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The Effect of Changes in Tidal Range on a Sublittoral Macrotidal Sequence, Bay of Fundy, Canada

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Abstract

Independent evidence of changes in sea level and tidal range in the Bay of Fundy during the last 9000 years is used to evaluate the lithologies in 17 cores from the sublittoral part of Chignecto Bay. The composite tidal sequence identified is complex because of changes from microtidal through mesotidal to macrotidal conditions associated with changing water depths. Despite the complex stratigraphy, lithology correlates well with the depositional environment on a bed-by-bed basis. We postulate that such variations in tidal range are important to the interpretation of "tidalite" deposits from the geologic record.

Introduction

Extensive and complex sequences of fine-grained sediments have been deposited under sublittoral (subtidal) conditions in Chignecto Bay, Bay of Fundy, Canada (Fig. 1). The sequence was unexpected given the "classic" depositional models developed for macrotidal estuaries dominated by a sandy, upward-fining littoral (intertidal) sequence and sublittoral deposits of cross-bedded coarse sand [1–6]. However, these models oversimplify the Holocene stratigraphy of Chignecto Bay and may reflect a general lack of data in previous studies of the sublittoral zone.

Numerous investigators [7–11] have provided evidence of considerable changes in tidal amplitude and, by inference, peak tidal flows in the Bay of Fundy during the last 15,000 years (Fig. 2). The 11.3-m spring tidal range of Chignecto Bay is a relatively modern feature that came into being circa 6000–4000 years B.P. It is predated by mesotidal conditions (8000–6000 years B.P.), by an earlier phase of macrotidal conditions (circa 9000 years B.P.) and, during deglaciation, by microtidal conditions. Thus as we now perceive it, the littoral zone is a modern phenomenon reflecting only the latter part of the evolution of the bay.

Hansen and Rattray [12] have shown changes in estuarine circulation and stratification as tidal influences change. Other investigators [13–15] have demonstrated the differences in sedimentation patterns that result from such changes. Detailed stratigraphy of the sublittoral sequence is, therefore, dependent on the variation in current speed and wave climate with respect to time [16].

In mesotidal estuaries dominated by fine-grained sediments, such as those in the North Sea described by Reineck [6], the sublittoral stratigraphic section is composed of channel sands and finer-grained channel wall deposits. Similar sediments from the Netherlands are not characterized by a fining-upward macrosequence, and instead abundant erosional surfaces with complex stratigraphies prevail [16,17].

Thus, it seems probable that the complex patterns of sublittoral deposits in Chignecto Bay reflect the changing patterns of estuarine circulation and the lack of coarse-grained sediment in the system. Our study of the Chignecto Bay sublittoral deposits was undertaken to: 1) evaluate the relationship of the lithology of dated horizons in the preserved sequence to changing sea-level and tidal range, and 2) develop a composite-type section of the Chignecto Bay tidal deposits for comparison with existing "tidalite" models.

Setting

Chignecto Bay forms the northernmost extension of the Bay of Fundy system (Fig. 1). It encompasses an area of 500 km^2

