Integrated sequence stratigraphy using trend logs and densely mapped seismic data

Farrukh Qayyum[1*] and David Smith[1] explore an analytical method that combines the relative lateral continuity of seismic imaging with the greater vertical resolution of well log data to optimize both types of data.

Sequence stratigraphy is most closely associated with the interpretation of seismic data that yields three-dimensional images of regional stratigraphic patterns in the sub-surface (Payton, 1977). Logs have significantly better resolution than seismic data, and – unlike seismic – their resolution does not diminish with increasing depth. However, 'sequence stratigraphic analysis of well log data is neither easy nor unambiguous' (Emery and Myers, 1996). Analytical methods that combine the relative lateral continuity of seismic imaging with the greater vertical resolution of well log data therefore lead to an optimum use of both types of data; we explore one such method in this paper.

In the context of sequence stratigraphic analysis, one of the important attributes of log data is the vertical *trends* in the data: both the make-up of individual systems tracts and their vertical disposition (their stacking patterns) may have characteristic vertical trends (for example in grain-size, bed thickness, etc.) that should be detectable in any log that is suitably sensitive to lithofacies. We start with a brief account of some earlier approaches to log data analysis, followed by a review of relevant aspects of sequence stratigraphy, before introducing the INPEFA transform and its potential for integration with the high-resolution seismically-derived HorizonCube. We illustrate our approach with synthetic data, siliciclastic and carbonate case studies.

Using time-series analysis, well logs are assumed to be composite waveforms. As such, they can be decomposed into sets of periodic functions – used to produce a trend curve representing the high and low frequency cycles. The extraction of trends used in this paper is based on linear prediction, which is related to maximum entropy time-series methods and is further explained in the methodology section.

Methodology

INPEFA logs

INPEFA is an acronym for Integrated Prediction Error Filter Analysis (Nio et al., 2005). An INPEFA log is the numerical integral of a prediction error filter (PEF). Such a filter attempts to predict the value of one data point ahead of a moving window, where the predicted value is the sum of the products of each of the data points in the window with a set of filter coefficients. The coefficients are optimized using a least squares approach, similar to that described in Vaseghi (2008). The prediction error is the difference between the actual and predicted data values. The INPEFA log is the integral of the prediction error log. An example of an INPEFA log is shown in Figure 1, which also shows the prediction errors and the predicted log values; the example is based on the synthetic dataset also used for Figure 4.

Although they are not normally seen in the case of real data, a visible expression of the filter coefficients can be seen in Figure 2, in which extremely simple synthetic data are used for illustrative purposes (in section 3, below). In Figure 2, the filter coefficients are expressed in the oscillations that persist above major 'breaks' for an interval corresponding to the size of the prediction window.

For operational work, the typical prediction window used is 10 m, but the shape of the resulting INPEFA is not sensitive to the exact window length. Also note that INPEFA is typically computed upwards from the bottom of the log. This results in a 10 m 'tail' at the base of the data, representing an interval for which INPEFA cannot be computed.

An INPEFA log may be calculated from an entire data set (a complete well log, for example), or from one or more segments of the data, e.g. for an individual stratigraphic sequence or formation. Because this log is always normalized, calculating it from part of a data set generally increases the apparent variance compared with the same segment of the data in the INPEFA of the full data set. This property of INPEFA is exploited in the hierarchical approach to its stratigraphic interpretation. Note that changing the interval through which INPEFA is calculated can affect the resulting trends; see Figure 3 for an example.

On a cautionary note, the normalization that is inherent in the computation of INPEFA (every INPEFA log is normalized to lie between values of zero and one) means

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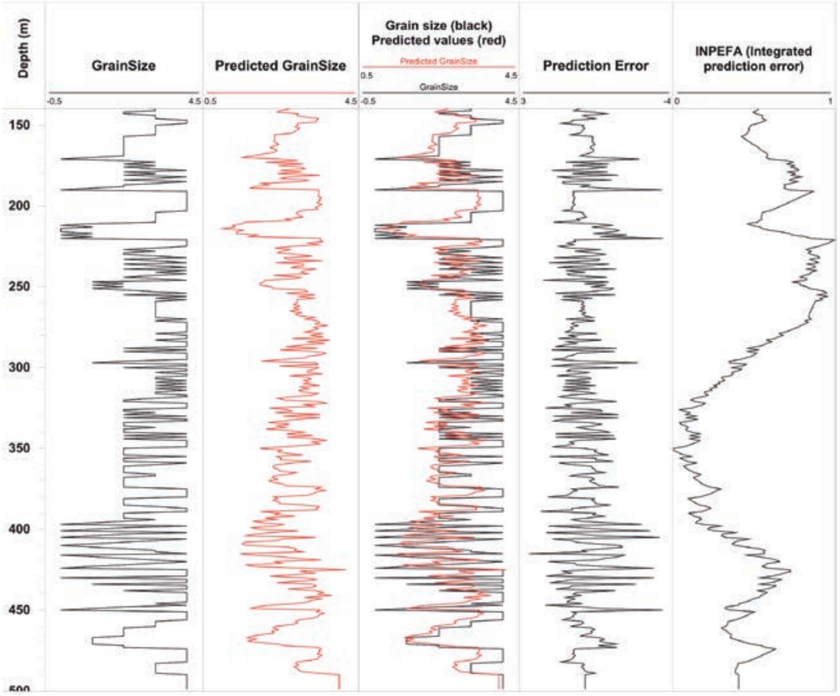


Figure 1 *Derivation of INPEFA from a series of data-points equally spaced in depth. The data (in the first column) is the synthetic grain-sized series also used in Figure 4. The second and third columns show the predicted data values using the Linear Prediction procedure described in the text; in the third column the predicted and actual data-series are overlaid. The fourth column shows the prediction errors (Actual value minus Predicted value), then integrated to give INPEFA (fifth column).*

