodic (i.e. regular) in thickness necessarily imply a process that is periodic in time.

Sander further asserted that the converse of proposal (1) is not true, and said in (2):

(2) Lack of regularity in thickness (i.e. repetition without spatial periodicity) does not necessarily imply lack of regularity in time.

The term "Cyclostratigraphy" was first used in the late 1980, has been explicitly linked with the concept of orbital-forcing of climate change, and it would probably now be wrong to use it in any more general sense. Schwarzacher, 1993; House & Gale, 1995; Weedon, 2003; Nio *et al.*, 2006 defined it in the climate stratigraphy principle and applications in subsurface correlation as follows: Cyclostratigraphy is the study of cyclic and repetitive of strata, and their relationship with orbitally forced cycles of climate (insolation) change.

Global Cyclostratigraphy, as introduced by Perlmutter and Matthews (1990), is an application of some of the concepts of cyclostratigraphy to particular problems in exploration geosciences. Global Cyclostratigraphy develops the idea that climate change goes through recognizable and predicable pattern and 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 modeling 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 Climate stratigraphy which operates at higher resolution by focusing on wireline log data.

3.3 Climate stratigraphy

Climate Stratigraphy (as practiced by ENRES) is an application of aspects of global cyclostratigraphy. The principles of the method of climate stratigraphy have recently been described in detail by Nio *et al*. (2005, 2006) and De Jong *et al*., (2007). Climate stratigraphy uses the fundamental findings of global cyclostratigraphy as the basis of a method of stratigraphic analysis and correlation, principally in the subsurface and using wireline log data.

Climate stratigraphy is based on the following principles:

- Climate is a primary control on lithofacies.
- Lithofacies succession is therefore a function of climatic succession.
- "Climate succession is mappable, and is a function of global position" (Prelmutter *et al.*, 1998)
- Lithofacies succession is therefore similar within any one climate belt.
- Bounding surfaces marking climatic changes are therefore near-synchronous geologic events within any latitude- related climatic belt.

The above set of principles is general enough to be applicable either at outcrop (where it implicitly underpins conventional methods) or in the subsurface. The essential principles for the subsurface and using the wireline log data require the following additional principles:

1. Climate change is a result of the primary orbital control.
2. Vertical lithofacies patterns retain a (distorted and incomplete) record of the nested orbital periodicities.
3. Climate change information is accessible through the spectral (wavelength, amplitude, phase) properties of a facies-sensitive log.

4. A facies-sensitive log provides a regularly sampled "time-series" suitable for spectral analysis.

Given the above principles, climate stratigraphy operates by extracting a curve representing the downhole changes in the spectral prosperities of a facies-sensitive wireline log, and correlating key features of those spectral change curves between wells.

The working procedures for climate stratigraphic analysis and interpretation consist basically of two parts (Figure 3.5):

A. The deterministic modeling and analysis of facies-sensitive wireline logs. The climatic and lithological changes, which are as "hidden" signal in the logs, are being filtered out and modeled in Maximum Entropy Spectral Analysis (MESA), Prediction Error Filter Analysis (PEFA) and Integral of Prediction Error Filter Analysis (INPEFA).

B. The interpretation of MESA, PEFA and INPEFA by using conventional geological models. A first comparison and validation with the logs should take place before the interpretation will take place.

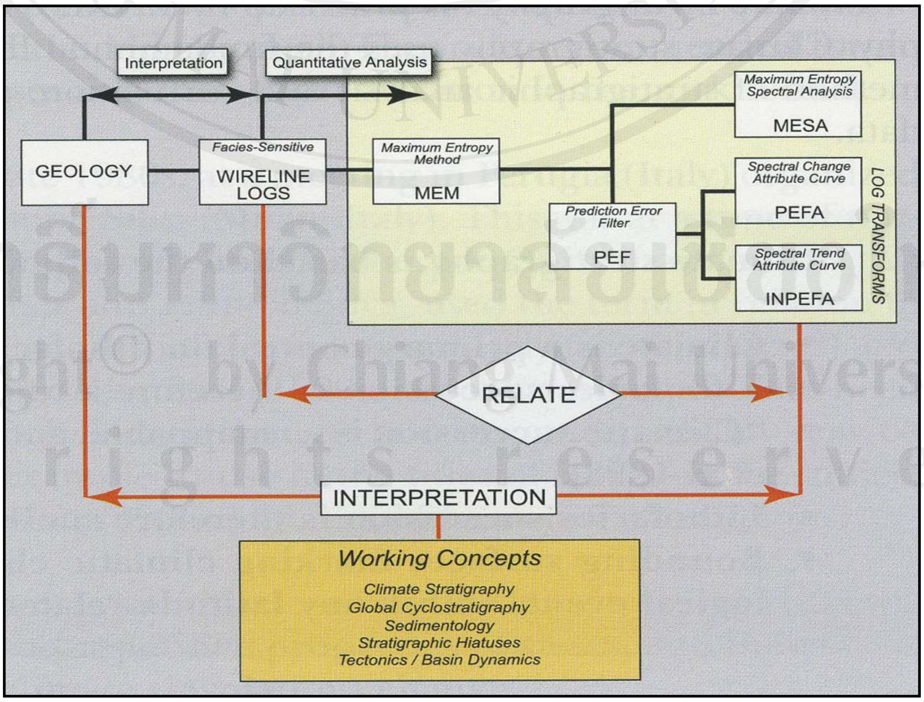

Figure 3.5 Flow chart of climate stratigraphy working procedures (Nio *et al.*, 2006).

3.3.1 Hierarchy of stratal units and geological dimensions in climate stratigraphy Stratal units

Climate stratigraphy seeks to subdivide and classify strata. Inevitably, this requires the use of terminology specific to the method. Climate stratigraphy is not sequence stratigraphy. Sequence Stratigraphy related to the system tracts result in a better understanding of the relationship between eustatic sea level fluctuations, basin subsidence, sediment supply and sedimentary facies development while, the Climate Stratigraphy link with the Sequence Stratigraphy by the sea level fluctuations, is orbitally climate driven (Figure 3.6). However, there are similarities between the two methods. Both recognize hierarchical sets of bounding surfaces, and both seek to characterize and interpret the intervening packages of strata. An essentially similar hierarchy of stratal units to that in general use for sequence stratigraphic analysis and this is summarized in Figure 3.7.

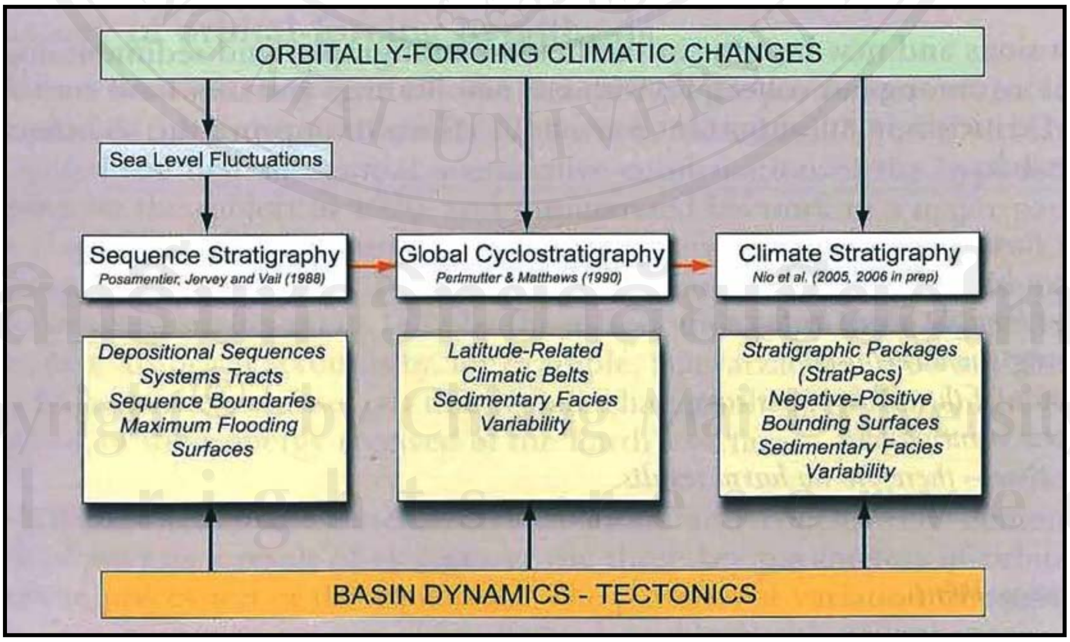

Figure 3.6 Overview of modern stratigraphic concepts as applied to the subsurface (Nio *et al.*, 2006).

