FACIES ARCHITECTURE AND ICHNOLOGY OF RECENT SALT-MARSH DEPOSITS: WATERSIDE MARSH, NEW BRUNSWICK, CANADA

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ABSTRACT: Identification of salt-marsh deposits in the rock record can aid in the paleoenvironmental reconstructions of ancient marginal-marine successions. Salt-marsh sediments exposed at Waterside Beach and in Waterside Marsh alongside the Bay of Fundy, Canada offer an opportunity to describe and define facies and facies associations in a temperate, mineralogenic salt marsh. Three facies associations are identified and represent the three main components of the Waterside Marsh–Beach depositional system. Facies Association (FA) 1 includes genetically related deposits that accumulate on the salt-marsh surface, FA2 comprises sediments deposited within the naturally formed tidal creeks, and FA3 encompasses sediments derived from the adjacent coarse-grained beach. Facies Associations 1 to 3 respectively comprise 3, 4, and 2 sedimentologically and ichnologically distinct facies.

Application of these facies and facies associations to the rock record is dependent upon the preservation potential of the facies and the relative sea level (RSL) regime of the system. RSL in the Bay of Fundy is presently rising. This results in transgression of Waterside Beach and erosion of the upper 4 to 5 m of salt-marsh sediment at the beach-marsh interface. Consequently, the probability of sediments being preserved increases with distance from the seaward limit of the marsh and with depth. Sediments deposited on the salt-marsh surface well away from the seaward edge of the marsh (FA1) and those deposited at the base of the tidal creeks (FA2) have a high probability of being preserved. Conversely, the coarse-grained clastic sediments of FA3 deposited near the seaward edge of the marsh will likely be eroded.

INTRODUCTION

Salt marshes represent areally significant components of both modern and ancient marginal-marine depositional environments. Occurring behind barrier islands, beaches, in estuaries and lagoons, salt marshes develop in response to tidal inundation of backshore environments, and thus are excellent indicators of marginal-marine conditions. It is the purpose of this paper to define facies and facies associations from salt-marsh sediments observed outcropping along tidal creeks at Waterside Beach, New Brunswick, Canada. These exposures correlate to deposits presently forming in the adjacent Waterside Marsh.

The two main components of salt marshes are a vegetated platform that is periodically submerged by the tide, and a network of tidal channels that branch and taper landward (Allen 1997, 2000; Pethnick 1992). Salt marshes are classified as mineralogenic—dominated by tidally derived inorganic sediment with less than 10% organic material—or organogenic—sedimentation dominated by organic sediment with only minor amounts of tidally derived inorganic sediment (Allen 2000). Sedimentation rates and tidal-creek patterns in salt marshes are complex and change with relative sea level (RSL), sediment composition, and tidal character (Allen 2000; French 1993; Pye and French 1993). During periods of stillstand or RSL fall, tidal waters rarely flood the marsh surface; thus, they tend to be organogenic. In these marshes, tidal channels are poorly developed or absent and the stratigraphy is dominated by extensive peat horizons (Allen 1990, 1997, 2000; Anderson and Race 1980; Redfield 1972). During RSL rise, organogenic marshes evolve into mineralogenic marshes and the deposits aggrade vertically at a rate proportional to RSL rise. With prolonged RSL rise, the high-order tidal creeks expand and increase in frequency, the marsh matures, and the low-order tidal creeks that dissect the salt-marsh surface silt in (Allen 1997).

Detailed descriptions of modern salt marshes focus either on the regional stratigraphy of a deposit or on the sedimentary and biogenic structures present. Van Straaten, for example, described salt-marsh bedding (van Straaten 1954), tidal-creek migration (van Straaten 1961), and the depositional processes responsible for sedimentation in European salt-marshes. Similarly, Evans (1965) provided comprehensive descriptions of sedimentary structures observed in salt-marsh deposits at The Wash, England. Wiemer et al. (1982) and, more recently, Allen (2000) summarized much of the work on the sedimentology and morphology of modern tidal flats and salt marshes. In North America, identification of subenvironments within salt marshes was undertaken at Sapelo Island, Georgia, U.S.A. (Basan and Frey 1977; Edwards and Frey 1977) and in New England, U.S.A. (Ander- son and Race 1980; Redfield 1972). Edwards and Frey (1977), and Basan and Frey (1977) defined creek-bank, low-marsh, transitional, and high-marsh environments. Similarly, Redfield (1972) differentiated peat, inter-tidal-marsh, and high-marsh environments based on vegetation cover. These zonation schemes are botanically based, which may be difficult to apply to the rock record. In fact, Basan and Frey (1977) acknowledge that diagnostic sedimentological and ichnological criteria for identifying high-marsh deposits are few and that the presence or absence of characteristic plants is used to define the zonation. Easily recognized, sedimentologically and ichnologically centered facies have not been presented in the literature.

The probability of salt-marsh deposits passing into the rock record (preservation potential) is partly dependent upon changes in RSL. In the Bay of Fundy the preservation of coastal sediments is strongly influenced by transgression resulting from rapid sea-level rise over the past 6000 years (Amos et al. 1991; Shaw and Courtney 2002). Transgression, especially on wave-dominated coasts, tends to result in headland erosion (Reading and Collinson 1996; Roy et al. 1994), thus the upper foreshore and backshore deposits of many Bay of Fundy coastal systems will either be partially preserved or removed. At Waterside Beach, wave-induced coastal erosion and high tidal energy has resulted in the exposure of recently deposited sediments (the last ~ 200 y). Although these salt-marsh sediments exposed in the foreshore of Waterside Beach have a low preservation potential, they provide an opportunity to compare the architecture and structures of re-excused salt-marsh deposits to active depositional environments in the...
adjacent marsh. Through this comparison it is possible to establish sedimentologically and ichnologically distinct facies and facies associations that are characteristic of salt-marsh deposits. The proposed facies associations are intended to improve the framework for identifying salt-marsh facies in the rock record.

