Recent coastal submergence of the Maritime Provinces, Canada[1]

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Received October 10, 1969
Accepted for publication January 7, 1970

Hydrographic, archeologic, and geologic evidence indicates that for the last 4000 y the Maritime Provinces have been submerging three to five times faster than the 6 cm/century rate of eustatic rise of sea level. After correcting for the eustatic change, the Bay of Fundy shows an anomalous submergence of 24 cm/century, of which at least 15 cm/century is probably due mainly to rise of high tide, or increase of tidal range, beginning 4000–6000 y ago as eustatic sea-level rise widened and deepened the entrance to the Gulf of Maine. Submergence of the Atlantic coast of Nova Scotia, on the other hand, exceeds the eustatic rate by 9 cm/century, which can be largely explained by new mathematical models as isostatic subsidence of the earth's crust as the sea deepened eustatically over the continental shelf. Only a small part of the residual anomalies of 9 cm and 4 cm/century for the Fundy and Atlantic coasts, respectively, can be attributed to a combination of additional subsidence due to geosynclinal downwarping and relaxation of a possible glacier-margin peripheral bulge, thereby implicating other modes of regional crustal lowering.

Introduction

The term submergence refers to partial inundation of land by sea, but does not imply whether the effect was produced by an absolute rise of sea level, or by a subsidence of the land surface, or both. Submergence of stable coasts provides a reference standard for the sea-level factor (comprising a world-wide or eustatic constituent, and local constituents, including volume and density terms, and tidal changes) to which other submergence records may be compared to isolate the crustal-movement factor. Hence the relevance of Maritimes' submergence to the problem of recent crustal movements in Canada.

This report outlines the writer's attempt to document the extent, age, sequence, rate, and causes of submergence in the Maritime Provinces, which was sponsored by the Geological Survey of Canada as a doctoral dissertation in geology for Cornell University.

Postglacial sea-level movements along the Atlantic coast of North America exhibit large local variations. South of the Pleistocene glacial limit near New York City, coastal and shelf deposits record a generally steady rise of 100–130 m during the last 15 000 to 20 000 y (Milliman and Emery 1968), that tide gauges indicate is still continuing (Donn and Shaw 1963). North of the glacial limit, in New England, earlier emergence due to deglacial crustal rebound, was succeeded by submergence, largely due to crustal subsidence (Redfield 1967) that has been underway for the last several thousand years. The Maritimes' region occupies a key position between the submerging and subsiding coast to the south, and an apparently emerging and still uplifting Newfoundland–Labrador coast to the north.

Recent marine submergence of the Maritimes has been the topic of numerous papers for more than 100 y. Dawson (1855*a*, pp. 30–40) was the first to perceive that salt marshes not only are evidence of submergence because their upward growth is limited by high-tide level, but also that their thickness is a measure of sea-level rise. Dawson (1855*b*) described a 'forest' of stumps and logs 35 ft (10.7 m) below high-tide level, being exhumed from a cover of salt marsh sediment near Fort Lawrence at the head of Bay of Fundy, and inferred a large recent rise of high tide, which he surmised was due to subsidence and possibly also to increase of tidal range. Gesner (1861) catalogued submergence phenomena, including evidence that sea level has risen 2 or 3 ft (.6 to .9 m) in the last few centuries. More recently Frankel and Crowl (1961) and Harrison and Lyon (1963) dated submerged trees from Northumberland Strait and Bay of Fundy, respectively, and attributed the variable submergence to differential tectonic downwarping of the crust.

[1]Presented at the Symposium on Recent Crustal Movements, Ottawa, Canada, March 17–18, 1969.

Datum

Tracing the history of the submergence event backward in time requires a present-day reference point or datum that is unique, ubiquitous, defined, recognizable, and dateable, both on the present shore and in the sedimentary record of submergence. The obvious choice is the highest regular extent of salt water, in other words, the level at which the marine environment is now replacing the terrestrial environment. Hydrographically, this is the tidal level that is attained fourteen times per year arranged over 20 y, termed Higher High Water at 'large tides' (HHWL). Botanically, it corresponds to the level at which trees are killed by salt water and which is marked by sedge plants (cattails, reed, and salt-water bulrush) spanning the transition between truly marine salt marsh and freshwater bogs and upland vegetation. Geologically, this level is recognized on the present shore by the highest driftwood line, by dead and dying trees, by sedge plants, and by the lower limit of flowers, and is represented in organic sediments that record the rise of sea level by preserving the fresh- to salt-water sequence, as either tree stumps overlain by salt-marsh peat or sedge peat containing the black corms and curved triangular stems of *Scirpus*, the salt-marsh bulrush. Sedge peat is distinguishable from woody, brown peat of freshwater bogs, and from silty, high-tide, salt-marsh turf containing the fine fibrous rootlets of *Spartina patens*, and the coarse yellow roots of *Spartina alterniflora*. This highest-tide, geobotanical reference level, hereinafter referred to as Datum, is the base to which former lower positions of sea level are related. The submergence trend is simply the plotted positions of radiocarbon and calendar age-determinations and spirit-level depth measurements on discrete samples of organic matter thought to have formed at or near the Datum plane.

Evidence

Contemporary Submergence

Relative movements of land and sea in modern times can be detected by geodetic re-levelling, since this procedure reveals changes in the height of bench marks above mean sea level. However, until the first regional re-levelling of the Maritimes is completed, the only alternative evidence that the Maritimes are currently submerging is provided by tide gauges, which reveal secular changes in the height of sea level with respect to fixed bench marks on land. Tidal records for Halifax, N.S., Saint John, N.B., and Charlottetown, P.E.I. (Fig. 1) show that for the past few decades mean tide level has risen fairly steadily at 41, 46, and 26 cm/century, respectively.

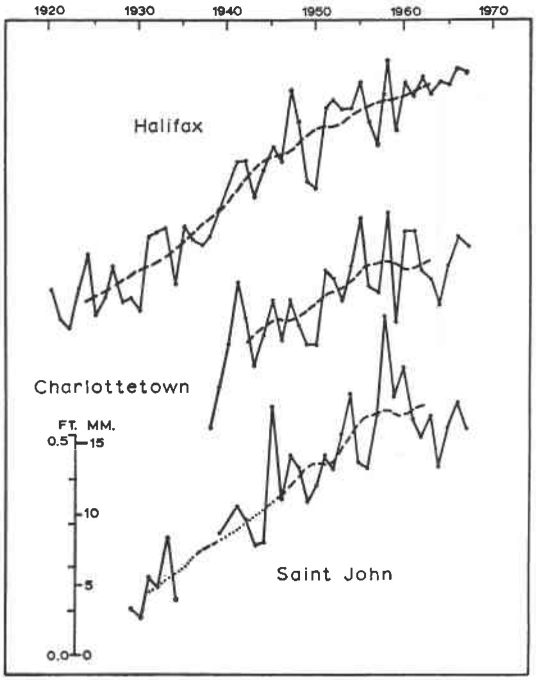

FIG. 1. Yearly mean tide levels (dashed line is 10-year moving mean).

