Recognizing seasonal fluvial influence in ancient tidal deposits

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Abstract: Seasonal changes in rainfall affect water and sediment discharges in fluvial systems. This is reflected within the rock record by changes in (1) the flow processes and structures created and (2) the composition and volume of sediment. This study demonstrates that high-resolution sedimentological studies of rhythms in ancient tidal bar deposits reveal a seasonal fluvial influence. The rocks studied belong to the Plio-Pleistocene Erin Formation on Trinidad, deposited under tropical seasonal conditions in the fluvial–tidal transition zone and tidally dominated palaeoenvironments. Time-series and stratigraphic analyses were undertaken of two rock subsections separated by an erosional surface. Spring–neap, monthly and semi-annual cycles were identified within the deposits. Sand-rich and mud-rich couplets showed neap–spring cyclicity, with gradual transitions between flaser, wavy and lenticular bedding. Seasonal changes in fluvial discharge were recognized by minor scours that marked periods of relatively higher discharge. The content and distribution of organic material varied through the seasonally influenced cycle. Rare and dwarfed trace fossils and bioturbated beds also showed a periodic pattern, interpreted as representing changes in palaeoenvironmental conditions due to seasonal freshwater discharge. As a result, reservoirs containing similar deposits may have porosity and permeability variations with seasonal depositional periodicity.

Supplementary material: The full set of measured time-series data is available at https://doi.org/10.6084/m9.figshare.c.3283376

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Paralic sequences are deposited in areas with alternating terrestrial and marine deposition. The lateral transition zone between the two sets of environments records spatial and temporal shifts resulting from changes in relative sea-level. The facies within the fluviatidal transition zone reflect the alternating conditions caused by both tidal and seasonal fluvial cyclicity. Small-scale heterogeneity in such environments greatly reduces the recovery of hydrocarbons from reservoirs (Choi et al. 2011), but the associated bioturbation of laminated layers can increase permeability (Tonkin et al. 2010; Gingras et al. 2012a, b; Hsieh et al. 2015). The study of heterogeneity from outcrops allows observation at a scale and resolution not reproducible by three-dimensional seismic, well or core data (Pringle et al. 2010). This study highlights the need to consider palaeoenvironmental interpretations with respect to the fluvial–tidal transition zone. This has yet to be applied to Trinidad reservoirs. Qualitative and quantitative methods were used to document relative fluvial influences in ancient tidal deposits from outcrop data. This analysis could be used to describe the expected heterogeneity in similar deposits and potential reservoirs.

The integration of statistical and observational data assists in determining the processes ongoing at the time of deposition and the resulting heterogeneity in the rock record. In areas with mixed influences, high-resolution stratigraphy allows a precise palaeoenvironmental interpretation. This study showed that time-series analysis identifies the tidal cycles in rhythms, whereas a close look at the corresponding sedimentology confirms cyclicity and reveals trends in depositional processes. Seasonal fluvial variations are recognized in tidally dominated deposits. Also shown are the differences in sedimentary structures and the preservation potential of rocks deposited in palaeoenvironments with varying fluvial influences.

Tidal cycles

Heterolithic rhythmic bedding is a lithofacies interpreted as indicating a strong tidal influence (Tessier et al. 1995; Dalrymple 2010b; Greb et al. 2011). This interpretation is confirmed where tidal periodicity can be identified by the quantitative analysis of time-series data recorded from the deposits (Kvale 1989, 2006, 2012; Dalrymple 2010b; Davis Jr & Dalrymple 2012; Longhitano et al. 2012). Statistical methods have been used to analyse both ancient (Kvale 1989; Martin & Sanderson 1993; Chan

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et al. 1994; Choi et al. 2001; Couéffé et al. 2004; Hovikoski et al. 2005; Gent & Sonnenberg 2014) and modern (Choi 2010; Greb et al. 2011) tidal rhythmites. Sections with rhythmites are considered to be records of continuous deposition (Kvale 1989; Eisma 1998; Choi & Park 2000; Couéffé et al. 2004). Several studies have discussed tidal cycles (e.g. Visser 1980; Chan et al. 1994; Tessier et al. 1995; Kvale 2006, 2012; Dalrymple 2010a, b; Davis Jr 2012; Longhitano et al. 2012) and a brief description is given here.