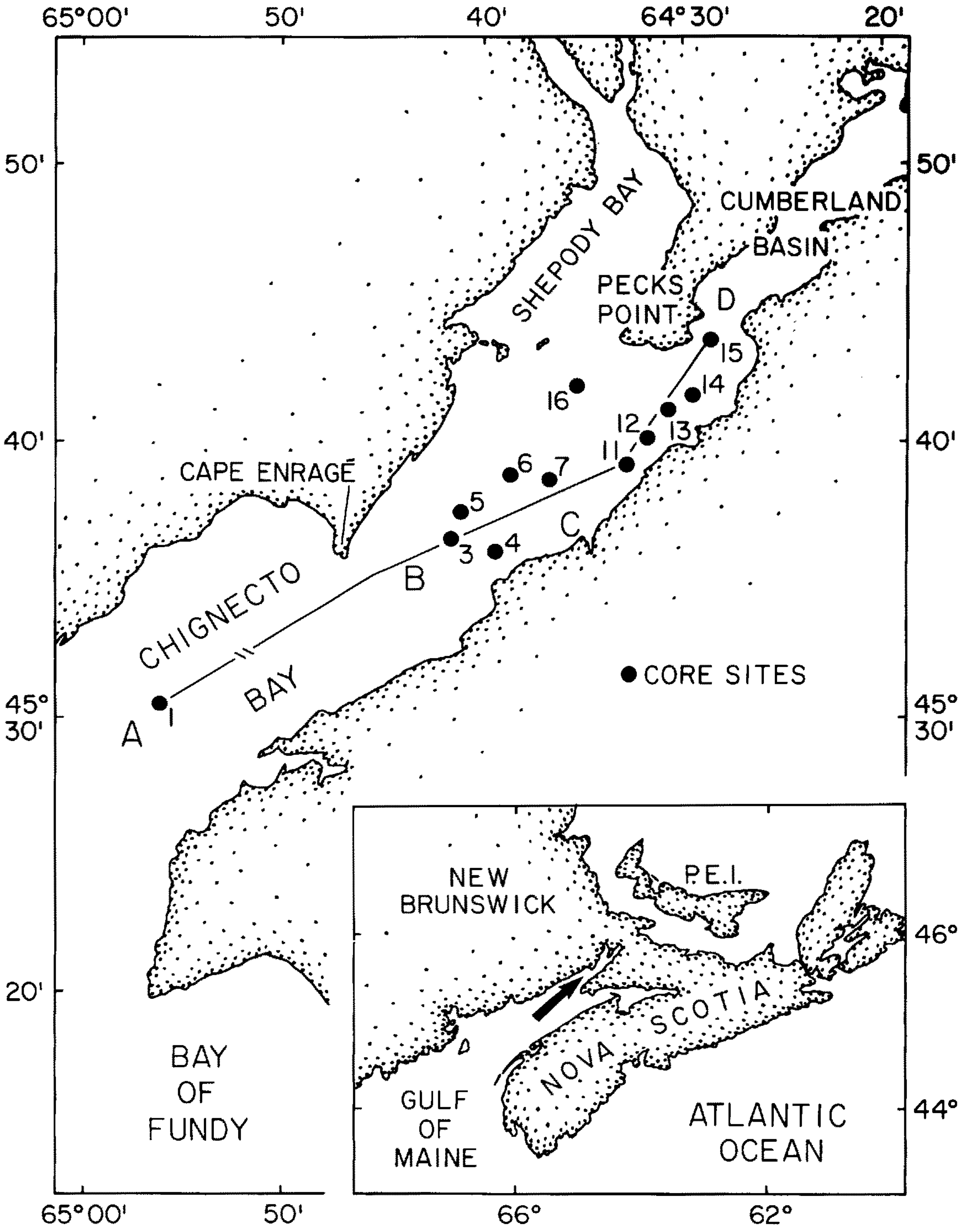

Figure 1. The location of Chignecto Bay, Bay of Fundy, indicating the locations of vibrocores used in this study and the position of the transect illustrated in Figure 3.

and is subject to a mean spring tidal range of 11.3 m. Peak nearbed (U_{30}) tidal flows vary between 100 and 125 cm/s. The water column is well mixed and has the characteristics of estuarine model type C described by Pritchard [18]. Flows show strong residual patterns that are flood-dominant along the eastern and western margins of the bay and ebb-dominant along the central axis [19]. The outer bay experiences waves with a peak significant wave height of 3 m (8 s period), which become attenuated to 1.5 m (8 s period) in the inner bay. Storm waves result in significant coastal erosion and the resuspension of bottom sediment [19]. The input of fresh water is limited (10 to 100 cfs) and, thus, the salinity of the estuary