Otherwise, no other direct, quantitative geological evidence of contemporary submergence is known. There are only indirect suggestions provided by conspicuous erosion in the Gulf of St. Lawrence (Forward 1960), the continued upward growth of salt marshes, and the transgression of barrier beaches, which collectively militate against emergence or coastal stability.

Historical and Archeological Evidence of Submergence

Sea level has risen appreciably during the 300 years of settlement by Europeans. Artifacts and refuse, discarded on the surfaces of salt marshes, have been buried by tidal mud as sedimentation kept pace with rising high tide,

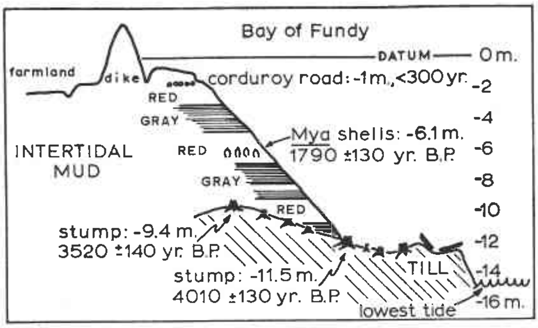

FIG. 2. Geological cross-section through Bay of Fundy coastal deposits exposed at low tide near Fort Beauséjour, N.B., showing submerged forest of logs and stumps rooted in glacial till, overlain by intertidal salt-marsh mud.

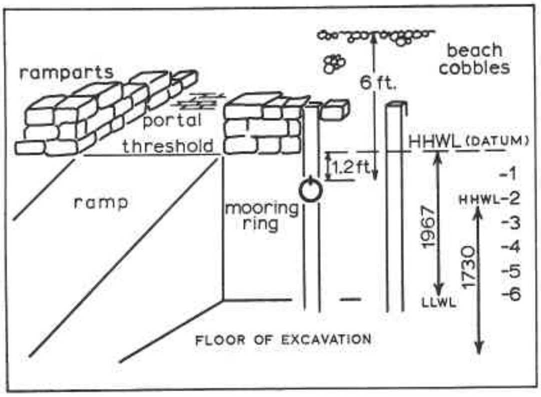

FIG. 3. Diagrammatic sketch of excavated sea wall at Fortress Louisbourg, N.S., showing presently submerged position of mooring ring and gate threshold.

and are now 30 to 50 cm below present marsh surface at several localities, notably Grand Pré in Bay of Fundy, and McNab's Island in Halifax Harbour. Near Fort Beauséjour, New Brunswick (Fig. 2), a corduroy road originally laid across the marsh surface, is now overlain by 1 m of high-tide salt-marsh mud. A more precise measure of the rate of rise of high tide in historical times has been uncovered during the restoration of Fortress Louisbourg, Cape Breton Island, Nova Scotia, built 1717 to 1737. Excavation of a seawall (Fig. 3) revealed mooring rings 1.2 ft (37 cm) below the level of present highest annual tides (Datum). Since the rings were probably set originally at least ½ m above the highest tides for convenience (John Lunn 1967),[2] this means that high tide has risen at least 0.8 m in the last 250 y. Considering the relative level of other high-tide related features in the seawall, the concensus of the archeologists at the fort is that high tide has risen almost 1 m since construction of the fort began in the early 1700's (Bruce Fry and Richard Cox 1967).[2]

Archeologic evidence as well indicates that Nova Scotia has been submerging for at least the last 1000 years. Erskine (1960) reported abandoned Indian encampments on the coast of southwest Nova Scotia. The period of occupation, dated culturally and radiometrically, ranged between 1150 and 750 y ago. A few sites are partly submerged, and at one near Port Joli, a shell heap 1 m thick lies 2 m below Datum, indicating a rise of high tide of 1 or 2 m in the last 1000 y.

Geologic Evidence of Submergence During the Last Several Thousand Years

Sedge peat and stumps of trees apparently killed by salt water are commonly found, in the Bay of Fundy, at the base of salt marshes (Fig. 2) and, on the Atlantic coast of Nova Scotia, on the seaward side of barrier beaches that are being driven landward and upward over brackish pond sediments by rising sea level. Easy access to submerged high-tide indicators is provided by the large (2–15 m) tidal range in the area, so that sampling and measuring can be done directly on natural exposures at any level down to low tide. As a result, areal and depth distribution of samples reflect the tidal access, with many more from the Bay of Fundy where tides fall the lowest, and where salt marsh is abundant.

Results

Figure 4 is an inventory of localities showing evidence of submergence. These are differentiated as to whether age was determined by ^{14}C analysis or inferred from a historical context, and whether the site was actually visited and sampled or merely inferred from airphotos, or whether other workers have provided the information. The wide distribution of evidence confirms that the entire region has been, and still is, submerging, particularly the Fundy embayment. Figure 5 displays all available age and depth determinations relating to

[2]Personal communication.

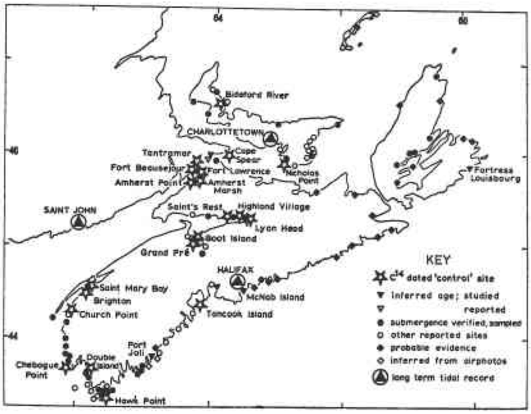

FIG. 4. Localities showing evidence of submergence in the Maritime Provinces.

the rise of high tide Datum in the Maritimes, except for two spurious determinations at −3 m with ages of 5000 and 8000 y, that were apparently misinterpreted as indicators of Datum when collected. The most significant feature of the age–depth plot is the striking overall continuity of the trend, starting from the tidal curve for the last 50 y, through the various historical submergences of the last 300 years, to the main geological evidence of the last 4000 y. Accordingly, the region as a whole appears to have been submerging at about 1 ft (30 cm)/century.

