SEDIMENTATION IN THE DULUTH-SUPERIOR HARBOR, LAKE SUPERIOR

A THESIS

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Figure 3. Minnesota Point and Superior Bay. Photo was taken from Duluth facing south (courtesy of U,S. Army Corps of Engineers, Duluth).

ABSTRACT

The sedimentary environment of the Duluth-Superior Harbor was investigated by examination of surface sediment samples, borehole stratigraphy, seismic reflection profiles, and aerial photographs. Harbor sediments are predominantly silt. Sand is found in a narrow band along the shores of the embayment, on the lower reaches of the St. Louis river bed, and at the base of constrictions on the floor of the dredged channels in Superior and St. Louis Bays. Lag is found upstream in the St. Louis River and in the ship entryways. Clay lies in isolated depressions on the harbor floor and in tributary embayments lining St. Louis Bay. Total organic carbon concentrations correlate well with grain size variation. Percentages range from 0.06 to 5 percent dry weight, with the highest concentrations occurring in the fine-grained sediments of the inner bays. Mineralogy of the harbor sediments is relatively uniform. The medium sand fraction is dominated by lithic fragments. Opaque minerals, amphiboles, and pyroxenes constitute the majority of heavy minerals in the fine fraction. In the clay-sized fraction, relative percentages of smectite, illite, kaolinite, and chlorite vary systematically with bulk-sediment textures. Kaolinite and chlorite are concentrated in the finer sediments, whereas illite is more abundant in coarser sediments. The distribution of surface sediment texture reflects exposure to currents produced by seiches, river currents, ship traffic and wind generated waves.

Engineering borehole data and 3.5 kHz seismic reflection profiles were used to reconstruct stratigraphy and Holocene history of the area. The variation of sediment types records changing water levels and environments in western Lake Superior. Boreholes 10 to 61 m deep contain 7 lithologic units: till, glacial outwash sand, glaciolacustrine clay, postglacial peat, silt, clay, and nearshore sand. Seismic profiles contain 3 main reflectors which roughly correspond to the lithologic units observed in borehole logs.

The two sets of spits outlining the harbor are Holocene features, possibly formed by emergence of offshore bars, submergence of coastline ridges, or spit progradation by longshore currents or "self generation". Post-formational modifications of the spits include breaching of inlets and inland sediment transfer by wind and water.

Numerous comparisons can be drawn between the St. Louis River estuary and coastal estuaries. The St. Louis River estuary is small in comparison to marine embayments, having boundaries determined by the geology of the region. Marine estuaries predate the St. Louis River embayment by a few thousand years, inundated in response to glacial melting and isostatic rebound, respectively. Circulation in a marine estuary, driven by tidal currents and wind, is based on density stratification caused by the mixing of saline and fresh water. In the freshwater St. Louis River estuary, there is no density stratification, and periodic currents are driven more by seiches than tides.

Shoreline changes over the past 120 years were described from historic maps and aerial photographs. Development of the shoreline and alteration of the environment through dredging have been accompanied by a rising water level on the southwestern shore of Lake Superior.

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CHAPTER I

INTRODUCTION

Purpose of Study

Increasing awareness of the complexity of estuarine sedimentation has prompted several symposia and major publications over the last two decades (Ippen, 1966; Lauff, 1967; Schubel, 1971; Nelson, 1972; Folger, 1972a; Cronin, 1973; Wiley, 1976; Kennedy, 1982). Harbor studies have been included in this wave of interest (Knebel *et al*., 1981; Collins *et al*., 1980), as it is realized that monitoring of water and sediment is an essential part of harbor maintenance. Industrialized freshwater estuaries, such as the Duluth-Superior Harbor, have been excluded from these studies because they are relatively few in number.

An understanding of the sedimentary framework of the Duluth-Superior Harbor/St. Louis River estuary is a natural prerequisite to future investigations of substrate or water use. Before human impact on benthic, aquatic, and terrestrial ecosystems can be assessed, information on sedimentary processes operating in the harbor is needed.

Several anthropogenic processes affect sedimentation in the harbor. Ship traffic continuously roils bottom sediment, outweighing in magnitude the natural currents and their effects on sediment reworking (Stortz and Sydor, 1980). Periodic dredging of the channels, necessary for maintaining navigational access to and within the port, poses disposal as well as resuspension problems. Channel dredge spoils are often contaminated so they can no longer be used as fill or stored in their adjacent mud flats, but must be permanently removed to land disposal sites. Whether or not this is the case in the Duluth-Superior Harbor remains to be determined, although some preliminary studies have been completed (U.S. Army Corps of Engineers, 1976, 1977). Dredging may also affect water stratification and circulation patterns, and the residence time associated with pollutants. Upstream damming can decrease sediment influx, and it has modified morphology and sedimentation in the harbor in some manner. All of these subjects will eventually require consideration in order to maintain the estuary as a harbor for ships and as a clean recreational area. As a consequence of recent water restoration efforts by the Western Lake Superior Sanitary District (WLSSD), the sediments are now an important source of pollution in the water, so they provide a logical place to commence such studies.

Interest in the Duluth-Superior Harbor is not limited to public concerns. Because of its size, the head of Lake Superior provides a unique geological setting for examining coastal and estuarine sedimentation. Greater understanding of lacustrine embayments may aid in distinguishing between oceanic and large lake deposits in the stratigraphic record, as the two probably have been confused in the past (Sly, 1980).

The purpose of this report is to characterize the bottom sediments of the Duluth-Superior Harbor and St. Louis River estuary and to use these results to understand sedimentation processes. Analyses included the determination of (1) sediment texture and composition by analysis of grain size, organic carbon, clay minerals and heavy minerals; (2) sediment stratigraphy by means of engineering borehole data and seismic reflection profiles; and (3) historic shoreline changes through use of aerial photographs and harbor charts.

The Setting and History

The Duluth-Superior Harbor is located at the extreme western end of Lake Superior at the mouth of the freshwater St. Louis River estuary. The harbor comprises St. Louis Bay and Superior Bay, which are separated from each other and detached from the open lake by two sets of spits: Rice's and Connor's Points are the inner set, Minnesota and Wisconsin Points are the outer set (Fig. 1).

The shapes of the two bays are different from each other. St. Louis Bay has a sinuous channel, intersected by numerous embayments. As a result of dredging in the lower bay, the central channel is divided into two branches, segregated by intervening shallows. Superior Bay has a straight-sided rectangular shape and channel. Total channel length is 30 km; widths range from about 0.8 to 1.2 km. In cross section, the harbor consists of a flat dredged channel floor, 8-9 m deep, which rises abruptly to shoreline flats, 0.5-3 m deep. Isolated depressions about 3.3-4.4 m deep within the flats were carved by the St. Louis River (Fig. 2).

Water level in the harbor fluctuates about 0.3 m annually.

Two inlets permit water exchange between the harbor and open lake: the natural opening, the Superior Entryway, is opposite the Nemadji River, and the Duluth Ship Canal is cut through the northern end of Minnesota Point. Jetties are constructed at both inlets. In or near both entryways, deep holes up to 15 m deep have been scoured by ship propellers.

The harbor lies within the Superior lowlands and is overlooked by

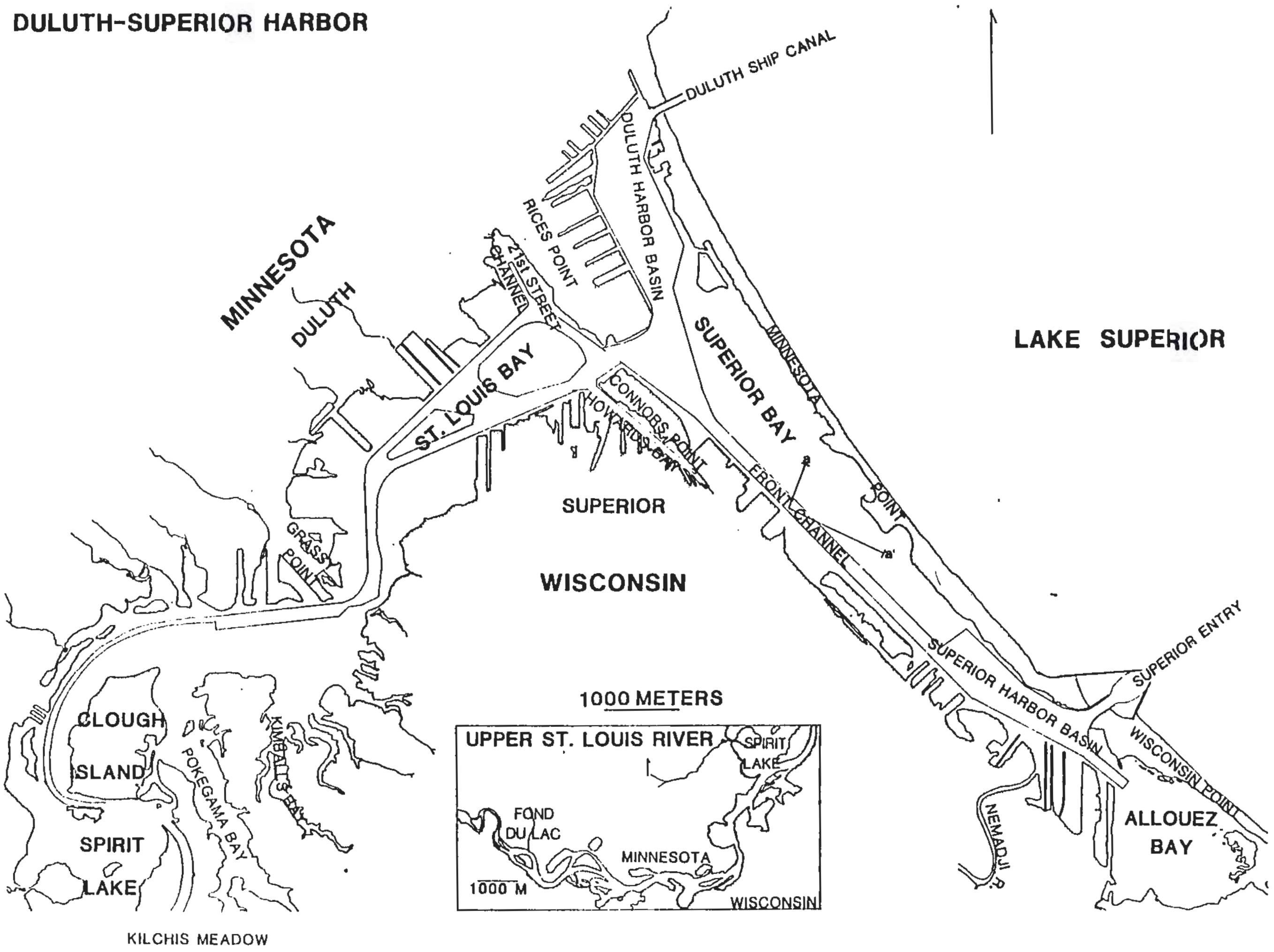


Figure 1. Site locations refered to in text.

