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*Chapter 10*

# SILICICLASTIC TIDAL FLATS

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## THE CLASSIFICATION OF TIDAL FLATS

Hans-Erich Reineck (1972), in an article titled "Tidal Flats", defined tidal flats as "...sandy to muddy or marshy flats emerging during low tide and submerging during high tide...". This definition, while useful, can be ambiguous as the positions of low and high tides are time-variable (Fig. 10.1). The frequency of tidal flat inundation, examined over long time-scales (months to years) shows that approximately the lower 25% of the extreme tidal range is intermittently exposed, while the higher 25% is intermittently inundated, leaving only the central 50% consistently within Reineck's definition. Consequently, some divergences in classification of tidal flats have resulted, particularly at the two extremes of exposure. Klein (1985) and Wang and Eisma (1988) proposed a tripartite subdivision of the intertidal (littoral) region, bound between the subtidal (sublittoral) and supratidal (supralittoral) regions. Figure 10-1 shows this classification: their higher tidal flats occur between mean high water spring tides (MHWST) and mean high water neap tides (MHWNT) and are intermittently inundated; their middle tidal flats occur between MHWNT and mean low water neap tides (MLWNT) and are inundated by every tide; the lower tidal flat is situated below MLWNT and is only intermittently exposed. The supratidal region is rarely inundated (the exception being storm surges) and the subtidal region rarely exposed.

The genesis and character of sediments deposited within each of these three zones differ. Reineck (1972) observed that these sediments "...form a wedge-shaped body which is elongated parallel to the shore line, but may be intersected by channels and river estuaries.". His definition embraced the supratidal salt marsh as did Evans' (1965) classification, whereas Knight and Dalrymple (1975) and Klein (1985) excluded it. Klein (1985) defined tidal flats as "...low relief environments containing unconsolidated and unvegetated sediments that accumulate within the intertidal range, including the supratidal zone. They are present where salt marshes are absent or between the marsh and the subtidal environment.". It is sediment associated with this latter definition that is described in this paper.

Reineck (1978) and Weimer et al. (1980) considered tidal flats to be part of a genetically-related group collectively termed *tidal deposits*. Such deposits form largely on: (1) *intertidal flats* where vertical and lateral accretion are primarily influenced by waves and to a lesser extent by tidal currents; and (2) *subtidal flats*, where lateral accretion is dominant and tidal flow dominates over wave motion. For present purposes, *tidal flats* are equated with *intertidal flats*, although it is recognised that tidal influences may extend well below the level of extreme low water.

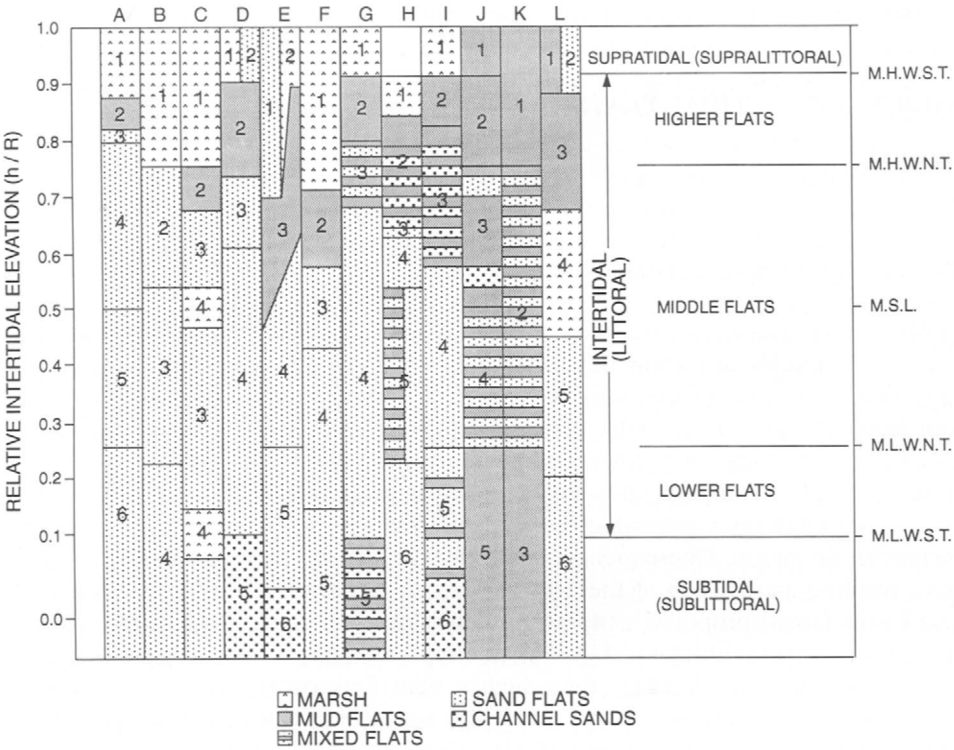


Fig. 10-1. A summary of the classification of tidal exposure and associated intertidal flat zonation. (*A*) Amos (1974; the Wash, U.K.): (*1*) salt marsh (silty clay); (*2*) higher mud flat (sandy silt); (*3*) inner sand flat (silty sand); (*4*) Arenicola sand flat (fine sand); (*5*) lower sand flat (fine sand); (*6*) channel sand (medium sand). (*B*) Carling (1981, Burry Inlet, S. Wales); (*1*) salt marsh; (*2*) higher sand flat; (*3*) lower sand flat; (*4*) subtidal channel. (*C*) Zhuang and Chappell (1991, SE. Australia); (*1*) salt marsh; (*2*) mangrove mud flat; (*3*) upper sand flat; (*4*) seagrass muddy sand flat. (*D*) Knight and Dalrymple (1975; Cobequid Bay, Canada): (*1*) salt marsh; (*2*) sand/gravel beach or mud flat; (*3*) mud flat (sandy silt); (*4*) braided bar (sand); (*5*) sand bar (sand); (*6*) basal gravel. (*E*) Amos and Joice (1977; Minas Basin, Canada): (*1*) high water storm beach (sand); (*2*) salt marsh (silty clay); (*3*) higher mud flat (sandy silt); (*4*) inner sand flat (silty sand); (*5*) lower sand flat (fine sand); (*6*) channel sand and gravel (medium sand to gravel). (*F*) Martini (1991; Hudson Bay, Canada); (*1*) upper salt marsh; (*2*) lower marsh; (*3*) higher tidal flat; (*4*) upper sand flat; (*5*) lower sand flat. (*G*) Reineck (1972, German Bay, Germany): (*1*) salt marsh (clay); (*2*) mud flats (clayey silt); (*3*) mixed flats (sand/silt); (*4*) sand flats; (*5*) channel deposits (mud and sand to gravel). (*H*) Evans (1965; the Wash, U.K.): (*1*) salt marsh (silty clay); (*2*) higher mud flats (sands and silty clay); (*3*) inner sand flats (very fine sand/silt); (*4*) Arenicola sand flats (very fine sand); (*5*) lower mud flat (sandy silt); (*6*) lower sand flat (fine sand). (*I*) Larsonneur (1975; Mont Saint-Michel Bay, France): (*1*) salt marsh (silt/clay); (*2*) higher mud flat (clayey silt); (*3*) muddy sand flat (sandy silt); (*4*) sand flat (fine sand); (*5*) biogenic sand (muddy sand); (*6*) biogenic gravelly sand. (*J*) Thompson (1968; Gulf of California, Mexico): (*1*) chaotic muds (clays); (*2*) brown laminated silt; (*3*) brown mottled mud (sandy silt); (*4*) gray burrowed clay; (*5*) gray laminated silty clay. (*K*) Wang and Eisma (1988; Wenzhou region, China): (*1*) higher mud flat (silty/clay); (*2*) middle mud flat (fine sandy/silt); (*3*) lower mud flat (silt). (*L*) Belperio et al. (1988, Southern Australia): (*1*) samphire salt marsh; (*2*) beach ridges (sand); (*3*) samphire algal mud flat; (*4*) mangrove; (*5*) sand flat; (*6*) *Zostera* flat and *Posidonia* seagrass banks.

McCann (1980) suggested four criteria for the classification of tidal flats: (1) sediment composition (carbonate or non-carbonate); (2) hydrographic position (intertidal or subtidal); (3) tidal range (macro, meso, micro); and (4) physiographic setting (estuary, delta, exposed coastline and continental shelf). He showed that tidal flats predominate in mesotidal and macrotidal (Hayes, 1975) settings of abundant sediment supply and low wave energy. Dionne (1988) followed closely the views of McCann (1980) and suggested that tidal flats be classified on the basis of: (1) tidal range; (2) geomorphological setting; (3) sediment type; and (4) geographic location. Ren et al. (1985) took a geomorphological approach to classify the tidal flats of China which are found in three distinct coastal settings: (1) embayment type; (2) estuarine type; and (3) open coast type. They also noted a distinction between: (a) prograding; and (b) receding types. China's tidal flats have been further subdivided by Wang et al. (1990) into: (1) silt flats; and (2) clay flats. This latter sub-division may be of wide application as the so-called mud flats of Minas Basin fall nicely into the silt flat sub-division (Daborn et al., 1993).

A summary of the gross geographical and geological factors leading to the development of tidal flats is given by Boyd et al. (1992) and Dalrymple et al. (1992). They propose that tidal flats prevail in regions sheltered from waves where the fluvial input is small; that is, they are the manifestation of progradation of sediments derived from a marine sediment source. According to Boyd et al. (1992), the morphological character and distribution of tidal flats depends on whether the coastline is transgressive or prograding; tidal flats on transgressive coasts are largely found in four geomorphic settings: (1) the low energy equivalent of a coastal strand plain on linear coasts; (2) the lateral portions of tidal-dominated estuaries; (3) the inner portion of wave-dominated estuaries; and (4) the inner portion of lagoons. Tidal flats on prograding coasts are more widely developed, but are largely found fringing the open coastline. Even the above elegant scheme is limited in application as it does not account for tidal flats on deltas such as those described by Kellerhals and Murray (1969) on the Fraser Delta and Wells and Kemp (1984) on the Mississippi Delta.