**Study Area**

On the north shore of the Bay of Fundy (Fig. 1) Waterside Marsh is situated landward of the northwest–southeast oriented Waterside Beach (Fig. 1C). The marsh exhibits an open-coast to open-embayment morphology (Allen 2000; Pye and French 1993) and is a mature (high) marsh. The beach–marsh system suffers a 12 m spring-tidal range that results in sub-aerial exposure of up to 1100 m of intertidal-zone sediments during spring low tides. Overmarsh flooding (Bayliss-Smith et al. 1979) occurs for only a few days during the high tide of spring-tidal cycles. Decapitated salt-marsh deposits sporadically crop out throughout the upper and middle intertidal zones at Waterside Beach. Where Newfoundland Creek debouches onto the beach from the marsh, downcutting by the tidal creek exposes vertical successions of older marsh deposits (Fig. 1C). Weathering of the sediment has enhanced the sedimentological and ichnological structures present in the deposits.

Anthropogenic modification of Waterside Marsh has been significant. In the 17th and 18th centuries farmers excavated many of the low-order tidal creeks that dissect the marsh surface. Similarly, salt-marsh erosion was hampered by the construction of a backshore dike system in about the 1650s. Abandonment of the dike in the 1940s because of changes in demographics and regulations has resulted in rapid erosion via natural processes over the past 60 years. Of particular significance is the large washover deposit located directly north of the mouth of Newfoundland Creek (Fig. 1C). This resulted from a 1997 storm that altered hydraulic flow and thereby the depositional and erosional patterns in the marsh.

**METHODS**

Outcrops of palimpsest salt marsh located at the mouth of Newfoundland Creek were studied in detail in July 2003 (Fig. 1). Ichnological and sedimentological characteristics of the sedimentary facies were recorded, as was their spatial distribution and lateral variability. From these data, facies associations are inferred. Facies identified in historical deposits were compared to modern (active) marsh deposits. This comparison aided in the interpretation of sedimentological and ichnological structures observed in outcrop and in drawing inferences pertaining to the preservation potential of the observed facies. In 2004, in situ sediment samples were collected from Waterside Marsh and Beach and imaged using X-ray radiography. Samples were collected with a 22.5 cm by 15 cm by 7.5 cm stainless steel box core as described in Bouma (1969). A slab, 22.5 cm by 14 cm by 2 cm thick, was then extracted using a plastic tray. This slab was X-rayed to assess sedimentary and bio sedimentary structures.

Samples collected from salt-marsh outcrops were analyzed for grain size and organic carbon content. Pretreatment of samples involved an initial drying period of 24 hours at 105 °C to remove interstitial water (McKeague 1978) followed by disaggregation with mortar and pestle. Total-organic-carbon content was measured through loss-on-ignition (LOI) analysis as outlined in Heiri et al. (2001). Disaggregated samples were dried for an additional 18 hours at 105 °C and then heated to 550 °C for 4 hours. Weight loss due to combustion of organic material during LOI was determined with an electronic scale accurate to 0.001 g. X-ray absorption analysis with a Micromeritics Sedigraph 5100 was used to assess grain size. Samples were analyzed before and after the removal of organic carbon; however, the values reported herein for sand, silt, and clay are those for samples pretreated to remove organic carbon. Prior to X-ray analysis, samples were sieved to remove grains larger than 250 μm (medium-grained sand). This coarse fraction was weighed and factored into the grain-size distribution of each sample. To prevent the flocculation of fines, 3 to 4 g of disaggregated sample was mixed with 30 to 40 mL of 0.05% sodium metaphosphate (NaPO₄)₆·Na₂O. Each solution was thoroughly mixed with a magnetic mixer for 5 minutes and a sonic mixer for 1 minute before analysis. Data were plotted in continuous grain-size curves from 250 to 0.49 μm (φ 2 to 11) ± 2%. Grain-size nomenclature is assigned on the basis of Shepard’s (1954) classification scheme with sand (S), silt (Z), and clay (C) fractions reported.

Airphotos of Waterside Marsh taken approximately every ten years from 1945 to 2001 and historical maps from 1789 and 1899 aided in assessing the extent and evolution of the salt marsh and in determining the possible depositional environments of facies observed in outcrop. We recognize that the term facies is normally reserved for descriptions of sedimentary rocks with a specific set of lithologic, structural, and organic characteristics. However, the terms facies and facies associations in this study are used to describe sediment, and genetically related sedimentary packages that otherwise meet the requirements of facies and facies associations. This is done in order to facilitate anticipated application and comparison to the rock record.

Herein, the degree of bioturbation is referred to as rare, low, moderate, high, or intense. These terms represent a range of burrowing intensities (Table 1) and are thus semiquantitative. The degree of bioturbation is partly dependent on the size of the organism. For example, the amphipod Corophium volutator rarely exceeds 1 cm long, 0.3 cm wide, and 0.15 cm thick.
Within the Bay, burrow densities of *C. volutator* range up to 63,000 individuals/m² (Thurston 1990). Individual U-shaped burrows do not occupy a significant area, and intense burrowing is not apparent until there are at least 20,000 individuals/m². Conversely, shells of the bivalve *Mya arenaria* are measured up to 8 cm long, 5 cm wide, and 3.5 cm thick, requiring only 250 individuals/m² to intensely bioturbate a substrate. *Nereis* populations were difficult to assess because of the multiple burrow openings and complex burrow networks constructed by this polychete. The degree of bioturbation is proportional to the number of burrow openings, although counting openings cannot assess the population density of *Nereis*. In any case, *Nereis* is a minor bioturbator in the salt marsh and their burrow densities are generally low in both the palimpsest and modern substrates. Illustrations of the main bioturbating infauna observed in Watershed Marsh are provided in Figure 2. Figure 2 also schematically depicts the resultant biogenic sedimentary structures produced by each organism.

