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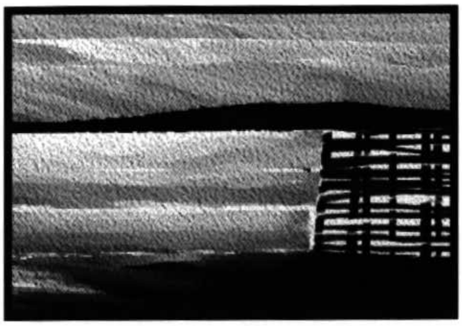

Bay of Fundy Tides

Con Desplanque
27 Harding Avenue
Amherst, Nova Scotia B4H 2A8

David J. Mossman
Department of Geography
Mount Allison University
144 Main Street
Sackville, New Brunswick E4L 1A7
dmossman@mta.ca

SUMMARY

Eastern Canadian seaboard tidal characteristics result from a combination of diurnal (daily) and semi-diurnal (twice daily) tides, the latter mostly dominant. Because of the proportions of the Bay of Fundy, differences in tidal range are governed by near resonance with Atlantic tides. Exceptionally high Fundy tides result from this phenomenon, with upper reach tidal ranges commonly >15 m. Although Fundy tide curves are sinusoidal, tide prediction requires consideration of marked diurnal inequalities. Overlapping of the cycles of spring and perigean tides every 206 days results in an annual progression of 1.5 months in the periods of extra high tides. Strong tides can occur at all seasons, depending on the year. Considerable variation results throughout the year, with six distinct cycles recognized. Tides play a major role in erosion and in complex interactions among Fundy physical, sedimentological, biological, and chemical processes. Recent observations on mud flat grain size alterations, overdeepening areas of the sea bed, and benthic community changes, indicate changing environmental conditions in the Bay, possibly caused by increased hydrodynamic energy in the system.

RÉSUMÉ

Les marées de la bordure marine orientale canadienne sont caractérisées par une combinaison de marées diurnes (une fois par jour) et semi-diurnes (deux fois par jour), les dernières dominant la plupart du temps. Étant donné les dimensions de la Baie de Fundy, les variations d'amplitude des marées sont déterminées par un phénomène de quasi-résonance avec les marées de l'Atlantique et, les marées exceptionnellement hautes de la Baie de Fundy sont une manifestation de ce phénomène; des amplitudes de marées dépassant les 15 m ne sont courantes. Bien que le tracé des marées de Fundy soit sinusoïdal, on doit tenir compte de fluctuations diurnes marquées dans la prévision des marées. L'effet combiné des cycles de marées de vive-eaux et de périgée, à tous les 206 jours, explique la progression (le décalage) annuelle de 1,5 mois des périodes des très grandes marées. Selon l'année, de fortes marées peuvent se produire en toute saison. Des fluctuations significatives qui se produisent annuellement, on a reconnu six cycles distincts. Les marées jouent un rôle majeur dans l'érosion et les interactions complexes des processus physiques, sédimentologiques, biologiques et chimiques de la Baie de Fundy. Les changements observés récemment dans la granulométrie des particules des vasières, le surcreusement du plancher océanique par endroits, ainsi que les changements dans la communauté benthique, sont autant d'indications de modifications environnementales dans la Baie de Fundy, résultat possible d'un accroissement de l'énergie hydrodynamique du système.

> ***I know not what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.***
>
> *Isaac Newton (1642-1727)*

INTRODUCTION

Tides, the longest of oceanic waves, are the periodic rising and falling of sea level due to the gravitational effects exerted on the Earth by the Moon and Sun. Tides thus generated in the deep ocean, in turn drive the tides in shallower waters along the continental shelf. Shelf width, water depth, and the shape of the coastline affect the tides even more than astronomical factors. This is illustrated by the exceptionally high tides found at the head of the Bay of Fundy between Nova Scotia and New Brunswick. Here, the tidal range pushes the 16 m mark at times of particular astronomical conditions, with or without exteme atmospheric influences.

Since time immemorial people have recognized that there is some connection between the tides and the positions of the Moon and Sun relative to Earth. The relative motions of these celestial bodies are by no means obvious, however, and their influence on tidal events results in complex flow patterns. Nevertheless, the magnitude of the effects which generate tides can be precisely calculated, the chief caveat being that the ocean's response is constrained by the presence and geometry of continental land masses, the Earth's rotation, the geometry of ocean basins, and the transience of weather. According to Newton's equilibrium tidal theory, an ideal wave forms instantaneously upon an earth uniformly covered by a deep layer of water, under the influence of the Moon's and Sun's gravitational effects. This theory is not actually intended to provide a realistic picture of what occurs in nature. However, it does allow very accurate prediction of the tidal periods, the relative forcing magnitudes, and the astronomical phases of the tides, considering only the astronomy (Clancy, 1969; OPEN, 1993). It is the cornerstone upon which tidal analysis and predictions are based.

Astronomical Effects

It is important to note here the three main astronomical reasons for these fluctuations:

1. *Variable distance between Moon and Earth.* This causes the greatest deviations from the average (mean) tide in the Bay of Fundy. Because the Moon's orbit is elliptical, once a month at perigee the Moon is closest to the Earth, and thus its gravitational pull the greatest, resulting in stronger than average tides. These so-called "perigean" tides recur every "anomalistic month" of 27.555 days.
2. *Variable celestial positions of the Moon, Sun and Earth relative to each other.* The cycle of the Moon's phases in which there are two sets each, of "spring" and "neap" tides, is the "synodical month" of 29.531 days. In the first set, spring tides are stronger than average because the Earth is either between the Sun and Moon (Full Moon), or the Moon is between Earth and Sun (New Moon). A week later, during the First or Last Quarter of the Moon, its gravitational influence is diminished by that of the Sun's, which is then acting at right angles. The resulting tides, weaker than usual, are called neap tides.
3. *Declination of the Moon and Sun relative to the Earth's equator.* Declination is the angular distance in degrees between a heavenly body and the celestial equator (the plane in which the Earth's equator is situated) when it passes through the local meridian. A complete cycle, in which the Moon crosses the equator twice, lasts 27.322 days and is called a "tropical month." However, it takes 18.6 years for the Moon to complete its cycle of maximum declination, ranging between 28.5° N and 28.5° S with reference to Earth's equatorial plane.

