Subsurface Correlation in the Upper Carboniferous (Westphalian) of the Anglo-Dutch Basin Using Climate Stratigraphic Approach

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Subsurface correlation in the Upper Carboniferous (Westphalian) of the Anglo-Dutch Basin using the climate stratigraphic approach

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Introduction

The Upper Carboniferous play in the Anglo-Dutch offshore continues to be a challenging exploration target, as well as providing a significant portion of the region's existing gas production. Despite the application of various techniques, a secure genetic stratigraphic framework, applicable at field as well as regional level, has continued to be elusive. This paper presents such a framework, using only routine wireline log data supported by the limited amount of published stratigraphic information.

In addition to their conventional properties, wireline logs conceal information encoded in their waveform properties. Treated as complex waveforms, logs are amenable to a range of 'time-series' analytical methods. Applying the concepts of *global cyclostratigraphy* (Perlmutter et al., 1990, 1998), so-called *spectral trend* (or INPEFA) curves, which show uphole changes in the waveform properties of the data, are used to generate a framework of near-synchronous well-to-well correlations.

Using this approach, we have subdivided the top part of the Carboniferous succession – essentially the Westphalian – into nine first-order stratigraphic packages, W1000 to W9000 from bottom to top. Most of these packages can be further subdivided into second-order packages, and some of these into third-order packages, taking the resolution of this scheme down to a few tens of metres, or even to a few metres. These packages have been identified in a total of over 50 wells in the offshore UK and offshore Netherlands sectors.

Comparison with the limited information publicly available on previous stratigraphic classifications indicates that our scheme is far more widely applicable, and probably considerably more reliable than any other previously attempted at the regional scale. Also, the scheme has the potential for further subdivision, to the limit of resolution of the log data, at the local (field/reservoir) scale. As our subdivisions are inherently time-related, they will now serve as the most appropriate framework within which to understand basin paleogeographic development, and the distribution of reservoir and seal facies within the Upper Carboniferous.

The purpose of the paper is two-fold. First, we present our stratigraphic scheme and the method of climate stratigraphy upon which it is based. Second, we show how systematic application of this method in well-to-well correlations leads to the identification of important intra-formational unconformities.

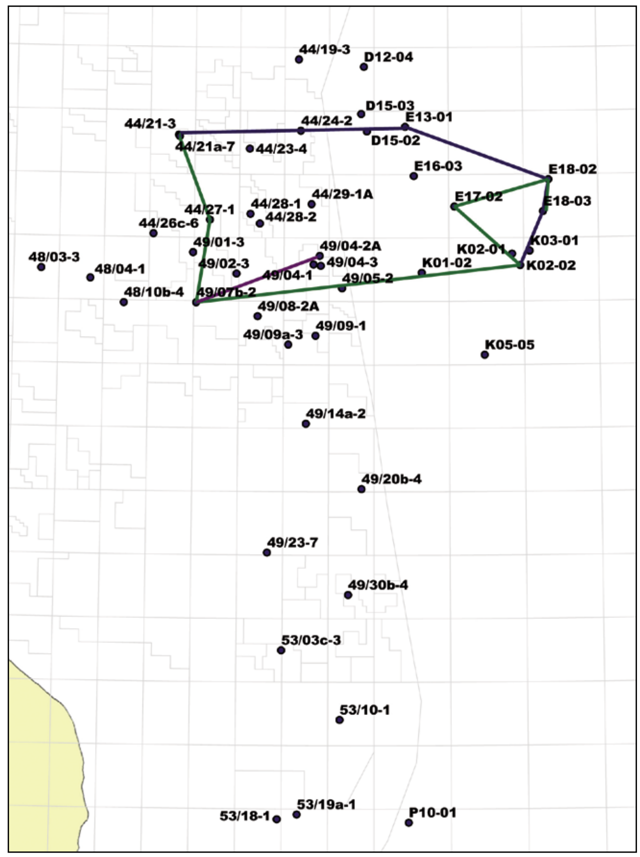

Figure 1 *Location map of the wells used in the present study. UK coastline shown for reference in lower left corner. Violet line – wells correlated in Figure 3; green line – wells correlated in Figure 4; indigo line – wells correlated in Figure 5.*

Geological background

The thick and lithologically monotonous Upper Carboniferous succession of the southern North Sea (SNS) 'has created a set of subsurface correlation problems that differ from any previously encountered in the North Sea' (Besly, 1998). The

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Westphalian succession, up to at least 1300 m thick, comprises fluvio-deltaic sandstones, siltstones, shales, and coals, the latter being important as the main source rock for the province's gas reserves. The difficulties of correlation in the Carboniferous are compounded by the variable extent of the erosion of the top of the succession beneath the Variscan unconformity.

Stratigraphic practice in the SNS Upper Carboniferous has evolved from a purely lithostratigraphical approach (Cameron, 1993), towards the integration of a range of methods including biostratigraphy, marine-band identification, and chemostratigraphy as advocated by the GdF/Conoco group (Spencer et al., 2004). The latter authors emphasized the critical importance of achieving a reliable chronostratigraphic framework within which to construct high quality depositional models. No single approach has yet yielded a consistent framework applicable across the entire basin. The following paragraphs summarize the methods that have been applied.

Lithostratigraphy. Lithostratigraphic schemes have been formalized for the UK sector by Cameron (1993), modified by Besly (2005), and by van Adrichem Boogaert and Kouwe (1995) for the Netherlands sector (Table 1). As initially set up, these schemes were strictly lithostratigraphic, defining formation boundaries on potentially diachronous criteria such as highest coal or lowest sandstone. Besly's modifications, which mainly concern the higher part of the Westphalian, rely in part on interpretations of climate change and sediment provenance, thus adding a greater degree of time-significance to successive units and their boundaries. Besly's scheme has been adopted by Shell (Moscariello, 2003) and is increasingly widely accepted in the industry.