Dispersion of the data-points about a mean, amounting to ± 500 y and ± 1.5 m, is due to a variety of factors. The standard errors of dating (± 100 y) and of spirit-levelling (± 15 cm) account for a small portion. A larger portion is attributable to additional age errors of ± 100 y, due to isotopic fractionation in the various organic materials, and depth errors of ± 1.5 m due to local variation and uncertainty in determination of Datum. Thirdly, the data points are not strictly comparable in that not all relate precisely to Datum-level. Some, like salt-marsh peat, originated slightly below Datum, while others, like trees and freshwater peat, died or were deposited an indeterminate height above it. Fourthly, the submergence event may be a series of fluctuations with periods of a few centuries and amplitudes of several decimeters, rather than a steady, linear rise. Lastly, and

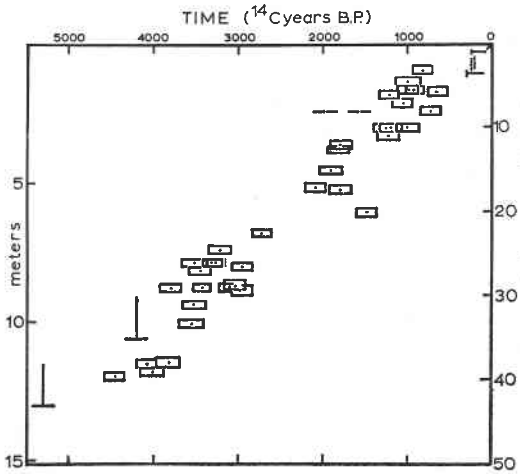

FIG. 5. Time-depth plot of presently submerged features, formerly at or above the highest tide level. (Rectangles denote limits of radiocarbon and surveying errors; other symbols represent determinations with less certain limits of age and depth error; short sloping line in upper right corner denotes modern rise of mean tide level.)

perhaps most importantly, the study area is large, and widely spaced localities may be submerging at different rates. For these reasons, particularly the possibility of regional variation, a single smooth curve has not been used to depict the submergence trend.

Figure 6 compares the data for relative rise of sea level in the Maritimes with a curve for absolute or eustatic rise of sea level based on a compilation by Shepard and Curray (1967) from submergence curves for the stable coasts of southern Florida and the Netherlands, and

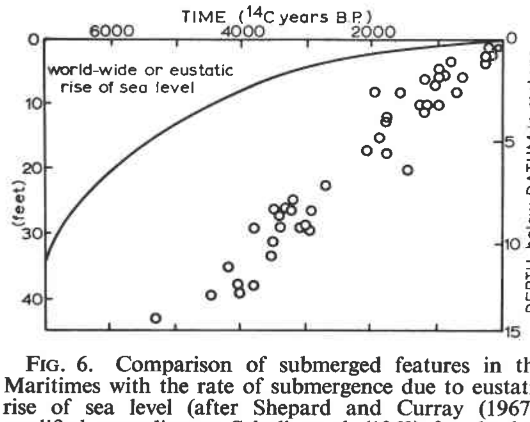

FIG. 6. Comparison of submerged features in the Maritimes with the rate of submergence due to eustatic rise of sea level (after Shepard and Curray (1967), modified according to Scholl *et al.* (1969) for the last 3000 years).

on more recent work in Florida by Scholl *et al.* (1969). Whereas world-wide sea level has risen eustatically at an average rate of only 6 cm/century during the last 4000 y, sea level around the Maritimes has been rising 30 cm/century, or five times faster. This implies that the Maritimes have subsided and/or high-tide level has risen faster than has mean sea level (the 'Datum' for eustatic sea-level curves).

Comparison of Maritimes data with other measured submergences in eastern North America (Fig. 7) further emphasizes the distinctly anomalous rate. Note particularly the contrast with curve 8, the submergence trend for southern Florida recently proposed by Scholl *et al.* (1969) as the most definitive statement of eustatic rise of sea level. The Maritimes have apparently submerged up to five times more, or 2–10 m more, than any other Atlantic coast locality yet studied. Recent authors (e.g. Redfield 1967) have also noted the variation in submergence along the East Coast, and to explain the disparity with the Florida eustatic submergence, they have invoked crustal subsidence as an obvious alternative, as had earlier investigators on more empirical grounds. Recently, Bloom (1967) suggested a mechanism that can produce regionally variable downwarping of the coast. Since there is no reason to suppose the Maritimes have escaped the influence of this general effect on the continental margin, the applicability of Bloom's subsidence mechanism is examined in a later section.

Thus far the submergence trend has been

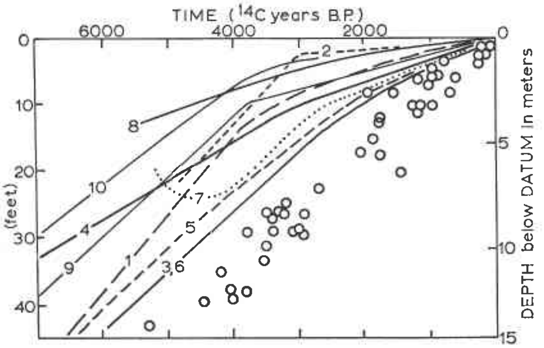

FIG. 7. Comparison of Maritimes submerged features with other measures of relative submergence in eastern North America (1 = Plum Island, Mass., 2 = Boston, Mass., 3 = Barnstable, Mass., 4 = Clinton, Conn., 5 = New Haven, Conn., 6 = Barnegat, N.J., 7 = Watchapreague, Va., 8 = southwest Florida, 9 = Mississippi deltaic plain, 10 = Chenier plain, La.

