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Chapter 12 (uncorrected proof)

Tidal rhythmites: their contribution to the characterization of tidal dynamics and environments

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Abstract

The present chapter aims in presenting what are tidal rhythmites, where do they preferentially deposit and are preserved, and why, and what is the information the analysis of ancient tidal rhythmites may provide.

Tidal rhythmites (TR) are made of vertically stacked sand-mud couplets that show rhythmic changes in thickness and/or shape directly related to tidal energy fluctuations and cycles, primarily neap-spring-neap cycles. They are known in modern tidal environments and recognized in rock records. TR can be considered as diagnostic sedimentary facies of internal estuarine tidal flat. Some examples are also described in deep subtidal pro-deltaic settings. Both depositional systems fulfill the conditions required for their deposition and preservation (sheltered environment, high enough sediment supply, accommodation).

The recognition of TR, especially in ancient successions, is based on spectral analysis applied to couplet thickness evolution series in order to demonstrate the consistency of their cyclic nature with tidal cyclicities. As a result of these analyses, complemented with facies description, tidal rhythmites are tools to better understand ancient tidal systems. Above all, they constitute an absolute evidence of the action of tides. Such information together with spectral characteristics of the signal encoded into the studied TR, provide major constraints for paleogeographic reconstruction and modelling. The deposition and preservation of tidal rhythmites allows to discuss as well about the fascinating issue of sedimentation rate and its tremendous variability in time and space. Since TR directly record Earth-Moon system dynamics, their spectral analyses to extract ancient orbital parameters developed as soon as their earliest recognition. On this basis, curves of the lunar retreat have been proposed, from Middle Proterozoic to late Paleozoic time. More researches on TR are needed to extract parameters of the very early Earth-Moon system.

Key-words: *Tidal cycles, Sedimentary Records, Tidalites, Proxies, Paleoenvironments, Paleotides*

Introduction

In the world of tidal sediments and facies, tidal rhythmites occupy a peculiar place as they are the result of deposition governed by the cyclicities of the tides. At a similar high frequency time scale, there is no other dynamic that leads to such rhythmic sedimentation, and before the recognition of tidal rhythmites at the end of the 1980's it was hard to believe that a sedimentary formation could be preserved over a few decimeters to a few meters during several months, sometimes years, of deposition without hiatus. Although this is not always straightforward, the identification of tidal rhythmites within an ancient rock record constitutes above all absolute evidence for the action of tides. But tidal rhythmites are much more than a simple tidal dynamic proxy. Their highlighting and analysis allow us to define environmental conditions of deposition, to

discuss sedimentation rate and time preservation, to constrain ancient tidal regimes, and to access orbital parameters of the Earth-Lunar system, to name but a few processes (see e.g., the review by Coughenour et al., 2009).

The aim of this chapter is to present what are tidal rhythmites and to propose a tour of the applications of their recognition and study.

Tidalites and tidal rhythmites: definition and first description

In tidal environments, tidalites are vertically accreted laminated facies made of a succession of couplets composed of sand and clay (or silt and clay...), with thicknesses of millimeters to centimeters (**Fig. 1a**). To simplify, one couplet represents one single tidal cycle. Couplets can show a large range of shapes, from planar to rippled, giving rise to the well-known facies terminology of planar-, lenticular-, wavy- and flaser-beddings. Their heterolithic nature as well as the possible occurrence of bidirectional pattern of ripple migration, are good indicators of tidal dynamics, so that these facies are called in general tidalites. Tidalites have been described for a long time, starting with the pioneer works in the 1960's of Reineck & Wunderlich (1968) on tidal flats of the North sea coasts, and they probably can be considered as emblematic features of facies models (Klein, 1977).

Fig. 1 here

Tidal rhythmites (TR) are defined as tidalites that show rhythmic changes in thickness and/or shape of successive couplets directly related to tidal energy fluctuations and cycles, primarily neap-spring-neap cycles as shown on **Fig.1b to 1g** (*cf.* the definition in Tessier et al., 1995), although Reineck & Singh (1973) used the term tidal rhythmites to name simple tidalites. Ashton et al. (1981) described carbonated laminated tidal facies they named tidal rhythmites in the title of the article, but they are “only” tidalites.

The record of tidal cyclicities in sediment succession was described for the first time in migrating bedforms such as hydraulic dunes (sandwaves, megaripples). This was at the beginning of the 1980's thanks to the works of Visser (1980) on subtidal dunes preserved into the Oosterschelde in the Netherlands. He demonstrated that the thickening and then thinning of the successive prograding foresets composing the dune, called “tidal bundles”, could be correlated to the increasing and then decreasing tidal current velocity during the fortnightly neap-spring-neap cycle. The number of sets (28) matched the number of tides during the cycle. Since then, neap-spring-neap cyclicities were recognized within many ancient formations into migrating bodies (e.g., Allen, 1981; Allen & Homewood, 1984; Boersma & Terwindt, 1981; Kreisa & Maiola, 1986; Yang & Nio, 1985; see reviews in Coughenour et al., 2009 and in Nio & Yang, 1991).

Curiously, the recognition of tidal cyclicities in tidalites (i.e., vertically accreted tidal bundles), occurred later than their identification within tidal dunes; the first descriptions are published at the end of the 1980's (Dalrymple & Makino, 1989; Kvale et al., 1989; Tessier & Gigot, 1989; Tessier et al., 1989; Williams, 1989a, 1989b). This relatively late recognition of tidal rhythmites (TR) probably highlights the difficulties one had, at that time of facies model development, to admit the high rates of sedimentation TR implicate; it was easier to accept that a dune could migrate very fast under the action of a strong tidal stream. It is worth noting that Terwindt (1981) is probably the first author to show TR in his review of tidal structures and bedding into the inshore deposits of the North Sea. He suggested that the rhythmic facies he described were related to the neap-spring-neap cycles, but he did not go further into their description and interpretation.