## SILICICLASTIC TIDAL FLAT RESEARCH

Early scientific descriptions of tidal flats were based largely on observations made in the embayments and estuaries bordering the North Sea. An excellent review of this literature is provided by Klein (1976). In this review we are acquainted with the attributes of tidal flats though surprisingly a rigorous definition of a *tidal flat* is not found. Although the term *tidal flat* may have been self-evident within the context of research in mid-latitude European cases, the proliferation of recent tidal flat research to other climatic and geographic regions tends to blur our earlier notions. These early notions came from Hantzschel (1939) who equated tidal flats with *wattenschlick* (tidal slime or mud) and associated sandy deposits that are found between high and low water levels of the German Bight. He showed remarkable insight in recognizing that the source of the sediments to the flats was largely the offshore, and that these sediments were intensively reworked by *sloughs* (creeks) that crossed the intertidal region. Van Straaten in the early 1950's extended our knowledge of tidal flat morphology and composition, and postulated on mechanisms for the formation of flats in the Wadden Sea. He also considered that *gullies* (creeks) were a major factor in reworking of tidal flat deposits, arguing that their lateral migration would in time largely rework the original facies of the flats leaving behind a series of basal lag deposits, and inclined heterolithic foresets (longitudinal oblique bedding of Reineck, 1972) diagnostic of point bar formation; only the inner flats would be spared this process. Evans (1965, 1975) broadened our understanding of tidal flats through a detailed study undertaken in the Wash. He expanded on the observations of van Straaten, and proposed a stratigraphic sequence of upward-fining sediments resulting from the lateral progradation and superimposition of adjacent sub-environments and preservation in a manner not unlike that of deltaic sedimentation. His marsh, upper mud flat and sand flat comprise the top-sets where vertical accretion dominates, and the lower mud flat and lower sand flat constitute the foresets where lateral progradation of the flat takes place. In his view, creeks were restricted to narrow belts on the tidal flats and consequently were of less importance in reworking the flats than was postulated earlier. The creek deposits would thus form narrow prisms of reworked sediments that would be oriented shore-normal, and which would be couched within the regional progradational sequence described below. These prisms would have a surface expression not unlike a meandering fluvial system (Reineck, 1975) with well-developed levées along which the landward-situated sub-environments would extend. The progradational sequence is evident as a series of shore-parallel sub-environments more or less in equilibrium with hydrodynamic conditions and exposure. Kestner (1975) contested the view of steady progradation and suggested that tidal flats were inhibited in growth by the fixed position of the low water tidal channel. He speculated that progradation would take place only in the presence of a sedimentation *umbra* cast onto the flats through reclamation of salt marshes or channel entrainment.

Kestner (1975) offered a further view of the role of creeks in tidal flat sedimentation. He proposed that the creeks enhanced vertical aggradation rather than lateral reworking; the levées of creeks being the pathways along which the salt marshes and mud flats of the Wash prograde seaward beneath the entrainment *umbra*. This mechanism was put forward to explain the origin of the seaward edge of the inner sub-environments which, though shore-parallel at a distance, are cuspate in detail. The cusps follow the creek levées seaward (Fig. 10-2). Kestner (1975) argued that the existence of cusps are diagnostic of a stable tidal flat in equilibrium with tidal inundation. Amos (1974) disputed this conclusion and proposed the opposite; that the cusps are diagnostic of active progradation: the larger the cusps, the greater the progradation rate. It follows that when no cusps are found the tidal flat would be either stable or in recession. Amos also proposed that creeks were responsible for a step-wise evolution of the tidal flats. Progradation would be rapid in those upper tidal flats fed by creeks, while the inter-areas would be relatively starved. In time, the inter-areas would capture the ebbing tidal flow, being relatively lower than the creeks, and the process of cusp development would begin again within the inter-areas.

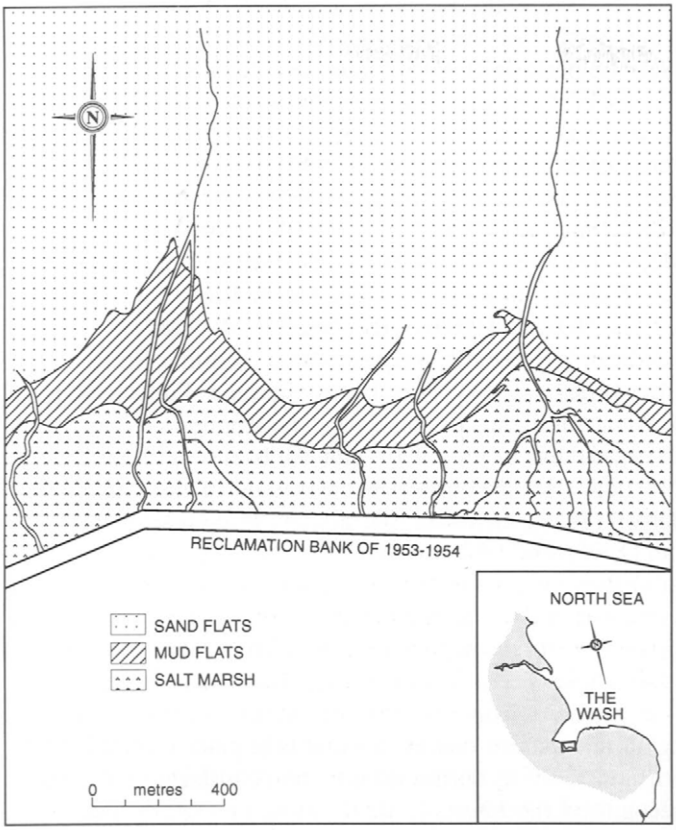


Fig. 10-2. The cuspate pattern of the salt marshes and inner mud flats of the Wash, taken from Kestner (1975). Note that the cusps follow the creek levées seawards. A smaller cusp appears in the process of development in the inter-area between the two major creek systems. The cusps have developed largely because of reclamation in 1868 and 1953/54.

The dominance of mud flats in turbid environments results in an abundance of creeks. Wang et al. (1990), working on flats adjacent to Bohai Bay and Huanghai (Yellow) Seas, showed that creeks occupy 10% of the flats by area and are the pathways for the transport of what little sand crosses these flats. Yet the shore-parallel zonation of sub-environments (a pattern that typifies sand-rich tidal flats) is still evident (Wang, 1983; Ren et al., 1983). Wang et al. (1983) suggested that the lower and middle flats prograde in a seawards direction in a manner similar to that of the tidal flats of the Wash where fewer creeks are found (Evans, 1965). The implication of this mode of development and the shore-parallel zonation of sub-environments favours sedimentation processes related to tidal inundation rather than one of creek reworking.

Tidal flats are found in three broad climatic regions (Dionne, 1988): (1) low-latitude tidal flats in arid and wet tropical or subtropical regions; (2) mid-latitude tidal flats of temperate regions; and (3) high-latitude tidal flats influenced by ice.

A review of the first group of tidal flats may be found in (but not restricted to) the collective works of: Thompson (1968) in the Gulf of California; Neumann et al. (1970) in the Caribbean Sea; Belperio et al. (1988) and Zhuang and Chappell (1991) in south Australia; Semeniuk (1981) in northern Australia; and Wells and Coleman (1981a,b) off the Orinoco and Amazon rivers. Papers on the second group of tidal flats include those of: Evans (1965), Evans and Collins (1975,1987) on the Wash; van Straaten and Kuenen (1957), Postma (1961), and Fitzgerald and Penland (1987) on the Wadden Sea; Klein (1963, 1985), Middleton et al. (1976), Amos and Long (1980), Dalrymple et al. (1990,1991), on the Bay of Fundy; Larsonneur (1975), Caline et al. (1982) on Baie Mont Saint-Michel; Carling (1981,1982) on the Burry Inlet, S. Wales; and Berner et al. (1986), Reineck et al. (1986), Dieckmann et al. (1987) in the Jade estuary and eastern Frisian Islands. Recently, a considerable amount of information on the tidal flats around the Bohai and Yellow Seas has emerged. This includes the work of Ren et al. (1985), Wang and Eisma (1988, 1990), and Zhang (1992) in China; and that of Frey et al. (1989), Adams et al. (1990), and Wells et al. (1990) in South Korea. The third group of tidal flats has largely been studied in the Americas by Champagne (1982), Anderson (1983), Grinham and Martini (1984), Dionne (1988), Smith et al. (1990), Martini (1991), and Isla et al. (1991).

Recent research on tidal flats has altered in focus from studies of morphology and internal structure to measurements of tidal flat dynamics. We are becoming aware that a bewildering variety of factors influence tidal flat sedimentation and stability (Nowell et al., 1981; Jumars and Nowell, 1984). Early papers account for the origin and evolution of tidal flats on the basis of the properties of the tidal inundation. It is becoming more apparent that events that take place during tidal flat exposure may be as important as those during inundation (Ginsburg et al., 1977). Anderson (1979, 1983) recognised the effects of desiccation, rain pit dislodgement, solar heating, plant and animal activity, and ice effects on the development of a mid-latitude tidal flat in the American northeast. Paterson (1989), Paterson and Underwood (1990) and Paterson et al. (1990) made similar observations on the tidal flats of the Severn and Tamar estuaries, U.K. The significance of exposure is also supported by the observations of Amos et al. (1988) and Daborn et al. (1993) in the Minas Basin, Canada. Twenty-fold increases in bed strength were measured over a summertime period when low water coincided with solar noon. Also, solar heating (by 2°C) occurred to a depth of 0.4 m below the sediment surface during a single exposure event (Piccolo et al., 1993), with consequent blooms of microphytobenthos and mucopolysaccharide production. Daborn et al. (1993) have linked increases in mud flat stability to significant increases in microphytobenthos production, the consequent population explosions of the amphipod *Corophium volutator* ($10^4/m^2$), and the subsequent frenzied feeding habits of the semipalmated sandpiper (*Calidris pusilla* L.). Similarly, the feeding habits of the snow goose (*Chen caerulescens)* appear to have an intense effect on the erosion of salt marshes in the Gulf of St. Lawrence, where deposition or ice effects normally dominate (Serodes and Troude, 1984). Faas et al. (1992) show graphic evidence of the effect of biostabilization in two photographs of quadrats of the mud flats of Minas Basin: one taken before application of poison to the quadrat region; and the other taken after poisoning.

The once adhesive mud flat was transformed in hours through poisoning into a non-cohesive rippled silt flat. The loss in strength was due entirely to the removal of a biofilm of mucopolysaccharides; a diatom exudate (Grant et al., 1986a). Such effects are not restricted solely to the mud flats; Grant (1981), Gerdes et al. (1985), Grant et al. (1982, 1986b), Montague (1984), Grant (1988), Meadows and Tait (1989), and Emerson and Grant (1991) have found similar effects of bio-stabilization on tidal sand flats.

The complexity of factors controlling tidal flat stability necessitates the use of innovative technologies and methodologies. The effects of microphytobenthos are largely restricted to the upper 2000 microns of sediment, so sediment indexes based on bulk properties are of limited use to explain them. This is perhaps most evident in the mismatch between measurements of the vane shear strength of marine sediments ($\sigma_v$), which is usually reported to be of order $10^3$ Pa (Christian, 1991), and the critical shear strength for erosion ($\tau_e$) which is usually of order 1–5 Pa (Amos et al., 1992). Given that $\tau_e$ is equated with the shear strength of the sediment (Mehta and Partheniades, 1982), we must acknowledge a discrepancy of three orders of magnitude in measurement.

The existence of fluid muds, gels and "fluff" layers are proving to be widespread in nature (Parker, 1987). The pseudo-plastic, non-newtonian, viscous behaviour of these sediment states is complex (Partheniades, 1984; Mehta, 1989,1991). It is strongly influenced by consolidation history and density (Hydraulics Research Station, 1980), physico-chemical activities within the sediment (Pamukcu and Tuncan, 1991), geochemical processes and redox state (Baeyens et al., 1991), as well as the rate of stress application (a rheological response, Faas, 1991; Julien and Lan, 1991). Opinions diverge on the influence of turbidity on the transmittal of fluid stresses to the bed and on the structure of the viscous sublayer, which is often millimetres thick. Consequently, a considerable amount of innovative work is in progress to determine the development of such bed states and the structure and density of slowly-consolidating seabeds at the micro-scale.