Biostratigraphy. The principal biostratigraphic method available is palynology, which can be applied to cuttings as well as core samples. The development of a palynological zonation specific to the Carboniferous of the North Sea has been described by McLean et al. (2005). Seven zones and fifteen subzones are defined for the Westphalian, based mainly on the first downhole occurrence of key taxa. A limited number of zone/subzone boundaries have been tied to the goniatite-bearing marine bands that define the chronostratigraphic subdivisions (A, B, C, D) of the Westphalian. The resolution of palynostratigraphy is acknowledged to be less precise than that of the goniatites (which are only rarely available in sub-surface material), and it is least applicable in the important 'Barren Red' facies at the top of the Westphalian.

UK (north) - Cameron 1993			UK - Bessly 2005		Netherlands - Cleaver Bank High
SCHOONER FORMATION	KETCH MEMBER	Upper	BOULTON FORMATION		STEP GRABEN FORMATION
		Lower	KETCH FORMATION	Upper	HOSPITAL GROUND FORMATION
				Lower	
	Lower Schooner Unit		CLEAVER FORMATION	Upper	MAURITS FORMATION
				Lower	
WESTOE COAL FORMATION			WESTOE FORMATION		
CAISTER COAL FORMATION			CAISTER FORMATION		KLAVERBANK FORMATION

Table 1 *Summary of lithostratigraphic schemes for northern UK sector and Cleaver Bank High area of Netherlands sector.*

Sequence stratigraphy. Seismic resolution is poor in the SNS, and this and the monotonous nature of the succession have combined to make a standard sequence stratigraphic approach more or less impossible to achieve. Multidisciplinary approaches have been more successful (e.g. Hollywood and Whorlow, 1993; Quirk, 1997) but no one has claimed to have succeeded in establishing a scheme that applies to the entire region. Quirk used a combination of seismic character, log data, and palynological data to divide the Westphalian into 6-7 sand-rich and 6-7 mud-dominated units, each of the order of 50-150m thick, but his scheme was tested only in the southern half of Quads 44 (UK), and Quads D, E, and northernmost J and K (NL). More recent work with chemostratigraphy (see below) has suggested that sand-prone and shale-prone units can be laterally equivalent to each other and do not make a good basis for correlation.

Cole et al. (2005) have recently proposed a log-based sequence stratigraphic scheme for the Westphalian of the southern North Sea. The scheme uses the macrofaunal (mainly non-marine bivalve) zones known at outcrop (onshore UK) as its basis, and claims to identify these zones from wireline log signatures in the offshore subsurface, using palynology as the principal means of age determination. The confidence with which the authors identify individual marine bands contrasts with our more cautious approach, and the use of the bivalve zone names for the offshore seems inappropriate. However, there are some similarities with the first-order units of our proposed scheme, and it may yet be possible to reconcile the two.

Chemostratigraphy. Multi-element major and trace element analyses can be used to characterize stratigraphic intervals by their chemical composition. The technique has been applied to inter-well correlations in the Westphalian C-D red bed section in UK Quad 44 (Moscariello et al., 2002; Pearce et al., 2005a, b). Interdisciplinary work suggests that the chemical variations are linked to changes in both provenance and climate (as expressed in pedofacies in wells for which core is available). The method is clearly very promising, but it has not yet been demonstrated to work at a more regional scale.

While it is clear that integration of results from all available methods is the way forward (Spencer et al., 2004), there remains a need for a stratigraphic framework that is applicable across the whole region, preferably based on universally available data, and preferably having genetic significance. We present such a scheme here, based primarily on wireline logs, analyzed for their waveform (spectral) properties, and interpreted using the principles of global cyclostratigraphy, i.e. *climate stratigraphy*. We briefly explain the methodology, and then outline its application to the SNS Carboniferous.

Principles of climate stratigraphy

We give only a summary here, as the principles of the method of climate stratigraphy developed by ENRES International have been set out in more detail elsewhere (Nio et al., 2005, 2006); see also the description in a companion paper on the Triassic of the UK Central North Sea (De Jong et al., 2006).

Briefly, the approach comprises two key elements:

1. A facies-sensitive log – normally the GR – is transformed to a spectral trend (or INPEFA) curve, which shows uphole changes in the waveform properties of the data. The software used for this is CycloLog, developed by ENRES.
2. The Global Cyclostratigraphy model of Perlmutter et al (1990, 1998) – i.e. the theory that climate change is a fundamental control on lithofacies succession - is then applied to the interpretation of this otherwise unexploited information.

The global cyclostratigraphic model of Perlmutter et al. (1990, 1998) was developed as a tool for the prediction of vertical lithofacies succession. 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. 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. The vertical stratigraphic succession in a basin is strongly related to climatic change (albeit in the form of a filtered and incomplete record), see Figure 2.

Vertical succession is exactly what is sampled by wireline logs. Therefore, an analytical tool that looks at the *pattern* of vertical lithofacies 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 INPEFA curve, with its emphasis on changes in the frequency content, is just such a tool (Nio et al., 2005).

In summary, the method of climate stratigraphy allows the development of a framework of near-synchronous well-to-well correlations by identification of (time-)equivalent, primarily climate-controlled, vertical lithofacies changes and trends in wireline log data.

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 hence on wireline logs) are in the order of 10,000s to 100,000s years. The processes of basin subsidence 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, see Figure 2. In our experience, any effects caused by shorter-term tectonic processes (such as fault movements) do not impact on our ability to interpret and correlate the INPEFA patterns.