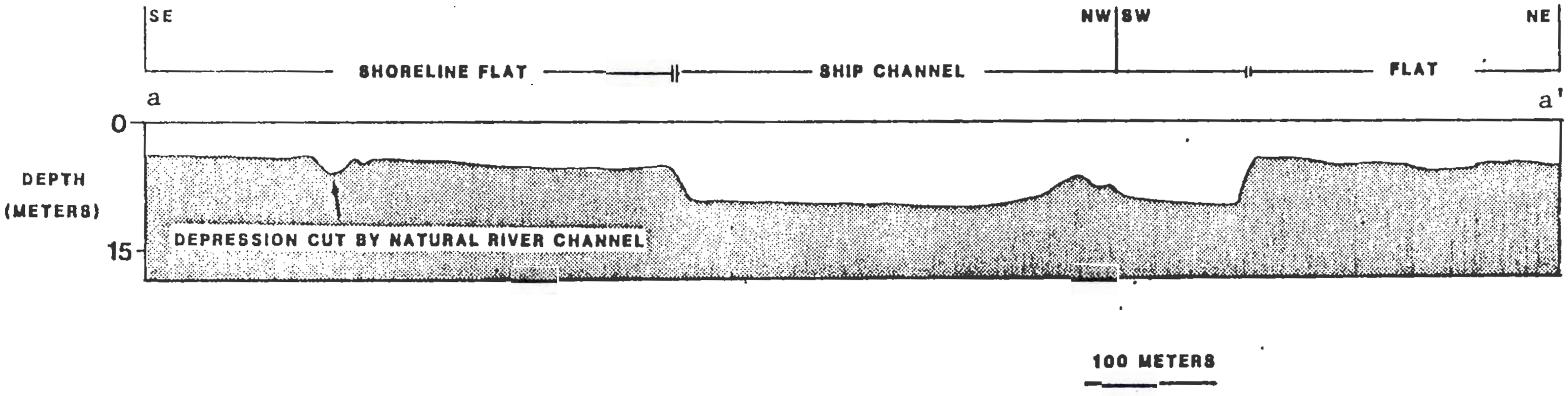


FIGURE 2. Depth profile illustrating main features of the harbor floor-Superior Bay.

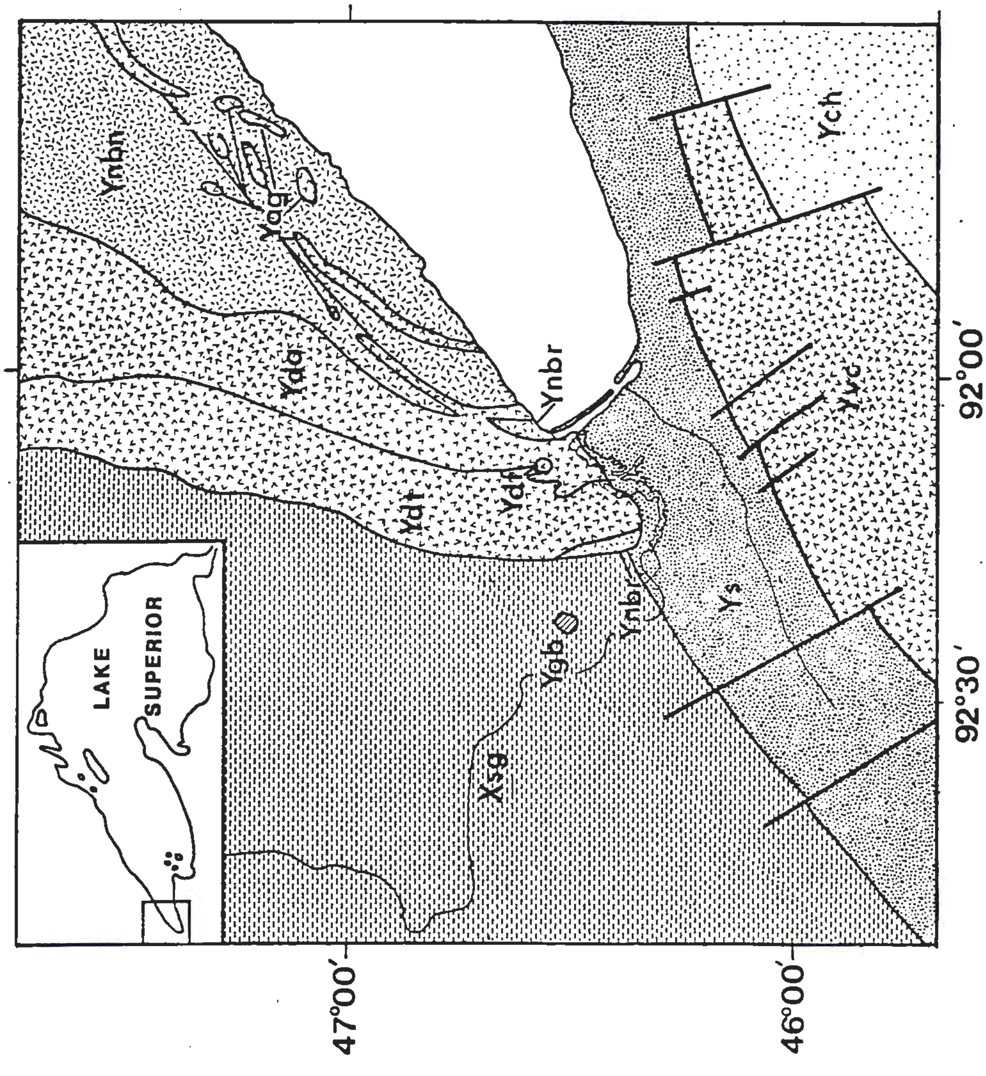
the high walls of the Superior upland to the northwest. Shorelines within the embayment differ enormously from one locale to another (Fig. 3). Docking facilities and their corresponding industries line the waterfront in the Superior and lower St. Louis Bays. Upriver from Grassy Point, forested bluffs of glacial till rise 30 m above the water on the Wisconsin shore, whereas on low-lying flat forested coastal plain occupies the Minnesota shore. Tributary embayments incised through the till outline the local drainage pattern.

The St. Louis and Nemadji Rivers are the major tributaries to the harbor. The St. Louis River flows through Duluth Complex, Animiki group, and Northshore volcanic rocks, which make up the Superior uplands. The Nemadji River enters Superior Bay from the Superior lowland which is underlain by Keweenawan metasedimentary rocks (Fig. 4).

The earliest industry in the Duluth-Superior Harbor was fishing, organized on Minnesota Point by 1836. The first wharf was built in 1853 at the southern end of Minnesota Point near Superior City. For almost 2 decades, the only passageway from Lake Superior to the bay was via the Superior Entryway. A 1030 ft. long timber crib breakwater at the base of Fourth Street provided a port for ship access to the city of Duluth. Dissatisfied with this facility, citizens excavated the Duluth Ship Canal in 1869, promoting construction of docks closer to their city and within the protective arm of Minnesota Point.

During the 1870's, a surge of development took place, primarily in the iron ore, grain, flour, coal, and timber industries. By 1900, the harbor comprised 119 piers, with 39 more to be built over the next 20 years. Several successive years of record breaking shipped-tonnage led

Figure 4. Pre-Cambrian bedrock map of the western Lake Superior region. Symbols represent the following formations or groups: Ys - Fond du Lac Formation and Hinckley Sandstone; Ych - Copper Harbor Conglomerate, conglomerate and sandstone; Yvc - Chengwatana Volcanic Group, basalt and associated rocks; Ynbn - North Shore Volcanic Group, basalt and associated rocks; Ydt - Troctolite and gabbroic rocks of the Duluth and Beaver Bay Complexes; Ydf - Granite and granophyric felsic rocks of the Duluth and Beaver Bay Complexes; Yda - Anorthositic, gabbroic and perdotitic rocks of the Duluth and Beaver Bay Complexes; Yog - Olivine gabbro in dikes and sills; Ygb - Gabbro and related rocks of uncertain affinity; Ynbr - North Shore Volcanic Group, basalt and related rocks; Xsg - Animiki Group (Thomson Formation) slate, metagreywacke, and associated metalvolanic rocks. (After Morey et al., 1982)


LAKE
SUPERIOR
Ynbn
Yag
Ydg
Ynbr
Ydt
Ydt
Ygb
Ynbr
Xsg
Ys
Yvc
Ych
92°00′
92°30′
47°00′
46°00′

the Duluth-Superior Harbor to become the foremost American port (in tonnage) in 1907, exceeding New York by 400,000 tons (MacDonald, 1958).