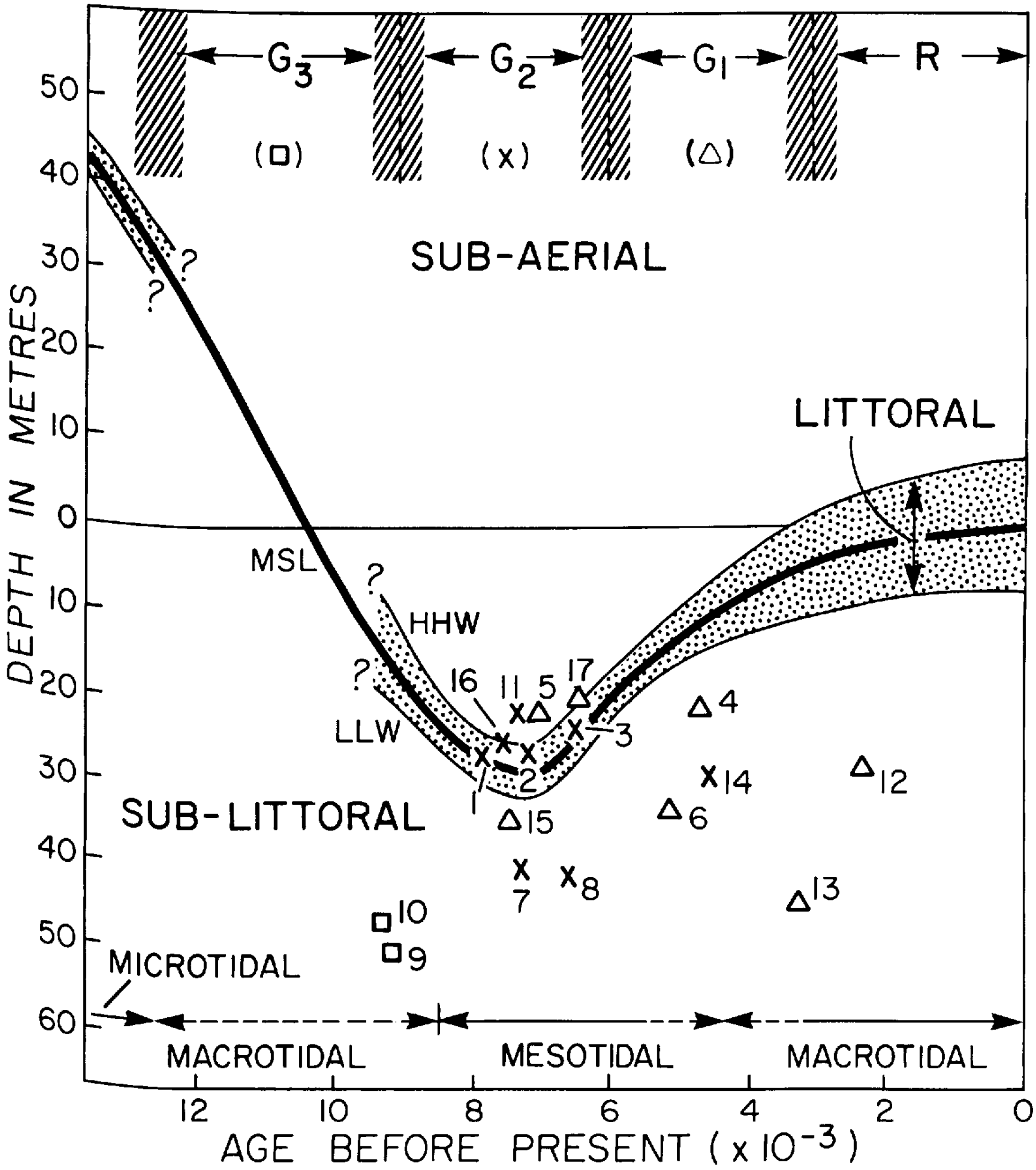

Figure 2. A proposed sea-level curve for the upper Bay of Fundy/Chignecto Bay region. The postulated tidal ranges for the period 9000 years B.P. to the present time are also shown based on independent studies reported in the text. The C14 datings of horizons within the vibrocores are shown in the depth/age position. It is on the basis of these data points that the environment of deposition (littoral or sublittoral) is interpreted. Squares refer to unit G3, crosses refer to unit G2, and triangles refer to unit G1.

fluctuates between narrow limits (30.to 31.5 ppt). The region is ice-infested during the winter months, during which time considerable mechanical abrasion of the intertidal zone takes place. Pan ice, which can cover the entire bay, transports material to the sublittoral zone by the process of ice rafting [20].

Chignecto Bay is surrounded by steep eroding cliffs up to 57 m high, which are composed of Paleozoic fluvio-deltaic sediments and volcanics overlain by a thin cover of Wisconsin–Late Wisconsin ablation till and glacio-fluvial sediments [21]. These cliffs, which are being eroded at rates between 0.4 and 1.0 m/yr, supply the majority of the clastic material to the bay [22]. A total annual volume of 1.03 × 10^6 m^3 is released by cliff erosion. The major part of this supply is composed of fine-grained particles.

Sea-level changes in the upper Bay of Fundy are well established (Fig. 2). The documented fluctuations are considered to be due to the isostatic effects of deglaciation [21,23]. Maximum submergence of the bay occurred immediately after local deglaciation, circa 13,500 years B.P. Highest high-water (HHW) at the time was 48-m higher than the present mean sea-level (MSL) [21]. Subsequently, MSL rapidly dropped 80 m to its lowest level, circa 7000 years B.P. (core 15, Fig. 3) and thereafter rose steadily at a rate of 15 cm/century to