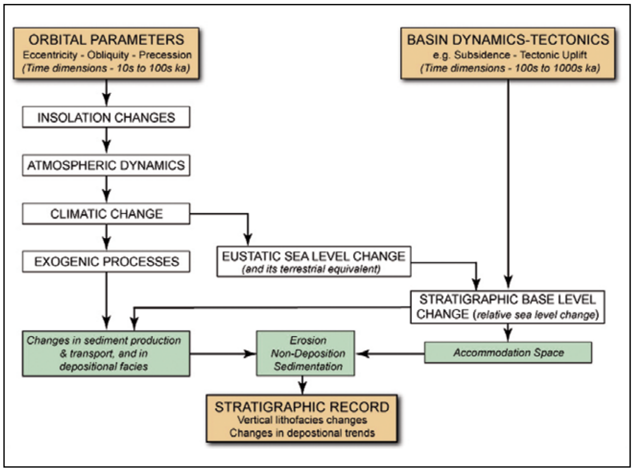

Figure 2 *Connection between the orbital parameters (top left) and their record in strata (bottom). Climate change is, hence, a key control on vertical lithofacies change.*

Correlation of curves

Although the analysis and correlation of the spectral trend curves of GR logs (INPEFA_GR curves) is largely a matter of experience, some general principles can be stated. A brief outline will be given here. More detail is available elsewhere (De Jong et al., 2006; Nio et al., 2006).

It is important to realize that the waveform properties can only be analyzed for sections that have been preserved. The INPEFA curves of GR will be identical for different wells only if and when the preserved sections are identical. Practically speaking, this does not occur. The interpretation of INPEFA curves, therefore, focuses on identifying *equivalent* breaks and trends rather than on finding identical patterns.

Intervals of positive (left-to-right) and negative (right-to-left) trend in the INPEFA curve are separated by *turning-points* . A *positive turning-point* is a point at which the trend (in an upward direction) changes from negative to positive (clockwise). A *negative turning-point* is a point at which the trend (in an upward direction) changes from positive to negative (anti-clockwise). After identification, the turning-points and intervening trends are, firstly, calibrated in lithological terms and, secondly, interpreted in stratigraphic terms. Turning-points that (a) signify changes in depositional trends (Embry, 2002) and (b) are correlatable between wells, are called *bounding surfaces*. Negative turning-points thus become *negative bounding surfaces* (NBS), positive turning-points become *positive bounding surfaces* (PBS). These are our (time-)equivalent, primarily climate-controlled, vertical lithofacies changes. Usually, an NBS marks the base of a trend with a progradational or related component, whereas a PBS represents the beginning of a period of retrogradation or related process.

A hierarchy of change is commonly observable in the INPEFA_GR curve, indicating a hierarchy of vertical lithofacies trends and changes. *StratPacs* (stratigraphic packages) are bounded by adjacent negative bounding surfaces of the same hierarchical rank. StratPacs represent systematic changes in (litho)-facies controlled by climatic variations. They are stratigraphically time-synchronous. The lithofacies units within a package are genetically linked: usually, a progradational or related trend is overlain by a retrogradational or related trend. In our nomenclature, the StratPac is named after the lower NBS: e.g., StratPac W1000 is bounded at the bottom by NBS W1000 and at the top by NBS W2000. Positive bounding surfaces are named after the StratPac within which they occur; they are labelled with an additional letter P.

The analysis and interpretation of the spectral trend curves is done in several iterative steps, with increasing detail in successive steps being achieved by focusing on intervals that are interpreted to be equivalent between wells. So-called *long-term INPEFA_GR* curves are generated for the total study interval and, as more detail is required, *short-term INPEFA_GR* curves are made for sub-sections. The long-term curves, typically, show relatively little detail; only the major turning-points and trends are obvious. The short-term curves usually show enhanced character, making detailed interpretations possible.

Generally speaking, the low-order stratigraphic bounding surfaces and stratigraphic packages are identified and correlated in the INPEFA curves with a high level of confidence. Often this is achieved by simple 'pattern-matching' of the INPEFA curves, combined with general geological knowledge of the study section. At this scale of resolution, biostratigraphic and seismic data, if available, will provide constraints to the interpretations. The identification of higher-order bounding surfaces and packages in the individual wells usually presents no problems. Their correlation from well-to-well, however, may not always be straightforward, due to the presence of lithofacies variations and/or hiatuses. If available, high-resolution seismic and biostratigraphic data may offer constraints also at this level of detail.

'Pattern-matching' of INPEFA curves has to be carefully tempered by considerations of the geological implications of one interpretation versus another. The principles of the fluvial-alluvial climate-stratigraphic model have been outlined by Nio et al. (2006). An example of its application is given by De Jong et al. (2006). This model has also been invoked in the interpretation and correlation of the INPEFA_GR curves of the fluvial-alluvial deposits of Westphalian age in the present study.

One important seismic reflector has been used as a key constraint in the correlation of the wells. One of us (SWN) participated in an earlier study in which spectral trend analysis was integrated with seismic data in the Dutch part of the Cleaver Bank High area (Geluk et al., 2002). One of the key bounding surfaces of that earlier study, then named W520tbs, was found to coincide with the base of a seismically reflective unit and with the base of the Maurits Formation; it was also interpreted to coincide with the marine band at the base of the Upper Westphalian B. The W520tbs surface is approximately equivalent to the positive bounding surface W4220p of the present study, which, in turn, is close to positive bounding surface W4000P as shown in Figures 3, 4 and 5. In the work by Geluk et al., the top of the reflective interval coincided with another cyclostratigraphic pick, W600, which is generally equivalent to the negative bounding surface W6000 in the present study.

Stratigraphic packages

Figure 3 shows the climate-stratigraphic interpretation and correlation of two wells that together cover most of the stratigraphic interval analysed in this study. The figure clearly shows how the rather flat nature of the long-term spectral trend attribute curve, which only shows the major breaks and trends, is enhanced by generating short-term INPEFA_GR curves. Figures 4 and 5 present regional well-to-well correlations from the UK offshore sector to the Dutch offshore sector (see Figure 1 for the location of these correlation lines).

