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EROSION AND SEDIMENTATION ALONG A COHESIVE SHORELINE – THE NORTH-CENTRAL SHORE OF LAKE ERIE

by

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ABSTRACT

A study of the distribution and texture of bluff and nearshore sediments of north-central Lake Erie was carried out to measure the patterns of erosion and sedimentation characteristic of a cohesive shoreline. Local shore bluffs consist mainly of cohesive glacial sediments. The postglacial deposit occurs as a narrow band of gravel to clay-sized sediments located between the shoreline and a broad offshore shelf of exposed glacial sediments. The width of the deposit increases from west to east and there is local widening and beach development at the three harbour areas of Ports Stanley, Bruce and Burwell as the result of entrapment and diversion by harbour structures. A new sediment budget proposed for the reach shows an annual input of 6 X 10^6 tonnes of silt and clay and 2 X 10^6 tonnes of sand and gravel. Bluff erosion account for 89% of the sediment supply and nearshore-slope erosion and stream discharge for 10% and 1% respectively. More than 99% of the sediment input is lost to the shoreline to the east and to the offshore basins by transport within the nearshore zone. The sediment remaining within the reach is coarser and better sorted than the source materials and appears to be stable in texture and distribution over the short term. Although harbour structures have a significant effect on the accumulation pattern of nearshore sediments, their effect on the sediment budget is minimal and transitory because of the high supply and transport rates.

ADDITIONAL INDEX WORDS: sediment budget, bluffs, nearshore sediments, coastal zone, sediment transport, harbour structures

RÉSUMÉ

Une étude de la répartition et de la texture des sédiments des falaises et du littoral des zones nord et centrale du lac Érié a été menée pour mesurer les phénomènes d'érosion et de sédimentation qui caractérisent un littoral cohésif. Les falaises de cette région sont constituées principalement de sédiments glaciaires cohésifs. Les dépôts postglaciaires forment une bande étroite de sédiments argileux ou de gravier, entre le littoral et un vaste plateau de sédiments glaciaires exposés au large des côtes. La largeur de la bande de dépôts augmente d'ouest en est. Il se produit un élargissement et la formation d'une grève dans les régions des ports Stanley, Bruce et Burwell en raison du piégeage et de la dérivation qui découlent des travaux d'aménagement des havres. Selon un nouveau bilan sédimentaire proposé pour le bief, il se dépose annuellement 6 X 10^6 tonnes de limon et d'argile et 2 X 10^6 tonnes de sable et de gravier. L'érosion des falaises produit 89 p. 100 des sédiments et l'érosion des pentes du littoral et le déversement des cours d'eau, 10 et 1 p. 100 respectivement. Plus de 99 p. 100 des sédiments se perdent sur la ligne de rivage à l'est et dans les bassins situés au large des côtes, car ils sont transportés dans la zone littorale. Les sédiments qui demeurent à l'intérieur du bief sont plus gros et mieux assortis que les matières à la source et leur texture et leur répartition semblent plus stables à court terme. Bien que les travaux d'aménagement des havres aient une incidence considérable sur l'accumulation des sédiments littoraux, ils n'influent que très peu et de façon temporaire sur le bilan sédimentaire en raison de la grande quantité de sédiments charriés et de leur taux de transport.

TERMES À AJOUTER AU RÉPERTOIRE : bilan sédimentaire, falaises, sédiments littoraux, zone côtière, transport des sédiments et aménagement des havres.

MANAGEMENT PERSPECTIVE

The north shore of central parts of Lake Erie is retreating northwards at significant rates. Fortunately the shore is not heavily developed.

Erosion causes physical problems for shore installations and because of the cohesive soils forming the north shore, standard or conventional control engineering techniques and analysis do not apply. Erosion products have a significant impact on lake water quality and sediment quality. Fine soil particles, attracts many undesirable chemical compounds which they carry with them to the bottom. High siltation rates continually bury the sediment. Erosion is therefore a factor in water quality. This study provides a comprehensive set of quantities and describes processes essential for lake management and in consequence gives sound consistent basic data for all nearshore studies.

T. Milne Dick
Chief
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PERSPECTIVE-GESTION

La rive nord des régions centrales du lac Érié se retire vers le nord à un rythme considérable. Heureusement, il n'y a pas trop d'installations sur la rive.

L'érosion cause des problèmes physiques d'aménagement d'installations sur les côtes et, vu les particules cohésives du sol qui constituent la rive nord, les techniques de contrôle et d'analyse régulières ou conventionnelles ne conviennent pas. Les produits de l'érosion ont une incidence considérable sur la qualité de l'eau et des sédiments du lac. Les particules fines du sol attirent de nombreux composés chimiques indésirables qu'elles entraînent avec elles dans le fonds. Vu les taux d'envasement élevés, les sédiments s'enfoncent sans cesse. Par conséquent, l'érosion joue un rôle dans la qualité de l'eau. La présente étude offre un ensemble complet de données sur les quantités et décrit les procédés requis en gestion des lacs et, par conséquent, elle présente des données de base solides et constantes pouvant servir dans toutes les études du littoral.

Le chef,

T. Milne Dick
Division de l'hydraulique

1.0 INTRODUCTION

The north shore of the central basin of Lake Erie is a bluff shoreline of glacial sediments with one of the highest rates of erosion in the Great Lakes. Bluff stratigraphy and hydrogeology, exposure to prevailing winds of long fetch, and limited sand supply for beach building are known to be factors contributing to the rapid erosion (Gelinas 1974; Boulden 1975; Quigley et al. 1977; Dick and Zeman 1983). Shoreline residents in the eastern part of the study area have suggested that harbour structures are also responsible for accelerated erosion locally and have sued the Canadian Federal Government for compensation for property losses. As a contribution to the Federal case, we were requested to measure the textures and volumes of eroding bluff sediments, and to determine the patterns and volumes of the resultant nearshore deposits. This paper reports the results of that study as a preliminary coastal sediment budget and discusses its implications with respect to the long-term sedimentation and erosion history of the reach and the role that harbour structures have played in the recent past.

2.0 BACKGROUND

The study area extends along the north shore of Lake Erie from Port Glasgow on the west to Clear Creek on the east and offshore to about the 10-m contour (Figure 1). It includes small harbour facilities at Ports Stanley, Bruce and Burwell, and generally undeveloped shoreline elsewhere. For ease of reference, we have subdivided the area into seven reaches - three associated with the harbours and four in the non-harbour areas.

The shore of the study area is primarily a bluff shoreline 10-40 m high and composed of interlayered tills and glaciolacustrine sediments. It erodes at an average long-term rate of 1.6 m/yr (Gelinas 1974) but extreme short-term rates can be as high as 50 m/yr (Zeman and Thompson 1982). Permanent beaches are restricted to the vicinity of the harbours at Ports Stanley, Bruce and Burwell and to the eastern end of the area; elsewhere beach development is limited to small, ephemeral beaches (Rukavina and St Jacques 1978). The offshore portion of the area consists of a narrow zone of modern sediments inshore and then a broad shelf of exposed glacial sediments extending offshore to depths of 15 to 20 m. Local widening of the inshore deposit occurs opposite the ports and at the approach to Long Point at the east end of the study area.

3.0 PREVIOUS WORK

The Quaternary stratigraphy of the north shore has been reported by Wood (1951), Dreimanis (1967), Gelinas (1974), Barnett (1983a,b) and Dreimanis and Barnett (1985), and detailed stratigraphic descriptions and borehole logs are available from several sources (Dreimanis and Reavely 1953; Dreimanis 1958; Quigley and Tutt 1968; Quigley 1977a,b; Quigley et al. 1977; Zeman 1976, 1978). Long-term linear recession rates of the shoreline have been documented most thoroughly by Gelinas (1974) while additional information on both short- and long-term rates is available from Wood (1951), Haras and Tsui (1976), Coakley (1980), Boyd (1981) and Zeman and Thompson (1982). Philpott (1983) has described the long-term recession of the nearshore slope. Wood (1960) has estimated the sediment supply required for the growth of Long Point. Nearshore sediments have been mapped by St. Jacques and Rukavina (1973) and Rukavina and St. Jacques (1978) and the same authors have developed a rudimentary sediment budget based on historical erosion rates reported by Boulden (1975).

4.0 FIELD WORK

4.1 Onshore

The 96-km long stretch of bluffs between Port Glasgow and Long Point was mapped and sampled at 84 stations (Figure 1), and an overlapping sequence of colour photographs was taken of the shore east of Port Burwell for which detailed stratigraphy was not available. At each shore station, samples representative of the local units were taken from the face of the bluff, and the accessible portions of the adjacent bluff were walked over and mapped. Details of the sampling and mapping procedures are described in Žeman (1983).