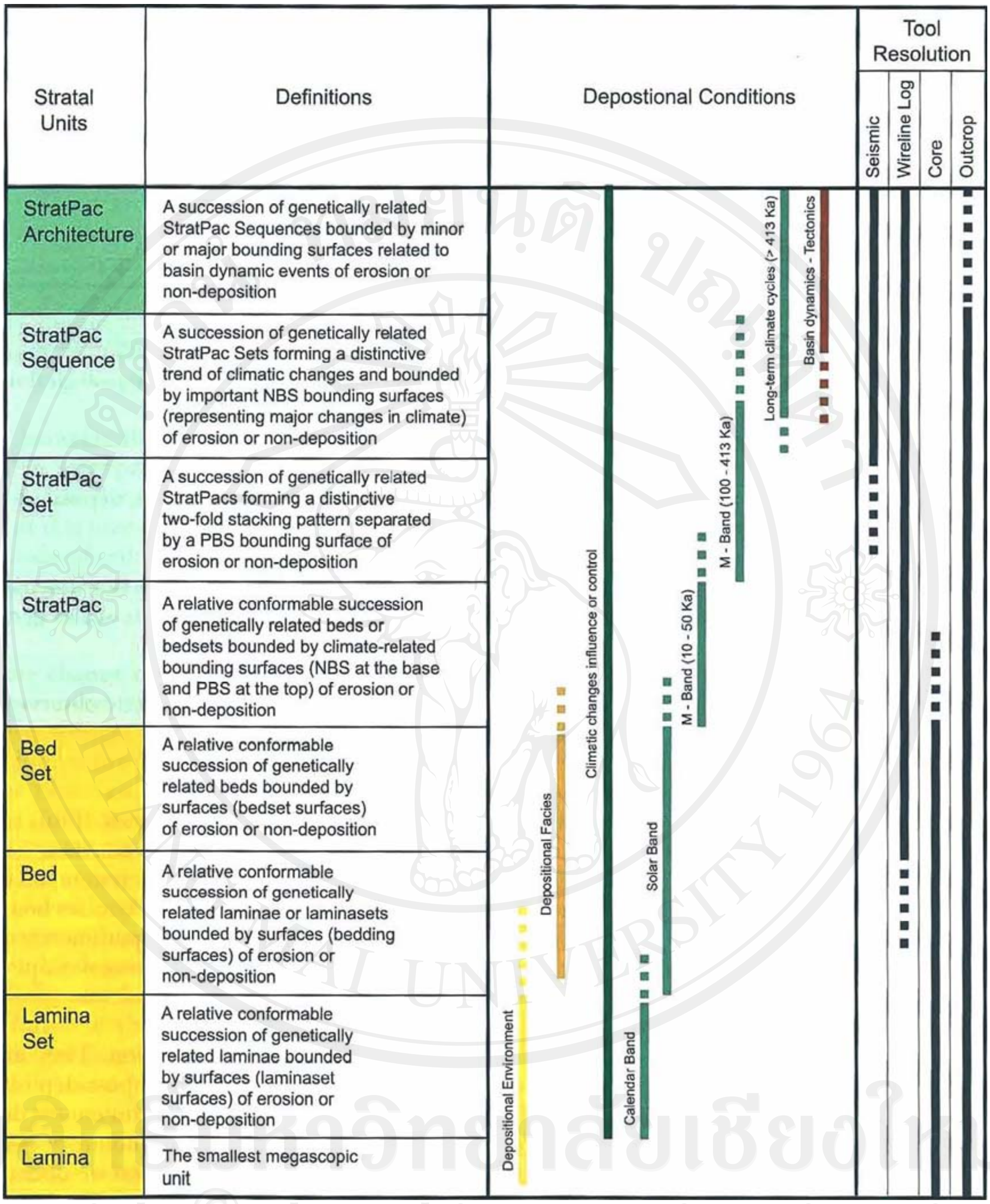

Figure 3.7 Hierarchy of stratal units as used in climate stratigraphy, indicating the approximate association of each level with different aspects of the deposition system, and with different parts of the geological time spectrum. Also showing the possibilities for resolving each type of unit depending on the source of data; seismic, log, core or outcrop (Nio *et al.*, 2006).

3.3.2 Relationship of hierarchical levels to geological time

Having defined a hierarchy of stratal units for use in climate stratigraphy, it is important to understand the relationship of the different levels in the hierarchy with geological time. Figure 3.8 shows the time-frame (on a logarithmic scale) for the various levels in the sedimentation system, from the depositional environment up to the scale of the basin.

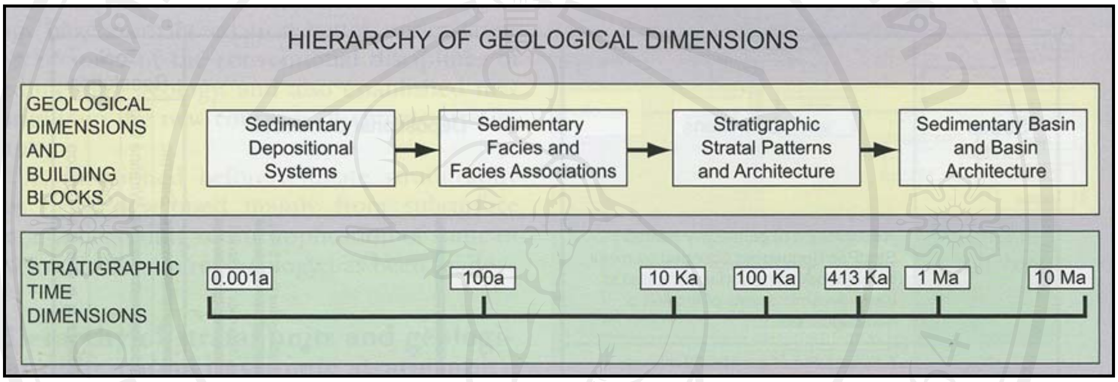

Figure 3.8 Hierarchy of geological dimensions and their relationship to the spectrum of geological time, show on a logarithmic scale (Nio *et al.*, 2006).

In between the sedimentological and sequence stratigraphic time- frames lies the 10,000 to 100,000 years part of the spectrum that has previously been inaccessible to any rigorous methodology. The climate stratigraphy has been taken the view that plays the major role in all aspects of stratigraphic development at this time-scale; climate controls sediment type (mineralogy and grain size); the rate, quantity and mode of sediment transport; accommodation space (including “negative accommodation space” during erosive intervals); and also the nature of the depositional environment itself (Table 3.1 and Figure 3.9).

Table 3.1 Control of climate on the production, transportation and deposition of sediments (Nio *et al.*, 2006).

