Journal of Coastal Research	9	1	87-96	Fort Lauderdale, Florida	Winter 1993

Analysis of Cliff Retreat and Shoreline Erosion: Thompson Island, Massachusetts, U.S.A.

J. Richard Jones,† Barry Cameron† and John J. Fisher‡

†Department of Geology
Acadia University
Wolfville, Nova Scotia BOP 1X0
Canada

‡Department of Geology
University of Rhode Island
Kingston, RI 02881, U.S.A.

ABSTRACT

JONES, R.J.; CAMERON, B., and FISHER, J.J., 1992. Analysis of cliff retreat and shoreline erosion: Thompson Island, Massachusetts, U.S.A. *Journal of Coastal Research,* 9(1), 87–96. Fort Lauderdale (Florida). ISSN 0749-0208.

Shoreline and cliff erosion rates between 1938 and 1977 were determined by photogrammetric analysis (1938, 1952, 1963, 1977 series) for Thompson Island in Boston Harbor, Massachusetts, in order to evaluate the influence of textural and shear strength properties on the erosion rates of the contiguous glacial cliffs with respect to the directions of most frequent storm approaches. Analysis of variance indicates that sediment textural characteristics and shear strengths are different by geographic exposure. A multiple regression analysis showed that percent gravel and sand:mud ratios accounted for about 70% of the variation in shear strength. The most resistant cliffs should, therefore, have the lowest average sand:mud ratios, low gravel content and high shear strengths.

The highest rates of cliff erosion were generally associated with cliffs with the highest sand:mud ratios and lowest shear strengths combined with an orientation subjected to frequent storms. The highest average rates of cliff erosion (0.4 to 0.6 m/yr) occurred in the northwest and southeast quadrants, but not in the northeast, storm-dominant quadrant. The northeast-facing cliffs have the lowest average sand:mud ratio combined with relatively high shear strengths. Average cliff erosion rates were highest for the southeast-facing cliffs where the average sand:mud ratio is high and the average shear strength measurements are the lowest.

Over this 39-year period, the mean cliff recession for the island's perimeter was about 0.3 m/yr which supplied over a quarter of a million cubic meters of sediment, while shoreline erosion was about 0.4 m/yr and supplied over 200,000 cubic meters of sediment. These sediment-budget estimates amount to nearly half a million cubic meters of materials removed from the island. They suggest that the Boston Harbor Islands can be a significant natural source of sediments for offshore areas.

Predictions of average cliff erosion rates may be more complex than predictions of average beach erosion rates. In addition to considering dominant storm directions, it is important to consider geotechnical properties, such as size, composition and shear strengths of cliff sediments in an attempt to predict their potential long-term erosion rates.

ADDITIONAL INDEX WORDS: *Boston Harbor, beach erosion, cliff erosion, cliff shear strength, grain-size composition.*

INTRODUCTION

The study of mass movement and slope failure processes crosses a variety of disciplines. From an engineering viewpoint, slope stability investigations tend to be site specific and of limited temporal duration. From a geological perspective, slope studies are generally long-term and include an analysis of the spatial variability of sediments, stratigraphy, structures and erosional processes. HANSEN (1984) summarized the factors influencing slope stability and suggested that they can be divided into three distinct categories: (1) the type of slope movement, (2) the morphology along the surface of movement, and (3) the geotechnical properties of the slope-forming materials. The first two areas broadly define or describe the resultant geomorphological form that slope failure achieves. Slope stability, however, is ultimately dependent upon the combined geotechnical properties of the slope-forming materials, such as sediment size distribution, porosity, permeability, shear strength, and slope angle, as well as structural weaknesses.

RICHARDS and LORRIMAN (1987) observed that erosion at or near a slope base can induce mass movement at rates significantly greater than would be associated with *in situ* weathering and/or increased pore-water pressures. Their study provides a general reference to the stability conditions found in unconsolidated marine cliff sediments.

The relative erosion rates of coastal cliffs con-

91120 received 10 December 1991; accepted in revision 28 May 1992.

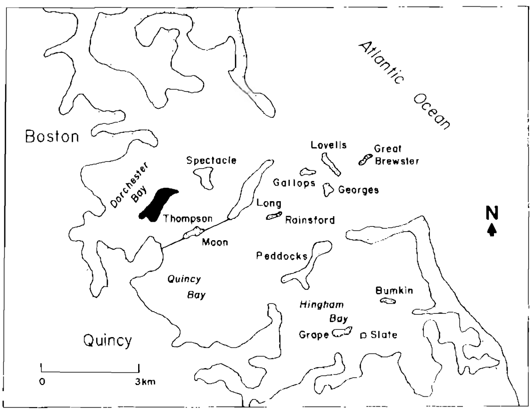

Figure 1. Boston Harbor Islands. Thompson Island is shaded in black.