4.2 Offshore

The regional distribution of nearshore bottom types is known from previous surveys (St. Jacques and Rukavina 1973, Rukavina and St. Jacques 1978) to be a broad shelf of exposed glacial deposits with an inshore zone of modern lake sediments. The current field work was concerned with improving the definition of the areas of modern sediment cover and with measuring sediment thickness. Echo-sounding traverses calibrated by Shipek grab samples were used to delimit the sediment areas, and jetting to refusal (Rukavina and LaHaie 1977) was used to measure sediment thickness. Data collection was concentrated in the areas opposite Ports Stanley, Bruce and Burwell where the sediment zone was widest; intermediate areas were represented by a series of profile lines (Figure 1). Two hundred and forty sites were sampled and jetted. Details of the sample, jet and echo-sounding procedures and data are described in Rukavina (1983).

5.0 GRAIN-SIZE ANALYSIS

Grain size of the bluff and nearshore samples was measured by sieve, pipette, settling tube and Sedigraph procedures (Duncan and

LaHaie 1979). Data were processed with the computer program SIZDIST (Sandilands and Duncan 1980) with output in the form of class frequencies and standard summary statistics.

6.0 RESULTS

6.1 Bluff Stratigraphy

The stratigraphy of the bluffs of the study area is presented in Figure 2 and age relationships are shown in Table 1; a more detailed description is available in Zeman (1983). Four till units interlayered with and overlain by glaciolacustrine deposits make up the shoreline. Although the stratigraphic pattern is complex in detail, it is possible to distinguish five basic shore types. The most extensive of these is Port Stanley till at lake level overlain by and interbedded with glaciolacustrine silts, clays and sands. The till is hard and occasionally fissured and has an average texture of 10% sand and gravel, 40% silt and 50% clay; the glaciolacustrine sediments average 16% sand and gravel, 53% silt and 31% clay. This shore type extends from the western boundary of the study area to Port Burwell. A second shore type occurs locally within the western portion of this reach where a much coarser-grained and durable Catfish Creek till exposed at lake level gives rise to the prominent headlands of Plum Point and Patrick Point; average texture of this unit is 7% gravel, 36% sand, 41% silt and 16% clay. East of Port Burwell, the Port Stanley till is replaced at the toe of the bluff by a waterlain till capped by a thick section of glaciolacustrine silt and sand. Till texture is 4% sand, 35% silt and 61% clay, and it is softer and more plastic than the Port Stanley till. The overlying silt is prone to internal erosion and gullying. Further east the silt and sand units descend to lake level for a few kilometres and are then replaced by the Wentworth till, which is similar to the Port Stanley till in appearance and geotechnical properties; average texture is 10% sand and gravel, 35% silt and 55% clay.

6.2 Distribution of Postglacial Sediments

The postglacial deposit is a narrow band of sediment located between the shoreline and a broad shelf of exposed glacial sediments (Figure 3). The maximum depth of the offshore contact is about 15 m. The plan of the deposit is complex - width ranges from a few hundred metres to a maximum of 5 km and tends to be less in the non-harbour areas. In general, the sediment zone increases in size from west to east and most of the sediment occurs in the area east of Port Bruce. Average thickness of sediment as determined by jetting is 1.1 m; the maximum thickness recorded was 7.2 m at Port Burwell. The inshore portion of the deposit is mainly sand and gravel. Grain size decreases in an offshore direction and silt-clay becomes the dominant size fraction at depths greater than about 5 m.

7.0 COMPUTATION OF SEDIMENT VOLUMES

7.1 Onshore Erosion

Volumes of size fractions supplied annually to the lake by bluff erosion were computed from stratigraphic data, grain-size analyses of bluff sediment samples and historical erosion rates. First of all the textural composition of the major bluff strata was obtained from the results of 326 size analyses of samples collected at the 84 stations (Zeman 1983). Then the shoreline was subdivided into segments 250 m wide and areas corresponding to the proportions of gravel, sand, silt and clay were determined for each segment. Values for linear, long-term (1810-1964), annual recession rates were then interpolated for each segment from the 1-km measurements reported by Gelinas (1974). And finally the products of the segment areas and recession rates were computed to determine the volumes of the four size classes contributed annually by each segment. Table 2 and Figure 4 show the resultant data grouped for the seven shore reaches.

The present computation of sediment supply from the bluffs is believed to be more accurate than previous estimates due to the relatively close spacing of sampling stations. The major source of uncertainty is the interpolation of the information on stratigraphy and recession rate between adjacent stations. Other factors of uncertainty include the spatial and temporal variability of recession rates. Both short-term and long-term rates for a variety of time spans are available for the study area. Short-term rates were not used because they are known to fluctuate in response to lake level changes. The historical rates of Gelinas (1974) were selected because they had the highest spatial density and covered the longest time span. A comparison of Gelinas' rates with modern short-term rates (Boyd 1981, Table D-2) shows that the latter are about 1.7 times higher. Consequently, we consider the computed volumes as low rather than high estimates.

7.2 Subaqueous Erosion

Philpott (1983) compared 1896 and 1979 nearshore profiles at 37 sites within the study area and found that the till shelf erodes to a maximum depth of 12 m. Profiles were located only in the non-harbour reaches and no comparable data are available for the harbour areas. Philpott grouped the profiles into six types: three types (1A, 1B and 1C) correspond to our reaches 1,3 and 5 and to the exposure of Port Stanley till at the toe of the bluffs; type 2 represents the exposures of waterlain till east of Port Burwell in our reach 7; types 3 and 4 are associated with bluffs in reach 7 consisting of granular sediments and Wentworth till respectively. We have used Philpott's profiles to compute a coarse estimate of the rates of nearshore slope erosion. For each of four reaches involved, the erosion area between the averaged 1986 and 1979 profiles was multiplied by the reach length to give the total volume eroded and the average annual erosion rate for the 1896-1979 period. The textural percentage of eroded sediment for each reach was estimated from the average texture of stratigraphic units occurring at the toe of the bluffs, and presumably also in the subsurface in the nearshore zone. The results (Table 3) indicate that the sediment volumes from subaqueous erosion represent from about 10 to 25% of the associated bluff erosion volumes. Average rates of downcutting range from 0.7 to 1.2 cm/yr; the highest rate (4.7 cm/yr) occurs in the easternmost reach within the waterlain till.

7.3 Nearshore Deposits

Estimates of the volumes and average grain size of the modern sediments were obtained by combining the acoustic data on the areal extent of the deposits, the jet data on sediment thickness, and the grain-size data for surface-sediment samples. Seven reaches were analyzed as in the onshore case. In the three harbour reaches where grid data were available, an isopach map of sediment thickness was produced from the jet data and sediment volume was computed from the areas between the thickness contours and the corresponding mean thicknesses. Size-fraction volumes were then determined by subdividing reach volume into gravel, sand, silt and clay components based on the average grain size of all the surface samples in the reach. Equivalent values for the remaining reaches were derived by interpolating the jet and textural data obtained along the profile lines. The resultant volumes and size-fraction volumes are tabulated in Table 4 and plotted in Figure 5.

The total volume of the deposit is just under 100×10^6 m^3. The Burwell deposit accounts for about 40% of the total, and the Burwell to Clear Creek reach for an additional 25%. The Port Stanley and Bruce deposits are small in comparison at between 5 and 10% each, and the remaining areas between the ports collectively account for only 20% of the total. The average texture of the postglacial deposit is 1% gravel, 58% sand, 28% silt and 14% clay - a muddy or silty sand according to the terminology of Folk (1974). Comparison of textures from the individual reaches shows up a number of areas which are texturally distinct

(Figure 5). The first consists of the four western reaches between Port Glasgow and Port Bruce. Only minor variations in texture occur within this area and average grain size is similar to that for the deposit as a whole. Gravel-sand content ranges from 57 to 64% with the lower values associated with the Stanley and Bruce port deposits. Reaches 5 and 7 are the coarsest with sand and gravel fractions higher than 80%. Reach 6 at Port Burwell is the finest; gravel is absent and silt-clay is the major component (64%).

Reliability of the data on nearshore volumes and textures is difficult to assess. In general, results for the port areas should be more accurate than those for the intervening areas because of the better acoustic control and higher sample and jet density. Some bias in both texture and thickness should be expected because of the non-uniform distribution of samples, particularly along the profile lines. Coarser, thicker inshore sediments are over-represented and this should lead to exaggeration of the sediment volume and average grain size. Sediment volume may also be overestimated because of jet thicknesses which include some of the underlying glacial sediments. Finally, the validity of the textural data depends upon the accuracy of the assumption that the surface sediment texture is representative of the average texture of the sediment column. The only data available to confirm this are textural profiles from two short cores collected within the study area. In both cores, surface grain size is within 6% of the average grain size for the entire core. This suggests that the errors introduced by relying on surface data alone will be small. In summary, the above comments suggest that the reported volume and grain-size figures are high rather than low estimates. Treating them as maximum values would seem to be the safest approach.