Each tidal cycle, from flood to high tide and from ebb to low tide, can deposit one or two couplets, each couplet being a pair of relatively coarser and finer grained layers (Fig. 1a). The resulting laminae indicate deposition due to alternating sediment transport processes. During the ebb and flood tides, sediments are transported and deposited by traction,
while during slack water conditions at high and low tides deposition is mainly from suspension. The number of couplets per cycle depends on the sediment and water discharge of the area, the inequality of the ebb and flood current energies, inundation v. exposure of the surface during low tide, and the preservation potential of deposits with successive tides (Dalrymple 2010b). The tidal regime of an area determines the duration of each tidal cycle. In a diurnal tidal regime, coastal areas experience one high and one low tide during a lunar day, with a tidal period of 24 hours 50 minutes. Regions with a semi-diurnal tidal regime experience two high and low tides during one lunar day, with a tidal period of 12 hours 25 minutes. This allows for a daily maximum of two couplets deposited in a diurnal regime and four couplets in a semi-diurnal regime. Diurnal inequality refers to two unequal tides in one day, which can lead to alternating couplet thicknesses. A large diurnal inequality can also result in the deposition or preservation of one or no couplets per day (see Table 1).

The period of time required for one revolution of the Moon around the Earth is 29.53 days; this is called a synodic month (Fig. 1b). The range and energy of the tides are greatest at the times of the new and full moons, resulting in spring tides. Neap tides are the conditions of lowest tidal range and energy; they occur during first and third quarters of each synodic month. There are therefore two neap–spring cycles during a synodic month, each having a period of 14.76 days. The periodic increase and decrease in tidal energy results in rhythmic tidal bedding. Spring–neap cycles are recognized in tidal deposits as alternating sand-rich and mud-rich lamina sets. The highest high tides and lowest low tides during spring conditions lead to thicker sand and thinner mud laminae in the preserved couplets. Conversely, during neap conditions, the lowest high tides and highest low tides result in the deposition of thinner sand and thicker mud layers. Successive spring deposits also show inequalities, which can be exaggerated by the forcing effects of lunar perigee (when the Moon is closest to the Earth) and apogee (when the Moon is furthest from the Earth).

### Table 1. Periods of tidal cycles and estimated couplets deposited per cycle

| Order | Tidal cycle           | Period (solar days) | Couplets per cycle |
|-------|-----------------------|---------------------|--------------------|
|       |                       |                     | One couplet/cycle  | Two couplets/cycle |
| First | Semi-diurnal          | 0.5                 | ~1                 | ~2                 |
| Second| Synodic neap–spring   | 14.77               | ~29                | ~58                |
| Third | Synodic month         | 29.53               | ~58                | ~116               |
| Fourth| Semi-annualseasonal   | 182.6               | ~365               | ~730               |

The variable and combined effects of both fluvial and tidal currents are recognized in the deposits of the transition zone. Fluvial flow decreases in energy seawards, while the tidal current energy first increases due to confinement and then decreases upstream. A tidal prism, or saline wedge, travels upstream from the river’s mouth. The resultant hydrodynamic forces lead to current reversals up to the tidal limit and tidal modulation of the river flow just landwards of it in the backwater zone (Dalrymple et al. 1992, 2012; van den Berg et al. 2007; Dalrymple 2010b; Martinus & Gowland 2011). The limits of the transition zone are dynamic, varying with base level changes, fluctuations in seasonal discharge and tidal cycles. High river discharge shifts the landwards limit of tidal influence downstream and low river discharge shifts the downstream limit of fluvial influence upstream. Within a tidal cycle, the flood retards the river’s flow and decreases or reverses the velocity, while the ebb draw-down causes an increased velocity downstream. Flood tides during spring conditions affect the fluvial flow further upstream than those during neap conditions. Seasonal variations are recognized in the deposits because a lower river discharge leads to a greater tidal effect further upstream.

Within the transition zone, there is a change in the sedimentological characteristics of the deposits from upstream to downstream. Based on studies of modern and ancient deposits (for example, Dalrymple & Choi 2007; van den Berg et al. 2007; Dashtgard et al. 2012), sedimentary structures indicative of unidirectional and bidirectional currents are found within the transition zone because the...
zone shifts regularly. Lithofacies corresponding to tidally influenced fluvial deposition change downstream to tidal deposits with a decreasing fluvial influence.

In the backwater section, just upstream of the transition zone, Martinius & Gowland (2011) observed that organic particles act as suspended material and are deposited as laminae following spring to neap cyclicality. Tidal modulation causes a reduced, but not reversed, flow that is amplified during spring conditions. The retarded flow allows for the deposition of organic laminae, while the decreasing effect of the flood tide leads to neap deposition that often does not contain organic material.