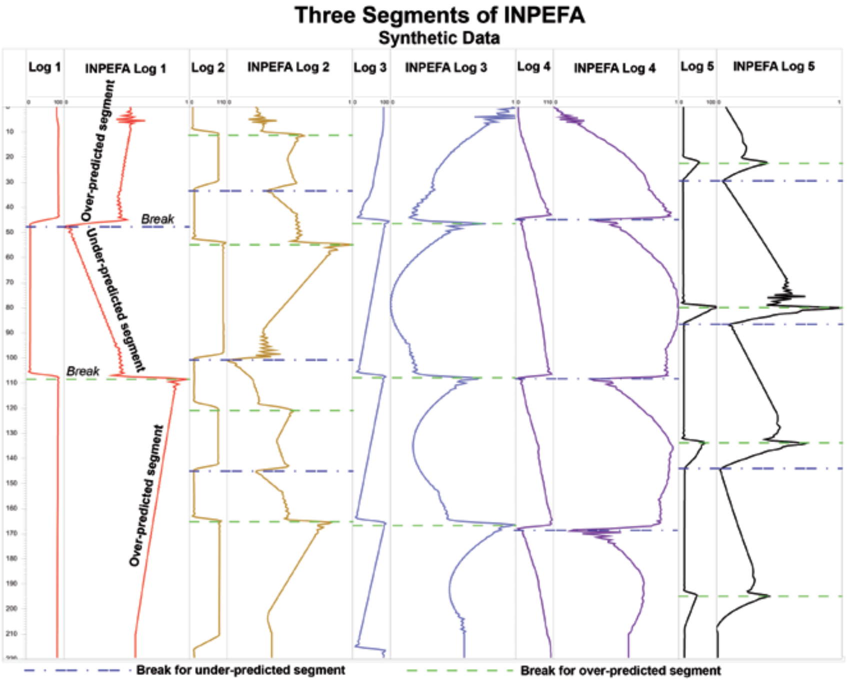


Figure 2 *Typical INPEFA trends and breaks in trend, using highly simplified synthetic examples. Each INPEFA log (1 to 5) is derived from the corresponding input log (1 to 5). Logs 1 and 2: Box-car/ blocky logs give typical over- and under-predicted trends. Logs 3 and 4: zig-zag logs resulting in C- or Inverse C-shaped INPEFA trends. Log 5: smooth log with abrupt changes ('spikes') within a low value background.*

that the local appearance of any segment of an INPEFA log is affected by the range of log values included in its calculation. Unlike the original log values, the value of the INPEFA function at any given depth is only relative and will change if more or fewer data are included in the calculation. Figure 3 shows an example of a segment of data in which part of the INPEFA trend is reversed when a shorter sub-set of the data is processed.

HorizonCube

Introduction

A HorizonCube is a dense set of auto-tracked seismic events used to perform high-resolution sequence stratigraphic interpretation (De Groot et al., 2010; Qayyum et al., 2012). This method aims to map all possible seismic reflectors using computer-aided tracking. It uses a pre-computed dip attribute volume to follow seismic horizons. The tracker is constrained by an initial framework of regional sequence stratigraphic surfaces and major faults, which are mapped conventionally.

There are several ways to compute seismic dips. The amplitude-frequency-based dips advocated by Tingdahl and De Groot (2003) are those preferred for sequence stratigraphic interpretation. Note that fluid contacts, multiples and other unavoidable seismic noise are no less common pitfalls for the auto-tracker than for any other method of seismic analysis.

Wheeler transform

Seismic data are generally displayed in two-way time (TWT). To represent such data in the chronostratigraphic (Wheeler) domain, they must be re-plotted against time. The auto-tracked events are arbitrarily numbered following the superposition principle to establish a Relative Geologic Time (RGT) scale. The seismic data is then transformed from the TWT domain into the Wheeler domain in which the vertical axis is RGT (Qayyum et al., 2014). The seismically derived Wheeler domain is directly equivalent to the original concept of a Wheeler diagram (Wheeler 1958) and to the chronostratigraphic charts of – for example – papers in Payton 1977. An example of a Wheeler plot is included in the clastic case study, below (Figure 5).

Co-visualization

To understand the depositional history of an area, both time and depth domains are best studied together. This co-visualization step allows the interpreter to scroll through the data stratigraphically such that each RGT slice is studied in 3D and the results are integrated with the available higher-resolution well data information. Co-visualization helps in observing and understanding vertical stratal stacking patterns, shoreline variations, accommodation changes and other spatio-temporal changes, towards the establishment of a model-independent sequence stratigraphic framework (Catuneanu et al., 2011).

Geological interpretation

The INPEFA log

INPEFA trends are typically of three types:
a. Over-predicted trend
b. Under-predicted trend
c. A break in continuity

Over- and under-prediction occur where the prediction errors are predominantly positive (negative) (i.e., where the actual value is higher (lower) than the predicted value), leading to an up-to-the-right (up-to-the-left) trend in the INPEFA log. They therefore characterize segments of the data in which the input log values are predominantly high (low) (e.g., Logs 1 and 2 in Figure 2).