New in situ devices such as INSIST (Christian, 1991), the Cohesive Sediment Meter (Paterson et al., 1990), the Sea Carousel (Amos et al., 1992), and benthic chambers (Buchholtz-Ten Brink et al., 1989) are providing information on bed stability and the complex links between biosphere, geosphere, hydrosphere and atmosphere. The recent upsurge in the development of multi-disciplinary field programs to monitor synoptically tidal flat processes and attributes (Gordon et al., 1986; Daborn et al., 1993; LISP-UK, 1992) offer exciting possibilities for future discovery. It is only through such discoveries that advances in our understanding of tidal flat evolution will occur.

## THE ZONATION OF TIDAL FLATS AND RELATIVE ELEVATION

Virtually all tidal flats exhibit common variations in grain size, benthic floral and faunal diversity and abundance, surface morphology and slope that may be mapped into coherent sub-environments. In most cases, these sub-environments are oriented shore-parallel and occupy distinct positions with respect to exposure and tidal inundations (Evans, 1965; Klein, 1985; Dieckmann et al., 1987). The number of such sub-environments together with the specific attributes vary considerably. Figure 10-1 shows a variety of tidal flat sub-environments and their relative elevations above extreme low water ($h/R$, where $h$ is the height above extreme low water, and $R$ is the extreme tidal range). Two major groups of tidal flats are apparent: (1) *sandy tidal flats*, where the mean inorganic suspended sediment concentration (SSC) of the inundating waters is generally less than 1 g/l (Fig. 10-1, references A–I, and L); and (2) *muddy tidal flats*, where the SSC is generally greater than 1 g/L (Fig. 10-1, references J and K). Group 1 salt marshes and mud flats dominate above MHWNT (the higher flats). Differences in the highest relative elevation of the mud flat are large ($h/R = 0.8$–$1.0$), whereas the lower limit of the mud flat is relatively constant ($h/R = 0.75$). The highest limit of the mud flat is predicated on the degree and type of its colonization as well as by its wave exposure (Kestner, 1975; Groenendijk, 1986). In some cases the mud flat is replaced by a wave-formed beach above MHWST (Amos and Joice, 1977; Knight and Dalrymple, 1975; Belperio et al., 1988); in other cases there is no marsh (Thompson, 1968; Wang and Eisma, 1988; Daborn et al., 1991). In the absence of a marsh, the maximum relative elevation is $h/R = 0.91$ (Kestner, 1975). The transition from a colonized marsh to exposed mud flat in a prograding situation is gradational as is the transition to a sand flat. The latter gradient results in the mixed flats.

The mixed flats dominate between MHWNT and MSL ($0.5 < h/R < 0.75$). Though it is not evident in all the zonations shown in Fig. 10-1, it is nevertheless present in the form of a gradual transition from cohesive to non-cohesive surface sediments across the flats. The vertical extent of the mixed flats varies considerably ($\delta h/R \approx 0.02$ in Evans, 1975, to $\delta h/R \approx 0.25$ in Larsonneur, 1975). The large extent of the mixed flats reported by Larsonneur is due at least in part to lateral variations in sediment supply and wave activity; factors that also affect the zonation of Minas Basin tidal flats (Amos and Joice, 1977) as well as those of San Sebastian Bay, Patagonia (Isla et al., 1991).

The sand flats are prevalent between MSL and MLWNT ($0.25 < h/R < 0.5$). The relatively small vertical extent of this zone is often masked by the wide areal expanse that is the result of its low slopes (1:100 to 1:500). The sand flats are largely composed of fine and very fine sand. This explains the absence of large-scale bedforms, which are formed in medium sand or coarser (Middleton and Southard, 1984), and the dominance of small-scale wave-formed and current-formed ripples (Amos and Collins, 1978; Dingler and Clifton, 1984). The lack of relief of these sand flats is undoubtedly due to the fineness of the sand, which is readily mobilized as sheet flow (Tables 10-1 and 10-2). The lower mud flat of the Wash (Evans, 1965) stands out as a notable exception to the above trends. Found between MSL and MLWNT, it intermittently occupies a position within sandy sub-environments. The typical concentration of suspended particulate matter over the flats of the Wash is between 100 and 1000 mg/l (Evans and Collins, 1975; Collins et al., 1981). This range overlaps the concentration range detected over the flats of Minas Basin, Bay of Fundy (Amos and Long, 1980) where no lower mud flat exists. Biological colonization of the sand flats is especially prevalent in low latitudes. The presence and relative elevation of mangroves, algal mats, bacterial mats, halophyte grasses, sea-grasses and green algae is highly variable, though generally restricted to $h/R > 0.3$ (Ginsburg et al., 1977). Elsewhere, the edible mussel *Mytilus edulis* is responsible for the generation of vast quantities of pseudo-faeces that overprint the normal trends in tidal flat zonation. Being composed largely of fine-grained material, it is these pseudo-faeces that have formed the lower mud flat of Evans (1965) in the Wash, in a region where medium sand would otherwise dominate.

The channel sands prevail below MLWNT ($h/R < 0.25$). They are largely composed of medium sand or coarser material. The transition from the sand flat to the low water tidal channel is associated with an increase in slope and an increase in grain size. The coarser material in this region is less easily fluidized and may, therefore support the higher slopes (Komar and Li, 1986; Li and Komar, 1986) diagnostic of the low water tidal channels and the associated banks and bars. Furthermore, the coarser size of material together with higher flows results in the characteristic large-scale bedforms (sand waves and megaripples), bars and flood and ebb tidal channels described by Dalrymple (1977), Knight (1977), Lambiase (1977), Klein (1985) and Boothroyd (1985).

Group 2 tidal flats are characterised by the dominance of mud flats and mixed flats and the lack of a sand flat. Even so, a seaward coarsening of surface sediment is apparent in the form of a clayey salt marsh that grades to a mud flat (mixed silt and clay) and ultimately to a silt flat near low water (Fig. 10-1, references G–I). There is a much lower diversity in biological colonization of this group than is evident in group 1. The upper (clayey) mud flat predominates above MHWNT ($h/R > 0.75$). This is the turbid equivalent of the salt marsh and mud flats of group 1. Group 2 mixed flats are present between MHWNT and MLWNT ($0.25 < h/R < 0.75$). They cover a much broader range in elevations than do group 1 equivalents, and they occupy the position of the group 1 sand flat. Group 2 lower mud flats are found below MLWNT ($h/R < 0.25$), where they occupy the position of the channel sands of group 1.

The lack of sand on the group 2 tidal flats may be a function of supply rather than process. For example, the mud flats of China (which comprise approximately 50% of its coastline), the western coastline of South Korea, and off the Orinoco, Amazon, and La Plata rivers (all highly turbid environments) show marked differences from those which fringe the North Sea. High amounts of suspended silt and clay from the Huanghe, Changjiang and Zhujiang rivers (Wang, 1983) result in the development of extensive clay-rich mud flats bordering the Bohai and Yellow Seas and the virtual obliteration of the sand flat sub-environment. The work of Thompson (1968) on tidal flats in the Gulf of California gives insight into the factors controlling group 2 tidal flats. He found that his tidal flats were undergoing conversion from mud flats to sand flats due to a reduction in the supply of fines to the flats brought about by the construction of hydro-electric dams on the Colorado River. Wells and Coleman (1981b) also found active mud deposition under the turbid plume of the Orinoco River in a region of "moderate" waves. Is, therefore, the extent of mud flats mainly a function of supply and concentration? Also, are the hydrodynamic effects during tidal flat inundation and the effects of tidal exposure of second order importance only? To examine these issues we must look at the processes of tidal flat sedimentation. In the next section we examine two well-documented tidal flats: those of the Wash, U.K., and the Bay of Fundy, Canada.

## TIDAL FLAT SEDIMENTATION — A COMPARISON BETWEEN THE WASH AND THE BAY OF FUNDY

### *Mud flat deposition and sediment supply*

The dynamics of tidal flat aggradation and progradation by tidal inundation requires a knowledge of both cohesive and non-cohesive sediment behaviour within the water column as well as on the bed. This involves complex processes of erosion, transport, deposition and consolidation (Dyer, 1986). Many studies of the transport and deposition of tidal flat deposits exist, but less work is available on bed consolidation and the processes of subsequent erosion. The characterisation of tidal flat deposition began with the long-term, detailed observations of Inglis and Kestner (1958) who, on the basis of these observations, postulated that tidal flats grow only because of influences of marsh reclamation. Deposition rates on these flats are indeed generally low (10–20 mm/a) and time-variable (Amos, 1974). Also, this rate will vary with relative height across the flats (Kestner, 1975; Dieckmann et al., 1987). Dalrymple et al. (1991) in a paper on mud flat deposition in the Bay of Fundy, indicate that the history of mud flat deposition may be divided into two phases: a short-lived period of rapid aggradation, followed by a longer period of quasi-equilibrium in which accretion is slow and the deposits are more intensively bioturbated. For the Wash, Kestner (1975) proposed a similar evolution of mud flats following the exponential forms:

$$\frac{\delta h}{\delta t} = 0.836 - 0.136h \tag{10-1}$$

and

$$h = 6.16 - 0.479\mathrm{e}^{-0.136xt} \tag{10-2}$$

where $h$ is the elevation and $x$ is distance across the flat. The relationship is purely empirical as it is independent of SSC, tidal current speed or wave exposure. Also the influence of creeks is unknown. Kestner (1975) measured accretion rates that were in excess of 60 mm/a adjacent to creeks, which suggests a possibly strong contribution from this source. Also he found that the accretion rate was accelerated by marsh colonization of *Spartina alterniflora*, although the maximum elevation for accretion remained the same as that of exposed mud flats (0.71 m below MHWST; Fig. 10-3). Accretion measurements made by Amos (1974) along three transects of the tidal flats of the Wash, and illustrated in Collins et al. (1981), show a shore-parallel arrangement in deposition rates. The highest rates (20–100 mm/a) are on the upper mud flats and sand flats, intermediate rates (10–20 mm/a) are on the marsh, and the lowest values (including erosion) are in the tidal channel. This pattern of accretion

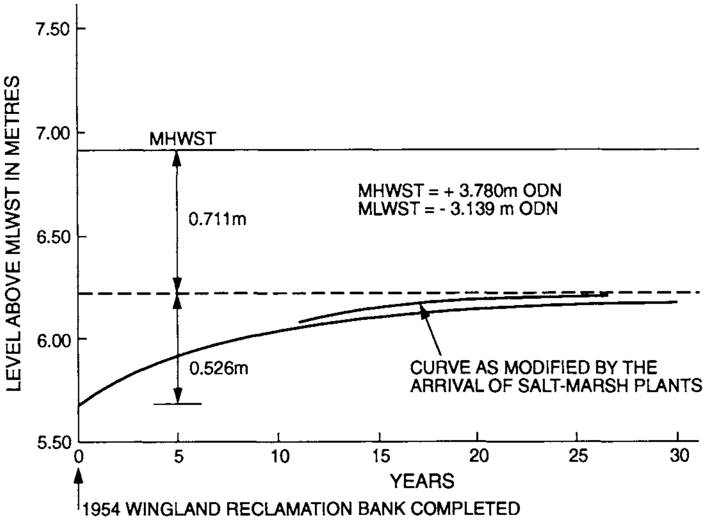


Fig. 10-3. The accretion of the mud flats in the Wash that has resulted since the construction of the reclamation dyke shown in Fig. 10-2. The pattern is asymptotic to a maximum elevation of 0.71 m below MHWST (*ODN* = Ordnance Datum, Newlyn). Notice that marsh plants may accelerate the process of accretion, but the asymptote is the same as for bare mud flats.

suggests that the colonization by halophytic plants takes place with a *reduction* in the rate of sedimentation on a mud flat; a trend opposite to that of Kestner (1975). Furthermore, the pattern of accretion across the Wash tidal flat is not consistent with the long-term progradation of an equilibrium profile (where accretion rate is in direct proportion to the slope). It does, however, lend support to the original hypothesis of Inglis and Kestner (1958) that marsh reclamation dominates the long-term progradation of the tidal flats. Yet this hypothesis must be flawed, as it disallows the existence of tidal flats where no engineering schemes exist.