Even more surprising, the first TR descriptions were published more or less simultaneously (in 1989), presenting both ancient successions and modern facies. The most fascinating work is probably the one published by Williams (1989a, b) on TR that remain, to date, the longest tidal rock record described. These TR (**Fig. 2**), from the Late Proterozoic Elatina Formation (South Australia) were first interpreted as varves and the rhythms they display as related to sunspot cycles (Williams & Sonett 1985). They were then re-interpreted as ebb-dominated deposits taking place into a pro-deltaic setting, and the rhythms attributed to tidal cycles (Sonett et al., 1988 and Williams, 1988, suggesting the Elatina rhythmites could be of tidal origin; Williams, 1989a). Here again, these impressive laminated facies were probably easier to conceive first as varved successions rather than tidal cycle controlled rhythmites.

Fig. 2 here

At the same time as Williams (1989a), Kvale et al. (1989) and Tessier & Gigot (1989) published other examples of TR, Pennsylvanian and Miocene in age, respectively. The detailed description and interpretation proposed by Kvale et al. (1989) of the Pennsylvanian tidal rhythmites (from the Mansfield Formation, Indiana, USA), with nearly 6 years of presumed continuous deposition, pointed out the potential of these rhythmic laminated tidal facies to allow conclusions to be drawn about the tidal regime (e.g., diurnal and semi-diurnal constituents, tropical vs equatorial tides, etc.) and about Earth-Moon system changes. The Miocene TR described by Tessier & Gigot (1989) from the subalpine foreland Basin of Digne, SE France, show “only” 5 months of tidal record in a subtidal environment controlled by a semi-diurnal regime with strong monthly inequality (from the perigean – apogean cycle). The measured outcrop is about 5 m thick, implying a sedimentation rate of 1 m/month. At the same time, Dalrymple & Makino (1989) and Tessier et al. (1989) described tidal rhythmites in the modern hypertidal settings of the Bay of Fundy (Canada) and the Bay of Mont Saint Michel (NW France), respectively. In the Cobequid Bay Salmon River estuary (Bay of Fundy), Dalrymple & Makino (1989) provided the first detailed description of tidal rhythmites within tidal flat deposits of the fluvio-tidal estuarine transition. The processes of deposition of individual tidal couplets (i.e., the vertically accreted tidal bundles) are outlined by the authors, explaining their differences in shape, constitution and thickness. The question of (in)completeness of neap-spring-neap (NSN) cycle record, i.e., of the number of individual tidal couplets according to the depositional area, is addressed as well. Modern tidal rhythmites of the Bay of Mont Saint Michel were described by Tessier et al. (1989) in the upper intertidal flat of the inner estuary, in order to explain that NSN cycle records are necessarily incomplete, and that the degree of incompleteness can be used in ancient records to differentiate subtidal TR and intertidal TR. The article by Tessier & Gigot (1989) provided a demonstration based on different outcrops of TR in the Subalpine foreland Basin of Digne (SE France) and was the first publication presenting both ancient and modern TR, explaining how modern TR study can help in better understanding ancient TR.

Note that among these initial articles describing TR, Williams (1989a, b) is the only author who used the denomination “tidal rhythmites” in the title and can be thus considered as the first introducing this term. However, Baird et al. (1986), in a study on taphonomic processes into Pennsylvanian formations of Illinois (USA), described rhythmic laminated facies, composed of successive sand-clay couplets they interpreted as tidal deposits and called TR. They suggested that the cyclic thickening - thinning packages of the successive couplets could be related to NSN cycles. Although TR successions are not precisely described by Baird et al. (1986), one may consider this is the first article where TR are evoked. As a last remark, as early as 1980, Ashton et al. described carbonated laminated tidal facies they named Tidal Rhythmites in the title of the article. However, they are tidalites, with no NSN cycle records.

Methodology for tidal rhythmite recognition

Successive sand-mud couplets, the thickness of which thicken and thin to form packages that repeat vertically, is the most obvious feature of TR in a sediment succession, and authorizes at first sight their recognition as TR laid down by the NSN cycle, both in modern deposits and ancient records. Counting the number of couplets per NSN package, where possible, to evaluate the consistency with typical tidal repeat cycles (14, 28, etc) is an additional and rapid approach to confirm a TR interpretation. However, such simple methods are usually not used on their own. Almost all TR interpretation include spectral analyses applied to couplet thickness evolution series. Using spectral analysis is considered as almost mandatory for proving the cyclic nature of deposition and its consistency with tidal cyclicities (Collins et al., 2018; Kvale, 2012). In the early studies, the very existence of TR was difficult to prove, and consequently solid proofs were needed, provided by spectral analysis, for the cyclical nature of the formations. More importantly, statistical and spectral analysis allow bringing out and quantifying characteristics of TR which are essential for a certain number of their applications, in particular those used, as it will be seen later, to calculate paleo-orbital parameters of the Earth-Moon system. Moreover, as it is pointed out by Coughenour et al. (2009) in their review, spectral analyses occasionally evidence other periodicities than tidal components, that may indicate for example seasonal variations in precipitation (e.g., Kvale et al., 1994).

In addition to simply use spectral analyses for studying ancient TR, a very useful approach is proposed by Kvale et al. (1995), Kvale (2012), and Archer et al. (1991). The principle is to compare a studied TR record and its spectral analysis results with predictive tidal height data set. This allows to directly fit the cyclic component spectrum contained into the ancient record with a given modern tidal system characteristics, and thus helping in precisely interpreting the TR. At last, and based on a similar principal, Archer (1991, 1995) and Archer & Johnson (1997) proposed to model TR deposition by using predictive tidal height data set and sediment erosion and transport equations, the reconstructed TR being compared with the ancient record.

This combined approach has allowed analysing ancient TR very accurately, by relating their detailed characteristics to specific tidal components and tidal systems. For instance, comparison with modern records can indicate if NSN cycles within studied TR are synchronized rather with the synodic month (i.e., the phases of the moon) in a semi-diurnal system, or with the tropical month (i.e., due to the lunar declination) in a diurnal or mixed diurnal dominated system. This could be an important issue for certain applications of TR since synodic and tropical months have not the same duration (modern values: 29.52 vs 27.32 days respectively).

Finally, although principles of actualism have been applied in general for TR recognition in rock records, relatively few articles deal with direct comparison between modern and ancient TR facies (e.g., Archer & Johnson, 1997; Lanier & Tessier, 1998; Pelletier et al., 2016; Tessier et al., 1989; Tessier et al. 1995).