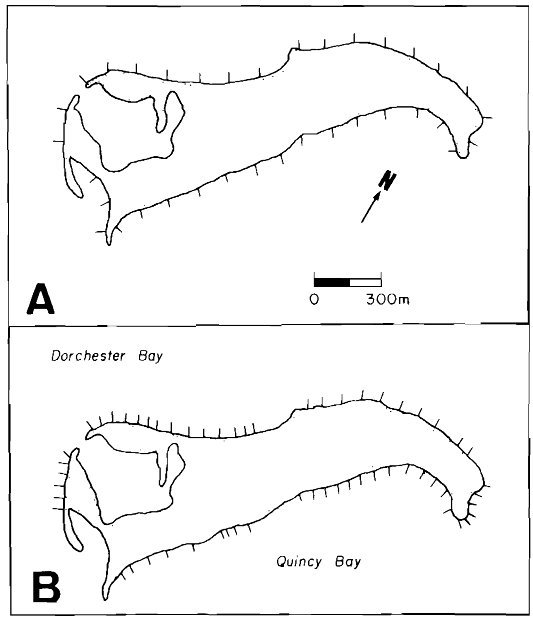

Figure 2. Thompson Island. Location of the control stations used for photogrammetric analysis (A). Location of the corresponding sediment and shear strength sampling stations (B).

sisting of unconsolidated sediments are affected also by variations in composition. It has been clearly demonstrated from studies in both marine and terrestrial environments that sediment composition controls the rates of erosion and subsequent recession, with silt-clay dominant slopes generally being more resistant than sand-gravel dominant slopes (SKEMPTON, 1964; THORNE and TOVEY, 1981; VAN EERDT, 1985).

Many lake and marine shorelines are fronted by cliffs composed of unconsolidated sediments. Because of the sediment composition and erosional aspects of such cliffs, they tend to be unstable and therefore are subject to recession. The eroded material produced during recession provides a source of sediment for subsequent beach development (MAY, 1977; MCGREAL, 1979).

GEIER and CALKIN (1883) and BRENNAN and CALKIN (1984) demonstrated that rates of cliff retreat and beach erosion for Lake Erie and Lake Ontario are related in part to the sediment composition of the adjacent cliffs. BUCKLER and WINTERS (1983) were, however, unable to confirm a relationship between sediment composition and the rates of cliff erosion along Lake Michigan shorelines.

There is a large amount of potential beach and offshore sediment contained in unconsolidated coastal cliffs. VALENTIN (1954) identified marine cliff recession rates averaging 1.2 m/yr for a 50 km long section of coast at East Yorkshire, England, while JONES and FISHER (1990) found cliff recession rates of about 0.8 m/yr around the 2 km perimeter of Grape Island within Boston Harbor, Massachusetts.

Thompson Island, Massachusetts, was studied in order to evaluate the influence of some geotechnical properties of receding cliffs on slope stability. JONES *et al.* (1985, 1991) used photogrammetric analyses to determine shoreline changes at Thompson Island and other Boston Harbor islands. These studies suggest that sediment composition of the contiguous glacial cliffs rather than orientation to wave approach may control the rates of recession on many Boston Harbor islands.

METHODS

Study Area

Thompson Island lies within a drowned section of the structurally complex Boston Basin (LAFORGE, 1932; CAMERON, 1979). The island is 2.6 km^2 in area and is one of the many drumlinoid islands in Boston Harbor (Figure 1). The island is sheltered from open-ocean wave approach except under extreme storm conditions. Sediments forming the island are mapped as drumlin and moraine deposits (LAFORGE, 1932; NEWMAN *et al.*, 1990). Bedrock is not exposed on the island and the beaches are composed of a mixture of sandy gravels, shingle, boulder and fragmented mussel shells.

Figure 3. Photograph of typical marine cliff exposure of bouldery muddy sand from the northwest quadrant.

Thompson Island was deposited as glacial sediment during the Late Pleistocene when sea level in the Boston Harbor was at least 20 m lower than at present (KAYE and BARGHOORN, 1964; JONES and CAMERON, 1986; NEWMAN *et al.*, 1990). The lower base was partially embayed by Holocene sea-level rise until the island attained its present configuration. Subsequently, erosion of the glacial cliffs on the island has provided a potential source of beach and harbor sediment (JONES, 1979; JONES *et al.*, 1985; KNEBEL *et al.*, 1991).