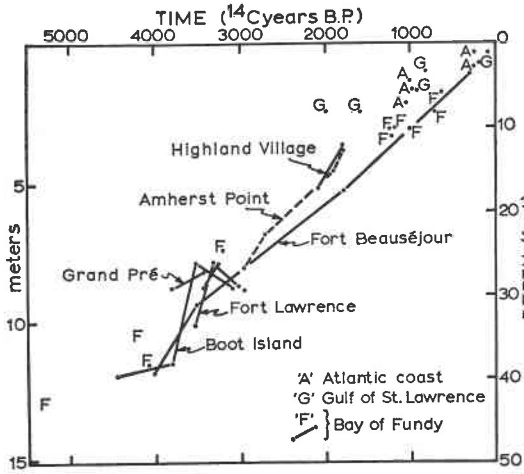

FIG. 8. Variations in submergence within the Maritimes region.

treated as a regional average, but Fig. 8 reveals significant variations within the region. The overall submergence trend is clearly determined mainly by information from the Bay of Fundy, where two localities with multiple determinations—Amherst Point and Fort Beauséjour—offer strong evidence that high-tide level has risen fairly steadily at about 1 ft (30 cm)/century for the last 4000 y, probably throughout the bay. In contrast, data-points for the Atlantic and Gulf of St. Lawrence coasts, while admittedly sparse, shallow and young, plot above those from Fundy, and, if a rate can be inferred from this limited information it would be about ½ ft (15 cm) per century for the past 1000–2000 y, or just half the submergence rate for Bay of Fundy. Regional variation of this amount is actually less than that shown for a similar-sized area of the United States Atlantic coast from Maine to New Jersey (cf. curves 1–6, Fig. 7). Therefore, it seems that much of the dispersion of the plotted points is indeed attributable to regionally differing submergence.

The Causes of Exaggerated Submergence

Figure 9 describes and explains the more probable reasons for single anomalous plots of Datum, as well as the reasons for locally differing submergence rates. Various mechanisms capable of producing exaggerated submergence can be reviewed individually. Depth anomalies introduced by using organic material

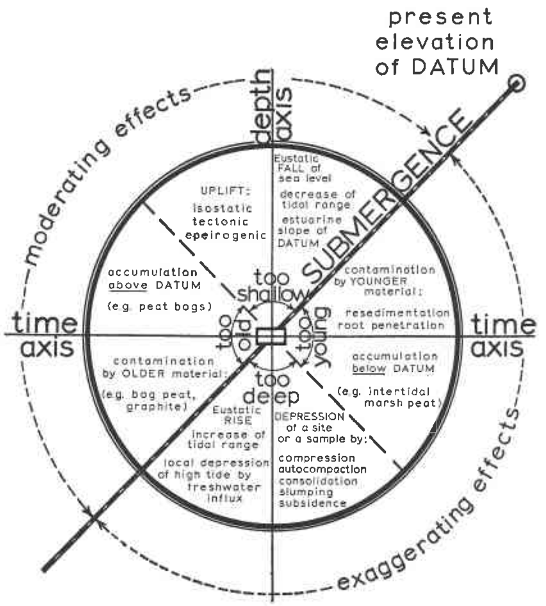

FIG. 9. Sources of error in submergence studies.

that accumulated below Datum can not be important, because only a few dates refer to intertidal salt-marsh peat; most are *in situ* supramarine tree stumps and brackish-water sedge peat. Contamination by younger material, while undoubtedly present, can not possibly affect systematically samples of such varying composition, great depth range, and widespread distribution. Restricting the choice to basal organic layers in contact with a firm substrate is believed to have virtually eliminated post-depositional changes of depth due to compression by a superimposed load, auto-compaction within a growing pile of sediment, consolidation by diagenetic reduction of pore-space, and slumping. Local depression of high-tide Datum by freshwater influx is possible only in long estuaries with voluminous discharge. The eustatic factor refers to possible fluctuations as yet unrecognized. However, Scholl *et al.* (1969) presented a precise eustatic submergence curve for southern Florida, and limited the amplitude of possible fluctuations to only ± 0.3 m, which is inadequate to account for the 2–10 m submergence anomaly in the Maritimes. Only two of the mechanisms shown on Fig. 8, that cause exaggerated submergence, remain as possible explanations. Depression of individual sites or areas by regional crustal subsidence is a definite probability in view of the general concensus that the Atlantic coast is sinking. Alternatively, and possibly also additionally, since Datum is a high-tide surface and not mean sea level, any increase in tidal range would effectively submerge the land. In view of the anomalous 15–m tidal range in the Bay of Fundy, tidal changes seem almost certainly implicated for at least the submergence of the Fundy region.

The Role of Crustal Subsidence in Maritimes Submergence

Among previous authors who inferred the middle North American continental shelf is subsiding, Redfield (1967) first ventured estimates of the onset and rate of crustal deflection for various coastal sites based on the excess of relative submergence over eustatic submergence. A new aspect was introduced when Bloom (1965) and Higgins (1965) independently suggested that much of the excessive submergence might be due to isostatic depression of the coast by the weight of water added offshore by eustatic sea-level rise. This concept of water-loading was further developed by Bloom (1967), who surmised that the earth's crust should respond measurably to the postglacial rise of the sea over the shelf, just as the increasing water load in Lake Mead reservoir had caused a detectable and proportional subsidence (Longwell 1960), and just as the draining of Pleistocene Lake Bonneville has caused a proportional upwarp of the shorelines (Crittenden 1963). Using Crittenden's method for converting actual bathymetry to average water depths, Bloom (1967) found a good correlation between the isostatic sinking that could be expected from any present average water thickness, and the amount of subsidence during the last 4500 y inferred by subtracting Scholl and Stuiver's (1967) eustatic sea-level curve from the submergence curves for various coastal sites. Water-loading is therefore regarded as the most promising means of producing variably excessive submergence.

Accordingly, a similar chart of average water depths (or thicknesses) was prepared by computer for the Maritimes region (Fig. 10). The Atlantic coast of Nova Scotia is theoretically being subjected to a water load of 30–50 m, which could depress the coast 9–15 m in 4500

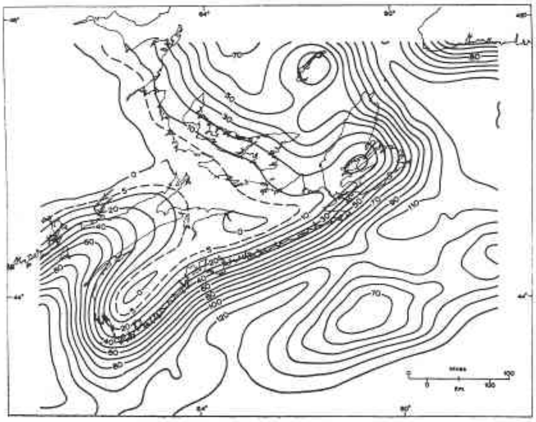

FIG. 10. Contours of equal average water depth ("isomesobaths"). (Contour interval = 10 m.) Canadian Hydrographic Service Chart 801, compiled from soundings spaced every 0.2 km along lines 1–2 km apart, contoured every 20 m at a scale of 1:1 000 000, was ruled with a 5-km grid and the depths at some 20 000 grid intersections were interpolated. Land areas were considered as zero depth, and depths greater than 125 m as 125 m, since that was the amount of post-glacial sea-level change. A univac 1108 computed the average of the 377 spot depths that occurred within a circle of radius 55 km centered on each grid point. This is a contoured mosaic of the printed output.

years, or 2.0–3.3 m in the last 1000 y. Yet the Atlantic coast seems to have subsided only 1.2 m during this period, if the eustatic sea-level rise of 0.3 m for the last 1000 y (Scholl *et al.* 1969) is subtracted from the 1.5 m of submergence (Fig. 8). Thus, Bloom's (1967) method of estimating potential subsidence due to water-loading more than explains the excessive submergence of the Nova Scotia Atlantic coast.