Environments of deposition of tidal rhythmites

Most modern TR have been described within deposits of middle to inner estuarine environments (**Fig. 3**), and mainly intertidal facies (e.g., Archer, 2013; Choi & Park, 2000; Choi, 2011; Dalrymple and Makino, 1989; Deloffre et al., 2006, 2007; Fan et al., 2012; Féliès & Tastet, 1998;

Frouin et al., 2006; Greb et al., 2011; Musial et al. 2012 ; Park & Choi, 1998; Tessier et al., 1989; Tessier, 1993). This could be primarily explained because these environments have the easiest access within estuaries, with possible direct observations of outcrops into bank cuts along tidal and fluvio-tidal channels (**Fig. 3a, b**), as evoked by Klein (1998). The second reason is that the record and preservation of tidal signals in the form of TR necessarily require quiet, sheltered environments, protected from wave action and with low fluvial discharge (both processes can alter the cyclic pattern of tidal dynamics and deposition). Furthermore, the sediment supply should be high enough to record each tide, and accommodation is required for the vertical aggradation of TR. These conditions are generally achieved in inner estuaries, and TR can be considered as a diagnostic facies of the fluvio-tidal transitional zone (Dalrymple & Choi, 2007; Tessier, 1993; van den Berg et al., 2007; Wells et al., 2005). The fluvio-tidal transitional zone in estuaries is generally the place for the development of the turbidity maximum, providing large amounts of fine-grained sediments favourable for TR deposition. This is also the domain where nicely formed tidal bores propagate, inducing strong sediment reworking and the high sediment supply propitious for TR deposition (Fan et al. 2012; Furgerot et al., 2016a, 2016b; Tessier et al., 2017). Few examples of TR are described in the outer segment of estuaries (e.g., Fan & Li, 2002; Changjiang Estuary, China).

Fig. 3 here

Modern subtidal TR are not frequently described as they only can be observed in sediment cores. Choi et al. (2004) described subtidal TR at the bottom sets of IHS (Inclined Heterolithic Stratification) from a large-scale infilling sequence of a deep distributary tidal channel of the Han River delta (Korea). Similarly, subtidal TR are present within fluvio-tidal to tidal deposits cored into distributary channels of the Mahakam tide-dominated delta, Indonesia (Gastaldo & Huc, 1992) as well as the offshore deposits of the Amazon delta (Jaeger & Nittrouer, 1995). Thanks to gravity cores, subtidal TR are described as well in a deep-water macrotidal fjord (Cowan et al., 1998 from the Muir Inlet, Alaska), and along the subtidal slope of a glacier-fed delta due to tidal drawdown (Smith et al., 1990, upstream the Muir inlet, Alaska). Deep-water TR due to internal tides have not been recognised so far (Dykstra, 2012).

In terms of tidal regime, modern estuarine and deltaic settings where TR developed are all macro- to mesotidal. Tidal rhythmites described into low mesotidal to microtidal environments have rarely been described, with the exception of Shi (1991) from the Dyfi Estuary on the Western coast of Wales. Moreover, present-day TR are encountered in semi-diurnal systems and not in diurnally dominated ones.

The range of depositional environments of ancient TR is larger although many examples are interpreted as estuarine or deltaic facies, like modern TR, but either intertidal and subtidal (e.g., Allport et al., 2022 ; Brenner et al., 2000; Chakraborty & Kumar, 2003; **Chen et al., 2014, 2015**; Coueffé et al., 2004; Feldman et al., 1993; Greb & Archer, 1995; Hovikoski et al., 2005; Kvale et al., 1989; Kvale & Archer, 1990; Lanier et al., 1993; Pelletier et al., 2016; Quijada et al., 2016; Tessier & Gigot, 1989; probably Chan et al., 1994). TR are also interpreted to have been deposited in subtidal delta front (Adkins & Eriksson, 1998). Multi-year TR such as those described by Williams (1989a, Late Proterozoic), Miller & Eriksson (1997, Carboniferous), and Mazumder & Arima (2005, Late Paleoproterozoic) are interpreted as marine ebb-dominated deposition accumulated by suspension in prodeltaic environments, below wave base action. Mazumder & Arima (2013) described Mio-Pliocene TR in Japan thought to have been deposited in deep canyon. Other examples of TR interpreted as so are provided in Dykstra (2012). Finally, Buatois et al. (1997), combining sedimentary facies and ichnologic data in the Pennsylvanian Douglas Group of Kansas (USA), concluded that TR could be related to fresh water tidal flats. Kvale & Mastarlerz (1998), on the basis geochemistry data,

stated that part of the Pennsylvanian TR in the Illinois Basin were deposited as well under fresh water conditions in a tidal flat environment subject to extreme rain and runoff resulting in massive freshwater plume. They argued that freshwater TR are probably much more abundant than expected.

Some examples of ancient TR are interpreted to be related to dominantly diurnal systems (e.g., the Elatina TR, Williams, 1998; The TR of the Permian Barakar Formation, Chakraborty & Kumar, 2003; maybe the Brazil Formation TR, Kvale et al., 1995). This could be questionable because no TR in modern diurnal systems have been described so far. Moreover, diurnal systems are in majority associated with micro- to meso-tidal ranges, and very rarely to macrotidal ranges. When looking at modern examples, macrotidal ranges seem to be one of the main conditions of TR deposition, making it probable that most TR have been deposited in semi-diurnal to mixed diurnal to semi-diurnal tidal systems.