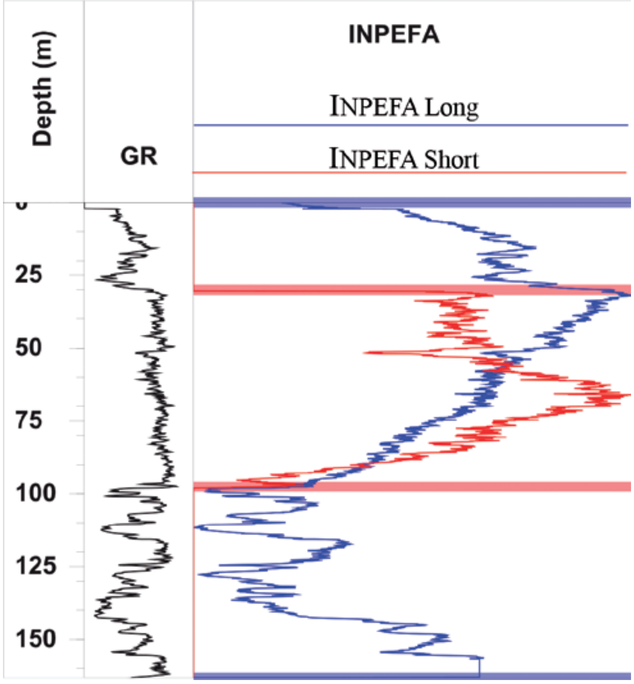


Figure 3 *Reversal of INPEFA trend in a typical GR log. Black: original GR log; blue: INPEFA calculated for the whole log; red: INPEFA calculated for the interval between the horizontal red bars. Note the change of trend in the interval 30-65 m, from up-top-the-right in the long-INPEFA log to up-to the-left in the short-INPEFA log. This can happen where a short INPEFA log is calculated for an interval of quite different mean and variance from that of the longer interval.*

Sharp changes in log value give rise to large prediction errors that are expressed as sharp steps in INPEFA; these are obvious candidates for identification as stratigraphic breaks (Figure 2, Logs 1 to 5).

Standard motifs of the INPEFA log

Blocky (or ‘boxcar’) trends are commonly observable on gamma-ray and (GR) logs. They are found in various depositional environments in both siliciclastic and carbonate settings, for instance, in delta fronts, deep-water fans, alluvial fans, point-bars, carbonate build-ups, etc.

In Figure 2, two blocky logs are shown. Log 1 includes a single thick (>50 m) low-GR interval. Log 2 contains several such intervals of differing thickness. Such patterns give rise to INPEFA logs with alternating over- and under-predicted segments, separated by sharp breaks. Log 3 and Log 4 show funnel/bell shape patterns and their corresponding INPEFA logs. Log 5 contains abrupt changes in a log whose values are mainly clustered around the minimum. The resultant INPEFA also shows sharp changes at those turning points.

For a segment of an input log in which the log value is steadily increasing (‘bell-shape’) or decreasing (‘funnel-shape’), the resultant INPEFA will show a C-shape or an inverse C-shape (respectively) with more or less sharp breaks at the top and base of the log motif (Figure 2, Logs 3 and 4).

If each segment of real log data is thought of as the sum of a simple longer-wavelength motif (blocky, bell- or funnel-shaped) with a more randomly varying and shorter-wavelength component, then it is easy to see that the resulting INPEFA will be the sum of the variable component plus a trend (over- or under-predicted), with breaks in the INPEFA log marking sharp changes in value at changes in log motif.

Low/high frequency trends

To further explain low- and high-frequency INPEFA trends, we use another synthetic example (Figure 4). This series of coded values simulates a grain-sized series measured at outcrop. Lower and higher values (on a scale of 0 to 4) represent coarser and finer grain size respectively, such that the dataset resembles a typical GR log. The INPEFA log of this synthetic dataset comprises three low-frequency (low-order) segments. The relative abundance of lower-than-average values in the upper and lower segments pulls the curve steadily over to the left. In the middle segment, a greater number of higher-than-average values pull the curve to the right. The main breaks in trend at this first-order level are at (a) a sharp influx of coarser material at 220 m, and (b) a change from dominantly coarser grain size below to dominantly finer above at 350 m. Within these long low-frequency trends, higher-order patterns also contribute towards a sequence stratigraphic interpretation of the data. For example, within the overall up-to-the-left trend in the upper 220 m of the data, repeated influxes of coarser sand pull the INPEFA log sharply to the left. At the top of each of these higher units, the trend is pulled back to the right by the interbedding of finer-grained layers. These can be interpreted as fourth order units.

Transgressive-regressive trends

It is important that the log being used is responding primarily to stratigraphically significant properties of the strata. For this reason the GR log is very often the first choice, being widely available (even for legacy data), and because its response is more closely controlled by lithology than by (say) porosity or fluid-type. In cases where the GR response is non-standard (conglomerates, high-GR sands, low-GR shales, etc.) the GR-INPEFA log must be interpreted with appropriate care and understanding. In such cases, it may be possible to use INPEFA derived from other logs (SP, acoustic, resistivity etc.).

Our synthetic grain-sized dataset in Figure 4 is used to illustrate the geological interpretation of the INPEFA trends. Of the lower-order trends in this dataset, the upper and lower under-predicted (up-to-the-left) segments are sand-dominated, whereas the middle over-predicted (up-to-the-right) segment is shale-dominated. So, in this dataset, the under-predicted INPEFA trends might suggest overall regression, while the middle, over-predicted trend might be interpreted as (relatively) transgressive.

Therefore, the major *changes* of trend may be candidates for important stratigraphic surfaces. The change from over- to under-prediction at 220 m might be a candidate sequence or parasequence boundary; while the opposite change of trend around 350 m might represent a transgressive (flooding) surface. Similarly, the repeated motif of sharp-based sand overlain by shale-sand interbeds above 220 m might be interpreted as parasequences within a first-order parasequence set. Such interpretations are more secure if tied to a seismic grid, as in the real examples that follow, but INPEFA logs can be used to suggest a standalone interpretation if no seismic data are available. We suggest that the two sequence stratigraphic surfaces for which INPEFA might be most indicative are the Maximum Flooding Surface (MFS) and the Maximum Regressive Surface (MRS).