**Bioturbation**

Biogenic structures are indicators of environmental conditions, such as the sedimentation rate, the coherency of the substrate, salinity, oxygen level, turbidity, food availability and type, subaerial exposure, water depth, light, temperature and depositional energy during deposition and at the time of surface colonization (McIlroy 2007; MacEachern et al. 2007a, b, 2010; Gingras & MacEachern 2012). The size, diversity and distribution of trace fossils are also indicators of the environmental conditions. The ichnofacies associated with different assemblages of trace fossils are used to infer the palaeoenvironment at the time of their formation (Seilacher 2007).

The distribution of trace fossils in a vertical section can be classified as homogeneous, regularly heterogeneous and sporadically heterogeneous (Gingras & MacEachern 2012). Homogeneously distributed biogenic structures indicate a continuous low rate of sedimentation with available food, such as on intertidal flats. In the fluvial–tidal transition zone, a strong seasonal difference in conditions would most probably be reflected by a regularly heterogeneous distribution, with lower sedimentation rates and higher salinity at times of decreased fluvial discharge allowing for colonization by organisms. By contrast, sporadically heterogeneous distributions of trace fossils that show no pattern are more likely to reflect complex and essentially random changes in conditions.

Tidal environments are considered to be stressed as a result of the periodically alternating salinity, water depth, suspended sediment concentration and current direction, duration and intensity. Adaptations to the harsh conditions lead to small sizes, sparse distribution and low diversity of trace fossils (MacEachern et al. 2010; Dalrymple et al. 2012; Gingras & MacEachern 2012). This brackish-water ichnofacies can then be used to help identify the fluvial–tidal transition zone. Changing conditions upstream through the transition from tidal to fluvial environments lead to a decrease in the size and diversity of biogenic structures (Gingras et al. 1999, 2012b; MacEachern et al. 2007b; Gingras & MacEachern 2012). Tidal influence can also be recognized directly if the burrow fill is rhythmic, and indirectly by the feeding patterns, simplicity of burrows, burrow lining and fill material, and rhythmic occurrences and diversities of trace fossils.

**Geological setting**

The Erin Formation was deposited on the NE South American continental shelf by the palaeo-Orinoco Delta during the Plio-Pleistocene (Kugler 2001). The deposits are found in the Southern Basin of Trinidad, an eastwards extension of the Eastern Venezuelan Basin. Thick sections of the rocks are exposed along the northern and southern coasts of the SW peninsula of the island (Fig. 2) with a structural dip of 3–10° to the NNE. A laterally continuous outcrop extends for more than 300 m at Granville Bay (10° 08′ 17.1″ N, 61° 48′ 04.5″ W). The measurements reported here were taken in 2013. High-energy waves along the coastline have since eroded the outcrop.

According to Kugler (2001), the Erin Formation rests on the Morne L’Enfer Formation and is unconformably overlain by the Pleistocene Cedros Formation. The Erin Formation includes major cycles of lignite and peat mantles, clay, silt and cross-bedded sand. Porcellanites are considered to be clay and shale material that has been baked or fused by the combustion of lignite. The lignitic beds are rich in plant material and often contain petrified tree trunks. The palaeoenvironments of deposition interpreted by Kugler (2001) consist of brackish-water and freshwater estuaries and coastal swamplands.

More recent palaeoenvironmental interpretations of the Erin Formation by the first author include sub-environments in the fluvial–tidal transition zone within a tidally dominated estuary (Fig. 3). The sections reported in this paper were deposited as tidal bar deposits. Heterolithic interlaminated planar beds with sand–mud and silt–mud couplets extend laterally for c. 20 m. Trace fossils vary in abundance and distribution and include dwarfed traces of the *Skolithos* ichnofacies and other unidentified burrows, suggesting a brackish water ichnofacies (Pemberton & Wightman 1992; Gingras et al. 1999; Buatois et al. 2005). Organic fragments sourced from overbank areas and coastal swamps are common among the deposits.

Sediments were deposited in a tropical seasonal palaeoenvironment, with a dry season and a rainy season that lasted for roughly six months each. Similar to present day conditions, a semi-
diurnal palaeotidal regime can be assumed because the astronomical factors have been constant for several million years (Sonett et al. 1996; Choi & Park 2000). The current microtidal range cannot, however, be assumed for the Plio-Pleistocene depositional palaeoenvironments because major differences between geographical settings affect the tidal dynamics of an area (Choi & Dalrymple 2004). The geomorphology of the area includes possible amplification of tidal waves by lateral constriction (Cummings et al. 2006) due to the presence of a mountainous terrain and subaqueous and subaerial tectonic ridges on the continental shelf (Pindell & Kennan 2001; Kennan & Pindell 2007; Pindell et al. 2009).