**Table 1.**—Relative bioturbation levels for infauna observed in Watershed Marsh. Values reported in burrows/m².

<table>
<thead>
<tr>
<th>Species</th>
<th>Rare</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>Intense</th>
</tr>
</thead>
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<tr>
<td><em>Mya arenaria</em></td>
<td>0</td>
<td>50–150</td>
<td>100–150</td>
<td>150–250</td>
<td>&gt;250</td>
</tr>
<tr>
<td>Macoma balthica</td>
<td>&lt;100</td>
<td>100–200</td>
<td>200–400</td>
<td>400–600</td>
<td>&gt;600</td>
</tr>
<tr>
<td>Corophium volutator</td>
<td>&lt;1,000</td>
<td>1,000–5,000</td>
<td>5,000–10,000</td>
<td>10,000–20,000</td>
<td>&gt;20,000</td>
</tr>
<tr>
<td>Nereis sp.*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talitrid amphipods</td>
<td>&lt;50</td>
<td>50–100</td>
<td>100–300</td>
<td>300–600</td>
<td>&gt;600</td>
</tr>
</tbody>
</table>

* Difficult to assess. Complex burrow networks.

**Facies Associations: Descriptions and Interpretation**

In the study area, salt-marsh deposits are divided into three facies associations: (FA1) salt-marsh deposits, (FA2) tidal-creek deposits, and (FA3) beach-related deposits. The three facies associations are further subdivided into nine sedimentary facies. All facies associations and facies are characterized by a distinctive suite of sedimentological and ichnological characteristics, which are summarized in Table 2.

**Facies Association 1: Salt-Marsh Deposits**

Facies Association 1 (FA1) facies are genetically related deposits that accumulate on the salt-marsh surface. FA1 comprises Facies 1, the main facies in the marsh, Facies 2, the sediments that accumulate in shallow salt-marsh pools or pannes, and Facies 3, a *Glossifungites*-demarcated surface (Bromley 1990; Gingras et al. 2001; Pemberton et al. 2001) formed via exhumation of Facies 1 sediment at the base of the tidal creeks (Table 2). This is the most extensive and easily recognized facies association in the salt marsh. The three facies share similar sedimentary characteristics, but vary in both color and ichnological signature.

**Facies 1 (F1).**—Facies 1 comprises greenish-gray, rooted, horizontal to undulatory, rhythmically laminated silt (Fig. 3A, B). The average grain size is 15.5 μm (S 2%, Z 90%, C 8%) with 6.9% organic carbon. Laminae sets are rhythmic (Fig. 3B, C) and continuous for at least tens of meters. Pebbles and cobbles are uncommon (Fig. 3A), and gravel occurrence decreases from the immediate sediment source—either the seaward edge of the marsh or the tidal channels (Allen 2000; Davidson-Arnott et al. 2002). This process of sediment accumulation is not damped or interrupted by ponded water on the salt-marsh surface, because the laminae continue across vegetated zones and small ponds (Edwards and Frey 1977). The heavily vegetated, undulatory surface of the salt marsh represents the upper surface of F1 and is the primary depositional surface of this facies. Individual pebbles and cobbles (Fig. 3A) and thin, discontinuous gravel lenses, randomly distributed throughout F1, F2, and F3 are deposited by ice. Spring-tide flooding during the winter transports blocks of sediment-laden drift ice from the beach onto the marsh. Subsequent melting of the ice results in random deposition of coarse clastic material on the salt-marsh surface.

**Facies 2 (F2).**—Gray, very weakly laminated clayey silt (Fig. 3C) defines Facies 2. The average grain size is 4.3 μm (S 0%, Z 66%, C 34%) with 11.8% organic carbon. This facies was not observed in the outcrops, but is defined from sediments presently accumulating at the base of pannes commonly encountered on the salt-marsh surface. Laminae and laminae sets are continuous for tens of meters but are composed of organic-rich soupy mud (Fig. 3C). Living plants are not apparent; however, the roots of old halophytic vegetation are commonly observed (Fig. 3C). Vegetation is restricted to algal growth at the base of the pool and in the water column. Large bird tracks, 20 cm long by 13 cm wide, are abundant and form depressions within the sediment. Shallow pannes dry out between over-marsh flooding events, resulting in desiccation and cracking of the exposed algal-matted surface.

Facies 2 sediments are deposited by the same processes as F1 with the addition of a longer-term low-energy depositional phase. Consequently, F2 deposits have considerably more clay than F1. The pannes in which F2 sediments are deposited tend to be anoxic. A limited influx of oxygenated water and the significant accumulation of decaying organic matter severely limits the long-term oxygen supply, resulting in a predominantly anoxic environment that is inhospitable for infauna. Vegetation in pannes is restricted (Fig. 3C) because of the propensity of halophytes to avoid drowned environments (Allen 2000; Davidson-Arnott et al. 2002; Redfield 1972). Desiccation cracks develop between over-marsh flooding events when shallow pannes dry out.

