AN EXAMPLE OF RIVER - OCEAN INTERACTION ZONE: THE FLUVIO - TIDAL CHANNEL IN ESTUARINE SYSTEM; A FACIES MODEL WITH CLIMBING RIPPLE BEDDING

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Abstract. Climbing ripples characterize a variety of sedimentary depositional settings in which suspension sedimentation exceeds the rate of traction transport, but are poorly documented from tidal environments. Research within a modern macrotidal estuary (Bay of Mont-Saint-Michel, France) demonstrates that this form of stratification is very common and also closely associated with tidal dynamics along the fluvio-tidal transition zone of macrotidal estuaries. Flood- and ebb-dominated climbing ripple facies (CRF) have been distinguished. Successive climbing ripple units are up 10 cm in thickness. Flood dominated CRF are associated with tidal channel levees found in the inner/straight channel zone of the fluvio-estuarine transition. In thicker CRF units, sedimentary structures indicate very high suspended sediment loads and rapidly decelerating flow velocity. Ebb-dominated CRF are found in chute channels and chute bars associated with the meandering zone of the fluvial-estuarine transition. The role of tidal dynamics in the formation of these CRF, both flood- and ebb-dominated, is indicated by the vertical organization and thickness evolution of the successive climbing ripple units. They are frequently arranged in packages of strata which thicken and thin progressively. These packages are tidal rhythmites and correspond to the sedimentary record of the neap-spring-neap cycle. The increasing energy from neap to spring tides is indicated by an overall decreasing angle of climb in the generalized bedding sequence (progradation is dominant), whereas the decreasing energy from spring to neap is evidenced by an increase of this angle (vertical accretion is dominant).

Résumé. Le litage de rides chevauchantes caractérise de nombreux environnements de dépôt dans lesquels le taux de transport en suspension est supérieur au taux de transport par traction sur le fond. Il est cependant rarement décrit dans les environnements tidaux. Des observations dans un estuaire macrotidal actuel (Baie du Mont-Saint-Michel, France) démontrent que ce type de litage se rencontre couramment et est associé intimement à la dynamique tidale le long du chenal de transition fluvio-tidale Des litages de rides chevauchantes (LRC) de flot et de jusant ont été distingués. Les unités successives à rides chevauchantes peuvent atteindre 10 cm d'épaisseur. Les LRC de flot sont associés aux levées de chenaux tidaux construites dans la partie rectiligne amont du système de transition. Dans les unités les plus épaisses, les structures internes indiquent clairement de très fortes charges en suspension et une décélération rapide de la vitesse du flot. Les LRC de jusant se rencontrent dans les chenaux et les barres de court-circuit associés à la partie méandriforme du système de transition. Le rôle de la dynamique tidale dans la formation du LRC de flot et de jusant est indiqué par le fait que les unités de dépôt sont fréquemment organisées selon des cycles de dilatation et d'amincissement qui matérialisent l'enregistrement du cycle de morte-eau/vive-eau/morte-eau. L'augmentation d'énergie depuis la morte-eau vers la vive-eau est également indiquée par une diminution de l'angle de chevauchement (progradation dominante) tandis que la diminution d'énergie de la vive-eau vers la morte-eau est reflétée par une augmentation de cet angle (accrétion verticale dominante).

Key-words: Estuary, macrotidal, climbing ripple bedding, tidal rhythmites, facies model, Mont-Saint-Michel Bay

INTRODUCTION

Climbing ripples or ripple - drift cross stratification are strata which are produced when ripples advance upslope, showing a positive angle of climb (Harms et al., 1982). Its formation requires a high suspended sediment load begins when deposition from suspension exceeds the rate of traction deposition. These sedimentary structures are generally associated with waning flow conditions and their aggradation is favoured by rapid deceleration of flow velocity when the transport capacity of the system in greatly exceeded.

Climbing ripple facies are very common in turbiditic, fluvial and deltaic overbank/ crevasse splay, and glacial outwash deposits where these fundamental physical parameters for their formation are common place. However, climbing ripples are poorly documented from tidal environments, both modern and ancient (Wunderlich, 1969; Yokokawa et al. 1995). It is the purpose of this paper to describe occurrences of climbing ripples from sedimentary facies located towards the fluvio - tidal transition from the Bay of Mont-Saint Michel estuary (France).