Methods

Outcrop data collection

Among the outcrops at Granville Bay, one section contains identifiable tidal rhythmites. An erosive surface divides it into two subsections containing different types and distributions of sedimentary structures. Two subsections were studied: GB1 below the erosive surface and GB2 above it (Fig. 4a). Magnified photographs of the subsections were used to measure the thickness of each couplet of sand–clay, sand–silt or silt–clay laminae. Each photograph included a constant scale in millimetres for measurement of the true stratigraphic thicknesses of the horizontal and wavy parallel-laminated couplets. The thicknesses of discontinuous or pinching couplets were measured at the thickest sections or on the foresets of rippled surfaces so that the maximum deposition for the event could be represented. Where deformation occurred in the section, the beds were traced laterally to continuous laminae that could be measured.

High-resolution stratigraphy

The rhythmic heterolithic bedded facies of the Granville Bay subsections (GB1 and GB2) were
measured and recorded as detailed sedimentary logs. Sedimentary structures and the presence or absence and distribution of organic content were noted. The presence or absence, distribution, intensity and diversity of trace fossils were also recorded using the bioturbation index (BI) of Taylor & Goldring (1993). This is used to distinguish different grades (0–6) based on the percentage of bioturbation, the ability to recognize the primary sedimentary fabric, and the abundance and overlap of burrows. These observations are represented as colour-coded markers at the corresponding couplet numbers. Comparison with the time-series data was then used to identify trends or cycles in the sedimentary features.

**Statistical analysis**

The thicknesses of 511 couplets from GB1 and 1284 couplets from GB2 were entered into a Microsoft
Fig. 4. (a) Photograph showing the scoured surface separating subsections GB1 and GB2. (b) Sedimentary log of subsection GB1 with interpreted cycles. Couplet numbers corresponding to sedimentary features of interest are listed in the column CN. Locations of photographs through the section are also shown.
Excel spreadsheet and numbered stratigraphically. Each dataset was then copied into the palaeontological software PAST (Hammer et al. 2001; Hammer 2010) for statistical analysis.

Graphs of the couplet thickness against number were generated. Where sinusoidal patterns were recognized, successive peaks and troughs were used to determine the number of couplets in the interpreted cycles. The periods of the cycles were then calculated using:

\[ T_n = \frac{(N_c \times t_c)}{24} \text{ days} \]  

where \( T_n \) is the period of the cycle of order \( n \) being calculated, \( N_c \) is the number of couplets in the cycle and \( t_c \) is the time taken for the deposition of each couplet. If two couplets were deposited during each first-order tidal cycle, then \( t_c \approx 6.2 \) hours. If only one couplet was deposited, then \( t_c \approx 12.4 \) hours. If deposition was not continuous as a result of erosion or a lack of deposition, the periodicity may be difficult to determine. The statistical methods outlined in the following gave values of \( N_c \) or \( f_n \), from which \( T_n \) could be calculated using equations (1) and (2).

**Autocorrelation.** The autocorrelation function was used to test for randomness in the datasets. A 95% confidence interval indicated random, independent values. Histogram plots of the autocorrelation function were interpreted in a similar manner to the thickness plots for values of \( N_c \).

**Sinusoidal modelling.** The datasets were fitted to sinusoidal models by searching for periodicity in the data. The amplitude, phase and periods \( (N_c) \) were output for each of the cycles recognized.

**Filtering.** The datasets were first transformed by subtracting the mean for each dataset from the data. The datasets were fitted to sinusoidal models by searching for periodicity in the data. The amplitude, phase and periods \( (N_c) \) were output for each of the cycles recognized.

\[ N_c = \frac{1}{f_n} \]

**Continuous wavelet transform analysis.** Continuous wavelet transform, which is essentially equivalent to fast Fourier transform (Prokoph et al. 2000), was used to detect non-stationary cyclicity. Two-dimensional representations of the datasets showed the decomposition of the spectra as image graphs. The Morlet function was used. Warmer colours indicated high-power spectra, representing significant cycle periods in the dataset. Values of \( y \) at high-power spectra were used to calculate the number of couplets per cycle using the following steps.