Bay of Fundy Tides

In the Bay of Fundy tidal predictions are made and published annually for the principal hydrographic station at the reference port of Saint John. A mathematical approach using harmonic analysis computes the actual tide as the combined effect of all the tide-generating variables. The result is a large number of cosine curves, so-called tidal constituents or "partial tides," each representing the influence or characteristic of the local tide. In practice, an accurate model of the actual tide can be computed considering just the seven main partial tides. Local tidal characteristics along the eastern Canadian seaboard result from a combination of diurnal and semi-diurnal tides. However, semi-diurnal tides are prevalent in the North Atlantic, and Fundy tides, amplified by resonance across Georges Bank and through the Gulf of Maine, are an integral part of the system (Davis and Browne, 1996).

Recent observations of the environmental characteristics of the Bay of Fundy suggest modern change in the dynamics of the system. These include changing grain size distributions on the tidal mud flats, anecdotal observations from the fishing community of increasing water depths in some areas, and changing benthic communities (Percy *et al.,* 1996). These concerns have led to a need to better understand the dynamics of the Bay of Fundy and efforts by concerned groups for a more detailed knowledge of seabed, oceanographic, and biological conditions. Could the changes observed apply to the entire tidal regime? Are the tides stable or are they increasing due to changes in water depth or resonance length of the Bay? What is the future of the tides and associated currents in the Bay? These are among questions central to the evolution of the Bay of Fundy and the sustainable management of its resources. In this paper we present an overview of the geology and evolution of the tidal regime in the Bay of Fundy, elaborate on the tides at Herring Cove, Fundy National Park, and examine the geological significance of the tides.

GEOLOGY OF THE BAY AND CHARACTERISTICS OF FUNDY TIDES

Geologic History

The Bay of Fundy (Fig. 1), a branch of the Gulf of Maine, originated during the Appalachian orogeny 286-360 m.y. ago. *Sensu stricto* a fault-bounded half-graben (Swift and Lyall, 1968), the rift boundaries of the Bay were established at the onset of the opening of the present-day Atlantic Ocean due to plate tectonic movements (Wade *et al.,* 1996). Sedimentary infilling began more than 200 million years ago during the Triassic Period (King and MacLean, 1976; Stevens, 1977). During a late-drifting stage immediately following the Triassic, basaltic lava erupted upon Triassic strata and was followed by dominantly clastic sediment deposition to the middle Jurassic (Mossman and Grantham, 1996). The entire sequence was then folded, uplifted, and tilted southwestward in a saucer-shaped structure. Cretaceous sedimentary deposits preserved in lowlands adjacent to the Bay of Fundy rest unconformably on Triassic and Carboniferous rocks (NATO, 1987), suggesting that the Bay of Fundy Basin may have been covered by Cretaceous (and possibly Tertiary) rocks, and subsequently exhumed.

Much of the 1400 km of the Bay of Fundy coastline consists of erosion-prone sandstones and conglomerates. Consequently, erosion rates exceed 1m/a in places like the Minas Basin (Amos, 1978), giving rise to a sandy estuary in which fine-grained clastic material accumulates in sheltered embayments. Certain coastal sections composed mainly of Paleozoic siltstones and shales, for example in Chignecto Bay (Amos *et al.,* 1991; Amos, 1995), contribute materials that persist in suspension through wave action and tidal cycling. Elsewhere, sections such as the basalt along much of the Nova Scotian coast, and the more massive igneous rocks, gneisses, quartzites, and limestones along the New Brunswick coast, are more resistant to erosion.

Glaciation has exercised very important controls on the geomorphology of the Bay of Fundy, as on its tidal regime. About 18,000 to 20,000 years BP the Laurentide ice sheet blanketed most of Canada and extended far south of the Great Lakes. Crossing the Bay of Fundy and the Gulf of Maine, its approach to the edge of the continental shelf left blankets of glacial outwash and huge terminal moraines peripheral to the ice sheet, as well as extensive drumlin fields. These deposits now form many of the banks and shoals along the Maritime and New England coastlines. Associated valley glaciers such as one believed to have occupied the Northeast Channel in the Gulf of Maine, were also a feature of the landscape (Grant, 1985, 1989). During the last glacial maximum they would have contributed to a global sea level lower by 100 m to 130 m than at present. Thus the Bay of Fundy has a sea level history in two major phases, namely an early glacial emergence, and a present continuing submergence.

During the last 14,000 years the depth of the Bay of Fundy changed appreciably as the Pleistocene land surface rebounded and sea level rose as the last ice sheets receded. Exploring the details of this region's geological history, and Holocene sea level fluctuations, is far beyond the scope of this paper. However, one of the main features of the Bay's post-glacial evolution was the depth of water over Georges Bank; inflow of tidal waters was evidently restricted at the lowest point of relative sea level (Scott and Greenberg, 1983). With progressive submergence of Georges Bank, the Bay of Fundy became more directly subjected to tidal forces. Mathematical modelling of the Gulf of Maine tidal system indicates that 7000 years BP, tidal ranges will have been 20% to 50% of the present range (Greenberg, 1979, 1987); by 4000 years BP they would have grown to 80%, reaching present strength about 2500 years BP when mean sea level was *ca.* 7 m lower than present. There is general agreement too, concerning continued sea level rise and bottom scouring, and that the macrotidal features of the Bay of Fundy continue to increase and evolve (Bleakney, 1986; Godin, 1992; Fader *et al.*, 1996). The timing of increased resonance is controversial, however. This is because geological evidence from detailed salt marsh records (Shaw and Ceman, 1999) indicates that tidal range was relatively subdued *ca.* 4000 years BP, a point earlier inferred by Grant (1970).

