“If a form appears too complicated, more often than not it will become understandable after our brain has absorbed it through the pencil.”
– Adolf Seilacher

University of Alberta

SEDIMENTOLOGY AND ICHNOLOGY OF A WAVE-DOMINATED, MICROTIDAL BARRIER ISLAND / EMBAYMENT SYSTEM, NEW BRUNSWICK, CANADA

by

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ABSTRACT

Kouchibouguac National Park in New Brunswick, Canada encompasses a large barrier island / embayment system within a microtidal setting (< 2 m tidal range). Fieldwork involved the scrutiny of estuary geomorphology, and sediment and trace distributions. The system fits well into the wave-dominated estuarine classification, having a tripartite (sand-mud-sand) distribution of facies. However, low fluvial discharge results in diminutive bay-head delta deposits in the landward extreme: a departure from the wave-dominated end-member model. X-ray analysis of tube cores reveals that much of the system is heavily bioturbated by a depauperate assemblage of benthic organisms: the burrower activities obscure or eradicate most primary physical sedimentary structures. Exceptions occur in the landward and seaward extremes of the system, resulting in the preferential preservation of primary physical sedimentary structures in these two areas (inner and outer estuary respectively). Infaunal diversity and vermiform burrow size decrease (size-diversity index) with decreasing and fluctuating salinities up the estuaries, most markedly proximal to the fluvial-marine transition.

For my family, who have always offered me unconditional love and support.

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Over the last two and a half years I have had so much fun and have learned so much. I have many people to thank for this. I must start at the beginning, when was I asked by Shahin Dashtgard to join him in the Bay of Fundy as his field assistant. Being the first potential work-related experience in geology, I did not pass up the opportunity. The Bay of Fundy was fantastic! Shah taught me a great deal about sedimentology and ichnology, and it was in the Bay of Fundy that I realized how truly incredible neoichnological work was. While in the Bay of Fundy we were visited by Murray Gingras and Kerrie Bann. Kerrie was the first to introduce me to the idea of a masters degree, and when Murray offered not long after, I did not think about it twice. Who would not want to continue to study a modern siliciclastic environment full of interesting burrowing creatures?

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CHAPTER 1 – INTRODUCTION

During the last half-century there has been a marked increase in the understanding of the facies architecture, stratigraphy, and sequence stratigraphy of transgressive incised-valley fill systems. This understanding has in part stemmed from an increase in the number of studies undertaken in recent estuarine environments along the world's coastlines. These studies facilitate the understanding of the distribution of facies in estuaries, and the physical and chemical processes by which these facies were deposited. Understanding the distribution of facies, and more specifically those of reservoir potential, is important in the search for hydrocarbons in estuarine deposits. This is especially critical considering that estuarine deposits within incised-valley fill systems account for an estimated 25% of off-structure petroleum plays in clastic reservoirs worldwide (Boyd et al., 2006). Furthermore, neoichnological studies can improve our understanding of evolutionary paleoecology within estuarine systems, and aid in environmental remediation through an understanding of the effects of pollution on the distribution of benthic invertebrates.

In examples of estuarine strata it is evident that the distribution of sediments and their stratigraphic arrangement are complex. Creating a need for predictive estuarine models to improve the understanding of these complexities. Modern estuarine systems have become essential analogues for ancient incised-valley fill systems (Kraft and Chacko, 1979; Frey and Howard, 1986; Dalrymple and Zaitlin, 1989; Allen, 1991; Boyd and Honig, 1992; Nichol, 1991; Nichols et al, 1991; Clifton, 1994). An important aspect recognized from modern coastlines worldwide is great variability in geomorphology. It was recognized early that tides had a strong influence on the geomorphology of coasts (Davies, 1964). Advancements came in the description of the variation, and ultimately the geomorphological classification of coastlines resulting from the dominant hydrodynamic energies (i.e., wave, tide, and fluvial influences) (Hayes, 1979; Boyd et al., 1992). Estuaries, as distinct geological systems, were eventually simplified through the creation of a predictive geological facies model, in which classification was accomplished according to dominance of either tides or waves (Dalrymple et al, 1992). Two end-members were recognized: the wave-dominated estuary and the tide-dominated estuary, with an intermediate case consisting of a mixture of the two energy inputs (i.e., mixed-energy estuary) (Dalrymple et al., 1992).

In addition to recent sedimentological and geomorphological advancements to the estuarine model, significant advances in the delineation of estuarine strata have been accomplished through ichnological and neoichnological studies. Estuaries experience a distinct set of environmental conditions (i.e., those condition associated with brackish-water settings) that act as significant limiting factors on infaunal colonizers. Through work in both ancient and modern estuarine deposits, it was recognized that brackish-water conditions result in distinct, recognizable, and recurring benthic assemblages (Pemberton et al., 1982; Frey and Howard, 1986; Pemberton and Wightman, 1992; Wightman and Pemberton, 1997; Gingras et al., 1999; Pemberton et al., 2001) The studies resulted in the establishment of the brackish-water ichnological model that greatly aided in the predictability of estuarine facies in the subsurface. Recently, the combination of sedimentology and ichnology has proven to be a very powerful tool in paleoenvironmental analysis of estuarine strata (MacEachern et al., 1999; Zonneveld et al., 2001; Buatois et al., 2002; Hubbard et al., 2004; Bann et al., 2004)

Modern neoichnological work has largely aimed at furthering the use of ichnology in paleoenvironmental analysis in settings characterized by large tidal ranges (i.e., meso- to macrotidal regime; 2-4 m and >4 m respectively). This is because high amplitude tides expose large areas of intertidal substrate during low tides. In contrast, relatively few studies exist describing the distribution and type of bioturbation observed in microtidal systems (tide range less than 2 m). This has important implications, as microtidal wave-dominated environments are distinct geological phenomena, and thereby merit further neoichnological study.

This study focuses on microtidal wave-dominated brackish-water deposits in Kouchibouguac Bay (Canada), and is distinguished from earlier studies by incorporating neoichnological data with sedimentological and geomorphological data from a microtidal, wave-dominated barred coast. Two field seasons were undertaken in the barrier island / embayment system of Kouchibouguac National Park. Acquisition of data was accomplished through a number of field techniques attempting to illustrate; 1) the geomorphology of the system with respect to well established estuarine models, 2) the distribution and texture of sediments, 3) the distribution and type of bioturbation, with respect to limiting factors such as sediment texture and other physico-chemical parameters like salinity, and 4) the potential stratigraphic implications and their applicability to the rock record.

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CHAPTER 2 – SEDIMENTOLOGY, SUBTIDAL GEOMORPHOLOGY, AND STRATIGRAPHY OF A MICROTIDAL BARRIER ISLAND / EMBAYMENT SYSTEM, KOUCHIBOUGUAC NATIONAL PARK, NEW BRUNSWICK, CANADA

INTRODUCTION

Microtidal Coasts

Barrier island systems are common along the world's coastlines, making up to 7% of the shoreline (Stutz and Pilkey, 2002). They commonly occur along coastlines with microtidal ranges such as much of the eastern coastline of North America. The recognition of estuarine barrier island facies and their stratigraphic significance in the rock record has come largely from the study of modern transgressive microtidal and mesotidal environments. The recognition of wave-dominated estuarine sequences is complicated by the fact that barrier-island systems are complex, consisting of a number of subenvironments in which geomorphology and facies relationships depend on such variables as antecedent geomorphology, and sedimentologic and hydrologic variables (Frey and Howard, 1986). The arrangement of these subenvironments is highly diverse, especially at the seaward end, which suffers the brunt of wave and tidal energy (Hayes, 1979). Estuaries and incised valley fills can be important hydrocarbon producing siliciclastic reservoirs and account for a significant amount of the world's oil production and reserves (Boyd et al., 2006). Therefore, an understanding of their geomorphology and facies relationships is essential in hydrocarbon exploration.

Sedimentological and geomorphological studies of modern barrier island deposits aid in the delineation of potential sand-body reservoirs in the subsurface, and have led to the classification of 7 common morphological components recognizable in the subsurface: (seaward to landward) the ebb-tidal delta, barrier bar, inlet, flood-tidal delta, washover fan, central basin (or lagoon), and bay-head delta (Fig. 2.1A) (Dalrymple et al., 1992). However, in truly wave-dominated systems the ebb-tidal delta experiences a strong longshore component in sediment transport and is thus poorly developed (Davis, 1994a). Original models describing the geomorphology of coasts with respect to tidal- and wave-regimes did not come into wide use until the 1960's and 1970's (Davis and Hayes, 1984). It was recognized that common morphological elements along barrier coasts could be distinguished with respect to the relative strengths of either tides or waves. Two endmembers were established depending upon the tidal range: the tide-

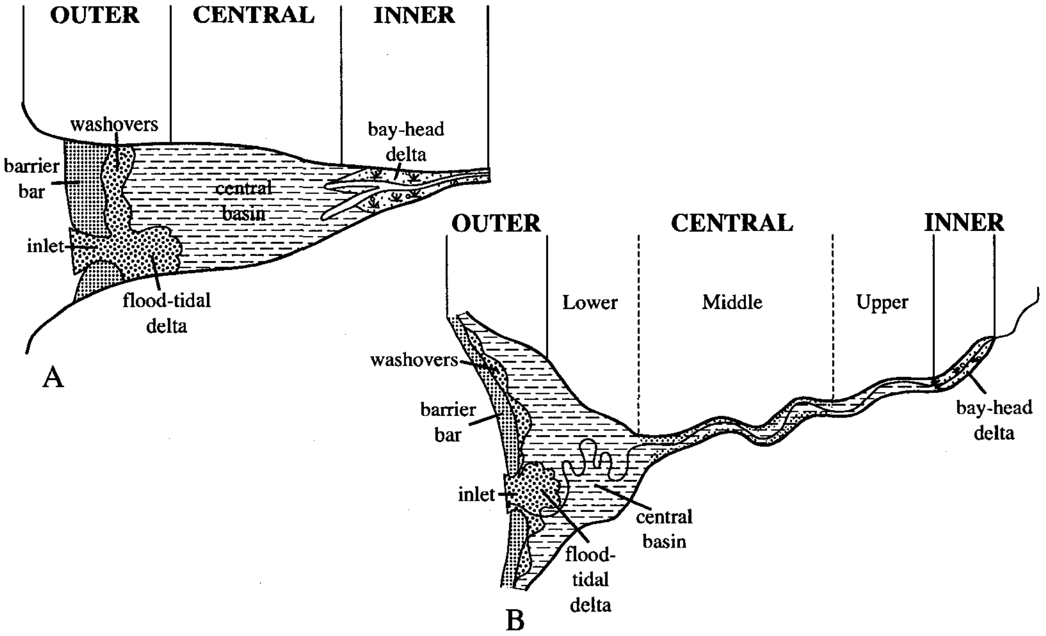


Figure 2.1- Morphological components typical of wave-dominated estuarine settings. A) Typical distribution of wave-dominated estuarine facies comprising a tripartite zonation (sand-mud-sand); an outer estuary marine sand plug, central basin muds, and sandy inner estuary deposits. The outer estuary includes many subenvironments due to the relatively high wave- and tidal-hydrodynamics associated with the marine influences. Modified from Dalrymple et al. (1992). B) Typical distribution of facies from estuaries in the wave-dominated Kouchibouguac Bay. The central estuary is further subdivided into the lower, middle, and upper due to significant textural variations therein. The bay-head delta deposits within the inner estuary are dimunitive due to low fluvial discharge and the narrow confines of the estuary funnel / fluvial valley.

dominated and the wave-dominated coasts (Davies, 1964; Hayes, 1979). Despite the fact that endmembers exist (i.e., tide- or wave-dominated coasts), there is much variation along the world's coastlines, with factors such as sediment supply, coastal gradient, drainage, and rates of sea-level change playing a large role in the geomorphology of the wave-dominated coastline (Roy et al., 1994). Major advancements in the understanding of ancient estuarine deposits came through the development of estuarine and incised-valley facies models (Frey and Howard, 1986; Nichols et al, 1991; Boyd and Honig, 1992; Dalrymple et al., 1992). Significant advancements in the understanding of estuarine systems continues at present (e.g., Boyd et al., 2006).

The organization of wave-dominated estuarine facies were compiled and simplified by Dalrymple et al, (1992), wherein the common estuary zonation consists of an outer, central, and inner estuary. These zonations are closely related to the physical processes occuring there and consequently, the facies within each of these estuary zones are distinct. In the outer estuary waves and tides dominate, in the inner estuary riverine influences are greatest, and in the quiescent central estuary all three forces are at work albeit at much lower strengths (Dalrymple et al., 1992). Examples of estuaries along the world's coastlines where this tripartite zonation of component energies and facies can be applied include the Miramichi River estuary to the north of Kouchibouguac Bay in New Brunswick (Reinson, 1976), the James River estuary in Virginia (Nichols et al., 1991), the Lawrencetown Lake estuary of eastern Nova Scotia (Boyd and Honig, 1992), and the Paranaguá Bay estuary in southern Brazil (Guilherme et al., 1998). Typically, when riverine influences are relatively small, conspicuous bay-head delta deposits (i.e., landward sand plug) are not fully developed (Fig. 2.1B) (Boyd and Honig, 1992; Dalrymple et al., 1992; Reinson, 1976). Consequently, the landward sand body in the tripartite division of facies is diminutive.

It is well established that the dominant transgressive sediment transfer on microtidal barrier island coastlines is that of inlet and washover sedimentation in a landward direction (Forbes et al., 2004). In a southern Gulf of St. Lawrence barrier island system, Armon (1979) indicates that over 90% of landward sediment transport over a period of 33 years occurred in association with tidal inlets. It is also well established that the sandy subenvironments of the outer estuary are preferentially preserved in transgressive systems tracts within the rock record (Dickinson et al., 1972; Kraft and Chacko, 1979; Galloway, 1986; Cattaneo and Steel, 2003). These sandy subenvironments often include flood-tidal delta and tidal inlet facies. Consequently much research has focused on bedform geomorphology and associated hydrodynamic conditions within these subenvironments (Hubbard et al., 1979; Reinson, 1979b; Matsushita and McCann, 1988; Dalrymple and Rhodes, 1995). These studies illustrate that the dominant current direction (i.e., flood or ebb tidal current) is manifest in dunes or sand waves that contain leeward facing slopes in the direction of dominant sediment-transport direction. On the microtidal coast of Prince Edward Island, Matsushita and McCann (1988) observed bedforms with flood-dominant transport directions within the tidal inlets, indicating the predominance of flood- over ebb-flow. On the large flood-tidal delta fronting the Miramichi River estuary, Reinson (1979b) observed a complex distribution of sand waves that show predominantly flood-oriented sediment transport directions. These studies help to illustrate the tidal imprint within subenvironments of the outer estuary from modern examples. This aids in the delineation of retrogradational stacking of facies associated with the marine sand plug in the rock record, and more importantly the production of useful models of estuarine sequences.

Numerous studies have been conducted seaward of the barrier islands in Kouchibouguac Bay. These include the sedimentology and facies relationships proximal to the barrier bars (Kranck, 1967; Greenwood and Davidson-Arnott, 1972, 1978; Davidson-Arnott and Greenwood, 1974, 1976; Greenwood and Mittler, 1985). Kouchibouguac Bay has also been discussed in the literature with reference to processes affecting coastal geomorphology on microtidal wave-dominated coasts (McCann and Bryant, 1970, 1972; Bryant and McCann, 1973; McCann, 1979). In contrast, literature is sparse describing the sediment distributions and geomorphology of the system landward of the barrier bars.

The barrier island system in Kouchibouguac Bay resides on a low gradient coastal plain which experiences microtidal ranges, and is sheltered significantly from wave activity due to its location in the Northumberland Strait. Consequently, the low energy estuaries that debouche into shallow back-barrier lagoons are long and narrow with poorly developed bay-head deltas far inland from the lagoons. The study of this low energy system and the distribution of major component subenvironments adds to existing literature describing end-member wave-dominated estuaries and their commonly described tripartite (sand-mud-sand) distribution of sediments (Fig. 2.1A) (Dalrymple et al., 1992; Nichols, 1992). More specifically, in the context of the wave-dominated estuarine classification, this study aims to: 1) describe the distribution of sediments and their textural parameters; 2) describe the distribution of bedforms within the system, with emphasis on the region landward of the tidal inlets; 3) describe the estuarine geomorphology; and 4) discuss stratigraphic implications.

Study Area

Kouchibouguac National Park is located in New Brunswick, Canada on the Northumberland Strait in the Southern Gulf of St. Lawrence (Fig. 2.2A, B, C). The park resides in the Appalachian Geographical Region, which is characterized by a peneplain dating from the Jurassic and Cretaceous Periods (Beach, 1988). Within this region, the coastline under study exists in the maritime plain, dominated by low-lying and flat topography (Beach, 1988). The park is underlain by medium- to coarse-grained Pennsylvanian sandstones, with minor clay and siltstones (Kranck, 1967, 1972). Thin surficial marine-reworked glacial deposits drape the bedrock, all of which are attributed to the retreat of the Wisconsin glaciation. A dynamic shoreline history marked by periods of regression and transgression has affected these deposits over the last 14,000 years, with establishment of a barrier island system between 5000 and 2500 years B.P. due to rising relative sea level (Beach, 1988).

Within the park, two main estuaries and their associated lagoons and tidal inlet

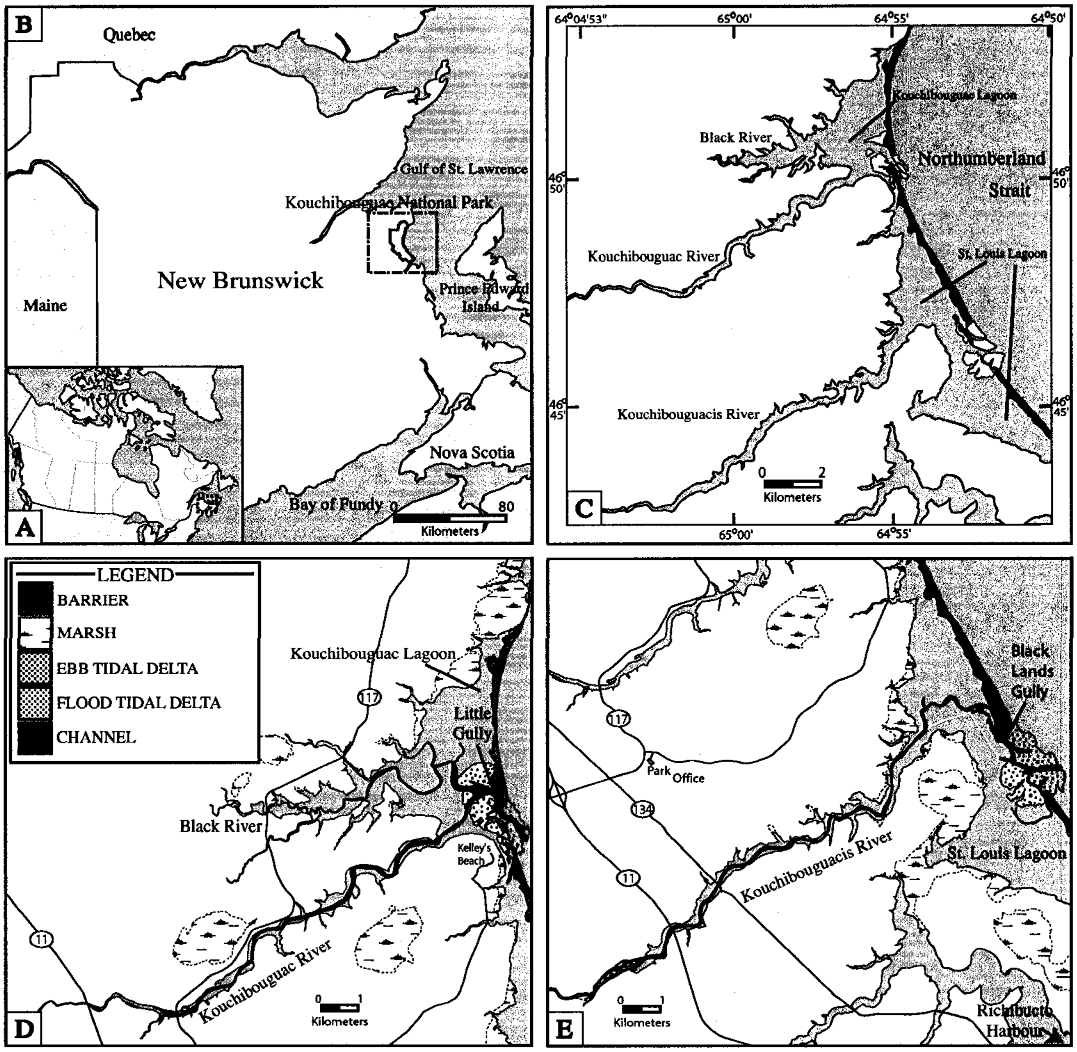


Figure 2.2- Location map of Kouchibouguac National Park. A) Location of New Brunswick in Canada. B) Location of Kouchibouguac National Park in New Brunswick. C) Detail of estuaries and associated lagoons studied in relation to the Northumberland Strait. D) Detail of the northern portion of the study area, including the Kouchibouguac River and Lagoon, and the Black River. E) Detail of the southern portion of the study area, including the Kouchibouguacis River and St. Louis Lagoon. General subenvironments are outlined in the legend of D).

areas were studied, 1) the Kouchibouguac River and Lagoon (Fig. 2.2D), and 2) the Kouchibouguacis River and the St. Louis Lagoon (Fig. 2.2E). In addition, the Black River and its sinuous lagoonal channel were studied in the northern part of the system (Fig. 2.2D). Two permanent inlets dissect the barrier through which tidal waters are exchanged between the embayments and the Northumberland Strait, the Little Gully to the north and the Blacklands Gully to the south (Fig. 2.2D, E). Estuaries and lagoons represent drowned preglacial valleys that were not greatly modified by the Pleistocene ice sheets (McCann, 1979). The barriers that protect the lagoons are classically long (29 km) and narrow, with well-developed flood-tidal deltas, and poorly developed ebb-tidal deltas, typical of barrier systems located on microtidal coasts (Davis and Hayes, 1984; Davis 1994b). The dunes backing the barrier beach rarely exceed 5 m in height, and consequently have endured multiple washover events (at least 15 since 1807) due to storm activity that have produced transitory inlets (Beach, 1988). Washovers that preclude the establishment of a new inlet are also commonplace. Both aforementioned activities act to move the barrier landward and contribute to the filling of the lagoon with marine-derived sand.

Wave activity is the dominant erosional and transporting force in the system, but is subdued by a limited fetch to the northeast. Winds in the summer and winter seasons are dominated by a west / southwest and northeasterly direction respectively. Consequently, longshore currents are dominantly southeastward (Kranck, 1967), causing active inlet sedimentation through spit migration, and the longshore erosion of ebb-tidal deltas. Tidal energy is low, with a mixed semidiurnal (Beach, 1988) microtidal regime consisting of a mean tidal range of 0.67 m, and a maximum of 1.25 m(McCann and Bryant, 1973; Davidson-Arnott and Greenwood, 1974). However, constriction of flow through the inlets results in measured flood- and ebb-tidal currents within the Little Gully as high as 1.1 m/s (Beach, 1988).

The lagoons are very shallow, rarely exceeding 2 m in depth, while channels within the lagoon can reach depths of 7.82 m. Estuaries within the system are typically narrow and shallow, with depths normally not exceeding 7 m. Due to the low coastal gradient of the maritime plain, the saltwater prism extends as far inland as 13 km. The river strength within the estuaries is low, with mean annual discharge rates for the Kouchibouguac River assessed at 3.74 m^3/s (Robinson et al., 2004). Similar data does not exist for the less studied Kouchibouguacis and Black Rivers. The catchment basin for the Kouchibouguac River is approximately 245 km^2, 230 km^2 for the Kouchibouguacis River, and 32 km^2 for the Black River (Ambler, 1975).

Anthropogenic influence in has been restricted within the park since its inception in 1969; however, dredged channels still exist within both the Kouchibouguac and St. Louis Lagoons for the purposes of commercial fishing. Beyond the borders of the park, a small, derelict hydroelectric dam resides on the Kouchibouguac River.

Methods

The dataset was collected during two summers of fieldwork undertaken in

July-August of 2005 and 2006. Most of the work was done from a small boat, with the exception of data collection on the flood-tidal delta areas of the Kouchibouguac Lagoon that were exposed during low spring tides. A number of transects were placed normal to the coastline through the lagoon, along which equally spaced stations were studied. Up-estuary stations were randomly placed up to the limit of saltwater intrusion. Other stations were placed within specific sub-environments (e.g., flood-tidal delta, back-barrier beaches). Snorkel was employed to observe the locale and collect data. In deeper channels of the system SCUBA was employed.

At each station observations of bedforms were made. Primary and biogenic sedimentary structures were assessed at each station through the use of a portable Soyee X-ray system (SY-31-100P) and Kodak Professional Series 25.4 cm^2 film. X-rays were taken from shallow 1 foot PVC tubing that was emplaced into the sediment at most stations. General X-ray settings that worked best include: 1) distances from X-ray source to sample ranging from 150 to 300 cm; 2) exposure times of 0.8 to 1.5 seconds depending on sample texture and heterogeneity therein; 3) Kvp of 60 to 70; and 4) mA of 25 to 30. Generally, greater distances coupled with longer exposure times resolved the greatest detail in the sediments.

1000 to 2000 g grain-size samples were collected from the upper 5 cm of each station and later sieved through screens of phi sizes –2 ø (4 mm) to 4 ø (0.0625 mm). If the fine fraction of the sample exceeded 2 % of the total, the fraction was heated to 550 °C to remove organics. To prevent flocculation, 30 to 40 ml of 0.05% sodium metaphosphate ($(\mathrm{NaPO}^3)_x \cdot \mathrm{Na}_2 0$) was added. The samples were then mechanically disaggregated for 10 minutes with a magnetic mixer, and 5 minutes in a sonification bath. Finally the samples were analyzed through X-ray absorption analysis using a Micrometrics Sedigraph 5100. The fines were then factored into the overall grain size distribution of the sample. Frequency histograms were produced from the overall grain size distributions following the Wentworth size classification. Further textural analysis was conducted through the construction of cumulative grain-size curves. Mean grain size (M), sorting (ø), skewness (Sk), and kurtosis (K) were determined through inclusive graphical analysis (Folk, 1974). Recorded mean grain sizes are represented by their geometric mean. For subenvironments within the broader estuary classification of outer, central, and inner (Dalrymple et al., 1992), averages of these values were compiled.

Bathymetric profiles of the Black River channel within the Kouchibouguac Lagoon were recorded using a Lowrance LMS–334C combined sonar and mapping GPS unit. Measurements were collected every second in order to compile a continuous dataset. Data was resolved using the computer program Surfer 8, and later hand-modified using

Adobe Illustrator. 2-dimensional bathymetric profiles of bedforms near the tidal inlet of the Black River channel were produced in Excel using the data from the Lowrance unit. Bedform parameters were determined from the duneforms therein.

In addition, ^{14}C age dates were established from *Mya arenaria* shells obtained *in-situ* from a tidally exposed firmground along the Black River channel within the Kouchibouguac Lagoon. The shells were analyzed at the KECK AMS (accelerator mass spectrometry) Lab at the University of California, Irvine.

DESCRIPTION AND RESULTS

Estuarine Geomorphology

The estuaries within Kouchibouguac Bay are subdivided into 3 major zonations following the scheme of Dalrymple et al. (1992) (Fig. 2.1A). From the barrier bar complex landward, these zonations consist of the outer, central, and inner estuary (Fig. 2.1) These major zonations correspond to major facies boundaries, thereby allowing comparison of these commonly cited facies zonations from other studies to those observed in Kouchibouguac Bay. In addition, due to the morphology of the estuary funnel and the complexity observed therein, the central estuary is sub-divided into the lower (seaward), middle, and upper (Fig. 2.1B).

In general, morphology of the estuaries and their associated lagoons and tidal inlets are as follows: The estuaries are narrow, residing within drowned river-valley systems. Where the tidal prism and its effects dampen with distance up the estuary, the rivers become considerably narrower. This occurs rather abruptly approximately 13 km inland. The main estuary channels (thalweg) of the inner and central estuary are generally very shallow, with depths not exceeding 7 m. The channels are not markedly meandering within the confines of the larger Kouchibouguac and Kouchibouguacis Rivers (figs. 2.3, 2.4). However, once the channels debouche into the lower-central estuary (lagoons), they take on a markedly meandering form. Thus the majority of the length of the estuary is dominantly "cuspate" in form (Dalrymple et al., 1992). In the less confined margins of the Black River (Fig. 2.4), the main channel is meandering intensely well into the upper reaches of this estuary. The channel continues its meandering form from the upper-central estuary into the lower-central estuary (Fig. 2.4, Kouchibouguac Lagoon).

Bedforms are markedly lacking in the majority of the system, even within the channels of the inner and central estuary. Hummocky undulations with in the sand of the inner estuary (approximately 30 cm in height) may represent sinuous duneforms produced

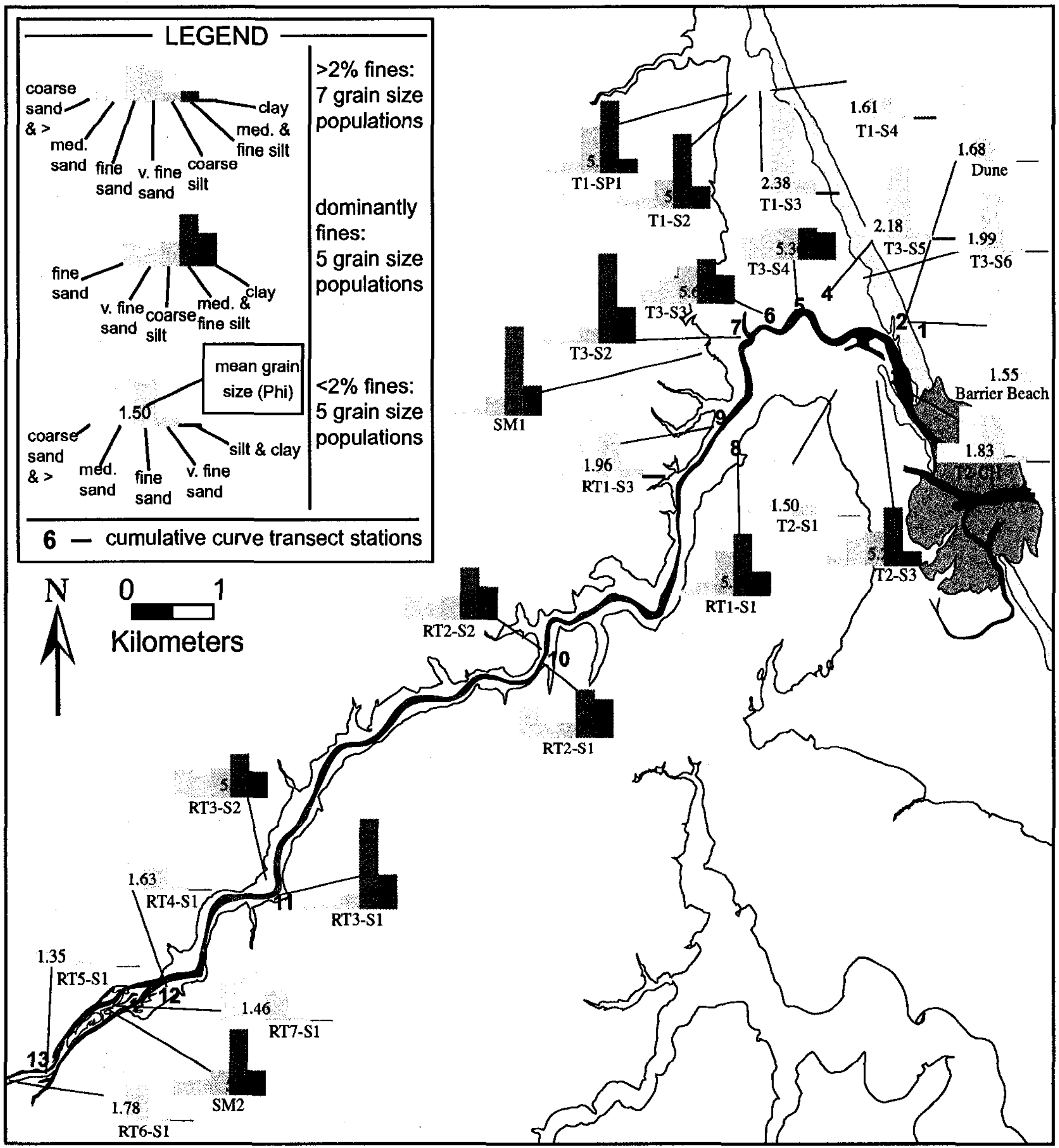


Figure 2.3- Map of sediment distribution from the southern Kouchibouguacis River and St. Louis Lagoon. Histograms generally consist of 5 grain-size populations, where either sand or mud fractions are less than 2% of the total fraction of the sample. Where fines are greater than 2% of the total fraction, histograms consist of 7 grain-size populations. Yellow colors represent the sand fraction, whereas orange and brown colors denote silt and clay. A general tripartite division of sediments is observed, wherein the outer and inner estuary are dominated by sand, and mud dominates the central estuary. Local variation in this trend is observed most commonly in the middle- and upper-central estuary (i.e., stations RT1 to RT3), where local bedrock sources increase the average grain size and decrease the sorting. Bold numbers represent the stations used to construct the cumulative curve transects of Figure 2.8 A.

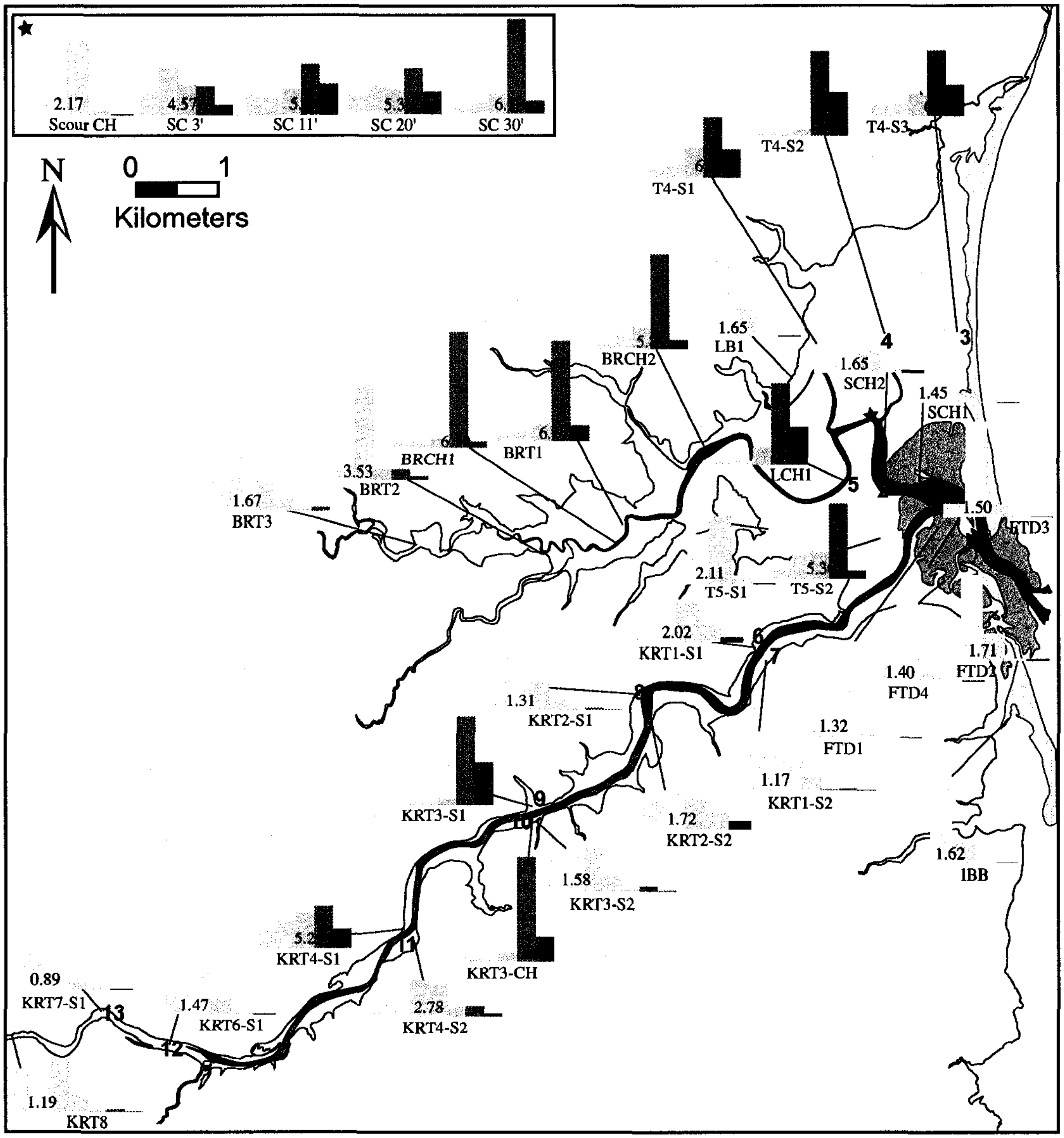


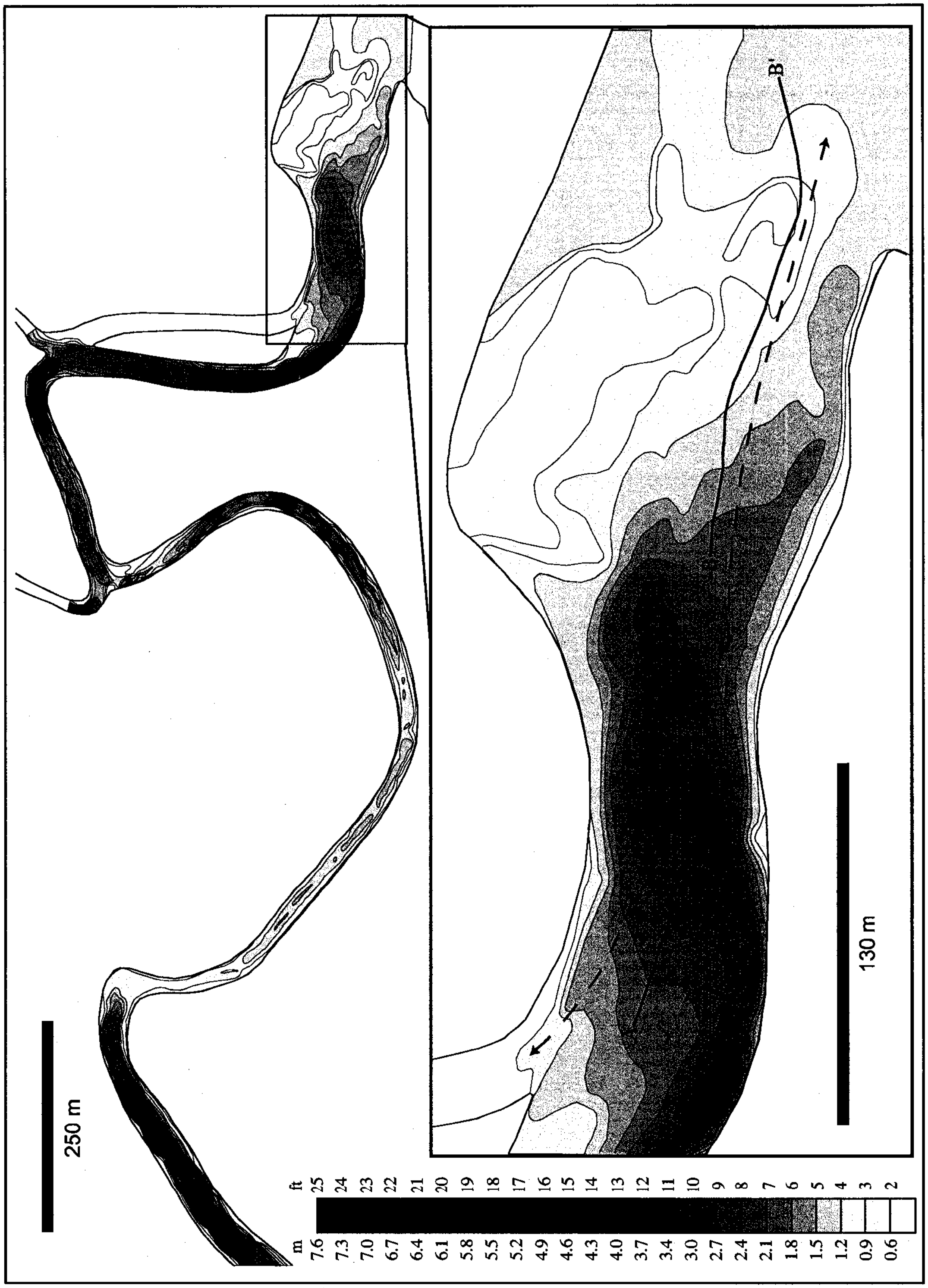
Figure 2.4- Map of sediment distribution from the northern Kouchibouguac River and Lagoon. Histograms generally consist of 5 grain-size populations, where either sand or mud fractions are less than 2% of the total fraction of the sample. Where fines are greater than 2% of the total fraction, histograms consist of 7 grain-size populations. Yellow colors comprise the sand fraction, whereas orange and brown colors denote silt and clay. The tripartite zonation of sediments observed is very similar to that of the Kouchibouguacis River and St. Louis Lagoon of the previous figure. The smaller Black River also exhibits a tripartite distribution of sediments. Local variation in the central estuary is more pronounced here, attributed to a greater abundance of local bedrock sources of coarse-grained material. This is due to the higher topography through which the Kouchibouguac River flows. Bold numbers represent stations used to construct the cumulative curve transects of Figure 2.8 B. The red star represents a firmground exposure, and the inset contains samples taken from the exposure.

during high runoff, subsequently modified by low discharge flow over the duration of the low runoff period. The only bedforms observed within the muddy channels of the central estuary were small-scale current ripples, formed of capitellid polychaete fecal pellets in the channel of the Black River estuary (Fig. 2.4, BRCH1). More conspicuous bedforms are commonly observed within the outer estuary where tidal and wave forces dominate.