Today, 50 privately owned docks line the 49 sq. miles of waterfront acreage. The Duluth-Superior Harbor is the largest commercial port on the Great Lakes, ranks twelfth in total waterborne tonnage in the U.S., and serves 24 nations. Grain, seeds, by-products, iron ore, taconite, cement, coal, limestone, salt, coke, and potash account for the majority of commerce. General cargo including lumber, steel products, scrap, woodpulp, newsprint, and fertilizer are also transported through the harbor. Decreasing use of iron ore is responsible for slowing exports; however, the Duluth-Superior Harbor is still among the largest ore exporting ports in the world.

Geologic History

The Duluth-Superior Harbor is situated within the Superior Province of the Precambrian Canadian Shield (Fig. 4). Throughout most of northern and east central Minnesota, Pleistocene glacial deposits unconformably overlie Precambrian bedrock.

The oldest bedrock of the western Lake Superior region is the middle Precambrian Thomson Formation of intercalated mudstone, siltstone and greywacke (Sims and Morey, 1976). The source of these clastics was the granite to the north, that was eroded during the Penokean orogeny. Folding, faulting, and pluton emplacement were also extensive, and deformation increased in intensity from east to west (Keighin *et al.*, 1976).

Late Precambrian formations of Keweenawan age are the most common surrounding the western Lake Superior shoreline. These were formed during a major rifting episode and include the North Shore Volcanics, which are primarily basaltic in the Duluth area (Green, 1976), and intrusions of anorthosite and troctolite, forming the southern part of the Duluth Complex (Bonnichsen, 1976; Phinney, 1976). Overlying the two igneous formations are sandstones and red shales, deposited in a subsiding basin (Tryhorn and Ojakangas, 1976). Keweenaw rifting, corresponding to all three formations, came to a halt about 1 billion years ago (Ojakangas and Matsch, 1982).

A major stratigraphic hiatus overlying the Keweenawan formations terminates with a discontinuous cover of glacial deposits over much of the western Lake Superior region. Glacial deposits up to 400 m thick are preserved beneath Lake Superior (Wold _et_ _al_., 1982). These include recessional moraines, outwash sand, and basal till (Landmesser _et_ _al_., 1982). Deposits only of Wisconsin age are identifiable, although several earlier glaciations did affect the state. Three interacting ice lobes advanced and retreated at different times from the west and from the east in response to signals at their northern source, the Laurentide ice sheet. Travel paths of the ice lobes were controlled by bedrock; in the Superior basin, relatively soft sedimentary rocks channeled the Superior lobe, which filled and climbed out of the basin in four main episodes (Wright, 1976). One final readvance, termed the Greatlakean stage, began to recede from the basin about 11,500 BP. During this retreat, extant shoreline features around the lake were produced in response to a series of progressively declining proglacial lakes, delimited by a waning ice lobe to the northeast and a high basin rim to the southwest. As drainage outlets to the east and north were uncovered, lake level fell rapidly, reaching a minimum at 75 m below present. Rebound has been the major cause of slowly rising water level since about 8,000 ybp (Saarnisto, 1975).

The shape and bathymetric features of the harbor are strongly influenced by the history of postglacial lake levels. Lake-level changes are discussed more specifically in relation to stratigraphy in Chapter III.

CHAPTER II

METHODS AND MATERIALS

Field Work

Surface samples were collected in 1980-81 at 58 locations and analyzed for grain size, total organic carbon (TOC), heavy mineral composition, and clay mineralogy. A poton grab sampler was used that retrieves a sample of about 200 cm^2 and 15 cm depth. A representative sub-sample of about one liter was obtained on board the boat by twice dividing the total material into quarters and discarding two diagonally opposite segments. All samples that were subsequently analyzed for TOC were frozen at the end of the field day within one to five hours after collection.

Navigation for collecting grab samples in the harbor was done by estimating distances and directions from charted landmarks and buoys. Stations were selected to reflect different energy and environmental regimes within the study area (Fig. 5). Sites were sampled along four transects in Superior Bay. Spot samples from Allouez Bay and additional sites in Superior Bay were also collected. In St. Louis Bay, grab samples were collected along two transects in the lower bay and from sites farther up the St. Louis Bay and River. Some sediment samples were discarded after recording their location, color and texture if they were similar in appearance to other samples taken in the vicinity that were retained for subsequent analysis.

Seismic reflection profiles were recorded on an EPC model 3200 Graphic Recorder in the spring of 1982. Seismic profiling in the harbor

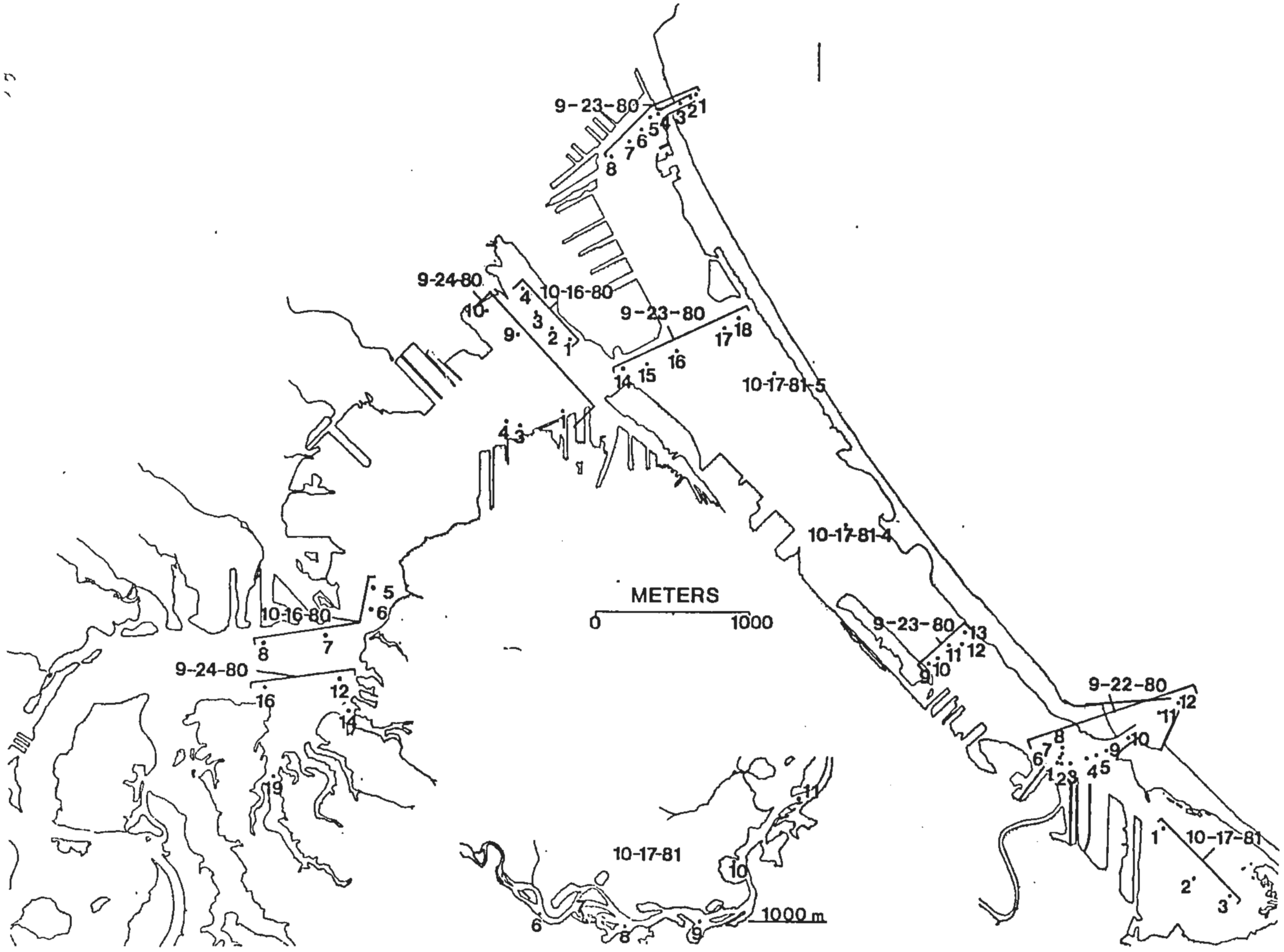


Figure 5. Grab sample locations obtained in 1980 and 1981.

was attempted with three separate systems: (1) An Ocean Research and Engineering (ORE) 3.5 kHz, 4-transducer towed vehicle Model (4000) was used as both transmitter and receiver. This method did not work in shallow water, because the transducers were still ringing from the outgoing pulse when echoes were coming back. (2) An Innerspace Technology Model (201) Minisparker was used as a sound source, with an Innerspace Technology 20-element towed hydrophone array for a receiver. The received signal passed through the Innerspace Technology Model (202) Amplifier/Filter. This method was unsuccessful because there was not enough energy emitted by the sparker to penetrate the organic-rich harbor sediment. (3) An ORE 3.5 kHz, 4-transducer towed vehicle (as in number 1) was used as a transmitter, with an Innerspace Technology hydrophone array (as in number 2) for a receiver. This method was marginally successful in some parts of the harbor.