Nine major stratigraphic packages have been identified and correlated in the study wells, labelled W1000 to W9000 from bottom to top (W=Westphalian). Seven of these StratPacs are present in a fairly typical development in the wells in Figure 3. StratPac W8000 is only incompletely preserved below the Base Permian Unconformity (BPU) in 49/7b-2. For StratPacs W8000 and W9000 see, for instance, well 44/21-3 in Figures 4 and 5; note that StratPac W9000, where present, is incomplete beneath the unconformity.

The base of the Westphalian *s.l.* succession, the W1000 NBS, is generally marked by a prominent negative (anti-clockwise) turning-point at the top of the uppermost fining-up trend of the Namurian Millstone Grit: the lowermost NBS, indicated by a thick solid horizontal red line, in well 49/4-2A in Figure 3. The basal boundaries of W2000 and W3000 are also very distinctive in the long-term INPEFA_GR curve of 49/4-2A. The importance of these bounding surfaces is confirmed by their strong expression and importance on the short-term INPEFA_GR curves. StratPacs W1000 and W2000 are, thus, well defined. Higher-order negative bounding surfaces (thin solid horizontal red lines in the figure) and StratPacs are identifiable between the low-order boundaries: a hierarchy is present. Four higher-order units have been identified in StratPac W1000: W1100 through W1400 from bottom to top. StratPac W2000 has been subdivided into three units: W2100 through W2300. A higher-order level of subdivision has been identified in the study: this is, however, not presented in this paper.

StratPacs W1000 and W2000 – and the higher-order units – are basically C-shaped in the INPEFA_GR curves. As can be seen in the coloured GR logs (coloured in 15 classes by log value, red representing low values and blue being high values), the basal boundaries of these C-shaped StratPacs correspond with the bases of relatively coarse-grained units, i.e. influxes of relatively coarse material. The positive turning-points correspond with often abrupt increases in GR values, where the supply of relatively coarse material