**Facies 3 (F3).**—Facies 3 comprises light reddish-brown and greenish-gray, burrowed, rooted horizontal to undulatory, rhythmically laminated silt. Sedimentologically F3 is similar to F1, yet exhibits markedly different biogenic structures. Facies 3 suffers moderate to high degrees of rooting, moderate colonization by *Corophium volutator*, and locally intense bioturbation by the bivalve *Mya arenaria* (Fig. 3D).

Exhumation of Facies 1 sediment via tidal-creek migration and erosion results in the secondary alteration of F1 sediment to F3. Exposure to nutrient- and oxygen-rich water results in: (1) oxidation of the sediment; (2) decomposition of organic matter; and (3) colonization by *Mya arenaria* and *Corophium volutator*. Given the compacted nature of F3 and the post-depositional colonization of the exhumed sediment, the upper contact of this facies represents a *Glossifungites* ichnocoerces (Fig. 3D). The light reddish-brown coloration of Facies 3 with no discernable change in grain-size composition relative to F1 is the result of oxidation of the reduced, greenish-gray F1 sediment. The low frequency of rooting in F3 occurs because of aerobic decomposition of roots in the oxygenated water of the tidal channels. Finally, the locally intense bioturbation by *M. arenaria* and moderate bioturbation by *C. volutator* is the result of exposure to nutrient- and oxygen-rich, mesohaline water in a sheltered environment (relative to the beach).

**Facies Association 2: Tidal-Creek Deposits**

Facies Association 2 (FA2) encompasses all sediment deposited in the naturally formed tidal creeks of Waterside Marsh. Areally, the tidal creeks are a minor component of the overall salt-marsh environment, yet are loci of rapid erosion and deposition. Deposition occurs when high-tide waters do not flood the marsh surface, and erosion when they do (French and Stoddart 1992). Tidal-creek deposits are divided into four main facies: Facies 4 accumulates via vertical aggradation within a slowly migrating tidal creek; Facies 5 is a tidal-creek abandonment deposit; Facies 6 represents
**Facies 4 (F4).**—Facies 4 consists of brown, low-angle, interbedded clayey silt and silty gravel. The average grain size, excluding the gravel component, is 10.6 μm (S 3%, Z 70%, C 27%) with 2.8% organic carbon. Beds are continuous for tens of meters and are axially oriented (Fig. 4A). Small discontinuous gravel lenses and larger continuous gravel beds are common in the unit. Small, concave-down structures filled with steeply inclined silty gravel beds that laterally translate into tangential toset beds are sporadically distributed throughout the unit. Continuous, low-angle, matted-organic laminae are regularly observed. Bioturbation in F4 is produced by Corophium volutator, Macoma balthica, and Mya arenaria, with minor populations of Nereis. M. arenaria is the main bioturbator and occurs in localized high-density populations. The population density of *C. volutator* is substrate dependent and varies from low to high. *C. volutator* populations are very rare to low in gravel-rich deposits but increase to high to intense in silt-dominated substrates. Similarly, the distribution of *Macoma balthica* is closely related to energy level and substrate caliber. In

<table>
<thead>
<tr>
<th>Organism</th>
<th>Burrow Morphology</th>
<th>Traces produced</th>
</tr>
</thead>
</table>
| **Mya arenaria**                 |                   | Profile:  
Siphonichnus (Si),  
Skolithos (Sk)  
Plan view:  
Lockeia (L),  
Siphon holes (H)  
Plan view:  
Siphonichnus (Si)  
Plan view:  
Lockeia (L),  
Lorenzinia (Lo)  
Arencolites (Ar)  
Diplocraterion (Di)  
Palaeophycus (Pa)  
Thalassinoides (Th)  
Polykladichnus (Po)  
Skolithos (Sk)  
Psilonichus (Ps)  
cryptic bioturbation |
| **Macoma balthica**              |                   |                                                     |
| **Corophium volutator**          |                   |                                                     |
| **Nereis sp.**                   |                   |                                                     |
| **Talitrid amphipods** (Talorchestia sp.) |       |                                                     |
low-energy zones dominated by silt deposition, *M. balthica* is encountered in high-population densities. Conversely, in moderate-energy environments, low population densities are noted. *M. balthica* is not observed in substrates where the surface material is not mainly silt or clay. Burrowing by *Nereis* is low to moderate and generally increases as grain size decreases. Rooting is uncommon and discontinuous but increases towards the contact with Facies 5. Continuous laminae of matted-organic detritus (twigs, leaves, and grass material) accumulate parallel to the main bedding.

Interbedded silt and silty gravel beds in Facies 4 are deposited via vertical aggradation of sediment at the base of tidal-organic gravel. Aggradation of sediment occurs either in response to RSL rise or from changing hydraulic conditions related to channel cutoff (Fig. 1C: Area B). Allen (2000) explains that channels expand in cross-sectional area with time, which is supported by historical data from Waterside Marsh. However, Facies 4 deposits accumulate as a result of base-level rise and aggradation of sediment at the bases of the channels and are not eroded by later channel expansion. During the winter months, gravel is transported into the tidal creeks through both storm washover and slow, upstream transport and trapping of sediment by ice. The second process is postulated n the basis of data presented by Desplanque and Mossman (1998) regarding the accumulation and trapping of ice in tidal creeks. In the tidal creeks, there is a general landward decrease in the amount of gravel reflecting the landward dissipation of tidal (Weimer et al. 1982) and storm energy. Silt deposition is observed occurring over the summer in the active marsh. The bedding in F4 tends to follow the topography of the channel and dip toward the channel axis.