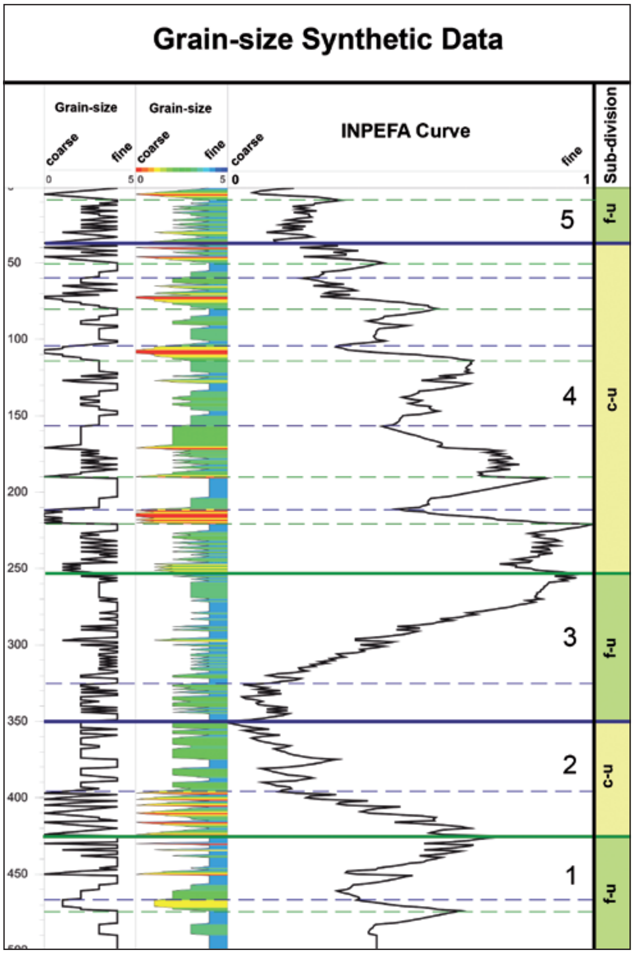


Figure 4 *INPEFA calculated from a synthetic grain-size data series. The data (columns 1 and 2) code – on a scale of 0 to 4 – for clastic sediment grain-size (coarse to fine, as in a GR log). A standalone INPEFA analysis divides this example into coarsening-up (under-predicted) or fining-up (over-predicted) intervals with breaks at the solid horizontal bars. The dashed lines represent candidate breaks at the next higher order of resolution.*

In terms of sequence stratigraphic principles and using the GR log as the standard for interpreting INPEFA logs, we suggest that (see also Log 1 in Figure 2):

- An over-predicted segment may approximate a transgressive-equivalent trend or a rise in base level;
- An under-predicted segment may approximate a regressive-equivalent trend or a fall in base level;
- The break between the over-predicted (below) and under-predicted (above) segments may be a candidate MFS;
- The break between the under-predicted (below) and over-predicted (above) segments may be a candidate MRS.

We stress that surfaces such as MFS and MRS cannot be securely picked from a single well or without integration with seismic data.

Case study examples

Siliciclastic example (The Netherlands, Pliocene)

In this example, the available 3D seismic data cover an area of 380 km^2. Information (well logs, mud logs, time-depth information, biostratigraphy etc.) is also available from several wells, of which F02-01 and F03-02 are used here. The objective was to investigate the transgressive-regressive nature of the Pliocene interval, and to build an integrated sequence stratigraphic framework (Qayyum et al., 2012).

Interpretation

In Figure 5 the INPEFA transforms of the two wells are shown against an arbitrary seismic transect through the HorizonCube. The line is also shown transformed into the Wheeler domain, which emphasizes the time gaps between mapped surfaces; it also shows the depositional trends.

The Pliocene interval can be broadly sub-divided into three distinct intervals based on the observed stratal stacking pattern.

Lower interval (Base to SU-1)

In this relatively thin interval, an overall coarsening-upward succession in the more distal well (F02-01) contrasts with an aggradational to back-stepping succession in the proximal well (F03-02). The top of this succession is defined by a regional surface (MFS-1) above which the strata prograde. It also defines the end of transgression and the onset of early normal regression (NR).

The Early NR-1a succession contains mostly sub-parallel geometries, representing an aggradational stage with relatively low sediment influx. The classic clinoform shapes of the succeeding Late NR-1a stage represent an increase in sediment influx. The entire interval is well-developed around F03-02, where the INPEFA logs mainly show an aggradational character. The shoreline trajectory of the NR-1a stage shows aggradational to progradational stratal stacking patterns. The top of this unit is defined by a composite surface i.e., subaerial unconformity (SU-1) and a correlative conformity (CC*) lying at the base of the overlying unit. As the underlying surface is a maximum flooding surface (MFS-1) with no significant hiatus, NR-1a can be considered as a highstand systems tract (HST-1).

The NR-1a stage is followed by a forced regression (FR-1) during which the topsets of earlier formed clinoforms are eroded. The shoreface becomes detached and offlapping stratal stacking patterns are formed; this is particularly obvious in the Wheeler diagram. The INPEFA log motifs are not correlatable for this interval. The end of this stage is marked by another composite surface i.e., SU-1+CC. This already shows that the hiatus between the HST-1 to FR-1 is significant as highlighted in the Wheeler diagram (Figure 5).

The base-level starts rising and a younger normal regressive stage (NR-1b) is formed. More sediments fill the basin while the proximal locations remain exposed. This unit is also not recognizable on the INPEFA logs as it is developed away from the proximal locations. Only the distal well (F02-01) shows a small-scale drift towards regression, which is below seismic resolution at this location. The top of this stage is defined as a maximum regressive surface (MRS-1). The upper segment of this surface is affected by seismic multiples which are apparently tracked by the HorizonCube also. This is highlighted on another random line extracted from the same dataset (Figure 6). The progradational nature (as clinoforms) of the system continues even above the multiple, which suggests that the entire unit above the FR-1 is mostly of a regressive nature (Figure 6c). The slopes of these clinoforms are affected by multiples making it difficult to distinguish between onlap and transgression. As this stage follows the underlying falling stage, it can be considered as a lowstand systems tract (LST).