Finally, TR occurrence highlights very specific conditions of deposition usually found within inner estuarine systems (apparently less rarely in deep offshore settings). These conditions ensure simultaneously the preservation of TR, since they allow rapid vertical accretion. However, long duration (multi-month to multi-year) TR in estuarine sediment succession requires other conditions for it to be preserved. Rapid infilling of abandoned or blind tidal channels provides favourable condition of accommodation for such TR preservation (Brown et al., 1990; Greb & Archer, 1998; Roep, 1991; Stupples, 2002; Stupples & Plater, 2007; in Greb et al. 2011). Kvale & Mastalerz (1998) suggested that the necessary accommodation for some Carboniferous TR of the USA to be preserved has possibly been generated by a rapid collapse of underlying peat. Greb et al. (2011) proposed that instantaneous earthquake-induced subsidence may create accommodation for tidal flat aggradation. For instance, during the 1964 earthquake in Alaska, the macrotidal Turnagain Arm estuary subsided several metres. In the Miocene foreland Basin of Digne (SE France) well-preserved multi-year TR (*cf.* Fig.1g) have been found to be associated with syn-sedimentary tectonic activity of *en-échelon* synclines. Thus, very rapid subsidence events are as well thought to create the required accommodation for these Miocene TR (Coueffé et al., 2004).

Implications of tidal rhythmite recognition and interpretation

From the very beginning of TR research, researchers realized the significance of these tidal facies and the various implications they could induce. Since TR are the direct product of Earth-Moon system orbital dynamics, and may record without hiatus several months, even years of the later in certain cases of favourable conditions of deposition and preservation, they early have been considered as a powerful tool to extract information about the astronomical system during ancient times. Although this astrophysical implication is probably the most spectacular and unique in the world of sediment facies models, when excepted varve successions, TR provide many other types of information.

Tidal rhythmites as proxies for ancient tidal dynamic and environment identification, and paleogeographic reconstruction

The first application of TR recognition within rock records is the absolute evidence of the action of tides in the paleoenvironment. They demonstrate primarily that the latter are (somewhere) connected to the open ocean, and that the conditions for TR deposition and preservation, at a given place and moment, are fulfilled (i.e., sufficient sediment supply; no wave action). In many cases, TR

are proxies of deposition along the fluvio-tidal domain in estuarine to deltaic environments. According to the modern analogues, TR can also be considered to be indicative of macrotidal systems, with only few examples available from mesotidal systems, and almost none in microtidal ones. But TR are virtually useless to precisely quantify tidal range. The very high contrast of thickness between thin neap couplets and thick spring couplets were suggested to be indicative at least of macrotidal range by Tessier & Gigot (1989) in a Miocene TR, but this is not necessarily the case according to modern data (see Archer, 1995). Spectral analyses of lamination thicknesses from ancient TR allow extracting the different tidal (and non-tidal) components of the signal encoded into the TR. Such data are critical for paleogeographical reconstruction and modelling (e.g., Collins et al., 2018; Wells et al., 2005; Zuchuat et al., 2022) since tidal components primarily depend on the morphology and size of the basin where the tidal wave is generated, and of the shelf and coastal settings where it propagates. The characterization of the tidal regime for instance, from dominantly semi-diurnal to dominantly diurnal, is important to define which of the main tidal constituents are amplified. For many reasons, as explained in Kvale et al. (1995), mixed semi-diurnal to dominantly diurnal regimes can hardly be deciphered from TR analysis. To illustrate this difficulty, when looking at the TR preserved within the inner most part of the Bay of Mont Saint Michel estuary (Tessier, 1993), a very clear alternation of thick – thin couplet can occasionally be recorded (**Fig. 4**). Couplets are all flood-generated, so that thick-thin pairs necessarily reflect a diurnal inequality, although the tidal regime of the Bay of Mt St Michel is almost purely semi-diurnal with a very weak diurnal inequality. This means that the tidal diurnal component is probably amplified in the inner estuary. Therefore, conclusions about tidal regime drawn from TR analysis should be cautiously used for inferring paleogeographic reconstruction since the diurnal component for instance can be very locally and significantly amplified. It could be all the more equivocal that TR deposition is usually restricted to inner coastal domains.

Fig. 4 here

Note that in many cases, the recognition of TR in ancient successions allowed to confirm or specify the paleogeographical context of deposition of a given formation. Occasionally, highlighting of TR has provided evidence that contradicted previous interpretation, notably that the depositional environment was marine/coastal and not lacustrine/continental (e.g., the well-known example of the Elatina TR, Williams, 1989a; see discussion in Feldman et al., 1993; Quijada et al., 2016).

Tidal rhythmites as proxies of depositional elevation in a tidal environment

Modern and ancient TR are encountered in deep subtidal to upper intertidal facies. However most modern TR are intertidal, and most ancient TR are interpreted as such. During a single NSN cycle of about 14 days, in a semi-diurnal system, the 28 tides do not reach the upper intertidal area due to too low tidal range during neap tides. This means that along the middle to upper intertidal zone, NSN cycles preserved within TR do not contain 28 tides. Consequently, the number of tidal couplets preserved in a NSN cycle can be a proxy for the elevation of deposition along the intertidal zone, with the number of couplets decreasing progressively from middle to upper intertidal (e.g., Archer, 1998; Choi, 2011; Dalrymple et al., 1991; Roep, 1991; Tessier et al., 1989; Tessier, 1993). However, the number of couplets should be interpreted with caution: it depends on the capacity of tidal currents to produce a couplet. This is not necessarily the case of neap tides so that NSN cycles within subtidal to low intertidal TR do not necessarily contain 28 couplets (or even close to 28). On the contrary: high velocity tidal currents during spring tides can result in erosional processes instead of depositional event, so that couplets can be missing or partially eroded, giving rise to incomplete NSN cycles. Since most TR are typical of inner estuarine or deltaic domain, as well as of deep prodeltaic areas, such environments being characterized by a quite pronounced asymmetry with a

strong dominant current and a weak subordinate one, the sand-mud couplets they are formed with are, most of the time, related to one complete tidal cycle (the subordinate phase not being recorded). However, subordinate current induced couplet that can be recorded, which complicates the use of couplet number per NSN cycle for inferring elevation of deposition within the intertidal frame.