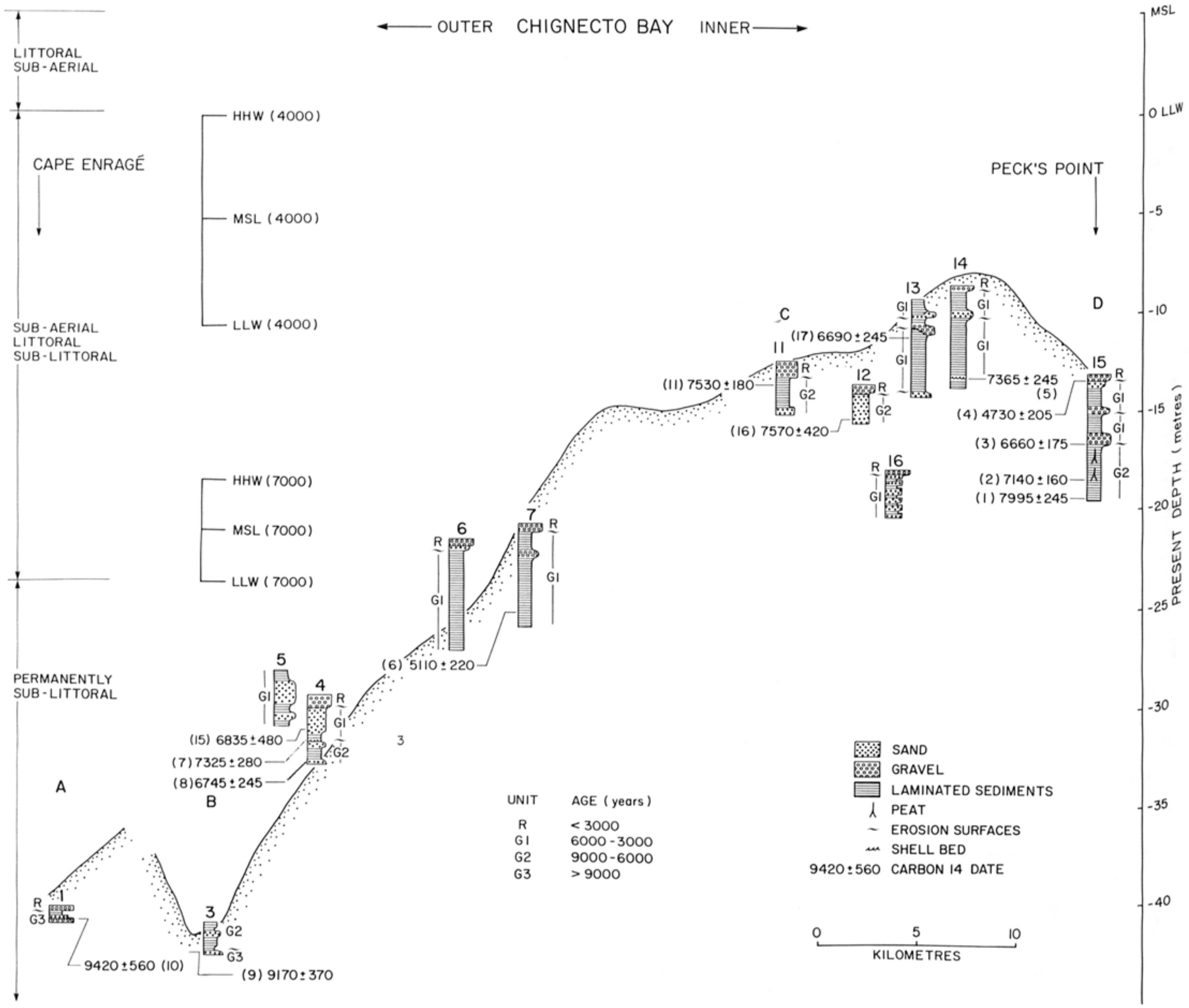

Figure 3. A bathymetric profile of Chignecto Bay along the line shown in Figure 1. The elevations of MSL at 4000 and 7000 years B.P. are also shown together with the positions of highest high-water (HHW) and lowest low-water (LLW) for the two dates. Superimposed on the profile are the simplified lithostratigraphic logs of 12 of the 17 vibrocores.

its present level [24,25]. It is during the period of rapid sea-level changes that the tidal regime has been shown to change based on numeric modelling [11]. Such modelling substantiates previous interpretations of tidal changes based on the stratigraphy from other parts of the bay [9].

The Data Base

A major survey was undertaken during 1978 to determine the sedimentary character of the Chignecto Bay system. The survey involved the collection of high-resolution seismic reflection profiles and side-scan sonograms (587 line km), air-gun seismic reflection profiles (230 line km), 12 gravity cores, 21 vibrocores, and 95 seabed grab samples [19]. Subsequently, 32 anchor stations were occupied during seven oceanographic cruises to measure the physical, chemical, and biological character of the water masses over complete tidal cycles. At the same time, two wave-rider buoys and two tide gauges were established, together with 11 self-recording current meter strings.

The cruise data have been reviewed by Amos and Asprey [26], and the bottom sediment distribution evaluated by Hussain [27]. Many of the initial findings are reviewed in the text by Gordon and Dadswell [28].

The location of the vibrocores referred to in this paper are shown in Figure 1.