A common problem arises from sound traveling directly from the transmitter to the receiver, resulting in a very strong signal at the top of the profile readout which obscures subbottom data. The problem was mitigated by trailing the hydrophones adjacent to the fish, thereby minimizing the distance between source and transducers, so the hard reflector appears at about the water surface.

Navigation for seismic profiling was accomplished by sighting on landmarks and buoys, and by LORAN C. The ship traveled at constant speed between known markers, so locations could always be approximated by interpolation between known endpoints (Fig. 6).

Sediment thickness was calculated from two-way travel time of sound, assuming a velocity of 800 fm/sec (1540 m/sec) both in water and sediment.

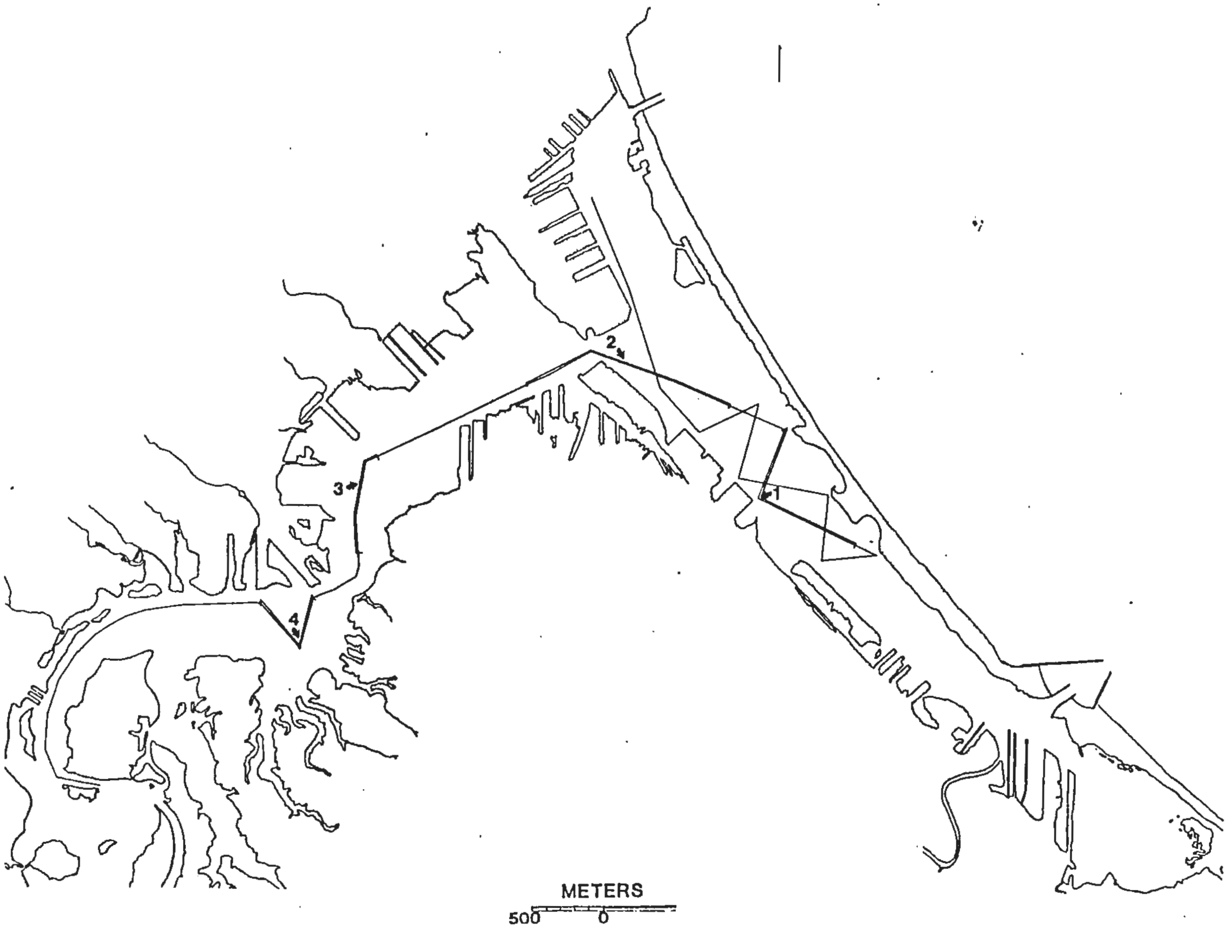


Fig. 6. Seismic reflection profile ship tracks. Double lines indicate locations of profiles illustrated in text.

Laboratory Procedures

Grain Size:

Grain size analyses were performed on all samples. Standard sieve and pipette techniques were employed to determine relative percentages of sand (coarser than 4 phi or 62 μm)), silt (4-9 phi or 62-2 μm), and clay (finer than 9 phi or 2 μm). The method is outlined in Folk (1974).

The suggested size of sediment required for analysis depends on the texture of the material: sand necessitates a larger subsample (50-75 g) than does mud (25 g) to yield an accurate determination of grain size fractions (Folk, 1974).

Prior to size analysis, organic matter was removed by oxidation in 30% hydrogen peroxide. The sample was then centrifuged, the liquid decanted, and the sediment agitated in Calgon (3.75 g per liter) on a wrist action shaker for a minimum of 20 minutes. The coarse fraction ($>$ 4 phi) was separated by wet sieving. When cobbles or gravel made up a large percentage of the sediment, they were screened with a -1 phi sieve. The sediment was rinsed free of Calgon with tap water, oven-dried, and weighed. The finer fraction ($<$ 4 phi) was then dispersed in Calgon solution in a 1000 ml cylinder. The cylinder was held in a water bath to insure constant temperature during pipetting. This action was later found to be unnecessary, however, because only the three size fractions were being measured. Aliquots were taken of silt-plus-clay and then clay, placed in beakers, oven-dried for 12-24 hours at 100°C and weighed. Weighing was done to 0.1 mg precision. Duplicates of samples yielded results that varied within 5 percent.

Sediment types were categorized as sand (greater than 50 percent sand), silt (less than 50 percent sand, greater than 25 percent silt), clay (less than 50 percent sand, greater than 25 percent clay), and mud (less the 50 percent sand, any combination of silt and clay).

Grain size data obtained by Pat Smith, a former graduate student in geology at University of Minnesota-Duluth, were also used in this study. Mr. Smith analyzed 90 grab samples from the Duluth-Superior Harbor in 1978-79 for percent sand, silt and clay (Fig. 7). Where grain size data were sparse in Superior Bay, information obtained by the National Oceanographic and Atmospheric Administration (NOAA) was used to complete the distribution map.

Organic Carbon and Carbonate:

Total organic carbon (TOC) was measured by loss on ignition and by means of an Oceanography International Model 0524B Total Carbon Analyzer. Carbonate content was determined by the former procedure.

Standard loss-on-ignition techniques were described by Dean (1974). A 10 ml crucible was filled with sediment, dried overnight at 100°C, and then weighed. Complete combustion of organic matter was then accomplished by heating the sample in a muffle furnace at 550°C for one hour. The difference between the new weight (after combustion) and the dry weight is a measure of total organic matter, converted to percent TOC by multiplication with a correction factor determined by Dean (1974). He calculated a correction factor of 1/2.13 for small lakes in Minnesota, which may be impractical for areas containing low amounts of TOC. This correction factor is discussed in the section on results.

Figure 7. Site location map for samples obtained in 1978 and 1979 (Smith).

Percent carbonate was determined by recombusting samples in the furnace for one hour at 1000°C. Weight loss between 550°C and 1000°C measures the CO_2 evolved from carbonate minerals. A multiplication factor of 0.44 is applied to derive the amount of calcium carbonate ignited.

A detailed outline of sample preparation and digestion is provided in Appendix I for TOC measured on the Total Carbon Analyzer.

Approximately 2.5 mg (see Appendix) of powdered sediment were placed in an ampule. First, the sample was treated with phosphoric acid, causing the evolution of CO_2 from inorganic carbon. This CO_2 was purged from the ampule, leaving only organic carbon to be evaluated. Potassium persulfate was then added as an oxidizing agent and the ampule was immediately sealed. CO_2 (organic) evolved in the closed ampule while it was heated for 12 hours in an oven at 100°C. After the digestion, the ampule was pierced and the CO_2 evacuated into the analyser where it was measured by IR absorption.

Mineralogy:

Sand grain mineralogy was determined with a petrographic microscope. Subsamples of about 10 mg of sand were used for heavy mineral separations. Heavy and light minerals were segregated gravimetrically with a separatory funnel and bromoform. Medium (.25-.62 mm) and fine (0.53-.25 mm) sand were dry-sieved and used for analysis. Etching and staining of light minerals were attempted, however, it proved to be unnecessary because the minerals of the light fraction were recognized with relative ease. Heavy minerals were sometimes difficult to identify when they were badly stained. Eight heavy mineral grain mounts were selected for identification; the sample location affected the quality of grains and percentage sand, and this is the basis on which slides were chosen for heavy mineral analyses. One hundred grains per slide were counted, assigning each to a category of quartz, feldspar, hornblende, tremolite-actinolite, pyroxene (clinopyroxene, orthopyroxene, colorless and pale brown), zircon, apatite, epidote, tourmaline, hematite, biotite, black and brown opaques, dark lithic fragments, and stained unidentifiables. Magnetic minerals were identified by employing a magnet, but were not identified individually.