From graph axes. \( y = \log_2 x \)

\[ \therefore x = 2^y \]

In this case, \( x = N_c \)

\[ \therefore N_c = 2^y \text{ couplets per cycle} \]

**Description**

**Sedimentology and ichnology of GB1**

The sedimentary log of GB1 is shown in Figure 4b. The recorded sedimentary features are highlighted.

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**Fig. 5.** Photographs of sedimentary features observed in subsections GB1 and GB2. (a) Lenticular bedding in an orange silty sand (OSS) layer, with organic fragments scattered in sand lenses above and below the OSS. (b) Wavy, parallel bedding with interlaminated silt–clay and sand–clay couplets. Thin discontinuous layers of organic material occur at the base of some clay laminae. Clay laminae increase in thickness up-section from spring to neap deposits. (c) Alternating sand-rich spring and clay-rich neap deposits, with organic material isolated to neap deposits. (d) Single organic fragment in mud-rich layer within interlaminated silt–clay couplets. Scour fill cut into deformed layer and filled with inclined sand–clay couplets. Scour fill includes an OSS layer. (e) Contorted layer deforms mud-rich couplets and an OSS layer above it. (f) Skolithos with rhythmic sediment infill. Bioturbated layer between successive OSS layers. Bioturbation index (BI) 2. (g) Bioturbated layer beneath a thin concretion layer (shown by white arrow). Rare Skolithos and Ophiomorpha occur with unidentified burrows; BI 2. (h) Skolithos with organic material. Thin concretion layer (shown by white arrow) above bioturbated layer with BI 1. (i) Thalassinoides in mud-rich layer of mud–silt couplets. (j) Cylindrichnus. Lenticular beds separate mud-rich couplets. (k) Skolithos in alternating neap–spring cycles of couplets. Photographs (a–i) from GB1; (j–l) from GB2. Lithology from photographs: light brown or orange colour indicates sand or silty sand, grey colour indicates clay and black colour indicates organic material. Neap (mud-rich) and spring (sand-rich) deposits are interpreted on the photographs as N and S, respectively.
at the corresponding couplet numbers by colour-coded markers.

**Sedimentary structures.** Parallel and wavy heterolithic bedding structures are common in the subsection, with average couplet thicknesses of 1–2 mm. Lenticular and flaser bedding occur in the sand-rich and mud-rich layers, respectively. The transitions between sand–silt, silt–mud and sand–mud couplets are gradational.

Laterally continuous orange silty sand (OSS) layers are interbedded with layers of heterolithic laminae, with gradual contacts between them. The OSS layers are up to 4 cm thick, poorly sorted and generally massive; some contain lenses of very fine white sand (Fig. 5a).

There is an overall increase in deformation within the beds up-section. Scours, contorted laminae and dewatering pipes occur below some OSS layers near the top of the measured subsection.

**Bioturbation.** Bioturbated layers with BI 2 (Fig. 5g–i) have a regularly heterogeneous distribution, occurring between successive OSS layers. Thin iron concretions occur at the top of bioturbated layers and are followed in the stratigraphy by continuous parallel and wavy laminated beds. Three such successions occur near the top of the subsection, but are absent in its lower part. Traces include unidentified vertical escape burrows. A few *Skolithos*, *Thalassinoides*, *Cylindrichnus* and *Ophiomorpha* occur in conjunction with the bioturbated layers.

**Organic material.** Organic material is not common throughout the subsection, but is concentrated in specific layers and is absent near deformed beds. In layers containing organic material, thin discontinuous laminae of organic fragments occur at the base of clay laminae. The laminae only occur among mud-dominated deposits. Among sandier deposits, organic material is disseminated as fragments. Organic material is found in a few *Chondrites* and *Skolithos* (Fig. 5i), but is absent in the regularly heterogeneous bioturbated layers (Fig. 5j).

**Sedimentology and ichnology of GB2**

The sedimentary log of GB2 (Fig. 6) shows sedimentary features highlighted by colour-coded markers.

**Sedimentary structures.** Similar to subsection GB1, wavy parallel interlaminated beds occur throughout the subsection, with lenticular and flaser bedding occurring at sand-rich and mud-rich layers, respectively. Scours and contorted layers are randomly distributed and are found above, below and between OSS layers. The OSS layers in subsection GB2 are massive and are up to 100 mm thick.