7.4 Beach Deposits

Permanent beaches occur at Ports Stanley, Bruce and Burwell as fillet beaches accumulating to the west of harbour jetties, and a 10-km beach is present near Sand Hills at the east end of the area. Data on the volume and texture of beach sediments is limited to several thickness measurements in the Burwell, Bruce and Sand Hills beaches, and to grain-size analyses for several waterline and onshore samples. We have used the average thickness multiplied by the total area of the exposed beach as a rough estimate of beach sediment volume, and then determined size-fraction volumes based on the average grain-size of the waterline samples (Table 5).

8.0 DISCUSSION

8.1 Coastal Sediment Budget

A coastal sediment budget is an accounting of all sediment input, accumulation and output affecting a particular shore reach. Table 6 lists the various factors which may be involved. In this case, sediment sources include bluff erosion, nearshore slope erosion, fluvial sediment input and littoral drift from adjacent reaches. Accumulation within the study area occurs as nearshore and beach deposits. Sediment is lost to the basin by offshore transport and to adjacent reaches by littoral drift. Sediment accumulation within harbours and loss by harbour dredging have not been included as factors because dredge spoil is disposed of within the nearshore zone with the result that there is no net loss or gain of sediment to the system.

Sediment input from bluff erosion and slope erosion and sediment accumulation as beaches and nearshore deposits have already been presented above (Tables 2,3,4,5). Data on fluvial sediment input to the study area are available only for suspended sediments (Ongley 1976); total annual input is about 50 000 tonnes. The quantity of littoral drift introduced from adjacent reaches has not been measured but is considered to be relatively small and to some extent self-cancelling. Littoral drift from both west and east of the study area can occur only for south and southeast winds which occur infrequently and for which fetch is limited.

No direct measurements of sediment loss to the basin have been made, but estimates are available from a Lake Erie sediment budget for silt and clay compiled by Kemp et al (1977). Their data suggest that bluff erosion of the north-central shore accounts for 35% of the total input to the lake and that most of this sediment enters the eastern basin and contributes to the annual accumulation rate of 5.8 X 10^6 metric tons. Our sediment distribution data appear to confirm this pattern of sediment transport and accumulation. The extensive shelf of glacial sediment separating the inshore silt-clay deposit from the basin sediments (Figure 3) is an area of erosion or non-deposition and shows no evidence of lakeward transport of fine sediment. A more likely route for silt-clay transport is suggested by the silt-clay deposit itself. It extends across the study area and eastward to Long Point at a depth of 9 to 15 m and within a zone of relatively high bottom shear stress (Kang et al. 1982) and dominant eastward bottom currents (Saylor and Miller 1983). These are conditions favourable to sediment transport and we consider the survival of the deposit in such an active zone as evidence that it marks a major pathway of sediment movement to the eastern basin. It is also possible that this route provides for some transfer of sediment to the central basin if there is southward and then westward diversion of flow down the ridge separating the central and eastern basins. At present these suggestions are speculative and based solely on the considerations noted above. They should be tested by the deployment of sediment traps across the proposed path and the measurement of associated bottom currents and thermal structure.

An estimate for sediment loss to adjacent reaches by littoral drift was obtained by converting values of wave-energy flux hindcast by Gelinas (1974) to littoral drift rates (Skafel 1975 and pers. commun.). Transport rates were computed for the NE through NW sectors for each of the 6 reaches defined by Gelinas and then summed to give the net rate and direction for each reach. Table 7 shows the net rates corresponding to our seven reaches. Strictly speaking, these rates are valid only for the transport of sand-sized material along a continuous beach where transport capacity does not exceed sand supply. Their application to the sand-poor shoreline of the study area is problematic since neither theory nor empirical data on littoral transport of a range of sediment sizes are available. Table 7 shows that the computed transport rate exceeds the sand and gravel input for reaches 1 to 6, and that net accumulation occurs only in reach 7. The excess transport capacity in the western reaches must be expended in one or more of shore erosion, bottom erosion and the transport of the silt-clay sediment, but prediction of the erosion or transport rates is not possible at present. Since our major concern is the net loss of sediment from the study area, we have used the transfer from reach 7 (Table 7) as an estimate of sediment loss by eastward littoral drift and assumed that only sand and gravel transport was involved. This gives an annual loss of sand and gravel of 572×10^3 m^3.

Table 8 compares the annual input rates from various sources with the total amount of nearshore sediment within the study area. Data have been converted from volume to mass units (Equation 1) to adjust for differences in the bulk density of glacial and modern sediments. The values used for the specific gravity of solids and for the void ratio are presented in Table 9.

$$Ms = Vt \cdot Dw \cdot Gs / (1 + e) \qquad (1)$$

where Ms - mass of solids

Vt - total volume

Dw - density of water

Gs - specific gravity of solids

e - void ratio

The ratio of the mass of nearshore sediment to the annual supply is the number of years required to generate the deposit assuming a uniform accumulation rate and no sediment loss. The time required is small, ranging from 7 years for silt-clay to 46 years for sand and gravel

(Table 8). This is equivalent to between 0.1 and 1% of the 4000-year time interval available for accumulation of the deposit, i.e. the time since the the latest water level was established following the drop from the Nipissing high (Coakley and Lewis, In Press). The implication of the high input/output ratio is that, on average, 99% or more of the sediment supply is lost to the basin or to the littoral zone to the east.

The coastal sediment budget which results from integration of the data above is shown in Table 10 and Figure 6. Total sediment input is about 8 X 10^6 tonnes/yr. Bluff erosion accounts for 89% of the supply, slope erosion for 10% and stream discharge for less than 1%. The estimate for bluff erosion alone agrees with earlier data from Rukavina and St. Jacques (1978) for the area west of Port Burwell and with Boyd's values for the entire reach (1981, Table D-7) if adjustments are made for his use of higher erosion rates. In both cases the earlier data overestimate the proportion of sand and gravel in the bluffs, presumably as the result of the lower density of sample stations. Our value for the silt-clay component of bluff erosion (5.4 X 10^6 tonnes/yr, Table 9) confirms the earlier estimate by Kemp et al (1977) of 5.2 X 10^6 tonnes/yr and is based on more detailed measurements. We have no direct measurements of the accumulation rates of beach and nearshore sediments or of the variability of the rates since the establishment of the current water level about 4000 years ago. Our best estimate is the net annual accumulation rate obtained by dividing the total mass of the deposit by 4000 years. This gives a very low accumulation rate relative to supply (less than 1%), and requires a net loss of sediment from the study area of about 2 X 10^6 tonnes of sand and gravel and 6 X 10^6 tonnes of silt and clay. We assume that sand and gravel loss is exclusively to Long Point to the east, and that the ultimate sink of the fine fraction is the central and eastern basin deposits. This seems a reasonable assumption given that the sand content of the basin sediments averages about 3% (Thomas et al. 1976).

Our silt-clay loss of 6 X 10^6 tonnes/yr accounts for only about 35% of the sediment accumulating in the central and eastern basins and lost to the Niagara River (Kemp et al. 1977). In light of the discussion above on sediment pathways, we believe the eastern basin to be the primary sink for fine-grained sediment from the study area. If this is the case, then about 60% of the sediment entering the eastern basin can be accounted for in this manner.

Our budget indicates a loss of sand and gravel to Long Point of approximately 2 X 10^6 tonnes or 1.2 X 10^6 m^3/yr. Independent estimates of the transport rate for sand and gravel are available from several sources. Coakley (1985) estimated the total volume of sand and gravel in the Long Point spit as 5.5 X 10^9 m^3. This is equivalent to an average accumulation rate of 1.4 X 10^6 m^3/yr over the 4000-year history of the spit, about 15% higher than our budget value. Much lower rates are suggested by Liard (1975) and by the analysis of Skafel (1975 and pers. commun.) which was discussed above. Liard derives a rate of 0.5 X 10^6 m^3/yr of sand and gravel from Wood's (1960) estimate of the annual extension of Long Point. Skafel's analysis of hindcast wave data provides a computed transport rate of 0.6 X 10^6 m^3/yr (Table 7). We consider the lower rates to be unlikely because they are inconsistent with both the volume of the Long Point deposit, which should reflect the long-term transport rate, and with the measured historical erosion rates which apply over the past 150 years. We suspect that the Liard-Wood value is low because it considers only accumulation occurring at the tip of Long Point. The low computer transport rate is really not in disagreement with our budget estimate since the procedure used is acknowledged to produce only an order-of-magnitude estimate (Greer and Madsen 1978). What is surprising is that the equations apparently underestimate the rate of sand-gravel transport which suggests that the transport capacity may be increased by the presence of silt and clay. Consideration of this question is beyond the scope of this paper but merits investigation if the problem of the rates and mechanisms of transport along shorelines of cohesive sediment is to be resolved. This is particularly important in the Great Lakes where cohesive shorelines are the dominant type and sandy shores are rare.