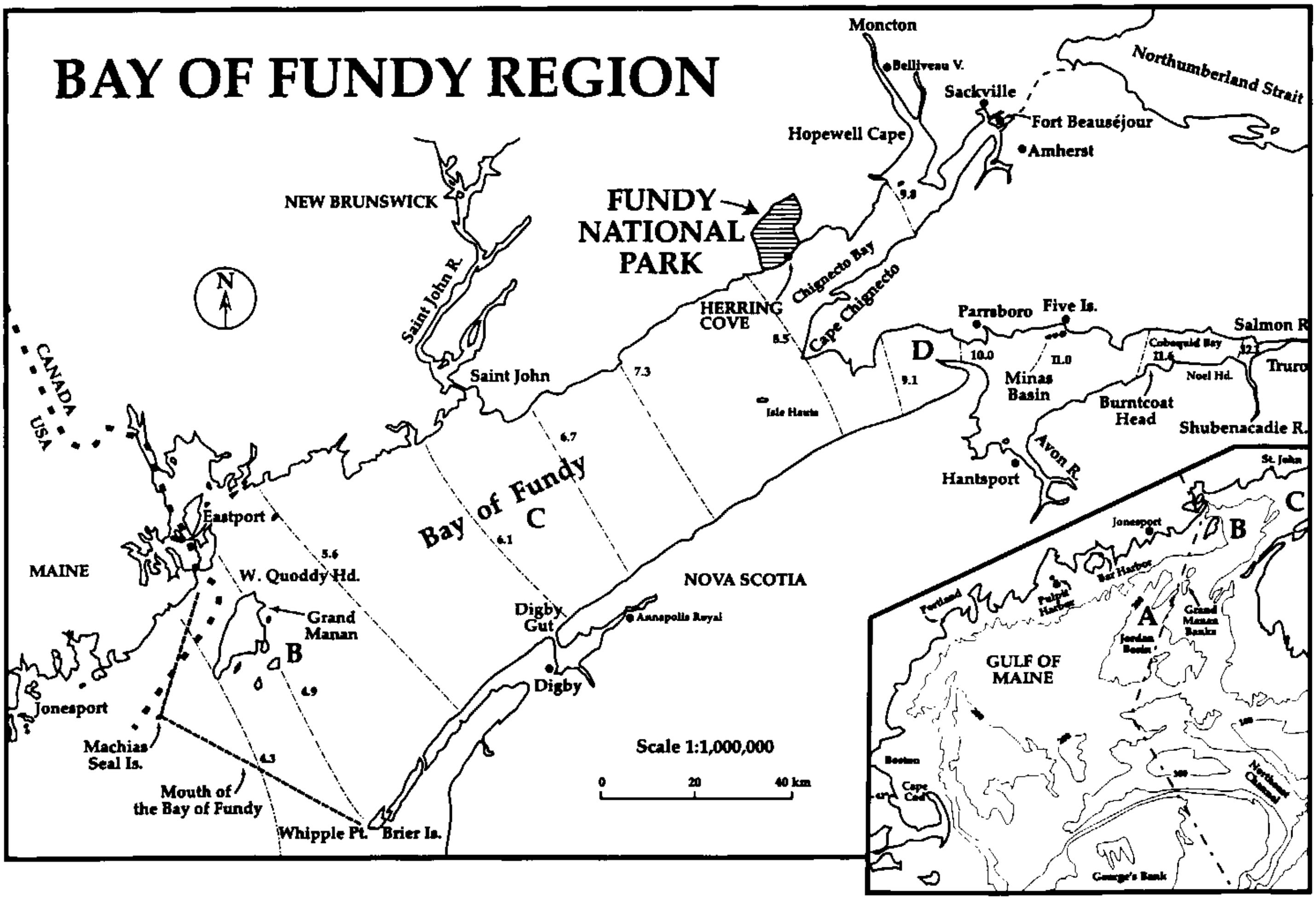

Figure 1 Location map of the Bay of Fundy and inset showing Gulf of Maine indicating various features and place names. Contours (broken lines) across the Bay at various locations show the mean tidal range at intervals ranging from 0.5 m to 1.3 m.

Resonance and Range of Modern Fundy Tides

Impelled by the oceanic tide through the Northeast Channel and across the Gulf of Maine (Fig. 1), an average single tidal flow into the Bay of Fundy matches the estimated total daily volume (*ca.* 104 km^3) of all the world's river discharges into the oceans (Clancy, 1969; Desplanque and Mossman, 1998a). Thus, during a lunar day (24 hours and 50 minutes), the water moving in and out of the Bay of Fundy is actually four times the combined discharge of all the world's rivers. During exceptionally high tides this volume may exceed 146 km^3 every 6.2 hours.

In effect, the tidal energy channelled into the Bay creates a slow, large-scale oscillation, or "seiche." Tremendous tidal amplification may occur through this near-resonant response. A comparison with the pendulum movement of a grandfather clock is instructive. In this instrument, the visible movements of a heavy pendulum are maintained by an imperceptible downward-moving weight, keeping the pendulum going through the escapement mechanism. By analogy, the oceanic tides maintain a co-oscillating seiche, and thus the tidal movements in the Fundy–Gulf of Maine–Georges Bank (FGM) system.

The appropriate formula describing these conditions (for an open basin like the Bay of Fundy) is given by:

$$\mathbf{T} = 4\mathbf{L}/(\mathbf{g} \cdot \mathbf{d})^{0.5}$$

where **T** is the resonant period in seconds, **L** the length of the basin in metres, the acceleration of the Earth's gravity **g** = 9.8 m/sec^2, and **d** the depth in metres.

Rao (1968) calculated the natural resonant period of the Bay of Fundy as approximately 9 hours. Garrett (1970) showed that the resonance of the Bay is combined with that of the Gulf of Maine to give a period of about 13.3 hours, a figure in agreement with Greenberg's (1987) estimate. This is very near resonance with the semi-diurnal Atlantic tide of 12.42 hours. Further complicating simple resonance calculations is tidal friction, which is believed to subtract considerable energy from the system (Greenberg *et al.*, 1996). Thus, accurate determination of the degree to which true resonance is approached in the Bay of Fundy is not a simple matter.

Resonance in the Bay results in high tidal amplitude and a tidal range several times greater than the open ocean tide. Tides at Bar Harbor, with a mean range of 3.1 m, result from the increase in the mean range in the oceanic tides of 0.9 m, through the Northeast Channel and across the Gulf of Maine over a distance of 335 km. At the mouth of the Bay of Fundy (Fig. 1) the average range of the tides is 5 m, halfway into the Bay, 7.3 m, and at the head of Chignecto Bay near Belliveau Village New Brunswick, 12 m, which at times can reach 15.2 m.

At Burntcoat Head, Nova Scotia, in Minas Basin near the head of the Bay (Fig. 1), the maximum range between successive low and high tides was observed on 16 July 1916 by Dr. William Bell Dawson, Superintendent of Tidal Surveys, being 53.43 feet (16.29 m), a world record. Here the mean range of 12.1 m is amplified about 13.5 times in relation to the oceanic tides over a distance of 735 km (Dawson, 1920). The difference between high tide and low tide in the upper reaches of the Bay of Fundy is illustrated in Figure 2.

In many estuaries and bays around the world, the range of the tides increases exponentially with distance.

Figure 2 Views 6 hours apart, of tidal conditions in the Shepody River estuary of the Bay of Fundy, during the summer of 1954, 2 years before the Shepody River dam was constructed near Riverside-Albert, New Brunswick. Photographs by Con Desplanque.