So how do sediments move headwards onto the flats and what factors control deposition? The mechanics of tidally-driven sediment motion onto and across a tidal flat was postulated to be the product of "settling and scour lag" originally defined by Postma (1954, in Postma, 1961) and van Straaten and Kuenen (1957). These authors attempted to explain the enrichment of fine sediments in the deposits of the Dutch Wadden Sea relative to the source (the North Sea). Postma (1961, 1967) used similar arguments to explain the gradient in SSC in the Wadden Sea where no apparent residual flows were found to justify it. He attributed a net landward drift in suspended solids to a change in sediment behaviour from high to low tide. This, he reasoned, was due to a longer high water still-stand (and therefore greater deposition) at high tide than at low tide, and the development of yield resistance of the newly-deposited sediment...

> "Towards high tide, when the flood current velocity has decreased sufficiently far, nearly all material sinks to the bottom. The sediment is not again brought in suspension by the returning ebb current before the latter has reached a velocity considerably higher than that

> of the flood current at the moment of deposition. In this manner the material is resuspended in a water mass the relative position of which is farther inward than that of the water mass which carried the material during the flood. At low tide a considerable part of the material remains suspended and is thus not subject to a process similar to that at high tide, which would otherwise approximately compensate the latter. Consequently, over a whole tidal cycle, this material undergoes a net inward displacement."

In short, it is the imbalance of the benthic (vertical) flux integrated over a tidal cycle that results in the shoreward residual motion of exotic material.

Groen (1967) pointed out the short-comings of the advective approached described by Postma (1961) and warned that:

> "In reality, only the statistics of the behaviour of the suspended particles is described by the current."

He used a diffusive approach to show that the shallow-water asymmetry of the flood and ebb current durations (while assuming the flood and ebb current speeds to be of equal magnitude, which is rarely the case) control vertical exchanges of sediment within the benthic boundary layer. These in turn produce vertical concentration gradients in the benthic boundary layer which influence the magnitude (not the direction) of the suspended sediment residual motion. A headward transport of suspended solids results, which may be up to 38% greater than the seaward motion. His explanation for this effect is:

> "the ebb current maximum is preceded by a much longer period of low current velocities than is the flood current maximum, so that during the former period there is much more time for the particles to settle down. And the ebb peak of the suspended load is the lower one because it has to be reached from a much lower preceding minimum."

The residual flux, according to Groen, is sensitive to the settling lag. It increases as the particle settling rate increases and as the mean water depth decreases. Perhaps the greatest insight into the process of residual sediment motion onto tidal flats comes almost as an after-thought wherein Groen warns us that:

> "as soon as (even by this very process) gradients [longitudinal] of concentration of suspended sediment have been built up, the process of ordinary tidal and turbulent mixing will cause a down-gradient exchange of matter which eventually will counter-balance the action of the former process."

Simply stated, the headward flux due to tidal asymmetry should be balanced by seaward diffusion due to a seaward-decreasing SSC-gradient. This, then raises several issues. Firstly, if such a balance exists then an equivalent equilibrium gradient in SSC should also exist. Secondly, if this equilibrium condition exists, then what is the mechanism of sediment import? Thirdly, if the equilibrium gradient in SSC is upset (for example by wave resuspension over the flats) can a largely-importing system export material? And if so, does this imply a (long) time-varying residual flux of material to and from the flats?

The answer to the first question comes from synoptic measurements of SSC taken along the length of Cumberland Basin, Bay of Fundy by Keizer et al. (1976) over a

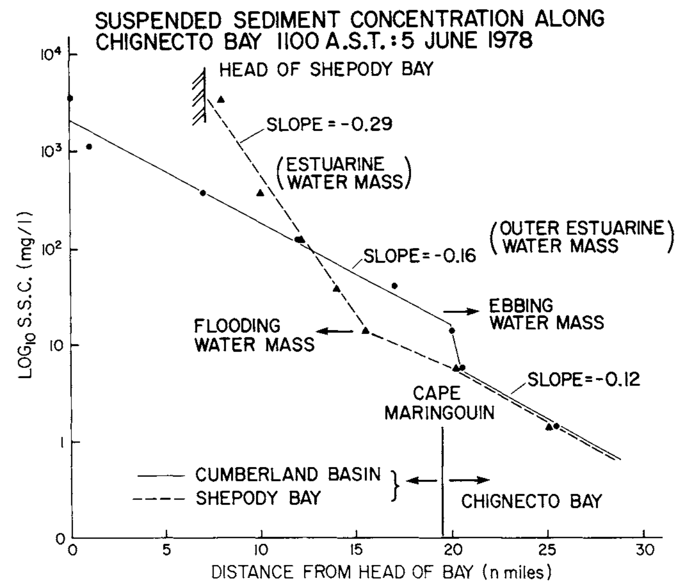


Fig. 10-4. The exponential decay of SSC as measured along the central axis of Chignecto Bay, Bay of Fundy (5th June, 1978).

period of two years. These observations clearly demonstrated a gradient of SSC that conformed in all cases to an exponential decay function of the form:

$$\mathrm{SSC}(x) = \mathrm{SSC}_0 \mathrm{e}^{-kd} \tag{10-3}$$

where $\mathrm{SSC}_0$ is the concentration in the turbidity maximum and $k$ is the decay constant which varied with season between −0.023 and −0.091 about a mean (storm-free) value of −0.049 (Fig. 10-4; Amos and Tee, 1989). The existence of the SSC-gradient yielded the means of accurate estimation of the total suspended mass in the Basin through integration of the product of SSC and cross-sectional area along the basin length. It was thus found that, for the two years that Keizer and co-workers carried out their measurements, the total suspended mass in Cumberland Basin remained remarkably constant at $10^5$ metric tonnes. This despite fluctuations in SSC in the inner bay (normalized to the tidal limit) of 0.6 g/l to 15 g/l. Similar gradients with similar decay constants were found by Amos and Tee (1989) in other embayments (of similar tidal range) of the Bay of Fundy. This finding points to the existence of an equilibrium SSC-gradient that is independent of local sediment supply, wave exposure, or basin geometry, and supports the notion of an equilibrium *capacity* of a restricted tidal water mass which is continually being upset, and which the system is continually striving to maintain.

So, the residual transport of sediments may be viewed as a diffusive rather than an advective process, and appears to be the product of a *dynamic balance* between landward transport due to tidal asymmetry and seaward dispersion due to the resulting SSC-gradient as suggested by Groen (1967). The nature of the *dynamic balance* in the SSC-gradient becomes apparent when it is understood that the SSC-gradient in the Bay of Fundy is largely controlled by the balances between the sources and sinks of sediment along the Bay. During periods of ice break-up and wave activity (resuspension from the tidal flats) the equilibrium gradient is exceeded through sediment input at its upper end with a consequent export of material in suspension (Amos and Tee, 1989). The mechanism of import, in the case of an abundance of sediment supply, appears to be governed by the capacity of the tidal flats to accommodate new material from suspension; precisely the concept proposed by Evans (1965). If there is no accommodation space for suspended solids, then export must balance import irrespective of settling or scour lag; the system is *accommodation space limited.* Where accommodation space is available, then import will take place either up to the rate of maximum mass deposition on the higher flats, or to the rate governed by supply. This latter case we may term *supply limited.* Within these two extremes, the headward sediment flux is most sensitive to SSC; the higher the SSC the greater is the flux. A sensitivity analysis of the parameters influencing this residual flux under conditions of zero SSC-gradient was carried out by Amos and Tee (1989). The parameters tested were: SSC; the critical threshold for deposition, the critical threshold for erosion; the erosion rate; and the settling rate. This analysis showed that variations in SSC (over observed concentration ranges) have a much larger effect on the residual flux of suspended solids than do variations in the thresholds for erosion and deposition, or indeed the particle settling rate. Changing the erosion threshold (over reasonable limits), the basis of Postma's (1961) hypothesis, did little to alter the residual horizontal flux.

The tidal region thus behaves somewhat like a *bellows*, constantly adjusting the sediment flux at its source to maintain a constant *sediment capacity.* This being so, then it follows that the residual flux across the tidal flats is a dynamic balance between the ability of the flats to accept sediments and thus prograde, and the supply of that sediment. Returning to the tidal flats of the Wash, we see that the reclamation *umbra* of Kestner (1975) provides the accommodation space for an increase in sediment import, and that this *umbra* extends half way across the flats (Amos, 1974). In the absence of such an *umbra*, sediment import would be reduced in order to be lock-stepped to natural progradational processes as defined by Evans (1965).

Evans (1965) proposed that the accretion and associated zonation of tidal deposits were the result of a gradual reduction in capacity and competency of the inundating tidal flows:

> "...The gradually decreasing velocity of the tidal currents as they move in over the intertidal flats causes a reduction in the capacity and competency of the waters and results in a gradual differentiation of the load."

This concept of competency is visualized by reference to Fig. 10-5. In this figure we see six (6) thresholds respecting sediment behaviour through which passes an hypothetical plot of asymmetrical tidal current speed. These thresholds are: (1) the threshold for mud deposition also approximately equal to the transport threshold of very fine sand; (2) the threshold for bedload motion of medium sand; (3) the threshold for the erosion of mud flat sediments; (4) the suspension threshold for

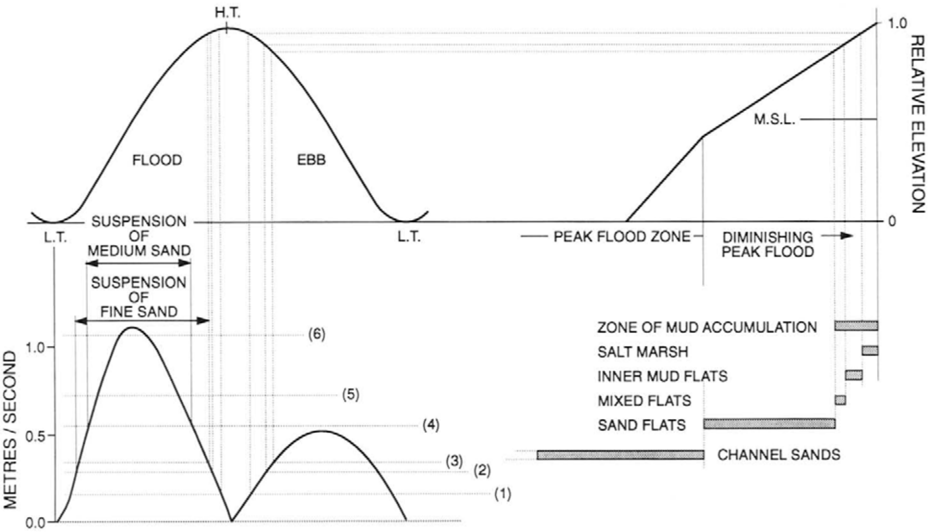


Fig. 10-5. A schematic illustration of the change in competency of the tidal flows over a tidal flat. Six thresholds are defined that appear to adequately explain the zonation of sediments in the Wash: (*1*) the threshold for deposition of fine-grained sediment; (*2*) the threshold for motion of fine/medium sand; (*3*) the threshold for erosion of mud flats, and the suspension of fine sand; (*4*) the suspension threshold of fine/medium sand; (*5*) the traction threshold of gravel; (*6*) the suspension threshold medium/coarse sand.

fine/medium sand; (5) the traction threshold for coarse sand and gravel; and (6) the suspension threshold of medium/coarse sand. Following each of these threshold lines upwards through the curve of tidal elevation, thence across to the tidal flat profile yields the relative elevations above which each of the thresholds is not exceeded by the inundating tidal flows. The regions between respective thresholds provide the spatial range in energetics within which discrete sedimentary sub-environments are potentially formed. In this example we see that only the region landward of (above) threshold (3) will accommodated mud flats and that the region between thresholds (3) and (4) will host the fine sand of the sand flats. The landward gradient in peak flow occurs only on the flats above approximate MSL. Below this level, the entire flats are subject to the peak in tidal flow, and so no zonation of the bed on the basis of peak tidal energy is possible.