Middle interval (SU-1 to MRS-2)

Following a rise in base level one may expect transgression over the coastal areas. However, considering the multiples, the clinoforms (Figure 6), and the seismic resolution, the transgression remains apparent or poorly resolved. On the other hand, the INPEFA logs show a subtle transgressive trend. However, this could be cryptic for the F03-02 well as here the log motif appears as an inverse C-shape, which may not be a true depositional shift (see the earlier discussion of INPEFA shapes). Therefore, the interpretation of the unit above FR-1 remains partially unclear. This can only be resolved if the data is reprocessed successfully or new well data becomes available.

Another normal regressive stage (NR-2) is recognized across the study area, with fluvial aggradation and shallow-marine progradation. The end of base-level fall is marked by MRS-2. The entire NR-2 stage is characterized by a common-regressive-INPEFA trend.

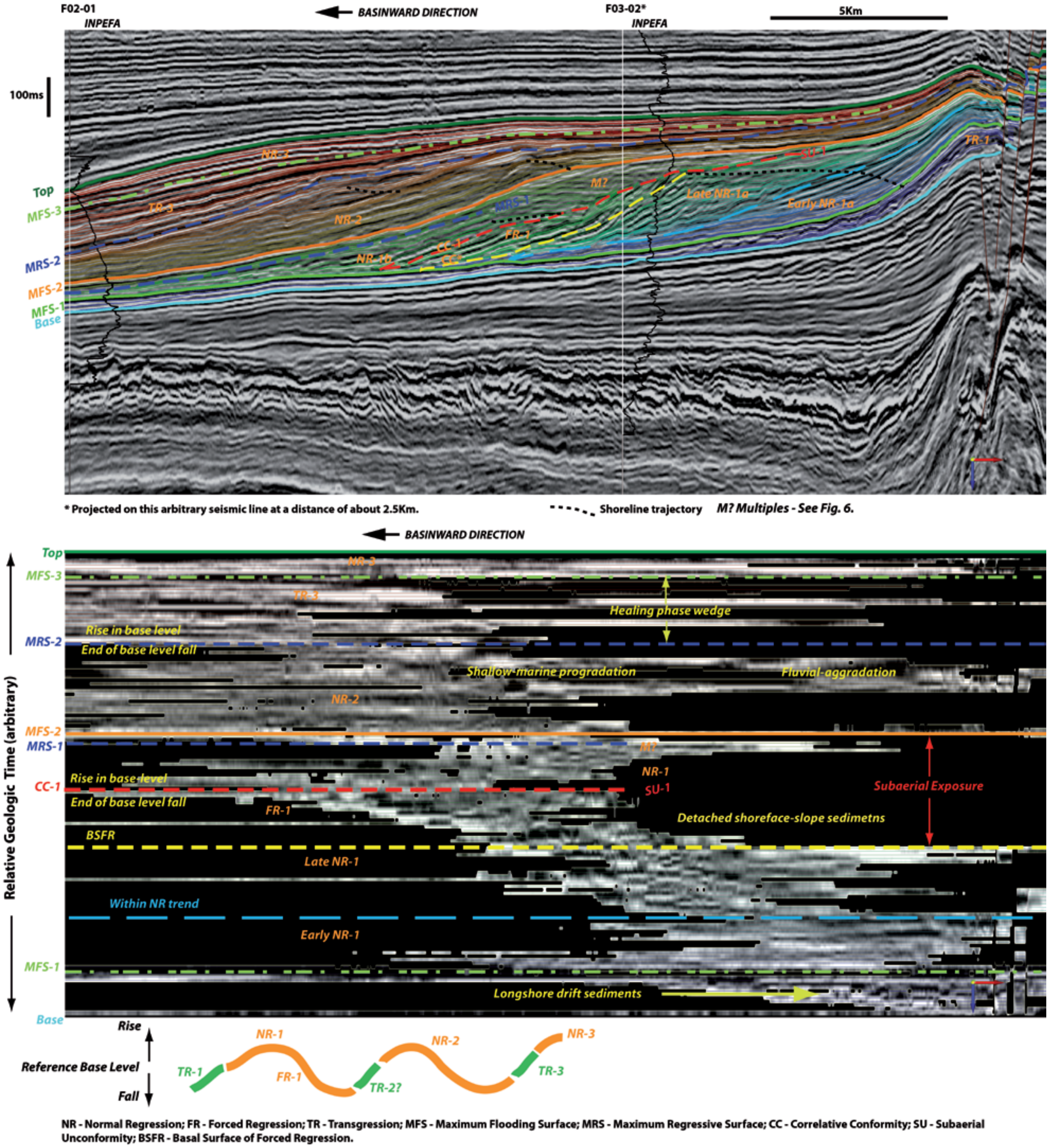


Figure 5 *Clastic case study (Pliocene, offshore The Netherlands): seismic-to-well integration of INPEFA logs and HorizonCube (colour-coded lines in the upper figure). Upper image: A structural view of an arbitrary seismic line passing through the F02-01 well and close to the F03-02 well, which is projected on to this line. Lower image: The same line is transformed into the Wheeler domain, emphasizing the spatio-temporal nature of each HorizonCube event.*

Upper interval (MRS-2 to Top)

Above MRS-2, marking the end of regression, the strata of TR-3 show onlapping stacking patterns; INPEFA logs contain an under-predicted interval in the distal locations. In the proximal area – a region of fluvial to shoreface deposition exemplified here by F03-02 – the INPEFA log shows a fining-upward trend. This pattern, combined with onlapping stratal stacking, helps to identify this succession as transgressive. However, the distal INPEFA is of coarsening upward trend because the shoreface, beach and longshore drift deposits have been transported and re-deposited downslope. This is considered as being equivalent to a healing phase (Posamentier, 1993).

During this stage, the sediments derived from transgressive erosion are re-deposited as back-stepping barrier beaches. This wedge is overlain by another normal regressive unit (NR-3).

This study clearly shows the importance of stratal stacking patterns in sequence stratigraphic interpretation, greatly assisted by the use of Wheeler diagrams and with INPEFA logs that are better appreciated when seen against the backdrop of the HorizonCube.