This is the case in the FGM system where, as the semi-diurnal tides advance, their range increases exponentially at a rate of 0.35% per km. This important relationship is relevant to issues as diverse as determining tidal boundaries (Desplanque and Mossman, 1999a) and evaluating proposed tidal power generation schemes in the Bay of Fundy (Gordon and Dadswell, 1984).

The Importance of Diurnal Inequalities

As noted above, the strength of tides is mainly modified by changing distances between Earth and Moon, and because the Sun and Moon act individually from varying directions. Diurnal inequalities (the range of successive tides is not the same) are due to changing declinations of the Moon and Sun with respect to the plane of the Earth's equator. The strongest diurnal inequality is possible when spring tides occur during the solstices, when both celestial bodies are near their maximum declination and acting together. As seen from the Earth, the Sun appears to move through the plane of the ecliptic, which makes an angle of 23.452° with the equator (see Fig. 3). The Sun is overhead at local midday at the equator on 21 March and 23 September, and the length of the day and the night are the same everywhere on earth. The Sun is said to have a north declination between the spring and fall equinoxes, and a south declination during the remainder of the year. It reaches its maximum north declination of 23.452° at the summer solstice in June (Fig. 3). The Moon goes through a shorter declinational cycle, lasting 27.322 days.

Figure 4 shows that due to inertia, in a frictionless system, the tides lag behind the forcing function by about 12 hours. To illustrate, assume that at noon, 21 June, there is a solar (or lunar) eclipse (see Figs. 4A, B) over the Greenwich meridian. At this time, in theory, the center of one "bulge" would be at, say 23.5°N, 0° longitude, the other at 23.5°S on the 180° meridian. In theory, the bulge should be over the Fundy area (65°W) around 16:00 hr GMT (*i.e.*, about noon, local time). However, observations in the Bay of Fundy will show that Higher High Water (HHW) on that day will occur at midnight (24:00 hr), and Higher Low Water (HLW) around 18:00. The peak of diurnal inequality will occur around 21:00, or about 9 hours later than the theoretical time.

In contrast, during a solar (or lunar) eclipse on 23 December (Figs. 4C, D) a "bulge" would occur around midnight north of the equator on the dark side of Earth. However, the peak of the diurnal tide would be around 9:00, with HLW about 6:00 hr, and HHW around noon. Thus in the Bay of Fundy, the HHW in spring and summer (*i.e.*, between the equinoxes) occurs during the nighttime (6 p.m. to 6 a.m.) and during the fall and winter (September to March) during the daytime. For the same reason Lower Low Water (LLW) occurs in spring and summer between midnight and noon (morning), and during fall and winter between noon and midnight (afternoon and evening). This situation results in a close coupling between tidal forces and biomass behaviour and production (Gordon *et al.*, 1985) especially in the macrotidal conditions in the upper part of the Bay. It also plays an important role in determining sea surface temperatures (*cf.* Cablio *et al.*, 1987) and winter ice conditions in the Bay (Gordon and Desplanque, 1983).

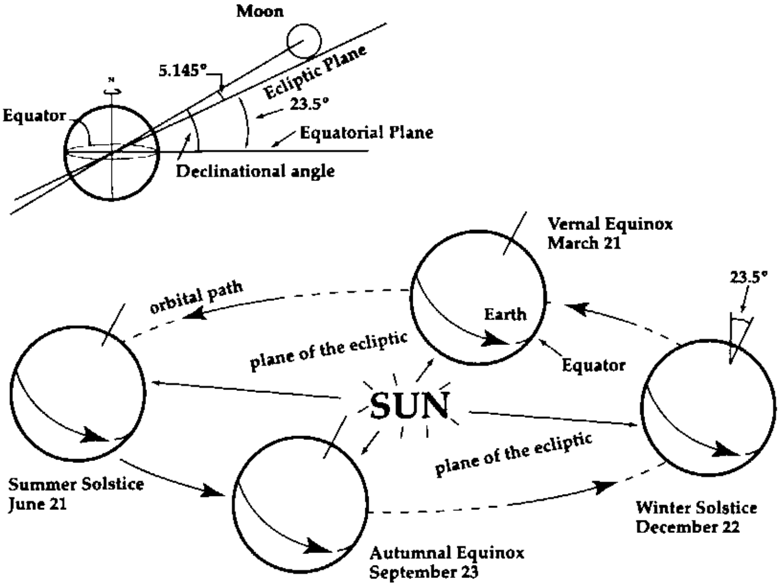

Figure 3 Earth's equator makes an angle of about 23.5° to the plane (ecliptic) in which it moves around the sun. The noonday sun at the summer solstice stands over 23.5° N latitude, and at the winter solstice over 23.5° S latitude. Adding to Earth's tilt, the Moon is at an angle of about 5° to the ecliptic; its declination is thus more variable than that of the Sun.

TIDES AT HERRING COVE, FUNDY NATIONAL PARK

Tidal Cycling

In the Bay of Fundy there is a close correspondence between the high tides predicted on the basis of astronomical conditions and those observed. This is demonstrated in Figure 5, which reveals the cyclic behaviour of the tides at Saint John, New Brunswick, over a 20 year interval. Thus, the 206 day perigee/spring tide cycle is clearly evident, as are its matching cycles at 14 month, 4.5 year, and 18 year intervals. Over the long term, exactly the same phenomena will be mirrored in the tidal behaviour at Herring Cove because throughout the Bay, all tides show virtually the same variations except for the range of local tides.

It is, however, instructive to examine more closely the variations in tidal cycles over the course of one year at Herring Cove. For example, in 1988 (Fig. 6) there were 706 tidal cycles: on most days there are two High Waters and two Low Waters, being the highest and lowest levels predicted. The levels are measured from the Mean Water Level (MWL) that the water surface would assume if no tide-producing gravitational influences of Moon and Sun were present. Of course, if the combined gravitational influences of Moon and Sun remained constant, the tidal fluctuations would also remain constant. However, the influences of the Moon and Sun do not remain constant, neither in strength nor direction.

As noted above, the angle of maximum declination of the Moon changes over a 18.6 year cycle. Thus, the situation depicted for Herring Cove in Figure 6 will not be duplicated until 2005 A.D. In 1987, the Moon's declination reached its maximum value. On 6 December 1987 the Full Moon was as high above the horizon as it could be. When the Moon is exactly above the equator, as happens every 13.6 days, there will be no difference in strength of the two daily tides (no diurnal inequality). But the inequality soon reappears and will be strongest 7 days later, when the Moon is either in its most northerly or southerly declination. At Herring Cove, this inequality results in differences in level reached by the daily tides of as much as 0.86 m for High Waters and 0.78 m for Low Waters. This occurred in January, July, and December, 1988 (see Fig. 6); however, these differences disappear every two weeks as indicated where the HHW and LHW curves intersect, likewise the the LLW and HLW curves.