Bioturbation in F4 is mainly due to *Mya arenaria*. These bivalves easily tolerate extreme salinity fluctuations and salinities as low as 5 ppt (Gosner 1978) and are well adapted to colonize the brackish tidal creeks. Furthermore, *M. arenaria* larvae settle preferentially in sheltered sites (Snelgrove et al. 1999). The low-energy environment of the tidal creeks, as a result of upstream dissipation of tidal energy and no direct wave assault is thus favorable for *M. arenaria* colonization. The ichnological signature of this facies can vary depending on the salt-march architecture and local hydraulic conditions. Area B (Fig. 1C) is an example of a previously moderate-energy environment that now experiences low-energy conditions. This occurred when storm-driven infilling of the old channel fairway with beach-derived sand and gravel altered flow conditions in the marsh. Redirection of hydraulic energy away from Area B resulted in the establishment of an environment conducive to infernal colonization by *Mya arenaria, Macoma balthica, Corophium volutator*, and *Nereis*.

**Facies 5 (F5).—** Facies 5 is brown, massive bedded to chaotically bedded clayey silt. The average grain size is 7.8 μm (S 5%, Z 74%, C 21%) with 2.9% organic carbon. Large blocks of F1 sediment with randomly oriented bedding are common in F5 (Fig. 4B). Parallel, low- to high-angle laminae are also common. Gravel clasts are rare (Fig. 4B, C). Facies 5 is contained within a linear exposure oriented northwest–southeast that is 5 m wide and at least 100 m long. Large logs (greater than 1 m in length) are observed along and parallel to the central axis (Fig. 4B). Bioturbation is observed throughout F5. The highest burrow densities occur along the edges of the unit and abruptly diminish towards the center. *Corophium volutator* is the main bioturbator, varying from moderate to high burrow densities on the edges and decreasing to very rare in the middle. Burrowing by *Macoma balthica* is moderate to high on the edges as well, and displays a colonization pattern similar to that of *C. volutator*. Rooting reflects the primary bioturbation pattern with common to abundant rooting on the edges and

![Table 2.—Summary table of facies and facies associations described in the text. See Figure 2 for definitions of incipient bioturbation and Table 1 for bioturbation intensities. Sedimentological and ichnological structures diagnostic of specific facies are highlighted in bold print.](image)
decreasing rapidly towards the center of the unit. Macroscopic organic detritus (logs and branches) exhibits the reverse relationship to other detritus (i.e., grasses, leaves, and twigs) and is concentrated along the axis of the deposit and decreases rapidly towards the edge.

Facies 5 is deposited contemporaneously within and adjacent to the F4 sediment with the diverse trace assemblage described above. Upon establishment of a low-energy zone in the tidal channel (Fig. 1C: Area B), the channel begins to infill with clayey silt. The sharp contact between F4 and F5 is the result of this abrupt shift in facies (Fig. 4D). Interbedded silt and silty gravel beds of F4 are replaced by deposition of clayey silt (F5) in the old channel fairway. Slump blocks of F1 and large branches brought in on the flood tide are preserved in the mud. The distribution of bioturbation is strongly influenced by channel morphology. As seen in Figure 4D, the central channel axis maintains low-level flow at low tide as water seeps out of the surrounding salt marsh and channel sediment. Infauna preferentially colonize the water-saturated sediment that is emergent for part of the tidal cycle, and thus do not colonize the sediment along the central channel axis. This colonization pattern is reflected in the bioturbation pattern of exposed Facies 5 deposits where high to intense burrowing along the edges recedes rapidly to very rare along the central axis. Rooting patterns reflect the process of salt-marsh reestablishment over the abandoned channel. Vegetation colonizing the edges of the abandoned channel (Fig. 4D) increasingly encroaches upon the channel axis as it continues to fill with clayey silt. The central channel axis is therefore the last part of the abandoned channel to be colonized by vegetation. The resultant rooting pattern is manifested as high to intense rooting on the edges and receding rapidly towards the central axis.

Facies 6 (F6).—Facies 6 is light reddish-brown, low-angle, laminated silt (Fig. 5). The average grain size is 18.1 μm (S 8%, Z 80%, C 12%) with 2.5% organic carbon. Beds are continuous for more than 10 m and dip at medium dip angles (7°-9°) in a landward direction (Fig. 5A, B). Silt beds and organic laminae form bedsets of relatively uniform thickness that repeat throughout the succession. Intermittent, discontinuous, bedding-parallel gravel lenses are uncommonly encountered. Generally, the number and thickness of gravel beds increases from rare to common in the updip or seaward direction. Gravel beds and organic laminae share an inverse relationship with gravel content, increasing as organic laminae decrease. Shallow, U-shaped structures either lined or infilled with silty gravel are also encountered (Fig. 5A, B). In some occurrences, gravels in the U-structures dip steeply to tangentially towards the center. Otherwise, the shallow U-structures are infilled with either massive silt or downward-deflecting silt and organic laminae. Bioturbation is extensive in F6. High to intense bioturbation by *Corophium volutator* and *Macoma balthica* is encountered on bedding-plane surfaces in outcrop (Fig. 5C). Individual *C. volutator* burrows are difficult to discern in the vertical section because of their high density and partial destruction of burrows during compaction. Similarly, individual bivalve traces are poorly defined in the vertical sequence, although *Lockeia* are readily apparent on bedding planes. Low to moderate densities of vertical, unlined *Mya arenaria* burrows are observed originating at the tops of silt beds and penetrating down through both organic laminae and silt beds. These burrows are commonly greater than 1 cm wide and 10 cm long and sometimes are underlain by
concave-down spreite. Low to rare Nereis burrows are observed. Rooting is essentially absent.