Photogrammetric Analysis

A zoom transfer scope was used to measure shoreline change and cliff recession from aerial photographs for the years 1938, 1952, 1963, and 1977. The 1977 series photograph was enlarged (1:400) and served as the base. Aerial photographs for the other three series were optically enlarged and superimposed on the 1977 base for change measurements.

The 1938 high-tide line was used as datum for subsequent measurements. Beach and cliff morphologies, and permanent island fixtures (*e.g.*, buildings, roads) were mapped in the field for verification of aerial photographic scales. The smallest unit of length that was measurable on the photographs and field verified was 4.5 m. The smallest measurable change per year was calculated by dividing the smallest measurable field distance by the number of years of photocoverage (TANNER, 1977). Accuracy of change for Thompson Island was therefore 4.5 m over 39 years of coverage or about 0.11 m/yr.

Dimensionally stable acetate sheets were used to trace changes through time in both the high-tide line and cliffs. For area measurements of beach change, the 1977 base aerial photograph was divided into thirty-six 150 m arc segments with a digital linear measuring probe (Figure 2a). The areas between segments for each air photograph were measured with a digital planimeter. Area change within each 150 m control station represents an average of three to five planimeter traces.

Figure 4. Photograph of typical marine cliff exposure of slightly gravelly muddy sand from the southwest quadrant.

Cliff Sediment Sampling

Sediment samples were collected from each of the fifty-five stations along the exposed cliffs around the perimeter of the island (Figure 2b). Figures 3 and 4 illustrate some of the compositional variation found along the island perimeter cliffs. More than one sample was collected from cliff faces at locations where a visual difference in either sediment size or stratification was observed. Shoreline areas with cliffs less than about 1.65 m in height or where erosion control structures were present were not sampled (Figure 2b).

From each sample, a 100 g split was processed according to methods for sediment size analysis (FOLK, 1974). This procedure included mechanical sieving of the sample splits at ½ϕ sieve intervals from -4ϕ through 4ϕ. The remaining pan fraction ($> 4\phi$) was analyzed with a hydrometer.

The size fractions were grouped into three separate classes: gravel ($< -1\phi$), sand (-1ϕ to 4ϕ) and mud ($> 4\phi$), and plotted on a triangular diagram (Figure 5; FOLK, 1954). These size groups were selected to test the relationship between shear strengths and particle size variability along the cliff faces. Because the particle size distribution of sediments can have an important influence upon shear strength (LAMBE and WHITMAN, 1969), it was believed that a size analysis of the cliff sediments would provide insight into understanding how the rate of cliff erosion might vary as a function of shear strength and sediment size distribution.

Shear Strengths

The shear strengths of the materials forming the slopes at the fifty-five sediment sampling stations (Figure 2b) were measured with a portable shear vane meter. This instrument operates on the same principle as the laboratory vane apparatus. Although it provides only an approximation to the shear strengths of the materials tested (HEAD, 1982), it does give an acceptable *in situ* estimate.