Tidal rhythmites as proxies of sedimentation rate measurement and time deposition estimates

Probably the most fascinating discussion resulting from TR occurrence is about sedimentation rate (e.g., Archer, 1991; Collins et al., 2018). Although the high rate of deposition TR imply is now largely understood and accepted, they can still be a source of astonishment and questioning from non-coastal sedimentologists. TR represent the sedimentary records of cyclic fluctuations of tidal dynamic energy that last from a few hours to a few years. By comparison, sedimentary records in wave- or storm-dominated environments can contain several hiatuses of undefined duration, whereas TR provide direct information on daily to monthly sedimentation rates because they have a very high potential for time preservation compared to wave-related facies. Daily to monthly sedimentation rates deduced from TR are generally of a few mm-cm to a few cm-dm respectively, but may reach up to 10 cm to 1 m, or even more, respectively. In all cases, such rates are extremely high at the scale of a sedimentary basin infill, particularly if they are reported at an annual scale. Except some rare cases of multi-year records (deep TR, abandoned tidal channel infill), TR usually record only a few months of continuous sedimentation, and only very rarely more than one year. This is mainly due to the dynamics of wandering estuarine (and tide-dominated deltaic) channels, the lateral movements of which are constant and rapid, inducing the reworking of previously deposited TR. Thus, a TR only features instantaneous sedimentation rates that cannot be extrapolated to a longer time scale, e.g., to the scale of an incised valley infill. However, TR provide information on the lateral variability of sedimentation rates within an estuarine tidal channel sub-environment, from subtidal and low intertidal zones close to the channel, to salt marshes, going through the middle to upper intertidal flat. The thickest and best-preserved TR, i.e., the highest sedimentation rate TR, generally develop within the middle to upper intertidal areas. Closer to the channel, due to high velocity tidal currents and enhanced erosional processes, TR are generally thin (and most of the time hardly recognisable, partly due to the non-preservation of mud drapes). Above intertidal elevations, thin to very thin TR develop in relation with very weak tidal dynamics and low sediment supply due to the reduced number of tides that submerge salt marshes. Elementary tidal sand mud couplets, generally less than a few mm in thickness, are still visible but NSN cycle records are no longer discernible. Tidal couplets are instead grouped in packages of annual origin, a few cm to a few mm thick, (Tessier, 1998; Archer, 2013; Allen, 2000). In these saltmarsh tidal facies, annual TR indicate sedimentation rates of the order of 1 cm/year, approaching average rates that can be estimated at a larger time scale of a tidal channel infill sequence and salt marsh growth, in accordance with the rate of sea-level rise (Allen, 1990; French & Spencer, 1993; French, 2006).

The TR preserved within tidal channel infill sequences and at a larger scale incised valley infill succession definitively highlight that the time preserved as sediment within a sedimentary record is absolutely not linearly distributed (as discussed in Archer, 1991 or Collins et al., 2018). When considering a complete channel fill sequence of about 5 m thick and representing a few 10 of years of infilling (i.e., representing the total displacement of the channel on the other side of the estuary, Billeaud et al., 2007) well-developed TR represent about one third of the succession. In total less than 1 year of cumulated time is maybe preserved as tidal couplets. Such estimate has been tentatively done in the Miocene foreland Basin of Digne (SE France) at the scale of 100 ka 5th order

sequences, up to 50 m thick, corresponding to incised valley infill succession in a tide-dominated deltaic system. The sequences contain a large amount of tidal facies, of which significant thicknesses of impressive TR (Couëffé et al., 2004; Tessier & Gigot, 1989). Time preserved as sediment within such tide-dominated sequences has been estimated to a few hundred to a few thousand years only (Couëffé et al., 2001).

The chronometer that TR represent, in addition to be useful for measuring rates of vertical sedimentation, is as well useful to study the rate and dynamics of lateral accretion of meandering tidal channels since TR are frequently preserved into IHS (inclined heterolithic stratification) packages (e.g., Choi et al., 2021; Choi et al., 2004; Cosma et al., 2022; Pelletier et al., 2016).

Tidal rhythmites as proxies of orbital parameter changes of the Earth-Moon system

Ancient TR have early been suggested as proxies for estimating parameters of the Earth-Moon system, such as the length of day and hence the Earth-Moon distance (Sonnet et al., 1988). Friction due to tides induces a deceleration of the rotation of the Earth, and consequently an acceleration of the rotation of the Moon that retreats (Bills & Gray, 1999). Accurate analysis of well-preserved TR allows quantifying variables, such as the number of lunar months and solar days per year, or solar days per lunar months, and by this way, going back to orbital parameters and their changes during geological times.

The analysis of TR to estimate Earth-Moon system parameters were developed for the first time on the spectacular TR of the Late Proterozoic (ca 620 Ma) Elatina Formation in South Australia (Williams, 1989a; 1990). The Elatina TR described by Williams (1989a) are a composite record of about 60 years of deposition, containing 1580 NSN cycles. The Elatina rhythmites were initially interpreted as varves, i.e., with individual laminae or couplet thought to be annual increments. The cyclicities they contain were found to be consistent with sun-spot variability cycles (Williams & Sonett, 1985). However, Williams (in Sonett et al., 1988; Williams, 1988) reconsidered his previous interpretation on the basis of new field information including other Late Proterozoic rhythmite outcrops from South Australia, the Reynella Siltstone and Chambers Bluff Tillite, in addition to the Elatina rhythmites (Williams, 1989a, 1989b). Although Sonett et al. (1988) are the first to decompose the tidal component spectrum contained into the Elatina TR, and to relate it with characteristics of the Earth-Moon system during Late Precambrian, Williams (1989a, 1989b, 1990, 1997) presented a detailed description of these Australian RT and their implications to reconstruct the history of the Earth rotation. Spectral analysis demonstrated that the Late Precambrian rhythmites represent the record of a full spectrum of tidal cycles, from semi-diurnal to the lunar nodal cycle. Williams (1989b) stated that these TR together provide a rare astrophysical window on the Late Precambrian Earth. From his analysis, Williams deduced that at ca. 620 Ma, a synodic month contained 30-31 solar days (29.53 today), one year about 13.1 synodic months (12.4 today), and thus that one year was 400 ± 7 solar days (365.25 today) and the solar day length 21.9 ± 0.4 hours (24 today). The lunar nodal cycle was estimated to 19.5 ± 0.5 years (18.6 today). This calculation provided the first value for the length of the day proposed for the Late Neoproterozoic. From the TR analysis, the mean rate of the lunar retreat as well was calculated and found to be much less than the measured present one. The Earth Moon distance was 96% of the present distance. To complement his TR data set, Williams (1989b, 1990) suggested that the banded iron-formations (BIF) of the Archean Weeli Wolli Formation, Western Australia, might be tide controlled, so might record information for very early Earth history. In 1998, Williams confirmed the paleotidal components previously found in the Late Precambrian

TR, and added for further demonstration the TR of the Big Cottonwood Formation (Utah, USA), the oldest TR so far highlighted, i.e., Late to Middle Proterozoic, 800 Ma to 1Ga (Chan et al., 1994).