**Bioturbation.** Trace fossils in this subsection consist of rare, dwarfed *Thalassinoides*, *Cylindrichnus* and *Skolithos* (Fig. 5j–l). Regularly heterogeneous bioturbated layers, such as those observed in subsection GB1, are absent in GB2.

**Organic material.** Disseminated fragments and thin discontinuous laminae of organic material are randomly distributed through subsection GB2.

**Statistical results**

The statistical analysis of the GB1 and GB2 time-series datasets generated plots (Fig. 7) and values from which *Nc* and *Tn* were derived using the appropriate equations. The results are given in Tables 2 and 3.

**Analysis**

The statistical analysis of each subsection includes interpretations of the tidal cycle, neap–spring, monthly and semi-annual periodicity in deposition. The juxtaposed colour-coded markers and time-series data show trends in depositional conditions (Fig. 8).

**GB1**

**Sedimentary structures.** Statistically interpreted cycles of roughly 30 couplets correspond to transitions from mud-rich to silt- or sand-rich layers in the section. This can be interpreted as neap–spring (second-order) cyclicity in a semi-diurnal regime, where only one couplet per tidal cycle is preserved. Alternatively, diurnal inequality may be responsible for the deposition and preservation of only one complete tidal cycle with the stronger tide daily (de Boer *et al.* 1989; Kvale *et al.* 1999; Mazumder & Arima 2005; Dalrymple 2010b). From either interpretation, it can be deduced that each couplet represents 12.4 hours in the time-series dataset in this study.

Cycles of *c.* 56 couplets can be interpreted to be monthly (third-order) cycles. Cycles of *c.* 100–150 couplets, corresponding to 2–3 months of deposition, can also be interpreted from the statistical results. These cycles correspond to the OSS layers in the sedimentary log. The massive nature of the OSS layers makes it impossible to statistically determine the time corresponding to the deposition of each layer. Scours, contorted laminations and dewatering pipes are interpreted as deformation due to high-energy flows and rapid deposition (Dzulynski & Smith 1963; Plint 1983; Frey *et al.* 2009).
Fig. 6. Sedimentary log of subsection GB2 with interpreted cycles. Couplet numbers corresponding to sedimentary features of interest are listed in the column CN. Locations of photographs through the section are also shown.
Fig. 7. (a) Sinusoidal model fit for time-series dataset of subsection GB1. (b) Plot of GB2 original (subtracted mean) and filtered (red line) dataset. (c) GB1 Lomb periodogram power spectra plot with noise cut-offs. (d) GB2 Lomb periodogram power spectra plot. (e) Continuous wavelet transform of GB1 dataset. (f) Continuous wavelet transform of GB2 dataset. Annotations in figure give couplet counts, frequencies and periods used in calculations, as interpreted from graphs and output data tables.
The increase in frequency of contorted laminae up-section can therefore be interpreted as a general increase in energy over time.

Bioturbation. Bioturbated layers with a regularly heterogeneous distribution indicate episodic increased salinity and marine influence (Gingras & MacEachern 2012). The thin iron concretions at the top of the bioturbated layers (Fig. 5h, i) mark periods of lower energy or little to no deposition, during which colonization of the surfaces and the deposits beneath them occurred (MacEachern et al. 2007a; Gingras et al. 2012b; La Croix et al. 2012). Rare Skolithos and Ophiomorpha can be interpreted as minor evidence of higher energy conditions (Droser & Bottjer 1989).

Organic material. The deposition of organic fragments is interpreted to have occurred during periods of reduced current energy by flood retardation (Martinus & Gowland 2011) and are scattered among coarser grained spring deposits. Among lower energy neap deposits, the deposition of organic material from suspension possibly preceded the settling of clay particles and this is found as discontinuous laminae. The absence of organic fragments from the regularly heterogeneous bioturbated layers may be due to their removal from the deposits by organisms, leaving feeding traces (fodinichnia) behind (Frey & Howard 1990). Organic material in some Ophiomorpha, Skolithos and Chondrites may be remnants of the actual organisms (Frey & Howard 1990).

GB2

Sedimentary structures. Cyclicity interpreted from the statistical analysis includes spring–neap and monthly cycles corresponding to c. 50 and 100 couplets per cycle, respectively. Semi-annual or seasonal (fourth-order) cycles were also interpreted at roughly 300 couplets per cycle. On the logged subsection, the seasonal cyclicity averaged to successive OSS–heterolithic bed couplets. As in subsection GB1, the time corresponding to the deposition of each OSS layer is impossible to determine, again due to the massive texture. The OSS layers can possibly be interpreted as seasonal event beds, deposited at the beginning of the rainy season when a high sediment influx results from river flooding. Heterolithic layers were deposited mainly during the rainy season, with little to no deposition during the dry season. This may have been due to relatively low fluvial discharge and sediment input.