CLIMATE AFFECTING THE PRODUCTION, TRANSPORT AND DEPOSITION OF SEDIMENT IN A BASIN	
Weathering	Seasonal temperature differences influenced mechanical weathering – aridity versus humidity affects chemical weathering
Erosion	Rate of erosion influenced by rates and type of precipitation, and by vegetation cover
Sediment Transportation (aquatic)	Strongly influenced by total runoff, and by seasonal variations. Also affected by changes in base-level
Lake Levels and Water Table	Controlled by balance of precipitation and evaporation
Sea Level	Controlled by volume of polar and continental-alpine glaciers
Depositional Processes and Environment	Directly affected by temperature, humidity and seasonality and indirectly by water table, lake level and/or area level

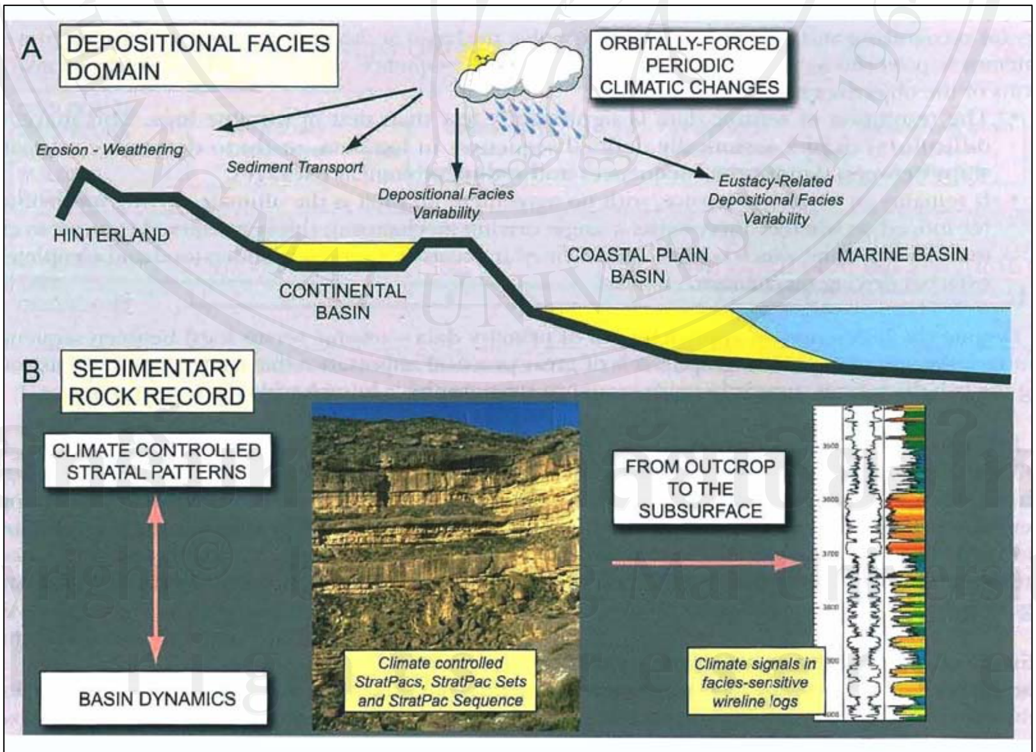

Figure 3.9 Cartoon summary of the role of climate and climate change on modern sedimentary depositional systems, and the stratigraphy record and its representation in subsurface log data (Nio *et al.*, 2006).

3.3.3 Climate change oscillation and basin dynamics

The preserve 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 3.10). The recurrence time interval has been divided in the Calendar, Solar, Milankovitch, sequence stratigraphy and Tectonic Bands. In this scheme, sedimentary processed for instance are active within the Calendar Band. Cyclic sedimentation 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 primary reservoir quality.

Processes related to climate stratigraphy are dominantly present during the Milankovitch Band. Note that the resolution of climate stratigraphy is in the scale of 10,000 years to around 500,000 years. It is important to realize that this method is looked 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 log correlations are related to stratigraphic process within the Milankovitch Band.

An interaction between processes of the Milankovitch and Tectonic Band will initially take place during the 100 ky. Tectonics and basin dynamic processes such as basin subsidence are becoming more important in the frame of 500 ky. and later.

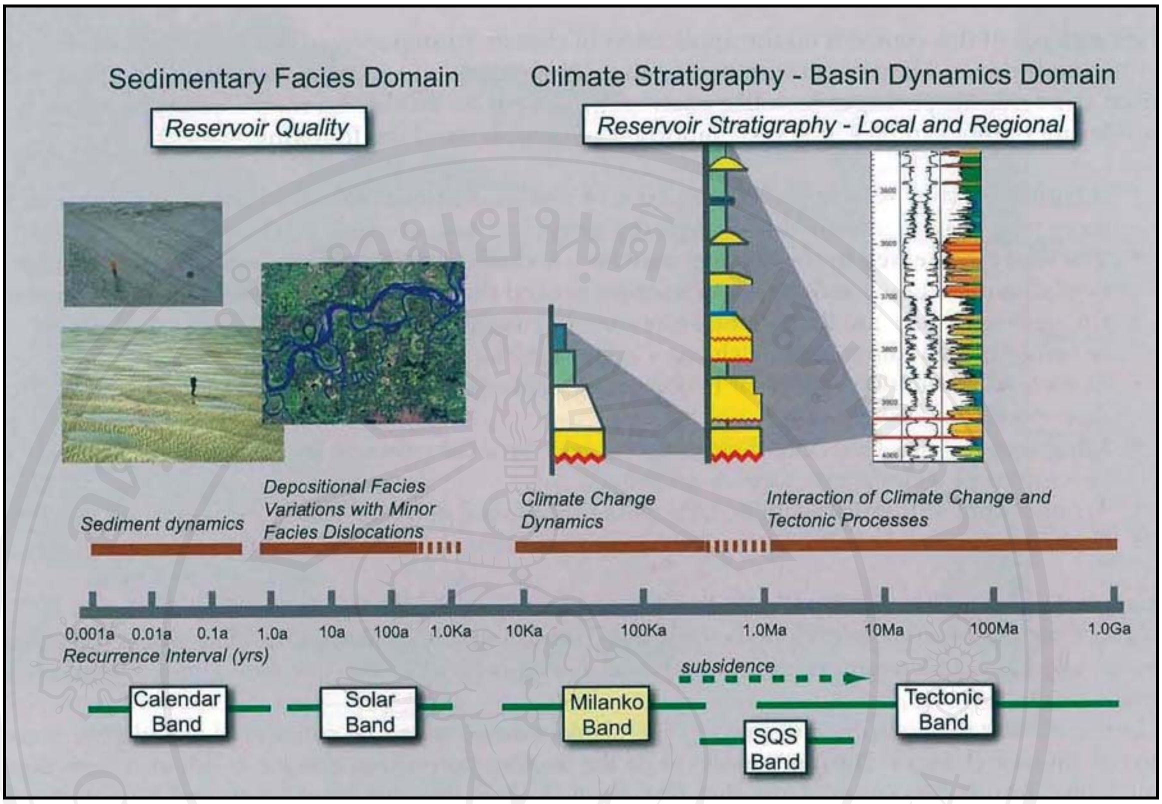

Figure 3.10 Time frame of processed that are responsible for the construction of the stratigraphic framework (Nio *et al.*, 2006).

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 are the result of climatic changes within the 100 ky and if basin accommodation is large enough, these blocks build up the stratal sequences and finally the stratal architecture.

3.3.4 Climate stratigraphic packages 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). In this method bring forward to the preservation of a stratigraphic package deposited during a Milankovitch cycle in relation to basin subsidence or basin accommodation (Figure 3.11). An example where the eccentricity 100 ky cycle has a wavelength of 5 m. If the basin subsidence creates an accommodation of 0.05 m/ky, the whole stratigraphic package of 100 ky will be preserved. However, if the subsidence only creates an accommodation of 0.03 m/ky, only part of the 100 ky stratigraphic package will be preserved.