The notion of capacity, particulary in the Wash, is less easy to define than is competency. The papers of Evans and Collins (1975, 1987) clearly show that the Wash is well below its capacity and that many of the turbid events that bring a large part of the sediment to its flats are unrelated to local conditions of weather or sea state, and are probably transported alongshore with the residual current. In order to maintain the integrity of these turbid *events* the settling rate of the constituent material must be extremely low. As a consequence, the relative importance of settling and scour lag is much reduced (Groen, 1967). Yet, as we have seen, deposition on the mud flats of the Wash continues to take place.

A graphic example of mud flat deposition can be seen in the Avon River estuary, Minas Basin. A solid-fill causeway constructed across that estuary resulted in the rapid development of a mud flat within the sedimentation *umbra* to its seaward side. The deposition rate and net accretion of this mud flat were found to conform to the trend inherent in eq. (10-2) and was still in excess of 360 mm/a nine years after causeway construction. It has now reached *phase 2* of mud flat development (Dalrymple et al., 1991). This mud flat is colonised by halophytic plants and is no longer actively accreting. It is, however, prograding seawards over the tidal sand flats at its seaward edge. Recent surveys undertaken by Vaughan Engineering Associates Ltd. (1993) show net accretion of 1–2 m (in the 20 years between 1972 and 1992; 50–100 mm/a) some 5 km seawards of the causeway. Thus the *umbra* of the causeway appears to be propagating down the estuary at an approximate rate of 200 m/a. The rate of mass settling ($\delta M/\delta t$) and the net deposition ($D$) on this tidal mud flat were calculated using the following equations of Krone (1962):

$$\frac{\delta M}{\delta t} = \mathrm{SSC}\, W_{\mathrm{s}} \left(1 - \frac{\tau_0}{\tau_{\mathrm{d}}}\right) \tag{10-4}$$

and

$$\text{Net deposition } (D) = \sum \mathrm{SSC}(t)\, W_{\mathrm{s}} \left(1 - \frac{\tau_0(t)}{\tau_{\mathrm{d}}}\right) \delta t \tag{10-5}$$

where $\tau_0$ is the ambient shear stress at time $t$, and $\tau_{\mathrm{d}}$ is the critical shear stress for deposition (Fig. 10-6), given as 0.12 $\mathrm{N/m^2}$ by Creutzberg and Postma (1979). Particle settling rates ($W_{\mathrm{s}}$) of the material in suspension over the Avon River mud flats varies between $1.2 \times 10^{-4}$ and $3.3 \times 10^{-4}$ m/s and the SSC of the inundating water mass is circa 100 mg/l (Amos and Mosher, 1985). The predicted mass settling [using eqs. (10-4) and (10-5)] and that observed on the causeway mud flat were within 20% (Amos and Mosher, 1985). The inferences of this are that (1) sedimentation within the *umbra* is purely the result of a reduction in flow speed, and (2) that the pattern of deposition may be estimated with reasonable accuracy provided in situ measures are made of the free parameters and that waves are unimportant. In situ monitoring of mass settling rate ensures that the appropriate mode of settling is used (floccule settling, mass settling or hindered settling; see Dyer, 1986 for review).

### *Mud flat erosion*

The erosion of mud flat sediments takes place in two ways: as Type I erosion — where the erosion rate quickly reaches a maximum and then decreases with time in an exponentially-decaying fashion; and as Type II erosion — where the erosion remains constant with time. The first type of mud flat erosion, also called *surface erosion* by Mehta et al. (1982), we term as *benign* as the process is self-limiting and short-lived. This pattern of erosion is equated with the breakdown of weak primary bonds of surface organic aggregates and pellets under hydrodynamically turbulent smooth flow. The erosion rate peaks within 30 seconds of application of the bed shear stress and is order $10^{-4}$ $\mathrm{kg/m^2/s}$. After attaining this peak it quickly drops back

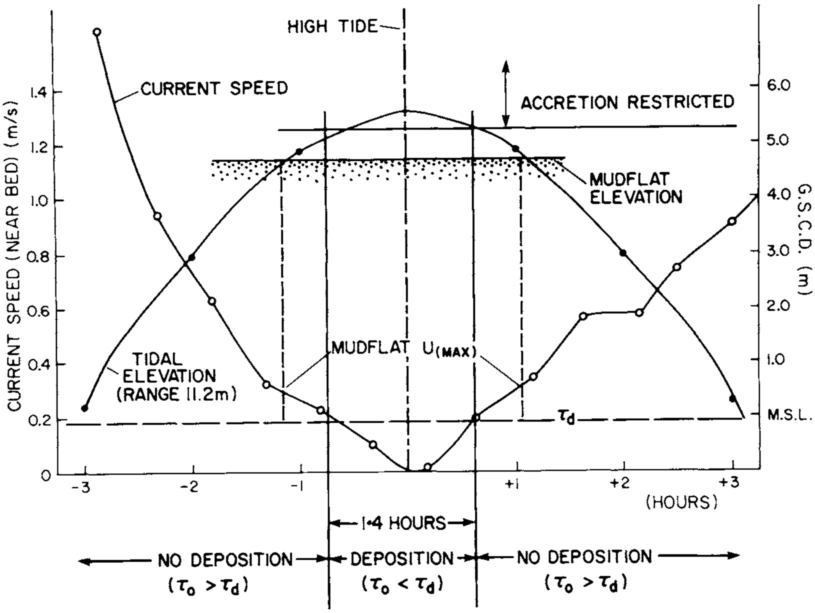


Fig. 10-6. A schematic diagram of the tidal inundation of the Avon River mud flat and associated current speed. The bed shear stress for deposition ($\tau_d$) is also plotted. Notice that deposition was possible for only 1.4 hours about high tide. Once the mud flat reaches an elevation whereby the inundation period is less than 1.4 hours the mud flat becomes *accretion restricted*.

to zero within 2 to 3 minutes. This erosion type takes place at relatively low bed shear stresses (0.2 to 2.5 Pa). Type II erosion, also called *bulk erosion* by Mehta et al. (1982), we term as *chronic* as much higher values of SSC are the possible result. The peak erosion rates are comparable with those of Type I erosion, however, the erosion continues unabated. This pattern of erosion occurs at bed shear stresses in excess of 4 Pa; that is, under turbulent rough conditions of flow. Under such conditions, excavation of roughness elements (through spatially-varying hydrodynamic pressure distribution) can take place with failure along planes of weakness defined by the microfabric of the sediment. Much of the evidence for the above comes from *in situ* observations made by Amos et al. (1992). They found 5-fold variations in mud flat strength (equated with the critical shear stress for surface erosion) over 20 days of observations, and spatial variations of the same magnitude. Also, the rate of bed erosion showed no relationship to the absolute bed shear stress, but was strongly correlated to the *excess* bed shear stress in the exponential form:

$$\ln\left(\frac{E}{5.1 \times 10^{-5}}\right) = 1.62[\tau_0 - \tau_e(z)]^{0.5} \qquad (10\text{-}6)$$

where $E$ is the erosion rate, $\tau_0$ is the applied bed shear stress, and $\tau_e(z)$ is the critical bed shear stress for erosion at depth $z$ below the original (un-eroded) sediment surface. Recent evidence with the Sea Carousel (unpublished data, 1992) shows that the erosion rates and threshold vary considerably with location. Consequently, accurate predictions of the responses of mud flats to applied stresses without prior in situ measurements are unlikely in the near future. There is, however, some hope in predicting the fate of newly-deposited sediments where the consolidation and stress histories are known.

*Sand flat stability and the transport of non-cohesive sediment*

The evolution and stability of the fine-grained sand flats (as distinct from the bars, channels and banks of the Bay of Fundy) has had less attention than the mud flats. The detailed measurements of Collins et al. (1981), however, shed insight into the stability of these sand flats. They detected considerable amounts of sand in suspension across the flats, the majority of which was in the fine sand range. The effects of peak tidal flows observed by Collins et al. (1981) and by Amos (1974) along the transect of the suspension measurements, are plotted against relative intertidal elevation in Fig. 10-7. The competency of the peak flow across the flats is expressed in terms of the bed shear stress ($\tau_0$), which decreases landwards across the sand flats in a linear fashion. The potential effect of the flow on seabed material [of mean diameters ranging from fine sand ($D_{50}$ = 100 microns) to gravel ($D_{50}$ = 2500 microns)] is expressed in the mode of transport (no motion, bedload or suspension).

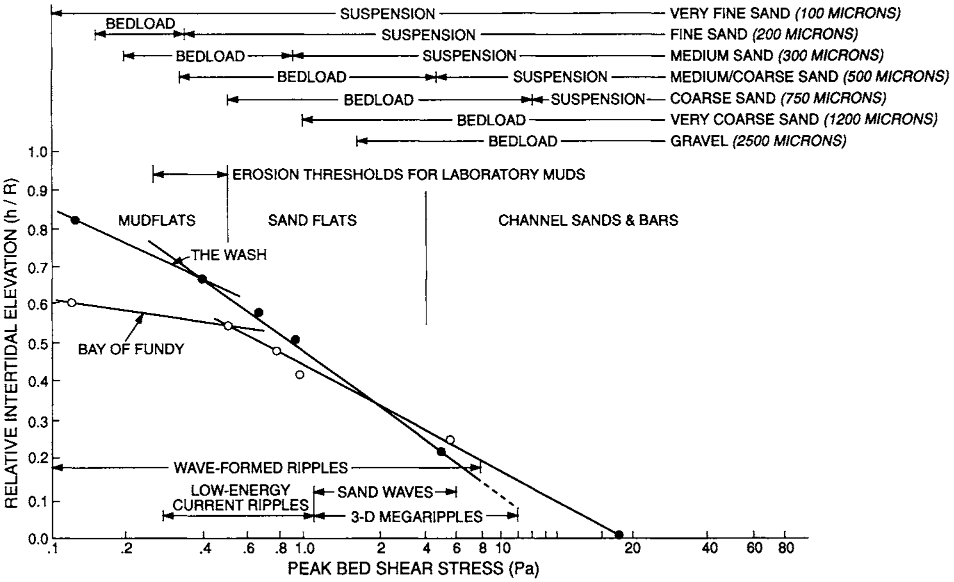


Fig. 10-7. A comparison between the peak bed shear stresses across the tidal flats of the Wash (•), and Minas Basin (○). Notice that the flows are comparable over the sand flats and in the low water tidal channel, but diverge over the mud flats and marshes. The higher nearshore current speeds in the Wash is reflected in the higher relative elevation of the mud flats and mixed flats. Also shown in the figure are the range of thresholds for erosion of laboratory muds (taken from Amos and Mosher, 1984), and the modes of transport (no motion, bedload or suspension) of sediments ranging in mean diameter from very fine sand (100 microns) to gravel (2500 microns).