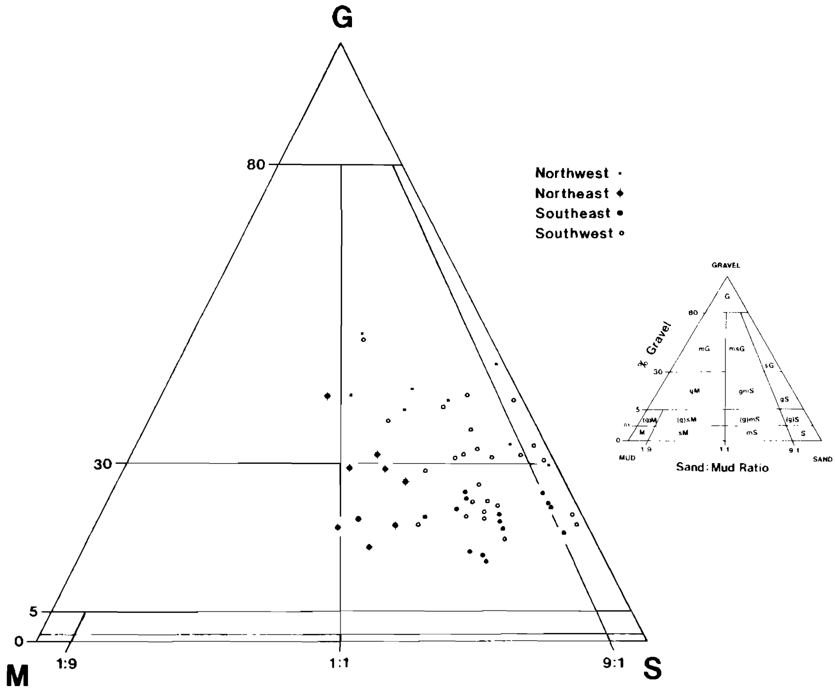

Figure 5. Textural classification of the sediment samples by geographic quadrant. Key to the right provides the classification boundaries (FOLK, 1954, 1974). (G—Gravel; mG—muddy Gravel; smG—muddy sandy Gravel; sG—sand Gravel; gM—gravelly Mud; gmS—gravelly muddy Sand; gS—gravelly Sand; (g)M—slightly gravelly Mud; (g)sM—slightly gravelly sand Mud; (g)mS—slightly muddy Sand; (g)S—slightly gravelly Sand; M—Mud; sM—sandy Mud; mS—muddy Sand; S—Sand. Note that key is not to scale.

The measurements were taken by placing the portable shear vane meter on the slope adjacent to and within a few centimetres of the sediment sampling stations (Figure 2b). The shear vanes on the bottom of the meter were pushed into the slope with the instrument rotated until shear failure occurred. An average of three shear strength measurements were taken at each station.

The shear strength values obtained from the portable shear vane meter for cliff sediments on Thompson Island were compared with shear strength values obtained from a conventional direct shear box apparatus for materials with similar textural properties (JONES and ACKMAN, 1990). Because the data corresponded well, we accept the portable shear vane meter values as generally representative of the strength characteristics for the Thompson Island cliffs.

ANALYSIS

The summary quadrant rates of beach erosion and cliff recession are presented in Figure 6. The northeast quadrant beach segments exhibit the greatest amount of erosion over the 39 year time period, averaging about 0.7 m/yr. The other three quadrants have beach erosion rates of 0.3 to 0.4 m/yr. Rates of cliff recession were greatest for southeast-oriented slopes (0.6 m/yr) followed by northwest-exposed cliffs (0.4 m/yr), northeast cliffs (0.2 m/yr) and southwest cliffs (0.1 m/yr).

Cliff sediments sampled from northwest cliff exposures essentially fell into the gravelly muddy sand group, while sediments from northeast and southeast cliffs generally represent a slightly gravelly muddy sand (Figure 5). Sediments from southwest exposures are more variable in regards to their compositional classification. Nearly all the samples had sand:mud ratios greater than 1:1. The sands from these cliffs are dominantly fine sands with 80% of the sand class ranging between 2 ϕ and 3 ϕ. All sediment samples analyzed were poorly sorted.

Southeast slopes had the lowest average shear strength (11.6 kN/cm^2). Northeast- and southwest-facing slopes had approximately equal shear strengths of 13.3 and 12.8 kN/cm^2, respectively.

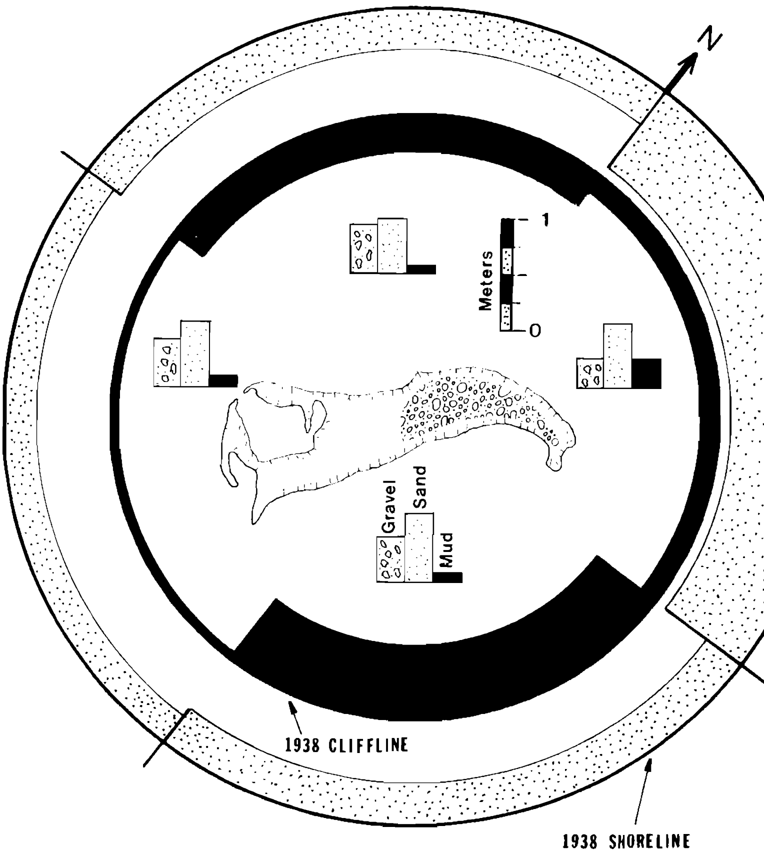

Figure 6. Summary quadrant rates of beach and cliff erosion for Thompson Island from 1938 to 1977. The 1938 shoreline and cliffline served as the baselines. Mean gravel, sand and mud percent histograms for the exposed cliffs are included within the respective quadrants. Scale is meters/year.