The bathymetric profile (Fig. 2.5) reveals that the Black River channel varies significantly in depth from the mouth of the Black River toward the main tidal inlet. The channel approaches 5.8 m in depth near the mouth of the Black River. Underwater observations here reveal that bedforms are not present, and the substrate is an erosionally exhumed stiffground, consisting of palimpsest, partly dewatered and compacted silt. Shell lag is abundant, consisting dominantly of the disarticulated valves of those burrowers commonly found within the outer estuary sands (*Ensis directus*, and *Mercenaria mercenaria*). Where the channel spills out of the more confined Black River it shallows significantly to 1.5 m, with no apparent bedforms present. Further along flow is forced around relatively tight meanders and depths approach 3.4 m. Bedforms are not developed in this area in the clayey silts. Underwater observations reveal that the sediments are thixotropic in nature, with local partial binding due to the presence of microbial mats.

One of the tightest meanders in the Black River channel exists mid-lagoon (lower-central estuary). The deepest recorded depths, approximately 8 m, occur along this bend (Fig. 2.5; Fig. 2.4, red star). Channel depth gradually deepens into the scour, which is largely confined to the outside curve of the meander. The channel takes on an asymmetric profile with a gradually sloping point-bar on the inside of the curve. On the outside of the curve, the scour has produced an approximately 6 m, nearly vertical palimpsest firmground exposure, consisting of lower-central estuary silty sand and sandy silt. Palimpsest firmground consisting of salt marsh silts are exposed at the base of the channel. A significant lag of bivalve shells is located in the scour. Another similar scour occurs down-channel at the next meander, where it reaches depths of 5.2 m. A significant shell lag is observed here as well.

Proximal to the tidal inlet, the Black River channel shallows and broadens considerably (Fig. 2.5, inset). The channel here comprises medium-grained sands. Consequently, bedforms are abundant here. 2-D bathymetric profiles reveal duneforms showing both ebb and flood orientation (Fig. 2.6). In the location of transect A to A' the bedforms consist of large wavelength (avg. 11.29 m), medium height (avg. 0.27 m) 2-dimensional compound dunes. The dunes are flood-oriented in this area. Whereas transect B to B' contains ebb-oriented medium wavelength (avg. 9.6 m), medium height (avg. 0.21 m) 2-dimensional compound dunes. Dunes from transects A to A' and B to B'


250 m
130 m
B'
m
7.6
7.3
7.0
6.7
6.4
6.1
5.8
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5.2
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4.6
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Figure 2.5 (previous page)- Bathymetric contour map of the Black River channel within the Kouchibouguac Lagoon. Depths range from 0.6 m to 7.6 m. The width of the channel proximal to the tidal inlet (inset) is significantly wider than the majority of the rest of the channel. Here tidal energy is highest and is manifest in the production of dunes. Due to the orientation of dunes observed from 2-dimensional bathymetric profiles (Fig. 2.6), two separate flow paths are interpreted. These flow paths are interpreted to represent mutually exclusive flow paths for ebb- and flood-flow, with ebb flow predominating proximal to transect B to B', and flood flow predominating proximal to transect A to A'. Where tidal energy dampens with friction up the channel, meandering channel form is observed. The deepest parts of the channel are associated with tidal scour in the meandering portion of the channel, which commonly occurs in the tight curves. Associated with the tidal scouring is exposures of stiffground and firmground substrates of lagoonal and salt-marsh affinity. Landward of the tight meanders exists a shallow zone within the channel proximal to the loosest meander. In this zone, deposits consist predominantly of fluid mud derived from fluvial processes. Further landward, the channel once again deepens considerably proximal to the mouth of the estuary of the Black River (see Figure 2.7 for location). Here the base of the channel consists of exposures of stiffground associated with erosion and sediment bypassing.

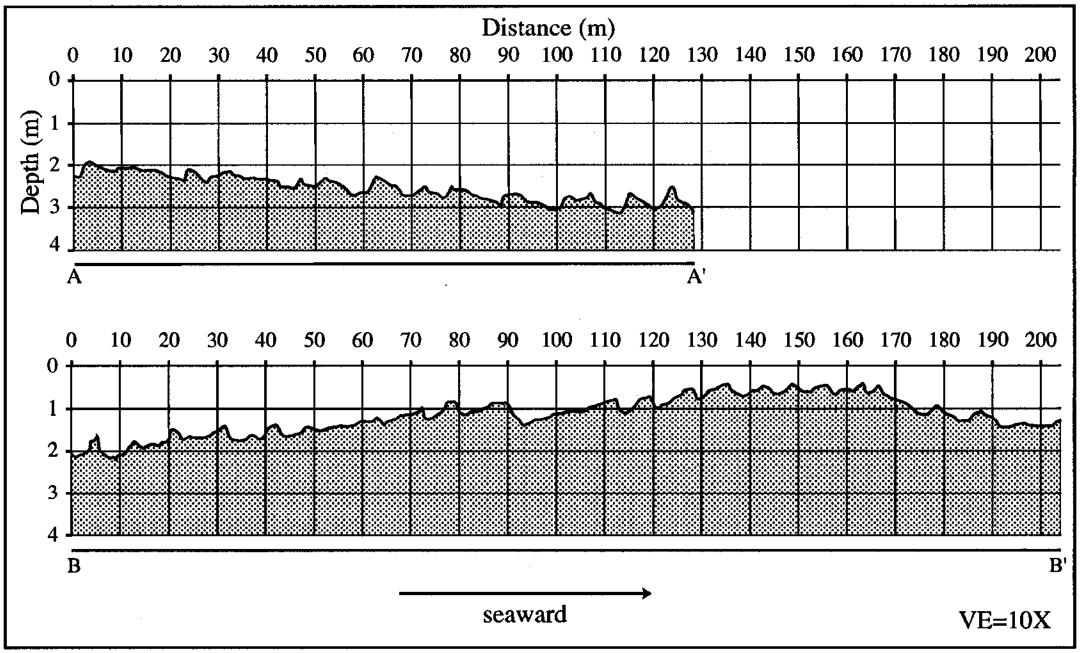


Figure 2.6- Bathymetric profiles taken from the Black River channel proximal to the Little Gully (tidal inlet). See Figure 2.5 for transect placement. Transect A to A' exhibits flood-oriented large wavelength (avg. 11.29 m), medium height (avg. 0.27 m) 2-dimensional compound dunes within medium-grained sand. Transect B to B' exhibits dominantly ebb-oriented medium wavelength (9.6 m), medium height (0.21 m) 2-dimensional compound dunes, and flood-oriented dunes seaward of the high (~ 180 m). Superimposed on dunes from both transects are current ripples oriented in the opposite direction of dune sediment transport. These superimposed current ripples are reverse-flow caps. Ripple indexes from the dunes in the channel range from 41 to 45, suggesting they are relatively flat bedforms. The significant decrease in depth seaward in transect B to B' is attributable to a small ebb-tidal delta (see Figure 2.7).

Figure 2.7- Digital orthophoto of the Kouchibouguac Lagoon and the meandering Black River channel, which flows through the Little Gully inlet. The white dashed line borders the channel from which the bathymetric contour map of Figure 2.5 was constructed. The lobate sand body in the channel proximal to the Little Gully is interpreted to be a small ebb-tidal delta (black arrow). Notice the well-developed, multi-lobate flood-tidal delta and the poorly developed ebb-tidal delta.

have ripple indexes (Allen, 1968) of 41 to 45 respectively, suggesting they are relatively flat bedforms. Superimposed bedforms from transect A to A' consist of ebb-oriented current ripples, while on transect B to B' they consist of flood-oriented current ripples. These superimposed small-scale bedforms can be observed well on the 2-dimensional bathymetric profiles (Fig. 2.6); the small, reverse-flow caps of Dalrymple and Rhodes (1995). From the dominant orientation of bedforms it can be deduced that landward of the tidal inlet, the rather wide channel contains mutually exclusive flow paths for ebb and flood tidal currents (Fig. 2.6).

The marked change in depth seaward on transect B to B' is conspicuous. At approximately 160 m (Fig. 2.6), the channel shallows considerably. Seaward of this high, dunes have a flood-oriented appearance. The shallow water here is attributed to a large lobate sand body observed on Figure 2.7. We believe this may represent a small ebb-tidal delta.

Bedforms observed on the intertidal portion of the flood-tidal delta in the Kouchibouguac Lagoon are complex and exhibit a wide variety of forms oriented in a number of directions. Orientation of bedforms generally consist of 3 types: 1) those oriented parallel to the axis of the barrier bar, 2) those oriented obliquely in two directions relative to the axis of the barrier bar, and 3) those with scattered orientation (bidirectional) relative to the margins of the flood-tidal delta. The margins of the flood-tidal delta (ebb shield) contain a number of large wavelength and medium height dunes with scattered orientation. The dunes are common along the margins of the flood ramp and ebb spits (Reinson, 1979a). Two different bedform lineations are observed on the flood-tidal delta oriented approximately perpendicular to each other. These large-scale lineations consist of depressions bordered by elevated ridges. Reinson (1979b) called these 'ridge and runnel' features, or current lineations on the flood-tidal delta of the Miramichi River estuary. He attributed these lineations to the drainage of ebbing tidal flow from the delta, which experiences secondary helical flow, resulting in the production of longitudinal bedforms. Superimposed on the majority of the surface of the flood-tidal delta are small-scale, ebb-oriented, sinuous crested current ripples oriented approximately parallel to the barrier-bar axis. These current ripples represent low-water sediment transport during ebbing tidal flow.

Estuarine Sedimentology

Table 2.1 summarizes the sediment texture from the 3 estuary zones in the system, which are further subdivided into dominant morphological components (sub-environments), and represent averages of sediment textural parameters. Nomenclature of sediments based on sand-silt-clay ratios follows that of Shepard (1954).

The frequency histograms of figures 2.3 and 2.4 reveal that the distribution of sediment types follows a general tripartite division, from sandy in the outer estuary, to dominantly muddy in the central estuary, and back to sandy in the inner estuary (sand-mud-sand). This trend can be observed seaward to landward in all three of the estuaries studied (figs. 2.3, 2.4). However, a significant deviation from this overall trend exists within the northern Kouchibouguac River (Fig. 2.4). From the mouth of the estuary landward to the stations designated KRT2, the mean grain sizes of the sediments are commonly medium sand, with a significant fraction of coarse-grained sand and of larger grain sizes (local pebbles and gravels). This deviation from the normal sand-mud-sand division can be accounted for by the higher topography of the headlands through which the Kouchibouguac River flows. The higher topography results in more significant outcropping of Pennsylvanian sandstone bedrock. Thus this bedrock is more commonly incorporated into the sediments of the Kouchibouguac River along its margins.

The general tripartite division of the estuaries is evident from cumulative curve transects from stations in the outer estuary to the inner estuary (Fig. 2.8A, B). The outer- and inner-estuaries of the Kouchibouguacis (Fig. 2.8A) and the Kouchibouguac Rivers

Estuary Zone	Sub-Environment	Sediment Texture	Common Sedimentary Structures
Outer	dune	well sorted, fine skewed, mesokurtic, m.g. sand (1.60 M, 0.45 ϕ, 0.19 Sk, 1.08 K) [1]	low- to high-angle (landward dipping) cross stratification; insect bioturbation moderate to absent
	barrier beach	very well sorted, fine skewed, mesokurtic, m.g. sand (1.55 M, 0.34 ϕ, 0.11 Sk, 0.92 K) [1]	low-angle seaward-dipping bedsets with common planar-erosional scours; bioturbation absent
	flood-tidal delta	mod. well sorted, nearly symmetrical, leptokurtic, m.g. sand (1.48 M, 0.51 ϕ, –0.03 Sk, 1.16 K) [4]	small- to large-scale bidirectional trough- and planar-cross stratification, wave- and combined- flow ripples; thin (3-5cm) pebble beds and lenses locally, common pebble-lined foresets; common shell debris; common bored wood debris; bioturbation rare to abundant
	tidal channels	mod. well sorted, nearly symmetrical, mesokurtic, m.g. sand (1.77 M, 0.61 ϕ, -0.03 Sk, 1.08 K) [4]	low- to high-angle cross stratification, trough-cross stratification; common shell debris; abundant bladed muddy rip-up clasts, which locally line foresets; bioturbation rare (commonly fugichnia)
	sandflats / washover fans	mod. well sorted, nearly symmetrical, mesokurtic, m.g. sand (1.87 M, 0.53 ϕ, 0.00 Sk, 1.04 K) [6]	low angle (landward dipping) planar beds, moderate weakly-defined wave ripples; moderate normal-graded bedding; pebbles common; bioturbation moderate to abundant
Central	lower-central estuary (mid-lagoon, muddy mid lagoon channel)	very poorly sorted, fine skewed, mesokurtic, m. silt (5.88 M, 2.09 ϕ, 0.16 Sk, 1.04 K) [14]	mostly homogenized, rare planar laminations, fluidized mud beds within channels; common articulated shells, moderate disarticulated shell debris; common roots; complete to abundant bioturbation
	landward lagoonal beaches	poorly sorted, fine skewed, mesokurtic, m.g. sand (1.65 M, 1.65 ϕ, 0.19 Sk, 1.08 K) [1]	common wave ripples; weakly-defined pebble to gravel (angular) beds; bioturbation moderate

Table 2.1- Summary of sedimentary character of depositional subenvironments.

Estuary Zone	Sub-Environment		Sediment Texture	Common Sedimentary Structures
Central (cont.)	middle-central estuary	muddy	poorly sorted, nearly symmetrical, leptokurtic, m. silt (5.90 M, 2.00 ϕ, -0.10 Sk, 1.17 K) [6]	mostly homogenized, rare planar laminations; common roots; bioturbation complete to abundant
		sandy	poorly sorted, nearly symmetrical, leptokurtic, m.g. sand (1.95 M, 1.27 ϕ, -0.10 Sk, 1.44 K) [6]	indistinct bedding structures; random pebble to gravel (angular) clasts, locally clasts define beds; rare firmground surfaces (salt marsh) at depth; bioturbation moderate to absent
	upper-central estuary	muddy	poorly sorted, fine skewed, leptokurtic, f. silt (6.24 M, 2.00 ϕ, 0.13 Sk, 1.11 K) [5]	mostly homogenized, rare planar laminations, fluidized mud beds within channel; common roots; common terrigenous plant debris; bioturbation complete to abundant
		sandy	poorly sorted, coarse skewed, very leptokurtic, f.g. sand (2.18 M, 1.76 ϕ, -0.13 Sk, 1.62 K) [2]	indistinct bedding structures, common random pebble clasts; common terrigenous plant debris; bioturbation moderate to absent
Inner	bay-head delta region		moderately sorted, strongly coarse skewed, mesokurtic, m.g. sand (1.43 M, 0.84 ϕ, -0.04 Sk, 1.06 K) [8]	low- to high-angle tabular-cross stratification; abundant terrigenous plant debris; bioturbation absent to moderate

(**Table 2.1** cont.)

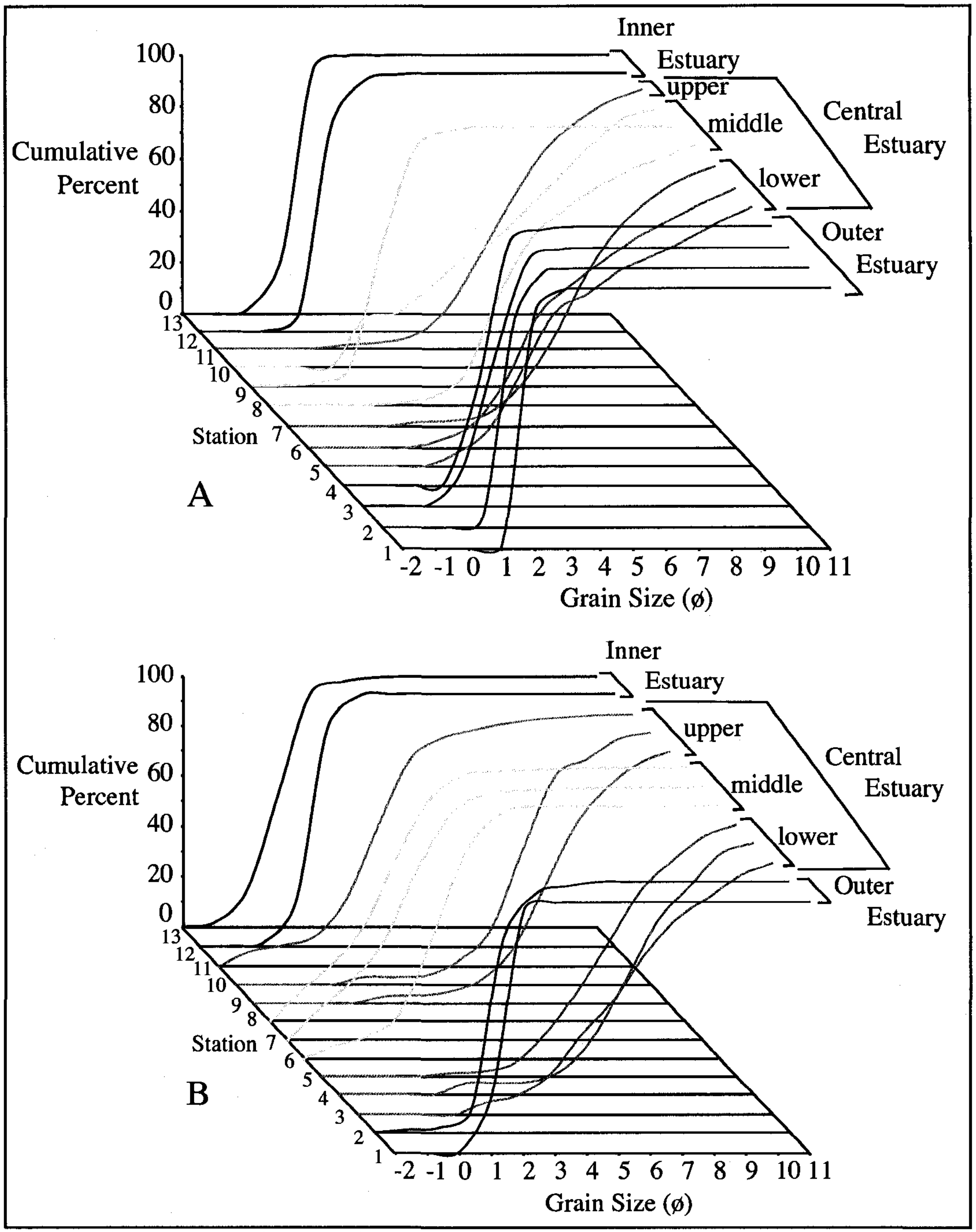


Figure 2.8- Transects of cumulative curves from A) the outer to the inner estuary of the Kouchibouguacis River estuary, and B) the outer to the inner estuary of the Kouchibouguac River estuary. Station placement can be found on figures 2.3 and 2.4 respectively. Both transects display a tripartite division in sediments, with a sandy outer estuary, mostly muddy central estuary, and a sandy inner estuary. Both the outer and inner estuaries comprise dominantly well-sorted medium-grained sand, whereas the central estuaries comprise much variability in sediment texture. The lower-central estuaries are typically fine-grained with cumulative curves displaying similar

(**Figure 2.8** continued) distributions from both estuaries. In contrast, the middle-central estuary contains much more variation in sediment texture due to local bedrock sources of coarse-grained sediments. The upper-central estuaries, similar to that displayed in the lower-central estuaries, are again dominantly fine-grained due to the position of the turbidity maximum, however local bedrock sources of coarse-grained sediments are present (e.g. station 11 of B).

(Fig. 2.8B) are both well sorted and texturally very similar. In contrast, the central estuary includes much variation in both average grain size and sorting. Whereas the sediments from both of the lower central estuaries (mid-lagoon) have similar cumulative curves, with subtle bimodality resulting from sand input from the margins of the lagoon, the sediments of the middle- and upper-central estuary are much more varied. In general, the middle-central estuary is coarser-grained than the upper-central estuary, especially in the Kouchibouguac River (Fig. 2.8B). As mentioned previously, bedrock sources of sand are partly responsible for this local coarse-grained texture. Cumulative curves from the upper-central estuaries exhibit finer-grained sediments than the middle-central estuary on average, however local coarse-grained areas are present here as well.

Average grain sizes measured from the system range from coarse sand (0.89 ø) in the bayhead delta region of the Kouchibouguac River (inner estuary), to fine silt (7.24 ø) in the muddy regions of the upper-central estuary of the Kouchibouguac River (Fig. 2.4). Well-sorted sediments are most common in the outer estuary and the inner estuary, whereas the average grain size increases slightly from 1.65 ø (lower medium sand) in the outer estuary to 1.43 ø (upper medium sand) in the inner estuary. The central estuary, which dominates the system in terms of area, is much more variable. The deposits here are typically poorly sorted. Average grain sizes of medium and fine silt can be found in the lower- and middle-central estuary, and the upper-central estuary respectively.

Outer Estuary.–The outer estuary zone comprises the subenvironments of the barrier beach, dune, flood-tidal delta, tidal channels, and the sandflats or washover fans (Table 2.1). The barrier beach and the dunes are similar texturally, consisting of lower medium-grained, fine skewed sand. However, sorting is greater in the barrier beach than the dune (very well sorted versus well sorted respectively). The barrier beach contains low-angle seaward-dipping bedsets, with common planar erosional scours typical of beach swash-zones. Bioturbation is absent. Landward, the barrier beach grades into aeolian dune sands. Sedimentary structures in the dune sand consist of gently to steeply landward dipping cross stratification. Insect and beach-hopper bioturbation is moderately abundant to absent.

Average grain size in the flood-tidal delta is upper medium. Average sorting

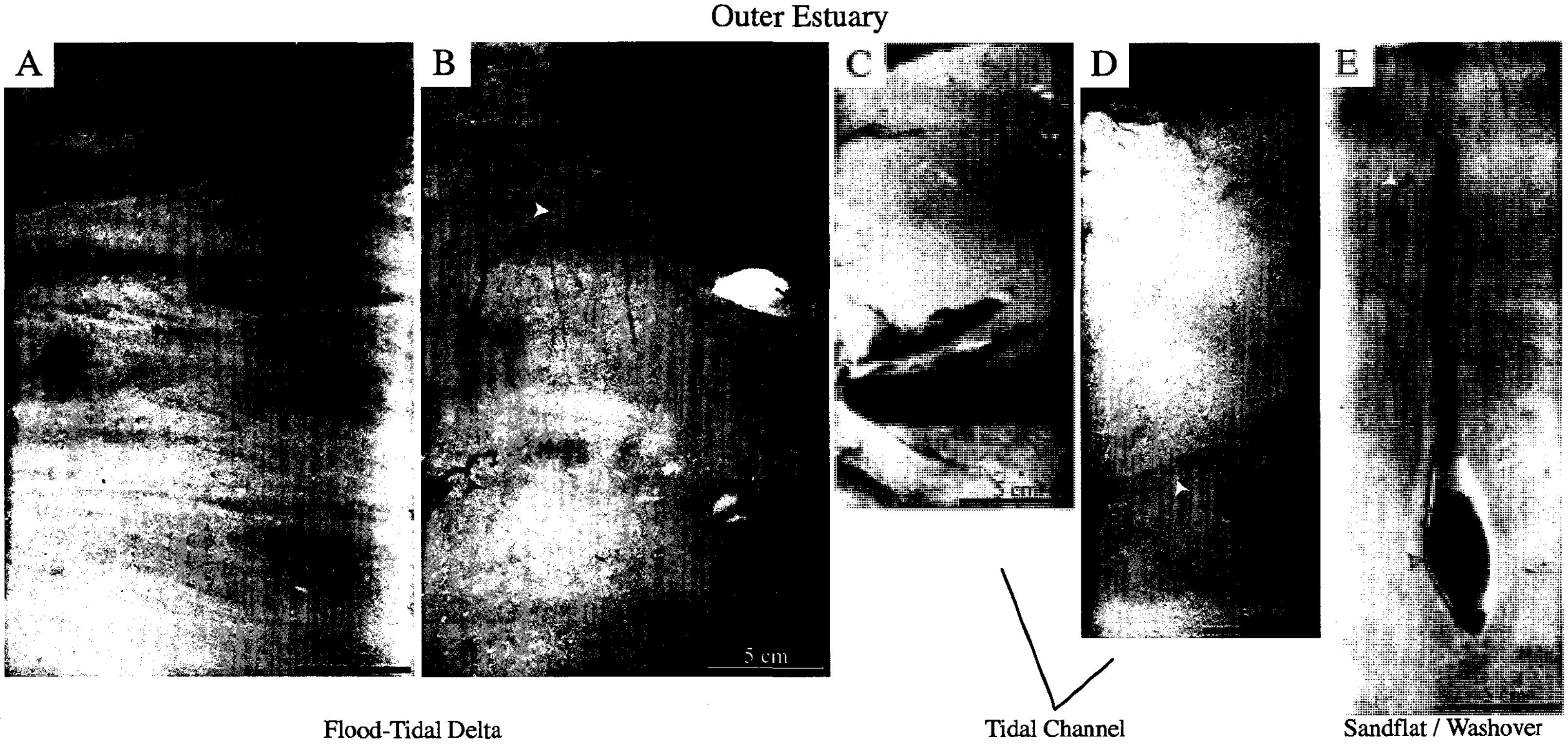


Figure 2.9- X-rays of sediments in the outer estuary. A) Flood-tidal delta deposits proximal to the main tidal inlet. Bioturbation is low and results in the preservation of primary sedimentary structures in the form of superimposed ripple-cross lamination. Trough-cross lamination is evident as well (black arrow). The dark circle is a hole for drainage of the sediments prior to X-raying. B) Flood-tidal delta deposits distanced from the main tidal inlet (more quiescent area). Preservation of primary sedimentary structures is low. Near the base pebbles and shell debris drape and define cross-stratification foresets. Burrows consist dominantly of marine polychaetes, such as the threadworm *Capitella* (white arrow), *Nereis* (black arrows), and the maldanid polychaete *Clymenella torquata* (grey arrow). *C. torquata* produces robustly agglutinated burrows with ring-like annulations near the sediment-water interface, which resemble *Skolithos annulatus*. C) Unbioturbated tidal-channel deposits from the Black River channel proximal to the Little Gully. Bladed rip-up clasts drape and define foresets (dark objects). The rip-up clasts comprise dewatered and compacted lagoonal deposits

(**Figure 2.9** cont.) derived landward from bends in the channel. D) Tidal channel deposits proximal to the Black Lands Gully in the St. Louis Lagoon. The deposits are mostly homogenous, and thus lamination or stratification is lacking. The white arrow points to potential *Capitella* bioturbation within a finer-grained bed. The burrows resemble *Chondrites*. E) Sandflat / washover deposits from the St. Louis Lagoon. The deposits are mostly homogenous, resulting in obscured lamination. Bioturbation by *Capitella* (black arrows), *Nereis* (white arrow), and the bivalve *Mya arenaria* (gray arrow) also act to destroy primary sedimentary structures.

decreases (moderately well sorted) due to the occurrence of silt that drapes the sediments in areas commonly distanced from the main tidal channels. The deposits have nearly symmetrical skewness. Sedimentary structures consist of multidirectional ripple cross lamination, with trough-cross lamination locally, and common erosional scours (Fig. 2.9A). Lamination is commonly enhanced due to pebbles and shells. Bioturbation appears rare to abundant. However, at depth and with distance from the active tidal channel and drainage channels on the tidal delta, stratification is largely destroyed or reworked by infuana, with only a few distinct burrows and sedimentary structures preserved (Fig. 2.9B). Consequently the flood-tidal delta consists dominantly of massive sand. Bored wood fragments and other marine-derived debris are common.

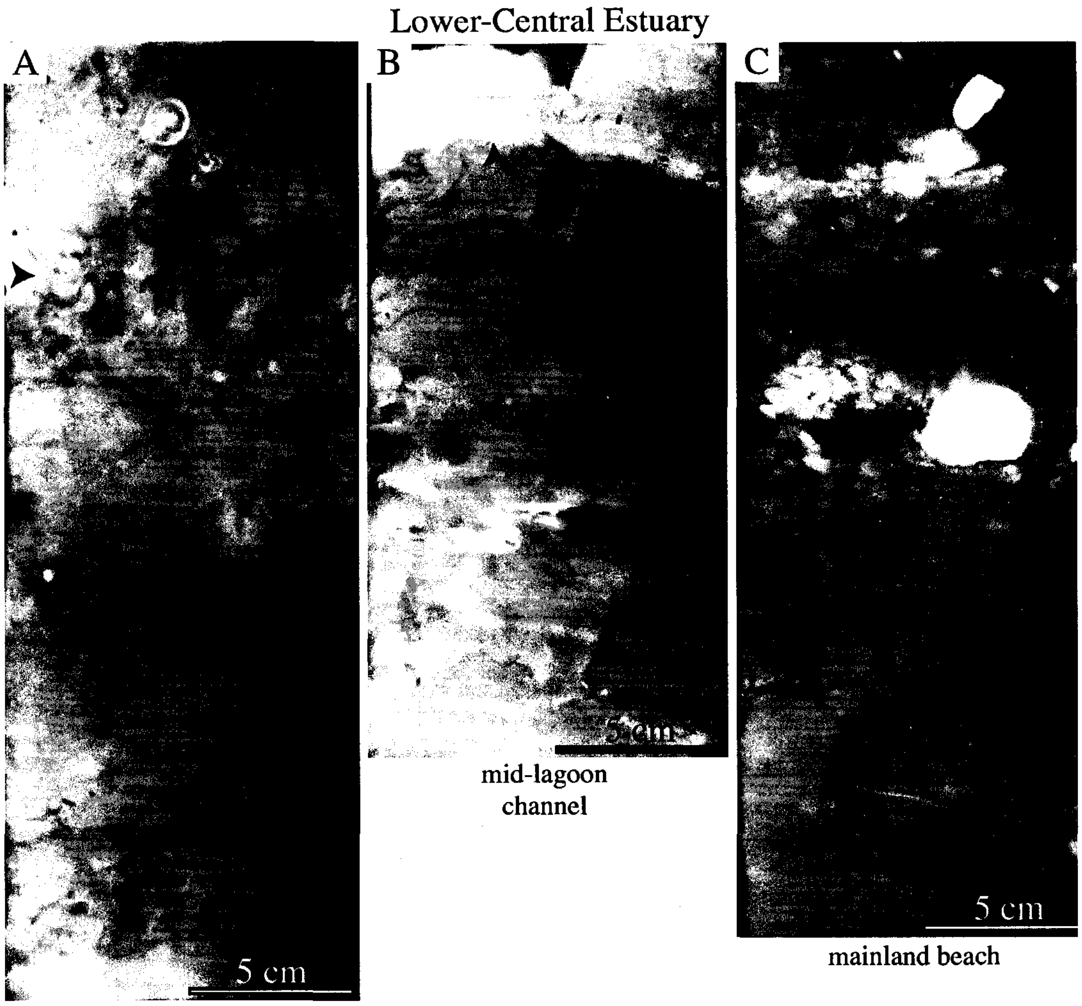
Sediments in the tidal channels near the tidal inlet consist of moderately well sorted lower medium-grained sand. Sedimentary structures commonly include low- to high-angle cross stratification (Fig. 2.9C), and trough cross stratification (Fig. 2.9D). Structures are typically washed on xrays due to the well-sorted nature of the deposits. Slump deposits and rip-up clasts of firm dewatered and compacted silt are commonly seen in the tidal channels, the bladed rip-up clasts of which commonly drape and define foreset laminations (Fig. 2.9C). The firmground clasts are derived from tidal ravinement into firm, lower-central estuary mud along the channel margins (e.g., near SCH2, Fig. 2.4). In proximity to the tidal inlet bioturbation is rare in the tidal channels. Rare escape structures (*fugichnia*) produced from mobile bivalves are observed.

The sandflats (washovers) landward of the barrier bar dunes comprise moderately well sorted lower medium-grained sand, similar to the tidal channels. The sands display nearly symmetrical skewness. The washovers grade laterally and interfinger with the fine-grained mud of the lower-central estuary (mid-lagoon). Sedimentary structures appear locally as low-angle landward dipping planar beds, with moderate occurrence of weakly defined wave ripple cross lamination (Fig. 2.9E). Normal graded bedding is observed. Seaward-derived pebbles from the washover events are evident locally. The activity of polychaetes (threadworms and *Nereis*) and bivalves (*Mya arenaria*) typically destroy primary sedimentary structures (Fig. 2.9E). Bioturbation is moderate to abundant, with the roots of eelgrass common locally.

*Central Estuary.–*The central estuary zone includes the subenvironments of the lower-central estuary (mid-lagoon), the landward lagoon beaches, the middle-central estuary, and the upper-central estuary. Due to complexities associated with the margins of the narrow estuary funnel, the middle and upper-central estuary are further subdivided as dominantly muddy or sandy (Table 2.1). In general, the central estuary exhibits deposits that are highly bioturbated. A very high biomass of benthic fauna results from the low energy and high food content within the central estuary. As such, the preservation of lamination or cross stratification is rare.

The average grain size of the lower-central estuary is medium silt. Sediments are very poorly sorted and are finely skewed (Table 2.1). The deposits are typically homogenized by the activity of burrowing infauna (Fig. 2.10A), and as such only rare planar laminations are observed. Shells fragments and articulated specimens, as well as eelgrass roots are common. Within the mid-lagoon channels, distanced from the tidal channels, the sediments are typically fine-grained (Fig. 2.4, fine-grained silt of LCH1). The mud appears thixotropic in nature; however, binding of the sediment at the surface by algal mats is common, lending some cohesiveness to the sediment-water interface. At depth the channel deposits have a strongly bioturbate texture (Fig. 2.10B). In contrast to the shallow lower-central estuary (lagoon), the channels exhibit a higher degree of lamination. Plant debris derived from eelgrass is common (Fig. 2.10B). Narrow fringes of beach sand or wave-scoured salt marsh deposits line the landward margins of the lower-central estuary. The beach sands comprise moderately sorted, fine skewed, lower medium-grained sand. The narrow sand deposits front outcrops of bedrock or glacial deposits locally. Angular to sub-rounded bedrock clasts are incorporated into the deposits as weakly defined pebble to gravel beds (Fig. 2.10C). Wave-ripple lamination is common, however, at depth moderate degrees of bioturbation typically homogenize the sediments.