Following Williams, Kvale et al. (1999) presented a very didactic article, partly included in Coughenour et al. (2013), explaining how to calculate orbital parameters of the Earth-Moon system using TR, mainly based on the numerous TR successions preserved into the Late Carboniferous formations of the Western and Eastern Interior Basin of the US (Kvale & Archer, 1990; Kvale et al., 1989). In the paper, Kvale et al. (1999) demonstrated that TR do not need necessarily to be of multi-year duration to encode orbital parameters, such as the Elatina TR that represent 60 years of deposition. In Williams' analysis, the number of NSN cycles per year is an important metric, and this number can be estimated with accuracy only in multi-year ancient TR. However, such formations are very rare. Based on predictive data of tidal heights at different locations, Kvale et al. (1999) demonstrated that only a few months of TR record is sufficient to extract Earth-Moon orbital parameters. The reliability of the approach was tested on modern tidal height data sets and the present-day values of orbital parameters and Earth-Moon distance. Based on their results, Kvale et al. (1999) presented an Earth-Moon distance curve (their Fig. 11) for the past 900 Ma, from the Middle to Late Proterozoic Big Cottonwood Formation (900 Ma) of Utah (the spectral analysis of which being done by Sonett et al. 1996; Sonett and Chan, 1998), to the Pennsylvanian Brazil Formation (305 Ma) in Indiana. Kvale et al. (1999) suggested that the changes in the rate of lunar retreat could be related with the formation of the Pangea super continent during the Paleozoic (that they propose induced an increase in tidal friction and thus a faster retreat; however see the results in Chapters 7-8 in this book and Green et al., 2017, for more recent results) and the subsequent break-up from the late Paleozoic. More recently, López de Azarevich & Azarevich (2017) added to the curve with the analysis of Early Cambrian TR (Puncoviscana Formation, NW Argentina) and new results were also provided by Daher et al. (2021, their Fig. 6b and Table 7). The issue with all of these studies is that they fail to put the Moon at the Roche limit (around 20000 km from Earth) at the time of the Moon forming event around 4.5 Ga, and more work into early-Earth tides are needed. Other limitations of the approach presented by Kvale et al. (1999) is that NSN cycles analysed in a studied TR succession should be complete, i.e., with no individual tidal couplets missing. Coughenour et al. (2013) concluded finally that short-duration TR studies provide estimations of the Earth-Moon distance of limited resolution and should be complement with multi-year TR analysis.

Conclusion

Tidal rhythmites are amazing sedimentary facies, the existence of which has however been difficult to admit, in particular because of the sedimentation rates they imply. Preserved in ancient sedimentary successions, they bear absolute evidence of the action of tides and, in certain cases, make it possible to reconsider previous interpretations concerning the depositional environments. The characteristics of the cyclic signal encoded in ancient tidal rhythmites were early considered a powerful way to explore ancient tides and ancient tidal regimes, so tidal rhythmites have major implications for paleogeography, as well as for calculating paleo-parameters of the Earth-Moon system. Tidal rhythmites are still the subject of research, first as tidal facies, in modern environments as well as in ancient formations, because they provide useful information on depositional processes and preservation conditions. Tidal rhythmites continue to be as well the subject of particular attention because they are the only geological object which would make it possible to trace the orbital parameters of the primitive Earth-Moon system.

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Figure captions

Fig. 1. From tidalites to tidal rhythmites. a) Tidalites from upper tidal flat in the fluvio-tidal transitional channel of the Sélune estuary, Bay of Mont Saint Michel (Polished slab sample stabilized with epoxy resin. Realisation: A. de Rességuier, photo B. Tessier). They are formed by stacked tidal couplets, of very variable thicknesses and shapes, but no cyclicities are obviously discernible. b, c, d, e) Modern Tidal rhythmites (TR), i.e., tidalites with rhythmic arrangement of successive tidal couplets into packages related to neap-spring-neap (NSN) cycles. b, c: TR into planar bedding (b: Inner Sélune estuary, Bay of Mont Saint Michel, photo. B. Tessier, bar scale: 3 cm; c: Inner Cobequid bay – Salmon River estuary, Bay of Fundy, thin section made from a sample collected in a video box, B. Tessier, total length of the section: 20 cm); d, e: TR into ripple bedding (Inner Sélune estuary, Bay of Mont Saint Michel, B. Tessier. Bar scale in d: 5 cm); f, g: Ancient TR, Miocene (Burdigalian), Subalpin foreland basin of Digne, photos B. Tessier (f: Saint Symporien cross section, cf. Tessier et al., 1989; g: The multi-year TR of La Rosée cross-section, cf. Couëffé et al., 2004). On all photos, but a and g, arrows indicate neap periods. On d: P, WB, FB for planar-, wavy- and flaser-bedding respectively, and N for Neap. On f, g: hammer as scale (i.e., 30 cm), red circled on g. In g, each layer, dm in thickness, represents one single NSN cycle.

Fig. 2. The tidal rhythmites described by Williams (e.g., 1989a, 1990), Late Neoproterozoic in age (South Australia), interpreted as ebb-dominated deposits settled down from suspension into an offshore pro-deltaic setting. a) from the Reynella Siltstone; b) from the Elatina Formation (Fig. 1 of Williams, 1998). N: Neap; arrows in a) indicate two of the thickest laminae (interpreted as diurnal increments) that contain 2 couplets (semi-diurnal increments).