X-ray diffraction analysis of the fraction finer than 9 phi (2 μm) was performed on 28 samples (10 in duplicate), and relative percentages of clay minerals were calculated after Biscaye (1964, 1965). Clay fractions were obtained by pipetting, and mounted on 0.45 μm millipore filter paper. About 5-10 ml of the clay-size aliquot were placed in a 20 ml beaker and held in a sonic dismembrator until emptied onto the filter in order to prevent differential settling of clays. The aliquot was vacuum filtered within about 3 minutes, again to prevent differential settling of clays. Filter papers containing sediment were then air-dried and glued to glass slides with spray lacquer. Slides were placed in ethylene glycol vapor overnight to aid in the identification of smectite.

Clay mineral percentages were determined on a Phillips X-ray diffractometer. Samples were analysed using Cu-K α radiation at 40 kv, 20 ma, with a scanning rate of the goniometer set at $2^{\circ}2\theta$ per minute. Clay mineral abundances were measured by tracing diffraction patterns from the printout onto thin paper, cutting the traced peaks out, weighing them to 0.1 mg precision to estimate peak area, and employing weighting factors of Biscaye (1964, 1965). Peak areas were weighed according to: one times the smectite 17Å glycolated peak, four times the 10Å illite peak, and twice the 7Å peak which encompasses both kaolinite and chlorite (Biscaye, 1964, 1965). The peak areas were then totaled to equal 100% and thus were a measure of relative rather than true percent. Kaolinite and chlorite were differentiated on 11 samples by running the goniometer at slow scan speed ($\frac{1}{2}^{\circ}2\theta$ per minute centered at 25.25°), allowing the separation of the 2 peaks. Duplicate samples for all other peaks were usually within 10% of the stated results.

Other Analyses

Borehole data:

Boreholes are drilled for engineering estimates of ground stability on which future construction or development is to take place. Borings (up to 60 m deep) were obtained by rotary drilling techniques: a high-speed revolving cutter is employed to open a hole, which is kept open by means of a viscous fluid. Sediment is sampled by a split spoon sampler wherever lithology changes.

Lithologic changes are the only information that can be gleaned from these records, because structures are disturbed in the process and sediment along the entire length is not retrieved.

Data from 129 borehole logs were used in this study to establish stratigraphy and identify sediment units indicated on seismic profiles (Fig. 8). Because judgment as to whether the sediment is predominantly

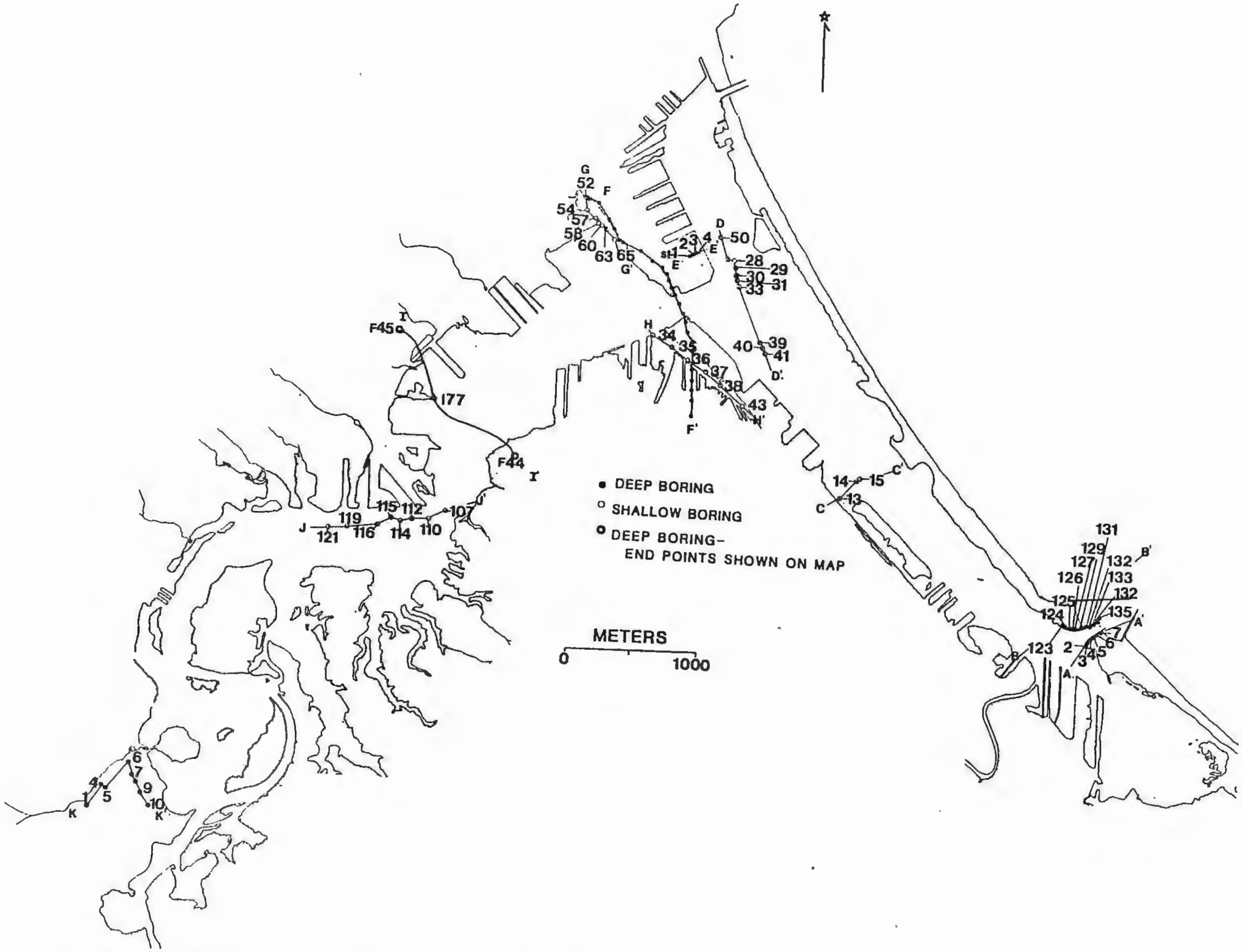


Figure 8. Borehole and cross section locations.

silt, clay, sand, gravel, or peat was made only visually, it is likely that opinions vary from one soils engineer to the next, especially in the range of silty clay/clayey silt. It is assumed that sand and peat are identified fairly consistently by all engineers. Material from boreholes taken for the Arrowhead bridge was obtained, and it was decided by observation that sediment types were defined accurately.

Lithologies chosen for distinction in the stratigraphic sections vary from one location to the next depending on how clearly lithologic units are defined in the borehole logs, and on the relative abundance in a specified group of boreholes. For example, in the Superior Entryway, coarse sand is combined with gravelly sand and gravel to compose one unit, whereas behind Rice's Point coarse to fine sand is noted on several borehole logs as one unit, and so the two lithologic types cannot be separated. At the Arrowhead Bridge site, sand, silt, and clay categories each contain all variations of those groups, i.e., silt could be sandy or clayey. Elsewhere, silty clay and clayey silt are not divided.

In transferring points from location maps sent with the shallow borehole logs, it was discovered that some very large discrepancies exist between the depth of water noted in the borehole logs and the depth indicated on the harbor charts, especially in St. Louis Bay in the vicinity of Grassy Point.

Appendix II contains a list of agencies responsible for the collection and storage of borehole logs used in this report.

Historic charts and aerial photographs:

Shoreline and land-use changes of the harbor between 1861 and 1977 have been documented by means of historic charts and aerial photographs. Outlines of the harbor were traced from the photographs and charts, and size scales were adjusted with a photocopy machine. The earliest chart is reproduced in Plate II. It contains depth measurements and information on sediment type on the estuary floor in addition to land patterns indicating forest and wetland cover. Similar land-use patterns were added to the tracing of the 1977 photograph to illustrate the development of industrial and residential areas during the past century.

Appendix III is a list of all photographs and charts collected for this study. The earlier charts were selected from the list for the amount of information they contained. Additional charts and photographs not used to illustrate this section, and the organizations from which all photos and charts were obtained are included in Appendix III to aid in future historic research of the harbor.

CHAPTER III

RESULTS AND DISCUSSION

Surface Sediments

Surface sediments in the Duluth-Superior Harbor range in color from light reddish-brown to very dark brown, depending on grain size, chemical composition, and mineralogy. Mud contains a greater percentage of organic material, enhancing its dark color, whereas sand owes its lighter color to a higher abundance of large quartz grains. For similar grain-sized material, detritus from the southern half of Superior Bay is redder than sediment from the remainder of the study area. This color difference is attributed to a high input of red clay from the Nemadji River. Grey mud was observed in only one sample, one from Kimball's Bay.

Grain Size:

Grain size data are listed in Tables I and II. The map of grain size distribution of the surface sediments (Plate I) shows consistent trends. Silt dominates the main estuary floor, clay is found primarily in isolated depressions and small tributary embayments; sand lines the shores around the harbor. Sediment from the upper St. Louis River and the harbor entryways consistently has more than 99 percent sand, and sediment from the lower river typically contains 75-99 percent sand. Sediment from the dredged ship channel in the Superior Bay contains 65-96 percent sand. Sediment from most of St. Louis Bay has between 30 percent and 50 percent silt (Fig. 9).