Facies 6 is interpreted to represent tidal-creek point-bar deposits (Fig. 5D). The lateral migration, or meander rate, of tidal channels in salt marshes is an order of magnitude slower than fluvial channels, as a consequence of the resistant nature of the heavily rooted salt-marsh sediment (Allen 2000; Letzsch 1983; van Straaten 1961; Weimer et al. 1982). Sediment accumulation on point bars in tidal creeks is proportional to channel migration; thus, these deposits suffer repeated colonization and erosion. Repeated colonization obscures and distorts primary sedimentary structures. This is apparent at Waterside Marsh, where individual burrows and sedimentary structures are difficult to discern in the silt beds, and the matted-organic laminae are typically discontinuous and distorted by burrowing (Fig. 5A, B). The small, U-shaped structures commonly observed in Facies 6 represent small drainage channels that dissect the point-bar deposit. Similarly shaped structures were reported by van Straaten as channel-fill sediments at Veslen, The Netherlands (Weimer et al. 1982) and were considered common features of tidal-flat and tidal-channel sequences. Gravel layers encountered in F6 are deposited when storm-swash currents deposit coarse clastic material on the point bar. Rooting is not apparent, which is likely the result of the location of the facies at the base of the tidal creeks. Allen (2000) explains that halophytes are normally not encountered below the neap-tide high-water level. The point bars at Waterside Marsh are significantly below the neap high-water level, and thus are not likely to be colonized by halophytes (Figs. 5D, 6).

**Facies 7 (F7).**—Facies 7 comprises reddish-brown to dark-gray, bioturbated clayey silt. It is not observed in outcrop and is a minor depositional facies in Waterside Marsh. The average grain size is 6.0 \( \mu m \) (S 4\%, Z 64\%, C 32\%) with 4.7% organic carbon. The grain size and sand content increases towards the main tidal channels and towards the seaward limit of the marsh. Pebble and shell lags and matted-organic laminae are commonly observed in this facies. Surface mud is soupy, but cohesiveness increases with depth. Rooting is not apparent. Bioturbation is common, with intense numbers of Mya arenaria and Corophium volutator burrows and low numbers of Nereis burrows.

Facies 7 represents sediments deposited in naturally formed, low-order tidal channels that dissect the marsh surface. The low-order creeks are a minor component of the marsh and are inundated during every high tide. The incoming tide is relatively low-energy, resulting in the deposition and accumulation of microscopic organic material, fine silt, and clay. Consequently, these channels are ideal locations for colonization by sedentary organisms such as M. arenaria and motile but small organisms like C. volutator. Matted-organic beds form via trapping of organic detritus in pools at the bases of the creeks. Shell lags are deposited in a similar manner, whereas pebble lags are likely sourced from the melting of trapped ice blocks.

**Facies Association 3: Beach-Related Deposits**

Facies Association 3 (FA3) encompasses most beach-derived sediment. Coarse-grained material is deposited in the salt marsh as washover fans, storm-driven tidal-creek fill, and landward-migrating gravel bars. Identification of FA3 deposits is important in paleoenvironmental reconstruction, especially as a beach proximity indicator. Waves and wave-generated currents rarely transport coarse clastic material more than 100 to 150 m inland; therefore, the presence of coarse clastic material in a salt-marsh succession
Fig. 5.—Photos and schematics of F6, interpreted as point-bar deposits. A) Photo mosaic and B) interpreted schematic of light reddish-brown, low-angle, laminated silt and matted-organic laminae. Note: discontinuous gravel lenses (G), large burrows of *Mya arenaria* (M), matted-organic laminae (O), U-shaped structures (U), small *Nereis* (N) burrows, and *Macoma balthica* (Ma) burrows. C) Bedding-plane surface of F6. Arrows indicate examples of the high density of *Corophium volutator* burrows. D) Deposition of a point bar in the active salt marsh.

is a good indicator of the adjacent beach. FA3 is composed of two recognized facies. Facies 8 represents sand and gravel beds deposited in the tidal channels and Facies 9 embodies sand and gravel deposited on the salt-marsh surface (Table 2).

**Facies 8 (F8).**—Facies 8 is defined by steeply dipping sand and gravel beds. These beds observed in outcrop typically dip landward at angles between 9° and 13° and a maximum angle of 20°. The predominant grain sizes are coarse-grained sand to small pebbles reflecting the palimpsest beach sediment. Grain-size composition changes rapidly in the landward direction from dominantly sand and gravel, to sandy, silty gravel, and finally gravelly, sandy silt. Facies 8 is devoid of bioturbation and rooting.

The steeply dipping sand and gravel beds of F8 are attributed mainly to storm-driven sedimentation in the tidal creeks (Fig. 6). During storms, large waves occasionally breach the narrow backshore dune complex and transport suspended sediment and traction-load coarse-grained sediment into the salt marsh. Where the sediment-laden swash encounters a tidal creek, rapid deposition forms steeply landward-dipping sand and gravel beds.

**Facies 9 (F9).**—Facies 9 is defined by nearly horizontal, parallel-lami-
nated sand and gravel. These deposits occur on the present-day marsh surface, and as interbeds in vertical successions within Waterside Marsh. Facies 9A is subdivided into two related but sedimentologically distinct subfacies: 9A and 9B. Facies 9A is dominated by medium- and coarse-grained sand with minor gravel. It is deposited as relatively flat, lobate prisms of sediment on top of the salt marsh. Directly behind the narrow dune complex the sediment prism may exceed 2 m in thickness, but pinches out within 50 to 70 m in the landward direction. A typical measurement of F9A indicates that the prism extends 63 m into the salt marsh with a depositional slope that decreases in the landward direction from 14.8° in the first 3.4 m to a relatively flat 0.71° over the main part of the lobe. Facies 9B is composed of very coarse sand to small pebbles (4–8 mm) deposited as a flat (less than 0.30°), sheet-like unit that extends between 80 and 100 m into the salt marsh. Facies 9B is usually deposited where the backshore dune is washed out or where the dune crest is significantly below the average dune-crest height. Bioturbation is rare in F9A and very rare in F9B. Where vegetation is low to moderate, rare burrowing by talitrid amphipods (Figs. 2, 6) is observed in F9A. In the sand-dominated fringe of F9B, very rare burrowing by talitrids is observed. Rooting is low to moderate over much of F9A and low to rare in F9B.