The middle-central estuary is subdivided into deposits that are dominantly muddy, or dominantly sandy (Table 2.1). Typically sandy sediments fringe the margins of the middle-central estuary, where local outcrops of bedrock (friable Pennsylvanian sandstone) are present. However, where these outcrops are absent, the margins of the middle-central estuary may be dominantly muddy. Variations and gradations of the two sediment types occur laterally from the estuary margins, as well as parallel to the estuary funnel. The sandy deposits consist of poorly sorted, nearly symmetrical, medium-grained sand. Primary sedimentary structures are typically indistinct due to the massive nature of the deposit, or to reworking by infauna (typically capitellid and nereid polychaetes, and the bivalve *Mya arenaria*) (Fig. 2.11A). Pebbles and gravels weakly define beds



mid-lagoon channel

mainland beach

mid-lagoon

Figure 2.10- X-rays of sediments from the lower-central estuary. A) Abundantly bioturbated mid-lagoon deposits of the lower-central estuary. In the mid-lagoon it is common to observe horizons along which helical *Gyrolithes*-like burrows of *Saccoglossus kowalevskii* are densely concentrated (black arrow). B) Muddy deposits from the mid-lagoon channel (Black River) in the lower-central estuary. The deposits show a higher degree of preservation of primary sedimentary structures compared with deposits on the lagoon floor. Abundant organic detritus, in the form of comminuted eelgrass, define and drape laminations. Distinct bedsets comprise individual accumulations of fluid mud (black arrow). C) Mainland beach deposits from the Kouchibouguac Lagoon in the lower-central estuary. Sedimentary structures consist of wave ripples (black arrow). Local bedrock sources of coarse-grained material significantly decrease the sorting, and may enhance bedding. Bioturbation is low to moderately abundant here, depending on the amount of coarse-grained material.

locally, or consist of random accumulations. Near the margins of the estuary, where sand is dominant, palimpsest firmground surfaces of salt-marsh origin are present (Fig. 2.11A). Bioturbation within the sandy deposits is moderate to absent. Absence of bioturbation

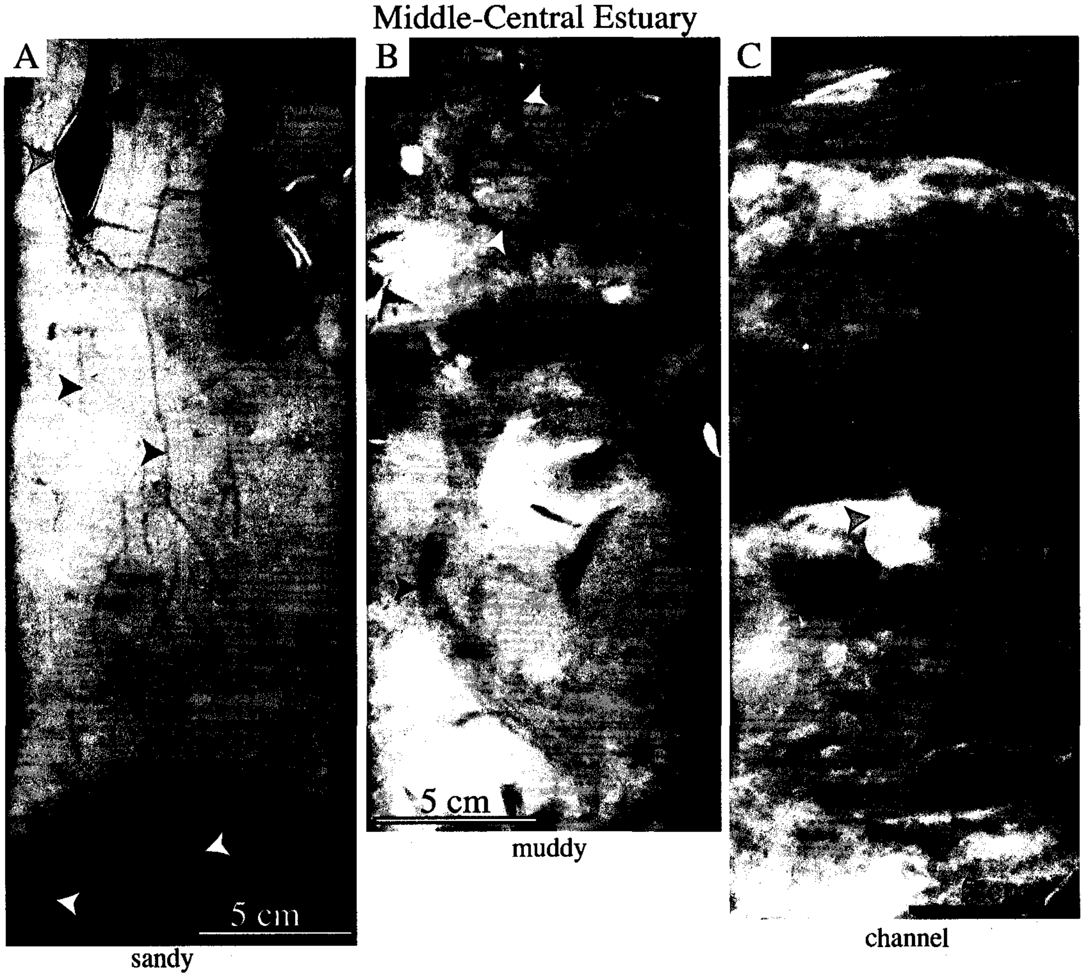


Figure 2.11- X-rays of sediments from the middle-central estuary. A) Sandy deposits from the margins of the middle-central estuary. Primary sedimentary structures are thoroughly reworked by infauna, which consist of *Capitella* (black arrows) and *M. arenaria* (grey arrows). The dark colored deposits at the base of the X-ray comprise palimpsest salt-marsh deposits exposed through bay-margin wave activity, subsequently burrowed with *Psilonichnus*-like structures (white arrows). B) Muddy deposits from the margins of the middle-central estuary. Only vestigial muddy laminations are observed here due to abundant bioturbation. Shell debris and eelgrass debris are common. Distinct burrow structures consist *Skolithos*-like burrows (white arrows) and *Teichichnus*-like burrows (black arrow) of *Nereis*. C) Muddy channel deposits from the middle-central estuary. Primary sedimentary structures are more likely to be preserved here, consisting in this case of ripple-cross lamination (black arrow). The current ripples form exclusively in the fecal pellets of *Capitella*. The temporally erosive nature of the channel and the resultant exposure of stiffground / firmground is evidenced by the presence of the firmground bivalve *Petricola pholadiformis* (grey arrow).

commonly occurs in deposits containing high percentages of pebbles and gravel. The muddy deposits of the middle-central estuary comprise poorly sorted, nearly symmetrical, medium-grained silt (Table 2.1). Primary sedimentary structures are uncommon, however vestigial mud beds and planar laminations are sporadically observed (Fig. 2.11B). The paucity of lamination is due to a high degree of reworking by burrowers (Fig. 2.11B), which include bivalves and polychaetes. The roots of eelgrass destroy the bedding as well. Shell debris is common, and terrigenous plant debris may be found at depth. Channel deposits in the middle-central estuary are dominantly muddy. Bioturbation is abundant in the channels, however laminations and ripple cross laminations are observed near the sediment-water interface (Fig. 2.11C). The channels have a very low percentage of sand, however ripples are produced due to the presence of consolidated fecal pellets of capitellid polychaetes (threadworms). These pellets, which are of sufficient size and shape to be affected by hydraulic currents, were observed to form current ripples on the floor of the channel. Accumulations of these pellets form the ripple cross lamination observed at depth (Fig. 2.11C). Shell debris and *in situ* bivalves are common.

The upper-central estuary, like the middle-central estuary, is subdivided into deposits that are dominantly muddy or dominantly sandy (Table 2.1). Sandy deposits are less common and decrease in average grain size in the upper-central estuary. Sandy deposits consist of poorly sorted, coarse skewed, fine-grained sand. Primary sedimentary structures are rare (Fig. 2.12A). If preserved they consist of weakly defined, low angle cross stratification. Pebbles are incorporated into the sediment at random, and rarely enhance bedding. More commonly, terrigenous plant debris is found within the deposits, typically enhancing bedding (Fig. 2.12A). Bioturbation in the sandy-upper-central estuary is moderate to absent. Muddy deposits are common in the upper-central estuary, consisting of poorly sorted, fine skewed, fine silt (Table 2.1). Muddy sediments are mostly homogenized by the activity of burrowers (Fig. 2.12B), however rare planar laminations can be observed. Planar laminations are more common within the channels, which are typically very muddy and appear to be thixotropic. However, at depth the channel deposits appear structureless due to the activity of burrowers (Fig. 2.12C). Eelgrass roots, shells, and terrigenous plant debris are common in the upper-central estuary mud.

Inner Estuary.–The inner estuary (bay-head delta region) is characterized by a relatively sharp facies shift into dominantly sandy deposits, typically lacking significant percentages of silt or clay (< 2%). Cross bedding is prevalent, and there is a marked decrease in bioturbation (Fig. 2.13A through C). Sediments comprise moderately sorted, strongly coarse-skewed, medium-grained sand (Table 2.1). Sedimentary structures include low- to high-angle tabular cross stratification, as well as weakly defined trough cross stratification (Fig. 2.13A, B). Normal graded bedding is present locally. Inner estuary deposits

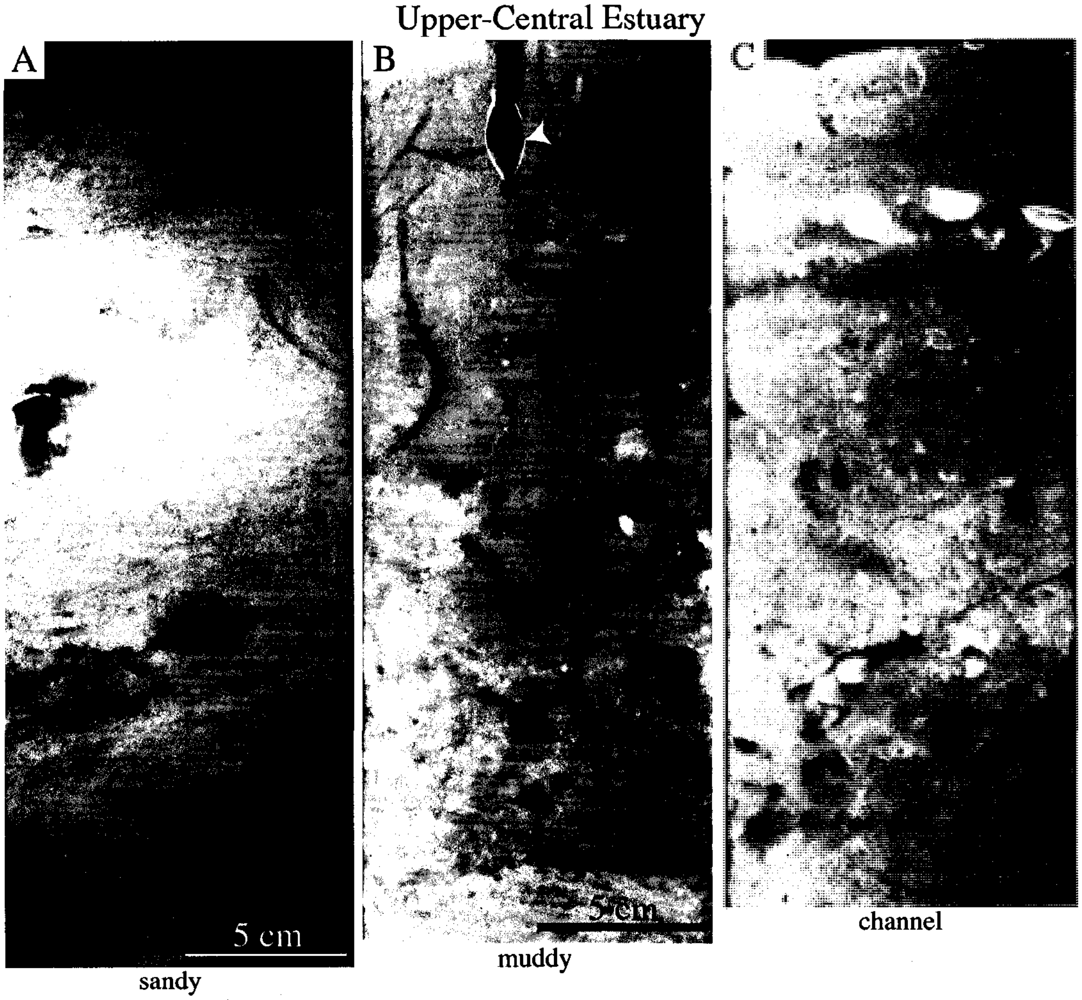


Figure 2.12- X-rays of sediments from the upper-central estuary. A) Sandy deposits from the margin of the upper-central estuary. Deposits are considerably more fine grained compared to the middle-central estuary. In the sandy deposits abundant comminuted eelgrass drapes and defines cross lamination (lower third of X-ray). Burrows consist almost solely of those produced by *Nereis* (black arrows). B) Muddy deposits from the margins of the upper-central estuary. Deposits are thoroughly reworked, with few distinctive burrows of *Nereis* (black arrows) and the bivalve *Macoma balthica* (white arrow) present. C) Muddy channel deposits from the upper-central estuary. Fluid-mud deposits are observed near the top of the X-ray, however this stratification is destroyed at depth by burrowing infauna.

contain abundant terrigenous plant debris, some of which enhance lamination or cross stratification (Fig. 2.13C). Bioturbation grades from moderate in the seaward extent of the inner estuary, to absent in the landward, more fluviatile reaches.

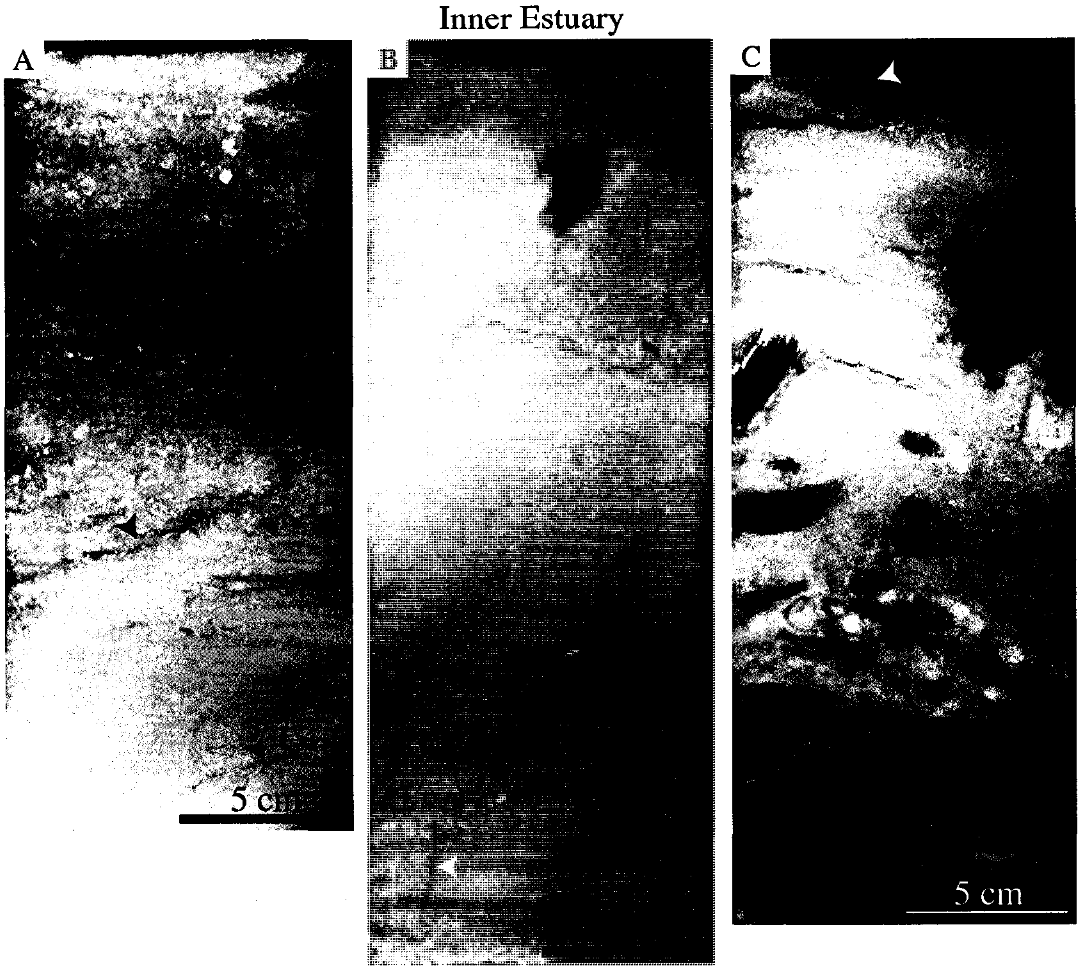


Figure 2.13- X-rays of sediments from the inner estuary. A), B) and C) Sandy deposits from the inner estuary. Primary sedimentary structures are almost completely preserved due to a paucity of burrowing infauna. Only rare and simple burrow structures of *Nereis* (white arrows) persist here. Sedimentary structures consist of shallow- to steeply-dipping planar-cross stratification (black arrows). Terrigenous plant debris (wood fragments) are super-abundant in places (X-ray C), but unlike the wood debris on the flood-tidal delta, the fragments do not contain borings. The plant debris commonly drape and define cross stratification.

Geochronologic Data

Figure 2.4 contains a red star, which denotes the location of a firmground exposure composed of varying degrees of dewatered and compacted lagoonal and, towards the base, salt-marsh deposits. At this location the firmground is a nearly vertical exposure of tidally scoured and palimpsest deposits (Fig. 2.14), presently burrowed by a substrate-controlled assemblage of infauna. The top of the exposure contains modern lagoonal softground deposits wherein lower-central estuary infauna presently construct

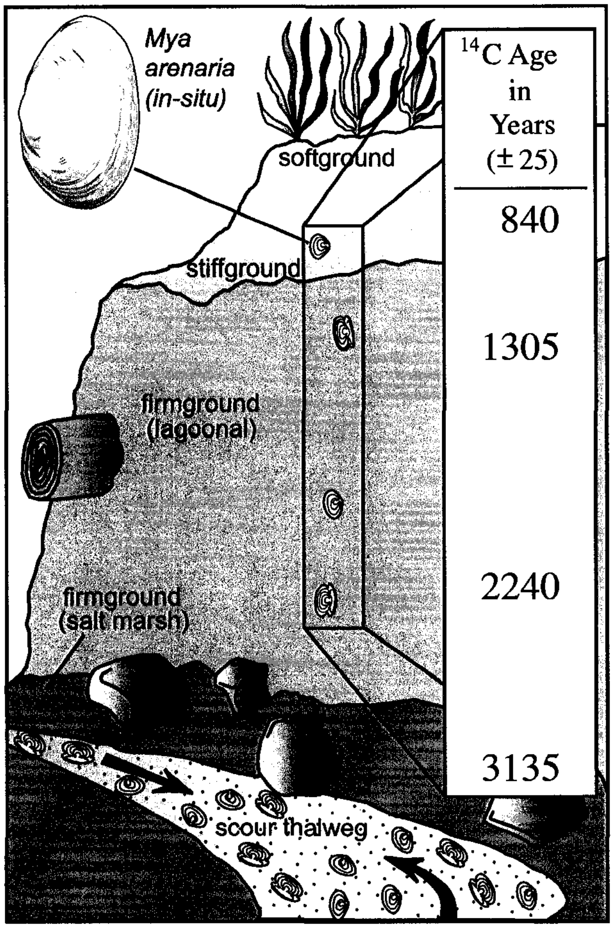


Figure 2.14- Schematic of the vertical firmground exposure from the Black River channel in the Kouchibouguac Lagoon (red star Figure 2.4). Tidal scour has exposed both dewatered and compacted lagoonal and salt-marsh deposits. The exposed lagoonal deposits range from softground sediments proximal to the present day lagoon floor, to stiffground, and then firmground deposits with depth. At the base of the channel scour salt-marsh deposits are exposed. A substrate-controlled assemblage of bivalves, crustaceans, and polychaetes construct burrows in the stiffgrounds and firmgrounds. The scour thalweg comprises dominantly shell lag material and a thin layer of fine-grained sand. Slumped salt-marsh blocks typically litter the base of the scour. Within the exposed lagoonal deposits four *in-situ Mya arenaria* shells were collected, with depths along the profile ranging from approximately 2.5 m to 6.5 m. The shells were dated using ^{14}C, resulting in the ages shown. The lowermost shell acts to constrain the formation of the embayment due to its proximity to the underlying transgressed salt-marsh deposits.

their burrows. Further down the exposure the lagoonal deposits become stiffgrounds, and begin to display a palimpsest character, with the modern lower-central estuary burrow assemblage cross-cut by a substrate-controlled assemblage. With depth and increased dewatering and compaction, the lagoonal stiffgrounds become firmgrounds. At the base of the channel, where not covered by the present-day accumulation of fine sand and shell lag, the scour thalweg has exposed firmgrounds of salt-marsh affinity (Fig. 2.14).

Within the lagoonal firmground, *in-situ* shells of the bivalve *Mya arenaria* were collected from varying depths along the vertical exposure for ^{14}C dating (Fig. 2.14). The lowermost shell, located proximal to the exposed salt-marsh firmgrounds, is dated to 3135 (±25) years B.P. Within the stiffgrounds proximal to the top of the exposure, the *M. arenaria* shells are dated to a considerably younger age of 840 (±25) years B.P. (Fig. 2.14).

INTERPRETATION

Estuarine Configuration and Textural Parameters

Three major morphological components related to sediment distribution are observed in the estuaries of Kouchibouguac Bay: 1) the sandy outer estuary, 2) the muddy central estuary, and 3) the sandy inner estuary (Fig. 2.1B). The surficial change in texture is readily observable as one moves landward from the barrier-bar complex to the bay-head delta region up-estuary (figs. 2.3, 2.4, 2.8). The barrier-bar complex comprises the outer estuary, and the deposits therein consist of > 98% sand. The efficient sorting of wave and wind activity affecting the beach and dunes results in the cleanest and most well sorted sands in the system. Landward of the barrier bar, the flood-tidal delta and tidal inlet consist of slightly coarser, moderately well sorted sands. Bedforms produced on the flood-tidal delta reveal overall flood dominant transport directions, with less efficient ebb-tidal modification. Within the tidal channels, the decrease in sorting is due to the inclusion of tidally scoured lagoon deposits along the meandering zone of the channels. In contrast, the decrease in sorting within flood-tidal delta deposits is due to surficial mud drapes along the more inactive regions (i.e., distanced from the flood ramp and longitudinal ebb-tide current lineations). The sandflats / washovers of the outer estuary exhibit a decrease in sorting relative to the seaward regions of the barrier bar. Average grain size decreases due to the inclusion of fine-grained sediment resulting from back-barrier quiescent conditions and the transport of suspended central estuary silt and clay toward the margin of the lagoon.

The first transition in facies occurs landward as the outer estuary sands interfinger with the fine-grained sediments of the lower-central estuary (lagoon). The lower-central estuary sediments present a marked contrast to the relatively clean sand of the outer estuary, being very poorly sorted, consisting of medium silt and locally significant portions of clay. In ancient back-barrier sequences this lateral change in facies is relatively abrupt (Reinson, 1979a). The lower-central estuary is a sink for the fine-grained silt and clay derived from the fluvial sources (Dalrymple et al., 1992). In addition, due to the long distance up-estuary to the fluvial reaches and associated suspended fines (Fig. 2.1B), a significant percentage of the silt in the lower-central estuary must also be derived from local erosion of older deposits along the margins of the recent and present day lagoon. Clay is especially common within the mid-lagoon meandering channel (e.g., Fig. 2.4, LCH1). This may be due to preferential channel deposition of fluid mud during periods of high river runoff. Traykovski et al. (2001) found that fluid mud deposition in the lower regions of the Hudson River estuary coincided with spring season freshets. Dalrymple et al. (2003) attributed dense fluid-mud bodies in channel bottoms of the Fly River to mud deposition during spring tides. From shallow cores (Fig. 2.10B) and bathymetric data (Fig. 2.5), it appears that the meandering channels landward of the tightest meanders in the lower-central estuary act as sinks for mud deposition (at least in mid-summer during the study).

In addition to the obvious textural differences from the outer to the lower-central estuary, the morphology of the tidal channel and the presence of large bedforms in the outer estuary is quite different from that observed in the lower-central estuary of the Kouchibouguac Lagoon (figs. 2.5, 2.7). In the outer estuary, the channel is wide (approximately 50 m) and contains abundant dunes resulting from tidal currents associated with ebb and flood tides. The orientation of dunes in the outer estuary channels near the Little Gully reveal that both ebb- and flood-tidal currents operate with mutually evasive pathways. Orientation of the dunes from 2-dimensional bathymetric profiles reveals the dominance of either flood or ebb tidal flow (Fig. 2.6), resulting in the approximate flow paths of Figure 2.5 (black arrows). The large lobate sand body (small ebb-tidal delta) near the tidal inlet of Figure 2.7 suggests that the channel is ebb-dominant overall.

The tidal currents in the system are strong enough to maintain relatively permanent tidal inlets; however much of the tidal energy is diminished with distance from the tidal inlet due to friction over the flood ramp and the tidal channels. The result is a “hyposynchronous” estuary (Dalrymple et al., 1992). The decrease in the tidal prism is evidenced in the sharp decrease in channel width into the lower-central estuary, where a markedly meandering form is observed (figs. 2.5, 2.7). The tight box-like meanders are bolstered by channel incision into firmground deposits of lagoonal nature. The scoured exposures of firmground contain traces akin to ichnofossils observed in ancient *Glossifungites* surfaces, and due to the depth of the channel (approximately 8 m), this surface has a strong chance of preservation upon further transgression of the system. If the steepness of the coastal gradient and the subsequent trajectory of the wave-ravinement surface result in preservation of transgressive deposits, deeper channels, like that of the tidal inlet, have a stronger preservational potential than other subenvironments landward of the barrier (Cattaneo and Steel, 2003). The meandering channels are narrow (approximately 5-10 m wide) with no apparent development of classical point bars and associated inclined heterolithic stratification. The lack of lateral migration of point bars in the channels is probably due to the entrenched nature of the channels, where the channels represent those in equilibrium with the tidal and riverine discharge (Fenies and Faugères, 1998).

Within the central estuary the next, albeit less significant, change in sediment texture occurs within the middle-central estuary (lower estuary funnel). The surficial sediments here, as a whole, are still very poorly sorted, with stations ranging from silty sand to silt, however average grain size increases significantly near local sand sources (figs. 2.3, 2.4, 2.8). The general distribution of sediments consists of a lateral change from poorly sorted silty sand with pebbles and gravel along the margins of the estuary, to more muddy sediments within small shallow embayments and towards the channel. Wave scour is likely responsible for the inclusion of local bedrock sources of sand along the margins, whereas high river-discharge rates are responsible for the finer-grained deposition in embayments of small tributaries and the main channel. A decrease in sorting and increase in grain size in the funnel is common in mesotidal and microtidal estuaries (Nichols et al., 1991; Reinson, 1976).

Along with textural differences from the lower- to the middle-central estuary, morphological changes in channel bathymetry and plan-form are evident. The channels change from meandering within the lower-central estuary (with the exception of the southern Kouchibouguac River estuarine channel, which is maintained by dredging out to the inlet) to relatively straight or 'cuspate' in plan-form within the middle-central estuary (figs. 2.3, 2.4). In the Black River channel this change in plan-form is accompanied by an increase in depth (Fig. 2.5). At the base of the channel underwater observations reveal exposures of dewatered and compacted sandy silt, forming a stiffground (Pemberton and Frey, 1985; Gingras and Pemberton, 2000). Sediment erosion and bypass are evident in the mouth of the estuary funnel here. The constriction of the tidal prism through the mouth of the estuary funnel is responsible for the scour in the channel, resulting in local 'hypersynchronous' effects. In mixed-energy estuaries where the tidal or fluvial forces are greater, the concurrent decrease in wave energy and increase in tidal energy up-estuary as the estuary narrows manifests in hypersynchronous effects and the production of longitudinal sandy bedforms (Allen, 1991), or a longitudinal facies distribution (Yang, et al., 2007). In Kouchibouguac Lagoon, although due to lower energy and at a smaller scale, hypersynchronous effects manifest in erosional processes in the mouth of the Black River estuary due to a scarcity of sediment. Up-estuary the channel reverts to a meandering form due to a decrease in tidal energy (Fig. 2.4). Within the larger Kouchibouguac and Kouchibouguacis Rivers, the hypersynchronous effects in the middle-central estuary may be partly responsible for the increase in coarse-grained sediments.

Another noticeable change occurs within the upper-central estuary (Fig. 2.1B), whereas channel morphology remains similar to the cuspate channel form common to the middle-central estuary, the average grain size of sand decreases to fine, and percentages of fine silt and clay increase (Table 2.1; figs. 2.3, 2.4, 2.8). upper-central estuary Sediment texture suggests that the transport competency of the river and tidal forces are low, resulting in the deposition of fines within a turbidity maximum. Measured turbidity during the study was highest within the upper-central estuary of the Kouchibouguac River. Like the middle-central estuary, areas of the margins of the upper-central estuary are commonly lined with admixtures of sand and pebbles, however these deposits are less common.

The last, more significant, facies change occurs at the boundary between the upper-central and inner estuary, wherein fluvially derived sand is deposited as the bay-head delta. The delta lacks the common birdsfoot morphology due to the narrow confines of the estuary funnel / fluvial valley (Dalrymple et al., 1992). Within both the Kouchibouguac and Kouchibouguacis Rivers, bay-head delta sand contains patchy marsh growth on what appears to be longitudinal bars. Sediments within the inner estuary consist of moderately sorted, strongly coarse-skewed medium-grained sand (Table 2.1; Fig. 2.8). This fluvial sand is deposited near the tidal maximum where the discharge of the river rapidly diminishes due to the enlargement of the cross-sectional area of the estuary. The transport competency of the near-bottom flow is partially attenuated by flood-tidal currents (Nichols et al., 1991). The decrease in competency results in the deposition of sand, with a relatively sharp change from the bay-head delta sand to the fluvially derived fines observed in the upper-central estuary. This is similar to that observed by Nichols et al. (1991) in the transition from the estuary funnel to the meander zone in the microtidal James River estuary in Virginia. However, unlike the James River estuary, bedforms in the inner estuary are decidedly lacking due to the low discharge rates of the rivers.

DISCUSSION

Stratigraphic Implications

Kouchibouguac Bay is currently undergoing transgression due to marine submergence. Measures of relative sea-level rise have shown that the present rate of sea-level rise in the Maritime provinces is approximately 20-30 cm/100 years due to climatic change (deglaciation in polar latitudes) (Stea et al., 2001), and crustal submergence following a period of emergence due to glacio-isostatic rebound (Grant, 1970). According to Shaw et al. (2002), relative sea level began to increase in the Northumberland Strait around 9 ka B.P. and has continued this trend to present day. Beach (1988) suggested that the barrier island system in Kouchibouguac Bay began to form between 5 ka and 2.5 ka B.P., with subsequent migration landward. Thus, composite sequences for the barrier island system in Kouchibouguac Bay can be constructed since the system is in a state of transgression. This is accomplished through the appreciation of Walther's Law, in which a vertical sequence will mirror the original lateral distribution of sedimentary environments (Nichols et al., 1991).

In-situ shell dates taken from an exposure of firmground within the meandering channel of the lower-central estuary (Fig. 2.4, red star; Fig. 2.14) confirm that the barrier island system was in place at least since 3135 ± 25 years B.P. *Mya arenaria* shells dated with ^{14}C were extracted from near the base of the exposure, where lagoonal firmground deposits directly overlie a tidally-ravined salt-marsh surface. The shells were taken along a vertical profile of the firmground exposure, the texturally characteristics of which are nearly identical to present day lower-central estuary sediments (Fig. 2.4, compare SC 11' with T4-S1). This evidence points to an embayed state of the system as: 1) the species of shells contained within the firmground are associated with brackish-water habitats, 2) the deposits are texturally very similar to fine-grained sediments presently accumulating behind the barriers, and 3) the palimpsest nature of the deposits (i.e., characteristic lower-central estuary ichnocoenoses cross-cut by firmground assemblage of burrowers). In addition, the exposed deposits at the base of the channel are transgressed salt-marsh deposits due to the similarity in texture to that of sediments accumulating in present day salt marshes (compare SC 30' of inset of Fig. 2.4 to SM1 of Fig. 2.3). Within the channel scour, the depth to the salt-marsh surface is approximately 8 m. The basin fill in the embayment is therefore relatively thin due to the low coastal gradient.

Figure 2.15 illustrates the estuarine sequences one might expect in areas of the embayment upon continued transgression of the sea and subsequent retrogradational stacking of facies. The seaward-predicted sequences (Fig. 2.15; numbers 3, 4, and 5) in Kouchibouguac are similar to those observed by Boyd and Honig (1991) in the wave-dominated, low mesotidal shore of eastern Nova Scotia. The authors observed cyclic patterns in sedimentation resulting from variations in controlling physical parameters, such as sediment supply and inlet location during a single transgression. This results in complexity in the overall sequence, which may be lacking in Kouchibouguac sequences due to the lower wave- and tidal-energy the system experiences. In the composite sequence of Boyd and Honig (1991), there is a conspicuous lack of bay-head delta deposits near the base of the section. This is similar to the case in Kouchibouguac if one

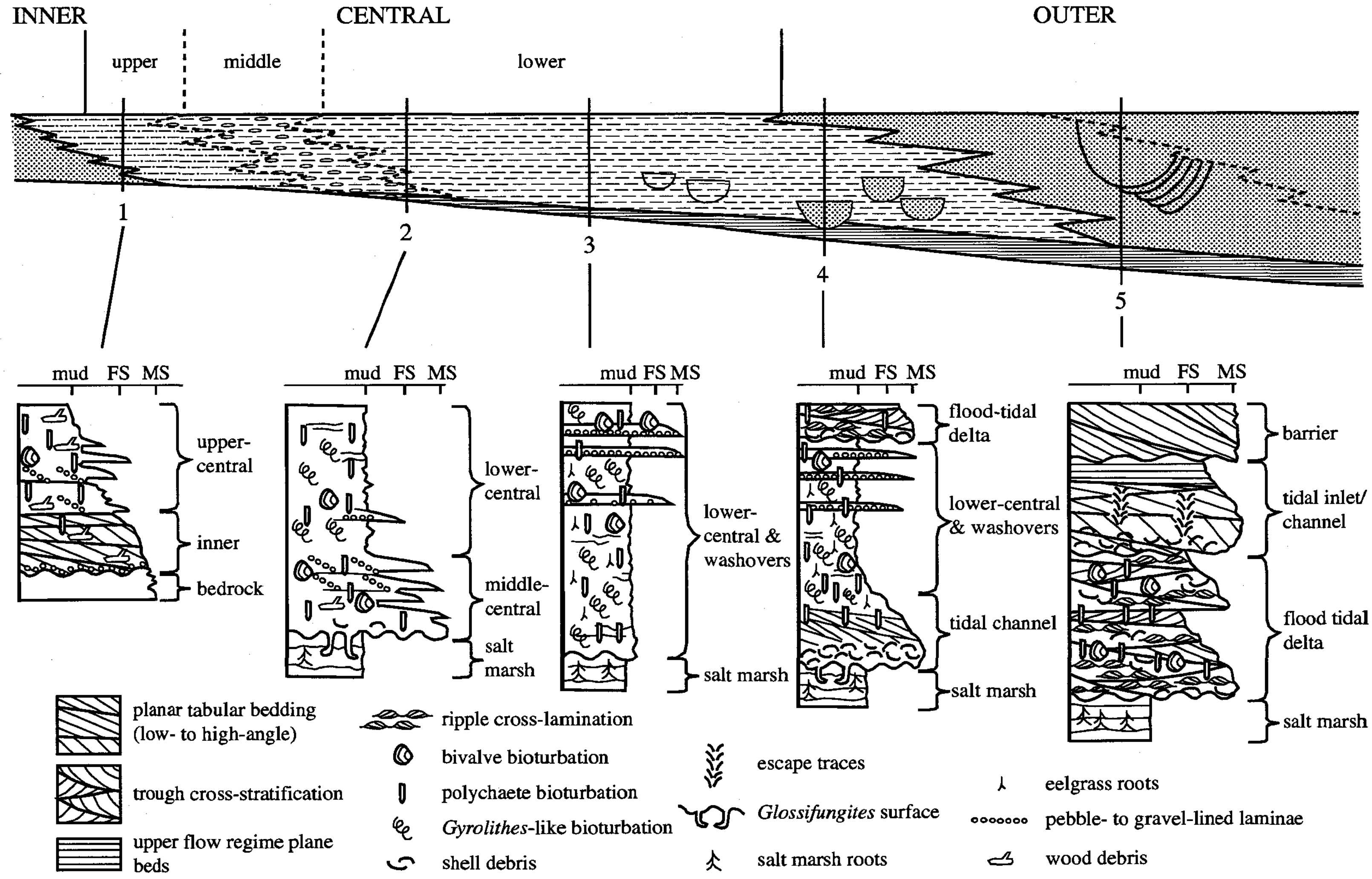

INNER
CENTRAL
OUTER
upper
middle
lower
1
2
3
4
5
mud FS MS
upper-central
inner
bedrock
lower-central
middle-central
salt marsh
lower-central & washovers
salt marsh
flood-tidal delta
lower-central & washovers
tidal channel
salt marsh
barrier
tidal inlet/ channel
flood tidal delta
salt marsh
planar tabular bedding (low- to high-angle)
trough cross-stratification
upper flow regime plane beds
ripple cross-lamination
bivalve bioturbation
polychaete bioturbation
Gyrolithes-like bioturbation
shell debris
escape traces
Glossifungites surface
salt marsh roots
eelgrass roots
pebble- to gravel-lined laminae
wood debris

Figure 2.15 (previous page)- Potential retrogradational vertical sequences produced in the Kouchibouguac Bay barrier island / embayment system. Due to the low fluvial discharge / influence, bay-head delta deposits are interpreted to be lacking in the bulk of the sequences. The central estuary sequences are complicated by local variations in sediment texture due to the narrow confines of the estuary funnel. Tidal channels in the central estuary consist of two types: those proximal to the tidal inlet in which sand dominates, and those proximal to the mid-lagoon in which mud dominates. Notice that the preservation of sedimentary structures is common only to the inner and outer estuaries, due to lowered and fluctuating salinities, and tidal- and wave-hydrodynamics respectively. Occurrences of surfaces with suites of traces akin to the *Glossifungites* Ichnofacies occur in tidally scoured channel deposits in the lower-central estuary (sequence 4), and wave-scoured deposits in the margins of the middle-central estuary (sequence 2). FS and MS are fine sand and medium sand respectively.

were to drill near the outer estuary (Fig. 2.15). This can be explained by the low-energy nature of the rivers in the system, in which flow competency is low enough that fluvial sand is not transported to the central estuary, and conspicuous bay-head delta deposits are therefore lacking. In contrast, Nichols et al. (1991) suggest that the base of the composite facies model of the microtidal James River estuary in Virginia would contain the characteristic fluvially derived bay-head delta deposits. This is predicted partly due to the high fluvial discharge the estuary experiences from the James River. Predicted sequences found in a landward direction in Kouchibouguac show the possibility of finding inner-estuary deposits (bay-head delta) underlying those of central estuary origin (Fig. 2.15, sequence 1).

Another evident absence from the sequences interpreted from the Kouchibouguac system is the lack of tidal flat deposits, which will often contain characteristic tidally-produced heterolithic bedding, such as flaser and lenticular bedding (Greer, 1975; Reinsen, 1984). The absence of tidal flats attests to the microtidal nature of the system, in which subaerial exposure is minimal.

In the estuarine deposits on the mesotidal Georgian Bight, Frey and Howard (1986) noted that one of the most diagnostic features of the overall sequence was tidally influenced channel-form deposits. A very common channel-form deposit observed in estuarine strata marked by higher tidal regimes are point-bar deposits, composed of inclined heterolithic stratification (IHS) (Smith, 1988; Wightman and Pemberton, 1997; Gingras et al., 1999; Gingras et al., 2002). Lateral point bar migration is typically lacking in any of the channels of the system in Kouchibouguac. Channel-form deposits, consisting of sandy cross strata, and fluid muds, are preferentially located within the outer- and lower-central estuaries respectively. This is due to the tidal forces, which are concentrated in the outer estuary due to the hyposynchronous nature of the system. Preserved channelized deposits would be expected in these areas (Fig. 2.15, sequences 4 and 5) since they are more likely to be preserved than shallow deposits, due to the depth at which they form. They are less likely to be cannibalized by wave- and tidal-ravinement upon further submergence.