TABLE I

Grain Size

Samples	Cobble/Gravel	Sand	Silt	Clay
1980				
9-22-1		99.18	0.67	0.12
2		81.95	11.92	6.13
3		89.12	3.72	7.16
4		81.47	15.84	2.69
5		88.44	11.39	0.17
6		83.37	10.77	5.85
7		90.23	6.70	3.00
8		77.42	15.58	6.99
9		99.88	0.11	--
10	99.94	1%	--	--
11		99.84	.16	--
12		58.46	36.37	5.16
9-23-1		99	--	--
2	34.37	63.28	0.94	1.4
3	99.93	--	--	--
4	84.03	15.69	.22	.05
5	88.44	11.39	.17	0
6		99.83	.17	--
7		90.43	.10	9.5
8		99.01	0.64	0.34
9		23.62	41.68	34.80
10		83.58	8.04	8.38
11		1.78	63.02	35.20
12		3.03	54.86	42.10
13		10.22	50.70	39.08
14		57.48	26.22	16.30
15		98.33	1.18	.49
16		92.19	4.78	3.04
17		2.69	53.67	43.36
18		12.91	49.57	37.52
9-24-1		12.37	82.61	5.02
3				
4		12.54	46.85	40.60
9		2.98	74.50	22.42
10		19.96	56.62	23.41
12		3.60	61.98	34.42
14		35.10	42.79	22.11
16		1.5	68.68	29.78
19		0.36	42.94	56.69

TABLE I - continued

Samples	Cobble/Gravel	Sand	Silt	Clay
1980 - continued				
10-16-1		7.10	67.7	25.1
2		9.4	57.5	33.0
3		8.0	69.5	22.4
4		2.4	64.0	33.6
5		4.2	74.4	21.3
6		38.3	38.5	23.1
7		92.8	4.4	2.8
8		11.6	63.3	25.1
1981				
10-17-1		11.45	63.7	24.8
2		2.28	43.69	54.03
3		11.86	52.39	35.75
4		4.8	58.92	36.25
5		5.5	60.12	34.38
6	53.09	38.70	4	4
7		88.40	9.2	2.40
8		15.36	73.83	10.81
9		31.78	57.22	10.99
10		91.92	5.35	2.73
11		27.58	55.56	16.84

TABLE II

Grain Size

Data of Pat Smith, 1978

Sample	Sand	Silt	Clay
1	97.9	2.1	--
2	59.9	24.0	16
3	20.7	79.3	--
4	19.8	34.5	45.7
5	51.7	25.5	22.7
6	48.1	32.1	19.8
7	9.6	35.2	55.2
8	24.0	52.4	23.6
10	31.0	46.0	22.9
11	54.4	21.6	24.0
12	70.9	17.7	11.4
13	90.6	2.1	1.1
14	27.2	58.6	14.2
15	10.5	63.2	23.3
16	21.8	57.6	20.5
17	3.1	39.2	57.7
18	24.5	59.1	16.4
19	11.4	65.0	23.5
20	14.4	57.0	28.2
21	14.8	77.6	7.6
22	4.0	39.0	57.0
23	11.0	44.5	44.4
24	6.8	69.4	23.8
25	3.9	61.3	34.8
26	17.5	24.6	57.9
27	65.0	31.0	4.0
28	57.54	12.8	29.6
29	86.20	6.2	7.6
30	99.0	1	--
31	5.0	58.7	5.6
32	99	1	--
33	99	1	--
34	34.0	59.3	6.6
35	86.4	4.8	8.8
36	97	2	1
37	99	4	4
38	96	3	1
39	97	2	1
40	85	12	3
41	24	65	11
42	97.3	2	1
43	34	54	12
44	72	23	5
45	99	<1	<1
46	11	67	22
47	14	53	32
48	50	41	8
49	59	33	7
50	87	8	4
51	13	50	37
52	1	47	52
53	44	21	35
54	12	26	62
55	5	35	60
56	4	36	63
57	4	49	53
58	15.0	40	45
59	11	34	55
60	<1	31	68
61	25	53	22
62	26	61	14
63	20	55	25
64	75	20	4
65	35	63	19
66	18	56	26
67	68	22	10
68	22	56	22
69	37	44	19
70	89	7	3
71	52	32	17
72	21	55	24
73	23	53	25
74	17	53	30
75	18	62	21
76	58	31	11
77	99	<1	<1
78	33	33	34
79	26	35	40
80	8	37	58
81	24	32	44
82	38	32	30
83	66	15	19
84	45	21	34
85	98	<1	<1
86	61	23	16
87	72	14	14
88	92	5	4
89	12	44	43
90	96	3	1

Where organic was included in the total %, data were recalculated making combined sand, silt and clay equal to 100%.

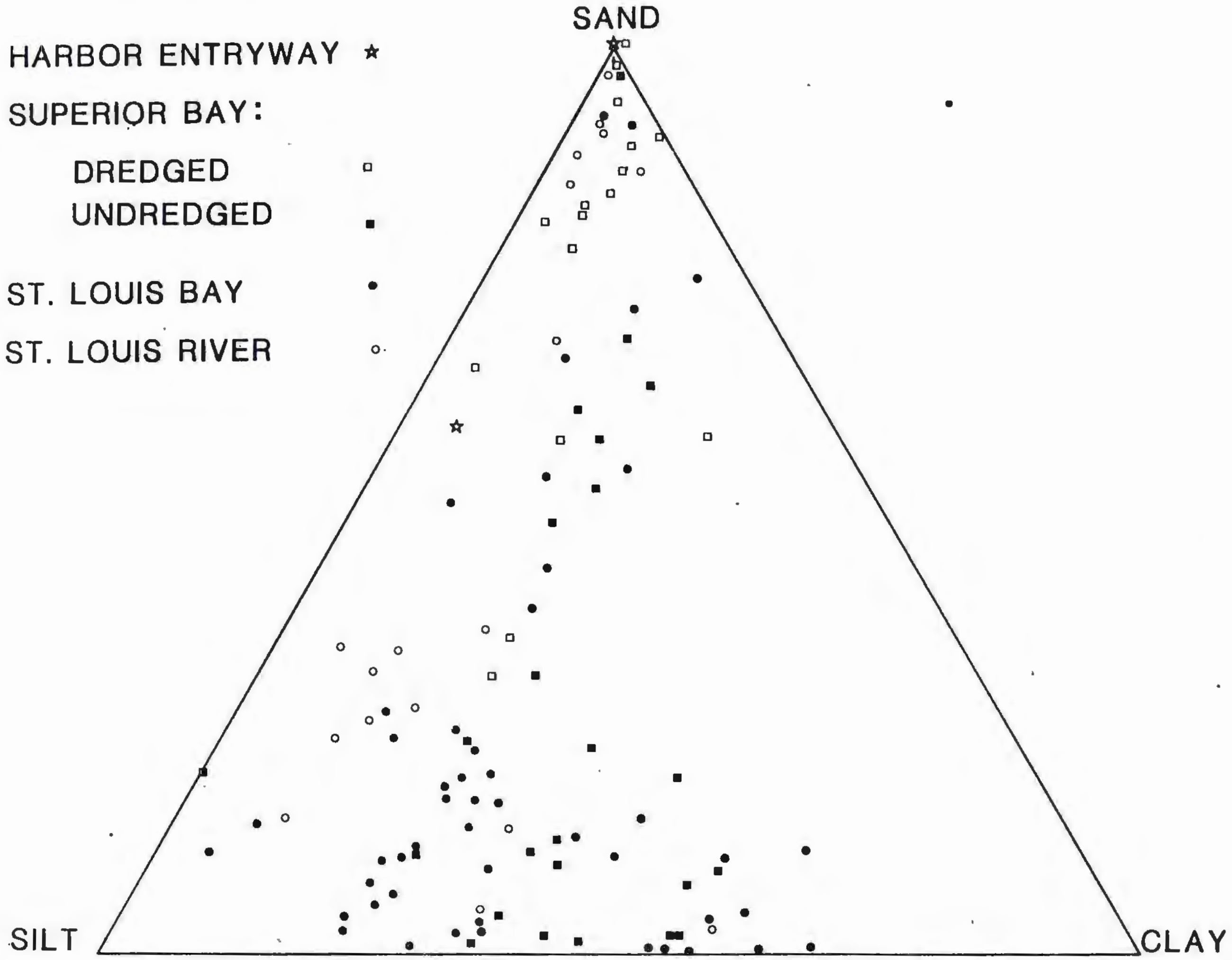


Figure 9. Plot of sand, silt, and clay with respect to location within the study area. Although only 2 symbols are shown on the sand endpoint, actually 10 samples fall on that point.

Lag deposits of sand and gravel lie in the bed of the St. Louis River above Fond du Lac. Strong river currents prevent mud from settling anywhere but in the quiet lakes and embayments alongside the river. Sand is concentrated on the banks of the inner bends of the river. Down river from Fond du Lac, sand fills the river channel. Coarse lag deposits are also found in the ship entryways.

Samples from the dredged channel of Superior Bay are primarily sand, usually covered with a thin coat of silt. This silt layer becomes thicker toward the center of the bay. Smaller particles accumulate in the shoals.

Silt, with isolated pockets of sand, coats the (formerly) dredged channels in St. Louis Bay. Unlike Superior Bay, channel sediments in St. Louis Bay are indistinguishable texturally from the mud that lies in the adjacent shallows.

Sand on the estuary floor is derived from three sources. (1) Runoff and eolian processes along Minnesota and Wisconsin Points can transport sand to their landward sides. Sand is well sorted on both the lakeward and bay sides of the points as a result of wave energy. (2) Erosion of the till bluffs that line the less developed regions of upper St. Louis Bay provide sand to the waterway. (3) Borehole data, described later, indicate that extensive sand deposits underlie much of Superior Bay. Dredging completely strips the overlying silt cover in places, exposing sand to the present depositional environment (Fig. 16).