Also shown is the potential range of bedforms (ripples, megaripples or sand waves) across the flats based purely on peak bed shear stress. The threshold for traction is based on a solution of the modified Shields parameter $\Theta$ (after Yalin, 1972):

$$\Theta = \frac{\tau_0}{(\rho_s - \rho_0) g D_{50}} = \alpha = 0.05 \quad \text{for} \quad \frac{U_* D_{50}}{\nu} > 2.3 \tag{10-7}$$

and

$$\alpha = f\left(\frac{U_* D_{50}}{\nu}\right) \tag{10-8}$$

so

$$\tau_{0\,\mathrm{crit}} = \alpha[(\rho_s - \rho_0) g D_{50}] \tag{10-9}$$

Also

$$\Theta = 0.1 \frac{\nu}{U_* D_{50}} \quad \text{for} \quad \frac{U_* D_{50}}{\nu} < 2.3 \tag{10-10}$$

where $U_* D_{50}/\nu$ is the grain Reynolds number, $U_*$ is the friction velocity, $\nu$ is the kinematic viscosity, $\tau_{0\,\mathrm{crit}}$ is the threshold bed shear stress, and $(\rho_s - \rho_0)g$ is the sediment buoyant unit weight. The suspension threshold is based on the suspension criterion of Bagnold (1966):

$$\Theta = \frac{0.64 W_s^2}{(\rho_s - \rho_0) g D_{50}} \tag{10-11}$$

The range of possible bedforms is based on thresholds defined by Allen (1982) for wave and current ripples, and Dalrymple et al. (1978) for large-scale bedforms.

The results of the above analyses are given in Tables 10-1 and 10-2 for the Wash and Minas Basin, respectively. Note that the peak flows have the competency to move gravel as bedload to the approximate position of MLWNT while coarse sand could

Table 10-1

The Wash — peak velocity ($U_{max}$), peak bed shear stress ($\tau_{max}$) and sediment transport mode as a function of relative elevation $(h/R)$[a], for a range of grain sizes found on tidal flats ($D$ in metres)

| $h/R$ | $U_{max}$ | $\tau_{max}$ | $D_1 = 0.0001$ | $D_2 = 0.0002$ | $D_3 = 0.0005$ | $D_4 = 0.001$ | $D_5 = 0.002$ |
|---|---|---|---|---|---|---|---|
| 0.95 | 0.05 | 0.01 | – | – | – | – | – |
| 0.82 | 0.15 | 0.12 | susp | – | – | – | – |
| 0.67 | 0.32 | 0.38 | susp | susp | – | – | – |
| 0.58 | 0.45 | 0.65 | susp | susp | bed | – | – |
| 0.51 | 0.48 | 0.86 | susp | susp | bed | bed | – |
| 0.22 | 0.98 | 3.40 | susp | susp | susp | bed | bed |

[a] $h$ is height above extreme low water, $R$ is extreme tidal range.

$D_1$: fine sand; $D_2$: fine/medium sand; $D_3$: medium/coarse sand; $D_4$: coarse sand; $D_5$: gravel; –: no motion; bed: bedload; susp: suspension.

Table 10-2

Minas Basin, Bay of Fundy — peak velocity ($U_{max}$), peak bed shear stress ($\tau_{max}$) and sediment transport mode as a function of relative elevation $(h/R)^a$, for a range of grain sizes found on intertidal flats

| $h/R$ | $U_{max}$ | $\tau_{max}$ | $D_1 = 0.0001$ | $D_2 = 0.0002$ | $D_3 = 0.0005$ | $D_4 = 0.001$ | $D_5 = 0.002$ |
|---|---|---|---|---|---|---|---|
| 0.60 | 0.20 | 0.12 | – | – | – | – | – |
| 0.55 | 0.27 | 0.49 | susp | – | – | – | – |
| 0.48 | 0.35 | 0.77 | susp | susp | bed | – | – |
| 0.42 | 0.50 | 0.93 | susp | susp | bed | bed | – |
| 0.26 | 0.90 | 3.7 | susp | susp | bed | bed | bed |
| 0.0 | 2.4 | 17.7 | susp | susp | susp | susp | bed |

[a] $h$ is height above extreme low water, $R$ is extreme tidal range.

$D_1$: fine sand; $D_2$: fine/medium sand; $D_3$: medium/coarse sand; $D_4$: coarse sand; $D_5$: gravel. –: no motion; bed: bedload; susp: suspension.

be moved as bedload to the seaward limit of the mud flat (MLWNT). Medium sand and finer grades could be moved in suspension across the entire width of the sand flats. The mode of transport is most sensitive to grain size changes over the medium sand range ($D_{50}$ = 300–500 microns). Fine sand ($D_{50}$ = 100 microns) and finer material would move largely in suspension across the entire flats of both regions. Applying the concept of *competency* to the development of the sand flats, we would expect to see a gravel fraction in its lower part, a very coarse sand fraction on the central flats, and a coarse sand component on the inner sand flats. This is not the case. Well-sorted medium sand dominates the lower sand flats, well-sorted fine sand prevails on the central flats, and fine to very fine sand typifies the inner sand flat. The two major gradients in the size of bottom sediments, the mud flat/sand flat boundary, and the sand flat/channel sand boundary, correspond to the thresholds for suspension of fine sand and medium/coarse sand respectively. Thus sand (in large quantities) appears not to be found landward of its threshold for suspension. Thus the distribution of sizes conforms more closely to the bedload/suspension transition than to the threshold for incipient motion of sand; but why?

It seems that for sediment to occupy a position on the tidal flat it must arrive onto the tidal flats in suspension in order to move up the steep landward flank of the low water tidal channel. This is perhaps demonstrated by Collins et al. (1982) who observed that measurable quantities of fine sand were suspended over the sand flats (circa 100 mg/l) and even over the mud flats (10 mg/l) during "quiet" conditions.

It is to be marvelled that the fine sand remains on the tidal flat and does not disperse seawards under storms. The fact that over the long-term it does not, underlines the importance of the tidal asymmetry and consequent residual transport over a tidal inundation. This tendency now presents us with a conundrum: as sand possesses no cohesion it cannot be subject to consolidation effect in the scour lag concept, which is one of the supposed main agents responsible for the headward residual motion of fines. Given that even coarse sand moves headwards regardless of its lack of cohesion why are we to believe that fines would not do the same irrespective of scour lag? The next section attempts to address this question.

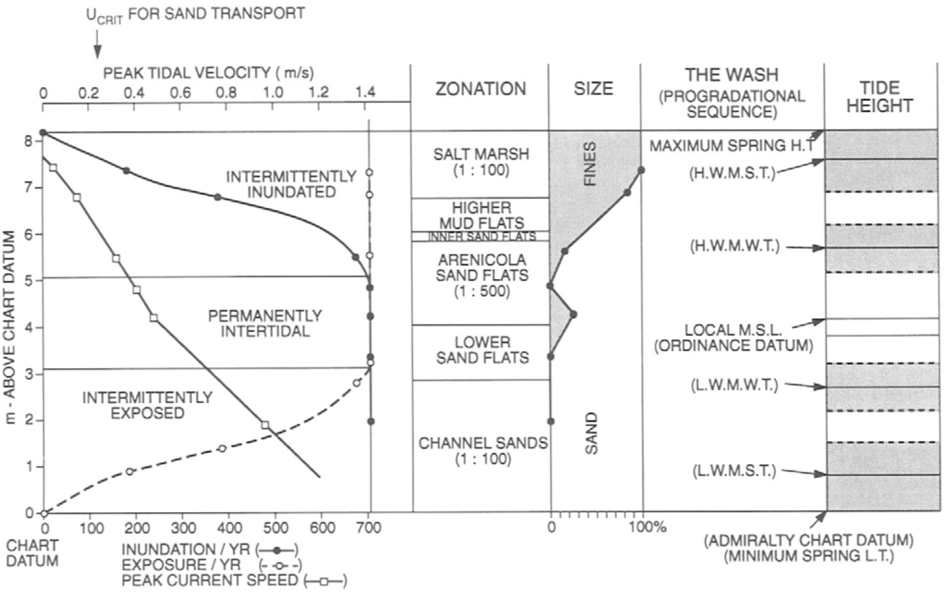


Fig. 10-8. A synthesis of the Wash tidal flat sedimentary character, peak tidal flow and exposure relative to elevation, taken from Amos (1974). The slope of each zone is given in brackets.

*A model for sediment accretion/erosion on the tidal flats of the Wash and Minas Basin*

The above concepts of tidal flat sedimentation take into account only the peak tidal flows. The development of a tidal flat and its lithology, on the other hand, is the time-integrated effect of the total tidal inundation. Due to landward decreases in both the duration of inundation and the peak bed shear stress, the total energy expenditure at the bed will decrease landwards across the flats in a non-linear fashion. Also the composition of the bed is likely to be the product of the size and quantity of material deposited versus that eroded, and so the seaward edge of the mud flat should be at the position on the tidal flat where the net erosion and net deposition of fine-grained sediment is equal.

A synthesis of the zonation, lithology, and peak tidal flow across the tidal flats of the Wash is given in Fig. 10-8. Notice that the transition from a mud flat to a sand flat occurs at the level of MHWNT. The peak tidal current speed shows a linear decrease landwards across the flats. It is greatest in the low water tidal channel (1 m/s), ranges from 0.3 to 0.7 m/s over the sand flats, and is generally less than 0.3 m/s over the mud flats and marsh.