Another very significant feature of the deposits of the Kouchibouguac system is the patterns of bioturbation. Frey and Howard (1986) stress the importance of biogenic sedimentary structures in the delineation of estuarine facies. The distribution of traces in Kouchibouguac estuaries is attributable to the low energy, wave-dominated, and low fluvial discharge nature of the system. Trends in brackish-water bioturbation are intimately linked to the dominant chemical and physical forces at work within each morphological component of the estuary (i.e., outer, central, and inner estuary). Traces in the outer estuary are characteristic of those emplaced in shifting sand influenced by tides and waves, while being in close connection to the sea and marine salinity. Bioturbation in the lower-central estuary is typical of those emplaced in quiet-water areas with abundant food. Bioturbation here is intense and most of the primary sedimentary structures are destroyed. With decreasing salinities toward the middle- and upper-central estuary, trace diversity decreases markedly, whereas density of traces is still very high and overall the deposits exhibit a strong bioturbate texture. The inner estuary is characterized by a sharp decrease in trace diversity and density, and is therefore easy to distinguish from the sandy sediments of the outer estuary.

In addition to the overall trends in bioturbation, several firmground exposures in the system comprise surfaces that contain substrate-controlled assemblages (Pemberton and Frey, 1985) of burrowers not typical of any other facies. These firmground exposures demarcate discontinuity surfaces in estuarine stratigraphy, and are therefore important in the delineation of boundaries of stratigraphic significance (MacEachern et al., 1992). Transgressive surfaces of erosion are found within the central estuary deposits of Kouchibouguac estuaries, and are attributable to tidal- and wave-ravinement (Fig. 15, sequences 2 and 4).

CONCLUSION

The estuaries residing within Kouchibouguac Bay contain many elements that are typical of the wave-dominated estuary end-member of Dalrymple et al. (1992). A tripartite distribution of facies is observed, resulting from influences of both marine and fluvial nature. The general morphology of the estuary reacts to, and is a result of, the “hyposynchronous” state of the system, where tidal energy is greatly diminished due to frictional processes through the tidal inlet and flood-tidal delta. However, there exist variations in both the sediment texture and morphology of the estuary in comparison to the wave-dominated end-member.

The fine-grained central estuary can be further subdivided into the lower, middle and upper due to fluctuations in the textural parameters of the sediments along the length of the estuary funnel. This is in response to the shallow coastal gradient and low fluvial discharge, which results in a shallow and narrow estuary funnel. The inner estuary sediments can be classified as deposits typical of a bay-head delta due to their fluvial derivation. However, the morphology of the sandbody is not typical of that often described from wave-dominated end-member estuaries (i.e., being lobate and having a 'birdsfoot' morphology). This again is due to the low fluvial discharge in the system and the narrow confines of the estuary funnel.

The majority of the readily observable bedforms in the system are seen in the sandy outer-estuary facies where tide and wave processes dominate. Bedforms reveal that the tidal channels close to the inlet contain mutually exclusive pathways for flood- and ebb-tidal flow. This carries implications for the presence of tidally induced primary sedimentary structures in the subsurface of the outer estuary.

A number of lines of evidence indicate that the system is in a state of transgression. Vertical sequences inferred from the lateral translation of facies vary depending on position within the system. Bay-head delta facies are lacking in the sequences in the seaward end of the system due to poor development resulting from the weak fluvial influence. Segments of the channels within the outer estuary and lower- to middle-central estuary, where tidal ravinement is taking place, have a good chance of preservation due to their relative depth and the shallow coastal gradient. Channels within the lower-central estuary exhibit palimpsest firmground exposures colonized by an assemblage of substrate-controlled burrowers. These burrowers are responsible for producing an incipient *Glossifungites* surface. Hypersynchronous tidal effects at the mouth of the estuary funnel are responsible for erosional and sediment bypass processes at the mouth of at least one of the estuaries (i.e., Black River), which results in incipient firmground production. This is important stratigraphically as the *Glossifungites* Ichnofacies produced in tidal-ravinement surfaces greatly aids in delineating bounding unconformities and parasequence boundaries.

The general lack of sedimentary structures in the system is evidence of its low energy, microtidal state. Commonly, abundant bioturbation is responsible for the lack of primary sedimentary structures in environments characterized by relatively higher hydrodynamic energies (i.e., outer estuary). Since infauna are strongly linked to physical and chemical processes at work in each morphological component of the system, trends in the distribution and type of biogenic structures may be of more use in resolving microtidal barrier-island facies than are primary sedimentary structures alone. Moreover, the general absence of tidally influenced sedimentary structures in the morphological components of the wave-dominated microtidal estuary, with the exception of the outer estuary, make determining potential marine influence difficult or erroneous in ancient successions. However, ichnology has the potential to greatly aid in the identification of such marine deposits in microtidal, wave-dominated systems.

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CHAPTER 3 – BRACKISH-WATER ICHNOLOGICAL TRENDS IN A MICROTIDAL BARRIER ISLAND / EMBAYMENT SYSTEM, KOUCHIBOUGUAC NATIONAL PARK, NEW BRUNSWICK, CANADA

INTRODUCTION

Previous Work

Brackish-Water Studies.– The recognition of brackish-water deposits has greatly aided in the delineation of ancient marginal-marine strata in the search for hydrocarbon resources. Ichnology, when combined with sedimentology, is a useful tool in paleoenvironmental analysis, through appreciation of physico-chemical parameters that may present significant limitations for the colonization of infaunal organisms. Within brackish-water environments, these factors include sedimentation rate, temperature, (dissolved) oxygen content of bottom- and interstitial-waters, sediment texture, salinity and salinity fluctuation, of which the latter two appear to be dominant (Carriker, 1967). In marginal-marine settings, it has been recognized for some time that salinity higher or lower than 'normal' marine values, and fluctuations in salinity, affect the diversity of organisms (Heckel, 1972). This reflects the difficulty that osmoregulation poses for many marine (and freshwater) organisms (Kinne, 1967; Croghan, 1983; Ferraris et al., 1994). For this reason, combined with the fact that estuaries are geologically ephemeral phenomena, brackish-water colonization has been characterized by multiple, sporadic phases throughout the Phanerozoic (Buatois et al., 2005).

An understanding of how the aforementioned physico-chemical factors affect the distribution of infaunal organisms has been the focus of numerous research groups working in modern marginal-marine environments. Early neoichnological work, concentrating on animal-sediment interactions on the North Sea, was undertaken by a number of German researchers from the Senckenberg Marine Institute. In these studies, organism-specific traces and their implications for the rock record were investigated (Seilacher, 1951; Reineck, 1957). The later work of Reineck (1958) described distributions of burrowing organisms within the tidal flats of the North Sea's Jade Bay. His 'actuopalaeontology' studies included laboratory experiments using aquaria to determine the reaction of burrowing organisms to differing sedimentation stresses. Schäfer (1962) produced a voluminous book written in German, and later translated into English (Schäfer, 1972), outlining the ecology and paleoecology of marine environments. Schäfer (1962, 1972) describes in detail numerous organisms from the southern North

Sea and their potential to leave traces in the sediment, with emphasis on benthic animal-sediment interactions, and the paleoecological potential of such traces.

This early work was followed by extensive studies undertaken in the 1970s on coastlines of the United States. Warme (1971) studied the shallow coastal Mugu Lagoon in southern California, while independently a number of researchers worked on the Georgia, USA coastal region (Hertweck, 1972; Frey and Howard, 1969; Howard and Frey, 1973, 1975; Dörjes and Howard, 1975). The research undertaken on the Georgia coastline began to outline criteria for the recognition of brackish-water deposits by reporting observations of trends in physical and biogenic sedimentary structures in estuarine systems.

After investigation of both ancient strata and modern brackish-water environments in North America, Pemberton et al. (1982) introduced what has come to be known as the brackish-water (ichnological) model. In this work it was shown that ancient brackish-water trace fossil associations, much like those observed in the modern, are recurring and distinct (Pemberton et al., 2001). The model was formally established, then refined, by Pemberton and Wightman (1992), and Wightman and Pemberton (1997). Pemberton and Wightman (1992) cite a number of generalizations that can be drawn from investigations of modern brackish-water systems: 1) benthic organisms are composed of a depauperate assemblage of marine phlya, 2) infaunal organisms outnumber epifaunal types, 3) soft bodied organisms predominate over organisms that contain calcareous tests, 4) organisms can exhibit significant size reduction relative to fully marine taxa, 5) some animals display bathymetric displacement, 6) they contain high numbers of trophic generalists that produce morphologically simple burrows, and 7) although the diversity of organisms may be low, numbers of individuals may be very high. These observations suggest that trace assemblages produced in brackish-water environments posses a characteristic ichnological signature. Further consideration of brackish-water trace-fossils used modern and ancient deposits at Willapa Bay in Washington to reveal similarities between brackish-water trace assemblages in modern and Pleistocene sediments (Gingras et al., 1999).

Since the development of the brackish-water model, numerous studies on Paleozoic and Mesozoic strata have used the following ichnological criteria to recognize brackish-water deposits: 1) low diversity of traces including *Skolithos, Arenicolites, Cylindrichnus, Gyrolithes, Palaeophycus, Planolites, Monocraterion,* and *Teichichnus*, 2) common escape structures and rooted horizons, 3) dominance of a single ichnogenus, 4) small and simple marine forms, 5) both vertical and horizontal traces common to the *Skolithos* and *Cruziana* ichnofacies, and 6) locally prolific trace densities (Pemberton and Wightman, 1992). These studies include those of transgressive estuarine, incised valley fill, and embayment settings (MacEachern et al., 1999a, 1999b; Zonneveld et al., 2001; Buatois et al., 2002; Hubbard et al., 2004; Bann et al., 2004; Mángano and Buatois, 2004), as well as deltaic systems (Gingras et al., 1998; McIlroy, 2004; MacEachern et al., 2005). A common theme among these publications, and a key generalization derived from modern environments, is that animal size reduction (diminution) leads to smaller trace fossils in environments affected by increasingly diluted marine salinities (i.e., freshwater influence). This has been ascribed to the overall stress brackish-water animals endure to achieve homeostasis, which involves osmoregulation (water) and ionic regulation (Kinne, 1967; Mantel, 1985). While a benthic lifestyle is one way to buffer the affects of salinity fluctuations (Pemberton and Wightman, 1992; Gingras et al., 1999), the salinity of the overlying water column still presents a challenge to brackish-water tenants. This is especially true considering fluctuations in salinity due to daily and monthly periodicity in lunar tides. Regulation of body fluids in adverse conditions requires more energy, and diminution may therefore occur due to growth sacrifice resulting from high-energy expenditure from osmo- and ionic-regulation (Gingras et al., 1999). Diminution may also represent the dominance of juvenile over adult forms due to high mortality rates in stressful environments (MacEachern et al., 1999a). Regardless of the cause(s), organisms in brackish-water settings do exhibit diminution; maximum animal size occurs in the marine part of the system, while up-estuary, the size generally decreases. Stunted individuals reside within the upper extremes of brackish-water reaches (Carriker, 1967). The recognition of diminution has the potential to aide in the differentiation of otherwise similar marginal-marine deposits from the rock record.

Specific studies that have shown a relationship between diminution and salinity are briefly outlined here. In a transect from the North to the Baltic Seas, Remane and Schlieper (1971) reported that the maximum length of four benthic mollusc species decreased significantly in response to lowered salinities toward the Baltic. In Willapa Bay, Gingras et al. (1999) observed a gradual decrease in diversity of organisms and size of burrows with decreasing salinities. A transect up the Palix River, showed the number of benthic species ranged from 12 in the lower estuary, down to 7 species in the upper reaches of the estuary, where salinity stresses were highest. In addition, burrow diameters decreased in size up-estuary, most notably in the vermiform burrowers. MacEachern et al. (1999b) studied deposits from the late Albian Viking Formation of central Alberta. Within the transgressive systems tract, estuarine-incised valley-fill complexes typically exhibit trace fossil assemblages that comprise dimunitive forms of marine ichnospecies. They attributed this trend partly to the stresses imparted by salinity reduction or fluctuations.

Gingras et al. (1998) observed diminution in trace fossils within allomembers of the Upper Cretaceous Dunvegan Formation showing that salinity reductions or fluctuations may affect deltaic settings as well. Finally, Middle Triassic deposits of the Liard Formation in British Columbia contain sabkhas and salinas that exhibit a decrease in diversity and burrow size of the trace fossil assemblage, linking diminution to hypersaline settings (Zonneveld et al., 2001).

Diminution is a common theme recited in literature concerning brackish-water deposits, but it has been applied somewhat dubiously. This is due to a paucity of literature that provides ***quantitative*** data pertaining to ichnofossil or organism diminution related to salinity gradients.

Microtidal Coasts.– Barrier islands and bars are typically associated with microtidal coasts, where wave energy is the dominant control on shoreline morphology. Lagoons are also a common feature in this setting, which comprises nearly 13% of the Earth's coastline (Cooper, 1994). Associated with barrier island settings, estimated to occupy nearly 7% of the Earth's open coastline (Stutz and Pilkey, 2002), these two environments are volumetrically important when considering potential brackish-water deposits of ancient coastlines. Pemberton and Wightman (1992) suggest that brackish water is a geologically ephemeral phenomenon. Brackish-water settings are most strongly associated with transgressive coastlines, wherein transgressive bays and estuaries are filled with sediment within short geological time frames (Cooper, 1994).

Clastic sediments deposited under inferred microtidal conditions have been reported from the subsurface of several basins (Galloway and Cheng, 1985; Hubbard et al., 2004; Strand, 2005). Overall, however, studies reporting specifically ancient microtidal deposits are lacking. This is attributed to the difficulty in distinguishing tidal regimes in ancient deposits. Ichnological studies in microtidal settings of modern coastlines will contribute to resolving tidal range from ancient strata.

Recent modern neoichnological studies have concentrated on environments in which high tidal ranges (i.e. meso- to macrotidal regime; 2-4 m and >4 m respectively) expose large areas of intertidal substrate during low tides (Frey et al., 1987; Gingras et al., 1999, Dashtgard and Gingras, 2005; Dashtgard et al., 2006), or where tidal energy is the dominant force (e.g., Georgia coastal region). In contrast, relatively few neoichnological studies have concentrated on the brackish-water areas of microtidal systems (tide range less than 2 m), where intertidal flats are essentially absent and sediment-dwelling animals are subject to little or no subaerial exposure during low tide.

This study focuses on microtidal brackish-water deposits in Kouchibouguac Bay

(Canada), and is distinguished from earlier studies by incorporating neoichnological data with sedimentological and geomorphological data from a microtidal barred coast. This is important because the distribution of animals may be related to ecological factors other than salinity. In addition, this study recognized the need for literature providing quantitative data relating ichnofossil or organism diminution to salinity gradients, which will aid in differentiation of similar marine deposits in the rock record.

Kouchibouguac Studies.– Modern studies of the marginal-marine environments of Kouchibouguac Bay have focused on the sedimentology, facies relationships, and coastal geomorphology proximal to the barrier-bar areas (Kranck, 1967; Greenwood and Davidson-Arnott, 1972, 1978; McCann and Bryant, 1972; Davidson-Arnott and Greenwood, 1974, 1976; Greenwood and Mittler, 1985), and further offshore in the Northumberland Strait (Kranck, 1971, 1972a, 1972b). Beach (1988) assembled a comprehensive study of the park's natural resources, which include geological, geomorphological, and other physical features. To date, the description of animal-sediment relationships are lacking in the literature. The aims of this research are to: 1) describe depositional subenvironments and categorize the ichnological characteristics therein; 2) reveal trends in the distribution, diversity, and abundance of benthic organisms with specific reference to salinity, total organic carbon (TOC), and sediment texture; and 3) establish quantitative data on the diminution of organisms associated with ecological stresses, such as salinity, within the microtidal barrier island / embayment system of Kouchibouguac Bay.

Study Area

This study encompasses two seasons of fieldwork undertaken in Kouchibouguac National Park located in New Brunswick, Canada (Fig. 3.1A, B, C). The climate of New Brunswick is temperate subarctic, with short, cool summers, long and cold winters, and overall low precipitation. Kouchibouguac's namesake comes from the Mic Mac word for "River of the Long Tides." The park borders Kouchibouguac Bay, which is situated on the Northumberland Strait in the Southern Gulf of St. Lawrence, and contains 29 kilometers of arcuate barrier islands fronting a number of lagoons and estuaries. The lagoons and estuaries represent preglacial valleys drowned due to transgression, which were not greatly modified by Pleistocene ice sheets (McCann, 1979).

Kouchibouguac Bay is a microtidal estuary, with a mean and maximum tidal range of 0.67 m and 1.25 m, respectively (McCann and Bryant, 1972; Davidson-Arnott

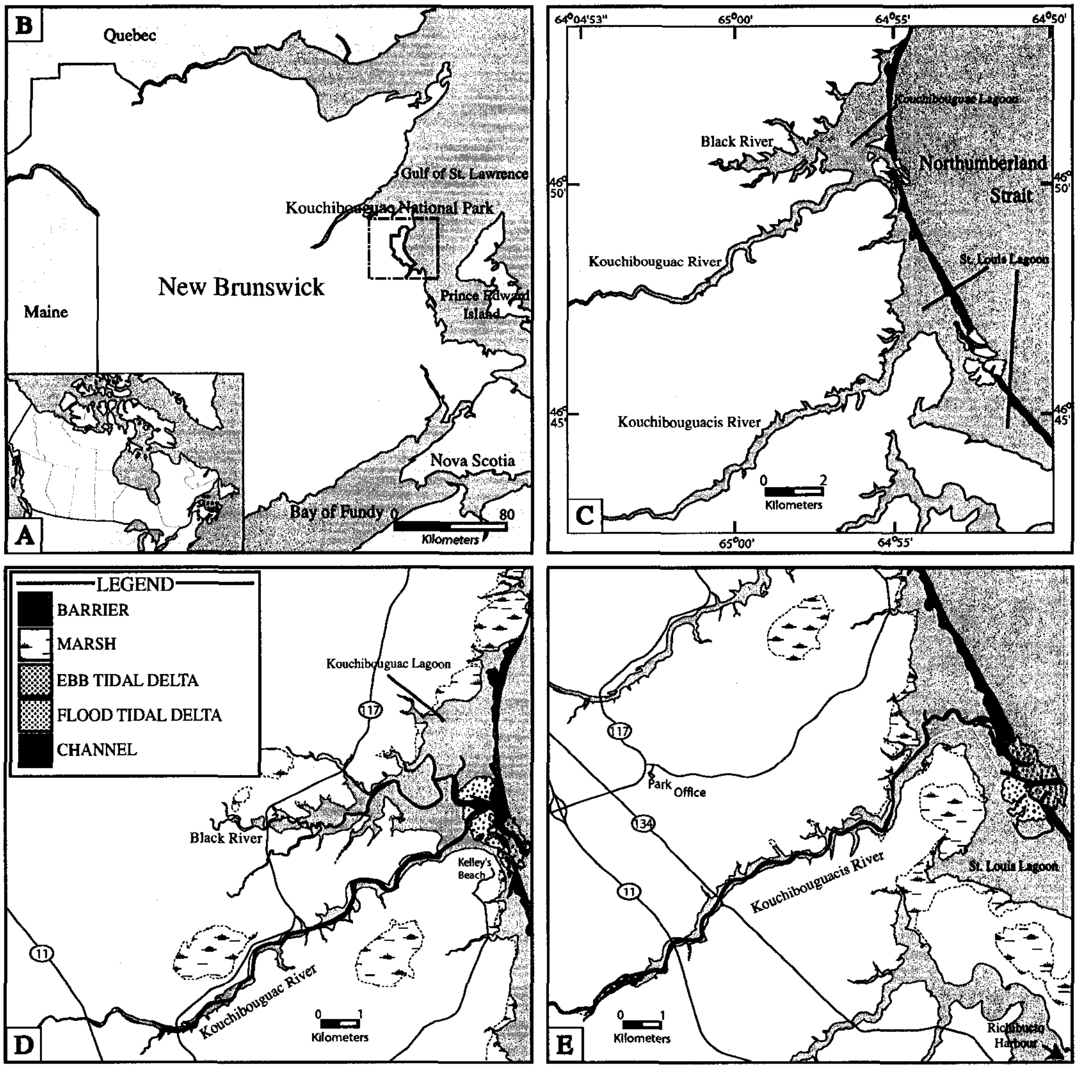


Figure 3.1- Location map of Kouchibouguac National Park. A) Location of New Brunswick in Canada. B) Location of Kouchibouguac National Park in New Brunswick. C) Detail of estuaries and associated lagoons studied in relation to the Northumberland Strait. D) Detail of the northern portion of the study area, including the Kouchibouguac River and Lagoon, and the Black River. E) Detail of the southern portion of the study area, including the Kouchibouguacis River and St. Louis Lagoon. General subenvironments are outlined in the legend of D).

and Greenwood, 1974). Throughout the year, winds from the southerly through westerly directions prevail. Storm winds are most frequent from the northeast (Beach, 1988). Winter storms are not particularly strong due to a very limited fetch to the northeast, with Prince Edward Island (Fig. 3.1B) sheltering the New Brunswick coast in this area. Winter ice conditions also contribute to the low-energy state of the system by protecting the shoreline from winter waves (Bryant and McCann, 1973). The Kouchibouguac lagoons are typically covered in ice for nearly 4 months of the year (McCann, 1979).

The barriers of Kouchibouguac Bay are long and narrow with few widely spaced inlets (three along the entire length), well developed flood-tidal deltas, and poorly developed ebb-tidal deltas. This is typical of barriers and associated inlet areas on other microtidal coasts (Davis and Hayes, 1984; Davis 1994). The barriers are subject to dominant southeastward longshore currents (Kranck, 1967), and spit migration corresponds to this direction of transport. The lagoons are shallow (water depths rarely exceed 2 m), with an average width of 600 m (Bryant and McCann, 1973). The coastal gradient is low, resulting in a saltwater prism that extends approximately 13 km inland. Barrier inlets are maintained dominantly by the work of the ebb- and flood-tidal currents, because of low river strength, especially in the summer when discharge rates are at a minimum (Bryant and McCann, 1973). The catchment basin for the Kouchibouguac River is approximately 228 km^2. The river's mean annual discharge rates have been assessed as 3.74 m^3/s (Robinson et al., 2004). No data exists for the Kouchibouguacis River to the south, but these values are presumably close, given the comparable drainage area and dimensions of both rivers. Medium- to coarse-grained Pennsylvanian sandstones underlie the area and are the provenance for most of the sands in the system. The Pennsylvanian strata also contain minor clay and siltstones (Kranck, 1967, 1972).

In this study, two estuaries and their adjoining lagoons within Kouchibouguac Bay were investigated. The St. Louis Lagoon and the Kouchibouguacis River are located to the south (Fig. 3.1E). The Saint Louis Lagoon is relatively large and extends southward, connecting with Richibucto Harbour. One large tidal inlet drains the majority of the water exchanged through tidal cycles. The inlet is separated into two distinct channels, the Saint Louis Gully and the Black Lands Gully. Ebb currents are strongest in the more northern Saint Louis Gully due to its closer proximity to the Kouchibouguacis River.

The other investigated estuary and lagoon are situated to the north, where the Kouchibouguac and Black Rivers debouch into the Kouchibouguac Lagoon (Fig. 3.1D). The barrier inlet and tidal delta in this system are located adjacent to the drainage systems. On October 28th and 29th of 2000, north-eastern winds with gusts of 80 to 100 km/hr lasting for 23 hours breached the barrier 1000 m south of the main "Little Gully" tidal inlet creating a second tidal inlet associated with the Kouchibouguac Lagoon. This new inlet is still active and contributes large amounts of sand into the lagoon in the vicinity of Kelley's Beach (Fig. 3.1D).

Anthropogenic influence in the last 38 years, since the establishment of the park, has been restricted to the dredging of navigational channels to dockyards located at estuary mouths for commercial (lobster) fishing vessels.

Methods

Herein, the term estuary is defined as " the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth" (Dalrymple et al., 1992, p. 1132). Within the system, station placement covers morphological components that are characteristic of wave-dominated estuaries, consisting of an outer, central, and inner estuary, as outlined by Dalrymple et al. (1992). Each of these zones is further subdivided into distinct subenvironments for detailed descriptions of the infauna therein.

Observations were made, and data collected, from stations placed along set transects in Kouchibouguac National Park. Within the lagoon, transects were placed normal to the shoreline. Up-estuary, two stations were positioned on either side of the estuary at intervals spanning the estuary length. At each station, subaqueous observations were made and photographs were taken by employment of snorkel or SCUBA to ascertain and document the activities of vagile epibionts, and establish signs of infaunal activity through the presence of burrow openings and fecal pellets / castings.

For analysis of grain size and trends in sediment texture, 1000 g samples of sediment from the upper 5 cm were collected and the sand fraction sieved through screens of phi sizes –2 ø (4 mm) to 4 ø (0.0625 mm). The fine fraction (below 4ø) of the samples was heated to 550 °C to remove organics. To prevent flocculation, 30 to 40 ml of 0.05% sodium metaphosphate ($(NaPO_3)_x \cdot Na_20$) was added. The samples were then mechanically disaggregated for 10 minutes with a magnetic mixer, and for 5 minutes in a sonification bath. Finally, the samples were analyzed by X-ray absorption analysis using a Micrometrics Sedigraph 5100. When the fines comprised a significant proportion of the total fraction of the sample (> 2%), they were weighed and factored into the grain-size distribution. Histograms were produced from the measured grain-size distributions following the Wentworth size classification.

In addition to the sediments collected for grain size and sediment texture analysis, sediments from the upper 5 mm were also collected from each station for evaluation of total organic carbon content (TOC). The Loss-on-ignition (LOI) method was applied to these samples following the procedure outlined by Heiri et al. (2001). Samples were dried for 24 hours at 105 °C to remove interstitial water, and then disaggregated with mortar and pestle. Dried samples were placed in a high temperature oven and cooked at 550 °C for 4 hours to remove organic carbon. Dry weights were measured before and after LOI,

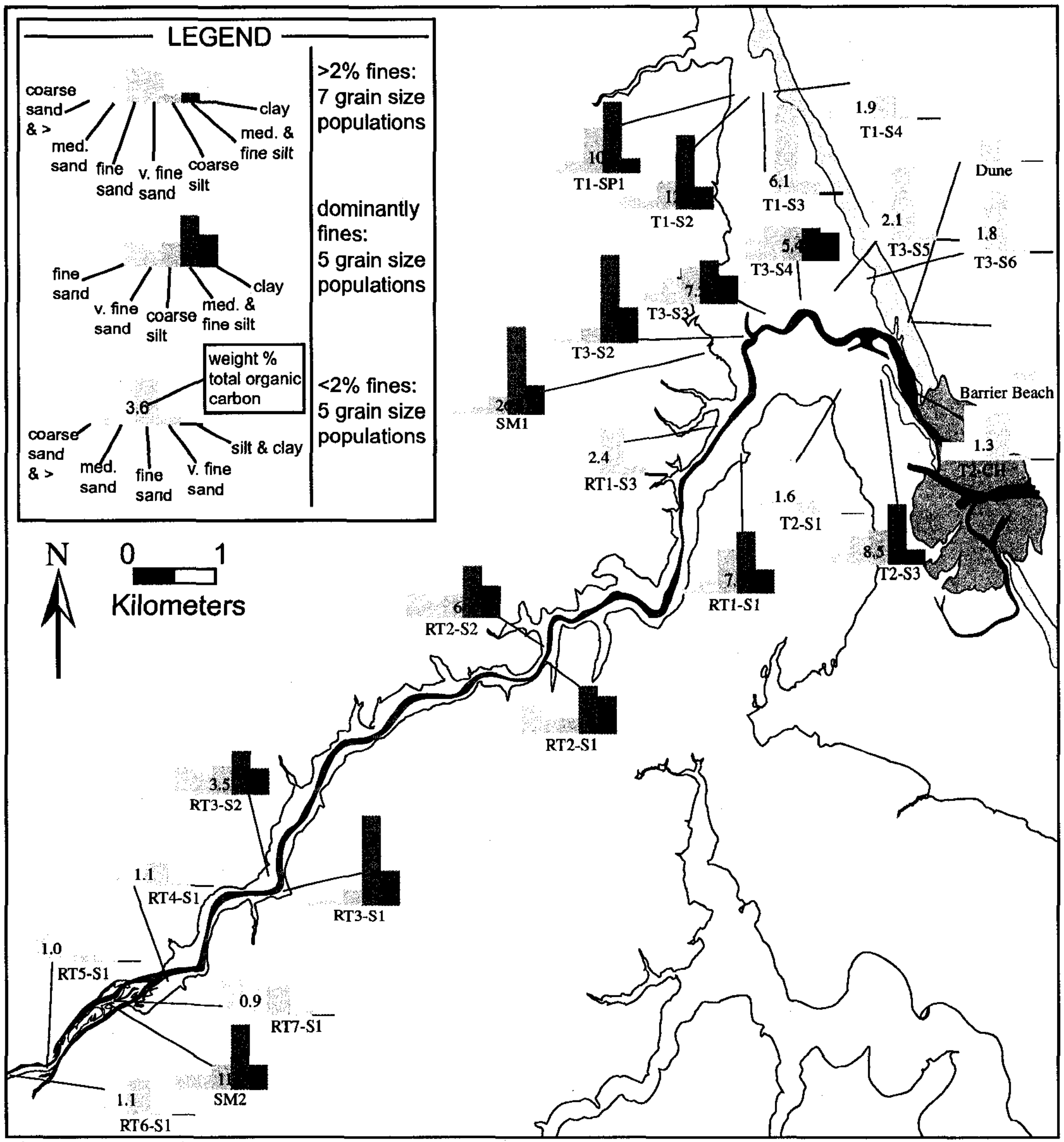


Figure 3.2- Grain-size distribution histograms of stations from the southern portion of the study area (Kouchibouguacis River and St. Louis Lagoon). Station identifiers are located under the histograms. Weight % total organic carbon (TOC) measured at each station is located within the histograms.

from which the weight percent of organic carbon at each station was determined (i.e., where TOC % = dry weight – post-LOI weight).

Coring at each station was completed using PVC tubes, having a 10.16 cm inside diameter and approximately 30 cm length. The tubes were capped, kept upright, and transported for preparation for X-ray analysis. The tubes were then split and 2 cm deep plastic trays approximating the core dimensions were impressed into the core and

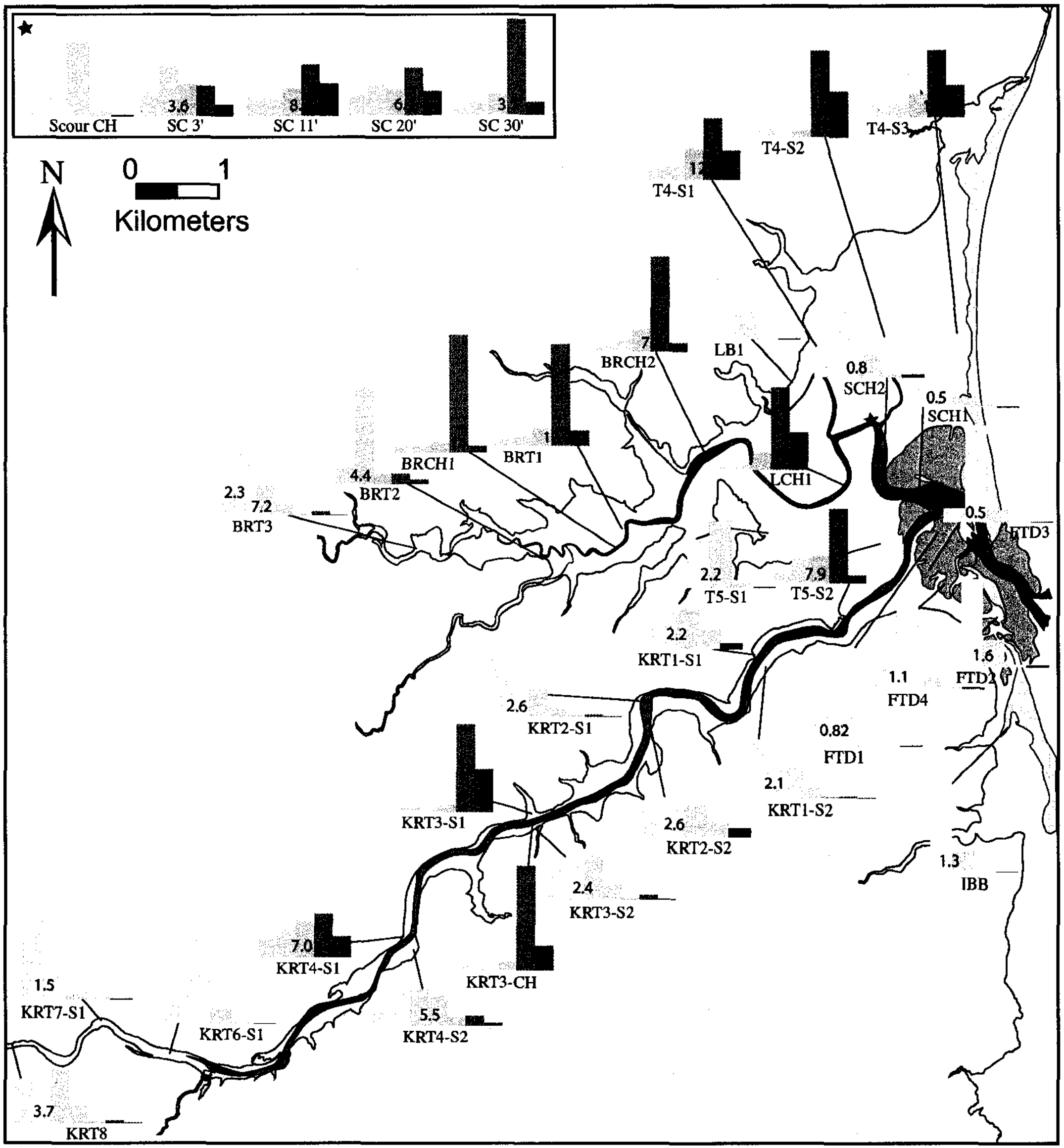


Figure 3.3- Grain size distribution histograms of stations from the northern portion of the study area (Kouchibouguac River and Lagoon, and the Black River). Station identifiers are located under the histograms. Weight % total organic carbon (TOC) measured at each station is located within the histograms. Legend located in Figure 3.2. Red star denotes samples taken from a firmground exposure.

mechanically planed off for uniform thicknesses. These sediment-trays were then imaged using a Soyee portable X-ray system (SY- 31-100P) and Kodak Professional Series 25.4 cm^2 film. General X-ray settings found to yield the best results include: 1) an X-ray source to sample distance ranging from 150 to 300 cm; 2) exposure times of 0.8 to 1.5 seconds depending on sample texture and heterogeneity; 3) 60-70 Kvp; and 4) 25-30 mA. Generally, the greatest detail in the sediments could be resolved by combining greater X-ray source to sample distance coupled with longer exposure times.

Shovels and clam guns (handheld cylindrical coring devices used to retrieve clams) were used to observe type, diversity and abundance of infaunal organisms at each station to a depth of approximately 50 cm. Organisms and burrows were collected and measured using a Vernier Caliper. Estimates of infaunal diversity were multiplied by the largest vermiform burrow diameter present. The numbers derived were plotted next to station locations on a map and contoured in order to determine trends in diversity and diminution in response to salinity stress.

Salinity was measured using a Symphony SR60IC conductivity meter and a handheld salinity refractometer in the field. Measured salinities were taken independent of the timing of the tides. General indications of salinity levels at select stations along transects up the Kouchibouguac and Kouchibouguacis Rivers give approximations of salinity stresses on infaunal organisms (Fig. 4A, B). Discrepancies in measurements with respect to the tidal cycle may account for some variation in average salinities from the estuary divisions (e.g., central and inner estuaries) from the Kouchibouguac and Kouchibouguacis Rivers. Discrepancies may also arise from station placement with respect to distance from tidal inlets.

Within the Kouchibouguac River and lagoon in the northern part of the study area, turbidity was assessed. Turbidity was measured in nephelometric turbidity units (NTU), using an Oakton T-100 portable turbidimeter.

Resin casts were emplaced in a number of intertidal sub-environments within the system in order to ascertain local 3-dimensional burrow morphology and incipient trace fossils, as well as other attributes discussed further on in this paper. "Ship-builders" polyester resin was used with a 1-2% per volume of resin admixture of MEKP (methyl ethyl ketone peroxide), which acted as the hardening agent. Casts were left overnight and collected approximately 24 hours after pouring to allow for full hardening.

RESULTS

The following sections describe the physical (sedimentological) factors that potentially affect the infauna, and later incorporate these factors with the observed ichnology. The results are described for each subenvironment observed in the system, with the goal of developing an ichnological model for microtidal estuary deposits.

Physical Factors Affecting Infauna

Sediment Texture.– Grain-size histograms and the station locations of sediment samples are shown in figures 3.2 and 3.3. These figures show the general sediment distribution in the St. Louis Lagoon and Kouchibouguacis River (Fig. 3.2), and the Kouchibouguacis River, Black River, and Kouchibouguac Lagoon (Fig. 3.3). The histograms show three general sediment types: 1) dominantly sandy, < 2% of material below ø 4 (5 populations); 2) dominantly silt, clay, very fine sand, and fine sand (5 populations), and 3) a combination of sand, silt, and clay, ranging from coarse sand and greater, to clay, where the overall fines were > 2% of the total mass of the sample (7 populations).

In general, the two estuary and lagoon pairs show similar grain-size distributions, with a tripartite division of sediment textures observed seaward to landward (i.e., sand-mud-sand). The sands of the barrier complex are the best sorted in the system, followed by those of the bay-head delta area (Fig. 3.2, stations RT4-S1 to RT7-S1). The lower-central estuaries are fine-grained, however sand content increases toward the bay margins. The middle-central estuaries (located within the estuary funnel) are marked by a noticeable decrease in the proportion of fines (Fig. 3.2, RT1-S3; Fig. 3.3, KRT1-S1, KRT1-S2, KRT2-S1, and KRT-S2). The Kouchibouguac River (Fig. 3.3) contains higher proportions of coarse materials in the middle-central estuary, attributed to its proximity to outcrops of Pennsylvanian sandstone. The upper-central estuaries are fine-grained with a lower proportion of coarse-grained material in comparison with the middle-central estuaries. The inner estuaries comprise medium-grained sand.

The flood-tidal delta area (Fig. 3.3, stations denoted FTD) exhibits grain size distributions similar to that of the barrier bar complex. The proportion of fine-grained sediment increases away from the main tidal inlets. This is also observed empirically on the flood-tidal delta, where thin veneers of fines drape the surface of the sand, however, at no place on the flood-tidal delta did fines make up a significant proportion of the sediments.

Sediments from stations set within channels (stations denoted with –CH) contrast between locales dominated by fluvial sedimentation and those dominated by tidal and wave sedimentation (Fig. 3.3) Stations set within the channels proximal to the flood-tidal delta are sandy (SCH1 and SCH2; <2% finer than sand). Much of the fine-grained material in these areas consists of rip-up clasts of autochthonous (cohesive) lagoon deposits derived from scours adjacent to the channels. Further up the system, in the mid-lagoon area, the channel deposits are composed predominantly of silt and clay (Fig. 3.3, LCH1), and are significantly water-saturated near the surface (?fluid mud). Deposits in channels from stations BRCH1 and BRCH2 have similar textures to that of LCH1 (Fig. 3.3). In the upper-central estuary, the channel sediments are muddy (Fig. 3.3, KRT3-CH).