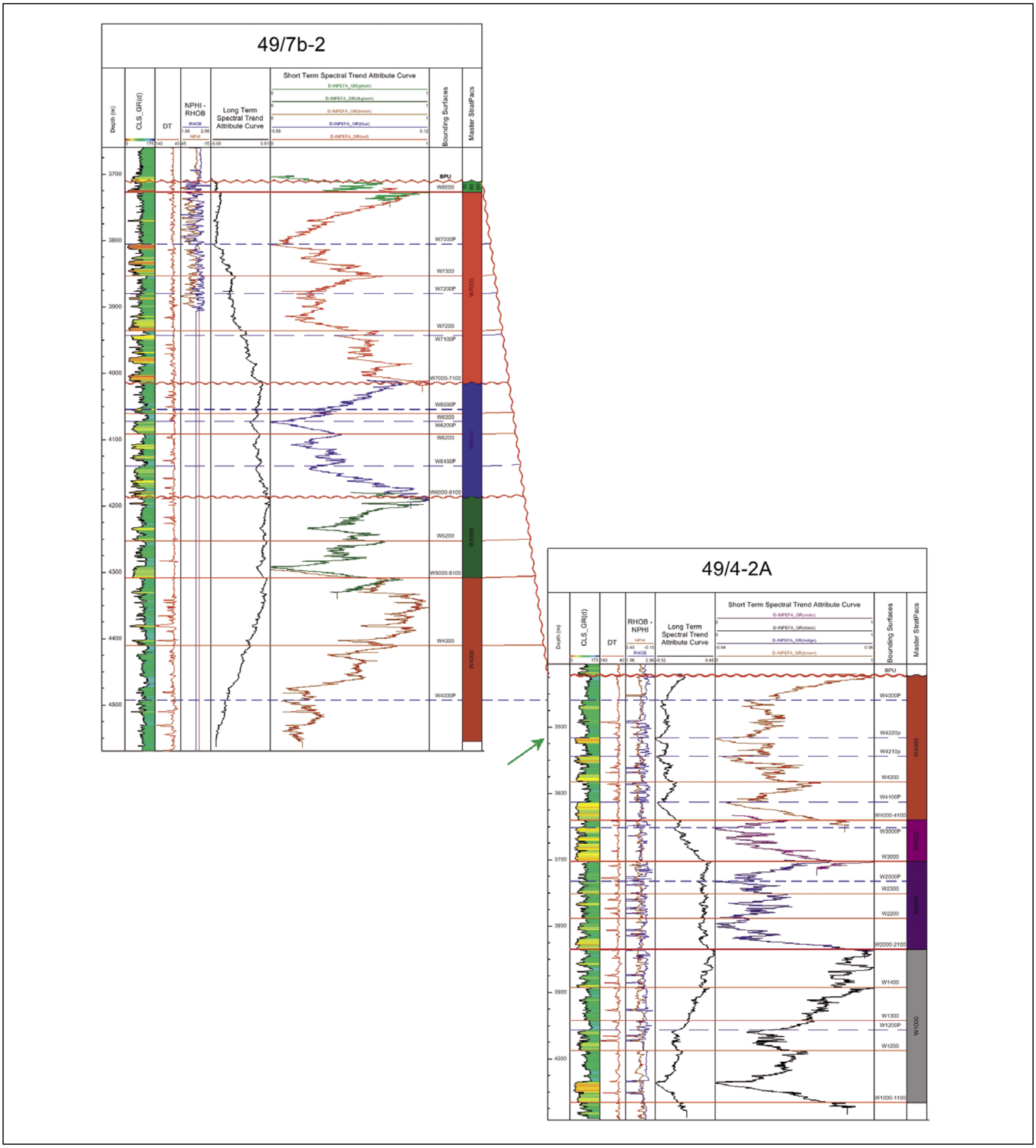

Figure 3 *Westphalian (s.l.) succession, illustrated in two UK sector wells. Key to well composites: track 1 – depth curve; track 2 – GR curve with colour fill; track 3 – sonic curve; track 4 – neutron-density curves; track 5 (black curve) – INPEFA_GR for the entire Carboniferous section in the well; track 6 – coloured curves are spectral trend curves for restricted parts of the succession, interpreted as stratigraphic packages (StratPacs) as defined in the text; track 7 – important bounding surfaces; track 8 – names of major StratPacs. Thicker red lines are first-order StratPac boundaries; thinner red lines are second-order StratPac boundaries; dashed blue lines are positive bounding surfaces; red wavy lines are unconformities. Green arrow indicates the correlative position of the seismic marker discussed in the text. Hanglevel is the W4000P surface. 49/4-2A (Chiswick Field) shows the lower part of the succession, W1000 through W4000 (lower part). 49/7b-2 shows StratPacs W4000 (upper part) through W8000 (lower part). Refer also to 44/21-3 in Figure 4 for W8000 and W9000 (incomplete). A higher order level of subdivision has been identified in the study; this is not presented here.*

has been 'switched off'. The C-shaped units in the INPEFA_GR curves, thus, consist of alternating 'fluxes' of relatively coarse- and relatively fine-grained material.

The nature of the characteristic C-shapes may vary somewhat from well to well, as can be seen for younger StratPacs in Figures 4 and 5. The patterns of changes and trends, however, are similar and correlatable, showing the synchrony of the vertical lithofacies changes and, thus, the synchrony of 'fluxes' of relatively coarse- and relatively fine-grained material. In other words, the INPEFA-based correlations offer a framework for analyzing lateral facies variations.

NBS W3000 is distinct in 49/4-2A. NBS W4000 is also distinct in this well. StratPac W3000, however, does not have a well-developed C-shape. This is quite typical for StratPac W3000 in the study wells. In lithological terms, StratPac W3000 consists of a stacking of predominantly sand-prone units. In most wells, StratPac W3000 is a distinct unit. In some wells, however, the boundary with the overlying W4000 StratPac is less distinct: erosion (scouring) preceding the deposition of the basal W4000 sands has resulted in amalgamation of W3000 and W4000 sands.

	Stratigraphic Scheme		
	NBS	NBS	PBS
Westphalian s.l.	BPU		
			W9200P
		W9200	
			W9100P
	W9000	W9100	
			W8000P
	W8000		
			W7000P
		W7300	
			W7200P
		W7200	
			W7100P
	W7000	W7100	
			W6000P
		W6300	
			W6200P
		W6200	
			W6100P
	W6000	W6100	
		W5200	
	W5000	W5100	
		W4300	
			W4000P
			W4220p
			W4210p
		W4200	
			W4100P
	W4000	W4100	
			W3000P
	W3000		
			W2000P
		W2300	
		W2200	
	W2000	W2100	
		W1400	
		W1300	
			W1200P
		W1200	
	W1000	W1100	

Table 2 *Climate-stratigraphic scheme of the Westphalian s.l.. Note that higher-order units have been identified. They are, however, not presented in this paper.*

StratPac W4000 is a relatively thick unit. The overall shape of the StratPac in the INPEFA_GR curves is C-shaped. A sharp positive bounding surface, labelled W4000P, occurs in the middle of it. This PBS marks the base of the very characteristic positive trend of the sand-starved, coal-rich interval of the Westoe (UK) and Maurits (NL) formations of the conventional lithostratigraphic schemes (Table 1), representing a more or less complete cessation of sand entering the depositional system. This 'switching-off' of the sand supply has occurred in steps, as can be deduced from the stacking of higher-order units in the interval W4000-W4000P. The actual lithofacies development varies from well to well.

Many wells show a well developed W4000P (Figures 4 and 5), thus offering tie-points for long-distance correlations. Note that the earlier mentioned seismic reflector of Geluk et al. (2002) corresponds in most wells with the positive bounding surface W4220p. In a few wells it corresponds with W4210p; both higher-order positive bounding surfaces occur not far below the W4000P surface. We recognize three second-order units in StratPac W4000 - W4100 through W4300. Higher-order units have been identified and correlated in the non-published part of this study.

The top of the W4000 StratPac is characterized by a trend reversal on the INPEFA_GR curves, corresponding with renewed and persistent sand input into the system. Generally speaking, the W5000, W6000 and W7000 (lower part) packages have increasing proportions of (increasingly clean) sands, as can be deduced from the colour changes of the GR curve of well 49/7b-2 in Figure 3.

StratPac W5000 is not present in many wells as will be explained below. Where present, it consists of rather fine-grained lithologies 'heralding' the overall progradational development of the W6000 and W7000 (lower part) StratPacs. Two higher-order units are distinct in the study wells: W5100 and W5200.

Negative bounding surface W6000 is a distinct anti-clockwise change of trend, corresponding with a marked increase in the sand supply. Negative bounding surface W7000 is an even stronger anti-clockwise turning-point, and the overall trend of the INPEFA_GR curves always swings to strongly negative. The W7000 NBS event is approximately equivalent to the base of the lithostratigraphic Ketch Formation, at which coal deposition ceases and redbed deposition generally starts. The W7000P positive bounding surface is another important turning-point: the trend again swings sharply to positive and sand input by-and-large ceases on a regional scale for a prolonged period of time. Refer, for example, to wells 44/21-3, E18-2, and E18-3 in Figure 5. The W7000P surface is the hang level in Figure 5.

The post-W5000 sands are generally considered laterally impersistent and notoriously difficult to correlate. Nevertheless, the INPEFA_GR curves allow confident subdivision of StratPacs W6000 and W7000 each into three higher-order packages (see Table 2), which, in turn, allow a higher level of detail for the correlations (not shown here). See for instance wells 44/21-3 and 44/21a-7 in Figure 4.