Lithofacies

Seven lithofacies and three subfacies (presented below) were defined on the basis of detailed visual and X-radiographic analysis of the vibrocores. The format used in modified from Miall [29,30] and is based on grain size, primary sedimentary structure, bioturbation, biogenic composition, and bedding characteristics [31].

(1) *Facies M—clay:* massive to indistinctly laminated clay exhibiting abundant vertical and horizontal burrowing and the presence of shell material throughout; the facies can contain up to 15% silt or very fine sand in isolated lenses.

(1A) *Subfacies Mp—gravelly clay:* as facies M, but includes 10 to 30% of randomly dispersed gravel.

(1B) *Subfacies Mpb—bioturbated gravelly clay:* similar to subfacies Mp, but the matrix is highly bioturbated.

(2) *Facies L—lenticular bedded fines/sand:* facies M (60 to 85%) interlaminated to interbedded with rippled silts or very fine sand; the sand laminae lie on erosional surfaces and show planar cross-laminations.

(3) *Facies W—wavey bedded sand/fines:* facies M (40 to 60%) interlaminated or interbedded with wavey bedded silt or medium sand; the sand lies on erosional surfaces and exhibits planar cross-lamination and low-angle reactivation surfaces; bioturbation, when present, occurs in the troughs of sand laminae.

(4) *Facies F—flaser bedded sand/fines:* rippled silt, very fine to medium grain sand (60 to 85%) laminae or lenses of facies M.

(5) *Facies S—sand:* massive medium to coarse grain sand characterized by an erosional base and often capped by a layer of coarse sand; abundant shell fragments occur throughout.

(5A) *Subfacies Sp—gravelly sand:* massive to poorly bedded gravel (15 to 25%) interbedded with beds of very coarse grain sand or granules 2 to 20 cm thick; the bases of the sandy units are strongly erosional.

(6) *Facies G—gravel:* massive bedded units of well rounded and well sorted granules or pebbles in a shell-bearing sandy matrix (20 to 40%); the upper surface of this unit is usually well defined and demonstrates an abrupt transition to the overlying unit.

(7) *Facies P—peat:* carbonaceous laminated clay exhibiting root structures interlaminated with massive clay and peat.

Seismostratigraphy and Lithostratigraphy

The distribution of surficial sublittoral sediments in the Chignecto Bay is controlled largely by the paleo-topography produced by submerged pre-Wisconsin drainage channels and adjacent wave-cut terraces. The paleo-channels are partially infilled with up to 60 m of unconsolidated sediments. The sequence is interpreted to be characterized by five seismostratigraphic units separated by four distinct acoustic discontinuities. An example of the seismic character of these units is shown in Figure 4. In general, the lithology, stratigraphy, chronology, and biostratigraphy derived from the analyzed vibrocores corresponded well with the established seismostratigraphic units. The following is the interpreted sequence:

Unit	Description	Age (yr)
(R)	Modern sand or gravel	<3000
(G1)	Interlaminated sand/fines	3000–6000
(G2)	Interlaminated sand/fines	6000–9000
(G3)	Massive sand and gravel	9000–13,500
(G4)	Glacio-marine or ablation till	>13,500

The 17 age determinations used are listed in Table 1, and the facies types characterizing each seismostratigraphic unit are given in Table 2. Appreciable differences both in facies and macrofaunal assemblages were detected between the sampled units.

Stratigraphic units G3 and G4 comprise up to 50 m of the section and are discontinuous in their distribution. G4 is interpreted purely on the basis of seismic data and is considered to be the lateral equivalent of proglacial outwash sands and ablation tills deposited under submarine conditions approximately 13,500 years ago [21,32]. Upper G3 was recovered in the base of cores 1 and 3 (Fig. 3) and comprises well sorted gravel and sand. C14 age determinations of shell material yielded dates of 9420 ± 560 (GX-6673) and 9170 ± 370 (GX-6674) years B.P.

Unit G2 varies in thickness from 5 to 10 m. It is composed of massive to indistinctly laminated clayey fines (44%), lenticularly bedded silts (39%), peat (7%), and minor amounts of wavey, planar cross-laminated or pebbly sands (10%). Laminae are disrupted by vertically and horizontally oriented burrows. The unit contains a rich macrofauna (*Acteocina canalicata, Crepidula fornicata, Cerastoderma pinnulatina, Mulinia lateralus, Mitrella lunata,* and *Macoma balthica*). Two horizons of salt marsh peat are interdigitated with lenticular bedding in the upper bay, forming cycles 1 and 2.5-m thick. The base of the peats yields a C14 date of 7140 ± 160 (GX-6689) years B.P. and delimits the local minimum stand of sea level.