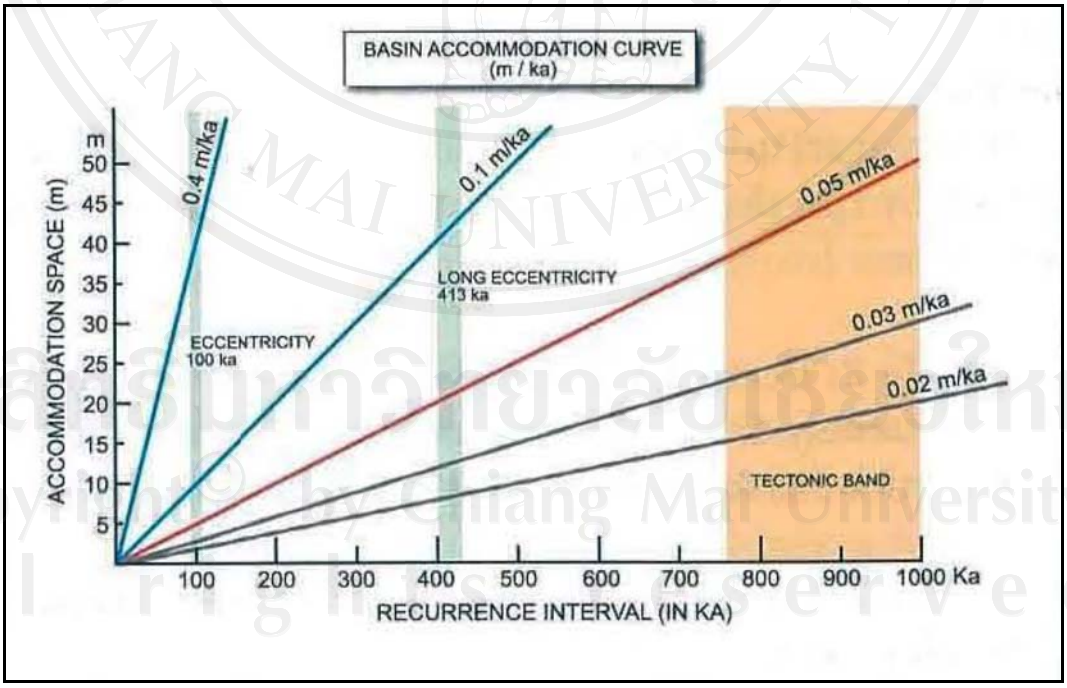

Figure 3.11 Preservation of the Milankovitch cycle stratigraphic packages versus basin subsidence or basin accommodation (Nio *et al.*, 2006).

3.4 Deterministic modeling and analysis of wireline log data

The concept that climate change is a major control on lithofacies development suggests that information may reside in another aspect of a stratigraphic profile such as a well log. Climate change is characterized by the underlying periodicity of the forcing mechanism; insolation change occurs in cycles with several nested periods, ranging from 21,000 to 413,000 years and possibly longer.

Insolation-change is forced by the interactions of a highly organized set of astronomical periodicities; the information content of insolation change is contained in its *waveform properties*. It is not just the fact of climate change -it is the pattern of climate change. If any of this information is preserved through the complex transfer functions that link insolation to climate change, and climate change to lithofacies variation, then at least some of this information is likely to be contained in the *waveform properties* associated with the resulting vertical stratigraphic profile. If this is true, then wireline log data are the ideal place to look for such information.

3.4.1 Wave and oscillating processes in the time and depth domain

Wave result from some kind of oscillating system. The variations in Earth's insolation are caused by oscillation in the solar system. The variations in Earth's climatic system are caused by oscillation of the insolation. The insolations all take place in the time domain.

Sedimentary cycles in the rock record, on the other hand, are a kind of spatial waveform, observed and measured in the depth domain. They are caused by oscillations in one or more environmental variables, such as climate and sea level.

In the simplest imaginable sedimentation system, the rock record would be a perfect recording of environmental change. Such a system is suggested in Figure 3.12. The wave form on the left represents a simple insolation-driven environmental variable, defined as Log (T). The vertical axis is time. The effect of the environmental variable is to switch the mode of deposition between a shale-prone state and a sand-prone state. The resulting stratigraphic record is shown on the right of the diagram, and consists of simple alternations of sand and shale, defined as Log (Z). Because it is assumed that subsidence (and therefore sediment accumulation) is both linear and uninterrupted, the sedimentary succession is perfectly cyclic; the sand-shale cycles in depth are a direct reflection of the environmental oscillations in time.

The relationship between wave period (T) and wave length (λ) is defined in equation $T = \lambda/c$, wave velocity (c). In simple model assume the wave velocity to be one wavelength per unit time; the wavelength becomes equal to the wave period. The phase of the sediment cycles is directly linked to the phase of the environmental oscillation in time.

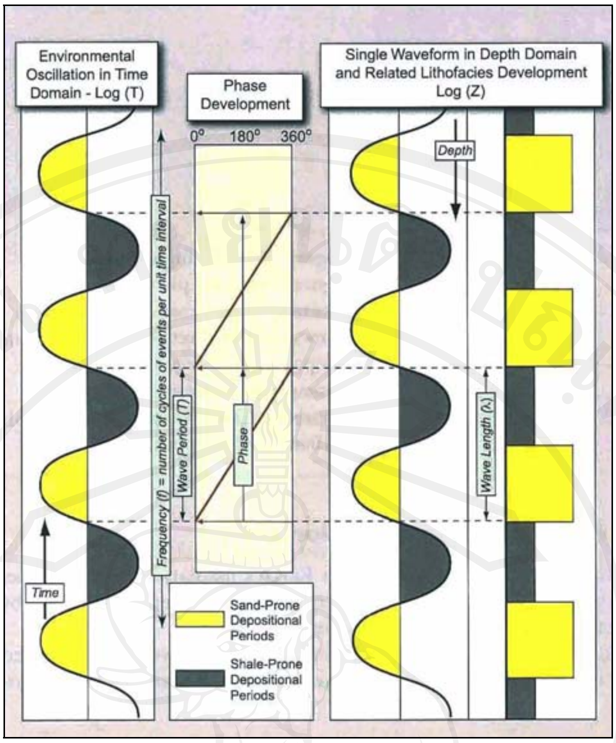

Figure 3.12 A simplified, conceptual sedimentation system in which a single input variable (left) oscillates in time between sand-prone and shale-prone states. The system responds by outputting a record (right) that consists of simple alternations of sand and shale in depth (Nio *et al.*, 2006).

3.4.2. Composite waveforms and principles of spectral analysis

All natural waves, such as acoustic waves, light waves, and the waves at the surface of the sea are composite. They are composed of many single waves, each with its own properties of wavelength, amplitude and phase. An example of the composite waveform of the insolation curve has been illustrated, which can be considered as the sum of five simple waves (Figure 3.13). In this example each wave has a wavelength representing one of the five main Milankovitch periods. *Note that this is not a realistic representation of a true insolation curve, as the amplitudes will not normally all be the same* (Nio *et al.*, 2006).

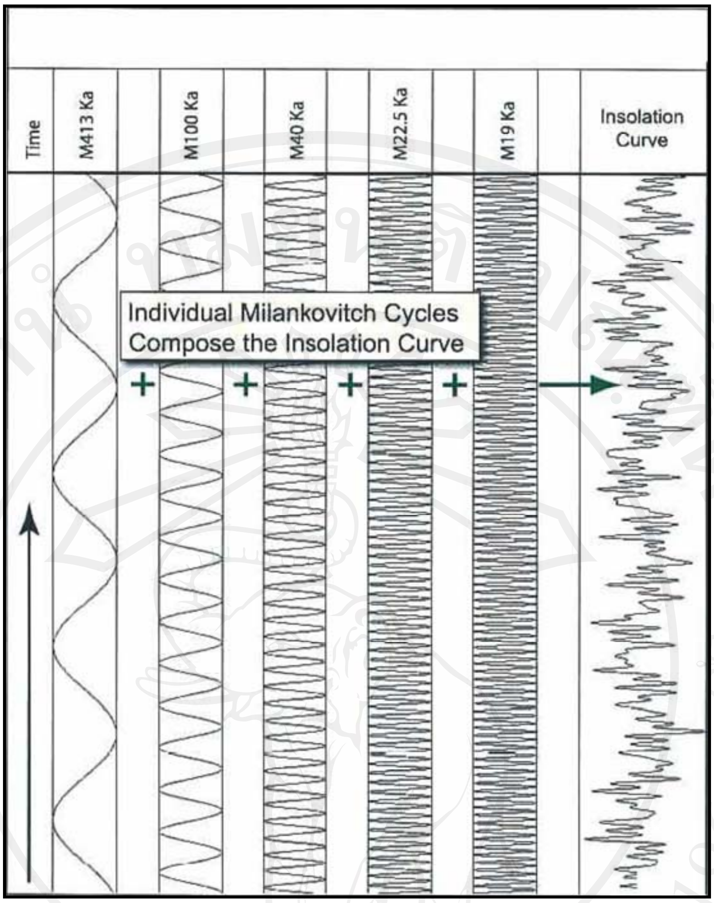

Figure 3.13 Schematic illustration of the principle of addition of simple waves representing the five Milankovitch periods to form a composite wave (Nio *et al.*, 2006).