Total Organic Carbon and Turbidity.– TOC is displayed on the grain size histograms in figures 3.2 and 3.3. TOC ranged from 0.5 wt % in the flood-tidal delta (Fig. 3.3, station FTD3), to 26.3 wt % in salt-marsh deposits adjacent to the lagoon (Fig. 3.2, station SM1). There is a direct relationship between grain size and TOC, with TOC positively correlated with an increase in the proportion of fine-grained sediments. This is best observed in deposits from the lower and upper-central estuary, where TOCs average 10.5 wt % and 8.1 wt % respectively. TOC is conversely lowest within the sandy sediments, such as those of the barrier complex (including the flood-tidal delta; average TOC = 1.4 wt%) and bay-head delta areas (average TOC = 2.4 wt %).

Turbidity levels were assessed within the Kouchibouguac River and Kouchibouguac Lagoon (Fig. 3.1D). Turbidity is relatively low within the system attributed to low rates of river discharge during sampling; however, systematic variations in turbidity levels within the estuary are discernible (Fig. 3.4C). A peak in turbidity is associated with the upper-central estuary of the Kouchibouguac River, where sediments are distinctly fine-grained and contain high TOC (see stations denoted KRT3 and KRT4, Fig. 3.3).

*Salinity.–*Measured salinity levels within the lower-central and outer estuary do not fluctuate greatly during low discharge, where measurements only vary over 6.8 ppt. Average salinity within the lagoon proper was 26.1 ppt (brachyhaline). The middle-central estuaries have salinities that range from 10.5 to 8.5 ppt in the Kouchibouguac River (KRT1 to KRT2) and 19.0 to 25.3 ppt in the Kouchibouguacis River (RT1 to RT2). The higher measurements of the latter are the result of proximity of these stations to the lagoon proper (Fig. 3.1E). The upper-central estuaries of the Kouchibouguac River (Fig. 3.3, KRT3 to KRT4) and Kouchibouguacis River (Fig. 3.2, RT4 to RT7) have salinities ranging from 2.0 to 4.0 ppt, and 6.7 to 14.6 ppt respectively, whereas the inner estuaries ranged from 0.5 to 2.0 ppt, and 0.2 to 0.4 ppt respectively.

Those stations set closest to riverine influences record salinities of 0.5 ppt in the Kouchibouguac River and 0.2 ppt in the Kouchibouguacis River, well into the oligohaline zone of the estuaries. Burrowing estuarine species were not found at either station; however, freshwater species were observed (presented below).

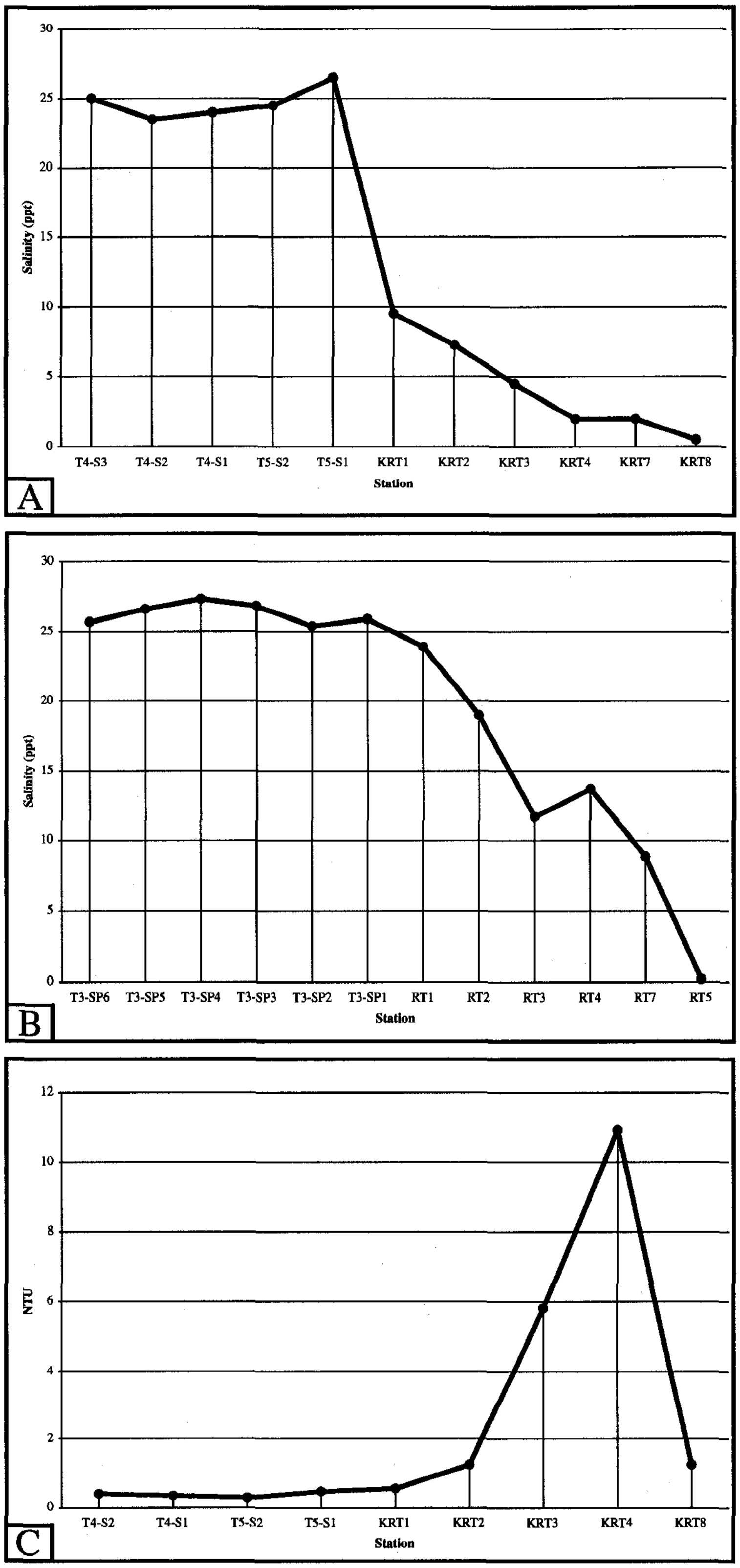


Figure 3.4- Salinity and turbidity measurements. A) Salinity transect taken from the Kouchibouguac Lagoon and River. Stations are denoted on the x-axis (see Figure 3.3 for placement). Salinity reaches oligohaline levels (<5 ppt) starting at station KRT3. Station KRT8 marks nearly fully freshwater conditions. B) Salinity transect taken from the Kouchibouguacis River and St. Louis Lagoon (see Figure 3.2 for station placement). RT5 marks fully freshwater conditions. C) Turbidity transect (nephelometric turbidity units) taken from the Kouchibouguac Lagoon and up the Kouchibouguac River (see Figure 3.3 for station placement). Turbidity is very low in the majority of the estuary and lagoon. A significant peak in turbidity occurs in the upper-central estuary (KRT3 and KRT4).

Tracemakers.– The organisms described in this section represent the common, distinctive tracemakers of the Kouchibouguac estuaries as observed during the course of this study. A total of twenty-one benthic taxa were repeatedly observed in the Kouchibouguac system. These are illustrated in figures 3.5 through 3.8. The main burrowers represent five phyla: 1) Arthropoda, including the Subphylum Crustacea and the Class Insecta; 2) Annelida, including the Class Polychaeta and the Subclass Oligochaeta; 3) Hemichordata (Enteropneusta); 4) Nemertea; and 5) Mollusca, including the Classes Bivalvia and Gastropoda. In terms of biomass and propensity to generate bioturbated sediment, the annelids are by far the most abundant.

Bivalves generally produce vertically oriented burrows, which can be found in nearly all subenvironments within the system (Fig. 3.5). *Mya arenaria* and *Macoma balthica* are especially tolerant of lowered and fluctuating salinities. As such, vertically oriented burrows of the two bivalves can be found well into the upper central, and occasionally inner estuary. *Lunatia heros* is a predatory gastropod that does not produce open burrows, and the bioturbate fabric is of general sediment deformation, or deflection of bedding laminae.

Vermiform organisms produce a variety of structures oriented vertically, horizontally, or obliquely to the sediment-water interface (figs. 3.6, 3.7). In general, when burrowing in sandy deposits, vermiform organisms have a tendency to produce vertically oriented traces, while their burrows in silty and muddy deposits are predominantely oriented more or less horizontally. One exception is *Polydora ligni,* which produces vertical traces within fine-grained sediment, however the causative tubes are emplaced in palimpsest firmgrounds. On the whole, vermiform organisms produce burrows that tend to exhibit greater morphological complexity compared to the other observed estuarine infauna.

At Kouchibouguac, crustaceans produce relatively simple burrow structures occurring in small numbers within the system (Fig. 3.8). This is the same for insects (Fig. 3.8), which become more common in the fresh-water reaches of the inner estuary.

Shoreface.– The ichnological characteristics of the shoreface are briefly described for comparative purposes. Unlike the protected lagoons and estuaries, the shoreface is within the fully marine realm (i.e., > 30 ppt salinity), and is subject to the full impact of wave activity within Kouchibouguac Bay. Large-scale evidence of wave activity is observed by the presence of bar and trough topography, whereas, at a smaller scale, wave activity

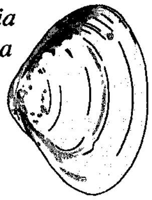
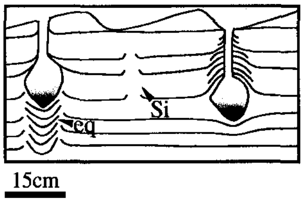
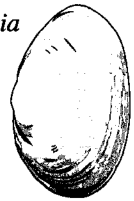
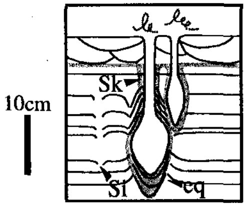
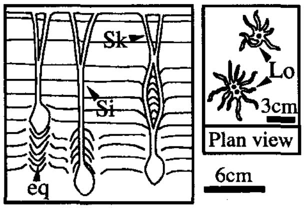
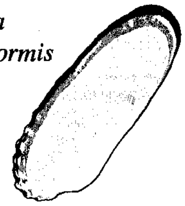
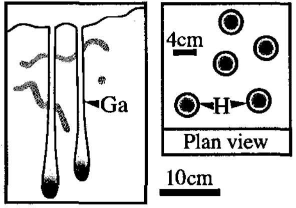
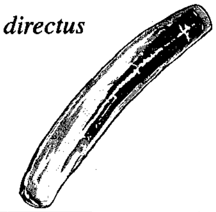
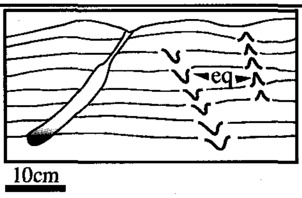
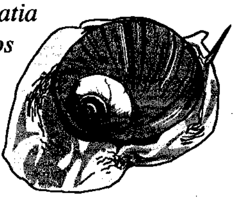
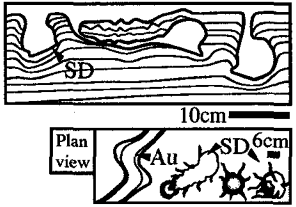
Mollusca	Behavior	Burrow Morphology	Incipient Trace Fossils
Mercenaria mercenaria 	filter feeder		*equilibrichnia* (eq) *Siphonichnus* (Si)
Mya arenaria 	filter feeder		*equilibrichnia* (eq) *Siphonichnus* (Si) *Skolithos* (Sk)
Macoma balthica 	interface feeder filter feeder (secondary)		*equilibrichnia* (eq) *Siphonichnus* (Si) *Skolithos* (Sk) *Lorenzinia* (Lo)
Petricola pholadiformis 	filter feeder		*Gastrochaenolites* (Ga) (*Glossifungites*) siphon holes (H)
Ensis directus 	filter feeder		*equilibrichnia* (eq)
Lunatia heros 	predator (various bivalves) scavenger		*Aulichnites* (Au) general sediment deformation (SD)

Figure 3.5- Burrowing molluscs within the system. Behavior, burrow morphology, and incipient traces are described. The first five organisms described are bivalves. *Lunatia heros* is a gastropod.

is evidenced by oscillation ripples on the bars and within the troughs. In the sediments, oscillation and combined flow ripples can be seen (Fig. 3.9). More quiescent zones within the trough contain algae that act to partially bind the surficial sediments together, indicative of lower wave energy. The dominantly medium-grained sands also locally

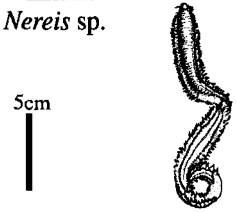
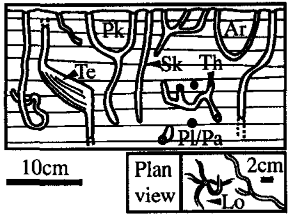
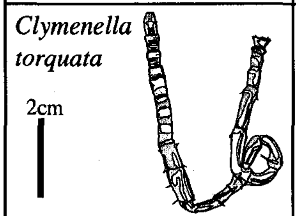
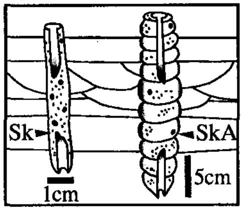
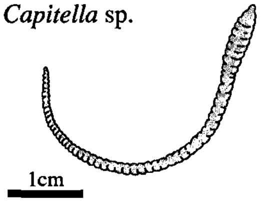
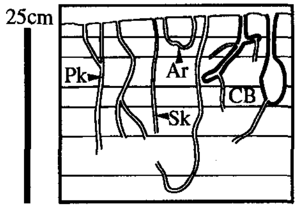
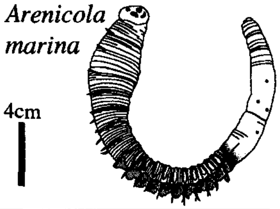
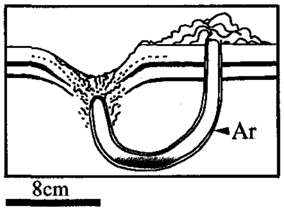
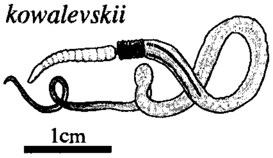
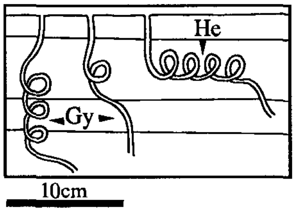
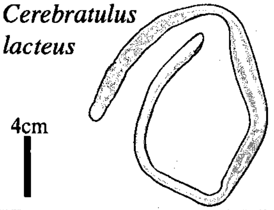
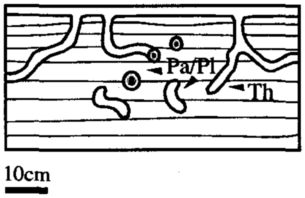
Vermiform	Behavior	Burrow Morphology	Incipient Trace Fossils
Nereis sp. 	filter feeder deposit feeder interface feeder passive carnivore active carnivore suspension feeder		*Arenicolites* (Ar) *Polykladichnus* (Pk) *Planolites* (Pl) *Palaeophycus* (Pa) *Thalassinoides* (Th) *Skolithos* (Sk) *Teichichnus* (Te) *Lorenzinia* (Lo)
Clymenella torquata 	deposit feeder		*Skolithos* (Sk) *Skolithos annulatus* (SkA)
Capitella sp. 	deposit feeder		*Skolithos* (Sk) *Arenicolites* (Ar) *Polykladichnus* (Pk) commensal burrows (CB)
Arenicola marina 	deposit feeder		*Arenicolites* (Ar)
Saccoglossus kowalevskii 	deposit feeder		*Gyrolithes* (Gy) *Helicodromites* (He)
Cerebratulus lacteus 	active predator passive predator		*Palaeophycus* (Pa) *Planolites* (Pl) *Thalassinoides* (Th)

Figure 3.6- Burrowing vermiform organisms within the system. Behavior, burrow morphology, and incipient traces are described. *Nereis*, *Clymenella torquata*, *Capitella*, and *Arenicola marina* are polychaetes. *Saccoglossus kowalevskii* is an enteropneust. *Cerebratulus lacteus* is a nermertean. The commensal burrows of *Capitella* include those extending from the burrows of *Nereis* and *M. arenaria*.

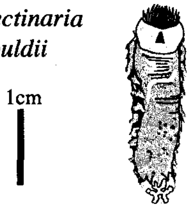
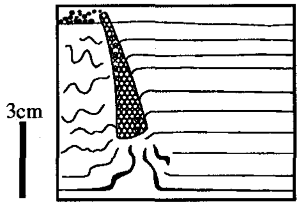
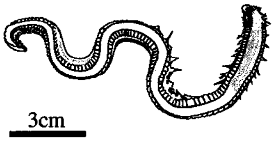
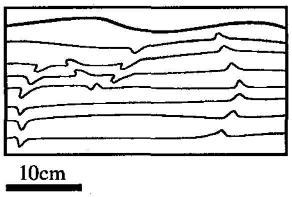
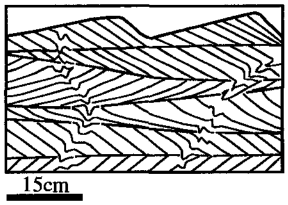
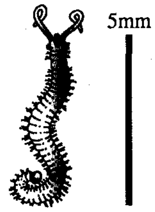
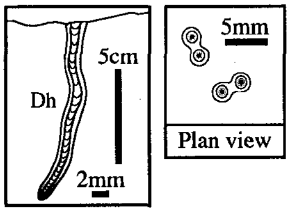
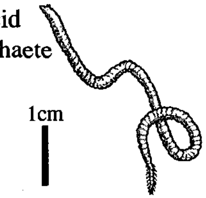
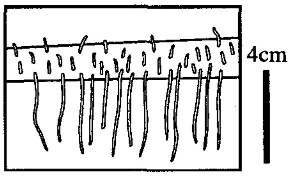
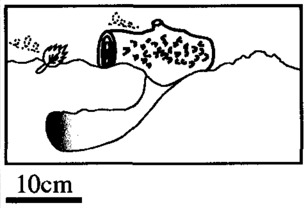
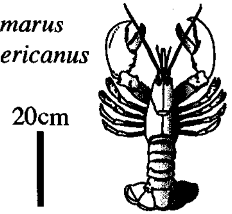
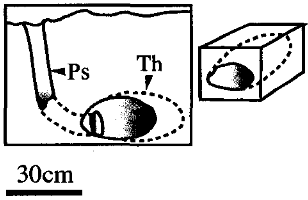
Vermiform	Behavior	Burrow Morphology	Incipient Trace Fossils
Pectinaria gouldii 	deposit feeder		general sediment deformation (SD)
Nephtys sp. 	active predator		cryptic bioturbation
Glycera dibranchiata 	active predator		cryptic bioturbation
Polydora ligni 	filter feeder		*Diplocraterion habichi* (Dh)
tubificid oligochaete 	deposit feeder		dimunitive *Skolithos*

Figure 3.7- Burrowing vermiform organisms within the system continued. The first four organisms described are polychaetes. The last is a freshwater tubificid oligochaete.

contain large numbers of pebbles, cobbles, and boulders (Fig. 3.9).

Burrowing organisms include the polychaetes *Clymenella torquata*, *Capitella*, and *Nephtys*. Other organisms include the bivalve *Mercenaria mercenaria*, sand dollars, and rock crabs. Rock crabs burrow shallowly up to their eyestalks, disturbing the sediments as they hide themselves. Numbers of burrowing organisms were relatively high, and epifaunal trace producing types (i.e., sand dollars and rock crabs) are more abundant compared to the embayment.

Tidal and Estuary Channels.– The channels studied in the Kouchibouguac Lagoon

Crustacea	Behavior	Burrow Morphology	Incipient Trace Fossils
Rhithropanopeus harrisii 	scavenger		*Psilonichnus* (Ps)
Homarus americanus 	scavenger active predator		*Thalassinoides* (Th) *Psilonichnus* (Ps)

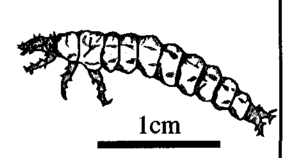
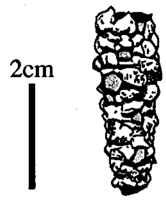
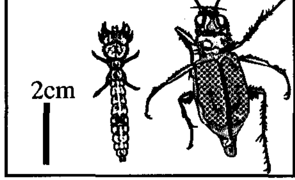
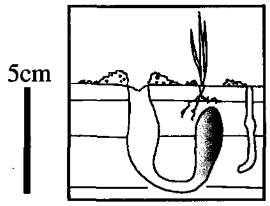
Insecta	Behavior	Burrow Morphology	Incipient Trace Fossils
Trichoptera (caddisfly) 	omnivorous scavenger		agglutinated sand, gravel, and organic detritus casings (mobile domiciles)
Cicindela sp. 	active predator passive predator (larvae)		*Psilonichnus* (Ps)

Figure 3.8- Burrowing arthropods within the system. Behavior, burrow morphology, and incipient traces are described. *Rhithropanopeus harrisii* is a brackish-water crab found only within the middle- and upper-central estuaries of the Kouchibouguacis River. *Homarus americanus* was only observed within the lower-central estuary channels of the Kouchibouguac Lagoon during the study. Caddisflies are freshwater insects located in the extreme reaches of the inner estuary. Their mobile domiciles are not burrows, but protective casings. *Cicindela* is a beetle that burrows within the foreshore zone of the barrier bar.

and Black River can be divided into sandy channels (affected by tides and waves) and muddy channels (affected predominantly by the river run-off) (figs. 3.2, 3.3, stations designated –CH). Sandy channels are typically located close to the barrier inlets (figs. 3.2, 3.3; SCH1, SCH2, T2-CH), where medium-grained sand is the dominant grain size and TOC contents are low. Stations SCH1 and T2-CH are characterized by shifting sands, forming both flood- and ebb-oriented large to medium wavelength (avg. 11.29 m), medium height (avg. 0.27 m) 2-dimensional compound dunes in SCH1 (Fig. 3.10K). In shallow profile, faint sub-horizontal laminae can be observed (Fig. 3.10C, D, E), locally

Figure 3.9- X-ray of sediments taken landward of the outer bar on the shoreface, adjacent to the Kouchibouguac Lagoon. Combined flow ripples predominate, and abundant pebbles are evident. Bioturbation levels are much lower than that of sandy sediments taken from the back-barrier areas.

lined with pebbles and shelly debris (Fig. 3.10E). In the Kouchibouguac Lagoon, tidal hydraulic energy is dampened by meandering turns in the channels (Fig. 3.1D), producing scours that exhume cohesive lagoonal deposits. Clasts of the lagoonal deposits, typically elongate and bladed in shape, are incorporated into the channel deposits proximal to the barrier inlet (Fig. 3.10C, E). Further away from the barrier, typically adjacent to tight meanders, the channels exhibit sizeable shell lags consisting dominantly of *M. arenaria* shells derived from the scours (Fig. 3.10B).

Within the Kouchibouguac Lagoon, silt and mud dominate the channel sediments

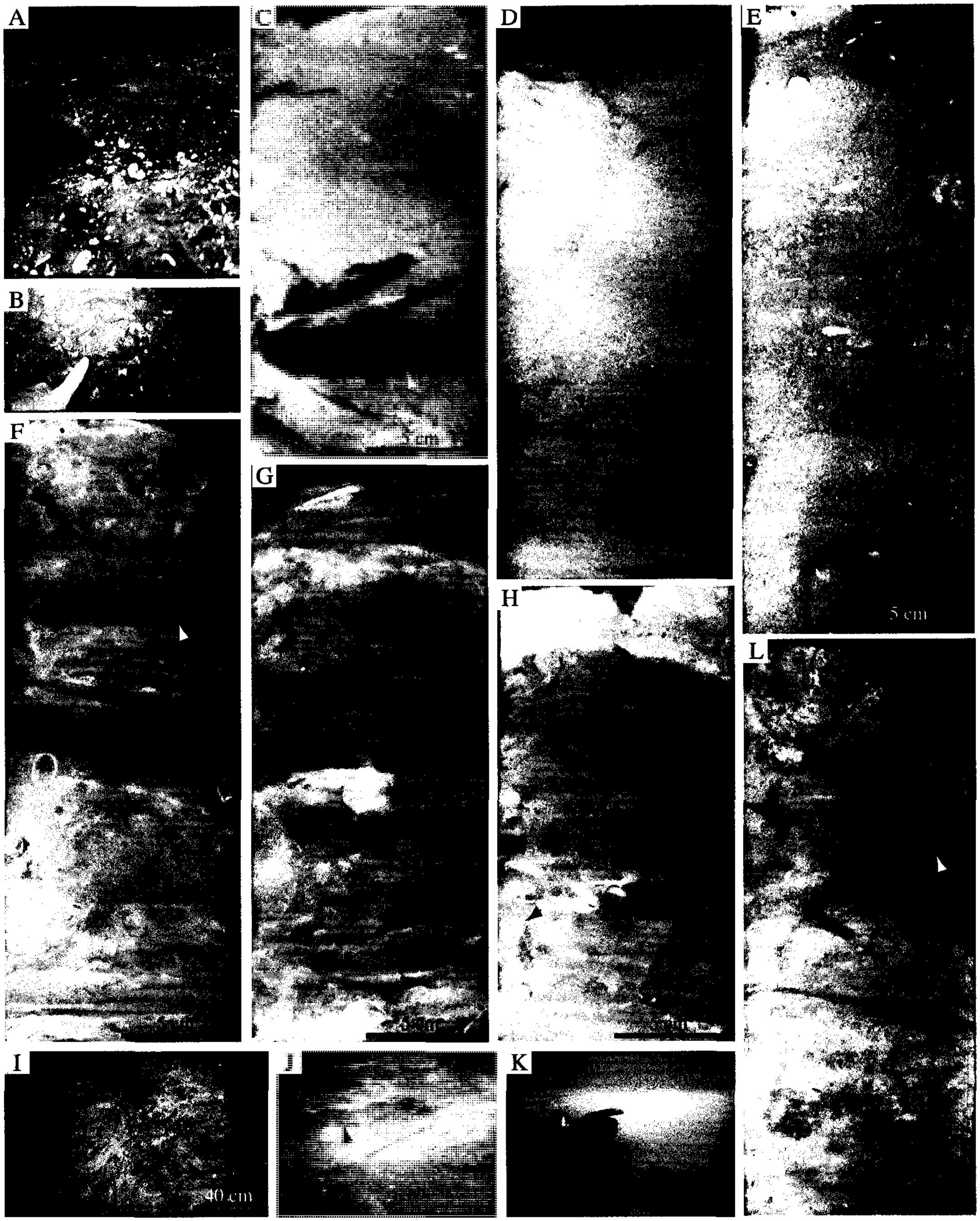


Figure 3.10- X-rays and underwater photographs taken from channels in the system. A) Shell lag and dead eelgrass detritus in the muddy channel of the middle-central estuary of the Black River (BRCH1). B) Shell lag at the base of the sandy channel in the outer estuary at station SCH2. C) X-ray of unbioturbated sandy channel deposits of the outer estuary at station SCH2. Notice the elongated rip-up clasts of autochthonous cohesive lagoon deposits (white arrows). The uppermost clasts drape and define the foresets of cross-stratification. D) X-ray of sandy channel deposits taken from outer estuary at station T2-CH. The silty layer (black arrow) appears to have been burrowed by *Capitella* (black dots), resulting in *Chondrites*-like burrows. E) Unbioturbated sandy channel

(**Figure 3.10** cont.) deposits taken from the outer estuary at station SCH1. Shells and pebbles line the shallowly dipping cross-stratification. Large black object at the base is a rip-up clast of cohesive lagoonal deposits. F) X-ray of deposits near the margin of the muddy channel in the middle-central estuary of the Black River at station BRCH1. Notice the large-diameter *Palaeophycus*-like *Nereis* burrow (white arrow). Primary sedimentary structures appear as alternating light- and dark-colored foresets. G) X-ray of deposits of the middle-central estuary at the base of the channel of station BRCH1. While biogenic reworking is abundant (*Planolites*- and *Palaeophycus*-like burrows of *Nereis*), evidence of primary sedimentary structures is evident in the form of cross-stratification near the top of the X-ray (black arrow). The foresets are composed entirely of *Capitella* fecal pellets forming the current ripples in J of this figure. H) X-ray of muddy channel deposits of the lower-central estuary at station LCH1. Black arrow points to a transported sand tube of *P. gouldii*. White layer near the top of the X-ray may be a fluid-mud layer deposit. I) Scoured margin of the channel where core F of this figure was taken. J) Base of channel of station BRCH1. Black arrow points to one of many undulatory-crested current ripples composed entirely of *Capitella* fecal pellets. (see top of X-ray G of this figure). K) Leeward face of large sand dune taken in the vicinity of station SCH1. Notice the abundance of debris in the trough. L) X-ray of stiffground deposits of the middle-central estuary at station BRCH2. Abundant bioturbation from *Nereis* in the form of large branching burrow networks (white arrow), and small and large *Arenicolites* (black arrows). Notice the large *Arenicolites* (large black arrow) contains sand-sized grains within and surrounding the burrow, possibly representing passive sedimentation stowing.

starting at approximately the mid-lagoon areas of the lower-central estuary (Fig. 3.3, LCH1). Medium and fine silt are the major grain sizes within the muddy channel deposits. Clay also makes up a significant proportion of the fines, however, clay is more common within the lower-central estuary (LCH1) and upper-central estuary deposits (KRT3-CH) than within other muddy channel deposits (BRCH1 and BRCH2). The fine-grained channel deposits are coincident with high levels of TOC (figs. 3.2, 3.3). At the surface, the deposits are featureless, however, near the channel margins there is evidence of erosion (Fig. 3.10I). Shell lags are present in areas of the channels, consistent with winnowing currents in these areas (Fig. 3.10A). In the cores, possible fluid mud layers are present near the sediment-water interface (Fig. 3.10H, uppermost layer).

Bioturbation within the sandy channels is less abundant compared to their muddy counterparts (Fig. 3.10C, D, E). Only *M. mercenaria*, *E. directus*, *Nephtys*, and *Glycera* were observed in the channel in close proximity to the tidal inlet (SCH1). Bioturbation in the shifting channels sands consists of cryptic bioturbation, *equilibrichnia*, and potentially *Siphonichnus* (*M. mercenaria*). Scavenging rock crabs scour the sediment surface and bury themselves in the sand, similar to behavior observed in the shoreface, typically in the leeward side of dunes (Fig. 3.10K). Approximately 800 m from the tidal inlet, but still within the sandy channels (SCH2), bioturbation remains low. *Nereis* is present producing agglutinated burrow structures within the sand, and *M. mercenaria* is no longer present. In general, small numbers of mobile benthic organisms produce traces in these locales.

Lower-central estuary muddy channels (Fig. 3.10H, LCH1) are heavily bioturbated by the polychaetes *Nereis* and *Capitella. Saccoglossus* also occurs sporadically here. Scavenging rock crabs and *L. heros* are present at the sediment-water interface. The mobile domiciles of *P. gouldii* are observed upright (Fig. 3.10H), suggesting they deposit feed in these locales.

At the mouth of the Black River embayment (BRCH2), channels exhibit sediment bypass, with stiffgrounds (Gingras and Pemberton, 2000) of lagoonal nature produced by tidal scour. Shell lag material, consisting of *E. directus*, *M. arenaria*, *M. mercenaria*, *L. heros*, *P. pholadiformis*, and oyster valves, is extremely abundant. Burrows are predominantly produced by *Nereis*. In the stiff sediments, *Nereis* produces *Arenicolites*-like burrows, as well as branching burrow networks, some of which are filled with coarser sandy sediment (Fig. 3.10L). Lobsters were observed producing simple domiciles under blocks of exhumed and collapsed lagoonal deposits.

Further up the Black River embayment, the channel is muddy with abundant bioturbation observed in the shallow subsurface (Fig. 3.10F, G). *Nereis* produces *Planolites*- and *Palaeophycus*-like burrows (Fig. 3.10F, G). *Capitella* is also abundant, however, their *Skolithos*-like burrows are not observed in X-rays within the muddy sediments. Shell litter is common, consisting of *M. arenaria* and *P. pholadifomis* valves, which can be observed in the shallow subsurface along with gastropod shells (Fig. 3.10F, G). X-rays exhibit bedding and foresets of what appear to be current ripples (Fig. 3.10F, G). Sand is a minor component of the sediments here, however, the fecal pellets of *Capitella* are abundant and of the appropriate size to be affected by hydraulic currents. At the surface, current-modified wave ripples composed entirely of fecal pellets (Fig. 3.10J) are observed. The foresets appearing in the X-rays (Fig. 3.10F, G) are likely composed of these fecal pellets.

Low numbers of predatory polychaetes and vagile suspension-feeding bivalves dominate the benthic biota in sandy channels. In contrast, high numbers of deposit-feeding polychaetes that produce permanent domiciles dominate muddy channel sediments.

Outer Estuary: Flood-Tidal Delta.– The flood-tidal deltas are the most dynamic subenvironments in the system, subject to the focus of ebb- and flood-tidal hydraulic energy. In addition, because of low average tides (0.67 m), flood-tidal deltas are one of the few subenvironments to be exposed subaerially during spring tides. Aerially, the flood-tidal deltas from the Kouchibouguac and St. Louis Lagoons are comparable in size, exhibiting typical morphology of tidal deltas formed due to the segregation of ebb and flood flow paths (Reinson, 1979). Compared to systems with higher-amplitude tidal ranges, these deltas are small due to the low tides.

The flood-tidal delta from the Kouchibouguac Lagoon was studied in detail, revealing a gradation in the bioturbate texture from areas in close proximity to tidal channels, to those further away (20 to 30 m). Areas close to the main tidal inlet, and other associated tidal channels, exhibit large-scale dunes. Oblique to these, ebb-oriented current ripples with heights up to approximately 10 cm occur superimposed (Fig. 3.11E, H). In shallow profile, opposing ebb and flood tidal currents responsible for deposition are revealed as amalgamated bedsets of ripple cross lamination, and larger scale tabular cross-stratification (Fig. 3.11J, K). Foresets and bedding planes may be lined with pebbles (Fig. 3.11D, K).

Bioturbation is sparse in those zones continually reworked by currents (Fig. 3.11J), consisting primarily of vertical traces produced by polychaetes and bivalves, as well as predatory polycheate navichnia (sediment swimming). Bioturbation gradually intensifies with time and as the focus of deposition shifts (Fig. 3.11A, B, K). In proximity to the margins, burrows of the maldanid polychaete *Clymenella torquata*, and the capitellid polychaete *Heteromastus filiformis* dominate (Fig. 3.6). *C. torquata* produces burrows that are large, robust, and strongly agglutinated with mucous, resembling *Skolithos annulatus* (Alpert, 1974) (Fig. 3.11I). In the sediment, the strongly agglutinated portion is oriented vertically extending down from the sediment-water interface. A thin lining coats the rest of the burrow, which may turn obliquely toward food resources (Fig. 3.11B). The very slender burrows of *H. filiformis* are coated with a thin mucous lining, and extend vertically down from the sediment-water interface, occasionally branching or changing direction at depth (Fig. 3.11B). Typically, the burrows resemble *Skolithos*.

With distance from the locus of deposition, the flood-tidal delta is more quiescent, marked by a decrease in grain size (Fig. 3.11A) and lacking surficial sedimentary structures (Fig. 3.11F, G). Thin veneers of silt and mud often cover or drape areas of the surface. Here, bioturbation is more intense, with an increase in the diversity of burrowers, including *Nereis*, *C. torquata*, *H. filiformis*, *Arenicola marina*, *Nephtys*, *Glycera*, *Mya arenaria*, *Ensis directus*, and *Lunatia heros* (figs., 3.5 through 3.7). A variety of *Nereis* burrows resembling *Palaeophycus* are observed in the flood-tidal delta, where burrow networks oriented in vertical and horizontal orientations are typical (Fig. 3.11K). *C. torquata* produces *Skolithos*-like burrows that are less robustly reinforced compared to areas closer to the tidal inlets (Fig. 3.6). *A. marina* constructs mucous-lined U-shaped burrows resembling *Arenicolites* (Fig. 3.6) as it stopes the sediment, ingesting grains and the organics. This leaves a distinct trace at the surface, characterized by a sunken anterior

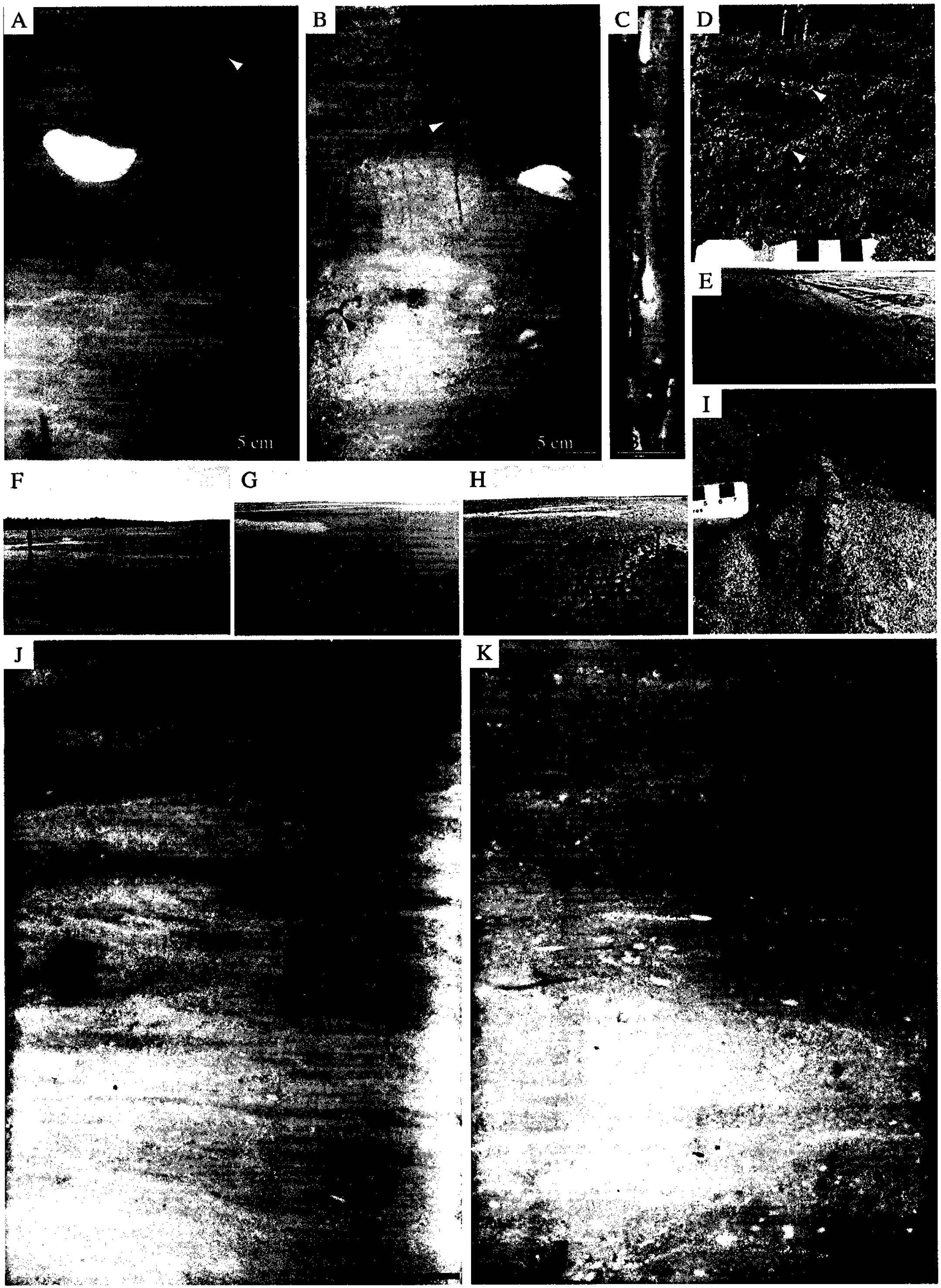


Figure 3.11- X-rays and photographs from the flood-tidal delta of the outer estuary. A) X-ray taken from station FTD2. Bright object is a *Mercenaria mercenaria* valve bored by sponges (black dots). Ripple cross-lamination is observed at the base. *Nereis* burrows are present (white arrows).