Bioturbation. The rare and dwarfed Thalassinoides and Skolithos and the absence of bioturbated layers in subsection GB2 indicate relatively low water salinity, with only brief periods of increased salinity. The lack of biogenic structures can be interpreted

| Statistical method               | \( N_c \) (couplets per cycle) | \( T_n \) (days) | Order* |
|----------------------------------|---------------------------------|-----------------|--------|
| Autocorrelation                  | 65                             | 33.58           | 3      |
|                                  | 118                            | 60.97           |        |
|                                  | 150                            | 77.50           |        |
| Sinusoidal modelling             | 133.8                          | 69.13           |        |
|                                  | 54.07                          | 27.94           | 3      |
|                                  | 16.51                          | 8.53            |        |
|                                  | 9.42                           | 4.87            |        |
| Filtering                        | 125                            | 64.58           |        |
| Spectral analysis – Lomb periodogram | 131.6                  | 67.99           | 2      |
|                                  | 16                             | 8.27            |        |
|                                  | 9.5                            | 4.91            |        |
| Spectral analysis – REDFIT       | 102                            | 52.70           |        |
|                                  | 73                             | 37.72           |        |
|                                  | 9.5                            | 4.91            |        |
|                                  | 56.8                           | 29.35           | 3      |
| Continuous wavelet transform     | 130                            | 67.17           |        |
|                                  | 54                             | 27.90           | 3      |
|                                  | 16                             | 8.27            |        |

*Cycle orders approximated from theoretical values.

Table 3. Values of \( N_c \) from different statistical methods conducted on GB2 time-series dataset and calculated values of \( T_n \)

| Statistical method               | \( N_c \) (couplets per cycle) | \( T_n \) (days) | Order* |
|----------------------------------|---------------------------------|-----------------|--------|
| Autocorrelation                  | 100                            | 51.67           |        |
|                                  | 250                            | 129.17          | 4      |
|                                  | 328                            | 169.47          | 4      |
|                                  | 440                            | 227.33          | 4      |
|                                  | 630                            | 325.50          |        |
| Sinusoidal modelling             | 304.8                          | 157.48          | 4      |
|                                  | 107.7                          | 55.65           |        |
|                                  | 35.97                          | 18.58           |        |
| Filtering                        | 300                            | 155.00          | 4      |
|                                  | 110                            | 56.83           |        |
| Spectral analysis – Lomb periodogram | 303                             | 156.55          |        |
|                                  | 107.5                          | 55.54           |        |
|                                  | 35.7                           | 18.45           | 3      |
| Spectral analysis – REDFIT       | 322.6                          | 166.68          | 4      |
|                                  | 35.7                           | 18.45           |        |
|                                  | 107                            | 55.28           |        |
| Continuous wavelet transform     | 315.17                         | 162.84          | 4      |
|                                  | 90.5                           | 46.76           |        |
|                                  | 32                             | 16.53           | 2      |
|                                  | 52                             | 26.87           | 3      |

*Cycle orders interpreted roughly fit theoretical values.

Table 2. Values of \( N_c \) from different statistical methods conducted on the GB1 time-series dataset and calculated values of \( T_n \)

| Statistical method               | \( N_c \) (couplets per cycle) | \( T_n \) (days) | Order* |
|----------------------------------|---------------------------------|-----------------|--------|
| Autocorrelation                  | 65                             | 33.58           | 3      |
|                                  | 118                            | 60.97           |        |
|                                  | 150                            | 77.50           |        |
| Sinusoidal modelling             | 133.8                          | 69.13           |        |
|                                  | 54.07                          | 27.94           | 3      |
|                                  | 16.51                          | 8.53            |        |
|                                  | 9.42                           | 4.87            |        |
| Filtering                        | 125                            | 64.58           |        |
| Spectral analysis – Lomb periodogram | 131.6                  | 67.99           | 2      |
|                                  | 16                             | 8.27            |        |
|                                  | 9.5                            | 4.91            |        |
| Spectral analysis – REDFIT       | 102                            | 52.70           |        |
|                                  | 73                             | 37.72           |        |
|                                  | 9.5                            | 4.91            |        |
|                                  | 56.8                           | 29.35           | 3      |
| Continuous wavelet transform     | 130                            | 67.17           |        |
|                                  | 54                             | 27.90           | 3      |
|                                  | 16                             | 8.27            |        |

*Cycle orders approximated from theoretical values.
as a relatively increased fluvial influence during the deposition of subsection GB2 compared with GB1.