Mud arrives in the harbor by slope wash of the red lacustrine clay bluffs along the Wisconsin shoreline (composed of 65% clay and silt) (Kemp and Dell, 1978), by seiche-induced currents, and by river. From the discharge and suspended solids measurements taken 1.2 km upriver from Fond du Lac at Scanlon, Minnesota (U.S.G.S., 1981) an upper limit sedimentation rate of St. Louis River sediment was calculated by

$$\frac{QxSS}{A}\ (g/cm^2\text{-}yr) \text{ or } \frac{QxSS}{A} \times \frac{1}{\rho_b}\ (cm/yr)$$

where Q is discharge (l/sec); A is the approximate area of the estuary (km^2); and SS are suspended solids (mg/l) and ρ_b is wet bulk density of harbor sediment Table III).

Usually grain size distribution reflects the distribution of energy within a basin: Coarse sediment implies a high energy regime, while fine sediment indicates a low energy regime. A direct correlation is usually observed between water depth and grain size as well, because depth promotes a quiet energy environment. This rule does not hold in the Duluth-Superior Harbor because the deepest water of the estuary is situated in dredged ship channels, which are also the areas of greatest turbulence from passing ships. Depositional patterns in the harbor reflect a combination of natural and human influenced processes, to be discussed at the end of this chapter.

Changes in sediment size since 1861:

Prior to the emplacement of the parallel piers at the Superior entryway in 1869, clay was charted as the dominant type of surface sediment in the inlet (Plate II). However, sand, rather than clay is preserved in the stratigraphic record laid down at that site (see borehole data section), so it may be assumed that fines in the inlet were

TABLE III

Discharge and suspended sediment concentrations on the St. Louis River at Scanlon, MN (USGS, 1981)

	Discharge		Suspended Solids
	cfs	l/sec	(mg/l)
Maximum - May 1981	8500	240,632	70
Minimum - September 1981	514	15,065	101

A = 56.95 km^2, bulk density (ρ) = 1.3 g/cc

May - 0.2 mm/yr

September - 1.5 cm/yr

Sample Calculation:

$$\frac{(2.4\text{x}10^5\ \text{l/sec})\text{x}(.07\ \text{g/l})}{30\ \text{km}^2} \text{ x } \frac{3.6\text{x}10^7\ \text{sec}}{\text{yr}} \text{ x } \frac{\text{cm}^3}{1.3\ \text{g}} \text{ x } \frac{\text{m}^2}{10{,}000\ \text{cm}^2} = 1.5\ \text{cm/yr}$$

carried away during storms, when waves poured through the inlet and discharge from the overloaded Nemadji and St. Louis Rivers flowed out to the open lake. Sampling at the Superior inlet for the 1861 map may have taken place after a long quiet period between storms, when clay had time to accumulate.

Within the bays, depressions containing clay coincide with the position and grain size of the paleo-river channel clearly delineated on the 1861 chart.

Sand lines the shores of the estuary below Grassy Point on the 1861 map, and is common along undeveloped shorelines today. However, the pattern of grain size distribution is obscured somewhat by development and dredge disposal on and near the shoreline.

In summary, grain size distribution has been modified by shoreline development, dredging, and ship traffic. However, outside of the ship waterways, the 1861 distribution patterns are still recognizeable on the modern grain size distribution map.

Organic Carbon and Carbonate:

Results of the total organic carbon (TOC) analyses by loss on ignition (LOI) and by the Total Carbon Analyser show poor agreement (Table IV). It was previously mentioned that the correction factor 1/2.13 used by Dean (1974) to convert organic matter combusted at 550°C to TOC may be inappropriate for sediments containing very small amounts of TOC, as is the case in the harbor. Results from the two methods of TOC measurement differ considerably, usually with LOI values greater by a factor of about two when Dean's coefficient is used. Dean's correction coef-

TABLE IV

Organic Carbon

Sample	% TOC by Total Carbon Analyzer	% Loss on Ignition at 550°C	TOC used for maps, graphs. If analyzer value not used, LOI value is multiplied by correction factor (see Fig. 10)	% Calcium Carbonate by Ignition Loss at 1000°
9-22-1	0.05	.31		0.05
9-22-2	0.30	1.51		0.36
9-22-3	0.39	1.81		0.12
9-22-4	0.30	1.58		0.31
9-22-5	0.1076	0.45		0.08
9-22-6	0.14	1.53		0.53
9-22-7	0.36	.98		0.40
9-22-8	0.55	1.68		0.62
9-22-9	0.09	.19		0.05
9-22-11	0.19	3.51*		0.08
9-22-12	0.22			
9-23-1	0.024	0.21		0.04
9-23-2	0.13	1.17		0.37
9-23-3				
9-23-4	0.25	1.04		0.29
9-23-5	0.10	0.30		0.04
9-23-6	0.10	0.58		0.28
9-23-7	0.34	1.30		0.07
9-23-8	0.10	3.20*		0.06
9-23-9	2.20	8.78		0.22
9-23-10	2.18	2.30		0.24
9-23-11	2.55	9.18		0.18
9-23-12	3.03	7.80		0.23
9-23-13	2.41	8.86		0.22
9-23-14	1.75	5.81		0.34
9-23-15	0.06	0.98		0.17
9-23-16	0.03	1.51		0.09
9-23-17	2.74	9.44		0.24
9-23-18	2.72	9.35		
9-24-1	.06*	3.66	1.10	0.72
9-24-3		0.43	0.13	0.11
9-24-4	0.30*	8.78	2.65	0.36
9-24-9	1.66	8.43		0.31
9-24-10	1.73	13.87	4.19	0.50
9-24-14	3.08	3.0		0.61
9-24-19	4.05	9.07		0.24
10-16-1	2.24	3.8		0.28
10-16-2	1.58	3.47		0.23
10-16-3	5*	3.74*		0.28
10-16-4	2	5.87		0.21
10-16-5	1.58			
10-16-6	1.94	2.15		0.21
10-16-7	0.23	.74		0.12
10-16-8	1.88	9.82		0.13

* value not used in graphs.

ficient was determined by finding the slope of a line plotting uncorrected organic carbon values found by LOI versus TOC as determined by chromatographic techniques. The correction factor was recalulated in this investigation by replacing chromatographic TOC with TOC measured on the Total Carbon Analyser (Fig. 10). The least squares fit of the data yielded a slope, or correction factor, of 0.26, slightly greater than one-half of Dean's coefficient. The recalculated coefficient was employed for samples that were analysed only by LOI.

Dewatering of clay minerals contributes to some weight loss when a sample is baked, however the amount is not accounted for when LOI values are used to calculate TOC. As the clay fraction increases, the disparity between LOI and real values (i.e. measured on the Total Carbon Analyzer) should grow as a consequence of increased dewatering. Although this trend is not distinct when graphed, dewatering of clays may be responsible for a portion of the difference in values measured by the two methods. Results from the Total Carbon Analyser are considered more reliable than those of LOI when TOC represents only a small fraction of the sediment, and so only the former values are reported in this section.

Distribution of TOC is inversely correlated with grain size: As sediment becomes finer, TOC percentages increase (Fig. 11). TOC is always less than 1 percent in the dredged channels of Superior Bay (Fig. 12). In the relatively undisturbed sections of both bays, TOC is always greater than 1 percent, and usually exceeds 2.2 percent. In the 21st Avenue West Channel, exceptionally high TOC is found (5 percent), possibly due to the sample location near a waste water treatment plant.

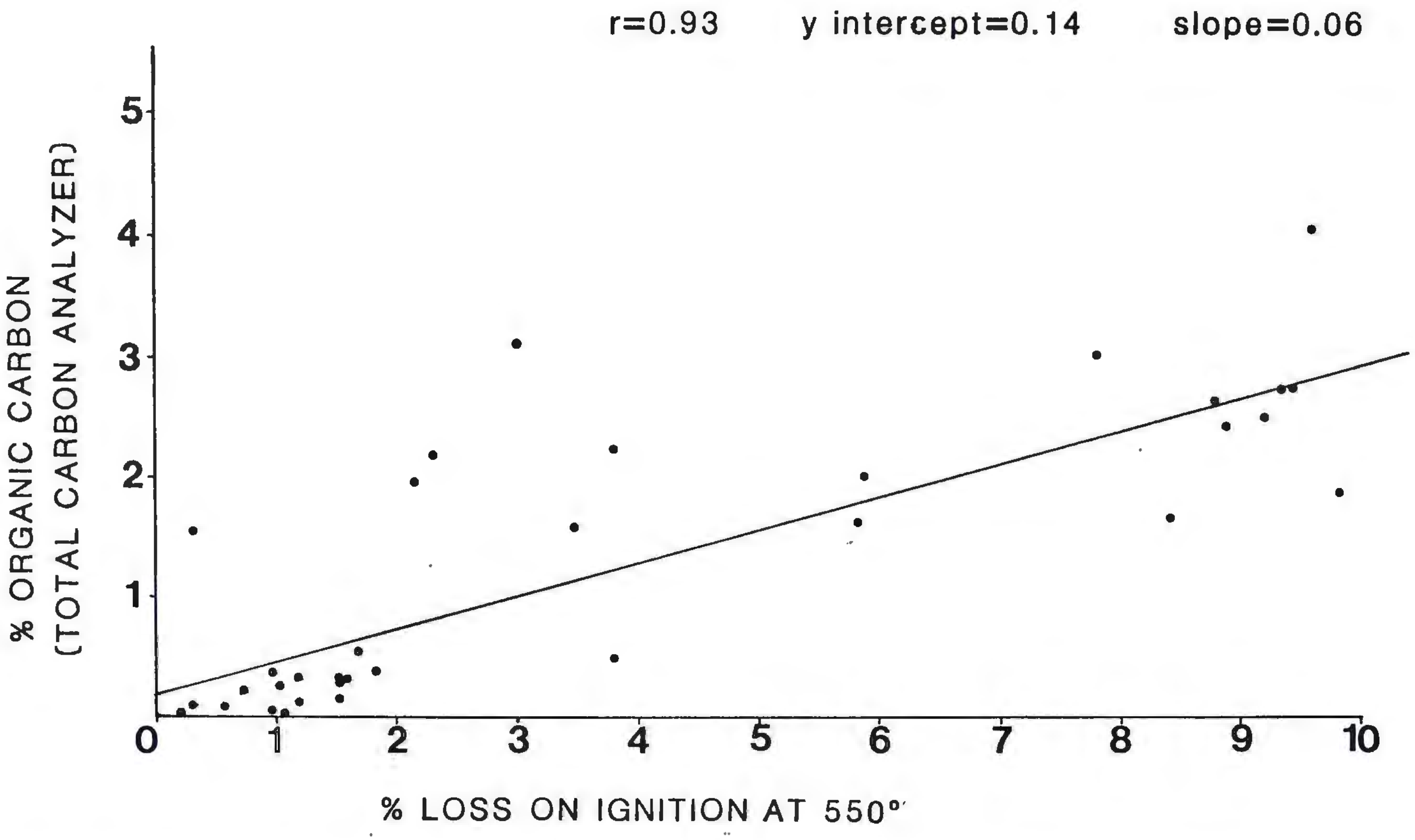


Figure 10. Percentage total organic carbon vs. percentage loss on ignition at 550 C.