(**Figure 3.11** cont.) B) X-ray taken from station FTD3. Bright object is a valve of *Mya arenaria*. Near the base of the X-ray pebbles line cross-stratification foresets. *Capitella* burrows (thin vertical burrows) and thickly agglutinated *Skolithos annulatus*-like burrows (white arrow; notice the slightly darker haze surrounding vertical segment of burrow). The two lowermost horizontal burrows are those of *Nereis* (black arrows). C) Bored wood fragment taken from the surface of the flood-tidal delta. Long linear burrows follow the grain of the wood and belong to teridolid bivalves. D) Two granule-rich layers defining the lowermost layers of fining-upward sequences (FTD4) (white arrows). E) Intertidal flood-tidal delta marked by 2 sets of large-scale, obliquely oriented current lineations, overprinted by small-scale sinuous-crested current ripples. F) and G) Quiescent regions (presently inactive) of the flood-tidal delta (FTD2). Algal mats cover areas of the surface, as well as with thin veneers of silt and clay. Low to moderate densities of the lugworm *Arenicola marina* are found in these regions. H) Margins of the intertidal zone of the flood-tidal delta marked by low-amplitude, medium-wavelength dunes, with superimposed small, lingoid-shaped current ripples. I) Burrow of *C. torquata* with thickly agglutinated ring-like annulations, resembling *Skolithos annulatus*. J) X-ray of flood-tidal delta sediments proximal to the main ebb-dominant tidal channel (FTD1), exhibiting superimposed ripple cross-lamination and trough-cross stratified bedsets in opposing directions. K) Burrowed flood-tidal delta sediments still retaining some primary physical sedimentary structures (FTD4). Majority of burrows belong to *Nereis*.

stoping pit adjacent to the fecal casts of the posterior end of the burrow. The predatory polychaetes *Nephtys* and *Glycera* produce general sediment deformation or cryptic bioturbation as they hunt for other polychaetes and young bivalves (Fig. 3.7). *M. arenaria* constructs more or less permanent domiciles resembling *Skolithos* and *Siphonichnus* (Fig. 3.5), however, the bivalve may also produce bioturbation analogous to *equilibrichnia* as it attempts to maintain contact with the sediment water interface. *E. directus,* a bivalve with a long and slender profile suitable for fast locomotion within the sediment (Fig. 3.5), produces *equilibrichnia. L. heros* is a large predatory gastropod possibly producing *Aulichnites*-like traces during surface locomotion, and sediment deformation during subsurface plowing in search for prey (Fig. 3.5).

The flood-tidal delta contains scattered allochthonous clasts of debris derived from the sea. Clasts include fragments of wood bored by teredolid bivalves (Fig. 3.11C). Smaller structures also riddle the surface of wood fragments, including the borings of species of the spionid polychaete *Polydora*, and structures attributed to boring isopods commonly known as gribbles (Gingras et al., 2004).

The burrows produced in the flood-tidal deltas are typically vertical types of both filter feeders (bivalves) and head-down deposit feeders (maldanid and capitellid polychaetes). In certain areas, marked by a decrease in energy, burrow networks consist of horizontal segments (i.e., those produced by *Nereis*). In general, more quiescent areas of the flood-tidal delta contain a higher diversity of organisms, while a truly depauperate assemblage of burrowers mark high-energy zones close to the tidal inlet and ebb shield.

Outer Estuary: Sandflats and Back-Barrier Beaches.– The sandflats and back-barrier beaches differ in amount of subaerial exposure, but otherwise share similar characteristics. Sandflats are comprised of the sands and pebbles derived from washover fans that have breeched the barrier bars. These may, in places, extend into the lagoon for a considerable distance, thus rarely experiencing exposure during low tide levels. Only during maximum low water levels, such as during the spring tides, are they exposed significantly (Fig. 3.12F, G). Conversely, the back-barrier beaches are relatively narrow zones of sand that have been reworked and welded to the back of the barrier bar and the landward margins of the lagoon. They normally border salt-marsh deposits, and the contact may be gradational between the two.

Back-barrier beaches are associated with the barrier bar complex and so have textural characteristics similar to that of the barrier dunes. They differ from the seaward barrier beaches by lower sorting, attributed to less effective wave reworking. The seaward barrier beaches consist of predominantly medium-grained sand, compared to the back-barrier beach, which has a larger fine sand fraction. In contrast, the sandflats contain an even higher fraction of fine sand, as well as silts and clays (Fig. 3.2, T3-S5, T3-S6, T1-S3, and T1-S4).

Cores from beach facies exhibit oscillation ripples where grain size permits (Fig. 3.12D), and occasionally horizons of peat accumulation where salt marsh grasses have attempted colonization before being covered by sand (e.g., lower two dark horizons on Fig. 3.12D, and sand accumulating on top of grasses in Fig. 3.12H). Landward barrier beaches occasionally contain large pebbles and gravels derived from the local Pennsylvanian sandstones, which define distinct bedding horizons (Fig. 3.12E). Sandflats are usually heavily bioturbated and / or contain minor lithological contrast in the shallow subsurface, and thus show no distinct bedding features on X-rays (Fig. 3.12A, B). Shelly material is a common feature in these deposits (Fig. 3.12 C).

Bioturbation in the back-barrier beaches is restricted to the activities of the polychaete *Nereis*, occasionally the polychaete *Capitella*, the bivalve *M. arenaria*, and in supratidal areas insects including both the adults and larvae of tiger beetles (*Cicindela*) (Fig. 3.8), which produce *Psilonichnus*-like burrows. Rooted horizons are also common, especially on the barrier side (Fig. 3.12D) where the interplay between deposition, erosion, and plant colonization are more dynamic. The lower intertidal zones of back-barrier beaches contain the burrows of *M. arenaria,* which appear to be more common in beaches on the landward side of the lagoon. In areas where coarse clasts are found (Fig. 3.12E), only *Nereis* and *M. arenaria* are capable of constructing burrows. Due to intertidal exposure, the back-barrier beaches are one of the few places where the activities

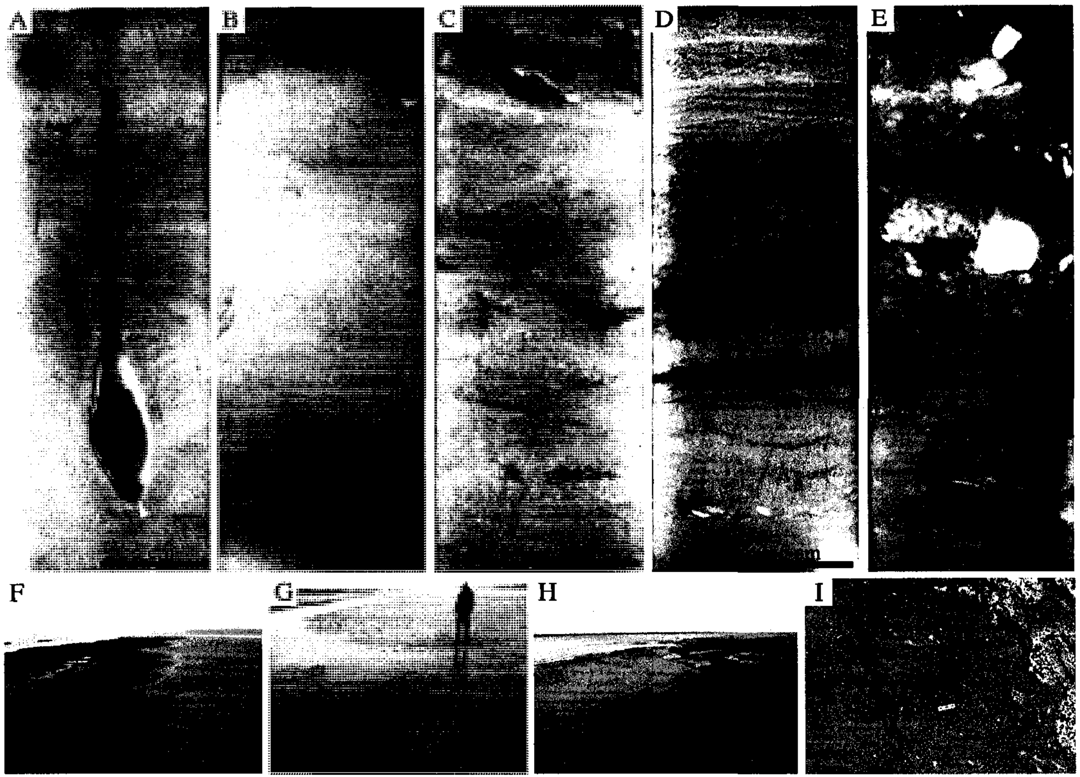


Figure 3.12- Sandflat / washover and back-barrier beach sediments of the outer estuary. A) Sandflat sediments are burrowed by the bivalve *M. arenaria* (white arrow), and the polychaetes *Nereis* (black arrow) and *Capitella* (grey arrow). B) Homogenous sandflat (washover) sediments with faint horizontal laminae. Abundant *Capitella* bioturbation is difficult to resolve. C) Sandflat deposits affected by wave activity due to proximity to tidal inlet. White arrow points to a *M. arenaria* valve. D) Seaward back-barrier beach sediments displaying fresh wave ripples with bubble-sand texture (top), and peat accumulation with rooted horizons (dark layers). E) Landward back-barrier beach with abundant locally derived bedrock sandstone clasts. Vertical striping is artificial and a result of X-ray development process. F) Migrating toe of a dune on sandflats close to the recently breached barrier (near Kelley's Beach). Underlying sandflat deposits are heavily bioturbated and contain a thin veneer of algal mats. (G) Active sand deposition (light colored sand) on sandflats bound by algal mats (dark colored sand). H) Recent sand accumulation on seaward back-barrier beach covering peat accumulations. I) Bioturbation on landward-lagoon beaches created by birds in search of bivalves and polychaetes.

of epifaunal organisms may be found. An example of such traces includes those produced by birds (unknown affinity) when searching for *M. arenaria* and *Nereis*. The trace consists of a shallow, bowl-shaped pit with excavated material scattered to both sides that the birds produce as they dig into the sand with their beaks (Fig. 3.12I).

Bioturbation in the sandflats is usually complete, leaving behind only vestigial mud and silt layers (Fig. 3.12A, B). However, on the barrier side of the lagoon, sandflats may be subject to subaerial exposure during low tides, and can be active areas of deposition and erosion, due to their washover-fan affinity (Fig. 3.12F, G). Freshly deposited washover fan deposits can be seen in Figure 3.12 C. With time, these deposits will be colonized by benthic animals and acquire bioturbate texture similar to that observed in Figure 3.12 A and B.

Organisms that preferentially produce vertical burrows, such as those constructed by the polychaetes *Capitella* and *C. torquata*, and the bivalve *M. arenaria*, usually colonize sandflats. *M. arenaria* may respond to sedimentation and / or erosion in these areas by vertical movements, producing deflected laminae (Fig. 3.12A). *Nereis* also preferentially produces vertical burrows analogous to *Polykladichnus* and *Arenicolites* in the sandflats (Fig. 3.13A) possessing two apertures that tend to be aligned parallel with the dominant tidal current flow. Burrow densities may be very high within the sandflats, as observed from the resin cast.

The mobile domiciles of the head-down deposit-feeding polychaete *Pectinaria gouldii* are also found within the sandflats (Fig. 3.7), however, numbers are much higher in subenvironments marked by finer-grained sediments. Rare occurrences of the predatory polychaete *Nephtys* were noted.

The burrows produced in the back-barrier beaches are dominantly vertical types, as well as insect-produced *Psilonichnus*-type burrows. Within the sandflats burrows are typically vertical types of both filter feeders (bivalves), head-down deposit feeders (maldanid and capitellid polychaetes), and vertical *Polykladichnus*- and *Arenicolites*-like burrows of *Nereis*.

Lower-Central Estuary.– Herein, the lower-central estuary refers to low energy mid-lagoon zones behind the barrier that are notably fine-grained. Sandflats (washover fans) originate from storms that breach the barrier bars, distributing sand into the lagoon. As such, the mid-lagoon area is placed more toward the landward side of the embayment. The lagoon exhibits grain size histograms with distributions skewed toward fine-grained sediments (figs. 3.2, 3.3). Medium and fine silt is the dominant grain size within the mid-lagoon. Coarse silt and clay also make up a significant proportion of the sediments.

The mid-lagoon areas rarely exceed 2 m in depth and are therefore significantly affected by variations in insolation and ambient air temperatures. Typically, these zones are marked by dense patches of eelgrass (*Zostera marina*) (Fig. 3.14A), which act to provide shelter, buffer wave oscillation, and provide a source of food for benthic invertebrates (Ha et al., 2006). Toward the bay margins, eelgrass growth becomes sporadic (Fig. 3.14C). The mid-lagoon rarely exhibits sedimentary structures at the surface and TOCs are typically very high. The sandy silt and mud is commonly disoxic,

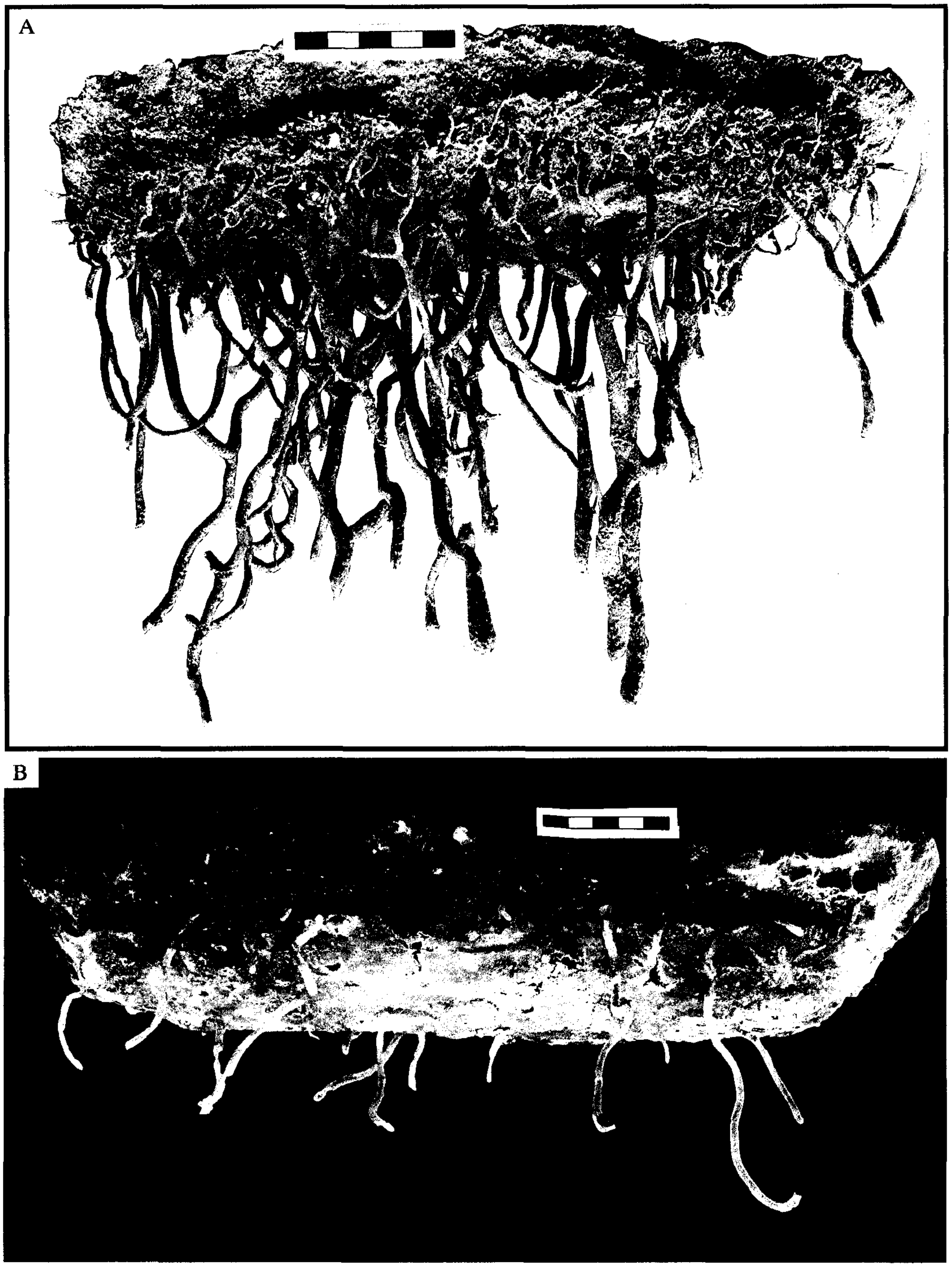


Figure 3.13- Resin casts taken from A) the sandflat of the Kouchibouguac Lagoon, and B) the upper-central estuary of the Kouchibouguac River. The resin cast from the sandflat contains burrows from a relatively high diversity of organisms, including *Nereis*, *Capitella*, and juvenile *M. arenaria*. Burrows resemble *Arenicolites*, *Polykladichnus*, and *Skolithos*. Large burrows are produced by *Nereis*. Small burrows are produced by *Capitella*. Resin cast taken from the Kouchibouguac River

(**Figure 3.13** cont.) displays a very low diversity of burrowing organisms with only *Nereis* burrows present, which resemble sinuous *Skolithos*. These burrows were associated with interface feeding at the surface, which results in *Lorenzinia*-like impressions (see Figure 3.6).

with burrows typically exhibiting oxic halos (Fig. 3.14D; bivalve in Fig. 3.15G). Shelly material, including the shells of bivalves and gastropods, are common, occurring as distinct aggregations along bedding planes (Fig. 3.14C, E).

Bioturbation within the mid-lagoon is very high; laminae are rarely preserved (figs. 3.15A through H). At the surface, bioturbation within the lagoon is easily recognized by the presence of numerous fecal castings of the deposit feeders (Fig. 3.14A, B) *Capitella* and *Saccoglossus kowalevskii* (Fig. 3.6). *Capitella* occur in dense populations (Fig. 3.14D), constructing burrows analogous to *Skolithos*, *Arenicolites,* and locally *Polykladichnus* (Fig. 3.6). *Capitella* may use the burrows of other benthic organisms as an extension of their own burrow to the sediment-water interface (Fig. 3.6). *S. kowalevskii* constructs distinct helical-shaped burrows specific to the mid-lagoon that resemble *Gyrolithes* and *Helicodromites* (Fig. 3.15A, D, E, and H). The burrows typically occur in dense numbers along distinct horizons (top of Fig. 3.15D). Other deposit-feeding polychaetes that inhabit the mid-lagoon include *P. gouldii* (Fig. 3.15C, black arrow) and *C. torquata. C. torquata* occurs sporadically due to its preference for sandy sediments such as that found in the sandflats.

The high numbers of *Nereis* within the mid-lagoon make it a prolific bioturbator. Typically, *Nereis* constructs mucous-lined, open burrow networks within the fine-grained sediments that are analogous to *Palaeophycus*, *Skolithos*, and occasionally *Thalassinoides* and *Planolites*. Locally, burrows of the large predatory nemertean *Cerebratulus lacteus* are observed, which resemble *Palaeophycus*, *Planolites,* and *Thalassinoides* (Fig. 3.6).

Bivalve bioturbation within the lagoon is normally restricted to the activity of *Macoma balthica* (Fig. 3.5), producing burrows resembling *Skolithos* and *Siphonichnus*. *Equilibrichnia*-like bioturbation is produced where the relatively mobile bivalve re-equilibrates with the sediment-water interface. At the surface, *Lorenzinia*-like burrows are formed as the bivalve deposit feeds at the sediment water interface. Locally, *Mya arenaria* may colonize portions of the mid-lagoon towards the margins where higher proportions of sand occur (Fig. 3.15G), producing burrows analogous to *Skolithos* and *Siphonichnus*. *L. heros* is also observed in the mid-lagoon, where it commonly produces *Aulichnites*-like traces in the search for prey (Fig. 5).

The mid-lagoon contains high numbers of benthic organisms whose actions thoroughly destroy primary sedimentary structures (Fig. 3.15A through H). Deposit feeding is the most common behavior, resulting in burrows that exhibit both vertical and

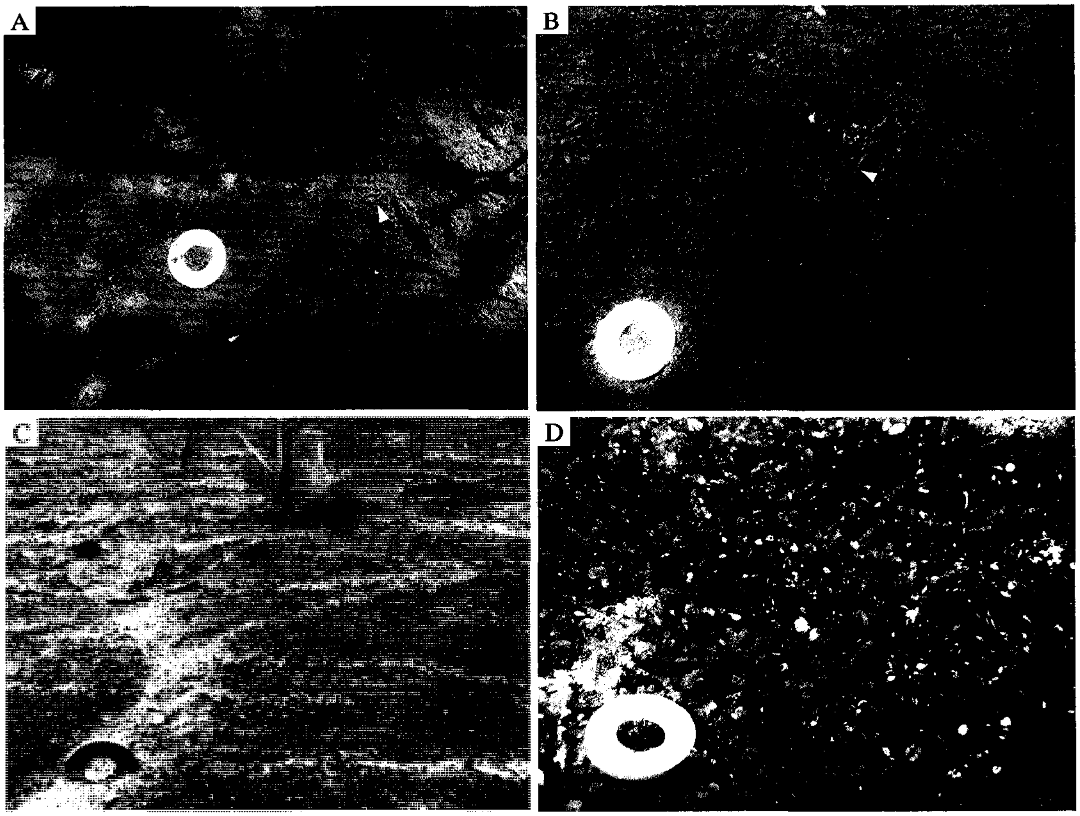


Figure 3.14- Underwater photographs of the lower-central estuary (5/16 washer for scale). A) Sandy silt of the mid-lagoon marked by *Z. marina* colonization and string-like fecal casting of *S. kowalevskii* (white arrow). B) Pellet-like fecal castings most likely attributable to *Nereis*. C) Sparse *Z. marina* colonization and surface-grazing gastropods proximal to the mid-lagoon margins. D) Dense population of agglutinated *Capitella* tubes in disoxic sandy silt of the mid-lagoon margin. Burrows display oxic halos.

horizontal morphology.

Middle-Central Estuary.– The middle-central estuary is the most poorly sorted area of the system, typified by mixtures of sand, silt and clay. Histograms locally consist of seven grain size populations, ranging from clay to coarse sand and greater (Fig. 3.3, KRT1-S2 and KRT2-S1). Silt and mud are more common in the middle-central estuary of the Kouchibouguacis River (Fig. 3.2, RT1-S1, RT2-S1, RT2-S2). Near the margins of the middle-central estuary, granule-to pebble-sized clasts are typical (Fig. 3.16B, C, D, and G). *Zostera marina* is very dense along the margins of the estuary and fringing the channels (Fig. 3.16I).

Bioturbation is intense in the middle-central estuary, however, there is a much lower diversity of benthic organisms. *M. arenaria*, *M. balthica*, *Nereis*, *Capitella*,

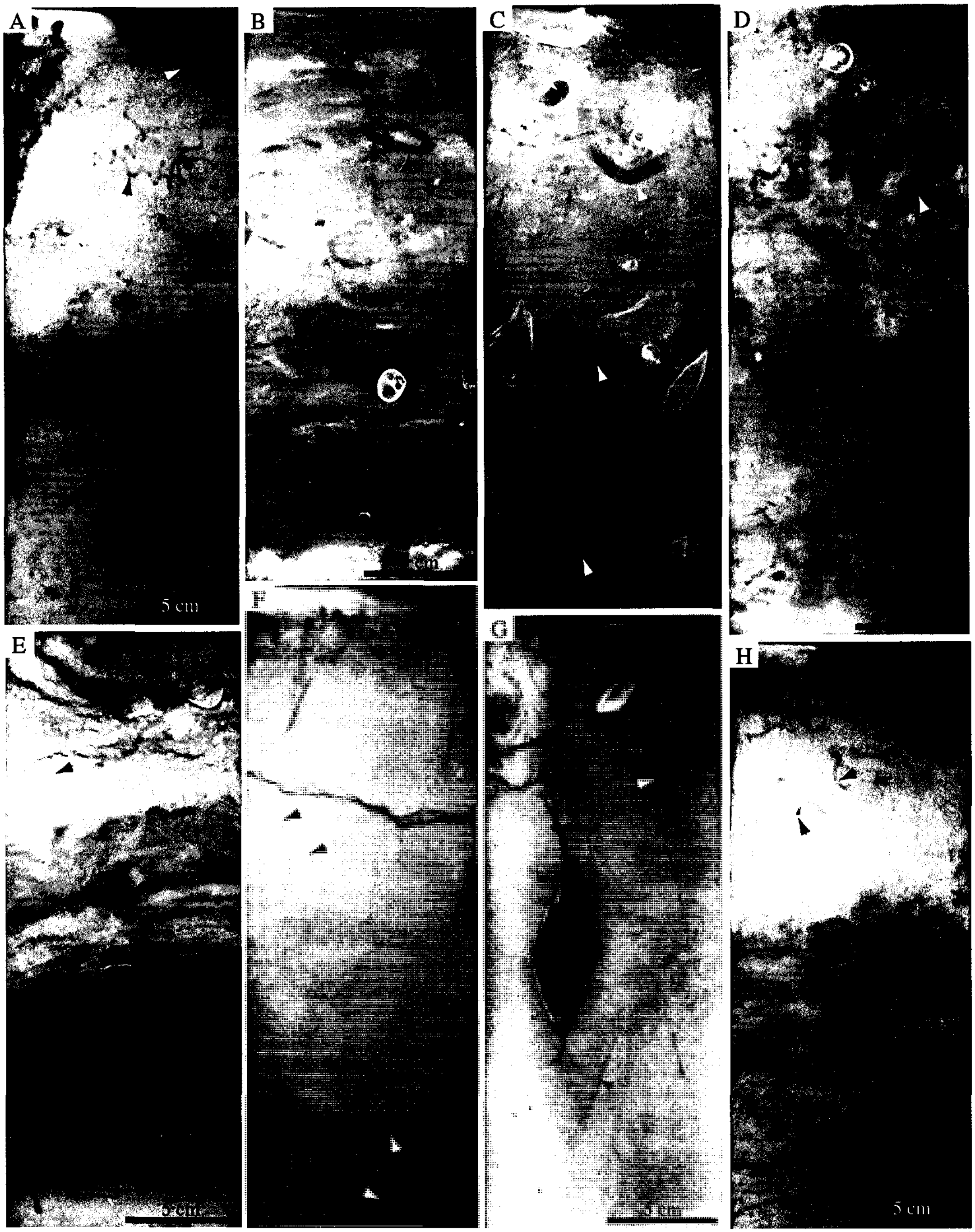


Figure 3.15- X-rays of sediments taken from the lower-central estuary. A) Heavily bioturbated sediments with thoroughly reworked clayey silt layer (dark layer middle of X-ray). Large burrow near the top constructed by *Nereis* (white arrow). Horizontally oriented helical burrows of *S. kowalevskii* resembling *Helicodromites* (black arrow). B) Heavily bioturbated mid-lagoon sediments with segments of complex burrow networks constructed by *Nereis* (black arrows). C) Mid-lagoon sediments rich in shell debris consisting of gastropods, *M. balthica*, and *M. arenaria*. Large burrows constructed by *Nereis* (white arrows). Black arrow points to in-situ *P. gouldii*

(**Figure 3.15** cont.) sand tube. D) Complete bioturbation consisting primarily of vertical *Gyrolithes*- and horizontal *Helicodromites*-like burrows of *S. kowalevskii*. Notice the dense production of these burrows along single horizons (white arrow). E) Mid-lagoon sediments marked by vestigial sandy layers and abundant distinct burrows. Notice the *Gyrolithes*-like burrow of *S. kowalevskii* (black arrow). F) Vertical *Skolithos*-like burrows near the mid-lagoon margin (black arrows). Dark clasts near the base comprise rip-up clasts of salt marsh origin (white arrow). G) *M. arenaria* and *Capitella* burrows (white arrow) in sediments near the mid-lagoon margin. Notice the oxic halo surrounding the burrow of *M. arenaria* (black arrow). The white shell belongs to *M. balthica*. H) Completely reworked mid-lagoon deposits with *Palaeophycus*- and *Planolites*-like burrows (dark circles), as well as helical segments of burrows produced by *S. kowalevskii* (black arrows).

and occasionally *C. torquata* are common benthic invertebrates. The activity of these organisms obliterates primary sedimentary structures (Fig. 3.16). Muddy areas are thoroughly bioturbated by deposit-feeding polychaetes such as *Nereis* and *Capitella,* as well as by the interface-feeding bivalve *M. balthica* (Fig. 3.16A, F). Locally, bioturbation may be so high as to preclude the preservation of distinct burrow structures (Fig. 3.16A). *Nereis* constructs *Teichichnus*-like burrows (figs. 3.16F, 3.6) in addition to open burrow networks, portions of which resemble *Palaeophycus* and *Planolites*.

Locally, extremely coarse zones of the middle-central estuary exclude the activity of burrowers (Fig. 3.16G). Within sandy zones or zones of high coarse-silt content (Fig.3.3, BRT2) an increase in filter-feeding is observed due to dense populations of *M. arenaria* (Fig. 3.16B, C, D, E, and H), approaching 50 individuals per m^2, and *Capitella* (Fig. 3.16E, J). *M. arenaria* typically produces burrows analogous to *Skolithos* and *Siphonichnus,* or *fugichnia* (figs. 3.5, 3.16B).

Primarily exposed by bay-margin wave activity, the middle-central estuaries locally display firmground assemblages containing *Psilonichnus*-like burrows (Fig. 3.16E), akin to the suites of structures attributable to the *Glossifungites* Ichnofacies.

Low diversity and high numbers of individuals typify the middle-central estuary. Deposit-feeding polychaetes (*Nereis* and *Capitella*) and bivalves (*M. balthica*) exploit organic-rich muddy deposits. Filter-feeding bivalves (*M. arenaria*) mark zones of the middle-central estuary where the sand fraction of the sediments increases. Middle-central estuary sediments are typically thoroughly bioturbated by the activity of these organisms.

Upper-Central Estuary.– The upper-central estuarine sediments of the Kouchibouguacis and Kouchibouguac Rivers are dominated by medium and fine silt (Fig. 3.2, RT3-S1, RT3-S2; Fig. 3.3 KRT3-S1, KRT3-CH, KRT4-S1). TOCs are high within the fine-grained deposits of the upper-central estuary. Similarly, turbidity levels peak in the vicinity of the upper-central estuary of the Kouchibouguac River (Fig. 3.4C, KRT3, KRT4). The upper-

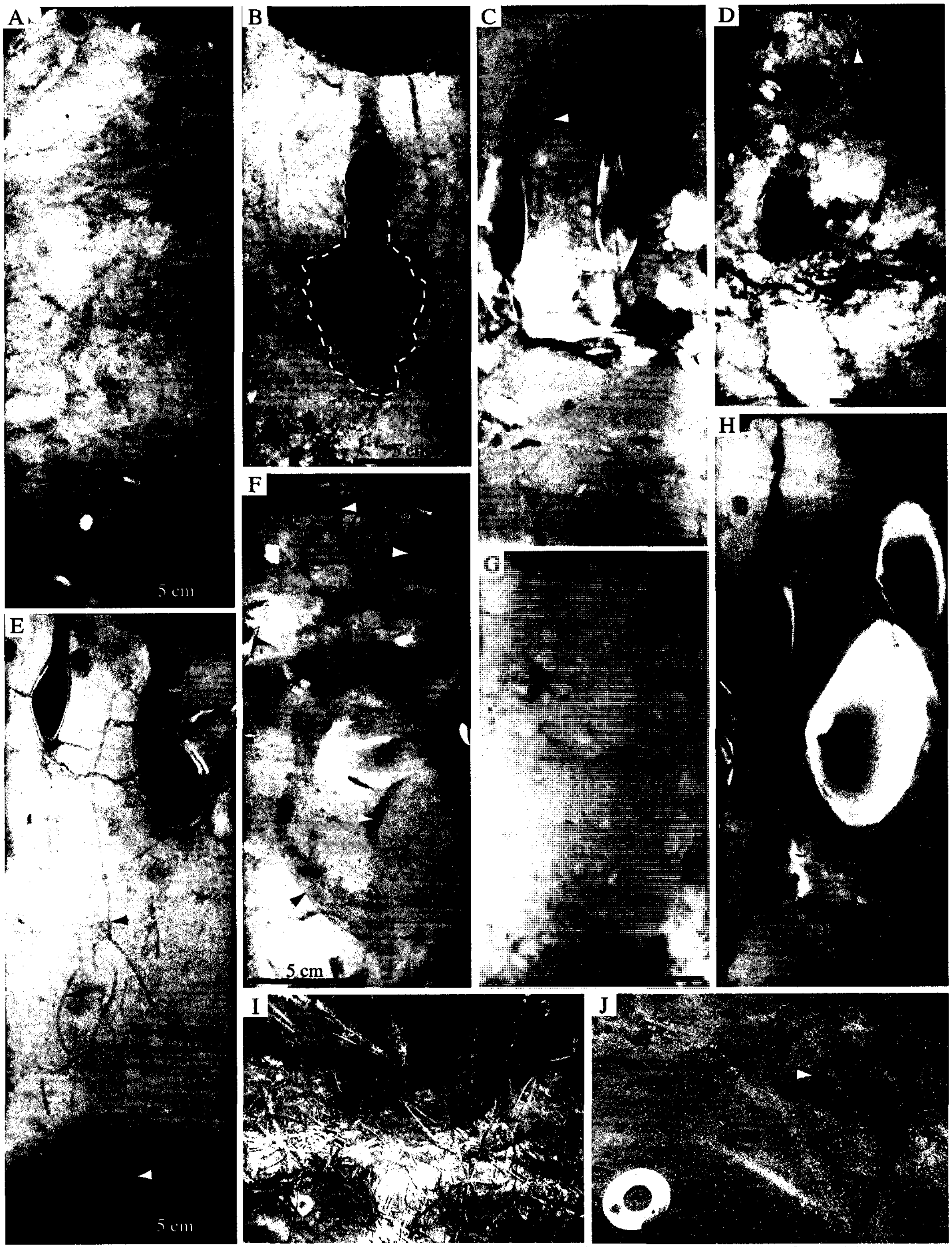


Figure 3.16- X-rays and photographs of the middle-central estuary. A) X-ray of muddy estuary margin deposits of station RT1-S1 displaying complete biogenic reworking with very few distinct burrows. B) X-ray of sandy silt and clay deposits of station RT2-S1 with *equilibrichnia*- or fugichnia-like bioturbation created from the upward movement of *M. arenaria* (white dotted outline). C) and D) X-rays of poorly sorted estuary margin sediments containing abundant granules and pebbles of local bedrock sandstone. Both X-rays contain abundant *M. arenaria*. Figure C

(**Figure 3.16** cont.) contains the vertical burrows of *Capitella* (white arrow). Notice the diminutive *Arenicolites*-like burrows of *Nereis* near the top of X-ray D (white arrow). E) X-ray of sandy estuary margin deposits of station RT1-S3. Notice the extremely dense populations of *M. arenaria* and *Capitella.* The *Capitella* burrows commonly branch toward the base (black arrows). White arrow outlines *Psilonichnus*-like burrows constructed in salt-marsh deposits. This surface contains attributes common to the *Glossifungites* Ichnofacies. F) X-ray of intense bioturbation in sandy silt and clay of station RT2-S2. Distinct burrow structures are produced by *Nereis* and include vertical *Skolithos*-like burrows (white arrows), as well as a *Teichichnus*-like burrow (black arrow). G) X-ray of sparsely bioturbated coarse sand deposits of station KRT1-S2. H) X-ray of dominantly very fine sand deposits of station BRT2. Extremely dense populations of M. arenaria mark the deposits. I) Dense *Z. marina* growth near the estuary margin of station RT1-S1. J) Dense populations of *M. arenaria* (black arrow) and *Capitella* (white arrow) at station RT1-S3 (see X-ray E of this figure).

central estuary, much like the middle-central estuary, is marked by intense colonization of *Z. marina.*

Bioturbation is intense in the upper-central estuary, destroying most primary physical sedimentary structures (Fig. 3.17). The diversity of benthic organisms is low. *M. balthica* is common within the muds of the upper-central estuary, where the bivalve produces *Siphonichnus-*, *Skolithos-*, and *equilibrichnia*-like burrows (Fig. 3.5). At the surface, interface feeding by *M. balthica* results in the production of *Lorenzinia*-like traces (Fig. 3.5). The siphons of *M. balthica,* one inhalent and one exhalent, commonly generate two vertical traces leading up to the sediment-water interface (Fig. 3.17A). *M. arenaria* is commonly associated with silty sand deposits in the upper-central estuary. In poorly sorted deposits, containing grain size distributions of sand, silt and mud, *M. arenaria* and *M. balthica* are both observed (Fig. 3.17C, D).