GENERAL PRESENTATION OF THE BAY OF MONT-SAINT-MICHEL ESTUARY (FRANCE)

The Bay of Mont-Saint-Michel, located in the wedge formed by the Cotentin and Britanny Peninsulas of Northwest France is a macrotidal embayment where tidal range reaches up to 15.3 m during high spring tides. The eastern part of Bay Mont-Saint-Michel defines the esturine portion of the system and is fed by two perennial river system, the See and Selune. Mean annual fluvial discharges are very low (10 to 20 m^3/s), and fluvial sediment input is similarly insignificant.

The system is tide-dominated. Maximum flood tidal currents during spring tides in this estuary can be as high as 2.5m/s in the channels, and range from 0.5 to 1m/s on the flats.

Flood velocities exceed those of the ebb flow (see Larsonneur, 1989 and 1994 for further description of the Mont-Saint Michel Bay).

According to Darlymple et al. (1992), tide - dominated estuaries into three main domains from the mouth to the head on basis of energy distribution: (1) an outer domain where elongated sand bars are developed; (2) an intermediate zone characterised by a braided system constituted by multiple channels and shoals; and (3) an inner domain represented by a single channel. This last, or inner portion of the estuary, is called the fluvio-tidal transitional zone which evolves from a relatively straight to a meandering channel, becoming straight again towards the opening of the outer estuary. The outer/ straight part of the transitional zone is tidally dominated, the inner/ straight part is fluvially dominated, and The meandering portion is a mixed zone that coincides with the lowest energy in the system (minimum tidal and fluvial energies).

This morphosedimentary model, which has been established for the macrotidal Cobequid Bay-Samon River Estuary (Canada), can also be applied to the Bay of Mont-Saint-Michel estuary. The major differences between the two macrotidal system is with regard to the lack of elongated sand-bar system within the outer portions (mouth) of the Mont-Saint-Michel estuary. Unlike Cobequid Bay in Nova Scotia, Mont-Saint Michel Bay is located along an open coast, and, as such, wave dynamics from the English Channel preclude the formation of elongate sand-bar systems. Moreover, sediments in this area of the estuary are medium - to fine-grained sands which do not allow for the formation of large dunes. Thus the mouth of the estuary consists essentially of a wide braid-bar system.

Climbing ripple stratification is very common upstream from the braid facies where the two river channels from the fluvial to estuarine transition. These two channels display a well developed straight-meandering - straight morphology, which is similar to the model of Dalrymple et al. (1992).

Along the fluvio - tidal domain, more or less extended intertidal and marsh areas are developed. They are characterised by silt - dominated sediments (very fine-grained sand to very fine-grained silt) that can contain up to 60% bioclastic, marine carbonate (shell debris) (Bourcart and Charlier, 1959, Larsonneur, 1994). This sediments is highly thixotrophic and easily reworked by currents. As a consequence, current stages during a typical tidal cycle are characterised by a very high suspended sediment load which can approach several thousand mg/l (Giraud, 1996).

CLIMBING RIPPLE FACIES: DESCRIPTION AND OCCURRENCE

Facies which characterise the intertidal domain along the fluvio - tidal channels of the Bay of Mont-Saint-Michel estuary are typically composed of heterolithic bedding such as planar -, lenticular-, wavy- and flaser-bedding. Vertical stratification sequences such as these are commonly associated with tidal rhythmites (TR). These stratification sequences correspond to the sedimentary record of neap - spring -neap cycles and can be considered as the most characteristic sedimentary facies along the fluvio- tidal domain in the Mont-Saint-Michel estuary (Tessier, 1993, Tessier et al., 1995). Climbing ripple stratification is also very common within the fluvio- tidal domain, and is frequently associated as well with tidal rhythmites. Both flood - and ebb-dominated climbing ripple facies (CRF) have been distinguished:

<u>Flood-dominated CRF</u>. Flood-dominated CRF are associated with channel levees found in the inner/straight channel zone of the fluvial to estuarine transition. Individual sediment-ation nits from the flood- dominated CRF can reach a maximum of 10 cm in thickness. The thickest units show a vertical sedimentary structure sequence from base to top consisting of normally graded, structureless (massive) stratification to planar laminae, through a transition to climbing laminae, and a mud drape. Climbing laminae display an upward evolution from a low to a progressively higher angle of climb. This evolution corresponds to a passage from erosional-stoss (Type A) to depositional stoss side (Type B) climbing ripple bedding (Jopling and Walker, 1968). The transition from climbing laminae to mud drape may be gradual, incorporating mud in the upper portions of climbing ripple sedimentation unit, but the contact is frequently sharp. The contact between successive units is sharp and generally non-erosive. The mud drape may be as thick as 1 cm and may create a smooth, planar upper surface which masks the underlying ripple morphology. In these cases, the morphology of the underlying rippled bedform has no control on the internal structuring of the subsequent sedimentation unit.

Frequently successive unit thickness asso-ciated with flood- dominated CRF thicken and thin progressively upwards. This pattern indicates the association of flood CRF with tidal rhythmites. The thickening is related to increasing energy from neap to spring and thinning related to decreasing from the spring to the neap. Thinner units in these neap- spring-neap records are normally graded with a thin mud drape.

Ebb-dominated CRF. Ebb-dominated CRF is associated with point bars in the meandering domain of fluvial- tidal transition. This facies more specifically characterises the upstream areas of point bars and the chute channel/bar system. Type B (Jopling and Walker, 1968) climbing ripple stratification is dominant in this facies and is formed by the superimposition of successive linguoid to sinuous crested ripple trains. Successive ripple crests are advanced to the lee side of the underlying ripple crest angle of the ripples is strongly controlled by the amount of sediment deposited from suspension and the substrate morphology. Mud drapes are generally absent or very thin in this facies, because of its intertidal position. However, when deposition takes place in a topographic, depression where standing water is retained during low tide, thin mud drapes may be formed and preserved.

Ebb-dominated climbing ripple facies are also associated with tidal rhythmites. This association is more obvious in the upper intertidal facies at the up- stream zones of tidal point bars. Neap- spring - neap cycles are recorded by progressive thickening and thinning of successive strata that vary, in this vertical succession, from thin parallel/wavy bedding to Type B climbing ripples, through thin wavy/parallel bedding. The increasing and decreasing energy during the neap - spring-neap cycle may also be materialised by progressive decreasing and increasing angle o climb in the Type B ripple succession. Thick mud drapes are lacking. Ebb-dominated CRF within chute channel/ bar facies of the point bars consist exclusively of Type B climbing ripples and are not so frequently associated with TR.

DISCUSSION

Within a fluvial transition to the open estuarine environment, climbing ripple facies could be assumed to be controlled primarily by fluvial dynamics. However, in the estuary of Mont-Saint-Michel, the occurrence of flood-dominated CRF, the low riverine discharge and the very low fluvial sediment loads which characterise this setting indicate that tidal currents play the dominant role in the deposition of sedimentary facies. Moreover, the association of climbing ripple facies with tidal rhythmites is compelling evidence that the sedimentation of these facies within the fluvio-tidal domain is closely related to tidal current dynamics. This correspondence also demon-strates that each climbing unit in the flood- dominated type and each ripple train in the ebb dominated facies, is the consequence of a single sedimentation event during flood and ebb stages respectively.

The deposition of climbing ripple bedding/stratification has been related to the rate of suspension sedimentation versus the aggradation rate of the traction load (Jopling and Walker, 1989). It has been established that the suspended load/bed load ratio increases from Type A to Type B climbing ripple stratification (Jopling and Walker, 1968).

In general, the formation of all types of climbing ripples for very-fine sands to silt-dominated sediment is favoured by a very high suspended sediment load and a rapidly decelerating flow velocity, such that from suspension exceed that of the bedload. The ratio of suspended silt to the traction load is also significant in this regard. In the Bay of Mont-Saint-Michel estuary, these hydrodynamic and sedimentation conditions are achieved during almost each single flood and ebb stage of the spring portion of the tidal cycle.

Measurements of suspended sediment load and current velocities in the Couesnon channel (Giraud, 1996), located in the southern part estuary, demonstrate that during flood stage of high spring tides, very high suspended sediment loads, reaching up to 10g/l, are induced by the passage of the tidal bore. Following this, current velocities decrease very rapidly. Although ebb current velocities are generally lower than those associated with flood flow, these measurements indicate that maximum ebb current velocities at mid flow are responsible for significant sediment reworking and thus very suspended sediment loads (1000 to 2000 mg/l). Such measurements have not been performed in the channels of the See and Selune Rivers where detailed observations of climbing ripple facies have made.