However, the correlation elsewhere in the area is less satisfactory. In the last 1000 y, the south coast of the Gulf of St. Lawrence has also submerged 1.5 m, of which 1.2 m is subsidence, whereas the water load is only 5–10 m, or only one-fifth that on the Atlantic coast, and could produce at most only 0.7 m of the inferred 1.2 m subsidence. The disparity is even greater for the Bay of Fundy. The heads of the bay have submerged 3.0 m, or have subsided 2.7 m, in the last 1000 years, requiring a water load of 37 m, whereas a water load of less than 5 m is indicated at the heads of the bay (Fig. 10) where the subsidence (submergence) rate is derived. It makes little difference to recalculate water loads to include the extra depth at high tide. Adding the 15 m tidal range to all depths within 55 km of the Grand Pré and Fort Beauséjour control sites increases their low-tide water loads of 2 m and 4 m to only 3.4 m and 7.0 m, respectively—still far short of the 37 m necessary. For the Bay of Fundy, at least, some mechanism other than subsidence by water-loading is needed to explain the exaggerated submergence. A later section shows that increase of tidal range is a probable cause.

To ascertain why the water-loading mechanism did not operate according to theory in the Maritimes, a more realistic expression for the process was prepared, with gratifying results. Rather than expect some function of present depth to reproduce a reaction in the past, rather than assume that total subsidence has occurred only in the last 4500 years, and rather than imply that crustal response is linear, an equation for crustal subsidence under an increasing water load was prepared.

Isostatic movement of the earth's crust in response to changing superimposed loads is an example of a general first-order differential equation of the form:

$$a \cdot \mathrm{d}f(t)/\mathrm{d}t + b \cdot f(t) = L(t) + f(t)$$

where a is related to the mantle viscosity, b is the ratio of mantle and seawater densities, $L(t)$ is the variation of load with time, which is simply the rate of postglacial eustatic rise of sea level, and $f(t)$ is the deflection of the crust with time, and is included also on the right-hand side of the equation by the assumption that the crustal deflection deepens the water thereby adding to the load. The inclusion of this term gives rise to what is called "feedback", in that the water load is being increased by the same deflection it is causing.

The exact trend of postglacial eustatic rise of sea level is imperfectly known, owing to the difficulty of obtaining reliable drowned sea-level indicators and the large range in ages of presumed sea-level indicators from any particular depth (e.g. Milliman and Emery 1968), but there is general agreement that eustatic sea level has risen between 120 and 130 m in the last 15 000 to 20 000 years. To avoid ex-

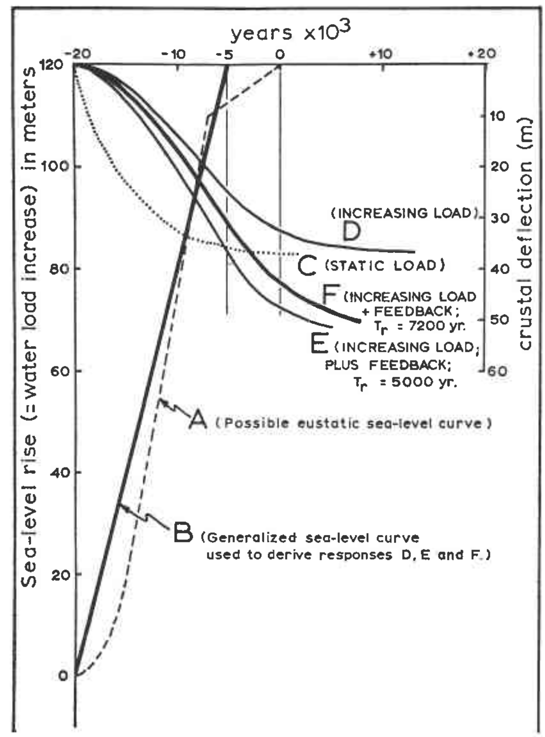

FIG. 11. Crustal deflection under the increasing load of water due to rising eustatic sea level.

aggerating the calculated crustal deflection, the rate of sea-level rise has been minimized by starting it at the earlier date (20 000 years B.P.) and from the lesser depth (−120 m). Finally, to simplify calculations, the resulting more or less sinusoidal trend (Curve A, Fig. 11) can be reasonably approximated by a straight line (Curve B, Fig. 11) depicting the linear addition of 120 m of sea water to a time 5000 years ago, after which sea level is held constant, because less than 4 m have been added since then (Scholl *et al.* 1969), and because future eustatic movements are unpredictable.

These two load functions require two expressions for deflection as a function of load. The first, for the period from 20 000 years ago to 5000 years ago, during which sea level rose linearly 120 m, takes the form:

$$f_1(t) = \frac{1}{k^2}\cdot\frac{L_{max}}{b}\cdot\frac{T_r}{t_1}\left[k\cdot\frac{t}{T_r} - 1 + e^{-kt/T_r}\right] \quad \text{for } 0 \leqslant t \leqslant t_1$$

where $f_1(t)$ is the deflection after any time t, k is a constant equal to 0.695 that arises due to the feedback mechanism, and has both the effect of increasing the overall deflection, as well as causing the actual response time to be longer than the natural relaxation time; L_{max} is the total 120 m postglacial water load; t_1 is the 15 000-year duration of increasing water depth; and T_r is the natural relaxation time, or the time it takes the crust to reach 63% $(1 - 1/e)$ of the total isostatic deflection after the instantaneous application (or removal) of a fixed load. For example, Crittenden (1963, p. 24) derived a relaxation time of more than 4000 years for crustal response to the sudden draining of Pleistocene Lake Bonneville. Hence, a natural relaxation time of 5000 years does not seem excessive for the crust under the Maritimes where the water load is also several hundred kilometers broad, but where the crust is thicker, cooler, less fractured, and hence less mobile than that under the Great Basin where Lake Bonneville existed. However, as stated above, the feedback aspect of the model effectively increases the time constant for the entire natural system from 5000 years to 7200 years, so that in effect the attainment of isostatic equilibrium is prolonged.