Since the New Moon is never more than 5° different from the Sun's declination, there is a close relationship between the Sun's declination, the phase of New Moon and its declination. Therefore the maximum diurnal inequality is centred on spring tides in June and December, and the weakest inequality during neap tides in March and September. When the perigean and spring tides coincide in June and December, the diurnal inequality causes one of the daily tides to be extra strong. This phenomenon, when combined with storm conditions, presents grave risks of destruction for property owners and settlements along the coastal zone (Taylor *et al.*, 1996; Desplanque and Mossman, 1999b).

One can expect stronger than usual tides a few days later than Full and New Moon, and weaker tides near the Quarter phases of the Moon. There is a certain inertia in the development of the tides, analogous to the fact that the months of July and August are, on average, warmer in the northern hemisphere than June, when the days are longer and the Sun is higher. Doubtless, friction is also an important constraint. For these reasons the highest tides occur a few days after the astronomical configurations which induce them.

Thus, as detailed in Figure 6, perigean tides at Herring Cove in 1988 coincided with one of the month's set of spring tides around 19 February. Perigee occurred on 17 February at 11:00 AST, while the New Moon occurred on the same day. One of the highest tides of the year (5.53m+MWL) was expected with a delay of 48 hours shortly after noon on 19 February. On the same day the water

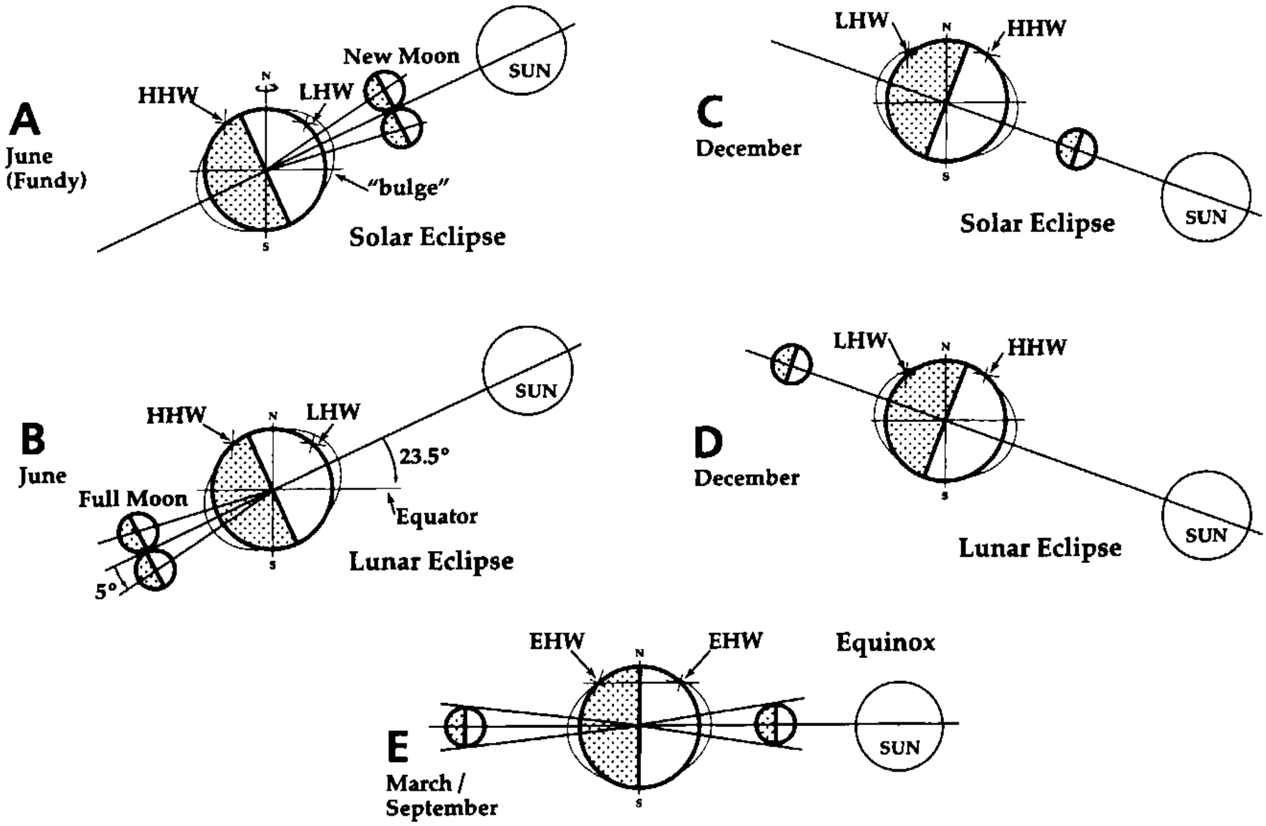

Figure 4 Contrasts in diurnal inequalities developed in Bay of Fundy tides are greatest when spring tides occur during the solstices when Sun and Moon are near maximum declination and acting together (A to D); HHW = Higher High Water; LHW = Lower High Water; During the equinoxes there is little diurnal inequality and therefore Equal High Water (EHW) occurs day and night (E). Note: the declination of the Moon in June and December will not be exactly 23.5°, but anywhere between 18.5° and 28.5° (see text for details).

was predicted to drop to its lowest level (5.87m-MWL). On 25 April, when apogee coincided with a Quarter phase of the Moon, the water dropped shortly after midnight to 2.79 m below Mean Water Level. One might expect the lowest High Water levels near the days that apogee coincided with one of the Quarter phases, as on 23 May or 1 December, when the water was expected to reach levels of 3.20 m+MWL. This is considerably higher than the predicted level of 2.70 m+MWL on 12 February, 12 March, or 22 August 1988. The explanation is that the first two dates were close to zero declination with nearly equal High Waters, while the latter three were close to maximum declination with 0.7 m diurnal inequality.