Carbonate example (Middle East, Cretaceous)

The objective here was to build a sequence stratigraphic framework of the carbonate-dominated Mishrif Formation (mid-Cretaceous) by studying INPEFA motifs to add to the facies-based correlation achieved by Burchette and Britton (1985).

The Shilaif Formation is mostly dominated by mudstones and shales. The Mishrif Formation is characterized by grainstones, rudist reefs, and slope deposits. It includes a wide variety of facies (Burchette and Britton, 1985), summarized in Table 1.

Interpretation

The Shilaif and Mishrif intervals are correlated among six wells using the INPEFAs derived from the GR logs. The

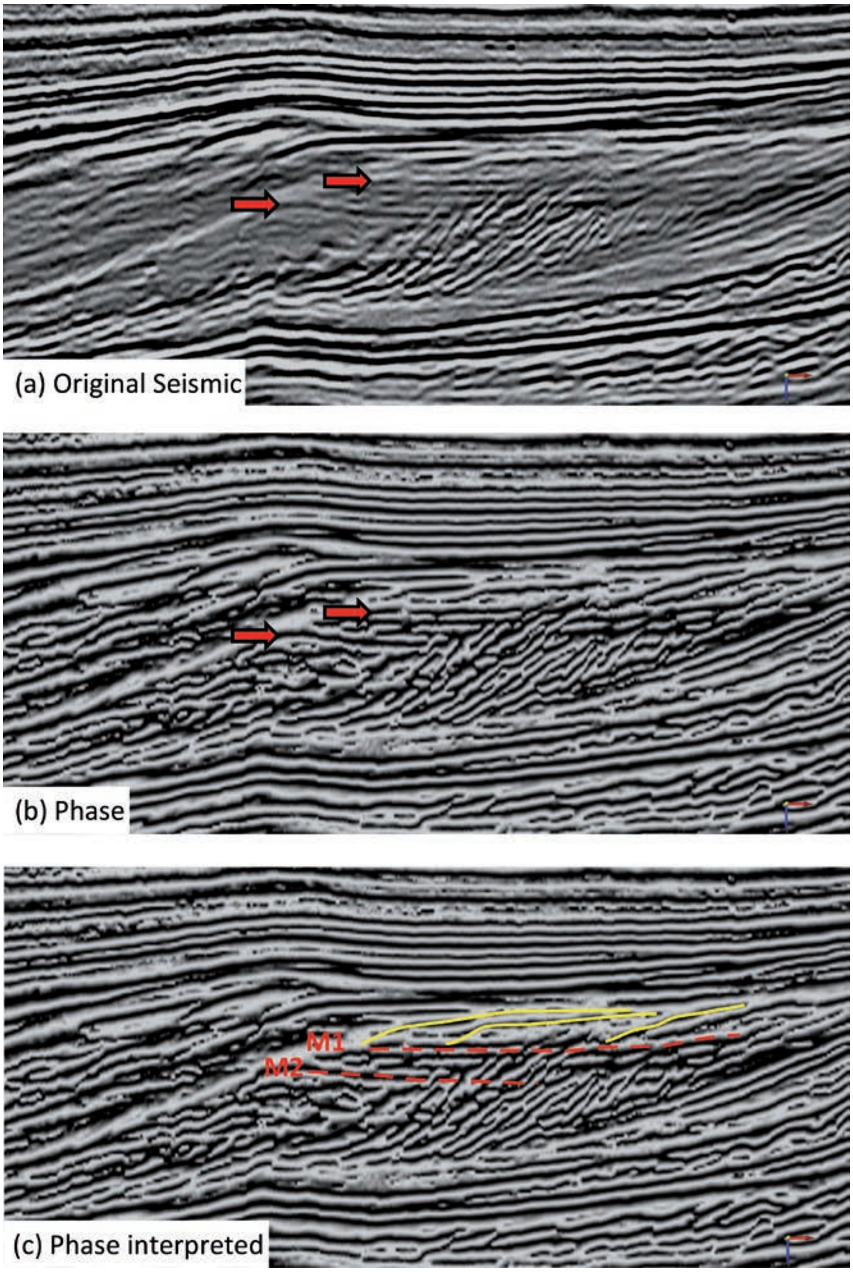
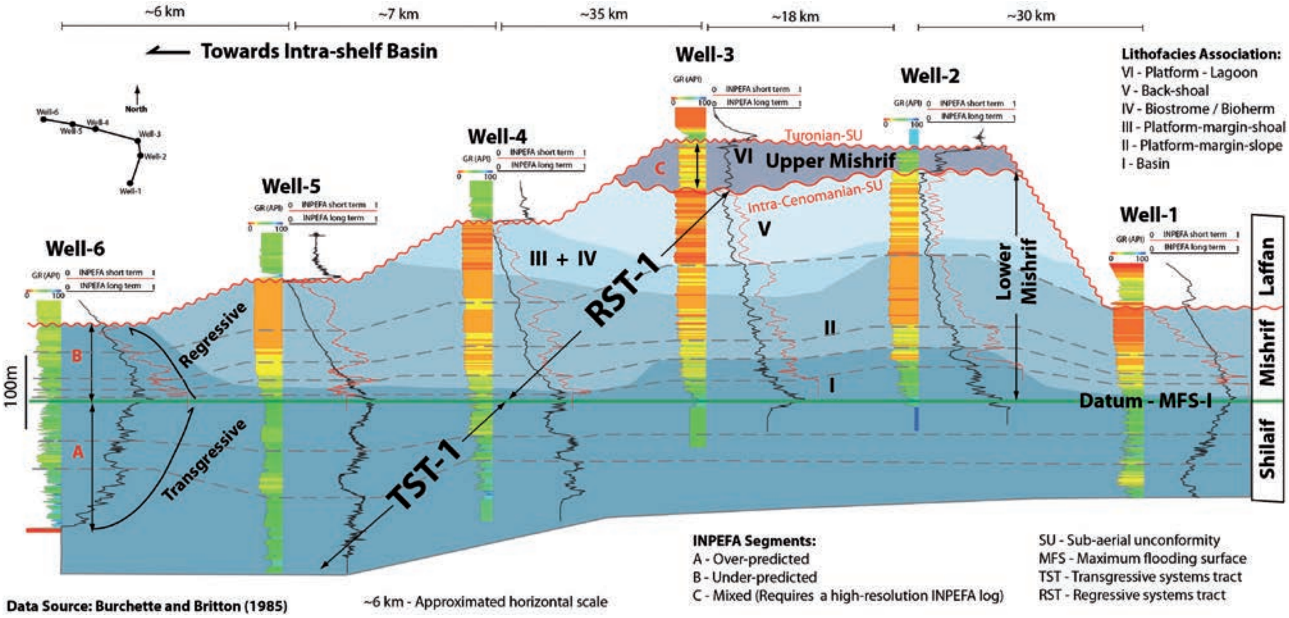