Stratigraphic package W8000 is present only in a few of the study wells, among which are 41/21-3, E18-2, and E18-3 (Figure 5). StratPac W9000 has been recognized only in a very small number of wells, and this is the highest package recognized in the Westphalian succession below the base-Permian unconformity in this study. Provisionally, two higher-order units have been differentiated in StratPac W9000. W8000 and W9000 are relatively sand-starved. Together they correspond to the Boulton Formation of Besly (2005), formerly the upper member of the Ketch Formation.

W6000 and W7000 surfaces in Figure 3 are shown as unconformities (wavy lines). Actually, in well 49/7b-2 the section is about as complete as we see in all wells in the study. The unconformities are demonstrated in other wells (Figures 4 and 5).

Intra-Westphalian unconformities

A Westphalian intra-formational unconformity at or at about the base of our W7000 StratPac has been recognised by several authors. Corfield et al. (1996) interpreted it as an onlap unconformity and their diagram was reproduced by Besly (1998). Besly (2005) and O'Mara et al. (2003a, b), however, clearly interpret the unconformity as primarily an erosional one, bringing basal Ketch Fm into contact with lower parts of the Cleaver Fm. O'Mara et al. (2003a), in a paper on the Tyne Field (UK block 44/18a, close to the 44/19-3 well in this study), state that the Lower Ketch unconformably overlies Westoe Fm. Moscariello (2003) states that there is an important erosional event at the base of the Ketch Fm. Spencer et al. (2004) also confirm the existence of a widespread regional unconformity at base-Ketch Fm level. These are all observations and interpretations made on UK wells and UK data. To our knowledge, this unconformity – or any intra-formational unconformity, for that matter – has not been recognized in the Dutch offshore sector.

Through our correlations of wells from both sides of the median line, we are able to demonstrate the presence of this unconformity in the Dutch offshore. We are also able to precisely indicate its position in the wells that have penetrated the relevant section of the Westphalian, i.e. at the base of StratPac W7000. Last but not least, our interpretation adds considerable clarity to the stratigraphic relationships in this critical part of the succession, and suggests that there is a second unconformity, i.e. at the base of StratPac W6000 (Figure 6).

Figures 4 and 5 show regional well-to-well correlations from the UK to the Dutch offshore sector. These wells have been chosen and are displayed to highlight the patterns that

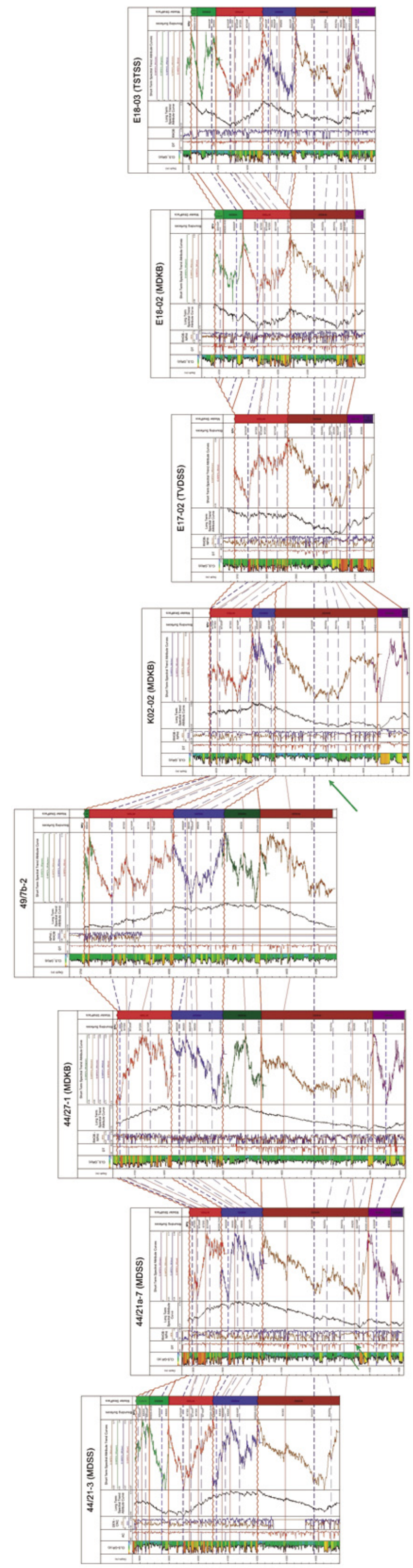

Figure 4 *Long-distance correlation between UK and Dutch wells. Format of well composites as in Figure 3. Hang level is the W4000P surface. Refer to text for explanation.*