Unit G1 varies in thickness to a maximum of 8 m. It is composed of lenticularly bedded fines (72%), flaser-bedded

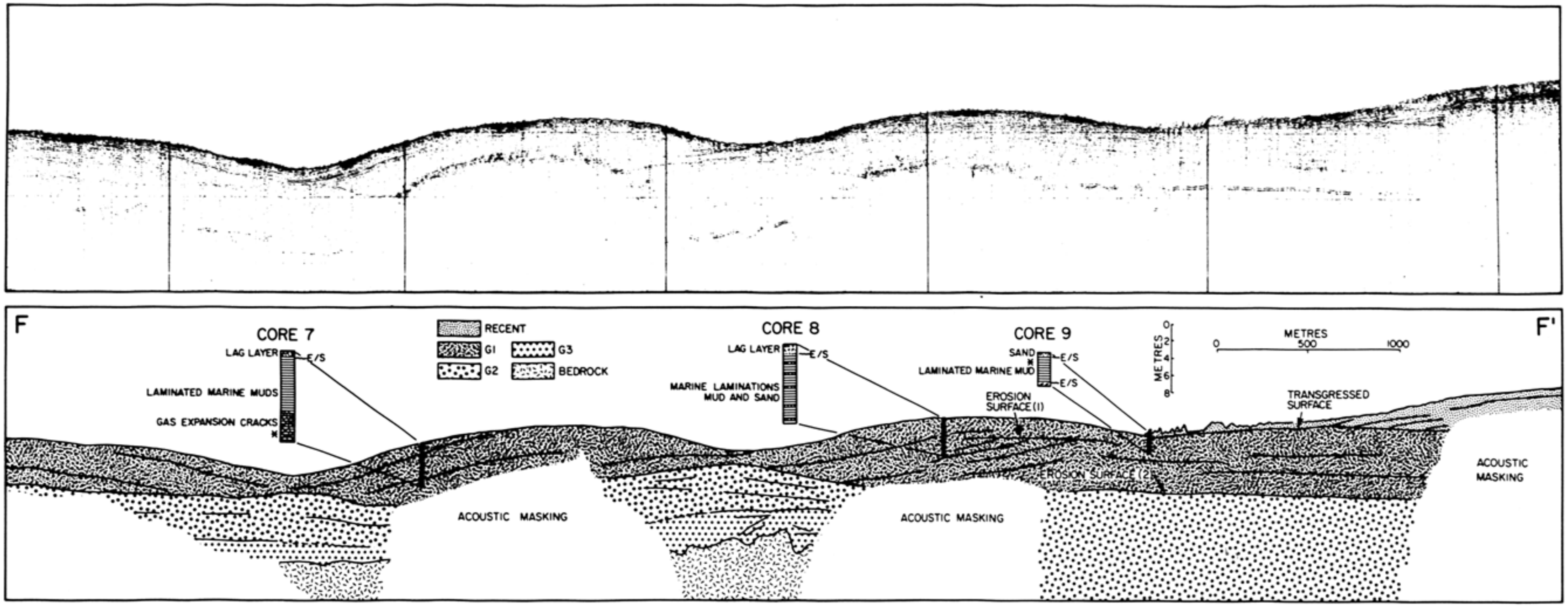

Figure 4. A north/south transect through central Chignecto Bay presented to illustrate the seismostratigraphic relationship of the various units and the correlation of these units to the lithostratigraphy evaluated in the 17 vibrocores collected in the bay. The example shows the positions of cores 7, 8, and 9.

Table 1. Correlation Between C14 Age Determination, Core, Sample Depth Below Mean Sea Level and the Seismo-Stratigraphic Unit Assigned to the 17 Analysed Horizons

Sample #	Core #	Depth (m)	Age	Unit	Lab #
1 (T)	15	25	7995 ± 245	G2	GX-6690
2 (T)	15	25	7140 ± 160	G2	GX-6689
3 (T)	15	23	6660 ± 175	G2	GX-6688
4 (T)	15	20	4730 ± 205	G1	GX-6687
5 (T)	14	20	7365 ± 245	G1	GX-6686
6 (T)	7	31	5110 ± 220	G1	GX-6679
7 (T)	4	38	7325 ± 280	G2	GX-6677
8 (S)	4	38	6745 ± 245	G2	GX-6678
9 (S)	3	42	9170 ± 370	G3	GX-6674
10 (S)	1	46	9420 ± 560	G3	GX-6673
11 (T)	11	33	7530 ± 180	G2	GX-6682
12 (S)	9	26	2485 ± 140	G1	GX-6680
13 (S)	18	25	3310 ± 190	G1	GX-6691
14 (T)	10	22	4660 ± 220	G2	GX-6681
15 (S)	4	36	6835 ± 480	G1	GX-6675
16 (S)	12	27	7570 ± 420	G2	GX-6684
17 (T)	13	18	6690 ± 245	G1	GX-6685

(S) indicates an analysis of the shell fraction only; (T) indicates an analysis made on the entire sample.

muddy sands (16%), clayey fines (6%), and wavey bedded muddy sands (4%). Gravel and planar cross-laminated sand beds occur throughout the sequence. The macrofossil assemblage is distinct from that in unit G2, but is equally as rich (*Ensis directus*, *Thyasira flexvosa*, *Oenopata harpularia*, *Lunatia pallida*, and *Hydrobia totteni*). This unit was deposited under littoral conditions in the inner portion of the bay, and under sublittoral conditions seawards. Upper G1, recovered from the inner bay, was also deposited under sublittoral conditions.