Importantly, the process of wave composition can be reversed. For any composite wave there exists a unique set of simple waves into which it can be de-composed (see Figure 3.14). A quantitative technique for analyzing a composite wave is Fourier Analysis, which is generally implemented through the Fast Fourier Transform (FFT). The method yields a power spectrum (the graph at the bottom of the diagram) in which the five strong peaks represent the wavelengths of each of the five simple curves that have been combined to make the composite curve. Because the frequency content of the curve is exactly the same throughout its length, the power spectrum for every part of the curve is the same, and this is shown in the continuous spectral image (the right column in Figure 3.14). The five spectral bands represent the five single waves. Because each of the five input waves was given the same strength, the Average Amputate Spectrum in Figure 3.14 shows the relative strength of the individual waves as being exactly the same. The principle of de-composing composite waves is known as spectral analysis.

3.4.3. Transformation of Logs

Logs contain the hidden information derived from climate change signals. To transform log data is the way that the information will be shown. Data collected by facies-sensitive logging tools can be considered as time-series usually equally spaced in time. Log data are equally spaced in depth, not in time, but the mathematical methods apply equally well and the branch of time-series analysis is the way to deals their waves and properties, that is, spectral analysis.

There are many methods of spectral analysis, of which the Fast Fourier Analysis (FFT) is the best known. Fourier Analysis works well if the composite wave consists of simple sines and cosines, as in Figure 3.12. However, geological data are never that simple and wireline log data therefore consist of a complex composite of waves representing many irregular series.

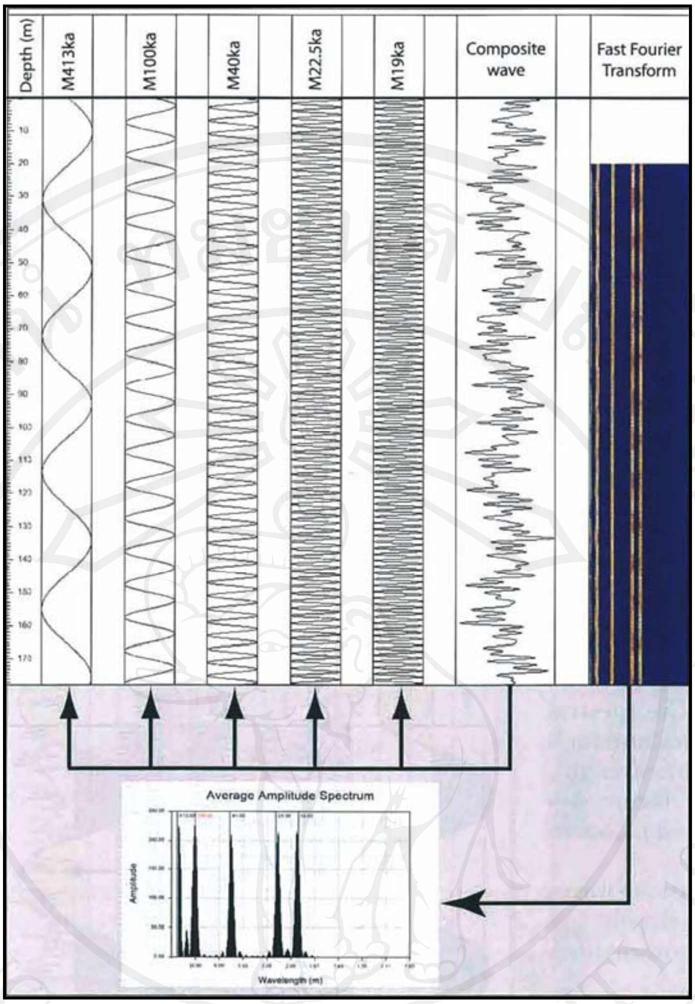

Figure 3.14 De-composing a composite waveform. Power spectrum of the composite waveform shows the peaks of the relative "power" of each wavelength contributing to the composite wave in the analysis window (Nio *et al.*, 2006).

Geological data are also characterized by significant discontinuities, and by variations in frequency related to irregular rates of deposition. The spectral properties of wireline logs are therefore highly variable through any individual well. Even within a single geological unit such as a formation, discontinuities, irregularities, and changes of rate of deposition are to be expected.

Spectral estimation based on for example the Maximum Entropy Method (MEM) or Wavelet Transform methods, is the more appropriate approach for application to wireline log data (Childers, 1978).

One of the basic concepts in climate stratigraphy is the deterministic analysis and modelling of wireline logs. The results of these analyses should support the stratigraphic and sedimentological interpretations and subsequently some new scientific and technical insights can be reached. The Maximum Entropy Method (MEM) has been used as the main quantitative method in the deterministic analysis of wireline logs (Figure 3.15).

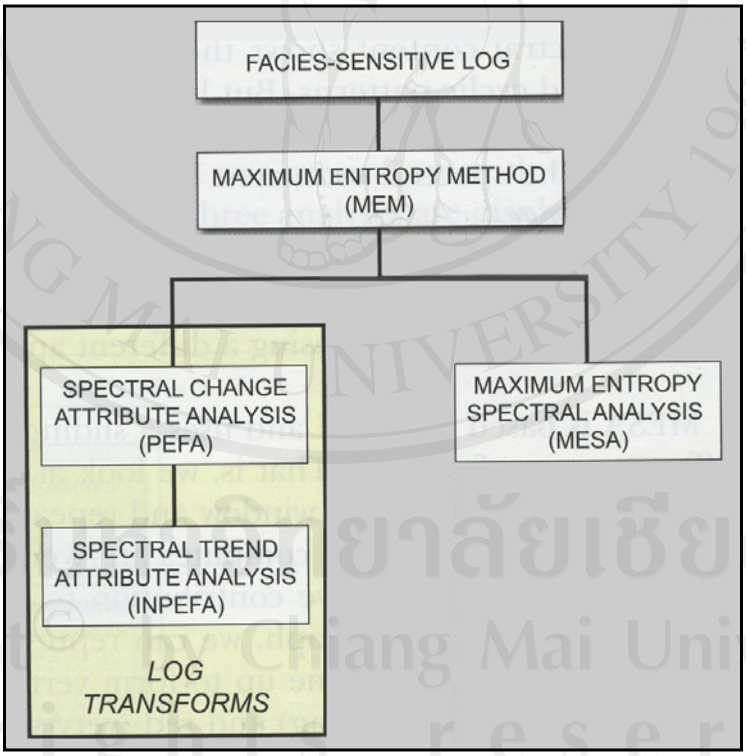

Figure 3.15 Maximum Entropy Method as the basis for (a) log transforms (PEFA and INPEFA), and (b) spectral analysis (Nio *et al*., 2006).

3.4.4. Maximum Entropy Method (MEM) and Maximum Entropy Spectral Analysis (MESA)

MEM is based in information theory, and has been used in a variety of fields, including voice recognition, radio astronomy, and image reconstruction, as well as spectral analysis. The method is specifically concerned with data that are both less regular and noisy - a good description of typical wireline log data.

MESA is based on MEM and uses a sliding window technique to calculate the spectral content of different parts of the log, a portion, or window, of the data, estimate its spectral content, and then slide the window and repeat the analysis. For each window, MESA computes an Average Amplitude Spectrum (AAS), which displays all the wavelengths in their relative contribution to the data. The peaks in the amplitude spectra line up to form vertical ridges (spectral bands), which have been coloured in blue (weak), yellow (strong) and red (very strong) to indicate their relative strength. Each spectral band in the spectral image thus represents a wavelength peak that persists through a certain thickness of the geological succession, revealing the way in which the spectral content of the data is changing through the succession, is summarized in Figure 3.16.