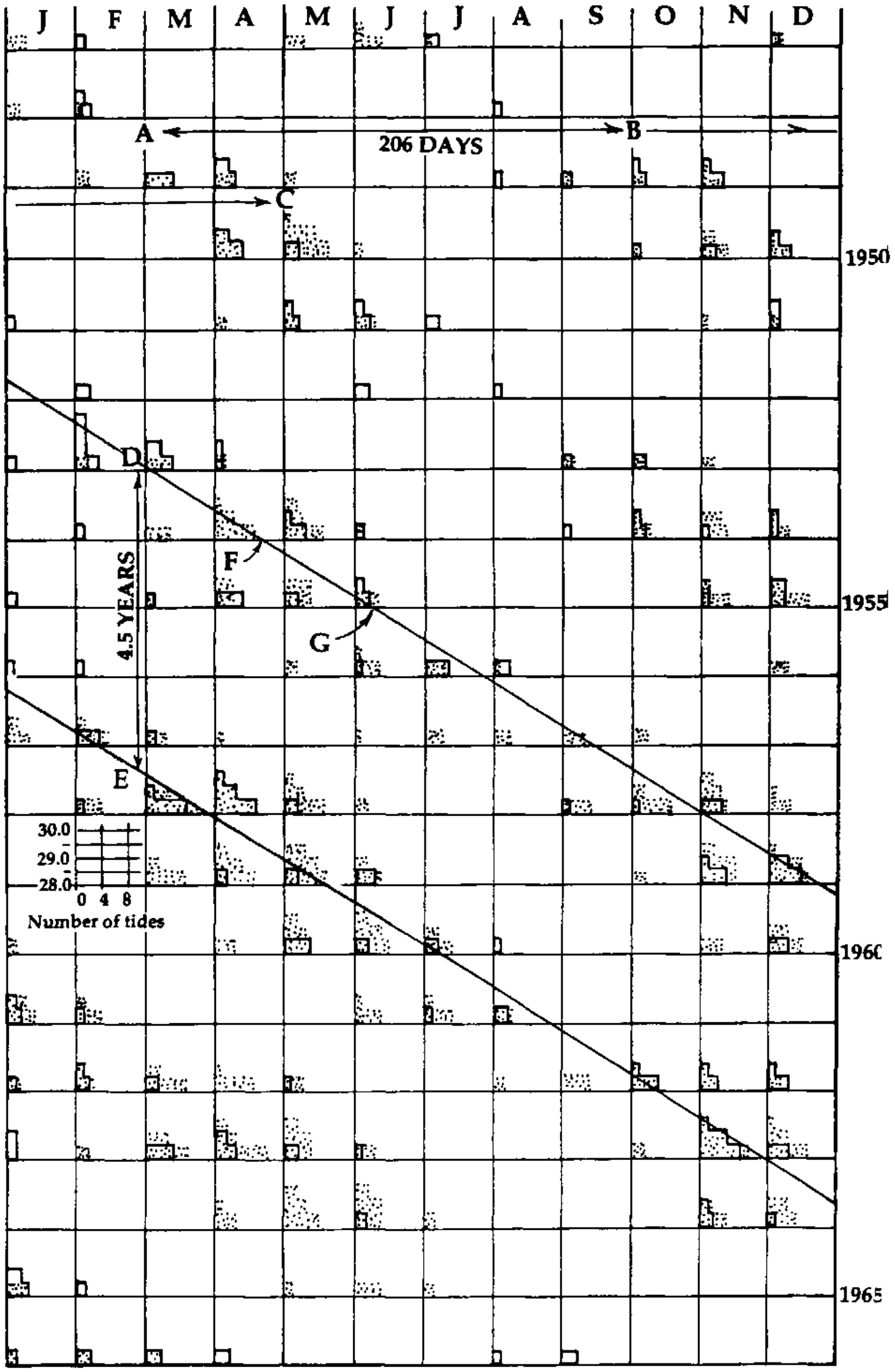

Figure 5 Number of predicted (dotted areas) *versus* observed (areas enclosed by solid block extreme High Waters per month at Saint John, New Brunswick, for the interval 1947 to 1966. Cyclic behaviour of the tides is indicated by the 206 day perigee-spring tide cycles at 7 month (A to B), 14 month (A to B to C), 4.5 years (D to E, vertically), and 18 year intervals. Also shown is the number of tides that reached 28.0 feet (8.5 m) and higher, abo Chart Datum. Note how the peaks shift 48 days (F to G - where the sloping lines cross the horizontal axis) to a later date each year.

Note that two weeks before or after 19 February, the spring tides coinciding with Full Moon were not much higher than average tides. This is because the Moon was at apogee. This situation is repeated after about 6 and 7 months when, in September and October, the Full Moon occurs close to perigee. The 206-day cycle of perigean tides coincident with spring tides occurs all over the world, but it is far more pronounced (and far more important!) in the Bay of Fundy because of the great tidal range. Two of these cycles last 412 days, meaning that each year the date that perigean tides are close to Full Moon is 47 days or about 1.5 months later on the calendar. This shift means that extra strong tides in the Bay of Fundy can occur during all seasons, depending on the year of observation.

IMPACTS OF BAY OF FUNDY TIDES

Erosion: A Specific Case

The geological significance of the Bay of Fundy tides is doubtless most evident when linked to processes of erosion and sedimentation. A case in point is the effect of waves along some sections of the Fundy shore. Consider, for example, the shape of the curved erosional indentations in New Brunswick's rocky shoreline. Recall that throughout the Bay of Fundy, the tidal range in absolute figures is high. Wave energy is concentrated near the surface of the water. One can also assume that the zone of the shoreline near the water surface will be most heavily subjected to wave action. Furthermore, during high water the foreshore is covered by a significant depth of water, and a much larger percentage of wave energy reaches the shoreline than when the tide is at low water.

Measurements of tidal levels conducted at Saint John, New Brunswick over an arbitrary 18 year interval are instructive (Fig. 7). Note that the percentage of time that the tide water surface is in the upper or lower x% of the tidal range can be calculated for any tidal cycle, given that the amplitude ranges from 0 to 1, or stated otherwise, from 0° to 90°. In the case of, say, the upper or lower 10%, the range is: [(arc sin 1 - arc sin 0.9)/90 · 100] = 28.7%. This figure contrasts with the percentage of time that the water surface spends in passing through the central 10% of the range. This later figure, calculated as (arc sin 0.05 - arc sin 0.0)/90) · 100 · 2), amounts to only 6.4 % of the cycle. Figure 7 (solid curve) shows clearly the focus of erosion exercised by tidal processes at Saint John upon a vertical profile of the shoreline over 18 years.