Northwest cliffs averaged the highest shear strengths at 15.2 kN/cm^2 (Table 1).

A one-way analysis of variance model (SPSS-X, 1988) was used to test if there are significant differences ($p \leq 0.05$) between gravel percent, sand percent, mud percent, sand : mud ratio and shear strengths for the four principal geographic orientations of the cliffs (Figure 6). Significant differences ($p \leq 0.05$) emerged between the four orientations and these five variables, indicating that both sediment composition and shear strengths of the cliffs around the island perimeter are different by geographic exposure.

In order to further test and predict possible

Table 1. *Cliff summary values by geographic quadrant.*

	Percent Gravel	Percent Sand	Percent Mud	Sand : Mud Ratio	Shear Strength (kN/cm2)	Avg. Retreat Cliff (m/yr)	Avg. Retreat Beach (m/yr)
Northwest	40	51	10	5	15.2	0.4	0.4
Northeast	25	50	25	2	13.3	0.2	0.7
Southeast	20	70	10	7	11.6	0.6	0.4
Southwest	29	62	10	6	12.8	0.1	0.3
Average	28	60	13	6	13.2	0.3	0.4

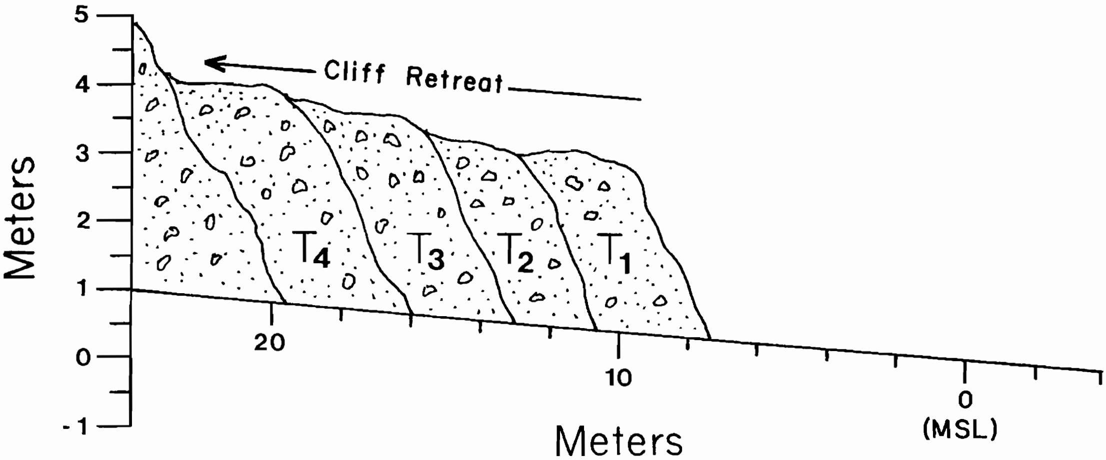

Figure 7. Idealized cross section perpendicular to the shoreline of an eroding sea cliff to illustrate how successive erosive events from time 1 to time 4 can create an area of erosional loss that resembles a parallelogram. The cross-sectional areas of beach erosion loss can also be approximated by the geometric shape of a parallelogram (McCormick, 1973).

relationships between the shear strengths and the textural characteristics of the cliff sediments, a multiple regression analysis was computed. For this analysis, the shear strength represented the dependent variable with percent gravel, percent sand, percent mud, and sand : mud ratio serving as the independent variables. The backward method of multiple regression analysis was selected to evaluate the relationship between shear strength and these four independent variables (Davis, 1986; SPSS-X, 1988). The backward regression procedure computes an initial equation which includes all variables in the analysis (Davis, 1986). The procedure then progresses backwards removing one variable at a time which does not contribute significantly ($p \leq 0.05$) to explaining the variance. The final product is an equation which includes only those independent variables that are statistically significant in predicting the relationship of the dependent variable. In this way each variable's contribution to the final regression solution can be evaluated and eliminated if not significant at each progressive step of the regression procedure.