Nereis is a prolific producer of bioturbation within the upper-central estuary. In muddy silt deposits *Nereis* constructs open, branching burrow networks (Fig. 3.17A, B, C, E, and G). Within silty sand of the estuary margins, *Nereis* constructs more simple burrows akin to *Arenicolites* (Fig. 3.17L) and *Skolithos* (Fig. 3.17J), as well as variations on *Arenicolites* that contain multiple branches (Fig. 3.17K). *Nereis* constructs *Lorenzinia*-like feeding stars at the surface (Fig. 3.17I), which at depth are associated with simple burrow structures (Fig. 3.13B).

The brackish-water crab *Rithropanopeus harrisii* (Fig. 3.8) is present in the upper-central estuary. At the surface, burrows contain large apertures (Fig. 3.17H) that lead to *Psilonichnus*-like dwelling structures (Fig. 3.8). *R. harrisii* may also make use of terrigenous plant debris, under which they construct semi-permanent domiciles.

Channels of the upper-central estuary are fine-grained, with high TOC (Fig. 3.3, KRT3-CH). Shell debris is abundant, consisting of valves of *M. balthica* (Fig. 3.17F). Low diversity, but very high numbers of individuals, characterizes deposits of the upper-

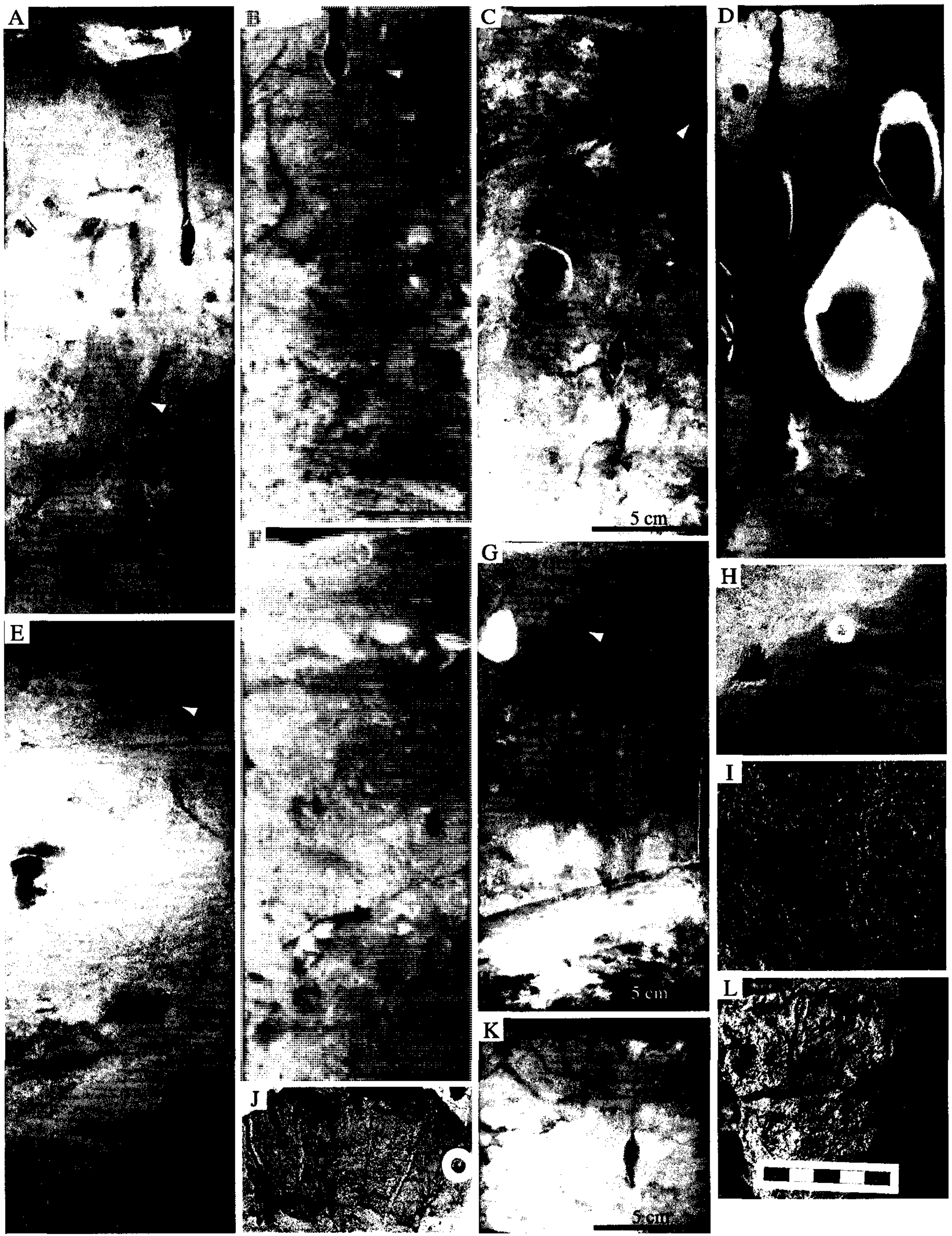


Figure 3.17- X-rays and photos of deposits from the upper-central estuary. A) and B) Heavily bioturbated clayey silt deposits of stations RT3-S1 and KRT3-S1 respectively. The large-diameter open burrows are produced by *Nereis*, comprising branched burrow networks (white arrows). *M. balthica* is very common in the muddy sediments in the upper-central estuary, producing burrows resembling *Skolithos* with their split siphon (black arrows). C) Heavily bioturbated sandy silt of station KRT4-S1. Increases in sand typically accompany bioturbation by *M. arenaria* (black arrow). *Nereis* produces simple open burrows in sandier sediments (white arrow). *Equilibrichnia*-

(**Figure 3.17** cont.) like behavior is observed in *M. balthica* burrows (grey arrows). D) Very fine sand at station BRT2, with dense populations of *M. arenaria*. The burrows of *Nereis* are evident at the base of the X-ray (black arrows). E) Sandy silt of station RT3-S2, in which some low-angle cross-stratified beds are preserved at depth (lower half of X-ray), enhanced by organic detritus from dead eelgrass. Branching burrow networks are produced by *Nereis* (white arrow). F) Silt at station KRT-CH taken from the channel of the upper-central estuary. Notice the abundant shell debris and laminated appearance that disappears with depth due to bioturbation. G) Poorly sorted sandy silt with granules at station KRT4-S2. Abundant terrigenous plant debris predominates in the lowermost portion of the X-ray. Horizontal and vertical burrows of *Nereis* are common (white arrow). H) Burrow aperatures of *R. harrisii* at station RT3-S2 (5/16 washer for scale). I) *Lorenzinia*-like feeding stars produced by *Nereis* as it deposit feeds along the margins of the upper-central estuary in the Kouchibouguac River. J) Vertical *Nereis* burrows produced in the upper-central estuary. K) Tightly-packed *Arenicolites*-like burrows of *Nereis*. Burrows are emplaced in poorly sorted deposits along the estuary margins from the upper-central estuary at station KRT3-S2. L) *Arenicolites*-like burrow produced by *Nereis* at station KRT3-S2.

central estuary. Particularly high levels of interface feeding are evidenced from both the high numbers of *M. balthica* and the surface-feeding stars of *Nereis*.

Inner Estuary.– The inner estuary of the Kouchibouguac and Kouchibouguacis Rivers is dominated by medium- and coarse-grained sand (Fig. 3.2; RT4-S1, RT5-S1, RT6-S1, RT7-S1; Fig. 3.3, KRT6-S1, KRT7-S1, KRT8). TOC is typically low in these deposits. Primary sedimentary structures are typically preserved in the upper estuary, consisting of planar to shallowly dipping tabular cross stratification (Fig. 3.18A, B, C, and D). With proximity to the oligohaline areas (<5 ppt salinity) the widgeon grass *Ruppia marina* begins to take over as the dominant underwater angiosperm. Terrestrial plant debris litters the surface and can also be observed in shallow cores (Fig. 3.18B).

Bioturbation in the low mesohaline areas of the inner estuary is restricted to the activities of *M. arenaria* and *Nereis* (Fig. 3.18E, F). Visual observations of population densities of the two benthic invertebrates suggest that numbers of individuals are generally lower than in the seaward parts of the estuary, however, locally population densities may be notably high (Fig. 3.18F). Species of *Nereis* produce thickly agglutinated and simple burrows that resemble *Skolithos*, and occasionally *Arenicolites* within the medium- and coarse-sand (Fig. 3.18A, B, C; black arrows).

In the oligohaline to fully fresh-water areas of the inner estuary, the estuarine species are replaced by a fresh-water biocoenose (Fig. 3.18D). Organisms include the caddisfly Trichoptera (Fig. 3.8), and tubificid oligochaetes (Fig. 3.7). Trichoptera are vagile omnivorous scavengers that protect themselves by encasing the length of their body within an agglutinated casing consisting of sand, gravel, and organic detritus. These casings are mobile domiciles from which the caddisfly may forage for food. Casings

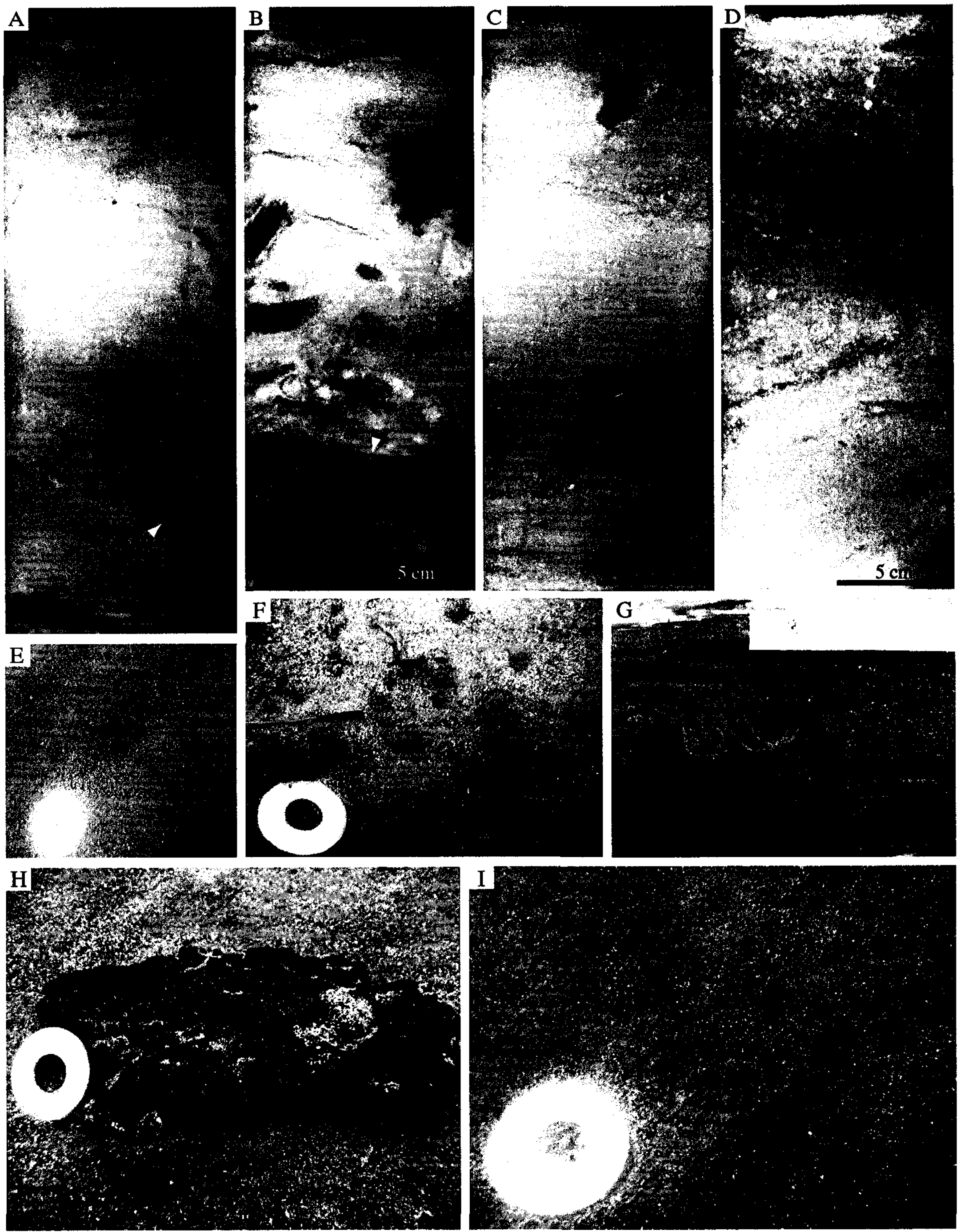


Figure 3.18 – X-rays and photos from the deposits of the inner estuary. A) and B) Low bioturbation within medium sand of station RT4-S1 and RT7-S1 respectively. Rare burrows produced by *Nereis* are observed (black arrows). Abundant terrigenous plant debris appears as dark clasts and mottled aggregations, commonly enhancing laminations (white arrows). C) Low bioturbation within medium sand of station RT5-S1. Black arrow points to a burrow most likely emplaced during high spring tides. D) Coarse-grained sand from the freshwater region of the Kouchibouguac River

(**Figure 3.18** cont.) (KRT7-S1). Bioturbation is absent. Low-angle cross stratification predominates. E) Siphon of *M. arenaria* in deposits marked by significant decreases in numbers of the bivalve due to low salinity levels in the vicinity of station RT4-S1 (5/16 washer for scale). F) Heavily agglutinated and dimunitive burrows of *Nereis* at station RT4-S1. G), H) and I) Sand tubes of tubificid oligochaetes at stations from the fully freshwater areas of the Kouchibouguac and Kouchibouguacis Rivers.

vary and the construction materials depend upon the species. Tubificid oligochaetes build agglutinated vertical burrows in locally high densities (Fig. 3.18I), and may attach these tubes underneath plant debris (Fig. 3.18G, H), wherein head-down 'conveyor-belt' feeding ensues (Tevesz et al., 1980). Organics are ingested at depths of 4 to 5 cm. The causative tubes resemble dimunitive unlined *Skolithos* (Fig. 3.7).

A low diversity of organisms characterizes the inner estuaries, wherein an abrupt shift from estuarine to freshwater species is observed. The salt-water prism periodically inundates the freshwater areas studied during high tides. As such, diversity is apparently low in the uppermost areas of the inner estuaries. Relatively simple burrows are produced, with locally dense populations.

Firmgrounds.– Subaqueous exposures of firmground were observed in a number of locales within the Kouchibouguac Lagoon (figs. 3.1D, 3.3). In most cases the firmgrounds occur at the margins of the lagoon tidal channels, where tidal scouring exposed cohesive lagoonal and salt-marsh deposits. A significant exposure occurs at a sharp bend in the Black River channel in the mid-lagoon, denoted with a red star on Figure 3.3. At this locale the channel is approximately 9 m deep and the outside of the channel bend contains a near vertical exposure of dewatered lagoon deposits. At the base of the channel, red colored, consolidated muddy and rooted sediments are exposed.

Grain-size and TOC analysis show that the firmground deposits exhibit grain-size distributions similar to that of modern lagoon sediments (i.e., composed predominantly of medium and fine silt). Samples taken from the firmground at the base of the channel display a very similar grain-size distribution to that of the modern salt-marsh deposits.

The firmgrounds are colonized by the bivalve *Petricola pholadiformis*, the diminutive polychaete *Polydora ligni*, and the crustacean *Homarus americanus*. *P. pholadiformis* constructs burrows preferentially within the firm lagoon deposits. The sharp-walled, nearly perfect cylindrical burrows, which expand toward the base and may reach 25 cm in length, are *Gastrochaenolites*-like (figs. 3.5, 3.19A, B). The burrows are produced at right angles to the surface of the firm substrate and appear as circular burrow apertures (Fig. 3.19D). Population densities of *P. pholadiformis* may be dense, as shown

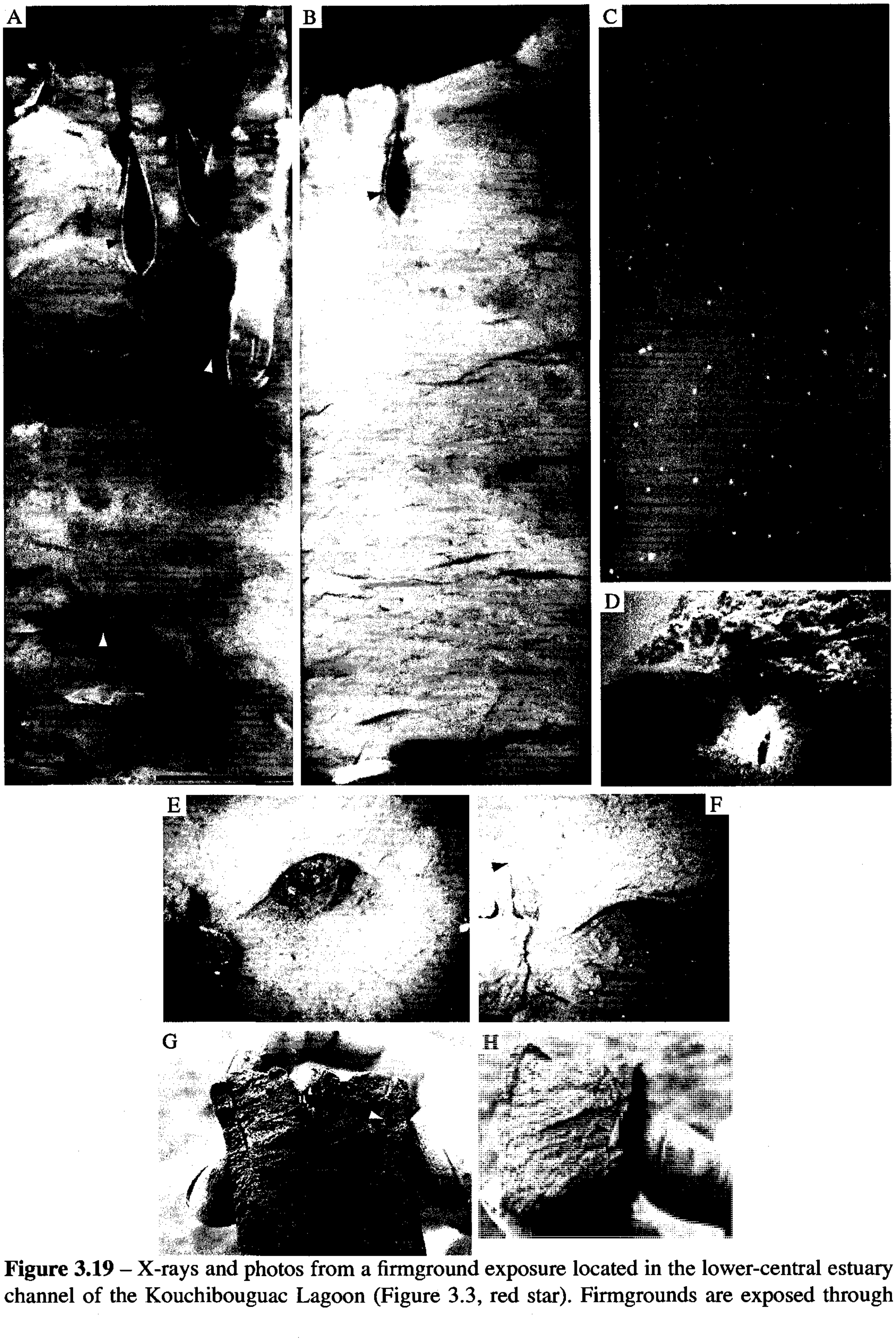


Figure 3.19 – X-rays and photos from a firmground exposure located in the lower-central estuary channel of the Kouchibouguac Lagoon (Figure 3.3, red star). Firmgrounds are exposed through

(**Figure 3.19** cont.) tidal scour. A) X-ray of palimpsest firmground consisting of lower-central estuary sandy silt (depth along vertical exposure ~ 3.4 m). *Gastrochaenolites*-like burrows of *P. pholadiformis* (black arrow) crosscut the background lagoonal assemblage including burrows of *Nereis* (white arrows). B) X-ray of firmground taken from ~ 6.1 m depth along the vertical exposure. *P. pholadiformis* densities are lower here (black arrow), and the palimpsest nature of the deposit is not as readily observed. C) X-ray of firmground taken from the base of the scour, where salt-marsh deposits are exposed. White spherules consist of concretionary maghemite forming around debris such as foraminifera. D) Photo of burrow aperatures of *P. pholadiformis* emplaced within the firmground exposure. E) and F) Photos of burrows produced by *H. americanus* within the firmground exposures. Most burrows are emplaced horizontally, but few are oriented vertically (black arrow), possible excavating pre-existing *P. pholadiformis* domiciles. G) Dimunitive *Diplocraterion habichi* produced by *P. ligni* within exposures of salt-marsh firmground at the base of the channel (white arrow). H) Dimunitive *Gastrochaenolites*-like burrow produced by *P. pholadiformis* within salt-marsh firmground exposed at the base of the scour (black arrow).

in Figure 3.19 A. Dimunitive specimens of *P. pholadiformis* produce burrows within exhumed salt marsh firmground (Fig. 3.19C) at the base of the channel (Fig. 3.19H). The burrows are significantly shorter in length and width than their counterparts in exposures of younger, less firm lagoon substrate. In cores, the mid-lagoon burrow assemblage is crosscut by firmground colonizers (Fig. 3.19A).

P. ligni constructs long and slender burrows (up to 6 cm in depth) within the salt-marsh deposits at the base of the channel. The burrows resemble *Diplocraterion habichi* (figs. 3.7, 3.19G). Visual observations of burrow densities within the base of the channels suggest they are low, with only a few burrows observed within a 25 cm^2 area.

Occurrences of *H. americanus* within the system were only noted from areas in close proximity to tidally exposed firmgrounds. The lobsters are found in makeshift domiciles within cracks and crevasses produced by dislodged and mounded blocks of exhumed dewatered and compacted lagoonal substrates. Here, they use the extremities of their limbs to excavate small, horizontally oriented 'caves'. Seemingly exploiting vacated *P. pholadiformis* burrows, small specimens of *Homarus* produce vertical burrows up to 40 cm in length, some of which branch or connect with larger, horizontally oriented burrows of other lobsters (figs. 3.8, 3.19E, F). The age and size-range of the lobsters present within the channels suggests that there are a great variety of burrow sizes produced. The lobster excavations resemble large *Thalassinoides*, and occasionally *Psilonichnus*, when emplaced vertically (Fig. 3.8).

Palimpsest lagoon firmground exposures in Kouchibouguac Lagoon consist of deposits marked by intense bioturbation common to modern lagoon deposits, crosscut by a low diversity of firmground colonizers, including *P. pholadiformis* and *H. americanus*. Firmground exposures of salt-marsh deposits are colonized by a low diversity of dimunitive benthic invertebrates in small numbers, consisting of *P. ligni* and *P. pholadiformis*. The salt-marsh deposits also contain concretionary spherules of maghemite (Fig. 3.19C, small white spheres), which form around debris such as tests of foraminifera.

Salt Marsh.– Two stations were set in salt-marsh deposits in the study area. One was placed in the salt marsh adjacent to the St. Louis Lagoon (Fig. 3.2, SM1), while the other was placed in salt-marsh deposits near the bay-head delta of the Kouchibouguacis River (Fig. 3.2, SM2). Whereas the marsh deposits are located in relatively distinct subenvironments, both locales show similar grain-size distributions, predominantly comprised of medium and fine silt, with abundant clay. However, the marsh deposits located near the bay-head delta (SM2) contain greater amounts of fine and very fine sand (Fig. 3.2). TOC levels are high in the marshes, ranging from 26.3 wt % near the lagoon, to 11.9 wt % near the bay-head delta (Fig. 3.2). The high level of organic materials in the salt marshes suggests that the deposits fall into the 'organogenic marsh' classification, being composed of >10% organic material (Allen, 2000). Salt marsh grasses heavily dominate both locales (Fig. 3.20C), consisting of *Salicornia europaea, S. laurentium, Limonium carolinianum*, *Solidago sempervirens*, and *Plantago oliganthus* (McCann, 1979).

Bioturbation in the salt marsh adjacent to the lagoon (SM1) appears to be predominant in the boundary between the salt marsh grasses and the sandy areas of the lagoon margins. Insects are the dominant burrowers here, including unidentified sweat bees (Halictidae). The sweat bees produce *Psilonichnus*-like burrows near margins of salt marsh grass populations (Fig. 3.20D, E, F). The causative J-shaped excavations may contain small branching offshoots in which eggs were observed (Fig. 3.20E). Other evidence of animal activity in the salt marshes next to the lagoon included the hoof prints of deer.

A core was extracted from a salt-marsh pool connected to the lagoon (Fig. 3.20C). Evidence of burrows was not observed at the surface. Intense algal matt colonization is easily discerned. Contrary to these observations, a bioturbate texture was evident in the core, showing horizontal bed boundaries from which *Skolithos*-like burrows extend down (Fig. 3.20A). A similar observation is made for the station set within marshes adjacent to the bay-head delta of the Kouchibouguacis River. Evidence for individual burrow structures are lacking, suggesting this may be bioturbate fabric produced by marsh grass colonization (Fig. 3.20B).

In summary, burrowing insects producing *Psilonichnus*-like burrows are present in salt-marsh deposits adjacent to the lagoon. Vertebrate tracks are also evident. Benthic invertebrates (possibly *Nereis* sp.) may burrow salt marsh pools near the lagoon. Evidence for benthic invertebrate burrows in salt-marsh deposits near the bay-head delta of the Kouchibouguacis River is absent.

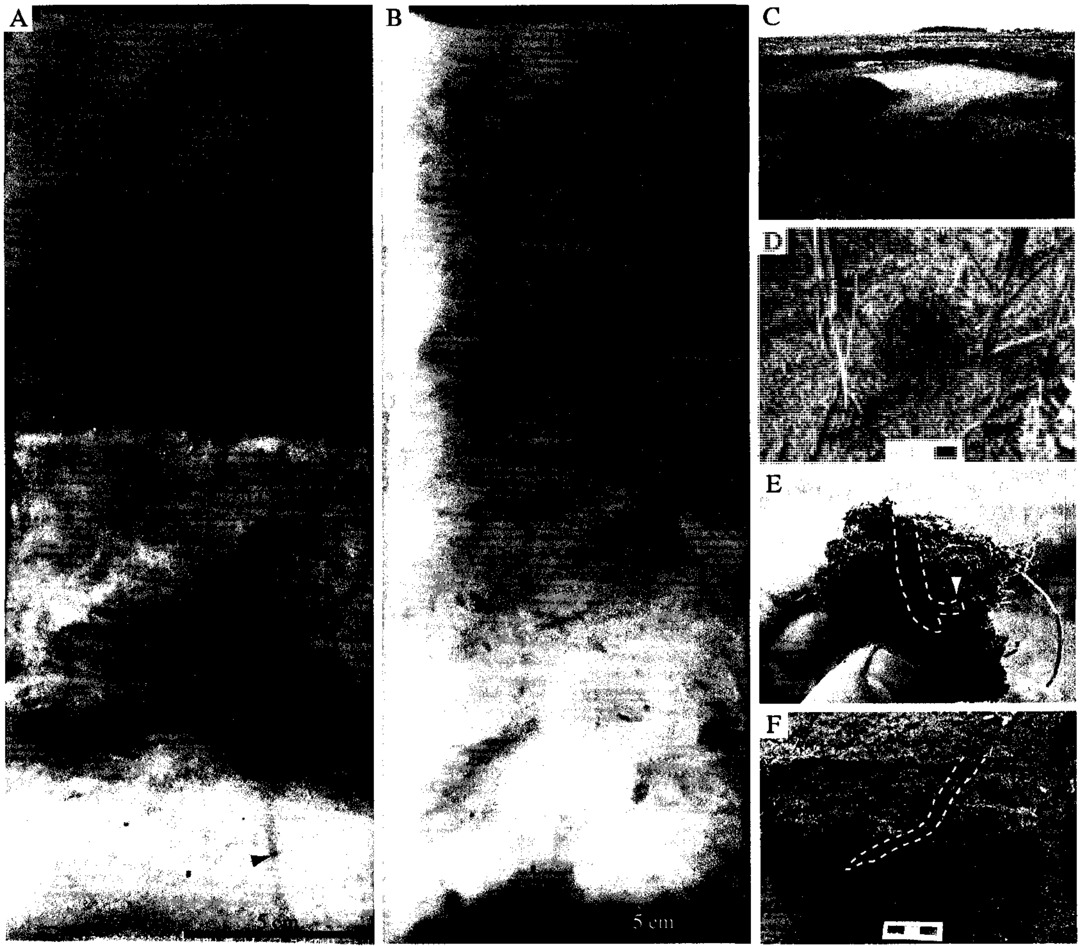


Figure 3.20 – X-rays and photos taken from salt marshes in the system. A) X-ray of salt-marsh deposits taken from station SM1 proximal to the St. Louis Lagoon margin. The lower half of the deposits may contain polychaete burrows (black arrow), however bioturbation may be dominated by roots. B) X-ray of salt-marsh deposits taken from the raised marshes on the bay-head delta region of the inner estuary of the Kouchibouguacis River (SM2). Deposits appear thoroughly bioturbated, most likely by roots. C) Photo of locale where the X-ray of A) was taken. D) Photo of an excavation of a burrow by a sweat bee near the margins of the salt marsh proximal to the lagoon (white arrow). E) and F) Photos of sweat bee burrows produced in the salt marsh. A distinct brood chamber can be seen in E) (white arrow).

Size-Diversity Index

Data collected to illustrate the response of benthic invertebrates to salinity stress reveal trends with respect to benthic organism diversity and diminution (size-diversity index) (figs. 3.21, 3.22). The size-diversity index recorded at each station represents the diversity of burrowers multiplied by the largest vermiform burrow therein. In terms of size-diversity index, trends within the St. Louis Lagoon and Kouchibouguacis River include: 1) high values within mid-lagoon locales; 2) decreasing values in proximity to tidal and riverine channels; 3) decreasing values in proximity to back-barrier shorelines; and 4) decreasing and low values up-estuary, with a sharp decrease in the size-diversity index in the vicinity of the fluvial-marine transition. Nearly identical trends are evident in the Kouchibouguac Lagoon and Kouchibouguac River (Fig. 3.22). However, the size-diversity index values are lower within the Kouchibouguac River compared to those obtained from the Kouchibouguacis River

INTERPRETATION AND DISCUSSION

Physical Parameters and the Distribution of Infauna

Sediment Texture.– Of the physical parameters studied, sediment texture poses one of the strongest controls on the distribution of infauna. Sediment texture gives a general indication of local physical parameters that influence the associated infauna. These physical parameters, and the resultant sediment texture, constrain the types of feeding behaviors and ultimately the morphology of locally produced burrows. While many of the benthic invertebrates in the system are 'facies-crossing' opportunistic animals exhibiting colonization within a range of sediment types from multiple subenvironments (Ekdale, 1985), some infauna construct burrows that are restricted to specific substrates (e.g., *S. kowalevskii* within mid-lagoon sandy silt and clay). Moreover, organisms that inhabit a variety of substrates commonly construct burrows exhibiting morphologies more or less specific to certain sediment types. For example, the opportunistic polychaete *Nereis* will produce *Polykladichnus*-like burrows within the sandflats (Fig. 3.13), while producing branching burrow networks resembling *Palaeophycus* and *Planolites* (Fig. 3.6), as well as *Teichichnus*-like structures (see also Seilacher, 1957; Schäfer, 1972) within sandy silt and clay of the system (Fig. 3.16F). In general, sediment texture not only plays a role in controlling the distribution of infauna, it also constrains burrow types produced by the organisms that inhabit multiple sediment types. Trends linking sediment texture and

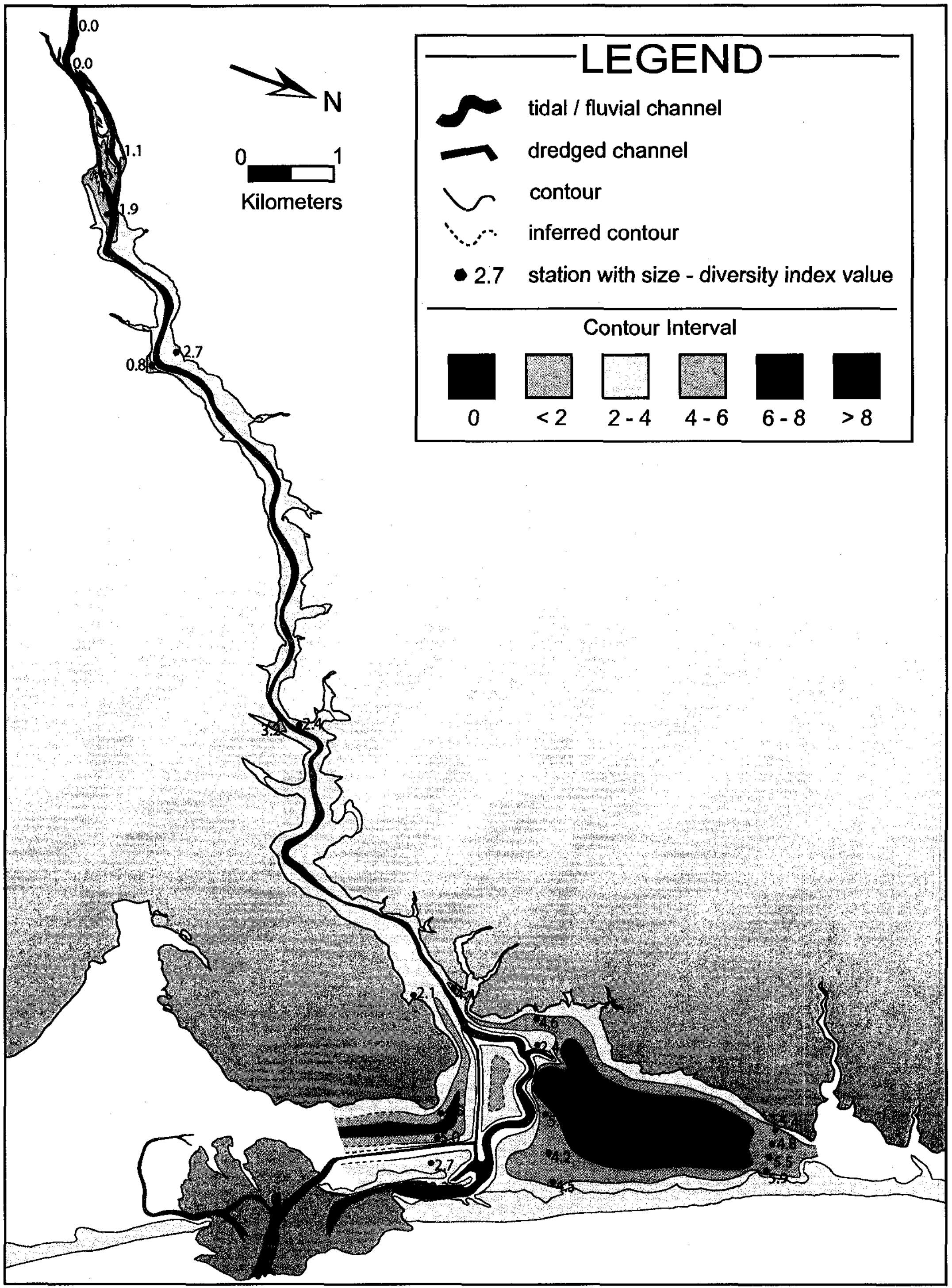


Figure 3.21- Contour map produced from measurements of diversity of infauna and size of largest vermiform burrow observed (size-diversity index) for the Kouchibouguacis River and St. Louis Lagoon. Size-diversity index values are largest within the mid-lagoon locale (lower-central estuary). Values decrease in proximity to the shoreline and channels within the lower-central

(**Figure 3.21** cont.) estuary. Values are consistent along the length of the estuary funnel with minor local variations. An abrupt decrease in the size-diversity index occurs at the boundary between the upper-central and inner estuary, where salinity is lowered and fluctuates most significantly.

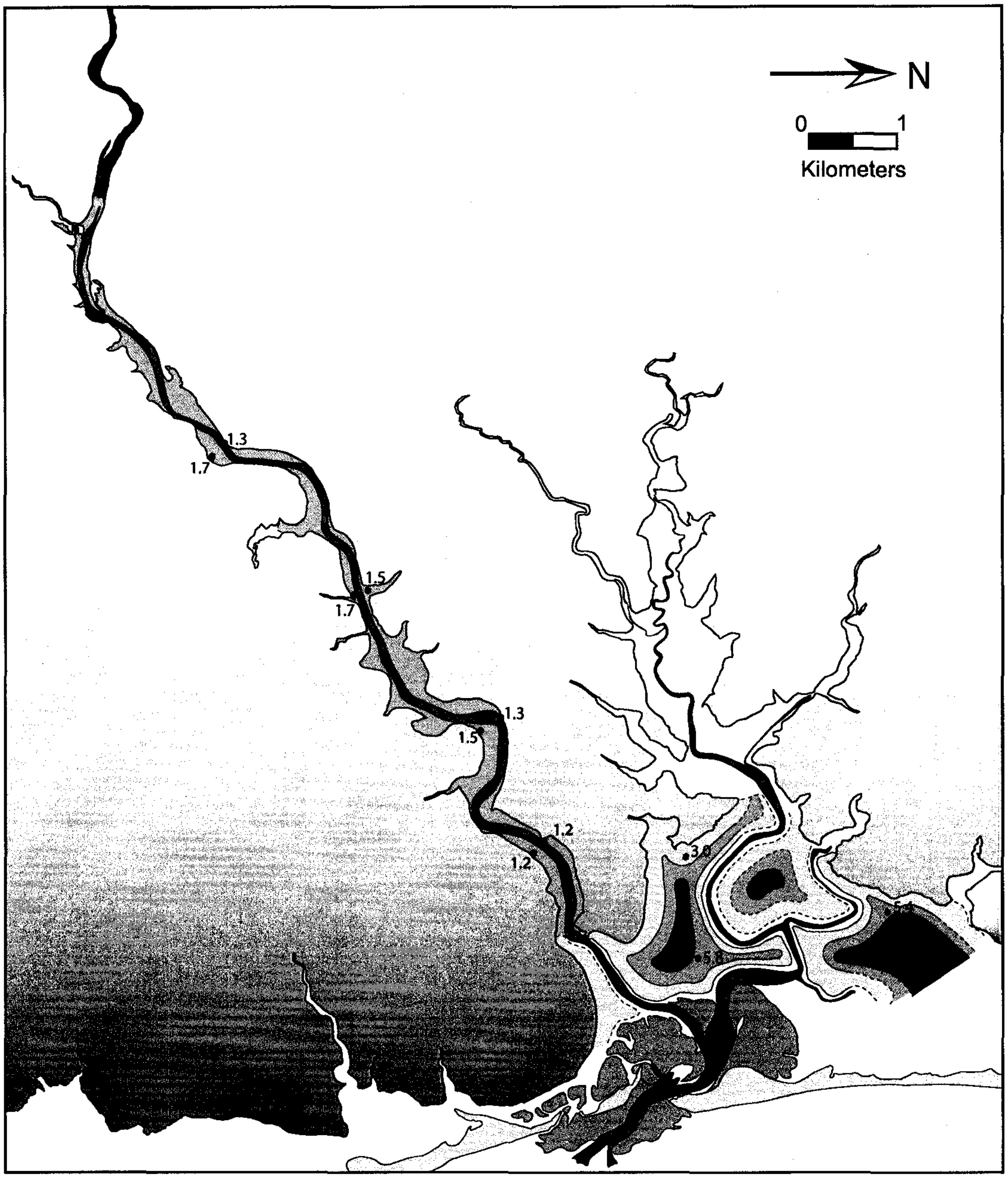


Figure 3.22- Contour map produced from measurements of diversity of infuana and size of largest vermiform burrow observed (size-diversity index) for the Kouchibouguac River and Lagoon. Much like the Kouchibouguacis River and St. Louis Lagoon, size-diversity index values are highest within the mid-lagoon locales of the lower-central estuary, with values decreasing in proximity to shorelines and channels therein. An abrupt decrease in values is observed at the mouth of the estuary funnel (boundary between the lower- and middle- central estuary). Another abrupt decrease is interpreted at the tidal-fluvial transition up-estuary in the vicinity of the border

(Figure 3.22 cont.) between the upper-central and inner estuary. Lower values along the estuary funnel in the Kouchibouguac River, when compared to the Kouchibouguacis River to the South, are interpreted as a result of eutrophication along the estuary due to anthropogenic influence (see text for discussion). See Figure 3.21 for legend.

bioturbation are thus discernable.