Unit R is the recent sedimentary unit considered to be in equilibrium with existing macrotidal conditions. It varies in thickness to a maximum of 6 m and is thickest within the flood-dominant region of western Chignecto Bay and at the mouths of the Cumberland Basin and Shepody Bay. The base of the unit is characterized by sublittoral sand that shows large-scale cross-bedding. The majority of the sequence is capped by a gravel lag layer considered to be the product of current winnowing or ice rafting of shoreline material. In the western part of the bay, the upper part of the sequence comprises a thin (1 m) layer of mobile transgressive sand exhibiting sand waves, two- and three-dimensional megaripples, and sand ribbons.

Table 2. Type and Abundance of Defined Facies and Subfacies for the Sampled Seismostratigraphic Units

Facies	Unit			
	G3	G2	G1	R
M	—	42%	6%	—
Mp	—	2%	—	13%
Mpb	—	—	—	8%
L	—	39%	72%	—
W	—	4%	4%	—
F	—	2%	16%	—
Sc		1%	—	12%
Sp	100%	2%	2%	67%
G		—	—	—
P	—	7%	—	—

Discussion

The relationship of the lithostratigraphy of the units defined in this report to changing sea-level and tidal range is demonstrated in Figures 2 and 3. A comparison is made between sequences and facies deposited under littoral and sublittoral environments subject to mesotidal or macrotidal conditions. Figure 2 shows the absolute elevation (relative to present MSL) of 17 C14-dated horizons and the relationship of the data points to the contemporaneous MSL and tidal extremes. Figure 3 shows the position and lithostratigraphy of 12 of the 17 vibrocores plotted on a longitudinal section of the Chignecto Bay. The simplified lithostratigraphic logs are illustrated with the appropriate unit designation and age determinations.

The depositional environment of unit G4, based on the sea-level curve shown in Figure 2, is sublittoral. This unit was detected on seismic records, but was not sampled in the coring program. Marine conditions at the time are interpreted to be microtidal [10].

During G3 times, Chignecto Bay was exclusively sublittoral marine. The water depth during this time interval became shallower by approximately 60 m. Despite this shoaling, the upper section of the unit observed in cores 1 and 3 was deposited 30-m below MSL. No independent information on tidal range is available for this time period. However, the prevelance of facies G and S (Table 2) is compatible with macrotidal rather than mesotidal or microtidal conditions.

The mean sea-level (MSL) during early G2 times continued to drop. The distinct seismostratigraphic discontinuity that separates G3 from G2 is accompanied by a change in lithology to a dominance of facies M and L. The base of unit G2 (core 3) shows a greater proportion of facies S than does the mid-portion of the unit. The discontinuity in facies type is believed to represent the transition from macrotidal to high energy mesotidal conditions that occurred between 9000 and 8000 years B.P. Only the lower portion of G2 is preserved in the outer bay. However, the middle and upper parts of G2 are well represented in the inner bay (cores 11 to 15). Faunal identification of the mid-section of core 15 shows it to have formed in the higher intertidal zone (Miller, personal communication, 1984). This evidence thus defines a low stand of sea level at 7000 years B.P. The predominance of facies P, L, and M agrees well with a transition from sublittoral to littoral conditions in the inner bay. The tidal range at that time is interpreted to be no greater than 25% of that at present and perhaps the smallest to have occurred during post-glacial times [11]. Seismic records of the sequence show it to be dissected by a number of erosional surfaces associated with channels.

The upper part of unit G2, preserved in cores 11 and 12, was deposited under conditions of rising sea level. The local depositional environment was littoral to sublittoral and characterized in the stratigraphic record by an increase in facies S. This increase is coincident with the amplification in tidal range that leads to the onset of macrotidal conditions at approximately 6000–4000 years B.P.