The second crustal deflection equation for the period of assumed constant sea level, from 5000 years ago to as far into the future as necessary to attain isostatic equilibrium, takes the form:

$$f_2(t) = \frac{L_{max}}{kb}\left[1 + \frac{1}{k}\cdot\frac{T_r}{t_1}\cdot(1 - e^{kt_1/T_r})\cdot e^{-kt/T_r}\right] \quad \text{for } t \geqslant t_1$$

These equations provided solutions giving individual increments of subsidence, at 1000 years intervals, from 20 000 years in the past, to 10 000 years into the future, caused by 120 m of water accumulating over a point on the earth's surface. The deflectional trend is plotted as Curve F in Fig. 11. According to this model the crust has subsided 11.2 m in the last 5000 years, and 1.8 m in the last 1000 years. (Not depicted is the solution for the possibility that sea level began rising 15 000 years ago rather than 20 000 years ago, in which case deflection is 14.5 m in the last 5000 years and 2.2 m in the last 1000 years.)

Points along the present shoreline, however, would be subsiding slower because the water depth has always been zero. Since nearly all points on the Atlantic coast of Nova Scotia lie within 30 km of the present 120-m depth contour, or well within the 56 km radius of the circle of influence of crustal loads (Bloom 1967, p. 1484), the present shoreline must be participating in the subsidence caused by offshore water loads. This, of course, is the essence of the water-load map (Fig. 10), which indicates the present coast is effectively overlain by 30 to 50 m of water. Crustal deflection at the present shoreline may be extrapolated as follows: A point loaded with 120 m of water now coincides with the 80-m isomesobath, and has been shown above to have deflected 1.8 m in the last 1000 years. The present shoreline, on the other hand, where the water depth is zero, but which is generally traced by the 40-m isomesobath, may therefore have subsided 40 m/80 m × 1.8 m, or 0.9 m in the last 1000 years. Alternatively, a similar result is obtained by arguing that the present coast is halfway between the 80-m isomesobath and the zero isomesobath (which can be considered a hinge line about which contemporary deflection is pivoting) and therefore should have subsided about half that which occurred beneath the 80-m isomesobath (the present 120-m depth contour). Possibly as well, both estimates could be adjusted upwards to take account of the catenary, rather than planar, profile of the deflecting crust. Even without this correction, however, the calculated crustal subsidence of 0.9 m in the last 1000 years compares well with the 1.2-m submergence anomaly on the Atlantic coast of Nova Scotia, leaving only 3 cm/century unaccounted for.

Three alternate crustal deflection curves are shown in Fig. 11 to illustrate the geological effect of neglecting certain mathematical terms. For example, in case the extended, 7200-year time constant may be contentious, Curve E is the solution using a relaxation time of 5000 years. Although one result is that attainment of isostatic equilibrium is hastened by 10 000 years, the amount of crustal deflection during the last 1000 years remains unchanged at 1.8 m. Secondly, should it be argued that inclusion of a feedback term is geologically unsound, Curve D depicts the subsidence neglecting that term. By this model, deflection becomes 7.3 m instead of 11.9 m in the last 5000 years, and 0.9 m instead 1.8 m in the last 1000 years (or 45 cm at the present shoreline). Finally, included mainly for the sake of argument, Curve C shows that if, on the one hand, the total 120-m water load was emplaced instantaneously 20 000 years ago, the crust would have subsided very little in the last 5000 years, whereas on the other hand, if the load was applied 5000 years ago, the crust would have subsided a full 3 m in the last 1000 years.

In conclusion, submergence data imply the Atlantic coast has subsided 1.2 m in the last 1000 years, and calculations of isostatic crustal response to rising sea level, by three alternate mathematical models, yield amounts of deflection in good agreement with the inferred subsidence. Unfortunately the Bay of Fundy and Gulf of St. Lawrence have insufficient water loads to explain their anomalous submergence, but tidal change in the Bay of Fundy is a possible explanation that can be considered next.

The Role of Tidal Amplification in Maritimes Submergence

Using high-tide level as Datum means that any fluctuations in the elevation of high tide, independent of changes in mean tide level, will be reflected as variations in the rate of submergence. The anomalously fast rate of submergence in Bay of Fundy could therefore be simply a faster rise of high tide with respect to mean tide level, in other words, an increase of tidal range. Tidal range in Fundy is 15 m compared with 2 m on the Atlantic coast of Nova Scotia and only 1 m in Gulf of St. Lawrence. This simple fact suggests Fundy tides could have varied considerably in postglacial time.

Present tidal geometry (Fig. 12) shows Canadian Geodetic Datum or mean sea level as the plane of symmetry about which the tide oscillates. Mean lower low water at large tides (Chart Datum) is as far below geodetic datum as mean higher high water at large tides (Submergence Datum) is above it. Hence the 250 values for depth of Chart Datum in the area (Fig. 13) provide a mirror image of the elevation of geobotanical submergence Datum which, as expected, is fully 20 ft (6 m) higher at the heads of Fundy than elsewhere.

Thus, if postglacial tides in Fundy have increased, then Fundy has submerged up to 6 m

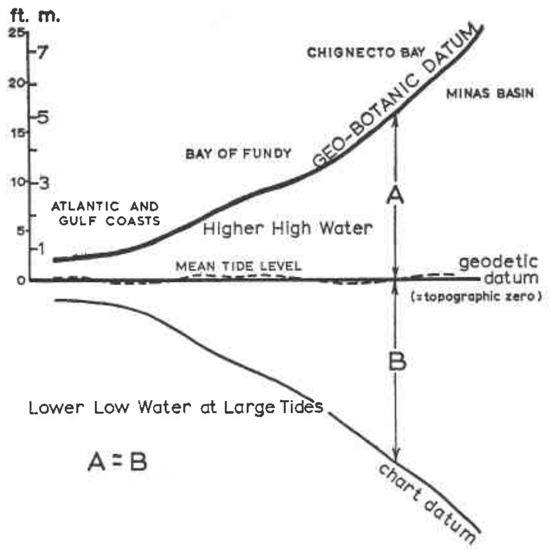

FIG. 12. Relationship of the geobotanical submergence Datum to Geodetic Datum.