Figure 6 *Another random line is presented to show the seismic multiples appearing as onlaps. It is extracted from the same 3D seismic data of F3 block. (a) Input seismic data for the HorizonCube results; (b) un-interpreted instantaneous phase attribute; (c) interpreted phase attribute. The arrows mark the multiples. The slope margin of the NR-1b is affected by seismic multiples (dashed lines i.e. M1 and M2) that apparently show an onlapping character on the results. The seismic phase attribute signifies the geometries of these multiples. It also shows the clinoform patterns above the M1. This confirms that most of the stratal geometries are prograding and the apparently onlapping reflections are multiples.*

Lithofacies Association	Lithology	Biota
VI (Platform-Lagoon)	Indistinctly-bedded, burrow-mottled, benthonic-foraminiferal and peloidal mudstones and wackestones.	Benthonic foraminifera: Dicyclina, Orbitolina, Ovalveolina, Praealveolina, Valvulammina picardi, Nezzazata conica, Pseudochrysalidina. Ostracodes, uncommon molluscs. Burrowers.
V (Back-shoal)	Interbedded, fine to very coarse grained bioclastic packstones, wackestones and grainestones.	Abundant Chondrodonta, scattered radiolitid rudists. Burrowing organisms.
IV (Biostrome/Bioherm)	Unbedded, extremely coarse, shelly bioclastic packstones.	Rudists: Praeradiolites sp., Radiolites sp., Sauvagesia sp., uncommon caprinids and monopleurids. Other molluscs: Chondrodonta, Tylostoma. Corals: Cladophyllia (rare). Uncommon benthonic foraminifera and echinoids.
III (Platform-margin shoal)	Unbedded, medium to very coarse grained bioclastic packstones and grainstones.	
II (Platform-margin slope)	Coarsens upwards from well-bedded, bioturbated silt-grade bioclastic packstones to poorly-bedded medium-grained bioclastic packstones.	Bivalves: Lima semiornata, Lithophaga sp., Plagiostoma sp., Argerostrea sp., burrowers.
I (Basin)	Well-bedded, locally bioturbated, stylolitized, silt-grade bioclastic packstones and wackestones.	Oligostegina; pelagic foraminifera; rare Placunopsis and Exogyra; uncommon burrowing organisms.

***Table 1** Mishrif Formation: lithofacies, lithologies and biota as interpreted by Burchette and Britton (1985).*



Data Source: Burchette and Britton (1985)

***Figure 7** Carbonate case study (Cretaceous, Middle East): lithofacies associations, INPEFA, and sequence stratigraphic interpretation of a 6-well transect across the Mishrif Formation (Cenomanian-E. Turonian) shelf. Logs are GR, colour-classified from red/orange (low values) to green/blue (higher values). Black log: long-INPEFA; red log: short-INPEFA (restricted to the Mishrif interval). For further details of lithofacies associations see Table 1.*

stratigraphic section (Figure 7) is flattened on a distinct break in the INPEFA logs, which separates the underlying Shilaif Formation from the overlying Mishrif Formation. The area that includes wells 1 to 4 can be considered proximal, while Well-6 is in a more distal location. No seismic data were available for this study.

The INPEFA logs clearly divide into three segments. These are separated by sharp breaks in most of the wells

(Figure 7); note that the corresponding contact for the lower break (Datum – MFS-1) is a much more gradual contact on the input GR logs.

Based on the INPEFA logs, the lower segment (A) – with an over-predicted (up to the right) INPEFA trend – is interpreted as a back-stepping system. This interval also contains some smaller scale regressive-equivalent intervals superimposed on the overall transgressive trend (e.g. Well-6 and Well-4). The low-resolution trend (which appears consistently in three wells) is mostly retrogradational to aggradational in nature; the entire system is therefore considered to be a Transgressive Systems Tract (TST).

The middle segment (B) – with an under-predicted (up-to-the-left) trend – is interpreted as regressive. The internal correlation suggests a broad stratal stacking pattern of aggradational to progradational nature. For some wells (e.g. 5 and 6) the INPEFA trend is quite clean, suggesting amalgamation of successive shoaling-up trends, whereas wells 2 and 3 show more clearly the internal structure of the regressive system. These wells can also be locally correlated and further subdivided after performing the high-resolution interpretation.

The upper segment (C) is identifiable only in wells 2 and 3, and is difficult to correlate in any further detail between these two wells; the interval is too thin for INPEFA logs to be of much help.

In terms of sequence stratigraphic interpretation, the Mishrif and Shilaif Formations form a composite sequence on the interpreted well logs. The entire succession is developed within an approximate time scale of 6 Ma and can therefore be considered as third-order in scale. Based on the studied wells, it is sub-divided into two transgressive-regressive (T–R) sequences: Sequence-1 (equivalent to A + B of the INPEFA interpretation) and Sequence-2 (equivalent to C). A proposed chronostratigraphic chart is presented in Figure 8 with annotated sequences, interpreted INPEFA logs, and the facies assemblages from Burchette and Britton (1985). The two sequences are separated by a distinct sub-aerial unconformity (Intra-Cenomanian SU, see also Figure 7), seen only in wells 2 and 3. Elsewhere, Sequence-1 appears to be lost to erosion at the Turonian Unconformity (Turonian SU, see also Figure 7).