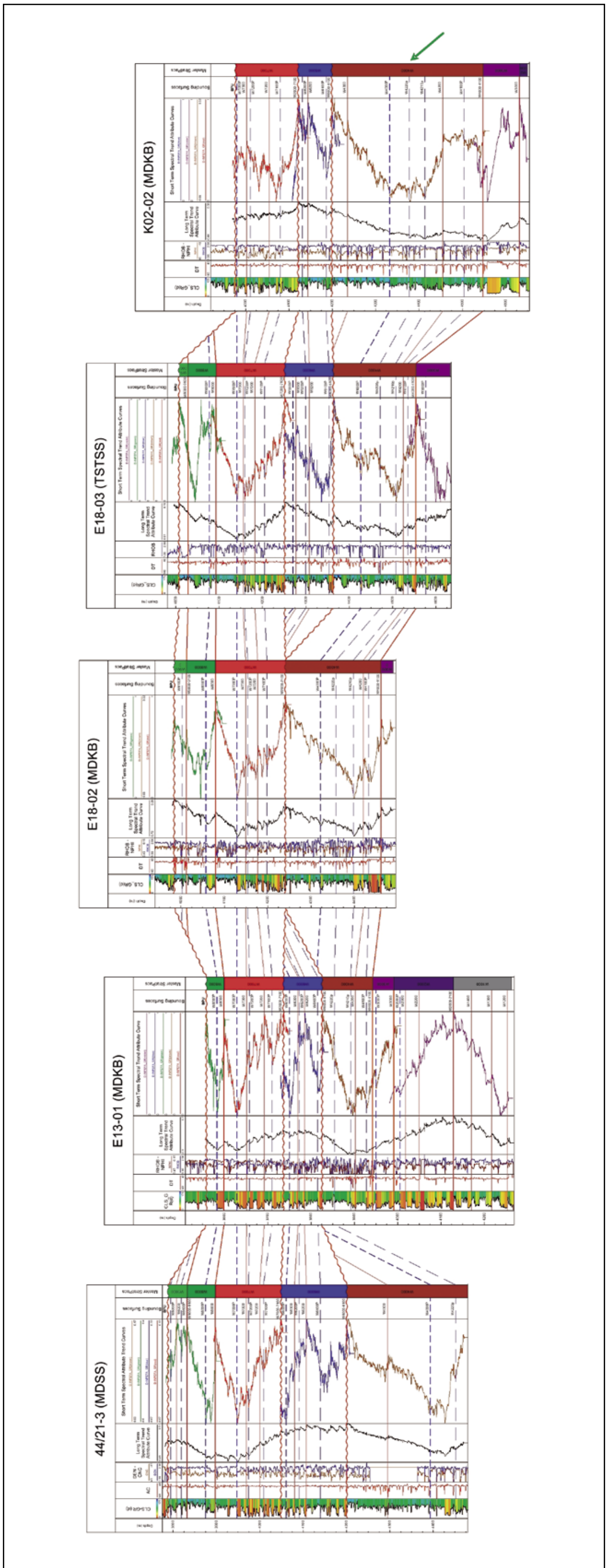

Figure 5 *Long-distance correlation between UK and Dutch wells. Format of well composites as in Figure 3. Hang level is the W7000P surface. Refer to text for explanation.*

demonstrate the presence and position of the unconformities, in the INPEFA_GR trends and in the underlying vertical lithofacies changes (coloured GR curves). Some duplication of wells between the figures is necessary to provide insight, given the importance of 'pattern-matching' of INPEFA_GR curves in the climate-stratigraphic approach. The hang level in Figure 4 is the distinctive, regionally important, and seismically constrained (Dutch part of study area) W4000P bounding surface, which forms the base of a long, well-developed, positive INPEFA_GR trend roughly corresponding with the Westoe and Maurits formations. The hang level of Figure 5 is the regionally important W7000P positive bounding surface. W7000P 'caps' the well-developed negative INPEFA_GR trend corresponding with the (majority of the) so-called Ketch sands; it forms the base of a distinct, relatively long, positive INPEFA_GR trend.

Figure 4 clearly shows that the positive INPEFA_GR trend overlying the W4000P surface is noticeably shorter in many Dutch wells than in many UK wells. Compare, for instance, 44/27-1 and E18-2. Figure 5 shows the laterally persistent presence of StratPac W7000 and StratPac W8000. Together these panels show the varying thickness of the interval between surfaces W4000P and W7000.

By carefully comparing and correlating the INPEFA_GR patterns and the underlying lithofacies patterns, we have concluded that StratPacs W4300 and W5000 as seen, for example, in 49/7b-2 and 44/27-1 are not present in wells E17-2 and E18-2. In the latter wells, the positive trend of W4000 is immediately succeeded by the negative trend of W7000 (Figure 5) suggesting erosion preceding the deposition of StratPac W7000. Comparison of 44/21-3 and 44/21a-7 on the one hand, and 49/7b-2 and 44/27-1 on the other hand, shows that StratPac W5000 is missing in the former suggesting a period of erosion prior to the deposition of StratPac W6000. Relatively sandy units, which are 'sandwiched' between the positive INPEFA_GR trend of StratPac W4000 and the negative trend of StratPac W7000, e.g., in E18-3, can then be understood as belonging to W6000 StratPac.

Integration of all study wells into the correlation framework has provided substance to the interpretation of a substantial hiatus being present at the W7000 boundary. Similarly, proposing an additional hiatus at the W6000 surface offers a very good solution to the correlation problems in the interval between PBS W4000P and NBS W7000. An alternative scenario of depositional thickening and/or thinning of stratigraphic units is considered unlikely: the INPEFA_GR patterns do not support such interpretation. The correlations show consistency of stratigraphic patterns. Faulting, therefore, is not considered the primary cause for the absence of section in study wells.

Figures 5-10 of Nio et al. (2006) show how understanding of the presence and position of intra-formational unconformities assists in generating a high-resolution, reservoir-scale correlation: the pattern of depositional onlap on to the W6000 unconformity surface predicts lateral discontinuity of sands.