**Discussion**

The studied section is traversed by an erosion surface. Heterolithic tidal rhythmites and OSS layers are recognized above and below this surface. However, the periodic distribution of sedimentary features differs between the two measured subsections. GB1 includes regularly heterogeneous bioturbation that is absent in GB2. Fluvial influence during the deposition of GB1 is, therefore, interpreted to have been relatively lower than during the deposition of GB2.

The OSS layers, interpreted as being deposited during high river discharge at the beginning of the rainy season, separate successive beds of tidal heterolithic deposits. Semi-annual cyclicity was more easily recognized in the GB2 subsection, possibly due to rapid and continuous deposition during the rainy season. Subsection GB1 was deposited relatively slowly, evidenced by erosion and bioturbated layers (Choi & Park 2000). It is suggested that a relatively lower fluvial influence may result in an incomplete record of tidal deposition. Palaeoenvironmental interpretations may therefore be more precisely determined with respect to fluvial influence.

Sedimentary structures, organic content and bioturbation variations through GB1 indicate a general increase in the energy of the depositional system up-section. Changes in sediment supply and fluvial influence in the area may have resulted from tidal channel abandonment. A relative fall in either the

![Fig. 8.](a) Plot of couplet thickness dataset for subsection GB1. (b) Plot of couplet thicknesses dataset for subsection GB2. Colour-coded markers identify major sedimentary features.
local or eustatic sea-level could also have led to the erosion of part of the tidal bar deposits in GB1. The erosional surface is at the base of the subsequent deposition recorded in subsection GB2.

The heterogeneity observed in subsections GB1 and GB2 is periodic, with a low vertical-to-horizontal permeability. Similar reservoir facies (Choi et al., 2011) experience reduced fluid recovery. A relatively stronger tidal influence, as interpreted in subsection GB1, can lead to increased vertical permeability in some of the heterolithic beds as a result of the bioturbated layers.

Although tidal signatures and seasonal fluvial influence can be inferred by observing the outcrop, the subsections have a very similar appearance. From the statistical analyses, we were able to identify differences in deposition between GB1 and GB2 relative to the degree of fluvial and tidal influence. Several of the heterolithic beds throughout the outcrop were of comparable thicknesses; however, the fluvial seasonal cyclicity in GB1 and GB2 was interpreted as c. 150 and 300 couplets/cycle, respectively. Without quantitative analysis, no significant distinction would have been made between the two subsections and without the comparative qualitative analysis seasonal cyclicity would not be as easily identified in GB1.

Detailed analyses of the kind presented here are unusual in subsurface studies, but the short sections logged and the focus on a detailed analysis of a limited width of outcrop make most of the workflow that we have used directly applicable to the study of continuous conventional core. Such an approach is perhaps increasingly valuable as workers seek to quantify the relative influences of wave, tide and fluvial processes in an attempt to predict lateral facies patterns (Ainsworth et al. 2011).

Conclusions

Sedimentological observations of a section of ancient tidal rhythmites influenced the interpretations made from time-series analysis. The relative fluvial influence on tidal deposition can affect the presence, abundance and distribution of sedimentary features, such as contorted beds, bioturbation and the distribution of organic matter. It was found that a greater fluvial influence is evidenced by a more complete depositional record during the rainy season as a result of a relatively higher and continuous sediment input.

Heterogeneity resulting from tidal and seasonal cycles is periodic, affecting the reservoir permeability. Although heterogeneity at this scale is not recognizable from seismic or well data, and may be missing from selective core retrieval, it should not be neglected when considering the estimates and justifications of hydrocarbon recovery using reservoir models. Still, not much is understood of the fluvial–tidal transition zone and the relative fluctuating influence experienced with respect to reservoirs. Additional work needs to be carried out to identify comparable rock sections.

Reservoirs in Trinidad and Tobago tend to be interpreted mainly from facies models, without consideration of the unique properties of each depositional system. Recognizing the fluvial–tidal transition zone in palaeoenvironmental interpretations will, as this study shows, increase and potentially predict the understanding of heterogeneity in similar reservoirs. This can help to account for anomalously low recovery rates and volumes.

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