Fig. 3. The preferential environment of deposition and preservation of tidal rhythmites: the estuarine fluvio-tidal transition (here, the Sélune river channel, Bay of Mont Saint Michel, photo B. Tessier). a) Gué de l'Épine locality, along the downstream straight section of the fluvio-tidal channel; b) Argennes locality, along the meandering section of the fluvio-tidal channel (cf. Dalrymple et al., 1992 for the section zonation along the fluvio-tidal transition; see Lanier & Tessier, 1998 for its application to the Sélune river estuary). In the foreground, the cross section into the channel bank cuts shows laminated facies that are tidalites. Most of the latter are tidal rhythmites (c, d, e). Arrows on c, d, e, indicate approximately neap periods, delineating successive neap-spring-neap cycles. In c, knife handle as scale: 15 cm.

Fig. 4. Examples of tidal rhythmites (TR) in the fluvio-tidal transition in the Sée-Sélune estuary (Bay of Mont Saint Michel, NW France) showing thick-thin pairs of couplets related to the diurnal inequality, although the Bay belongs to an almost pure semi-diurnal system. a) in the Innermost Sélune river estuary, Pontaubault locality. Coin for scale: 1 cm; b) in the Innermost Sée river estuary, Le Rivage locality. On a) and b), dark full lines highlight successive thick-thin pairs (with the dotted line inside to delineate individual couplets).