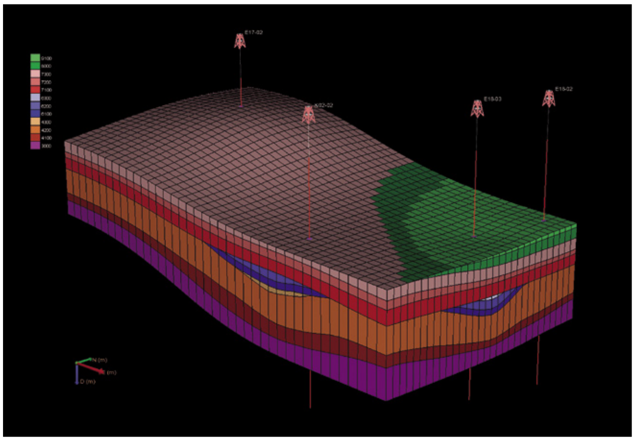

Figure 6 *Block diagram showing a 3D model of the layer distribution in the E17-2, E18-2, E18-3, and KO2-2 area. Note the truncation at the top surface (Base Permian unconformity), below StratPac W7000 (reddish layers) and below StratPac W6000 (blueish layers). The 3D model was generated by JOA in Jewel Suite software.*

Discussion

This study has demonstrated that a scheme of nine stratigraphic packages and their higher-order subdivisions, based on interpretation of spectral trend curves, provides a regionally applicable stratigraphic framework. The scheme has been applied to more than 50 wells, extending from UK Quad 44 and Netherlands Quads D, E and F in the north, to UK Quad 53 and Netherlands Quad P in the south. It is the first to provide a unifying framework across the international boundary, and the first to meet the need to correlate at a detailed level across significant facies changes. It has the advantage of needing no more than routinely available wireline log data as the starting point for its application. Guided and constrained by the available lithostratigraphic, biostratigraphic and seismic data, and applied by experienced geologists, the INPEFA-based interpretations provide new insight and new answers, with reduced ambiguity and with good reproducibility.

What is critical to the success of the method is that the spectral trend curves reveal a normally hidden dimension in the log data; that is, the changing waveform properties of the data. The spectral trends, in combination with global-cyclostratigraphic theory, provide the link to the systematic changes of climate that are, in the background, a primary cause of vertical lithofacies variation. Climatic change being regionally synchronous, the recognition of equivalent INPEFA features between different wells is therefore the recognition of near-synchronous events in those wells. A stratigraphic framework based on the careful interpretation of INPEFA therefore has chronostratigraphic, and hence genetic, significance.

A detailed comparison with previous classification schemes is not possible here, but we have summarized the range of published dates and lithostratigraphic attributions in Table 3, using our scheme as the standard. Data have been published for about 15 of the wells in our study, and the table compares our classification into StratPacs with the published chronostratigraphic and/or lithostratigraphic attributions. For example, strata that we have assigned to W3000 are variously dated by others as Westphalian A or Westphalian B, and assigned either to the Caister or the Westoe Formation. W6000 strata have been dated as either Westphalian B or C, and assigned either to the Cleaver (lower Schooner) Formation or to the Ketch Formation. Although these comparisons are rather superficial, they serve to indicate the difficulties previously experienced in using any kind of stratigraphic classification for correlating between wells at the regional scale. A definitive statement of the relationship between our scheme and others will probably have to await further work, including better integration with other categories of data.

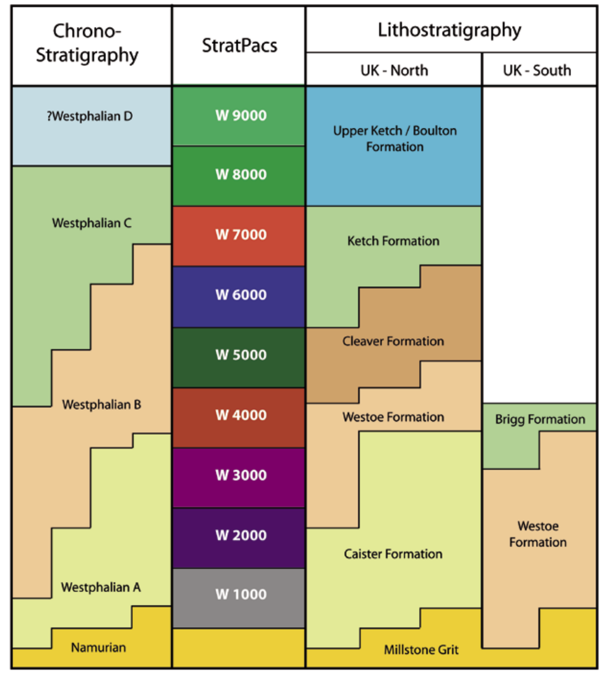

Table 3 *Comparison between our classification into StratPacs, and the published dates and lithostratigraphic attributions that are available for some 15 of the UK wells in this study. Sources include Besly (1998), Cameron (1993), Quirk (1997). The comparison clearly shows that many of the previously defined, primarily lithostratigraphic units are diachronous.*

Conclusions

- Climate stratigraphy seeks to identify genetically significant stratigraphic packages (StratPacs) from the spectral trends in facies-sensitive wireline log data.
- The principles of Climate Stratigraphy have been successfully applied to the analysis and correlation of about 50

wells through the Upper Carboniferous (Westphalian) of the southern North Sea, UK, and Netherlands offshore.

- Our analysis and interpretation have identified nine low-order StratPacs (W1000 to W9000), approximately equivalent to the Westphalian. These can all be confidently identified throughout the study area, which extends from UK Quad 44 and Netherlands Quads D, E, F in the north, to UK Quad 53 and NL Quad P in the south.
- The low-order StratPacs can be subdivided into 20 second-order packages, many of which can also be recognized and correlated across the entire study area. A higher-level of detail for the subdivisions is possible, but not presented in this paper.
- This is the first stratigraphic framework to be successfully applied at such a regional scale, both across the international border, and across significant facies changes.
- Careful identification and correlation of StratPacs reveal significant unconformities at the base of both StratPac W6000 and StratPac W7000. The equivalent of the latter unconformity, at about the base of the lithostratigraphic Ketch Formation, has been documented in the literature before. Our work significantly improves the understanding of it in terms of accurate position in the wells, regional extent and magnitude of the hiatus involved.
- Comparison with the limited publicly available data shows that previous attempts at correlation through a lithostratigraphic approach or through dating methods have given quite erratic results.
- The correlations offer a framework for more detailed correlations at reservoir-scale, allowing evaluation of lateral facies variations within a near-synchronous correlation framework.

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