The simulation of tidal inundation ($H$) and tidal current speed ($U$) over the Wash tidal flats was calculated following the method of Doodson and Warburg (1941) using the first four dominant tidal constituents ($M_2$, $S_2$, $K_1$, and $O_1$):

$$H(t) = A_1(\sin \omega t - \beta_1) + A_2(\sin \omega t - \beta_2) + A_3(\sin \omega t - \beta_3) + A_4(\sin \omega t - \beta_4) \tag{10-12}$$

and

$$U(t) = U_1(\cos \omega t - \beta_1) + U_2(\cos \omega t - \beta_2) + U_3(\cos \omega t - \beta_3) + U_4(\cos \omega t - \beta_4) \tag{10-13}$$

where $A_1$ to $A_4$ are the elevation amplitudes of each constituent (3.15, 1.00, 0.14, and 0.18 m), respectively, and $U_1$ to $U_4$ are the amplitudes of the current speeds of each of the four constituents (0.42, 0.13, 0.02, and 0.03 m/s). Also $\omega = 2\pi/T$, where $T$ is the tidal constituent period ($M_2 = 12.42$ h; $S_2 = 12.00$ h; $K_1 = 23.94$ h; and $O_1 = 25.82$ h), and $\beta_n$ are the phase lags (6.33, 7.70, 20.01, and 10.25 h). Tide height and current speed were determined at 30-minute time-steps for 993 hours or eighty $M_2$ tidal cycles. For each time-step, bed shear stress was evaluated adopting the quadratic stress law:

$$\tau_0 = C_d \rho_0 U(t)^2 \tag{10-14}$$

Also assigned were: the critical shear stress for deposition of fines $\tau_d = 0.1$ Pa; the critical shear stress for erosion $\tau_e = 0.5$ Pa; the mass settling rate $W_s = 0.00027$ m/s; and the drag coefficient $C_d = 0.003$. Mass settling rate was determined using eq. (10-5). Erosion rate was computed using eq. (10-6). Continuity of mass in suspension was determined assuming no lateral or longitudinal advection (a closed system). The starting SSC was set in turns to 10, 100, 1000 and 10,000 mg/l and was assumed to be constant across the flats. In all cases, the net balance in sedimentation was determined for each of 200 elevations spaced equally between extreme low and high water levels. For each elevation the following parameters were calculated: (1) the time of inundation; (2) the time series of water level; (3) the instantaneous bed shear stress; (4) the cumulative deposited mass; (5) the cumulative eroded mass; (6) the SSC; and (7) the mean (time-averaged) bed shear stress. The total sediment deposition and erosion of the entire flats (integrated over the eighty tidal cycles) was also determined.

The time-series of results for the Wash for a starting SSC of 100 mg/l is shown in Fig. 10-9. The figure shows a clear 20-day modulation of the tidal elevation (Fig. 10-9a) and current speed (Fig. 10-9b) for a position at MLWST. Notice that the total predicted (across flat) deposition and erosion show complex time-variability (Figs. 10-9c and d). For present purposes of demonstration, we have assumed an infinite supply of all sediment sizes across the flats. Peak erosion appears to exceed peak deposition during spring tides; during neap tides the converse is evident. The net predicted result is one of long-term erosion of the flats and an overall increase in SSC that is modulated by the spring–neap cycle. Notice that net deposition is predicted to be relatively steady with time (i.e. insensitive to the peak tidal current speed), whereas erosion is highly sensitive to tidal current speed and appears absent during neap phases of the tide.

The net deposition and erosion (integrated over the eighty tidal cycles shown in Fig. 10-9a) is shown against elevation across the Wash tidal flat in Fig. 10.10. In this case, predicted net deposition and potential erosion are shown for a starting SSC of 1000 mg/l. Notice the asymptotic decrease in mean bed shear stress across the tidal flats. Also notice that net erosion follows this general trend decreasing in an

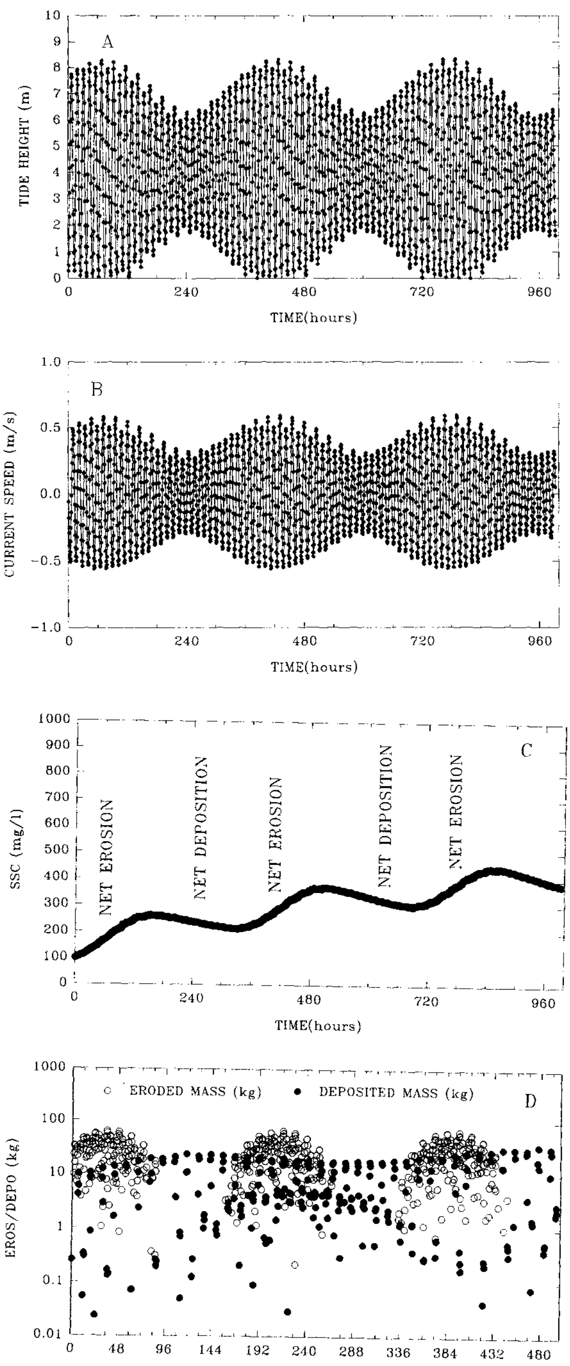


Fig. 10-9. Time-series plots of the predicted tide height (a), tidal current speed (b), suspended sediment concentration (c) and net deposition and erosion (d) for the tidal flats of the Wash, U.K. Eighty $M_2$ tidal cycles were simulated (993 hours) at a time-step of 30 minutes. Notice the strong 20-day modulation of the tides, and the resulting complex time-variability between erosion and deposition.

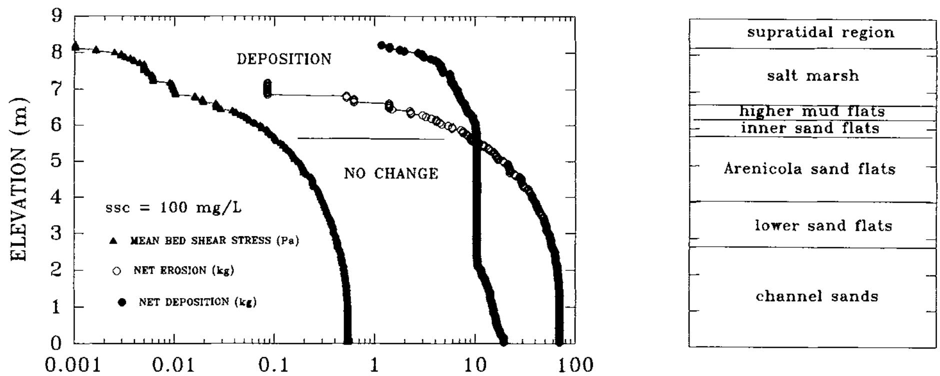


Fig. 10-10. The predicted mean bed shear stress, potential erosion, and net deposition for the Wash, U.K. plotted against tidal flat elevation for a starting suspended sediment concentration of 100 mg/l. Notice that the elevation where deposition and erosion intersect corresponds closely with the seaward limit of the mud flats.

hyperbolic fashion with elevation with an asymptote at the level of the higher mud flats. Net deposition, on the other hand, is predicted to be virtually constant across the middle flats, but to decrease above an elevation of circa 6 m (over the salt marsh). Also note the peculiar trend of *increasing* deposition in the low water tidal channel (reflecting deposition at both high and low water slack tides, and the diminishing effect of exposure time).

We stated earlier that the seaward limit of the mud flats should be defined as the elevation where long-term erosion and deposition of fines are equal. We may now test this hypothesis by reference to Fig. 10-10. Notice that the net deposition curve intersects the net erosion curve at circa 5.7 m. Examination of the adjacent tidal flat zonation shows that this level corresponds to the seaward edge of the inner sand flat (where a significant silt content is to be found). It would thus appear that there is a reasonable closure between the mapped tidal flat zonation of the Wash and the predicted sedimentation trends. Insofar as these trends omit the effects of waves, we conclude that the zonation in the Wash is largely controlled by currents of the tidal inundation and not by waves.

The net deposition and erosion trends predicted for the Wash tidal flats are plotted against elevation for differing starting SSC's (10, 100, 1000, and 10,000 mg/l) in Fig. 10-11. Notice that these curves intersect the erosion curve at different elevations; the greater the SSC the lower the elevation at which the intersection occurs. Notice that at circa 1000 mg/l, deposition exceeds erosion across virtually the entire middle tidal flats to the tidal channel with a resulting development of a mud blanket over fine sand. Such mud drapes are known to occur, but are ephemeral due to short-lived elevations in storm-induced SSC. Nevertheless, tidal flats subject to consistently high levels of turbidity (such as typify northern China) would be expected to be dominated by mud flats by virtue of this concentration, even under energetic tidal conditions.

Now let us examine the tidal flats of the Minas Basin. A synthesis of these tidal

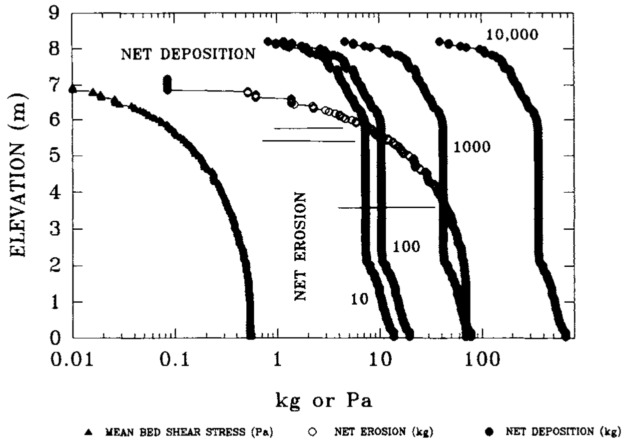


Fig. 10-11. The predicted mean bed shear stress, potential erosion, and net deposition for the Wash, U.K., plotted against tidal elevation for starting suspended sediment concentrations (SSC) of 10, 100, 1000 and 10,000 mg/l. The figure demonstrates the dominating influence of SSC on mud flat development.

flats is given in Fig. 10-12. The profile is much narrower and steeper than is the Wash. The mud flat has a slope of 1 : 16, the sand flat slopes at 1 : 50 and the channel has slopes in excess of 1 : 100. The transition from the mud flat to the sand flat varies considerably (Amos and Joice, 1977), but typically is found between MSL and MHWNT (i.e. below the region of intermittent inundation). Also note that the mud flat/sand flat transition is lower on these flats than it is in the Wash. A decrease in peak current speed across the flats is also evident. However, the gradient is curvilinear showing the largest gradient across the inner flat.