In this study, analysis of the INPEFA logs has led to a sequence stratigraphic framework within which the earlier facies interpretation can be (a) better understood, and (b) used more predictively. The study shows what may be achievable with INPEFA in the absence of seismic.

Discussion

We summarize some of the key advantages of the co-application of INPEFA and high-resolution seismic data for the sequence stratigraphic interpretation of exploration datasets.

Results

INPEFA is routinely used, often in the absence of seismic data, as a tool for well-to-well correlation. With high-quality seismic data and the HorizonCube approach, it is possible to track large numbers of horizons, increasing the resolving power of the data towards that of well logs. INPEFA works in the opposite direction by helping to reveal the lower-frequency patterns in log data in which such patterns can otherwise be obscured by the higher-frequency detail. With the combination of HorizonCube and INPEFA, the resolution gap between seismic and well logs can be narrowed, if not eliminated.

While not reliably identifying all types of sequence stratigraphic surface (as our case studies show), INPEFA can

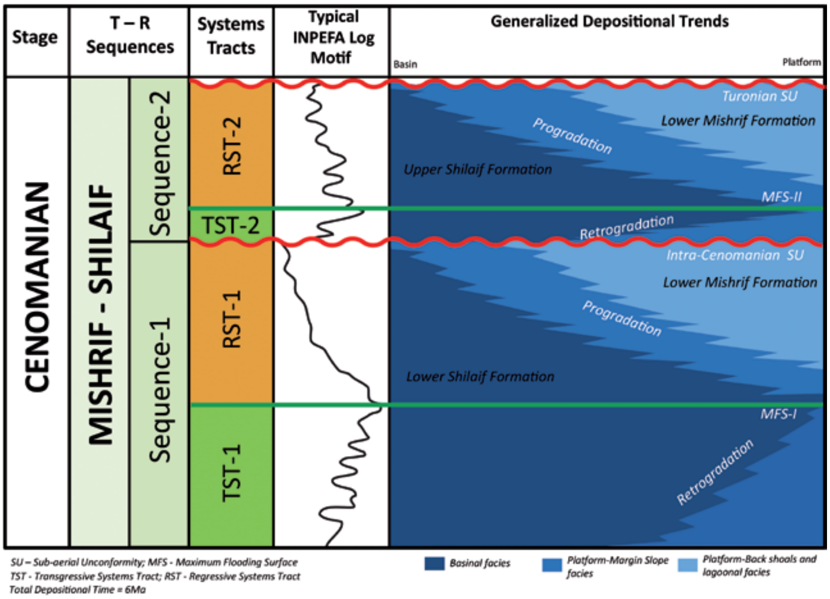


Figure 8 Chronostratigraphic chart of the Mishrif Formation of the Middle East along with a typical INPEFA log motif. The chart is the result of integration of the INPEFA interpretation (Figure 7) and the earlier work of Burchette and Britton, 1985.

certainly indicate the key maximum flooding and maximum regressive surfaces, from which the fundamental T-R patterns can be deduced. Within this framework, TWT and RGT-based displays of HorizonCube information can be used to complete the sequence analysis. Such integrated analysis can have significant applications for exploration and development, concerning not only reservoirs and seals (for which the discrimination of transgressive and regressive systems tracts may be enough) but also for predicting stratigraphic traps. The identification of INPEFA breaks, and their 3D extension through the HorizonCube, may also yield important conclusions for field development.

Pitfalls and caveats

There are a number of caveats to be considered:

- The interpretation of INPEFA is contingent on an understanding of the geological (and especially the stratigraphic) significance of the original log data.
- Due to the normalization built into the INPEFA calculation, a single outlying data-point – a 'spike' – can have a disproportionate effect on the shape of the INPEFA log.
- The stratigraphic record is discontinuous at all scales, and its representation as a continuous function (which is what well logs appear to do) can be dangerously misleading.
- It is rarely possible to build a reliable stratigraphic framework from INPEFA alone; starting from known regional unconformities (and calculating INPEFA for the intervals between such markers) is a better way forward.
- INPEFA trends can often be interpreted as retrogradational or progradational. Aggradational trends are also preserved but are significantly less evident: an overpredicted segment may represent an aggradational trend, but under different circumstances may represent either a progradational or an aggradational trend.
- The HorizonCube is vulnerable to non-stratigraphic effects, such as reflection multiples and other sources of noise.
- Seismic resolution is not equal to well resolution, hence not all surfaces will be identifiable on both datasets. These gaps must be bridged by careful observation and interpretation.
- Finally, all global seismic interpretation solutions (Hoyes and Cheret, 2011; De Groot, 2013) are a result of autotracking and can go wrong in complex geological settings (e.g., too much channelization, extensive faulting, salt tectonics etc.).

Conclusions

HorizonCube helps in seismic mapping and understanding the stacking patterns in 3D while INPEFA helps in extracting vertical trends. HorizonCube-based Wheeler diagrams work with INPEFA logs to help in establishing a unified stratigraphic framework.

Conventional sequence stratigraphic analysis depends primarily on seismic data, whether 2D or 3D; well logs can be more difficult to analyse because of high-frequency information which can obscure the longer-wavelength/lower-order information relevant to sequence analysis.

Together, the co-application of INPEFA and high-resolution seismic data can have a crucial impact on sequence stratigraphy and the interpretation of exploration datasets. This article is the first published account of how this can be achieved.

Acknowledgements

INPEFA logs and some figures were generated using CycloLog (ENRES International); we would also like to thank dGB Earth Sciences and members of the SSIS Consortium, and Paul Fisher (Axiom Communications) for editorial assistance.

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