8.2 Effect of Harbour Structures

The above discussion assumes that the historical data used to construct the sediment budget apply throughout the 4000-year history of the current water level. In fact, there is evidence that the installation and extension of harbour structures during the past 150 years have increased the quantity of sediment retained within the study area. Figure 5 shows the volume of nearshore sediment within each reach expressed as a volume per unit length of shoreline. The three harbour reaches have values 4 to 9 times greater than those of non-harbour reaches 1, 3 and 5. We interpret the larger volumes to be the result of accumulation of fillet beaches on the west side of harbour structures by the interception of littoral drift, followed by shoaling offshore as sediment bypassing occurred. This process has been documented for the Port Burwell deposit by historical and modern survey records assembled by Kolberg (1967). Kolberg's data suggest that accumulation occurs until the 5-m contour advances to the offshore limit of the structure, after which bypassing is possible. Accumulation in this manner should result in local deposits whose volume is proportional to the total length of the structure. This is generally true for the study area; jetty length and the volume of associated deposits both increase from Bruce to Stanley to Burwell but the relationship is not a simple cubic one, presumably because of differences in the littoral transport rate and the nearshore bathymetry. In the case of Burwell, jetting data show a buried valley which extends offshore from the harbour mouth and which is now filled with sediment to the grade of the adjacent slope. This results in the retention of a larger volume of sediment than would be expected as the result of the influence of the harbour structure alone.

A rough estimate of the effect of the harbours on sediment accumulation can be obtained by computing the excess mass of harbour sediments per unit length of shore relative to the unit mass in the non-harbour reaches. This yields a total excess mass of approximately 15×10^6 tonnes, about 40% of the total mass of the nearshore deposit.

Although this represents a significant difference between post- and pre-harbour accumulation, it has virtually no effect on the sediment budget itself because net accumulation accounts for less than 1% of the total input to the study area (Table 9). Furthermore, the sediment mass associated with the harbours represents only an 8-year supply (40% of 19.2 years, Table 8) assuming the long-term erosion rate and average sediment texture. Thus the effect of the harbours on the extraction of sediment from the coastal system appears to be both minimal and transitory. This is one of the factors that was recognized by the Federal Court in its rejection of the Port Burwell shore-damage suit referred to previously (Rouleau 1985).

8.3 Stability of Bottom Types

The current sediment data provide the equivalent of a snap-shot of the bottom sediment distribution as it occurred during the survey period. Some indication of the short-term stability of bottom type is available from a comparison of the current samples and contacts with those of the 1972-74 survey. In Figure 7 matching samples from nine sites within the area of postglacial sediment cover have been plotted on triangular graph paper to compare their grain size. Arrows connect the sample pairs and show the direction of any shift in texture. Changes in the proportion of a single component range from a few percent to a maximum of 28%. There is no obvious trend towards decrease or increase in grain size, however, and, in fact, the net change for the combined samples (4%) is within the error of the size analysis procedure. Although this may be fortuitous, it is more likely an indication that local changes in grain size due to addition and redistribution of sediment have little net effect on the texture of the deposit as a whole, at least in the short term.

There has been no comparable attempt to assess the short-term changes in the extent and volume of the nearshore deposit. No jet data were collected during the earlier survey and the lower density acoustic data permitted only a general definition of the offshore boundary of postglacial sediments. It was noted, however, that there was excellent agreement in the position of acoustic contacts where the two surveys did overlap sufficiently to make comparison possible. This suggests that there has been no appreciable change in the shape and presumably volume of the deposits over a time scale of about a decade.

8.4 Textural Changes from Source to Sediment

The relationship between the size distribution of source material and lake sediment is shown in Figure 8. The figure is a reach-by-reach comparison of the average texture of combined bluff, slope and stream sediments with that of adjacent beach and nearshore sediments. The average change observed is a shift from sandy mud in the source sediment to silty or muddy sand in the lake sediment. This involves a doubling of the gravel/sand fraction, a one-third reduction in the proportion of silt and a 50 percent decrease in the clay content. The differential sorting indicates that the transport rate is considerably higher for fine sediment than for sand and gravel. The scatter in the values for individual reaches appears to be the result of introduction of sediment from updrift reaches, loss of most of the locally-generated sediment and variations in the local wave energy available for sorting and transport.

9.0 CONCLUSIONS

New information on bluff stratigraphy and the distribution of nearshore sediments has been used to prepare a coastal sediment budget for the north-central shore of Lake Erie. This is an area of rapidly eroding shore bluffs of cohesive sediments and as such differs from the sand-rich coasts to which sediment budget calculations are usually applied.

The most conspicuous feature of the resultant budget is the very low accumulation rate within the survey area relative to the abundant sediment supply. The average annual input of sediment is more than 8 X 10^6 tonnes derived principally from bluff erosion (89%) and to a lesser extent from nearshore slope erosion (10%) and stream discharge (1%). Less than 1% of this sediment remains within the study area; the balance is lost to the shoreline to the east and to the offshore basins. The sediment pattern and data on nearshore circulation suggest that the entire nearshore zone of the study area is a major pathway for sediment transport between the central and eastern basins. Eastward longshore drift transports about 2 X 10^6 tonnes of sand and gravel to the Long Point spit. Silt-clay transport within the nearshore zone moves about 6 X 10^6 tonnes of silt and clay into the eastern basin and accounts for about 60 per cent of the annual loading to that basin.

Our data on the sediment budget and on transport pathways are in general agreement with the lakewide budget for Lake Erie proposed by Kemp et al. (1977). Both budgets suggest a general eastward movement of sediment from the central to eastern basin and agree closely on the input rates from bluff erosion. Our budget also provides an estimate of the sediment supply from erosion of the nearshore slope and from stream discharge, data which were not previously available.

Our estimate of sand-gravel transport/loss is in accord with Coakley's estimate (1975, Table 3-7) of the total volume of sand and gravel in Long Point and falls within the range of the order-of-magnitude estimate predicted by the longshore transport equations.

A comparison of harbour and non-harbour reaches suggests that harbour structures may be responsible for about 40 per cent of the sediment accumulation within the study area in the form of fillet beaches and an expanded nearshore deposit. It appears, however, that the adjustment to the structures takes place very quickly because of the very high input and transport rates. The total sediment supply to the study area is sufficient to account for the excess volume of the harbour deposits in a period of about 8 years.

Sediments accumulating in the study area are coarser and better sorted than their source materials apparently because of faster transport of the silt and clay fractions. The percentage of sand and gravel is doubled and there is a 1/3 to 1/2 reduction in the proportion of silt and clay respectively. Comparison of grain-size data from this survey with corresponding data from an earlier survey suggests that little net change in the overall texture of the nearshore deposit occurs on a time scale of about a decade.

The sediment budget proposed in this paper raises a number of questions about the processes and rates of erosion and sedimentation of a cohesive shoreline which should be addressed by further research. We recommend that the following additional studies be carried out:

1. Installation of sediment traps across and along the nearshore zone to measure the rates and directions of suspended sediment transport.
2. Use of tracer techniques to measure suspended and bedload transport rates.
3. Collection and analysis of cores of the inshore silt-clays to determine the depositional history and the likely mode of transport.
4. High-precision measurements of subaqueous erosion of the nearshore till surface.
5. Theoretical analysis of the mechanisms of coastal erosion and transport of sediment with a range of particle sizes.

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TABLES

TABLE 1

LEGEND FOR BLUFF STRATIGRAPHY (FIG. 2)

NO.	STRATIGRAPHIC UNIT	TENTATIVE AGE CORRELATION
1	Glaciolacustrine Silt and Clay	Port Talbot Interstadial
2	Sand and Gravel	Plum Point Interstadial
3	Catfish Creek Till	Nissouri Stadial
4	Sand	Erie Interstadial
5	Port Stanley Till	Port Bruce Stadial
6	Glaciolacustrine Silt and Clay	Port Bruce Stadial and Mackinaw Interstadial
7	Glaciolacustrine Silty Sand to Sand	Port Bruce Stadial and Mackinaw Interstadial
8	Waterlain Till	Port Bruce Stadial or Early Mackinaw Interstadial
9	Glaciolacustrine Silt and Sandy Silt	Early Mackinaw Interstadial
10	Wentworth Till	Early Mackinaw Interstadial
11	Sand	Mackinaw Interstadial to Recent
12	Dune Sand	Recent
13	Alluvium	Recent

TABLE 2

BLUFF EROSION VOLUMES

$M^3/YR \times 10^3$

REACH	GRAVEL	SAND	SILT	CLAY	TOTAL
1	6.3	98.5	419.0	436.7	960.5
2	1.1	32.0	126.7	88.6	248.4
3	3.7	277.2	378.9	411.1	1070.9
4	2.3	41.1	79.7	89.5	212.6
5	2.7	35.5	179.5	153.7	371.4
6	0.6	57.3	191.8	95.4	345.1
7	1.0	463.3	373.5	196.3	1034.1
TOTAL	17.7	1004.9	1749.1	1471.3	4243.0