Equations (10-12) and (10-13) were again used to compute the tidal elevation and tidal current speed. In this case, however, the first four major constituents were the $M_2$, $N_2$, $S_2$, and $K_2$. $A_1$ to $A_4$ are the elevation amplitudes of each constituent (5.64, 1.10, 0.83, and 0.22 m) respectively, and $U_1$ to $U_4$ are the amplitudes of the current speeds of each of the four constituents (1.08, 0.21, 0.16, and 0.04 m/s). $\beta_n$ are the respective phase lags (0.48, 12.34, 1.97, and 1.96 h). The critical shear stress for deposition ($\tau_d$) is 0.12 Pa, and the erosion bed shear stress ($\tau_e$) is 2 Pa (after Amos et al., 1992).

The time-series of tidal elevation and tidal current speed are shown in Fig. 10-13a and b. Notice the vastly different tidal range and 20-day modulation in tidal amplitude to that of the Wash (Fig. 10-9). This produces a similarly unique prediction of the net erosion and deposition patterns through time (Fig. 10-13d) with a consequent steady increase in SSC (Fig. 10-13c). The patterns of erosion are highly variable with three periods of high erosion punctuated by two periods of no net erosion. The predicted peak erosion is almost always less than peak deposition which is relatively steady throughout the time-series. Why then, does the predicted SSC increase (diagnostic of net erosion)? The reason, of course, is that the net balance

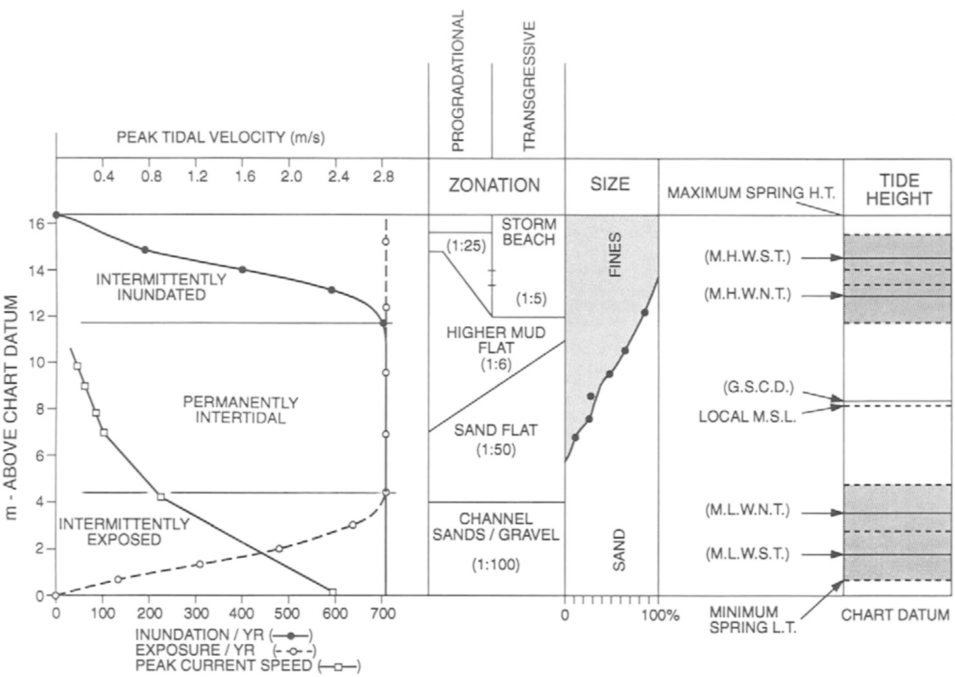


Fig. 10-12. A synthesis of the Minas Basin sedimentary character, peak tidal flow and exposure relative to elevation, taken from Amos and Joice (1976) and Daborn et al. (1991).

in the sediment flux is the time integration of the entire tidal inundation and not just the peak. This attribute alerts us to the dangers of extrapolation of short-term measurements, and the possible mis-use of peak fluxes to characterize net trends.

Similar trends to the Wash are evident in the predictions of erosion/deposition across the Minas Basin tidal flats for a typical summertime SSC (100 mg/l, Fig. 10-14). Notice that the intersection of the two curves (erosion and deposition) is situated at an elevation of circa 12 m above datum. In reality, the seaward limit of the Minas Basin mud flat edge is further seawards (lower) than was predicted. This mismatch may be due to the use of a low value of SSC (neglecting the effects of storms) that can elevate the turbidity to over 1000 mg/l through wave resuspension. Thus our model may represent an unanticipated *source limited* condition. A sediment source that is absent from the model is the tidal flat itself. How then may we accurately account for sediment supply without including a term for wave erosion of the flats?

## THE INFLUENCES OF WAVES ON TIDAL FLATS

Waves play a strong role in the resuspension of sediments on tidal flats. A series of papers have been written on the effects of storms, hurricanes and typhoons on

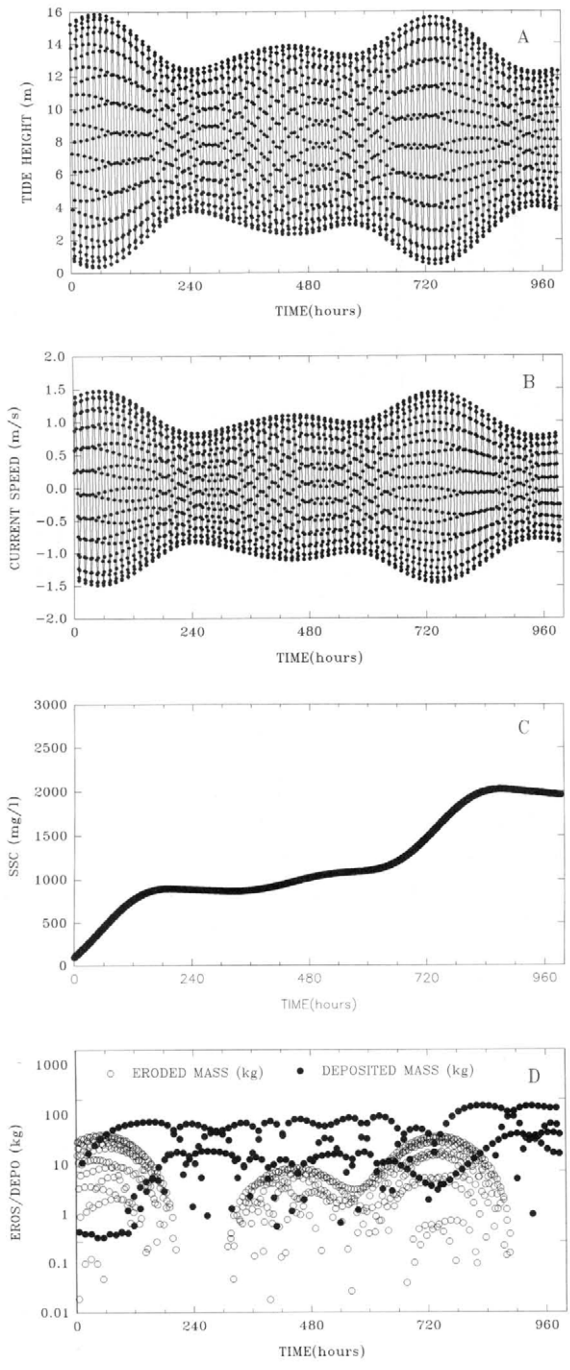


Fig. 10-13. Time-series plots of the predicted tide height (a), tidal current speed (b), suspended sediment concentration (c) and net deposition and erosion (d) for the tidal flats of the Minas Basin, Canada. Eighty $M_2$ tidal cycles were simulated (993 hours) at a time-step of 30 minutes. The 20-day modulation of the tides is variable, resulting in a complex time-variability in erosion and deposition that differs markedly from that of the Wash (Fig. 10-9).

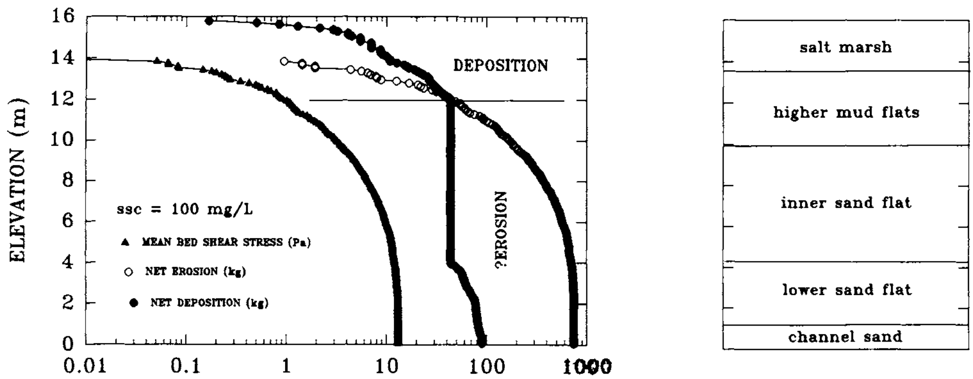


Fig. 10-14. The predicted mean bed shear stress, potential erosion, and net deposition for the Minas Basin, Canada for a starting SSC of 100 mg/l.

tidal flats (Yan et al., 1981; Champagne, 1982; Ren et al., 1985; Wanless et al., 1988; Wang and Eisma, 1990; Wang et al., 1990; Wells et al, 1990 amongst others). In a broad sense, it is wave climate that limits the location of tidal flats (Boyd et al., 1992). The non-periodic occurrences of wave magnitude means that even sheltered regions are subject to wave influence at times. The degree of this influence is often visible across the tidal flats in the form of erosion of the seaward edges of salt marshes and mud flats (Evans, 1965), in the development of sandy beaches on top of the salt marsh at the MHWST level (Amos and Joice, 1977; Knight and Dalrymple, 1975; Belperio et al., 1988) and in the development of wave-formed ripples across the sand flats (Amos and Collins, 1978; Dingler and Clifton, 1984). Thorne (1979) measured the sand resuspension by waves in the Great Ouse, and found that a near-bed oscillatory flow of only 5 mm/s could double the transport of fine sand by tidal currents. Measurements over the tidal flats of the Wash made by Collins et al. (1981) showed that as much fine sand was suspended over the sand flats in storms as silt and clay. They also found that the SSC was an order of magnitude greater in storms than at other times and that the greatest values were on the middle and lower flats; a reversal of the fair-weather trends. Waves may either amplify or reverse the headward flux of suspended sediment. In the upper Bay of Fundy, where significant wave heights can reach 4–6 m, wave erosion prevails with a consequent export of suspended sediment (Amos and Asprey, 1979). In turbid environments of moderate to low wave energy the reverse may be true due to the presence of solitary waves and Kelvin–Helmholtz billows along lutoclines (Wells et al., 1990; Frey et al., 1989).

The varying influences of waves is often apparent in the tidal flat zonation and associated sediment texture. Isla et al. (1991) for example showed that the tidal flats of San Sebastian Bay, Patagonia, were developed only in the most sheltered part of the bay; around that Bay the inner fine-grained zones became narrower and were replaced by coarser-grained facies in response to increasing wave exposure. A similar contrast was shown by Wang (1983) and others between the mud flats bordering the more sheltered Bohai and Yellow Seas to the more exposed sandier flats bordering the South China Sea (Yan et al., 1981; Zhang, 1992). As a final note, we may conclude that the effects of waves on tidal flat development are important but largely unpredictable. Cyclic loading, the associated pore-pressure amplification, and subsequent liquefaction of tidal flat sediments have not been quantified and offer rich potential for future research.

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