The initial regression analysis including the four independent variables produced an equation which explained 71 percent of the variation. Percent mud was the first variable eliminated from the subsequent analysis which yielded $R = 0.838$ and $R^2 = 0.702$. Percent sand was the next variable eliminated. These two eliminated variables contribute about one percent to the total variation in shear strength.

The final regression solution included percent gravel and the sand : mud ratio as significant ($p \leq 0.05$) independent variables ($R = 0.836$; $R^2 = 0.699$). The total explained variation accounted for by these two variables is 69.9 percent.

SEDIMENT BUDGET

A sediment budget can be estimated by using the rates of shoreline and cliff recession determined from photogrammetric analysis (Jones *et al.*, 1985). This includes consideration that the cross-section, taken perpendicular to the shoreline, of the eroded volume of sediments from both the cliffs and the beaches on Thompson Island approximates the geometric shape of a parallelogram (Figure 7). McCormick (1973) also arrived at this conclusion in his study of the beaches of southeastern Long Island, New York.

The mean cliff recession for Thompson Island was calculated to be 15 m (38 cm/yr) for the 39 years of photogrammetric coverage studied (1938–1977). Considering that the average vertical cliff height for the island is about 3 m and that the island perimeter is about 6,000 m, a volume of sediment equal to about 270,000 m^3 was supplied to the contiguous beaches from these cliffs.

The 39 year total beach erosion or recession was about 18 m (46 cm/yr) along this 6,000 m island perimeter, suggesting a faster beach-erosion rate than cliff-erosion rate. Given a Boston Harbor tidal range of about 2 m, a volume of sediment equal to about 216,000 m^3 was eroded from the beaches of Thompson Island.

All of the eroded cliff volume of 270,000 m^3 plus the beach loss of 216,000 m^3, totalling nearly half a million cubic meters of sediments, have passed through the dynamic beach system to the offshore. This represents about 81 m^3 of materials per meter of coastline eroded from these cliffs and beaches over a 39-year time span. It, therefore, is not unreasonable to assume that much of the 486,000 m^3 of sediment removed from Thompson Island serves as a source for offshore subtidal deposits. This sediment budget analysis appears to confirm the suggestion of the U.S. ARMY CORPS OF ENGINEERS (1977) and KNEBEL *et al.* (1991) that the Boston Harbor Islands serve as "point" sources of sediment for Boston Harbor.

DISCUSSION

Shear strengths of the materials forming the marine cliffs are well predicted ($R^2 = 0.70$) by the sand : mud ratio and percent gravel from the multiple regression analysis. Although the water content, porosity, permeability, or vegetative cover at the cliff stations were not sampled, it is not unreasonable to assume that these factors may account for a large portion of the 30% unexplained variation in shear strength (MAY, 1977).

The relationships of cliff retreat and beach erosion over the 39-year period studied relative to cliff sediment composition and shear strength is presented in Figure 6 and Table 1. Southeast-facing cliffs, with the lowest average shear strength (11.6 kN/cm^2) and the highest average sand : mud ratio (7.22), had the highest average yearly rate of retreat at 0.6 m/yr. The average rate of erosion for the proximal beaches was 0.4 m/yr which is about average for the island.

Northeast-facing cliffs had a low average cliff-recession rate of 0.2 m/yr with a low average sand : mud ratio of 2.27 and an average shear strength of 13.3 kN/cm^2. The rates of contiguous beach erosion, however, were the highest, averaging 0.7 m/yr.

Northwest cliffs had an average retreat rate of 0.4 m/yr, an average shear strength of 15.2 kN/cm^2, an average sand : mud ratio of 5 and an average beach erosion rate of about 0.4 m/yr.

Southwest-facing cliffs experienced the lowest average retreat rate of about 0.1 m/yr, even with a high average sand : mud ratio of 6 and an average shear strength of 12.8 kN/cm^2. The average rate of beach erosion was also the lowest of the four quadrants (0.3 m/yr).

Direct relationships among these variables for the four quadrants are not, initially, apparent, but a pattern emerges when the direction of dominant storm-wave approach and relative sediment composition of the cliffs are considered. Nearly 70 percent of the storms that approach the Massachusetts coast originate from the northerly and easterly quadrants, with the most severe storms coming from the northeast (JONES and CAMERON, 1979). The highest measured rates of beach erosion (1.1 m/yr) correspond to the northeast and northwest storm-origin quadrants (Figure 6). The northeast quadrant exhibits the largest average beach erosion rate (0.7 m/yr) which corresponds well with the quadrant from which the most severe storms originate. Southeast-facing cliffs, however, exhibit the greatest amount of average cliff erosion (0.6 m/yr) because they have the lowest shear strengths and the highest sand : mud ratios (Table 1). This is in spite of the fact that they are fronted by the widest island tidal flat and a broad shallow offshore zone which should attenuate wave energy. In contrast, the southwest-facing cliffs have the lowest average cliff-erosion rates in spite of their high average sand : mud and relatively low average shear strengths (Table 1).