TABLE 3

SLOPE EROSION VOLUMES

$M^3/YR \times 10^3$

REACH	GRAVEL	SAND	SILT	CLAY	TOTAL
1	1.9	13.0	35.2	35.0	85.1
3	0.4	12.8	31.5	49.3	94.0
5	0.8	6.0	25.7	28.2	60.7
7	0.5	106.8	59.6	80.7	247.6
TOTAL	3.6	138.6	152.0	193.2	487.4

TABLE 4

NEARSHORE SEDIMENT VOLUMES

$M^3 \times 10^3$

REACH	GRAVEL	SAND	SILT	CLAY	TOTAL
1	131.8	6265.7	4220.7	1677.7	12295.9
2	285.0	4511.6	1923.2	880.2	7600.0
3	68.4	2884.8	1179.4	465.6	4598.2
4	204.8	2187.8	1265.8	743.0	4401.4
5	30.7	2282.6	786.1	531.6	3631.0
6	651.4	16617.7	14562.6	6789.1	38620.8
7	0.0	16362.8	3605.1	1740.8	21708.7
TOTAL	1372 .1	5113.0	27542.9	12828.0	92856.0

TABLE 5

BEACH SEDIMENT VOLUMES

$M^3 \times 10^3$

DEPOSIT	GRAVEL	SAND	SILT	CLAY	TOTAL
STANLEY	135.4	440.8	5.3	7.1	588.6
BRUCE	249.6	43.4	0.0	0.0	293.0
BURWELL	545.4	4303.6	59.5	49.6	4958.1
SAND HILLS	0.0	199.5	3.9	2.1	205.5
TOTAL	930.4	4987.3	68.7	58.8	6045.2

TABLE 6

ELEMENTS OF SEDIMENT BUDGET FOR STUDY AREA
(Modified after CERC, 1984)

OFFSHORE ZONE	(+) transport from offshore	(-) transport to offshore		
SHORE ZONE	(+) bluff erosion	(+) beach erosion	(-) beach storage	(+) streams
NEARSHORE ZONE	(+) slope erosion (till)	(+) nearshore erosion (modern deposits)	(-) nearshore storage (modern deposits)	(-) dredging
LONGSHORE ENDS OF NEARSHORE ZONE	(+) longshore transport in	(-) longshore transport out		

(+) source (mass/unit time)
(-) sink (mass/unit time)

TABLE 7

TRANSPORT RATE VS SAND/GRAVEL INPUT

M^3/YR X 10^3

	REACH					
	1	2	3,4	5,6	7	LONG PT
TRANSPORT RATE	358	330	468	522	593	
LOCAL INPUT	120	33	338	103	572	
TRANSFER FROM ADJ. REACH	---	120	33	338	103	572
NET ACCUM.	-238	-177	-98	-81	82	

TABLE 8

INPUT VS ACCUMULATION

INPUT	TOTAL	S+G	SILT	CLAY
		TONNES/YR x 10^3		
BLUFFS	7160.1	1725.7	2951.6	2482.8
SLOPE	822.5	240.0	256.5	326.0
STREAM	48.7	0.0	24.3	24.3
TOTAL	8031.3	1965.77	3232.4	2833.1
ACCUMULATION		TONNES X 10^3		
NRSHORE	144746.1	81815.0	42934.5	19996.6
BEACH	9423.4	9224.6	107.1	91.7
TOTAL	154169.5	91039.6	43041.6	20088.3
ACCUMULATION/INPUT				
	19	46	13	7

TABLE 9

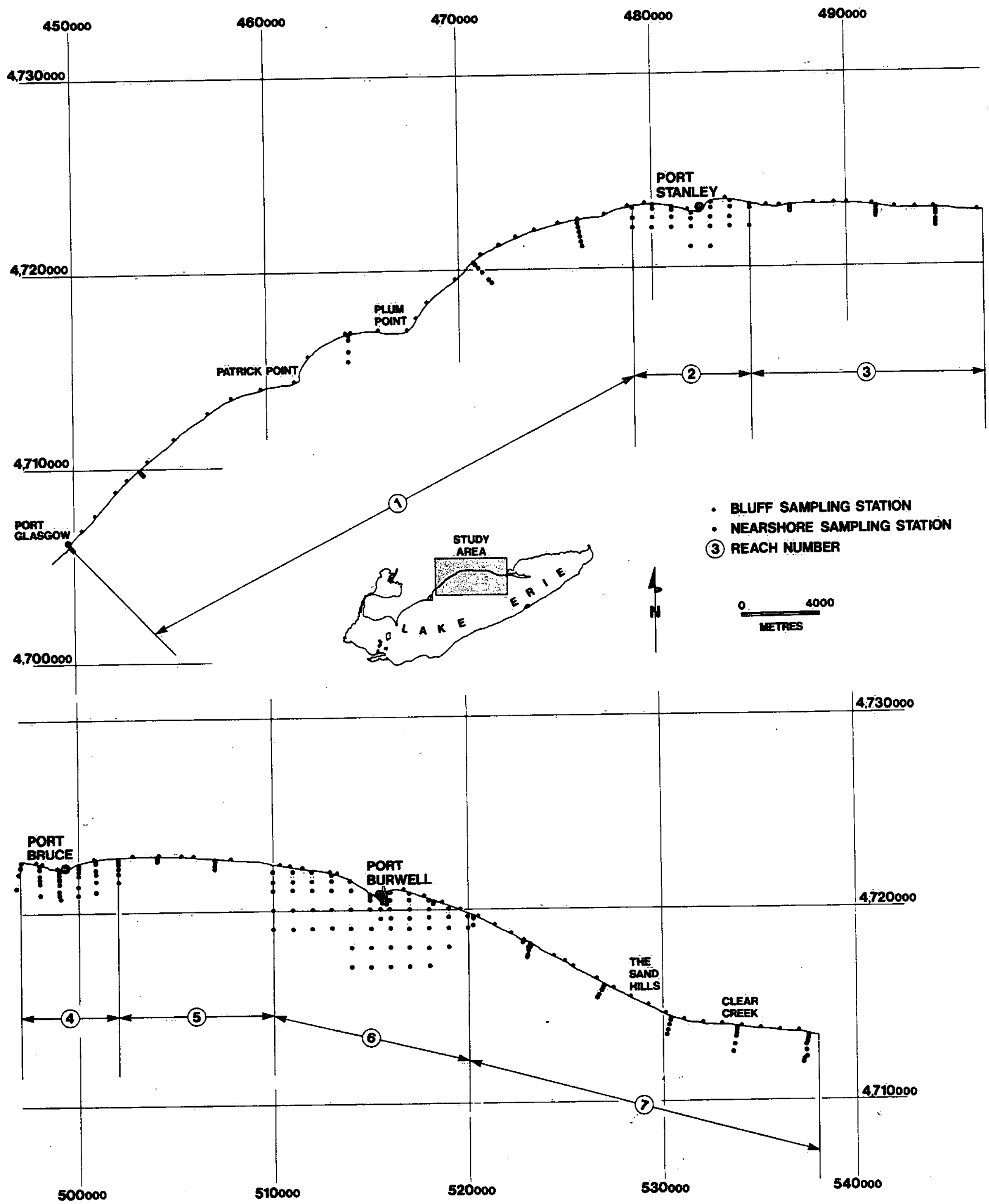
VOID RATIO (e) and SPECIFIC GRAVITY (Gs) VALUES

Sediment	e	Gs	Reference
Shore Bluff	0.6	2.70	Bou 1975, Lo 1977 and Kezdi 1974
Nearshore Glacial Slope	0.6	2.70	Zeman 1983
Beach Deposit	0.7	2.65	Kezdi 1974
Nearshore Post-glacial Sand	0.5	2.65	Cheng and Grass 1981
Nearshore Post-glacial Silt and Clay	0.9	2.70	Cheng and Grass 1981