A specific example is provided by "The Rocks," a tourist attraction at Hopewell Cape, New Brunswick, just east of Fundy National Park (see Fig. 8). Here, the continually sculpted erosion profile is a true reflection of the total time that the water surface is situated at certain levels throughout all tide cycles (Desplanque and Mossman, 1998a; *cf.* Trenhaile *et al.*, 1998). The profile corresponds only with the upper half of the "% Delta t" line indicated in Figure 7. This is because the bottom half of the profile could not be formed due to the collected debris protecting the lower rocks from wave action.

Owing to high tidal range, wave energy is expended over a considerable range of elevations, the highest being those in certain estuaries leading into the Bay. Using marigrams of various Bay of Fundy estuaries, we have documented the progressive reshaping of the tidal wave over its course and how its sediment-carrying and erosional capacities vary as a consequence of changing water surface gradients; likewise, how intertidal ice conditions contribute additional variations to an already complex tidal regime (Desplanque and Mossman, 1998b). Clearly, Bay of Fundy tides play significant roles in a range of important geological processes centered on erosion and sedimentation, and bearing directly on coastal construction/installations, dredging, dam and causeway construction, fishing *etc.*, (Daborn and Dadswell, 1988; Thurston, 1990; Percy *et al.*,1996).

Sedimentation and Related Processes

Current regimes are critical to sediment dynamics and have significant scientific and economic applications, especially in the area of environmental marine geology. The results of Pelletier's (1974) pioneering work in the Bay of Fundy suggested that major pulses of hydrodynamic energy

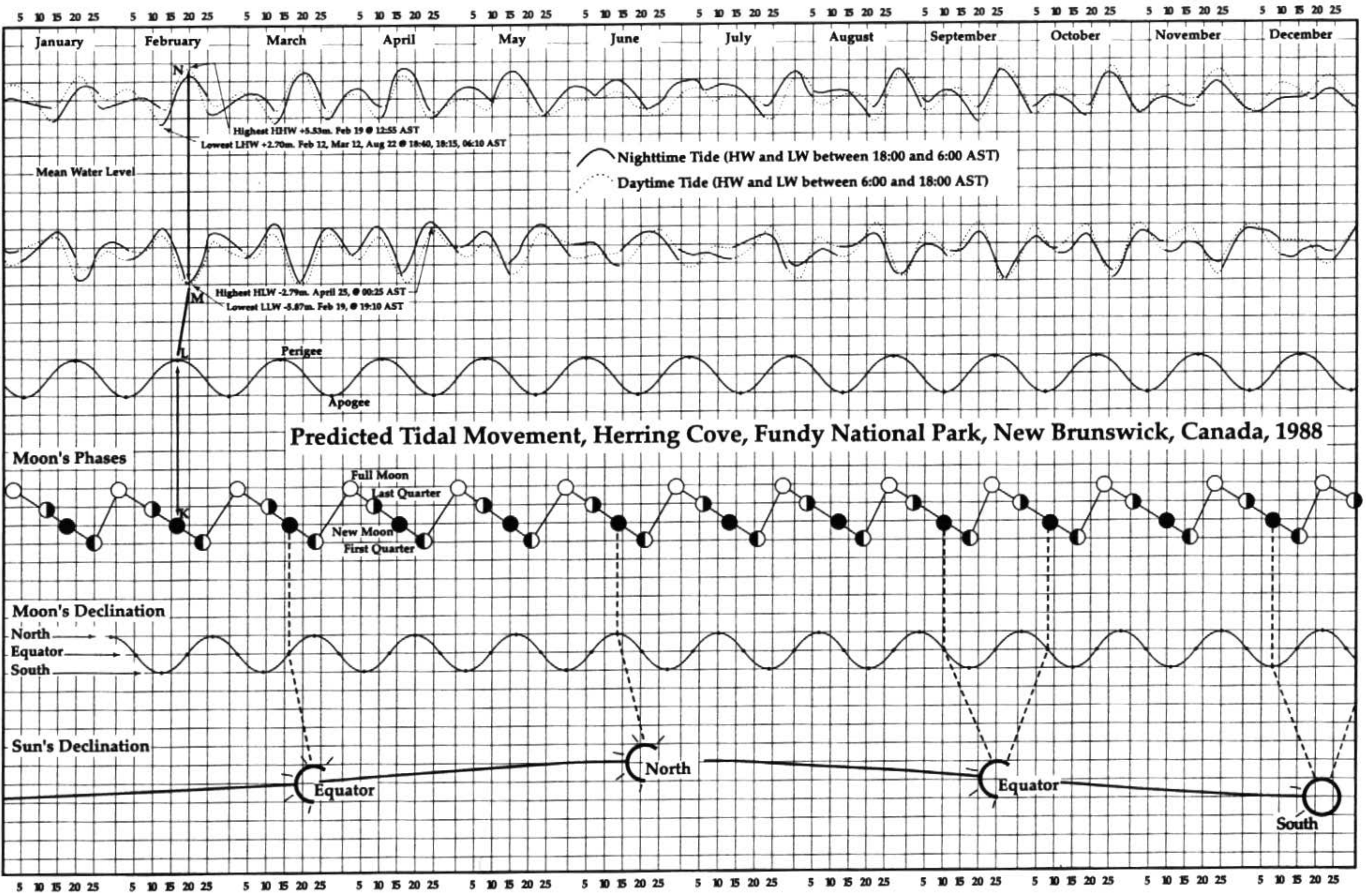

Figure 6 Chart shows predicted tidal movements throughout 1988 at Herring Cove, Fundy National Park, New Brunswick. Solid lines indicate nighttime tides (HW and LW between 18:00 and 06:00 AST). Daytime tides shown by dotted lines (HW and LW between 6:00 and 18:00 AST). Moon's distance, phases and declination, and Sun's declination are shown. Note (KLMN) the coincidence of Full Moon and perigee just before the year's highest (and lowest) tides on 19 February.