CONCLUSIONS

(1) During the 39-year period from 1938 to 1977, over a quarter of a million cubic meters of cliff sediments were eroded from the 6,000 m perimeter of Thompson Island in Boston Harbor. This material would have first been integrated into new beach sediments. Beach erosion on this island, however, adds an additional 216,000 m^3 of eroded sediment volume from Thompson Island. This nearly half million cubic meters of sediment must have been removed offshore, indicating that the island is a significant source of sediment for the offshore.

(2) The highest average rates of beach erosion occurred along beaches facing north and east which are the dominant directions from which storms originate. The highest beach erosion rates occurred in the northeast quadrant which is associated with the most severe storms.

(3) With multiple regression analysis, it was demonstrated that shear strengths of cliff-forming materials are well-predicted by the sand : mud ratio and the percent gravel. The more resistant

cliffs should have a higher mud (or clay-silt) content and lower sand and gravel contents (see northeast quadrant, Figure 6).

(4) The highest rates of cliff erosion were generally associated with cliffs having the highest sand: mud ratios and lower shear strengths combined with an orientation facing frequent storm directions. High average rates of cliff erosion occurred in the northwest and southeast quadrants which have high sand: mud ratios. But, high rates of cliff erosion did not occur in the northeast quadrant, as expected from storm data. These northeast-facing cliffs have the lowest average sand: mud ratio combined with relatively high shear strengths. Average cliff erosion rates were highest for the southeast-facing cliffs where the average sand: mud ratio was high and the average shear stress measurements were lowest. On the other hand, the southwest cliffs with similar sand: mud ratios and low average shear strengths had the lowest average rate of cliff recession. This, however, is predictable from storm data.

(5) Predictions of average cliff erosion rates may be more complex than direct predictions from average erosion rates of the contiguous beaches. In addition to considering dominant storm directions, it is important to consider also geotechnical properties, such as sediment-size distribution and shear strengths of cliffs, in attempts to predict erosion rates of sea cliffs.

(6) This study has shown that gravel content, sand: mud ratios, shear strength and dominant storm directions must be considered together in order to explain and/or predict erosion rates of cliffs composed of unconsolidated sediments.

ACKNOWLEDGEMENTS

John Fisher passed away during the preparation of this manuscript. We miss his friendship and research collaboration. Ken La Sota (Robert Morris College), Jim Allen (National Park Service) and Mike Woldenberg (SUNY, Buffalo) reviewed earlier drafts of this paper. Joe Kelley (Maine) and an anonymous reviewer are thanked for improving the manuscript through the editorial process. The Natural Sciences and Engineering Research Council of Canada General Grant to Acadia University provided partial funding for this project.

LITERATURE CITED

Brennan, S. and Calkin, P., 1984. *Analysis of Bluff Erosion Along the Southern Coastline of Lake Ontario, New York.* Albany, NY: New York Sea Grant Institute, 74p.

Buckler, W.R. and Winters, H.A., 1983. Lake Michigan bluff erosion. *Annals, Association of American Geographers,* 73, 89–110.

Cameron, B., 1979. Age of the Boston Basin—A review of the problem. *In:* Cameron, B. (ed.), *Ninth International Congress on Carboniferous Stratigraphy and Geology—Field Guidebook Number 5.* Falls Church: American Geological Institute, pp. 65–74.

Davis, J.C., 1986. *Statistics and Data Analysis in Geology.* New York: Wiley, 646p.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *Journal of Geology,* 62, 344–359.

Folk, R.L., 1974. *Petrology of Sedimentary rocks.* Austin, Texas: Hemphills, 182p.

Geier, R. and Calkin, P., 1983. *Stratigraphy and Bluff Recession Along the Lake Erie Coast.* Albany, NY: New York Sea Grant Institute, 58p.

Hansen, M.J., 1984. Strategies for classification of landslides. *In:* Brunsden, D. and Prior, D.B., (eds.), *Slope Instability.* New York: Wiley, pp. 1–25.

Head, K.H., 1982. *Manual of Soil Testing, Volume 2: Permeability, Shear Strength and Compressibility Tests.* New York: Wiley, pp. 335–747.