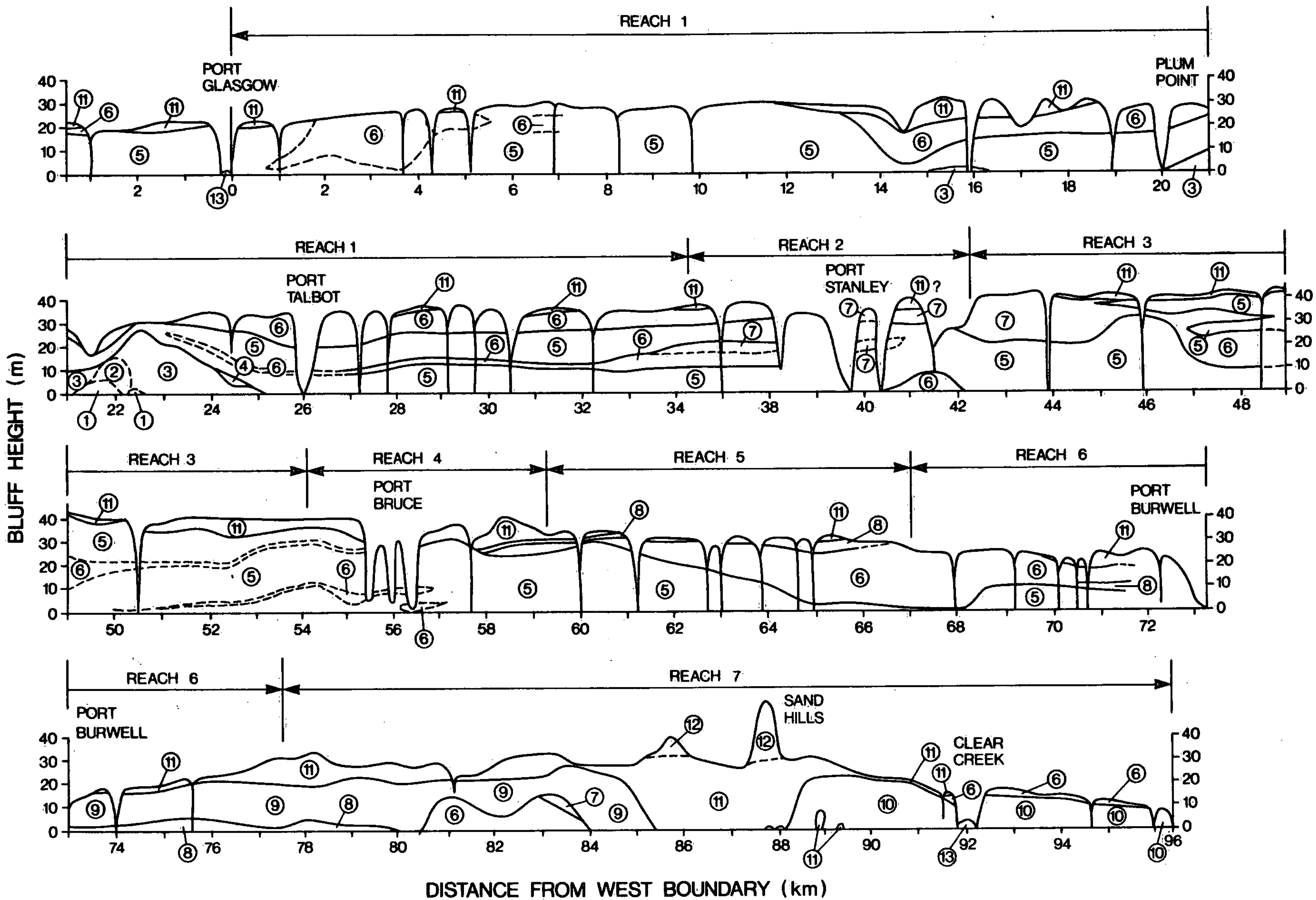
TABLE 10

COASTAL SEDIMENT BUDGET

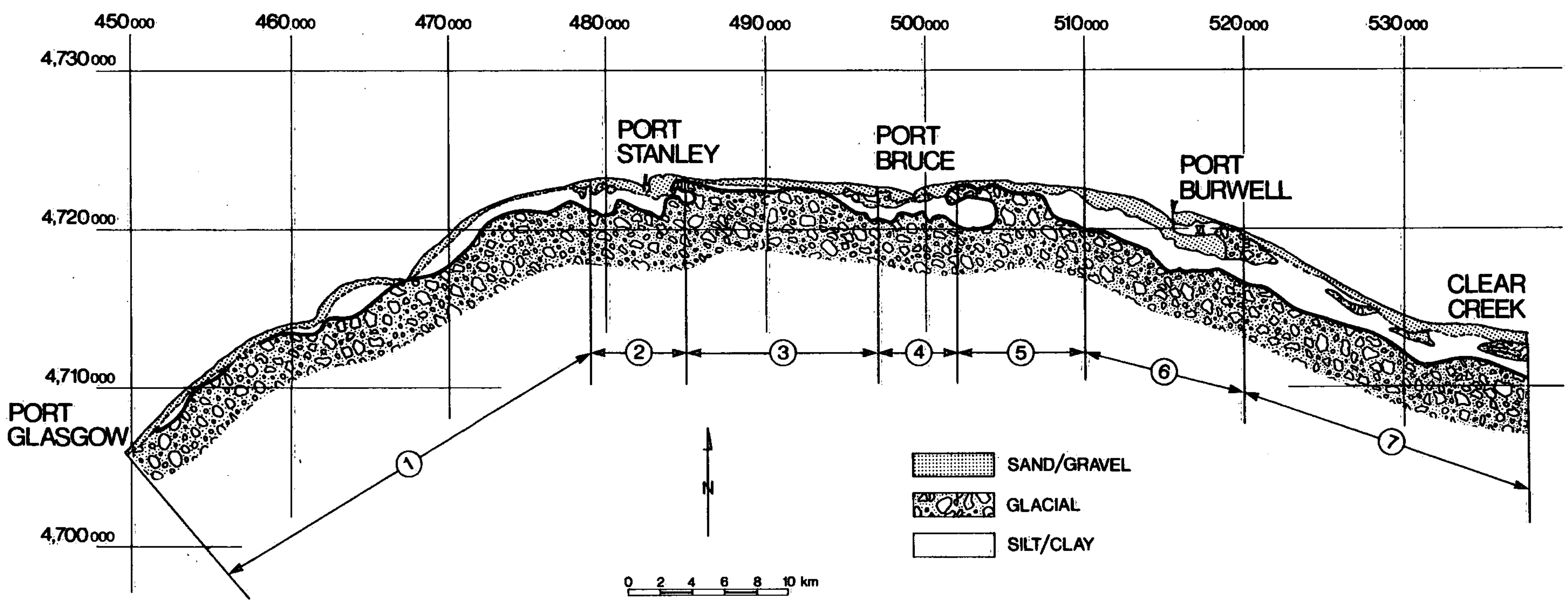
	TOTAL	S+G	SILT	CLAY
	TONNES/YR X 10^3			
ANNUAL INPUT				
BLUFFS	7160.1	1725.7	2951.6	2482.8
SLOPE	822.5	240.0	256.5	326.0
STREAM	48.7	0.0	24.3	24.3
TOTAL	8031.3	1965.7	3232.4	2833.1
ANNUAL ACCUMULATION				
NEARSHORE	36.2	20.5	10.7	5.0
BEACH	2.4	2.3	---	---
TOTAL	38.5	22.8	10.8	5.0
ANNUAL LOSS				
	7992.8	1942.9	3221.7	2828.1
SINKS				
LONG POINT	1942.9	1942.9	------	------
CENTRAL AND EASTERN BASINS	------	------	3221.7	2828.1