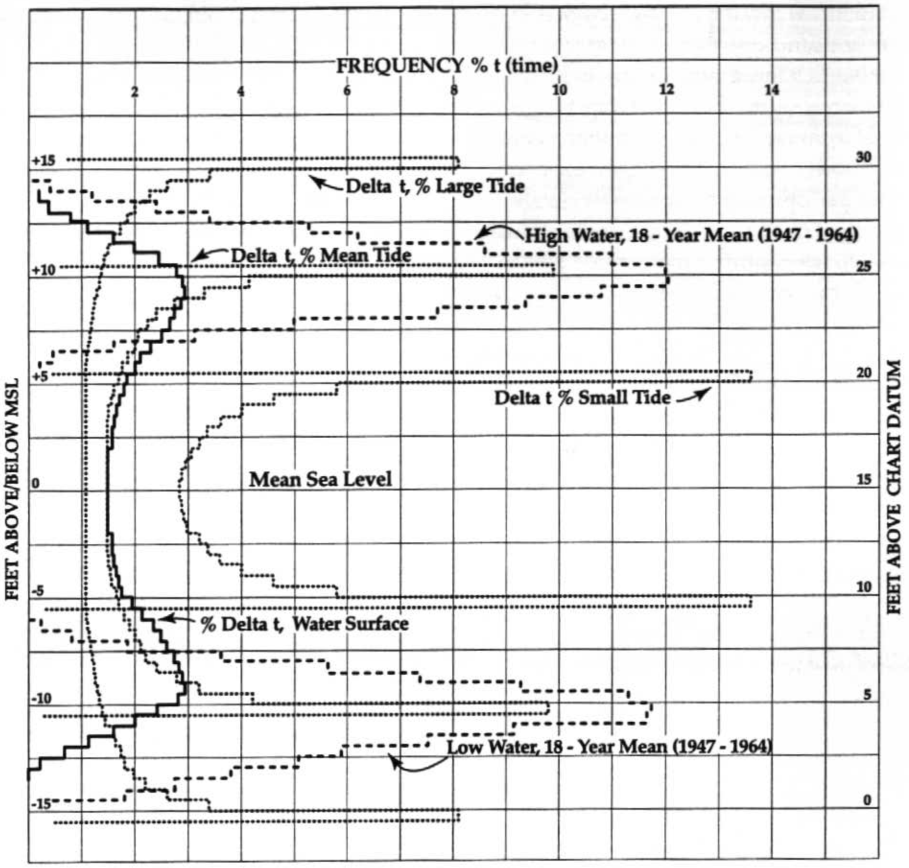

Figure 7 An 18-year record at Saint John, New Brunswick (1947-1964). Three histograms (dotted lines) show profiles across the average range of: large tides, mean tides, and small tides, giving the percentage of time that the water surface is located at a particular elevation during different tides [Mean Sea Level (MSL) = 14.36 feet + Chart Datum (CD)]. The histograms also show the percentage of occurrence at high water and at low water of the water surface at particular elevations (with respect to MSL and CD) during observed tides. Data apply to 1949, 1958 and the average for the period 1947-1964. There is a slight variation in the MSL record during this time. The two curves (broken lines) show the 18-year mean frequency (Delta t) of (LW and HW) tides with respect to MSL. The area beneath the "% Delta t, water surface" curve (solid line) gives the percentage of time that the water surface occupied the indicated elevations.

are reflected in the coarse-grained sedimentary material concentrated as transverse bands across the central portion of the Bay and at the extreme eastern and western approaches. Pelletier (*ibid*, p.92) considered it likely that tidal velocities dominate over residual current velocities, and that interaction with the sea floor would produce a "wash-board" pattern of sediment distribution. His conclusions are elegantly complemented by the results of recent work by Fader *et al.* (1977, 1996) who have assessed surficial sediment stratigraphy, aggregate resources, and seabed dynamics of the inner Bay of Fundy using a new multibeam bathymetric mapping system. Fader *et al.* (1996) show the presence of extensive areas of thin gravel lag overlying thick glaciomarine sediments. Overlying the gravel are large transverse fields of active sand bedforms, likely formed by winnowing processes initiated by increases in tidal range *ca.* 8000 years BP. The numerous symmetrical sand waves range in length from 0.3 km to 0.8 km and are oriented normal to the length of the Bay.

Fader *et al.*'s (1996) interpretation of the bedforms and related processes suggests that the large sand waves are presently inducing scour of the adjacent seabed by virtue of their presence, size and redirection of flow. This localized scour has coalesced in some areas, resulting in major erosion and deepening of the seabed of up to 10 m. The result is the release of large quantities of glacial mud to the water column, leaving behind residual sand deposits. Input of this

Figure 8 Photograph of the shoreline at "The Rocks," Hopewell Cape, New Brunswick, at low tide, 3 p.m., Thursday, 29 June 2000, showing the vertical profile eroded by tidal processes in the sub-horizontal Pennsylvanian clastic sedimentary rock outcrops exposed here. Individuals circled at lower left provide scale. Photograph by Thaddeus Holownia.

subsea glacial age mud was not previously accounted for in the determination of sediment budgets. It could explain recent textural alterations on the mud flats, of increasing mud content, with implications to the survivability of migratory bird populations (*e.g.*, Shepherd *et al.*, 1995). Indeed, scour of the seabed with localized overdeepening could also explain observations, by the fishing community, of changing bathymetry. Perhaps more importantly, the apparently active and increasing erosion of the seabed could signal that the Bay of Fundy is experiencing a level of dynamics never before measured. Models of resonance length at present are too coarse to validate these observations, but the observations indicate an important connection between tides, currents, sedimentation, erosion, and the biological community. Implications of these findings have yet to be applied to seabed fishery management practices.

SUMMARY AND CONCLUSIONS

Bay of Fundy tides are an intimate part of the larger picture in the western North Atlantic Ocean. Hydrodynamically, they exhibit the effects of a co-oscillating tide superimposed upon the direct astronomical tide. Thus, through the forcing of the Atlantic tide, the Fundy tides are driven primarily by standing wave conditions developed through resonance; differences in the tidal range through the FMG system are, in effect, governed by the rocking motion of a tremendous seiche. Although dominantly semi-diurnal, Fundy tides nevertheless experience marked diurnal inequalities. The overlapping of the cycles of spring and perigean tides every 206 days results in an annual progression of 1.5 months in the periods of extra high tides. These strong tides can therefore occur at all seasons in the Bay of Fundy, depending on the year in question. The result is considerable tidal variation throughout the year. Distinct cycles of 12.4 hours, 24.8 hours, 14.8 days, 206 days, 4.52 years and 18.03 years are recognized. With Saint John as the reference port, tidal movements at Herring Cove effectively illustrate the annual variations that can be expected. The hydrodynamic vigour of the Bay of Fundy rules over such geologically significant processes such as erosion, sediment dynamics, and the Bay's natural resources and ecosystems. Recently observed changing environmental conditions in the Bay of Fundy may signal an increase in the dynamic energy of the tides, and that the resonant period is not yet optimized. There is a clearly perceived need to more precisely evaluate the dynamics of the tidal regime and to better understand the myriad geological processes at work.

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