Substrate consistency (firm versus soft sediments) has proven to be a strong control on the distribution of infauna (Ekdale, 1985; Frey and Pemberton, 1985; Gingras et al. 1999). Substrate texture (grain size and composition) has been purported to have little direct impact on tracemakers, however, obvious associations between tracemakers and grain-size classes arises from their "mutual responses to hydrography" (Frey and Pemberton, 1985). In modern environments, trends in grain size and tracemaker distributions demonstrate that a relationship exists. Namely, certain organisms preferentially colonize sediments of a specific grain size, thereby imparting organism-specific bioturbate fabric. However, this relationship may be indirect and not causal, being more closely related to other local hydrodynamic and chemical physical parameters, as mentioned above. In Buzzards Bay, Massachusetts, Sanders (1958) observed a dominance of deposit-feeding fauna in mud, whereas in sandy sediments of Long Island Sound Sanders (1956) observed a dominance of filter feeders. From these studies, it is suggested that the distribution of deposit feeders is related to the organic material associated with clays in mud (sediment composition and grain size), whereas the distribution of filter feeders in sandy sediments is likely dependent on the local, hydrodynamic conditions.

Gingras et al. (1999), in modern sediments of Willapa Bay, Washington, reported that many benthic invertebrates have a strong preference for muddy or sandy substrates. Much like that observed in Kouchibouguac, there is significant overlap in this preference (e.g., *Nereis* and capitellid polychaetes). In Willapa Bay, a number of organisms construct burrows preferentially within the muddy end of the spectrum, including *Corophium*, *Saccoglossus*, and terebellid polychaetes. Conversely, *Paraonis fulgens*, lugworms (such as *Arenicola*), and species of thallassinid shrimp display clear preference for sandy substrates. The infauna produce distinctive traces preferentially within the two sediment endmembers (mud versus sand), leaving ichnological characteristics that are specific to subenvironments which are characterized, in part, by sediment texture.

In the Mugu Lagoon, California, Warme (1971) found a strong correlation with some benthic invertebrates and the texture of bottom sediments. High numbers of suspension feeding organisms were found within clean sands of the system, whereas abundant deposit-feeding organisms inhabited muddier areas. However, exceptions to this rule were observed. Some suspension feeders were found to be abundant in mud, with some deposit feeders abundant in sand. This is similar to the case in Kouchibouguac, where abundant head-down deposit-feeding polychaetes, such as *C. torquata* and *Capitella*, are found inhabiting subenvironments with sandy substrates (*C. torquata* almost exclusively). However, the occurrence of suspension feeding in muddy sediments is not clearly observed at Kouchibouguac.

Sand is the dominant grain size in the seaward portion of the Kouchibouguac system (i.e., barrier bar complex and associated subenvironments such as the sandflats). Of the bivalves that occur in the system, two varieties are restricted to these sands. The relatively mobile *E. directus* and *M. mercenaria* preferentially produce *equilibrichnia*- and *Siphonichnus*-like burrows within the shifting sand. While the hydraulic currents in this environment must provide ample suspended materials for a filter-feeding routine, they also pose a restriction to less mobile organisms that cannot keep pace with an occasionally rapidly shifting sediment-water interface. Within areas of the system dominated by sand or silty sand, such as the margins of the lagoon and estuary, the occurrence of *M. arenaria* is much more common. Moreover, dense occurrences of *M. arenaria* are restricted to areas characterized by these sediment types (Fig. 3.16E, J). The predatory polychaetes *Nepthys* and *Glycera* were also most commonly observed in the sands of the barrier bar complex. Both polychaetes have the means for effective and fast locomotion in the sandy sediments. The correlation between predators and higher-energy environments, characterized by mean grain sizes greater than fine sand, has been observed in other coastlines (Carriker, 1967).

Sand is also the dominant grain size in the inner estuary (bay-head delta area) in both the Kouchibouguacis and Kouchibouguac Rivers. In areas of the bay-head delta where brackish water persists, *M. arenaria* and *Nereis* produce vertical burrows. The burrows of *Nereis* are commonly deep and well agglutinated, resembling *Skolithos*. Areas of the bay-head delta dominated by fresh-water contain abundant tubificid oligochaetes, which were observed in dense populations producing diminutive *Skolithos*-like burrows in sand (Fig. 3.18I). The oligochaetes are head-down deposit feeders. While the causative tubes are small and weakly agglutinated, dense populations of up to 100,000 m^{-2} have been observed in other studies (Tevesz et al., 1980), suggesting that the potential for the oligochaetes to bioturbate the sediments is significant. Bay-head delta deposits in Permian strata of New Mexico contain ichnofossils dominated by *Skolithos* (Mack et al., 2003), possibly attributable to the work of oligochaetes.

The sands of the flood-tidal delta contain organisms restricted to this subenvironment, as well as more cosmopolitan organisms that produce burrow structures specific to this subenvironment. The lugworm, *A. marina,* is an example of the former, which produces *Arenicolites*-like burrows within the quiescent areas that are distal from the tidal channels. An example of the latter is the maldanid polychaete *C. torquata*, which forms *Skolithos*-like agglutinated sand tubes found within a wide range of sandy subenvironments in the system. In contrast, *C. torquata* produces thickly agglutinated burrows with ring-like annulations resembling *Skolithos annulatus* (Fig. 3.11I) within the energetic areas of the flood-tidal delta.

Areas of the system dominated by sand have these common ichnological and sedimentological characteristics: 1) cryptic bioturbation produced through the activities of mobile predatory polychaetes; 2) more robustly agglutinated *Skolithos*-like burrows in areas characterized by high hydraulic energy; 3) high numbers of burrows with vertical morphologies; 4) increases in suspension feeding deduced from the presence of filter-feeding bivalves such as *M. arenaria* and *M. mercenaria*; 5) increased likelihood of the production of *fugichnia*- or *equilibrichnia*-like bioturbation than in fine-grained deposits (Fig. 3.16B); 6) decreases in the size-diversity index (within the lagoon proper) as observed from figures 3.21 and 3.22; and 7) lower levels of biogenic reworking resulting in preservation of primary sedimentary structures in areas characterized by high hydraulic energies. Due to the freshwater influence and the resulting dilution of salinity, only points 3), and 4) pertain to the inner estuary sands.

Some of the common ichnological characteristics drawn from observations of sandy areas in the system can be explained by the ecological parameters that affect tracemakers. Sand is more mobile and therefore limits the colonization of more sessile organisms that cannot respond to sedimentation stresses, or results in the permanent domiciles built by these organisms being reinforced (Fig. 3.11I).

Aerially, silt and clay represent a large portion of the system (figs. 3.2, 3.3). Ethologically, these deposits are dominated by deposit-feeding organisms, resulting in bioturbate textures associated with this behavior. Some of the infauna displaying deposit-feeding behaviors specifically populate subenvironments characterized by mud. This is the case for the mid-lagoon, where *S. kowalevskii* produces very distinct *Gyrolithes*- and *Helicodromites*-like burrows. In addition, the large, open burrow networks produced by *C. lacteus* were sporadically observed in the fine-grained deposits of the mid-lagoon. As mentioned earlier, *Nereis* produces burrows with branching and / or horizontal segments preferentially within deposits having a high fraction of fine-grained material. Another burrower common to fine-grained deposits is the bivalve *M. balthica*. The highest population densities were typically observed in sediments in which silt and clay were the highest constituents. These areas most commonly occurred in the mid-lagoon, middle-central estuary, and upper-central estuary (more sporadically within the Kouchibouguac River due to a more sand-rich middle-central estuary). Since *M. balthica* is dominantly an interface feeder, abundant *Lorenzinia*-like feeding traces are produced within fine-grained areas of the system (Fig. 3.5).

Deposit feeding in areas dominated by fine-grained sediments convects large amounts of excavated material to the sediment-water interface, where it may be subject to transport and redeposition in other subenvironments. In estuaries, areas of low energy can contain bottom sediments consisting of 30 to 50 % fecal pellets (Carriker, 1967). In the muddy channel deposits in Kouchibouguac, fecal pellets represent the main sand-size fraction. This results in production of mud-dominated sedimentary structures composed of fecal pellets (Fig. 3.10F, G, J). At Kouchibouguac, the majority of the fecal pellets are derived from the activities of dense populations of *Capitella*. Fecal pellets of the polychaete are known to accumulate as biogenic layering (Elders, 1975).

Areas of the system dominated by silt and clay share the following ichnological and sedimentological characteristics: 1) deposit feeding is ethologically dominant (including interface feeding); 2) a high proportion of burrows contain segments that are oriented horizontally or obliquely to the sediment-water interface; 3) within the lagoon proper a high size-diversity index is observed (figs. 3.21, 3.22); 4) a very high degree of biogenic reworking of the sediment results in obliteration of primary sedimentary structures; and, 5) high numbers of unyielding fecal pellets and castings are available for transport and redeposition.

Common ichnological characteristics that can be drawn from observations of silt- and clay-rich areas in the system are explained by the ecological parameters affecting the tracemakers. Mud contains abundant food that can be accessed through deposit feeding. However, organisms that exhibit such behavior in muddy deposits must maintain an open connection with the sediment-water interface. This restricts the activities of benthic invertebrates that typically do not construct permanently open burrows (e.g., sediment swimming of *Nephtys*). Also, fine-grained sedimentation commonly accompanies turbid conditions in which filter feeding may be hampered (Buatois and Lopez Angriman, 1992; MacEachern et al., 2005). The highest levels of turbidity in the northern Kouchibouguac River were observed in the upper-central estuary areas (Fig. 3.4, KRT3, KRT4), coincident with relatively low numbers of suspension-feeding *M. arenaria*, even in sandy upper-central estuary deposits (Fig. 3.3, KRT3-S2, KRT4-S2).

Given that the two estuaries and their associated lagoons studied exhibit a general tripartite sediment division of sand-mud-sand, the ichnological characteristics outlined previously have considerable implications for the suites of bioturbation expected in a low energy, microtidal barrier island / embayment system. These ichnological characteristics are, to some extent, complicated by two factors, 1) the deviation from the tripartite sand-mud-sand division within the middle-central estuaries (see estuary funnel of figs. 3.2 and 3.3), and, more importantly, 2) the effect of reduced and fluctuating salinity on benthic infauna in areas of the estuary. Both factors are discussed below.

The significant amount of coarse-grained material in the middle-central estuary of the Kouchibouguac River compared to the Kouchibouguacis River is attributed to the nature of the green sandstone outcrops from which the coarse materials are derived (Krank, 1967, 1972a), and also to elevation contrasts. The Kouchibouguac River flows over land at elevations ranging from 15 to 30 m above sea level, whereas the southerly Kouchibouguacis River flows over lower lying terrain 0 to15 m above sea level (Beach, 1988). Outcrops of Pennsylvanian standstone are present on both Rivers. The Carboniferous bedrock comprises coarse-grained materials that are friable and particularly susceptible to erosion. These deposits impose a sediment-texture limitation to the colonization of certain infauna (such as *M. balthica*), and promotes the colonization of others (such as *M. arenaria*).

As mentioned above, it is well established that substrate cohesiveness is a strong control on the distribution of infauna (Ekdale, 1985; Frey and Pemberton, 1985; Gingras et al. 1999). Examples from the modern have shown that marginal-marine firmground biocoenoses are dominated by permanent, open domiciles (Frey and Pemberton, 1985; Pemberton and Frey, 1985; MacEachern et al., 1992; Gingras et al., 2000; 2001). In Kouchibouguac, inhabitants of exposed firm lagoon and salt-marsh deposits construct permanent domiciles from which they filter feed or scavenge. Firmgrounds result in part from exhumation due to erosional currents. These currents also deliver food in suspension and as detritus available for the firmground colonizers.

A depauperate assemblage of burrowers colonizes firmground substrates, producing burrows akin to those observed in ancient examples of the *Glossifungites* Ichnofacies. The two dominant burrowers are the bivalve *P. pholadiformis* (Fig. 3.5), and the diminutive polychaete *P. ligni* (Fig. 3.7). Both invertebrates produce biogenic structures in firmground (also woodgrounds and hardgrounds) deposits (Gingras et al., 1999), producing *Gastrochaenolites*-like burrows and *Diplocraterion*-like burrows respectively. The lobster *H. americanus* has been observed to produce large burrows within lagoon or estuary deposits of this study (figs. 3.8, 3.19E, F), however, they are not as common compared to numbers of *P. pholadiformis* and *P. ligni*. The European lobster *Homarus vulgaris* produces burrows; some with Y-shaped branches in the shoreface of Swedish waters (Dybern, 1973), and *H. americanus* is known to inhabit estuaries of the North American coastline during the summer months (Watson et al., 1999). Large *Thalassinoides* burrows dubbed 'subway tunnels' have been recognized from the Upper Cretaceous shoreface deposits of the Western Canadian Sedimentary Basin (Pemberton et al., 1984). Due to fossil specimens closely associated with the burrows, the authors suggest that the most likely candidate is that of the planurid lobster *Linuparus canadensis*. In a rare occurrence, numerous fossil lobsters *Mecochirus* were found within their *Thalassinoides* burrow systems in Lower Cretaceous deposits of Portugal (Carvalho et al., 2007).

Total Organic Carbon.– High TOC contents are closely linked to the presence of fine-grained sediments (figs. 3.2, 3.3). This relationship has also been observed in other studies (Carriker, 1967). High TOC occurs in the mid-lagoon (Fig. 3.3, T4-S2), muddy channels (Fig. 3.3, LCH1, KRT3-CH), upper-central estuary (Fig. 3.3, KRT3-S1, KRT4-S1; Fig. 3.2, RT3-S1), and in salt-marsh deposits (Fig. 3.2, SM1). With the exception of the salt-marsh deposits, very high rates of bioturbation are exhibited in cores taken from these subenvironments. This is due to exploitation of the organic-rich sediments by deposit-feeding, vagile infauna.

The eelgrass *Z. marina* is most dense in areas characterized by fine-grained substrates, and it is especially abundant in the mid-lagoon areas. Eelgrass is an effective baffler of wave-oscillation within the lagoon, trapping fine-grained material along with organic detritus (Boothroyd et al., 1985). The eelgrass thereby contributes potential food to the benthic invertebrates. Carriker (1967) suggests that the portions of an estuary most densely populated by invertebrates are those areas colonized by eelgrasses. Likewise, in eelgrass-dominated lagoons of Kouchibouguac Bay, the size-diversity index (figs. 3.21, 3.22) is highest.

Sandy sediments within the system typically have very low TOC (figs. 3.2, 3.3), and typically contain higher numbers of filter-feeding infauna that derive nutrients from the water column rather than from the sediments they inhabit. This is attributed to the local hydrodynamics, rather than the TOC content of the sediments (Sanders, 1958). Sediments containing low TOC contents are not devoid of deposit feeders and dense populations of head-down deposit-feeding polychaetes (*C. torquata* and *Capitella*) inhabit many of the sandy subenvironments in the system. The densest populations of these two polychaetes, based on visual estimates, were noted from the sandflats, where TOC are typically greater than 1 percent (Fig. 3.2, T3-S5), whereas the lowest populations were found in areas of the flood-tidal delta where TOC fell below 1 percent (Fig. 3.3, FTD1, FTD3).

Salinity and Diminution.– It is well established that salinity is a strong limiting factor in the distribution of organisms in modern brackish water systems (Carriker, 1967). In ancient deposits, trends in the distribution and diminution of ichnofossils in response to interpreted salinity stress have been recognized from marginal-marine deposits ranging from the Precambrian to the Cenozoic (Buatois et al., 2005).

In Kouchibouguac Bay, the measured salinity levels within the lagoon (lower-central estuary) were polyhaline and close to normal marine salinity, averaging 26.1 ppt. Measured salinity levels were fairly stable within the lagoon, fluctuating over a range of only 6.8 ppt. On the lagoon side of the barrier bar, visual observations of population densities reveal that much higher numbers of infaunal organisms are present compared to the sandy upper shoreface on the opposite side of the barrier. This is related to sedimentation stresses associated with wave activity rather than salinity (Carriker, 1967). In the lagoons, trends in the distribution of infauna are primarily related not to salinity, but to sediment texture and consistency, TOC content, hydraulic conditions, and other physico-chemical parameters. Consequently, trends revealed from figures 3.21 and 3.22, especially within the lagoon, represent animal diversity trends associated with these environmental parameters. For example, the sporadic distribution of infauna in the flood-tidal delta areas can be related to eposidic deposition and / or high deposition rates, as opposed to salinity fluctuations (Buatois et al., 2005). High diversity and large burrow size in the mid-lagoon area are related to abundant food resources associated with fine-grained sedimentation and quiescent conditions.

In the estuarine areas of the study area (Kouchibouguac River, Kouchibouguacis River, and Black River), salinity exerts a strong control on both the diversity and size of benthic invertebrates. A rapid drop in the diversity of organisms is observed from the lagoon to the inner estuary. The middle-central estuary is commonly bioturbated by *M. arenaria*, *M. balthica*, *Nereis*, sporadically by *P. gouldii* and *Capitella,* and infrequently by *C. torquata*. This diversity drops to only three burrowers by the upper-central estuary, where only *M. arenaria*, *M. balthica*, and *Nereis* are observed (the truly estuarine crustacean *R. harrissi* is found within the middle- and upper-central estuary of the Kouchibouguacis River as a recently introduced species). In the vicinity of the bay-head delta of the inner estuaries, only *M. arenaria* and *Nereis* are capable of withstanding the highly reduced and fluctuating salinities.

On average, the size of vermiform organisms decreases from the lagoon to the inner estuary. In the St. Louis Lagoon and Kouchibouguacis River, the average diameter of nereid polychaetes and their burrows is 0.54 mm and 0.41 mm, respectively. Whereas, the average diameter of nereid polychaetes is 0.50 mm in Kouchibouguac Lagoon and 0.41 mm in the Kouchibouguac River. Gingras et al. (1999) observed the same trend in diminution of vermiform organisms in Willapa Bay in an up-estuary direction.

Decreases in the size-diversity index in the estuary areas are abrupt (figs. 3.21, 3.22). One such sharp decrease in the size-diversity index is associated with the fluvial-marine transition, where salinity drops to low mesohaline and high oligohaline levels. Low ambient salinity levels pose osmoregulation stresses on infaunal organisms, and moreover, it is in these zones that salinity fluctuates markedly.

Trends in diminution of organisms with increasing salinity stress is relayed directly into the rock record, namely in the size of ichnofossils. Numerous ancient marginal-marine strata contain ichnofossils that display diminution and decreases in diversity with increased salinity stress. For example, Hubbard et al. (2004) analyzed Cretaceous Bluesky Formation strata from the Western Canadian Sedimentary Basin, wherein lower-, middle- (central), and upper-estuarine facies were scrutinized. Both the diversity and the size of the ichnofossils decrease along the length of the estuary, from the barrier inlet facies to the freshwater influence in the bay-head delta deposits. The authors attributed this trend as the signature of salinity stress on the ichnological assemblage. Other studies linking trends in diminution with salinity stress include those undertaken in the Cretaceous Viking (MacEachern and Pemberton, 1994) and McMurray Formations (Wightman and Pemberton, 1997).

Ichnological Model for Microtidal Estuary Deposits

From the ichnological characteristics described in detail in the previous sections, an ichnological model is put forth to summarize these data to simplify observations made from the Kouchibouguac system. The ichnological summary will outline characteristics observed within the tripartite distribution of morphological components common to the wave-dominated estuary model of Dalrymple et al. (1992). Describing ichnological observations in terms of the tripartite sediment division not only reinforces the relationship between sediment textures and distribution of infauna and their burrows, it also: 1) delineates salinity stresses endured by infaunal organisms through the comparison of the two sand-dominated areas of the system (i.e., the outer and inner estuary deposits), the landward of which endures significantly lowered and fluctuating salinities; 2) elaborates a well-established sedimentological framework describing wave-dominated barrier island / embayment systems by adding ichnological criteria; and, 3) summarizes observations in a manner that may be more easily applied to the rock record, where delineation of numerous subenvironments may be difficult due to data limitations.

Outer Estuary.– Herein, the outer estuary refers to the sand-rich barrier island and associated facies. The outer estuary comprises the portion of the extreme upper shoreface (Fig. 3.9), the flood-tidal delta (Fig. 3.11), the back-barrier sandflats (washover fans) and barrier beaches (Fig. 3.12), and the sandy tidal channels proximal to the tidal inlet (Fig. 3.1). In terms of sedimentation and erosion, these sandy areas are by far the most active parts of the system. In the shoreface, wave activity hampers colonization by certain infauna, whereas in the back-barrier areas, tidal currents are responsible for sedimentation stresses. Currents in these areas sweep organic material from the surface that otherwise would be available to deposit- or interface-feeding fauna (Hubbard et al., 2004). Therefore, a predominance of filter-feeding bivalves and predatory polychaetes is observed in areas experiencing the strongest currents (i.e., sandy tidal channels), resulting in *fugichnia*-, *Skolithos*-, and *Siphonichnus*-like bioturbation. Head-down deposit feeding is also common in the outer estuary. Commonly, the vertically oriented burrows display strongly agglutinated walls (e.g., *C. torquata*). Other polychaetes, such as *Nereis*, produce burrows akin to those typically observed in ancient environments characterized by shifting sands, such as *Arenicolites* and *Polykladichnus*. In terms of ichnology, the outer estuary is characterized by: 1) common suspension feeding; 2) common 'conveyor belt' deposit feeding; 3) mostly vertical burrows; 4) strongly agglutinated burrows locally; 5) common cryptic bioturbation produced through the activities of vagile predatory polychaetes; 6) *equilibrichnia*-like bioturbation produced through the activities of vagile suspension feeding bivalves; 7) construction of burrows analogous to *Skolithos* (and *S. annulatus*), *Siphonichnus*, *Arenicolites*, and *Polykladichnus*; and 8) less commonly, burrows analogous to *Psilonichnus*, *Planolites*, and *Palaeophycus* (typically produced by facies-crossing infauna such as *Nereis*).

Central Estuary.– Herein, the central estuary refers to the dominantly fine-grained, low-energy portion of the system. The subenvironments mentioned are typically dominated by silt and clay, but exceptions to this are observed where tidal channels connected to the rivers deliver coarse material, typically accompanied by high fractions of fine-grained sediments, to the lagoon. Coarse sediments are restricted aerially, and commonly correspond to areas of the middle- and upper-central estuary where outcrops of bedrock occur. These coarse deposits may be over-represented because of sampling bias close to the river edge. The central estuary deposits are further subcategorized into lower, middle, and upper to assess distinctions in both sediment texture and bioturbation (especially with decreasing salinity in the latter). The lower-central estuary consists of the mid-lagoon deposits (figs. 3.14, 3.15) as well as muddy channel deposits located in mid-lagoon locales (Fig. 3.10). The middle- and upper-central estuary comprise the majority of the estuary funnel (figs. 3.16, 3.17). In addition, muddy channel deposits were observed in these locales as well (Fig. 3.10F).

With the exception of bay-margin sediments, deposits of the lower-central estuary are composed mostly of fine-grained sediments, with the exception of the landward beaches that rim the lagoon. The fine-grained sediments, together with overall quiescent conditions, are amenable to deposit-feeding infauna. Vermiform organisms and the bivalve *M. balthica* are the predominant deposit feeders in the mid-lagoon and the muddy channels. High diversity and large vermiform organism size characterize these locales. The activity of deposit-feeding infauna results in a bioturbate fabric wherein primary sedimentary structures are rarely preserved. Distinct burrows and their ichnological expression are difficult to interpret here. However, *S. kowalevskii* is restricted to the lower-central estuary and constructs distinct *Gyrolithes*- and *Helicodromites*-like burrows. The predominance of deposit feeders (including interface feeding) in the lower-central estuary results in a wide variety of burrows that include classic morphologies oriented vertically, horizontally, and obliquely to the sediment-water interface, many of which resemble *Skolithos*, *Palaeophycus*, and *Planolites*. Ichnologically, the lower-central estuary is characterized by: 1) common deposit feeding; 2) burrows with morphologies ranging from vertical to horizontal, or a combination thereof; 3) near complete destruction of primary sedimentary structures resulting from a high density of infauna; 4) distinct burrows occurring along singular horizons resembling *Gyrolithes* and *Helicodromites*; 5) high size-diversity index values, most notably within the mid-lagoon (lower-central estuary); 6) construction of burrows analogous to *Skolithos*, *Palaeophycus*, and *Planolites*; and, 7) less commonly, burrows resembling *Thalassinoides* and *Siphonichnus*.

Due to local outcrops of Pennsylvanian bedrock, the middle-central estuary deposits are sedimentologically variable in the Kouchibouguac system. The margins of the middle-central estuary are sporadically lined with a variety of sizes of coarse-grained material derived from these outcrops. This is most notable along the margins of the northern Kouchibouguac River (Fig. 3.3). The range and sporadic distribution of sediment textures dictate, in part, the distribution of benthic organisms in the middle-central estuary. Where sediments consist of a high fraction of coarse-grained material, bioturbation may represent mixtures of filter-feeding and deposit-feeding and / or interface-feeding infauna. Particularly high fractions of coarse-grained material may even preclude colonization by benthic organisms. Sediment textures in the middle-central estuary may dictate burrow types produced by facies-crossing infauna such as the polychaete *Nereis*. For example, *Nereis* preferentially produces simple burrows including *Arenicolites*-like burrows within deposits with significant coarse-grained fractions. In general, coarser sediment textures correlate with an increase in filter feeding, noted from the presence of the bivalve *M. arenaria*. Conversely, fine-grained sediments contain only deposit and / or interface-feeding organisms, such as the bivalve *M. balthica* and the polychaetes *Nereis* and *Capitella*. Ichnologically, the middle-central estuary is characterized by: 1) margins lined sporadically by coarse-grained sediments in which an increase in filter feeding is observed; 2) dominantly muddy deposits with high densities of infauna dominated by deposit-feeding and interface-feeding types; 3) high degrees of biogenic reworking of sediments, especially within muddy areas; 4) sporadic areas of coarse-grained materials with sparse to absent bioturbation; 5) decreases in size-diversity index values due to lowered and more strongly fluctuating salinity levels; 6) in poorly sorted sediments with high factions of coarse materials construction of burrows analogous to *Skolithos*, *Arenicolites*, and *Siphonichnus*; and, 7) locally *Teichichnus*- and *equilibrichnia*-like bioturbation.

The sediments of the upper-central estuary are dominantly fine-grained, although poorly sorted sandy / pebbly sediments occur sporadically. The highest measured turbidity levels from the Kouchibouguac River were taken from the upper-central estuary (Fig. 3.4C, KRT3, KRT4). In addition, high TOC levels are measured from fine-grained deposits in the vicinity of the upper-central estuary (Fig. 3.3, KRT3-S1). Measured salinity is significantly lower, with oligohaline levels (< 5 ppt) observed during the course of study. This results in a sharp decrease in diversity of burrowing organisms, with only the bivalve *M. balthica*, and *M. arenaria*, and the polychaete *Nereis* persisting. However high numbers of individuals that occur here result in a high degree of biogenic reworking of the sediment (Fig. 3.17). The channels observed in the upper-central estuary are fine-grained (Fig. 3.3, KRT3-CH), also showing a high degree of biogenic reworking as well (Fig. 3.17F). Due to the dominantly fine-grained nature of the upper-central estuary, low numbers of the filter-feeding bivalve *M. arenaria* were observed. *M. balthica* and *Nereis* both dominated the biota, producing abundant evidence for interface feeding in the form of *Lorenzia*-like feeding stars (Fig. 3.17I). This feeding behavior in *Nereis* seems to result in the production of burrows resembling *Skolithos*, *Arenicolites*, and branching burrow networks with multiple apertures to the surface, most of which resemble *Palaeophycus*. In the southerly Kouchibouguacis River, the estuarine crab *R. harrisii* produces *Psilonichnus*-like burrows in the upper-central estuary (Fig. 3.17H). Ichnologically, the upper-central estuary is characterized by: 1) common deposit feeding, especially in the form of interface feeding; 2) thorough biogenic reworking of sediments; 3) muddy channel deposits with high degrees of biogenic reworking; 4) a decrease in filter feeding due to the dominantly fine-grained nature of the deposits; 5) a decrease in size-diversity index values due to lowered and more strongly fluctuating salinity levels, however, very high numbers of individuals persist; 6) common construction of burrows resembling *Skolithos*, *Arenicolites*, *Siphonichnus*, *Lorenzinia*, and general open burrow networks resembling *Palaeophycus*; and, 7) less common *Psilonichnus*-like burrows produced from crustaceans.

Inner Estuary.– The sediments of the inner estuary are dominantly sandy, and correspond to the bay-head delta where sands are derived from fluvial processes. Terrigenous plant debris is abundant in the inner estuary. Due to the low energy of the rivers, the bay-head delta deposits persist to long distances up-estuary, where salinity drops considerably. Lowered and strongly fluctuating salinity coupled with the sandy nature of the sediment, results in a sharp decrease in the diversity of burrowing organisms. Only the bivalve *M. arenaria* and the polychaete *Nereis* construct burrows in the inner estuary. Population densities of *M. arenaria* are very low (Fig. 3.18E), whereas locally population densities of *Nereis* may achieve substantial levels (Fig. 3.18F). In areas of the inner estuary where freshwater was encountered, tubificid oligochaetes predominate (Fig. 3.18G, H, I), producing diminutive, agglutinated sand tubes resembling *Skolithos*. Sediments commonly exhibit low levels of biogenic reworking which enables them to retain primary sedimentary structures (Fig. 3.18). The low levels of biogenic activity here is attributable to low (and sporadically high) population densities. Burrows produced in the inner estuary commonly resemble *Skolithos* and *Siphonichnus* (where *M. arenaria* endure). Ichnologically, the inner estuary is characterized by: 1) dominantly vertical burrows attributable to a very low diversity of infauna; 2) low levels of biogenic reworking; 3) burrows constructed by freshwater species in the uppermost extremes; 4) an increase in filter feeding (*M. arenaria*), compared to the upper-central estuary, due to dominantly sandy sediments; 5) very low size-diversity index values; 6) construction of burrows resembling *Skolithos* and *Siphonichnus* are most common.

Firmgrounds and Salt Marshes.– Firmgrounds exhibit suites of traces akin to those found in the *Glossifungites* Ichnofacies. Sporadically, central estuary margins contain firmgrounds consisting of salt-marsh deposits with burrows resembling *Psilonichnus*. Exposure of firmgrounds along the central estuary margins is attributed to storm wave activity. Palimpsest firmgrounds also occur mid-lagoon in the central estuary, along the margins of tidal channels. Exposures consist of cohesive lagoonal and salt-marsh deposits, burrowed by a depauperate assemblage of firmground infauna. Filter feeding is the dominant behavior. In addition, lobsters (*H. americanus*) produce temporary domiciles during the summer months within these cohesive sediments. Ichnologically, firmgrounds are characterized by: 1) a low diversity of dominantly filter-feeding infauna; 2) locally high burrow densities; 3) construction of burrows resembling *Gastrochaenolites* and dimunitive *Diplocraterion habichi*; and, 4) large *Thalassinoides*- and *Psilonichnus*-like burrows produced from lobsters.

Salt marshes fringing the lagoon and estuaries of Kouchibouguac Bay are small in comparison to marginal-marine systems with stronger tides. Salt marshes adjacent to the central estuary contain mostly burrows of insects, producing *Psilonichnus*-like burrows. Vertebrate trackways are common. Salt marsh pools adjacent to the lagoon, and in open connection with it, may contain *Skolithos*-like burrows, whereas salt marshes in the vicinity of the bay-head deltas in the inner estuary exhibit bioturbate textures that may be due to marsh grass roots.

CONCLUSION

Microtidal brackish-water deposits in Kouchibouguac Bay are complex, exhibiting a wide variety of subenvironments that contain characteristic bioturbate fabrics. Sediment texture and associated TOC level are a strong control on the distribution of infauna, and, consequently, on the distribution and type of bioturbation observed in the system. In areas where salinity is mostly stable and relatively close to that of marine levels (such as in the outer estuaries and lower central estuaries), the distribution of infauna is dominantly affected by these two parameters. In the upper central and the inner estuaries additional parameters including lowered and fluctuating salinities, in addition to sediment texture and TOC content, control the distribution and diversity of infauna. The size and diversity of benthic organisms are thus the highest within the lower-central estuary (mid-lagoon), and lowest in the inner estuary, closest to the freshwater influence.

The activity of infauna typically destroys all primary sedimentary structures in the system, with the exception of the outer and the inner estuary. In the outer estuary the barrier complex, most notably the tidal inlets and flood-tidal deltas, experience strong currents, attributable to waves and tides. The inner estuary near the bay-head deltas experiences riverine currents and freshwater influences. As a consequence, primary sedimentary structures are preserved in these two areas. In the outer estuary, hydrodynamics limit infauna colonization, whereas lack of bioturbation in the inner estuary is predominantly the result of reduced and fluctuating salinities.

A number of generalizations can be drawn from the observations outlined above: 1) the benthic invertebrates in the lagoons and estuaries comprise a low diversity of mostly marine faunas, however, locally very high densities of individuals populate some of the subenvironments in the system; 2) a relatively low diversity of incipient trace fossils are constructed by these infauna, including (in no specific order) *Arenicolites*, *Polykladichnus*, *Planolites*, *Palaeophycus*, *Thalassinoides*, *Skolithos*, *Teichichnus*, *Lorenzinia*, *Gyrolithes*, *Helicodromites*, *Diplocraterion*, *Siphonichnus*, *Gastrochaenolites*, *Aulichnities*, *Psilonichnus*, *equilibrichnia*, and cryptic bioturbation; 3) deposit feeding is the dominant behavior in the system, with an increase in filter feeding in those subenvironments characterized by substantial sand fractions; 4) the central estuary contains the highest vermiform size-diversity index values, and these values decrease up estuary because of lowered and fluctuating salinity levels; 5) within the central and outer estuaries, vermiform size-diversity index values are indirectly proportional to the amount of sand in the deposits; 6) size-diversity index values decrease abruptly in vicinity of the fluvial-marine transition in the inner estuaries, where salinity levels are extremely low; and, 7) primary sedimentary structures are best preserved at the landward and seaward extremes of the system, due to a paucity of burrowers and strong hydrodynamic conditions, respectively.

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CHAPTER 4 – CONCLUSIONS

In Kouchibouguac observations were taken from ten major wave-dominated estuarine subenvironments including dunes, barrier beaches, flood tidal deltas, tidal channels, sandflats / washover fans, lower-central estuary, middle-central estuary, upper-central estuary, and inner estuary (bay-head delta), from which geomorphology, sediment texture, and patterns in bioturbation were resolved. These subenvironments can be further subdivided into large-scale genetically related geological components due to textural similarity and patterns in bioturbation. The result is a tripartite division including the outer, central, and inner estuary, which conforms to the well-established wave-dominated estuary model (Dalrymple et al., 1992). These three morphological components are a result of the dominant hydrodynamic energies associated with deposition in these areas, and consequently, the geomorphologic entities are texturally distinct from one another. In the outer estuary marine influences are manifest in wave (primarily storm activity) and tidal hydrodynamics. Deposits consist dominantly of medium-grained sand of marine affinity, which contain tidal and wave-induced sedimentary structures indicative of these energy regimes. The central estuary is a relatively low energy, highly bioturbated zone affected by a mixture of marine- and fluvial-influences, resulting in deposition of fine-sand, silt, and clay. Within the central estuary, the estuary funnel (i.e., landward, narrow portion of the drowned valley) contains greater lithological and textural variation due to local sediment sources and seasonal dislocation of the turbidity maximum. The inner estuary is a seasonally active and spatially restricted zone due to the narrow confines of the drowned valley and overall low fluvial discharge. Deposits consist dominantly of medium-grained sand derived from fluvial processes and sources. Primary sedimentary structures exhibit a general lack of tidal influence; however, marine influence can be resolved through the distribution of invertebrates and their traces.

In addition to discrete sedimentological textural parameters within the tripartite zonation of estuarine facies, neoichnological trends act to support the recognition of these estuary divisions, whereby trends in biogenic sedimentary structures (i.e., diversity and type) are distinctive within each major zone of the estuary. Characteristic bioturbate texture is in part constrained by the dominant physical and chemical processes affecting each of the three zones, such as hydrodynamic energy, sediment texture, TOC content, and salinity gradients. These factors play a major role in the style of infaunal colonization. Where salinity gradients are relatively stable and close to that of normal marine salinities (i.e., outer estuary and lower central estuary, with salinity averaging 26 ppt), trends in bioturbation are controlled dominantly by hydrodynamics and the resultant sediment texture. Within the estuary funnel (i.e., middle- and upper-central estuary, and the inner estuary), in addition to sediment texture, lowered and fluctuating salinities become significant limiting factors on the distribution of infauna. The resultant patterns in bioturbation act as important indicators of salinity stress. Patterns resolved from the combination of diversity and size of vermiform burrowers (size-diversity index) reveal that all three limiting factors (sediment texture, TOC, and salinity variations) play a considerable role in the type and size of incipient traces produced in estuarine deposits. These patterns also reveal that diminution of brackish-water vermiform burrowers occurs most distinctly within the estuary funnel and longitudinally up-estuary to the fluvial-marine transition, where salinity is lowest and fluctuates the most. This has implications for the identification of facies and facies architecture through the recognition of salinity stress within ancient wave-dominated estuary deposits.

The combination of sedimentological and neoichnological fabrics yield important information regarding the potential physical stratigraphy and retrogradational sequences formed within transgressive wave-dominated systems. This study demonstrates the utility of combining neoichnological data with both sedimentological and geomorphological data in the description of marginal-marine systems. Furthermore, it reinforces aspects of the brackish-water (ichnological) model, and highlights its potential as an aide in the resolution of ancient estuarine equivalents.

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