Facies 9A and 9B represent washover-fan deposits. These sediments are deposited on the salt-marsh surface when storm-driven sediment-laden
swash breaches the backshore dune complex. In the transgressive Waterside Beach–Marsh system, storm processes have resulted in the coalescence of washover fans into a washover terrace that extends the full length of the beach (Fig. 1C).

**DISCUSSION**

**Stratigraphy of Waterside Marsh**

The facies identified at Waterside Marsh are representative of mineralogenic salt-marsh sediments deposited in a mature marsh during a stage of relative sea-level rise. The facies associations identified correspond to three distinct sedimentary environments. Facies Association 1 encompasses sediment that accumulates or accumulated on the primary depositional surface of the marsh. FA1 includes deposits that form within the tidal creeks, and FA3 describes sediment that is sourced from the adjacent, coarse-grained beach. The interaction of processes and sediments from these three environments controls the facies architecture and stratigraphy of Waterside Marsh deposits.

Figure 6 schematically illustrates the horizontal and vertical relationship of the depositional environments and their associated facies. Scales are provided as approximations because the dimensions of the depositional environments vary with distance away from the seaward edge of the marsh and with time. In Figure 6A, the relationship of Facies 1, 2, and 7 are depicted. Both F1 and F2 are deposited on the salt-marsh surface. The interaction of these facies is laterally and vertically complex and changes as the salt marsh matures. Redfield (1972) delineates five stages in the evolution of a sand flat to a fully mature marsh. In particular, the marsh passes through a stage dominated by pannes (F2), which decrease in abundance during maturation (Redfield 1972). It is suggested that the frequency and thickness of Facies 2 deposits increases with depth, reflecting the earlier stages of marsh development. A shallow channel cutting across the marsh surface and an infilled channel preserved in the vertical sequence represent Facies 7 (Fig. 6A). Studies concentrating on the stratigraphy of marshes in Europe indicate that during the early stages of sea-level rise and establishment of a mineralogenic marsh, low-order creeks are abundant and increase in density and depth with marsh accretion (French 1993; Pye and French 1993). As the marsh matures, the low-order creeks infill with silt (Allen 1997) and tidal energy is increasingly concentrated in the main tidal creeks. At Waterside Marsh, the early stages of marsh development were not evident in the exposed deposits; however, because this is a mature marsh in a transgressive system, it is assumed that low-order tidal channels (F7) are more abundant in the historical record than at present.

Tidal-creek facies relationships are illustrated in Figure 6B and C. In Figure 6B, the accumulation of sediment at the base of the tidal creek occurs in response to increased sedimentation rates and potentially RSL rise (i.e., base-level rise). Base-level rise results in the deposition and aggradation of sediments at the bases of the tidal creeks (F4). With time, the creeks expand and Facies 1 and 2 deposits are exposed along the channel walls and base. Those deposits exposed at the bases of the creeks are then colonized by *M. arenaria* and *C. volutator* (F3), thereby generating a *Glossifungites* ichnofacies (Bromley 1990; Gingras et al. 2001; Pemberton et al. 2001). It is important to note that this ichnofacies develops in response to autogenic processes and is not regionally mappable.

Figure 6C illustrates the facies relationships in a tidal-creek point bar near the seaward edge of the marsh. In the salt marsh, point bars migrate very slowly because cutbanks erode into cohesive sediment stabilized by vegetation. Normally, this erosion is contemporaneous with establishment of low-marsh deposits on the inner edge of the point bar (Fig. 5D); however, Figure 6C depicts a point bar in the zone of storm-wave swash that is sporadically inundated with beach-derived sediment (F8). This inhibits revegetation of the inner point bar. Facies 9, the washover fan, accumulates on the salt-marsh surface seaward of channel-bound F8 deposits.

**Application to the Rock Record**

Facies and facies associations defined from the Waterside Beach outcrops and from Waterside Marsh are applicable to mineralogenic salt-marsh deposits preserved in the rock record. The application of these results is dependent upon the preservation potential of the facies, which varies as a function of elevation in the vertical marsh succession, distance from the seaward edge of the marsh, RSL rise, and headland erosion rate. Salt-marsh deposits exposed in the foreshore of Waterside Beach are not likely to pass into the rock record. The upper 4 or 5 m of presently accreting marsh deposits located in close proximity to the beach will be eroded as transgression results in the landward shifting of facies and the erosion of the backshore (Reading and Collinson 1996; Roy et al. 1994). Conversely, sediments below 5 m depth in a salt-marsh sequence will be armored by sediment aggradation in the offshore (Reading and Collinson 1996; Roy et al. 1994), and therefore have a greater probability of preservation. In the landward direction, the preservation potential of recently deposited sediment increases because of accretion on the marsh surface and thickening of the vertical sequence. Consequently, the facies with the highest preservation potential, and thus the most applicable to the rock record, are those deposited either in topographic lows or well landward of the seaward edge of the marsh. On this basis, the facies can be ranked in terms of preservation ability as follows: F1, F2, F7, F3, F4, F6, F5, F8, and F9 (Table 2). Facies 1 and 2 are the most widely occurring deposits and have the greatest preservation potential. Facies 7 deposits extend deep into the marsh and also have a good chance of preservation. Tidal-creek facies—3, 4, and 6—are likely to be preserved because of their location at the bases of the channels. Facies 8 and 5 are considered to be anomalous and will not occur in most marsh sequences. Facies 9 is deposited on the marsh surface in close proximity to the seaward edge and will generally be removed by subsequent transgression.