Jones, J.R., 1979. Geomorphology of the Boston Harbor Islands. *In:* Aubrey, D.G. (ed.), Proceedings Workshop on Coastal Zone Research in Massachusetts. *Woods Hole Oceanographic Institute Technical Report WHOI-79040.* Woods Hole, pp. 87–88.

Jones, J.R. and Ackman, T.E., 1990. Shear strength analysis of grouted coal waste materials associated with mine out-slopes: A laboratory analysis. *International Journal of Mining and Geological Engineering,* 8, 227–240.

Jones, J.R. and Cameron, B., 1979. Reply: Landward migration of barrier island systems under stable sea-level conditions: Plum Island, Massachusetts. *Journal of Sedimentary Petrology,* 49, 332–333.

Jones, J.R. and Cameron, B., 1986. Rates of sea level rise for southern New England: A space-time concept. *Physical Geography,* 7(1), 46–52.

Jones, J.R. and Fisher, J.J. 1990. Environmental factors affecting Prehistoric shellfish utilization: Grape Island, Boston Harbor, Massachusetts. *In:* Laska, N. and Donahue, J. (eds.), *Archaeological Geology of North America.* Geological Society of America, Centennial Special Vol. 4, pp. 137–146.

Jones, J.R.; Cameron, B., and Fisher, J.J., 1991. Photogrammetric analysis of shoreline change for islands within Middle Boston Harbor, Massachusetts: 1939–1977. *Northeastern Geology,* 13(1), 3–10.

Jones, J.R.; Fisher, J.J., and Reigler, P., 1985. Shoreline change at Thompson Island, Boston Harbor, Massachusetts. *Physical Geography,* 6, 198–206.

Kaye, C.A. and Barghoorn, E.S., 1964. Late Quaternary sea-level change and crustal rise at Boston, Massachusetts, with notes on the autocompaction of peat. *Geological Society of America Bulletin,* 75, 63–80.

Knebel, H.J.; Rendigs, R.R., and Bothner, M.H., 1991. Modern sedimentary environments in Boston Harbor, Massachusetts. *Journal of Sedimentary Petrology,* 61, 791–804.

LAMBE, T.W. and WHITMAN, R.V., 1969. *Soil Mechanics*. New York: Wiley, 553p.

LAFORGE, L. 1932. Geology of the Boston Area, Massachusetts. *U.S. Geological Survey Bulletin No. 839*, 105p.

MAY, V.J., 1977. Earth cliffs. *In:* Barnes, R.S.K. (ed.), *The Coastline*. New York: Wiley, pp. 215–235.

MCCORMICK, C.L., 1973. Probable causes of shoreline recession and advance on the south shore of eastern Long Island. *In:* Coates, D.R., (ed.), *Coastal Geomorphology,* Publications in Geomorphology, State University of New York at Binghamton, pp. 6–71.

MCGREAL, W.S., 1979. Marine erosion of glacial sediments from low-energy cliffline environment near Kilkeel, Northern Ireland. *Marine Geology,* 32, 89–103.

NEWMAN, W.A.; BERG, R.C.; ROSEN, P.S., and GLASS, H.D., 1990. Pleistocene stratigraphy of the Boston Harbor Drumlins, Massachusetts. *Quaternary Research,* 34, 148–159.

RICHARDS, K.S. and LORRIMAN, N.R., 1987. Basal erosion and mass movement. *In:* Anderson, M.G. and Richards, K.S. (eds.), *Slope Stability*. New York: Wiley, pp. 331–357.

SKEMPTON, A.W., 1964. Long-term stability of clay slopes. *Geotechnique,* 14, 75–102.

SPSS-X USERS GUIDE, 1988. 3rd Ed., Chicago, IL: SPSS Inc., 1072p.

TANNER, W.F., 1977. Standards for measuring shoreline change: A study of precision obtainable and needed in making measurements of changes (erosion and accretion). Wilmington, DE: Coastal Plains Center for Marine Development Services, 88p.

THORNE, C.R. and TOVEY, N.K., 1981. Stability of composite river banks. *Earth Surface Processes and Landforms,* 6, 469–484.

UNITED STATES ARMY CORPS OF ENGINEERS, 1977. *Shore Protection Manual*. Fort Belvoir, Virginia: U.S. Army Coastal Engineering Research Center, pp. 4–123.

VALENTIN, H., 1954. Der Landverlust in Holderwess, Ostengland, von 1852 bis 1952. *Die Erde,* 3, 296–315.

VAN EERDT, M.M., 1985. Salt marsh cliff stability in Oosterschelde. *Earth Surface Processes and Landforms,* 10, 95–106.