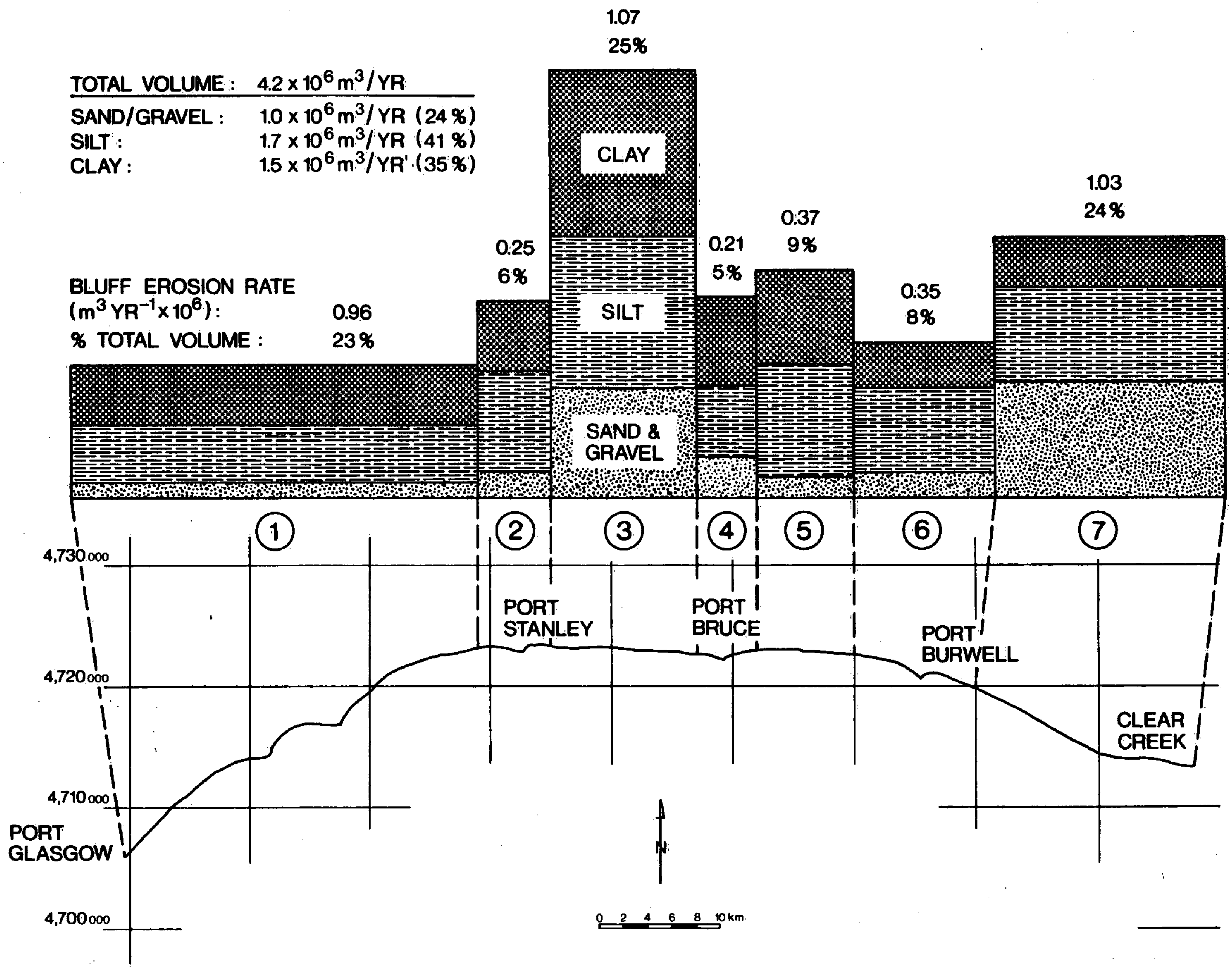
1. Study Area and Sample Sites



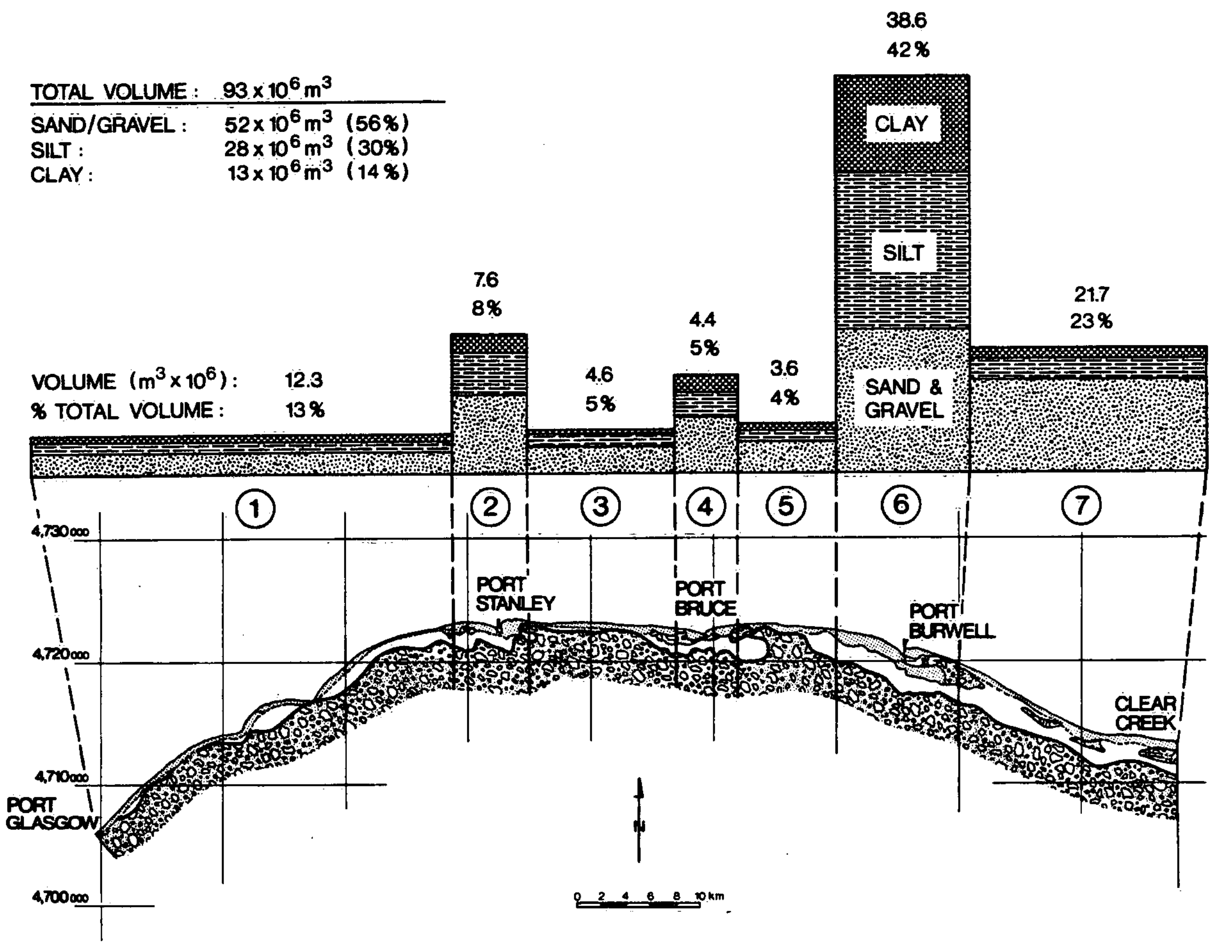
2. Bluff Stratigraphy



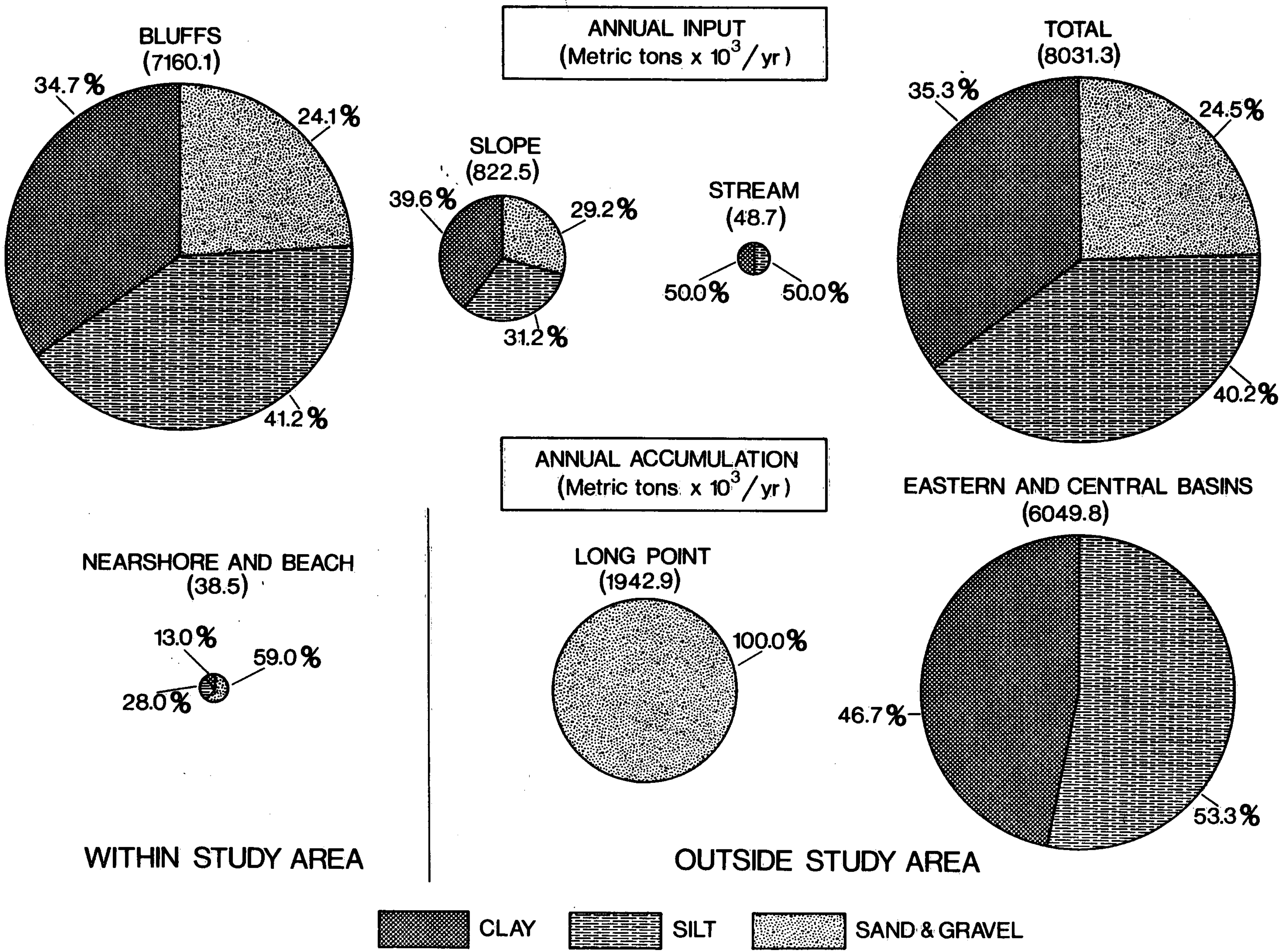
3. Nearshore Sediment Distribution



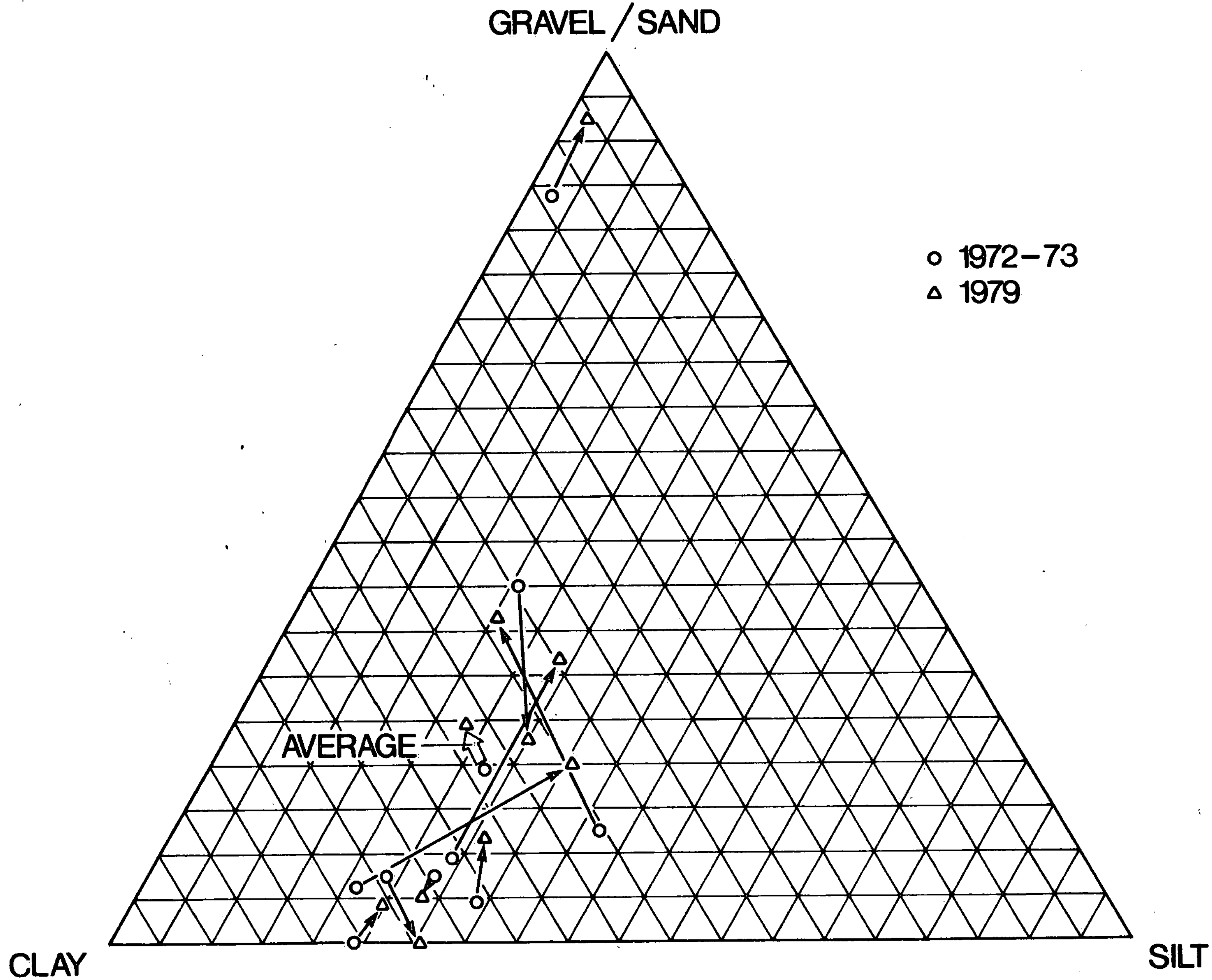