MESA is transforming the original GR log from the depth domain into a spectral image, which is in the depth-wave number domain. Note that the wave number $k = 2x/\lambda$, which means that the long wavelengths are on the left and short wavelengths are on the right side of the spectral image.

In summary, Maximum Entropy Analysis (MESA) is an efficient way to decompose a composite wave such as facies-sensitive GR logs, and generates a spectral image showing downhole changes in the spectral properties of log data.

Spectral bands representing the individual single waves show numerous discontinuities, which are related to brakes in the cycle successions, as well as show lateral shifting which indicate changes in frequency content.

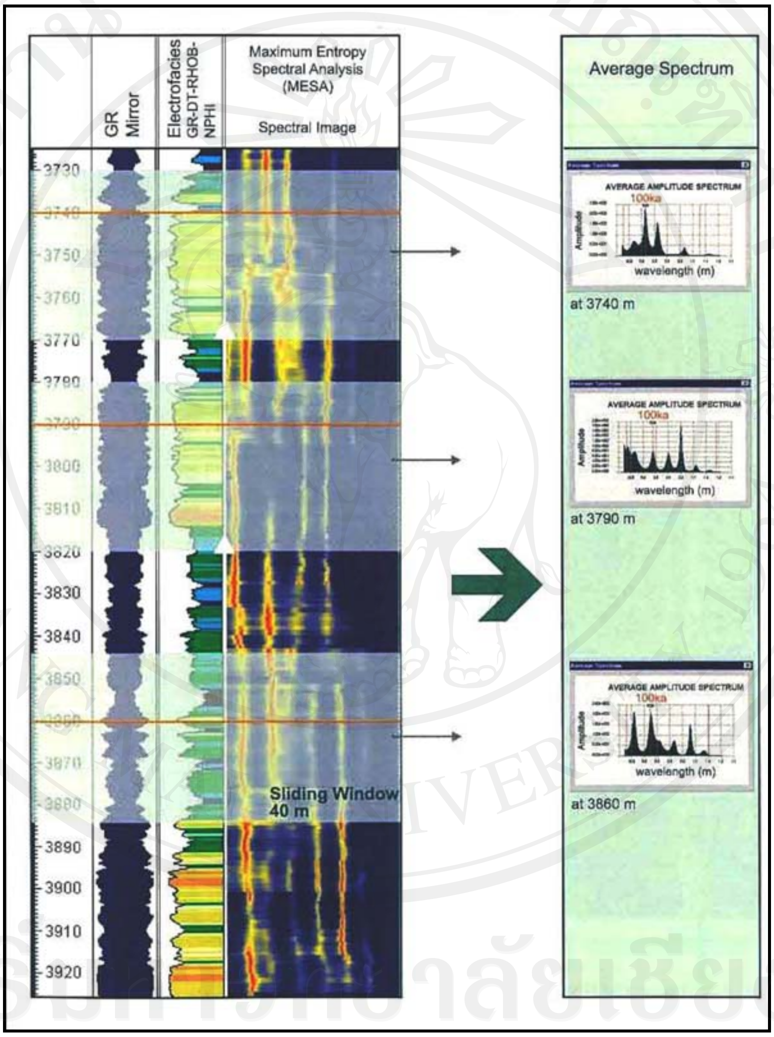

Figure 3.16 Principles of Maximum Entropy Spectral Analysis (MESA), using a sliding window of 40m. The result is displayed in the spectral image column showing the pattern of the different contents of the frequency band. An average spectrum is computed for each of a number of overlapping windows (of which only three are shown for clarity). The Spectral Image is a contoured representation of changes in the amplitude peaks (Nio *et al.,* 2006).

3.4.5 Spectral Change Attribute analysis (PEFA)

Maximum Entropy Spectral Analysis (MESA) of facies-sensitive wireline logs is essentially dealing with decomposing the composite waveform of the log. These spectral changes can be seen in the spectral images as discontinuities and shifts in the spectral bands. Basically, that MESA or any other spectral analysis methods is dealing with waves.

The Spectral Change Attribute Analysis or PEFA has been specially designed for this purpose. MEM uses the theory of linear prediction to construct a statistical probabilistic model (Childers, 1978), which holds the characteristics of the input log data. In PEFA, this probabilistic model is transformed into a prediction error filter, which visualizes the effects of both changes and discontinuities in waveform properties in any composite waveform such as a facie-sensitive log. PEFA is transforming the logs into patterns which are indicating different types of breaks in the depth domain and is an entirely new source of valuable stratigraphic information.

Basic principles of PEFA

Spectral Change Attribute Analysis (PEFA) is using the Climatic-Lithology Model which is generated from the facies-sensitive log (e.g. the GR log) with the Maximum Entropy Method (MEM). The folIowing calculating steps made for generating PEFA (Figure 3.17):

1. MEM is extracting a set of relationships inherent in a chosen interval containing the climatic change signals with respect to the lithological changes, and then combines these rules into a statistical model of the data in the internal, which is both accurate and compact - the MEM Model.

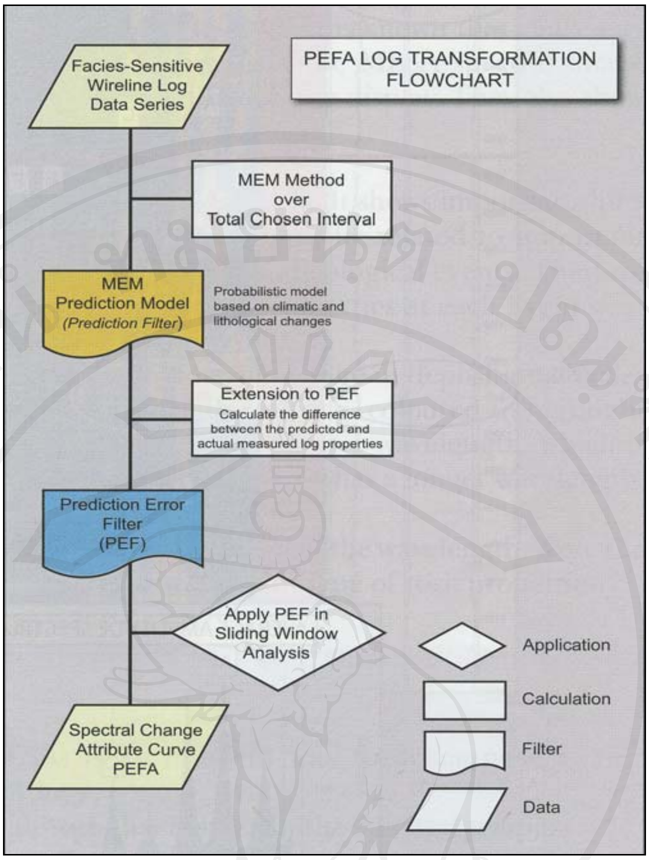

Figure 3.17 Flowchart showing the different steps in the PEFA log transformation (Nio *et al.*, 2006).

2. The MEM model, which can be used as a prediction filter to predict the window's next data point based on the data points in the window, is extended into a prediction error filter. Instead of returning a prediction, the filter returns the error in the prediction. The error is the difference between the predicted data point and the true data point.

3. Using a sliding window technique the filter is applied on the chosen interval and all the errors in the prediction is stored in the PEFA curve.

During the application of the prediction error filter (PEF) on the data in the sliding window analysis, the error between the predicted value and the actual measured log value is calculated. This application is shown in Figure 3.18. The MEM Prediction model, represented by the prediction filter coefficients in the orange box is used for prediction. The data series in the sliding window (the gray box) is used as input for the MEM prediction model. Each value in the data series is weighted by multiplying the value with a prediction filter coefficient. The predicted value is then obtained by a summation of all the weighted data series values. In the last step the difference between the predicted and the actual measured value is calculated, giving the PEF value. If all the PEF values belonging to each window in the sliding window analysis are integrated in one curve, the PEFA curve is generated.