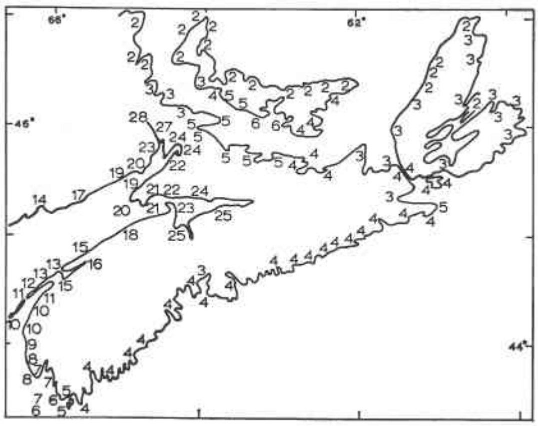

FIG. 13. Regional variation in the elevation of Datum (figures are heights in feet above Canadian Geodetic Datum).

more than the rest of the area, when measured with reference to a high-tide datum. The length of time taken to achieve the disparity, that is, the rate of tidal submergence, depends on when tidal amplification began increasing to the present 15-m range from the 2-m range elsewhere on the open Atlantic coast. The relative straightness of the submergence trend (Figs. 5 and 8) for the last 4000 years suggests the change began at least that early. Hence, the 30 cm/century Fundy submergence rate could be reduced, at most, by a factor of 6 m in 4000 years or 15 cm/century to remove the tidal effect, leaving a net submergence of 15 cm/century and thereby achieving a reconciliation with submergence rates elsewhere in the region. However, a more rigorous estimate of the starting date for tidal amplification is necessary before any meaningful apportionment of a tidal correction can be made.

Early Postglacial Tides

Beginning with the postglacial appearance of the Bay of Fundy about 14 000 years ago (Prest 1969), water levels were 45–70 m higher on the south and north coasts at the mouth (Prest *et al.* 1968). Average depth throughout the bay was then about 100 m, or 30 m more than at present. If tidal range is determined by the basin's natural period, which is given by Merian's formula:

$$\text{Period} = 4 \times \text{length}/\sqrt{g \times \text{depth}},$$

then the natural period at the high-level marine stage was only about 7 hours, and so out of phase with the main tide-producing force—the 12.42-hour lunar semi-diurnal component—that tidal range must have been minimal (D. B. Rao 1968).

Moreover, the corresponding position of eustatic sea level was 60–100 m lower. Shelf-edge Browns and Georges Bank were emergent, so that the Bay of Fundy did not then have the present free communication to the open Atlantic via the 400-km wide Gulf of Maine, but was part of a semi-enclosed body (termed the DeGeer Sea by Lougee (1953)), served only a 40-km strait between the Banks. Rao (1968) showed that tidal amplifications up the Bay of Fundy stems from the large ranges prevailing across the wide mouth of the bay. For this reason, D. B. Rao (personal communication, 1969) surmises that if the mouth of the system was once restricted to only one-tenth its present width, little if any tidal fluctuation could have been possible.

Thus, on both empirical and experimental grounds, early postglacial tides were minimal (except possibly for seiches), and geological evidence supports this hypothesis. Well-developed foreset stratification, indicating tides of less than 2 m, occurs in proglacial and postglacial deltas seen in southwestern Nova Scotia by the writer, reported from Minas Basin in the upper Bay of Fundy by Swift and Borns

(1967, p. 696), and mapped in southern New Brunswick by N. R. Gadd (personal communication, 1969).

Holocene Tidal Conditions

Following an initial period of insignificant tidal range, glacio-isostatic rebound in the Bay of Fundy produced falling relative sea levels, thereby reducing the effective average depth, and increasing the natural period. Meanwhile, rising eustatic sea level had begun to overlap the enclosing shelf-edge banks.

Referring to Figs. 14 and 15, which illustrate the critical relationship between eustatic levels and depth of threshold into the Gulf of Maine – Bay of Fundy system, it appears that prior to 8000 years ago, threshold width was less than half the present width, effectively precluding any possibility of tidal amplification. At 8000 years B.P. the sea overtopped Georges Bank, greatly increasing the width of the entrance, but average depth was negligible. By 7000 years ago, although threshold width had suddenly increased to 90% of present width, average depth was still only a few meters.

Thereafter, depth and not width was the controlling factor and probably therefore it was not until 6000 years ago that threshold cross-sectional area was large enough to begin its history of determining the ultimate range of any tides 'upstream'. The nature of tidal hydraulics is such that the ensuing amplification would be non-linear, probably exponential, with time. A suggestion of the inferred growth of tides is appended to Fig. 15. It is believed that by 4000 years ago most of the impedance to large flux through the threshold cross-section was removed, after which most of the increase in tidal range could transpire. Hence most of the present range difference of 20 ft (6 m) (or 24 ft (7.3 m) if the DeGeer Sea began tideless), which is inferred as the exaggerating submergence factor, has been created during the past 4000 years. Therefore, cancellation of the tidal effect involves a simple rotation of the submergence curve upward from the 4000-year depth by 6 or 7 m, or at least 15 cm/century. The Bay of Fundy submergence rate of 30 cm/century exclusive of tidal effects, is thereby transformed to a rate equal to or slightly less than the rate of 15 cm/century on the Atlantic coast. However, a negative anomaly, of 7–9 cm/century with respect to the Florida eustatic rate, still remains.

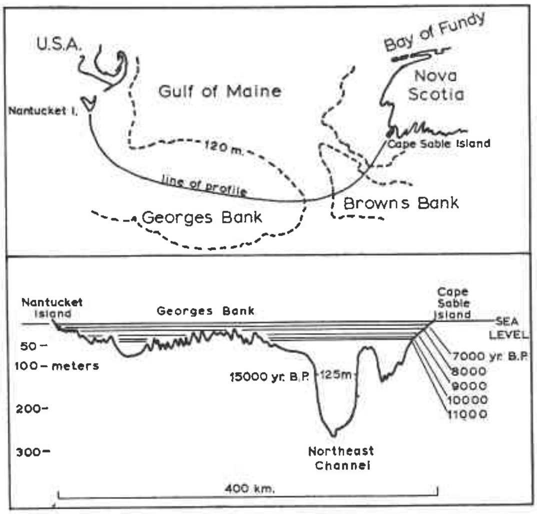

FIG. 14. Eustatic rise of sea level in relation to the longitudinal profile of the threshold to the Gulf of Maine.