4. Bluff Erosion Volumes



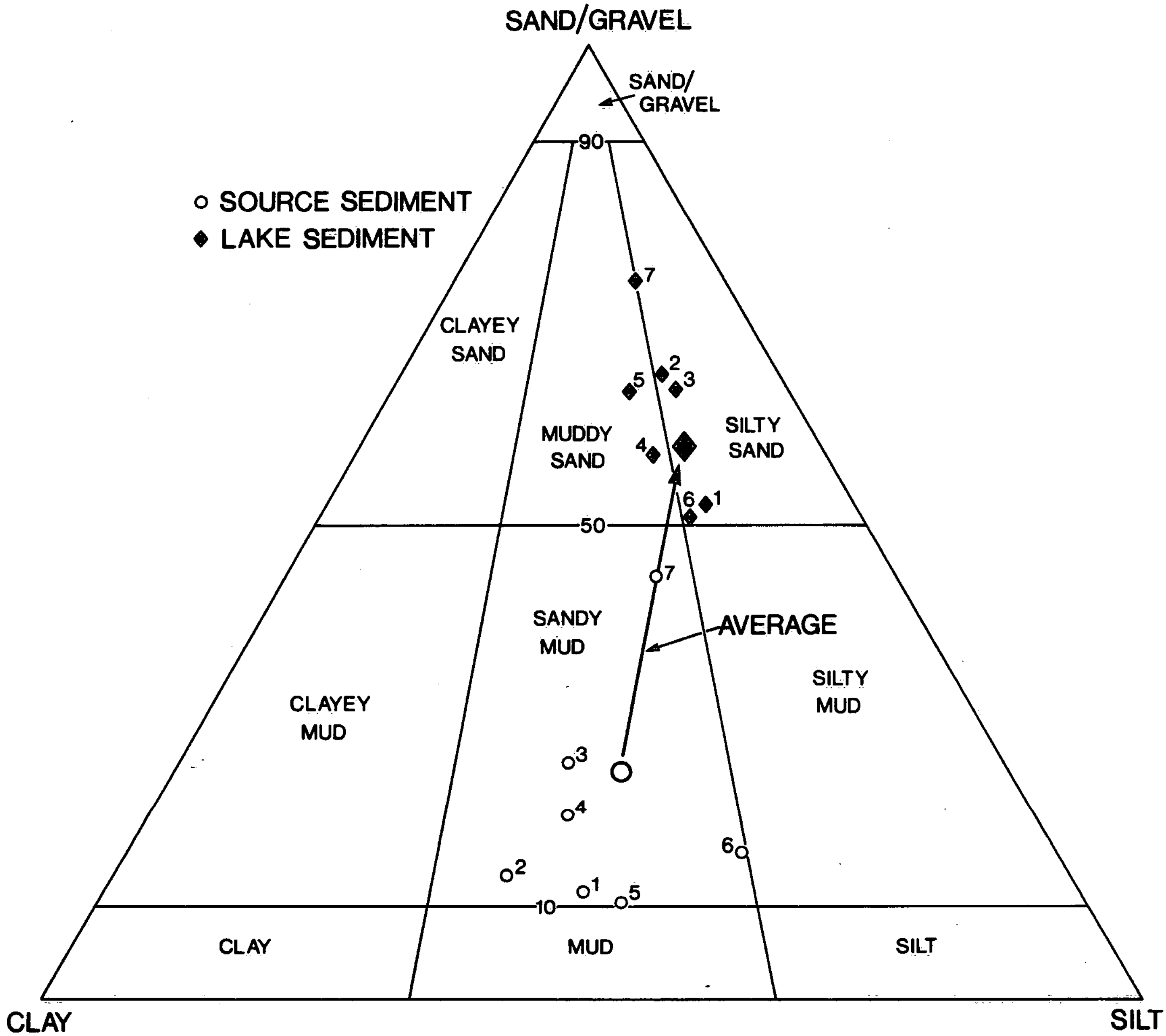
5. Nearshore Sediment Volumes



6. Coastal Sediment Budget



7. Comparison of Grain Size of 1972-73 and 1979 Samples



8. Comparison of Grain Size of Source and Lake Sediments