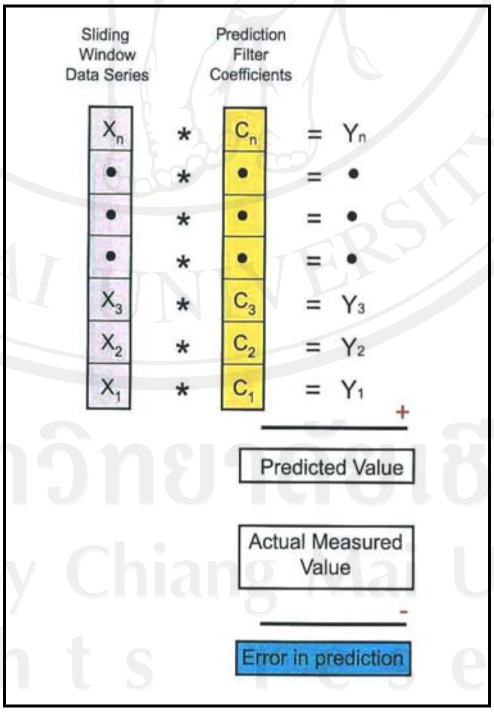

Figure 3.18 Graphical representation of the calculation of a single PEF value (Nio *et al.*, 2006).

Effects of discontinuity

Mathematically, any spectral change is related to a phase jump, an amplitude changes or a frequency change. These spectral changes can be formed by the following processes:

- Missing section of the waveform which geologically can be interpreted as an erosional surface.
- A change in the amplitude of the waveform, which geologically may be related to an important change in lithofacies.
- A change in the frequency of the waveform, which in geology can be related to a lithofacies change or a change in net accumulation rate.

The stratigraphic record is well known to contain numerous hiatuses, at all scales. Stratigraphic discontinuities at all scales can be expected as any combination of phase jumps, frequency changes and amplitude changes. The synthetic data shows PEFA detects these discontinuities (Figure 3.19).

3.4.6. Spectral Trend Attribute analysis (INPEFA)

The integral of the PEFA curve is called Spectral Trend Attribute curve or INPEFA curve (for Integrated-PEFA), and an example is shown below In practice the INPEFA curve is computed from the PEFA values by a numerical integration from the bottom to the top of the interval (Figure 3.20). The INPEFA calculation will then generate the pattern of changes in PEFA values with depth. A predominance of either positive or negative PEFA spikes becomes a positive or negative trend on the INPEFA curve, which is best plotted on a wider than average track in order to fully visualize these trends.

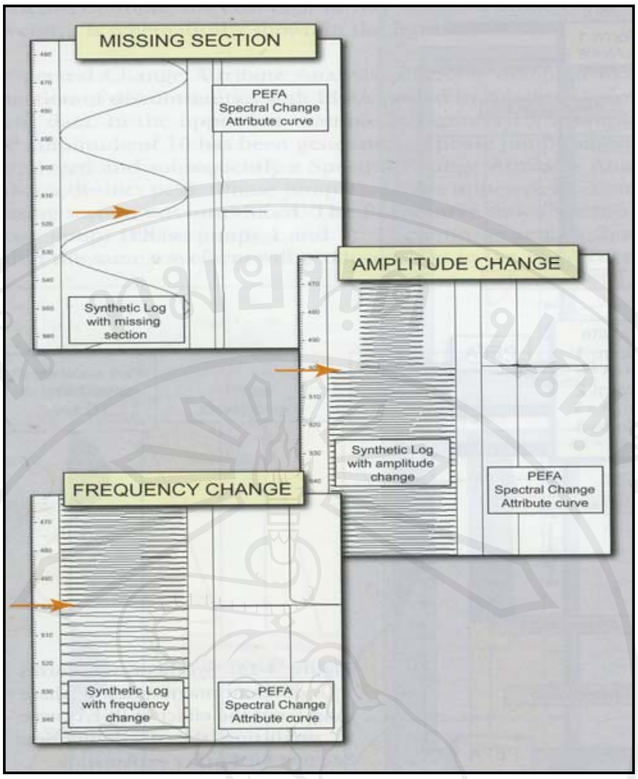

Figure 3.19 Phase jumps produced by missing section, amplitude changes and frequency changes are detected by PEFA (Nio *et al*., 2006).

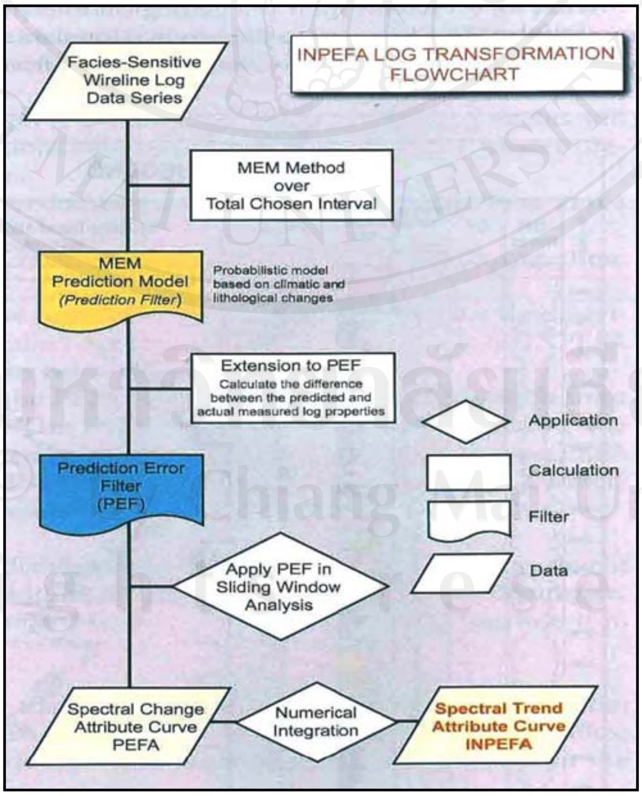

Figure 3.20 Flow chart of the INPEFA log transformation (Nio *et al.*, 2006).

3.4.6.1 The INPEFA trends

In terms of changes in spectral properties:

A negative trend of the INPEFA curve marks an interval in which PEFA values are predominantly negative (see Figures 3.21 and 3.22) and PEFA is seen that a negative error means that the actual measured log value at this depth is larger than the log value predicted by the model for the total log data series. This means that the prediction filter has under-estimated the true value. A succession of predominantly negative PEFA values produces a negative INPEFA trend and means that a consistent under-estimation has occurred.

A positive trend of the INPEFA curve marks an interval with predominantly positive PEFA values. A positive PEFA value means that the actual measured log value at this depth is smaller than the predicted log value. The prediction error filter has over-estimated the true value. In this case a succession of predominantly positive PEFA values produces a positive INPEFA trend. In this case a consistent over-estimation has occurred.

INPEFA Feature		Mathematical Interpretation	Geological Interpretation
Positive Trend	/	Persistent under-estimation of log properties (e.g. values)	Shale-prone or "transgressive" trend
Positive Turning-Point	<		Baselevel rise - "flooding" surface
Negative Trend	\	Persistent over-estimation of log properties (e.g. values)	Sand-prone or "regressive" trend
Negative Turning-Point	>		Low baselevel - possible erosion surface - new influx of coarser clastic PB352-131

Figure 3.21 Interpretation of INPEFA trends and turning points in an alluvial-fluvial setting (De Jong *et al*., 2006).