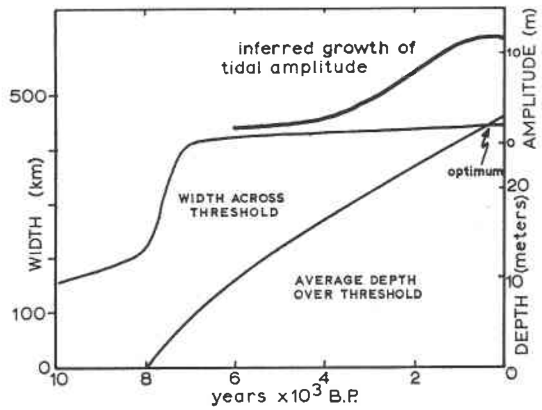

FIG. 15. Inferred tidal amplification (= rise of high-tide Datûm) in the Bay of Fundy as a function of increasing depth and width of the entrance to the Gulf of Maine due to eustatic rise of sea level.

Additional Factors

Neither tidal amplification nor water-load subsidence account fully for the anomalous rate at which the Maritimes have been submerging. Deducting these effects plus the eustatic constituent leaves a net rise of 3–9 cm/century unexplained. Other mechanisms capable of independently depressing the land surface or elevating the sea surface might be examined.

Atmospheric and Oceanographic Elevation of Sea Level

Certain postglacial changes may have raised sea level, much like shorter-term climatic fluctuations produce marked perturbations of water level. For example, the sea surface responds like an inverted barometer to atmospheric pressure at the rate of 1 cm/millibar pressure decrease. North of latitude 40 degrees, sea level annually fluctuates 15 cm due to seasonal pressure change (Lisitzin and Pattullo 1961). Lamb *et al.* (1966) showed a long-term decrease of mean annual surface barometric pressure during the last 4000 years over the Maritimes region, which would have caused a definite, albeit small, rise in sea level. Secondly, sea level responds directly to heat content like a thermometer. Inasmuch as the present annual water-temperature cycle of 8 °C, at Bermuda for example, produces a yearly sea-level change of 20–30 cm (Donn *et al.* 1964), the postglacial increase of sea-water temperature of 6 °C or more could therefore have raised sea level by several centimeters in the last 4000 years. Heat content was further increased by advection due to changing wind patterns (as pC air masses prevailing during glacial times were gradually replaced by mP and mT air masses) and current patterns (as the Labrador Current weakened, allowing the Gulf stream to approach within 150 miles (240 km) of Nova Scotia). However, sea-level rise by all means of thermal expansion was probably less than 1 cm/century. Finally, postglacial wind changes may have raised sea level locally by the "set-up" effect. The paleo-isobaric maps of Lamb *et al.* (1966) show a shift of geostrophic winds that would have progressively increased on-shore stress components. Each of the above processes could have produced a small secular rise of ocean level within the Maritimes region, and although they were concurrent and therefore cumulative, the net change could only have been a relatively minor portion of the anomalous measured rise of sea level.

Other Subsidence Mechanisms

Long continued epeirogenic downwarping is reflected in the geologic framework. The continental shelf is the submerged portion of a coastal plain comprising one flank of a geosyncline centered under the continental rise. Several thousand meters of Mesozoic and Tertiary sediments, and several hundred meters of shallow-marine, Oligocene–Miocene sediments underlie the Scotian Shelf, indicating deposition in a subsiding basin (Bartlett 1968; Marlowe 1969). The ages and thicknesses imply an average subsidence rate of less than 1 cm/century.

A more recent kind of subsidence may be of greater magnitude. Emery and Garrison (1967) concluded that excessive submergence of the Atlantic Shelf was due to subsidence caused by northward flow of subcrustal material to compensate for rebound of formerly depressed, glaciated areas. Newman and March (1968) concurred, and suggested that a collapsing bulge, peripheral to the last ice sheet, could be a specific source of the subcrustal excess and a locus of the subsidence. McGinnis (1968) found that such a bulge was a natural mechanical consequence of subglacial loading and submarginal tilting, and predicted that the uplifted belt should be 80–185 m high along an axis 66 km from the ice front. Possible evidence for a former bulge might be the belt of unglaciated Tertiary strata on the Scotian Shelf, 50 km wide and 30–50 km beyond the last glacial limit, that shows dissection to depths 100–200 m below the lowest probable Wisconsin eustatic sea-level position of −130 m. If such a bulge did exist on the shelf off Nova Scotia it would still be subsiding, but the present coast would be participating very little, if any in the subsidence, unless the bulge tended to follow the retreating ice northward, in which case present coastal subsidence could amount to several centimeters per century.

Summary and Conclusions

Maritimes' submergence rates greatly exceed the eustatic rate, as do the rates for other sites farther south along the Atlantic coast. The crustal subsidence that has been inferred for the latter region, has probably also exaggerated the Maritimes' relative change.

One source of subsidence is crustal deflection caused by the load of postglacial eustatic rise of sea level. This mechanism accounts for most if not all of the submergence anomaly along the Atlantic coast of Nova Scotia.

The Bay of Fundy, in contrast, owes about half of its excessive rate to differential rise of the high tide datum through increasing tidal range. Before 8000 years ago, emergent banks effectively isolated the Gulf of Maine from Atlantic tidal dynamics. Tidal amplification in the Bay of Fundy commenced about 6000 years ago, but most of the differential accumulated during the last 4000–5000 years.

Even after allowing fully for tidal change and water-loading, a residual submergence of 3–9 cm/century remains, part of which could be a combination of additional subsidence due to geosynclinal downwarping and relaxation of a former ice-marginal bulge. The inadequacy of all of these factors combined seems to implicate additional regional tectonism.

Acknowledgments

I am grateful to the Geological Survey of Canada for generous support of all field work and for the twenty-five radiocarbon dates that form the bulk of the evidence. J. G. Fyles suggested the topic and V. K. Prest, as project supervisor, expedited the research in many ways. Also with the Department of Energy, Mines and Resources, G. C. Dohler, chief tidal officer, advised on present tide conditions, while D. B. Rao, formerly Marine Sciences Branch, helped reconstruct former tide conditions. I. K. Crain, formerly Computer Science Division, wrote the program that mapped water load over the Maritimes. At Cornell University, A. L. Bloom directed the research, while J. P. Barlow and S. S. Philbrick advised on oceanographic and engineering aspects respectively. My brother, Ian Roger Grant, University of Waterloo, produced the mathematical expression for crustal deflection as a function of water load. H. H. Harries, Mount Allison University, helped establish the ecological basis for defining Datum. J. T. Neelands assisted the field study in 1967. This paper greatly benefited from critical reading by K. O. Emery.

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