Application of these facies and facies associations to the rock record requires recognition of the sedimentological and ichnological characteristics and architecture (Fig. 6) of the overall deposit. In general, rooted, unbuiturbated, rhythmically laminated silt observed in the rock record is akin to Facies 1 of this study and probably accumulated on the salt-marsh surface. Unbuiturbated, very weakly laminated, organic-rich clayey silt (Fig. 3C) interbedded with F1 sediments represent the pannes (F2) that occur intermittently on the marsh surface. If rooted, rhythmic, horizontally laminated silt exhibits bioturbation—particularly with *Skolithos, Siphonichnus, Arenicolites*, and/or *Diplocraterion*—then the surface from which these traces originate was an erosionally exhumed *Glossifungites* surface (F3, Fig. 3D). If the surface is overlain by shallowly dipping, interbedded clayey silt and muddy gravel (F4, Fig. 4A) or by shallowly dipping interbedded silt and matted-organic laminae (F6, Fig. 6A), then it likely developed in response to autogenic, tidal-creek processes. Rock-record examples of Facies 4 and 6 can be identified by their sedimentary structures, such as rhythmic bedding, and by their ichnological character. *Skolithos, Siphonichnus*, and *Arenicolites* may be observed between gravel clasts and in interbedded mud beds of vertical F4 successions. Rhythmic, dipping beds of silt and matted-organic laminae sets, and high degrees of bioturbation with *Arenicolites* (Fig. 5C), *Diplocraterion, Siphonichnus*, and *Skolithos* are diagnostic of Facies 6 (Table 2). Intensely bioturbated, laminated clayey silt that exhibit a gradational upper contact with either F1 or F3 is possibly similar to Facies 7 deposits of this study. Continuous beds of sand and gravel in a salt-marsh succession may be similar to Facies 8 or 9 and do not necessarily indicate a major change in depositional environment. These deposits, however, are proximity indicators of coarse-grained beach deposits.

The stratigraphic character of salt-marsh deposits varies as a function of climate, hydraulic conditions, and the morphology of the coastal system. Climate exerts a large influence on salt-marsh stratigraphy; thus, observations of temperate marshes cannot be directly applied to salt-marsh deposits.
globally. In Georgia, U.S.A., marshes, for example, decapods burrowing in tidal-creek banks is cited as a major form of bank erosion (Lettsch and Frey 1980). Conversely, randomly scattered ice-derived gravel clasts are not likely to be observed. Hydraulic conditions (influenced by tidal range and proximity to shore) also strongly influence sedimentation patterns (Allen 2000; Bayliss-Smith et al. 1979; Davidson-Arnott et al. 2002) and contribute to tidal-creek expansion (Pestrong 1965). Hydraulic processes are partly controlled by the morphology of the deposit (Pye and French 1993), which in turn determines whether a marsh is expanding, such as the Barnstable Marsh in Massachusetts, U.S.A. (Redfield 1972) or eroding, as in the case of Waterside Marsh. The location of a salt marsh relative to other marginal-marine environments not only influences the morphology of the deposit (Pye and French 1993) but also controls the extent and grain size of beach-derived sediment deposited in the salt marsh. Salt marshes landward of mud flats do not develop muddy-gravel deposits at the bases of their tidal creeks. Similarly, salt marshes landward of sand beaches likely exhibit an increased sand content in all salt-marsh facies, particularly in the creek facies.

Salt-marsh successions in the rock record are not present prior to the evolution of grasses. Although the first pollen grains of grasses are reported from the Maastrichtian, these plants were not dominant until the Paleocene (Kellogg 2000). Consequently, the earliest salt marshes probably date back to the early Cenozoic and not before.

SUMMARY

The sedimentological and ichnological characteristics of salt-marsh facies vary with changes in RSL, climate, hydraulic conditions, and associated marginal-marine environments. However, the general facies relationships and architecture do not vary significantly between marshes. Modern and exposed historical deposits at Waterside Beach and in Waterside Marsh provide an opportunity to describe and define salt-marsh facies and facies associations in a temperate, mineralogic salt marsh.

Three facies associations are identified: (1) salt-marsh deposits, (2) tidal-creek deposits, and (3) beach-related deposits. These represent the three main components of the Waterside Marsh depositional system. The facies associations are subdivided into nine facies, of which six (Facies 1, 2, 3, 4, 6, and 7) have a high preservation potential and are applicable to rock-record successions. In general, sediments that accumulate far landward of the seaward edge of the marsh or at the bases of the tidal creeks have a high probability of being preserved.

In a vertical salt-marsh succession preserved in the rock record, the six facies likely to be encountered can be identified by their sedimentological and ichnological character and by their relationship to other facies. Facies 1 and 2 occur together in the marsh and are interbedded. Low-order tidal creeks that dissect the marsh surface are manifested in preserved sediment as thin and narrow Facies 7 deposits and can be identified by an upper gradational contact with either F1 or F2 sediments. Facies 3, 4, and 6 represent deposition in the main tidal creek. Facies 3 commonly defines the basal contact of the tidal creeks and is overlain by either F4 or F6 deposits. The beach-derived deposits of FA3 are not likely to be preserved in a transgressive system because of their proximity to the beach and their location near the top of the salt-marsh surface. If either Facies 8 or 9 is observed, then it is an excellent indicator of an adjacent beach environment.

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