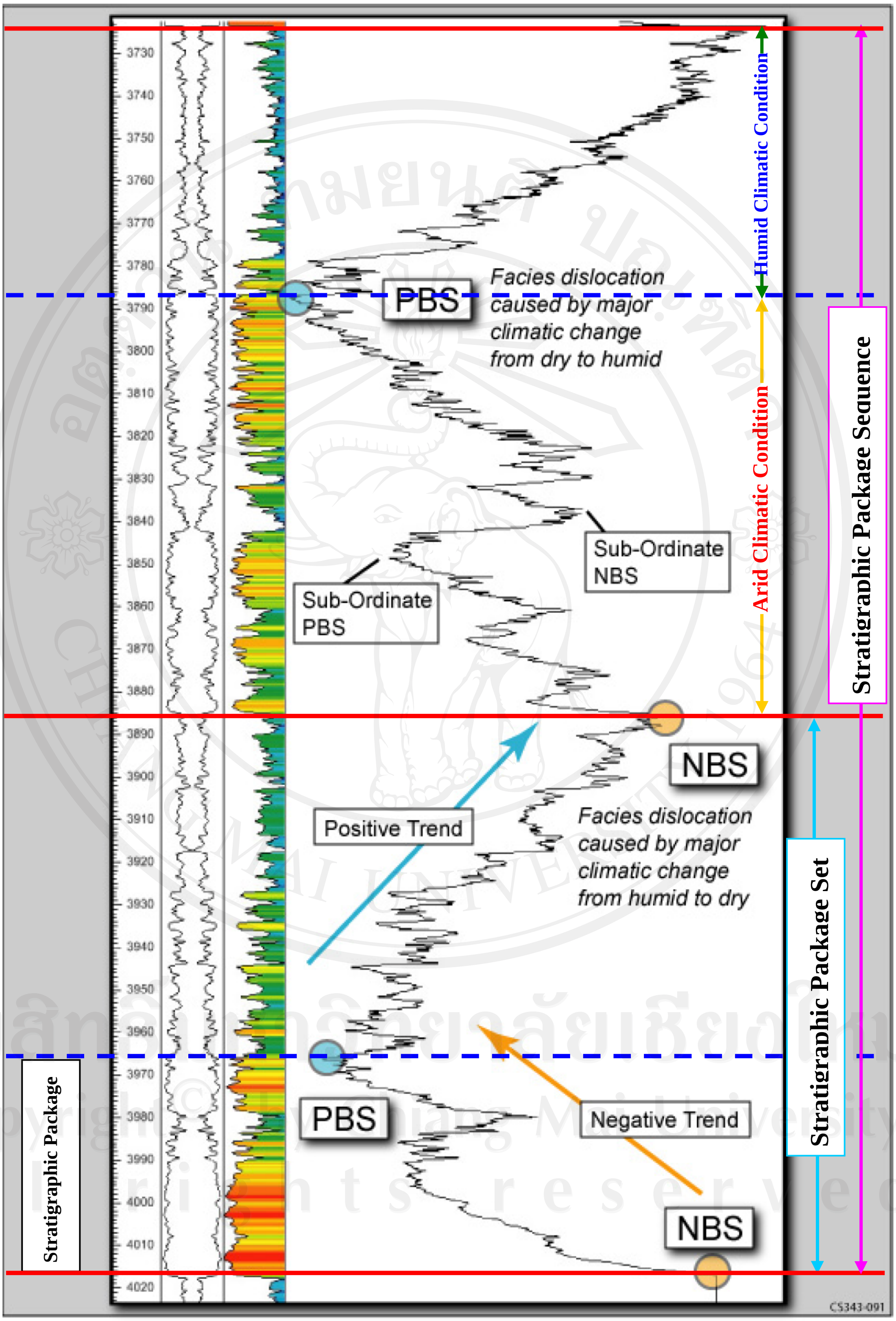

Figure 3.22 Terminology and definitions associated with the interpretation of INPEFA curves (modified from Nio *et al*., 2006).

In terms of lithofacies development in clastic sediments

For where have alternating sandy and shaly lithologies (Figure 3.22):

A negative trend of the INPEFA trend means an upward transition to more sandy values. This means that interval is more sand-prone than predicted or dealing with a cleaning upward trend of the sands.

A positive trend of the INPEFA means an upward transition to more shaly values, or the interval is more shale-prone than predicted.

In terms of lithofacies developnent in carbonate sediments

For where have alternating "clean" carbonates and marl-shale lithologies:

A negative trend of the INPEFA means an upward transition from wackestones to grainstones or boundstones.

A positive trend of the INPEFA means an upward transition to more marly or shaly values.

In terms of geological interpretation for clastic or carbonate depositional facies

A negative trend represents regression, or decreasing water depth or lowering of base level which relate to the arid climatic condition, or decreasing accommodation space, or decreasing distance from sediment source.

A positive trend represents transgression, or increasing water depth or rising base level which relate to the humid climatic condition, or increasing accommodation space, or increasing distance from sediment source.

3.4.6.2 The INPEFA turning points (Figure 3.22)

Intervals of positive and negative trend are separated by turning-points and these are the most important features of the INPEFA curve. All the turning-points are called bounding surfaces. The identification and interpretation of these turning points or bounding surfaces are playing an important role in evaluating facies development and well correlations. In order to keep the terminology as objective as possible, there are using the following definitions (Figure 3.22): - A positive turning-point or Positive Bounding Surface (PBS) is the point at which the trend changes from negative to positive.

A negative turning-point or Negative Bounding Surface (NBS) is the point at which the trend changes from positive to negative. There is a hierarchical order of these bounding surfaces. The main bounding surfaces are separating the main INPEFA trends, while sub-ordinate bounding surfaces are separating shorter or sub-ordinate INPEFA trends. This hierarchal order may be related to the different frequencies of the Milankovitch cycles.

In lithofacies development terms, again assuming that the INPEFA is derived from e.g. a GR log in a section of alternating sandy and shaley lithologies:

A negative turning-point or NBS marks the end of a shaling-up trend, and the beginning of a sand-prone trend.

A positive turning-point or PBS marks the end of a sandy upward trend, and the beginning of a shale-prone trend.

The bounding surfaces in the INPEFA curve are generated from the spectral analysis of the log. They are machine-objective options for stratigraphic interpretations. So in stratigraphic terms the following interpretations can be made.

A major negative turning-point or NBS mostly represents the beginning of a period of renewed sand-influx or progradation. In sequence stratigraphy this can be a candidate for a sequence boundary.

A major positive turning-point or PBS mostly represents the beginning of a shale or fine-grained interval. It also often represents an onlap surface and can be interpreted as a flooding surface.

INPEFA bounding surfaces are not sedimentary facies boundaries. They may, however, coincide with a change in depositional facies or more often with facies dislocations or facies 'jumps". INPEFA bounding surfaces are being formed within a completely different time frame as sedimentary facies boundaries. This method was mentioned earlier that the geological events as it can be seen in the INPEFA curve are in the time ranges of 10 ky to several 100 ky and more. This is why INPEFA bounding surfaces are often marked by sharp contacts at which significant erosion may occur (Figure 3.22).

3.4.6.3 Long-term and short-term Spectral Trend Attribute (INPEFA) curves

INPEFA has the option to analyze a smaller interval, which results in a higher resolution of the climatic change patterns. The principle is that during a shorter time span climatic changes are more pronounced than as within a longer time span because in a longer time span, all the extremes of climatic changes are being averaged effect only the major turning point and trend are obvious.

- The long-term INPEFA was generated based on a prediction filter of the total interval, show a little detail, only the major turning point and trend are obvious. The long-term INPEFA used for the lower order classification (major classification).
- The short-term INPEFA curves were generated with a prediction filter over smaller intervals, show enhanced character and used for the higher order classification (minor classification). Note the differences in the resolution of the patterns of climatic changes.
- The main bounding surfaces, e.g. NBS and PBS, were picked according to the main turning points of the long-term INPEFA. There is no discrepancy between the turning-points in the long-term and short-term INPEFA curves.

A certain hierarchical order can be seen not only in the bounding surfaces, but also in the stratigraphic intervals between these bounding surfaces. The terminology of the stratigraphic intervals between these bounding surfaces can be described as follows;

- A Stratigraphic Packages or StratPac is bounded by a NBS at its base, and by a PBS at the top (Figure 3.22).
- A StratPac Set is bounded by two successive Negative Bounding Surfaces (NBS). A StratPac Set is usually divided into two parts, separated by a Positive Bounding Surfaces (PBS). In clastic sediments with an alternation of sand and shale, the lower part is often sandy while the upper part is more shaley. Often the shale interval is eroded by the subsequent sand interval (Figure 3.22).
- A StratPac Sequence contains a number of StratPac Sets (Figure 3.22).