However, because of their comparable size and morphosedimentary characteristics compared with the Couesnon river, it is assumed that very similar processes occur in these channels as well.

Contrary to common tidal bedding, formed by planar-, lenticular-, wavy-and flaser bedding, that are widespread within the fluvio-tidal transitional zone, flood- and ebb-dominated climbing ripple facies appear to be associated with very specific depositional facies in the Mont-Saint-Michel estuary. The flood-type forms part of the levee facies in the inner/straight part of the fluvial-tidal zone, and the ebb-type characterises chute bar deposits in the meandering portion.

Along the fluvio-tidal channels of Mont-Saint-Michel estuary, natural levee aggradation can only occur during spring flood tides when the rising water overtops the channel shortly after the passage of the tidal bore. Fluvial levee formed by river flooding do not exist within this zone of the system. Moreover, these tidal flood levees are only found in the inner/straight channel portion of the transitional zone. Channels within the meandering zone of the system are apparently too wide to allow levee construction. In the inner/straight zone, however, the flow is concentrated in a narrower channel cross- section, limited on each side by marsh, and the intertidal flats are only a few meters wide. Channel overbanking occurs suddenly and remains restricted to the immediate channel margins so that levees can aggrade. Floods- dominated climbing ripple units are thought to be deposited at this time, and probably within a relatively short time interval insofar as reversal, from flood to ebb, is very short. Flood flow velocity decelerates and suspended silt- sized sediment load decreases rapidly during this transition. Mud drapes can be deposited during the relatively brief slack- water interval between flood and ebb.

Ebb-oriented climbing ripple facies have been identified within the meandering zone of the fluvio-tidal transition. These sedimentary structures are found at mid- to upper levels of point bars immediately downstream from the cross-over reach of the meander loop. They are somewhat less common, however because average ebb current velocities are generally too low to erode and transport a significant sediment load. The occurrence of ebb-dominated CRF in chute channel/bar facies is, however, consistent with the fact that ebb current velocities are herein dominant and thus can potentially lead to significant sedimentation. High sediment loads are transported from the channel and current velocities decelerate in the chute channel as flow velocities wain. In purely fluvial environment, climbing ripple lamination are present in chute bar facies sequences. But these fluvial chute channel sequences are deposited only during high river flood conditions are capped by mud drapes (Levely, 1978). The sedimentation of ebb-oriented climbing ripples found n Mont-Saint-Michel is not controlled by fluvial processes, although the hydrodynamic/sedimentologic conditions of their formation may be quite similar, but is related to current dynamics and the falling water stage during the ebb phase of the tidal cycle. High concentrations of silt-sized sediments are derived by erosion within the inner zone of the fluvio-tidal transition during maximum spring tides, and subsequently deposited as CRF during waining stages of ebb flow on the upstream zones of point bars and within chute channel/bar facies. The lack of a slack-water phase during this interval of the tidal cycle explains the fact these CRF do not commonly show mud drapes except in low-standing areas of the chute channel.

These observations of climbing ripples along the fluvio-tidal channels of the Mont-Saint-Michel estuary demonstrate that CRF deposition is closely related to the hydrodynamic and morphosedimentary characteristics that are specific to this setting. Thus, the distribution of flood CRF and ebb CRF as described herein may not necessarily define a general pattern that can be applied to all other macrotidal estuaries. For instance, in the Cobequid Bay- Salmon River estuary in Canada, flood CRF are found in the outer/straight to meandering part of the fluvio-tidal domain (Dalrymple and Makino, 1989, Dalrymple et al., 1991). this is never the case in the Mont-Saint-Michel estuary where flood CRF are restricted to the inner/straight channel zones of the system. Given this fact, flood-dominated climbing ripple facies may not be specific sedimentary facies indicators within the depositional setting along the transitional estuarine domain. Ebb-dominated CRF, however, remain strong evidence of deposition in the meandering zone of these system and are specifically associated with sediments deposited at the upstream ends of point bars and within chute channel/bar system.

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