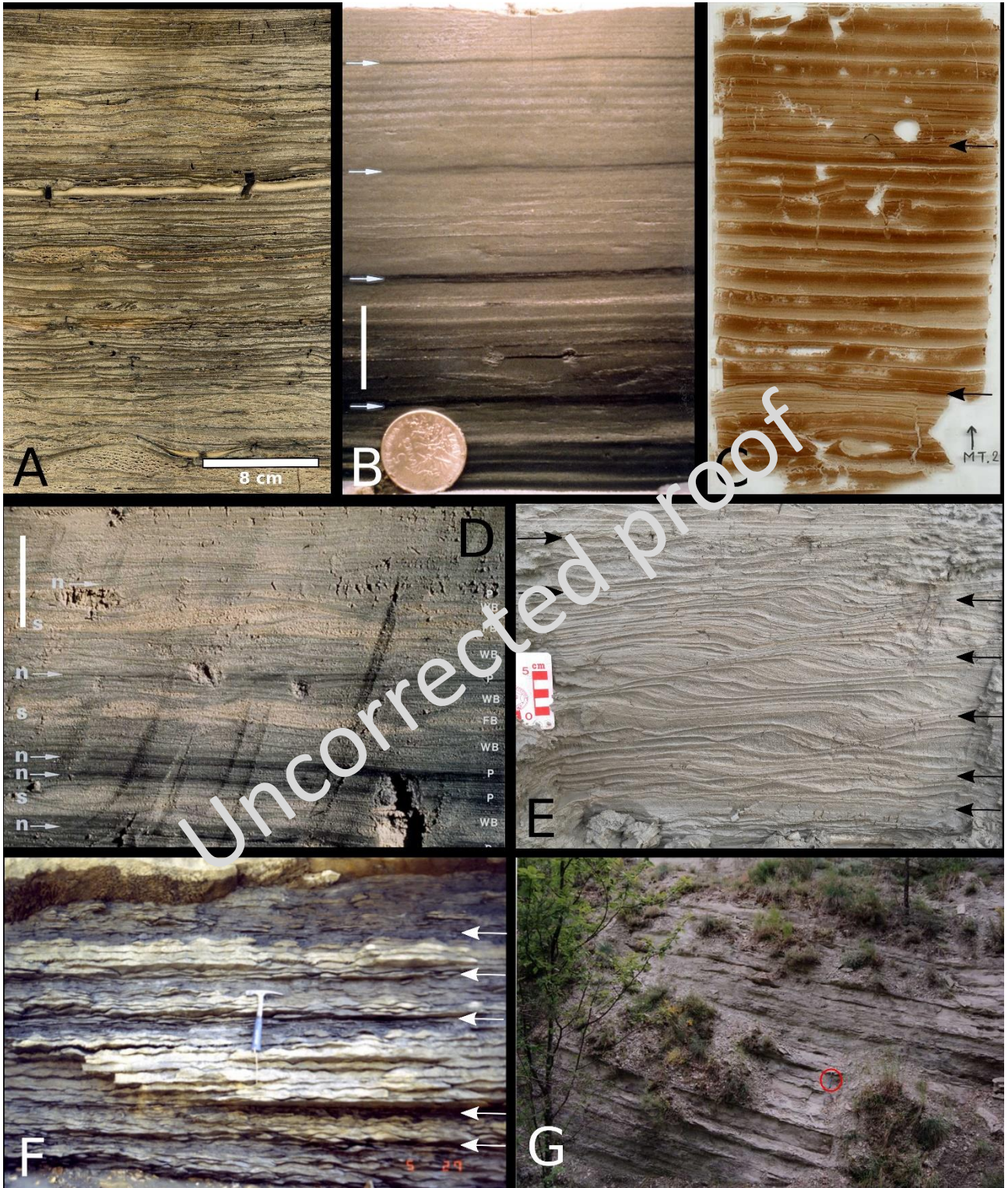


Figure 1

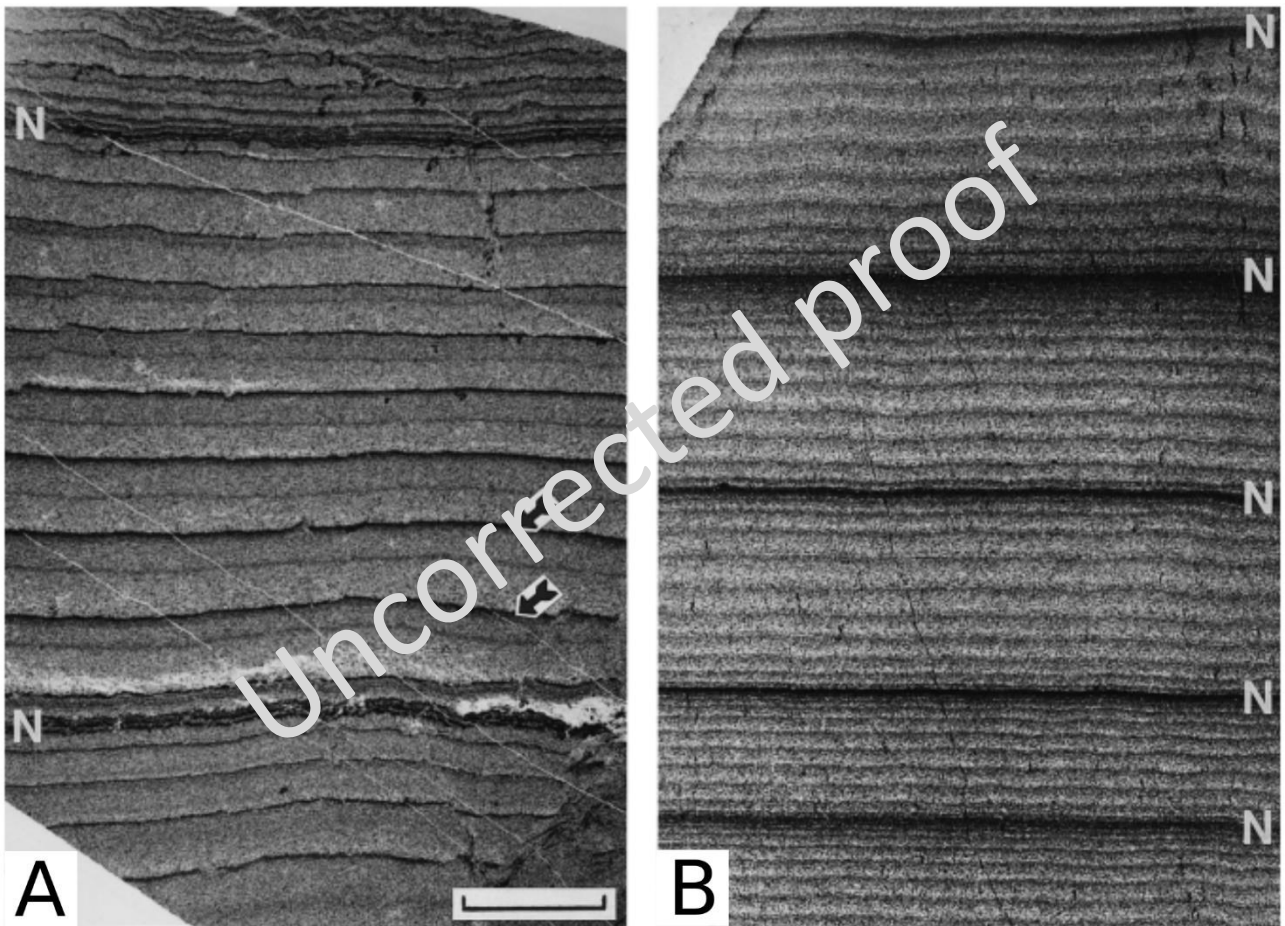


Figure 2

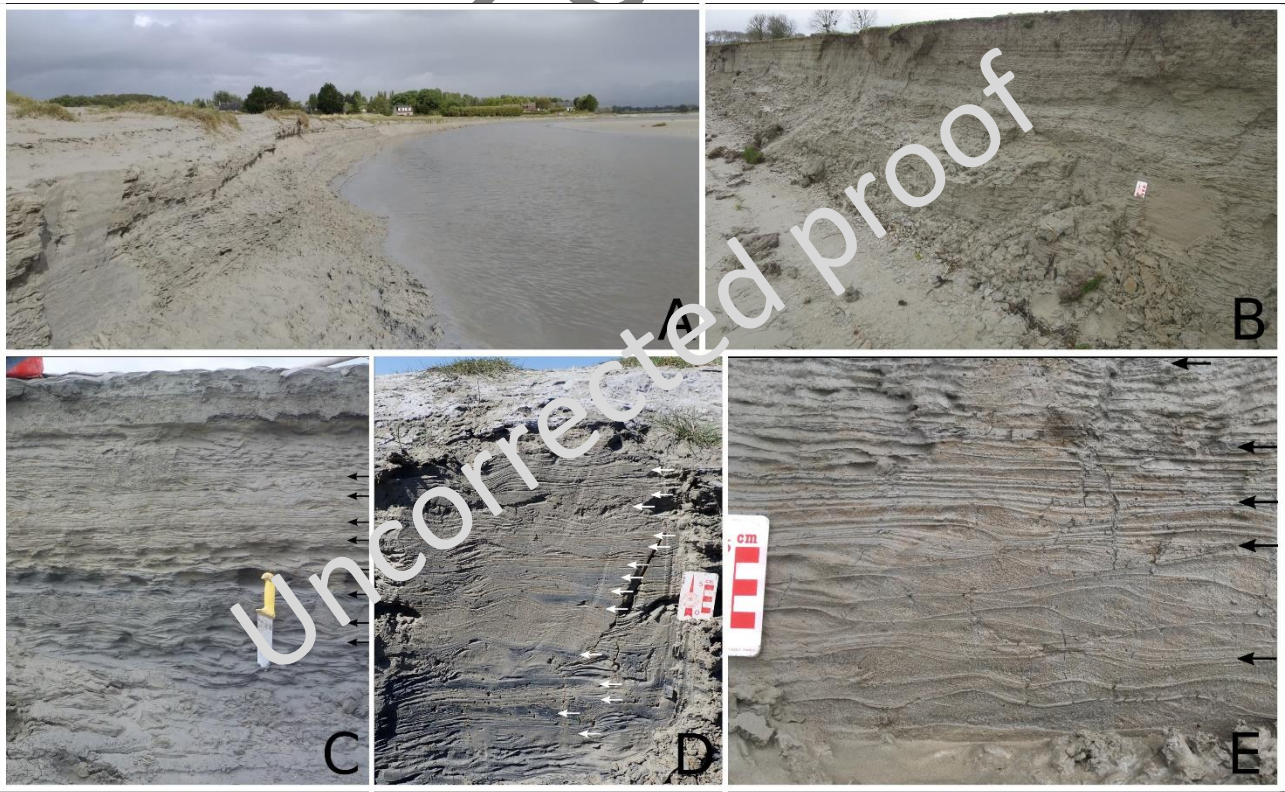


Figure 3



Figure 4

UNCORRECTED