During the formation of unit G1, sea level rose rapidly and was associated with a 100% amplification of the tide to a range of approximately 10 m. Unit G1 was deposited in the outer bay in a sublittoral setting (35-m below MSL). The unit is characterized by isolated sequences of facies S interbedded with facies L and F. The dominance of facies L and F with a decrease in facies M appears more typical of the mesotidal channel wall deposits described by Terwindt [17]. In the inner bay, lower G1 is littoral (dates 5, and 17; Fig. 2) and is characterized by thick sequences of facies L and W interspersed with lesser amounts of facies S than exist seawards. The upper part of the sequence is sublittoral macrotidal and characterized by thick sequences of facies L and F interspersed with massive beds of facies S.

Only the sublittoral portion of unit R was sampled in the coring program. This unit was deposited under high energy macrotidal conditions and shows the predominance of facies Mp and S. In contrast to the littoral zone, the sublittoral section is poorly preserved and represented by thin migrating sand bodies or erosional lags. The unit rests on a nearly ubiquitous erosional surface that has removed up to 40-m of prerecent sediments.

A synthesis of the this interpretation is given in Figure 5. A different stratigraphic sequence emerges from the inner and outer portions of the bay, reflecting the relative positions of sea level through time. Contributing to the complexity of the sequence are the clearly observable effects of a changing tidal range. In addition, the absence of a supply of sand during recent times has limited the development of a full sublittoral sequence. Constraints in sequence development imposed by the budget of sediment to Chignecto Bay are, therefore, considered significant. Thus, the resulting tidal sequence is far more complex than existing models allow and suggests that many tidal sequences, although generally identifiable in the geologic record, may be misinterpreted in terms of their detailed evolution.

It is noted that the observed lithologic relationships to tidal range and sea level correlate well with those presented by Terwindt [16]. Both sets of data were derived from estuaries

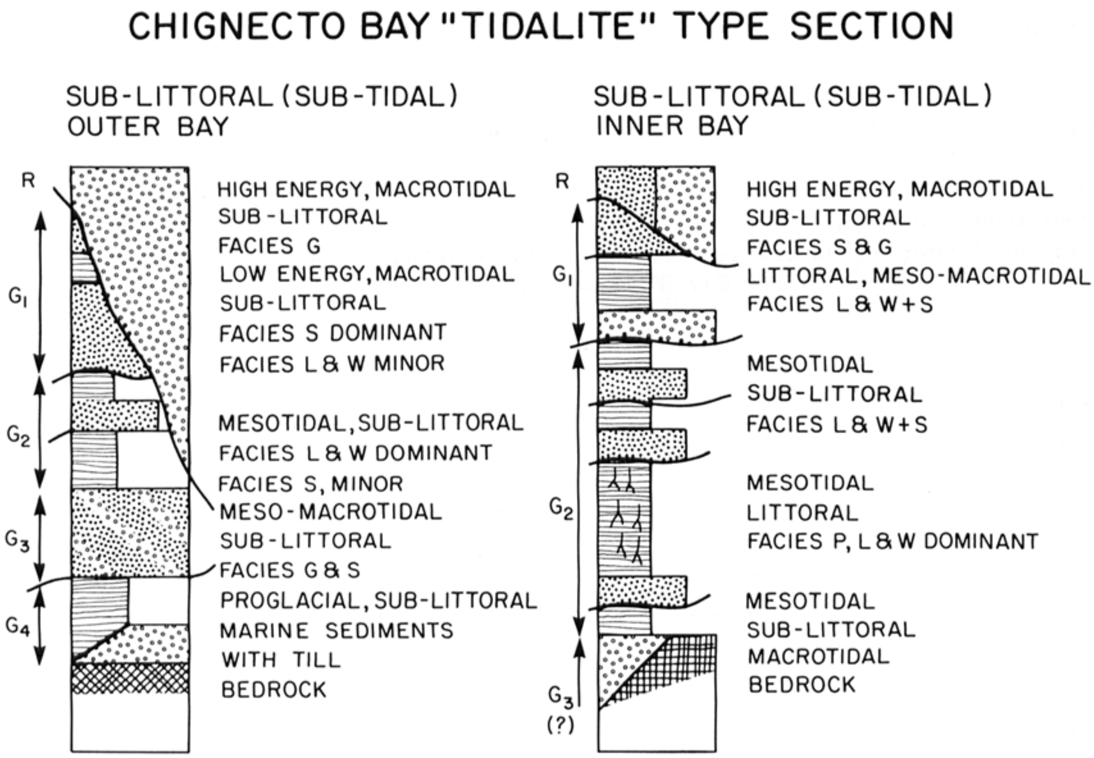

Figure 5. A schematic section of the sublittoral stratigraphy of the Chignecto Bay region for the inner and outer portions of the bay.

dominated by fine-grained sediment and do not conflict with the interpretations of Boothroyd [33], who worked in sand-dominated estuaries. The composite stratigraphy of a sand-dominated estuary subject to a post-glacial history similar to that of Chignecto Bay is unknown at this time.

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