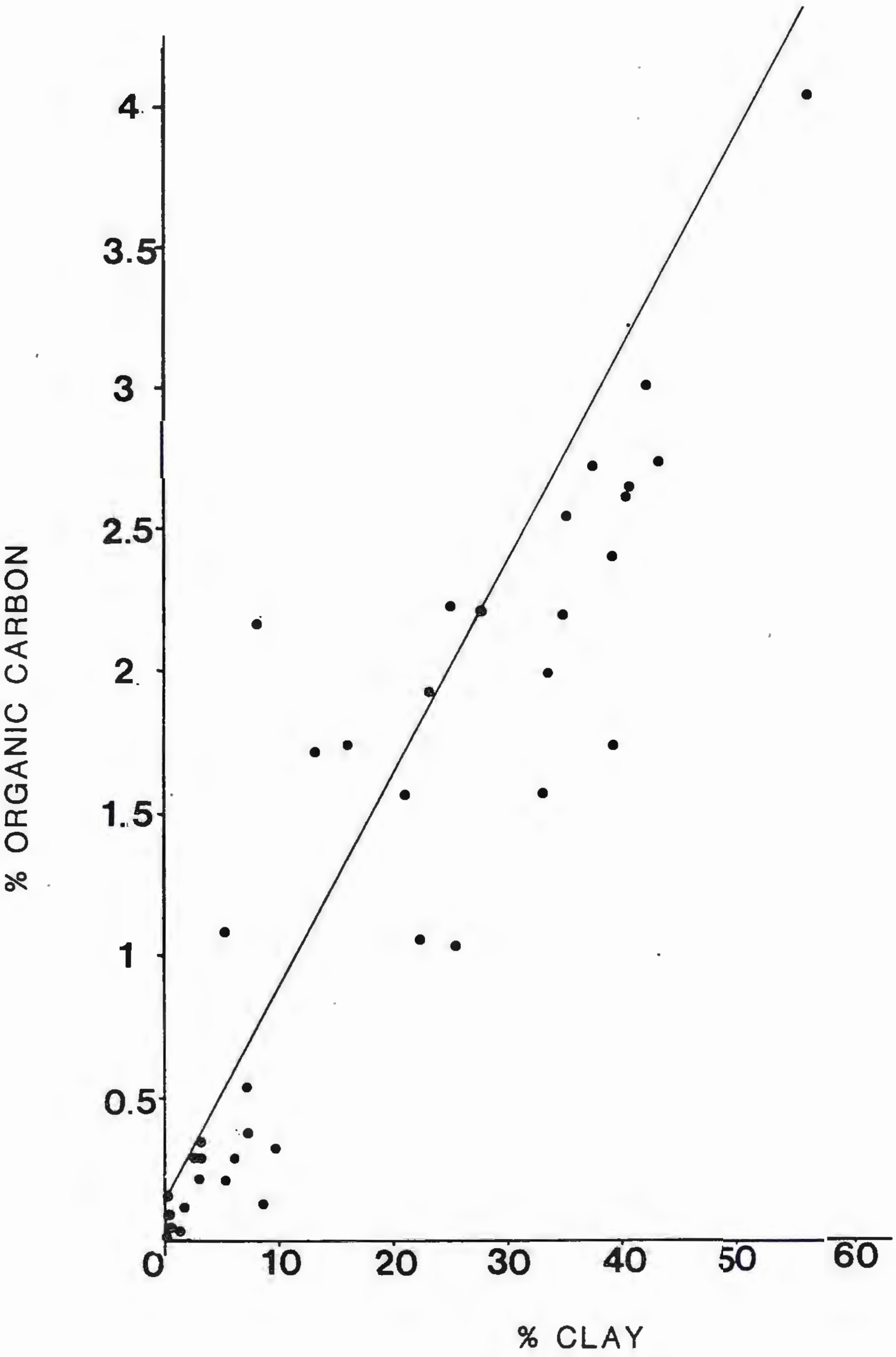


Figure 11. Percentage total organic carbon vs. percentage clay.

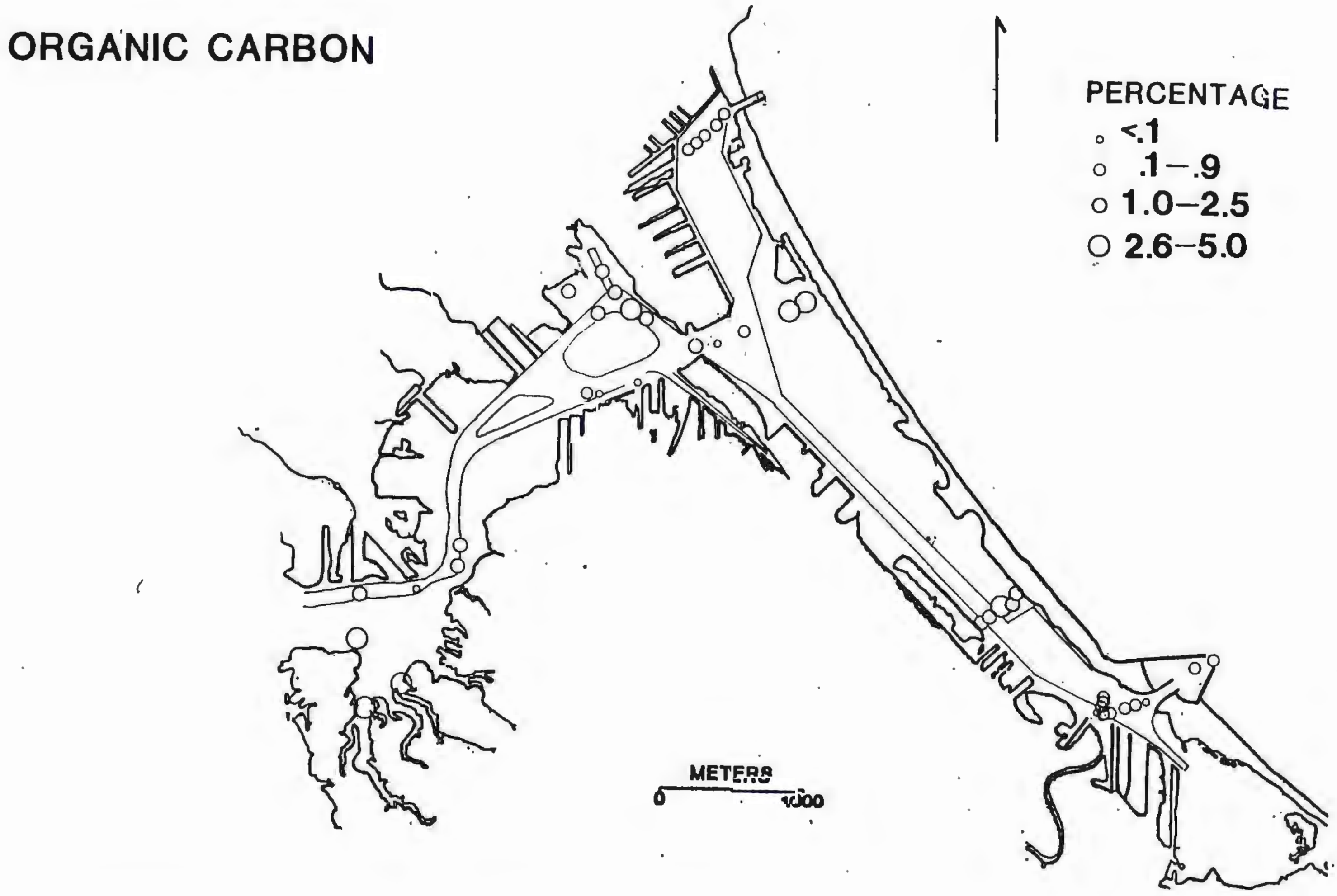


Figure 12. Distribution of total organic carbon.

Organic carbon usually increases with depth, following the distribution pattern of very small particulate matter. This rule is broken in the harbor because the deepest waters are the dredged channels, which today contain some of the coarsest detritus.

Organic carbon levels in the St. Louis River Estuary are comparable to levels measured in marine estuaries. In unpolluted areas, organic carbon rarely constitutes greater than 5 percent of a sample, and is usually less than 3 percent. Sands contain less than 1 percent organic carbon. Exceptions are found in unusually deep estuaries, where anaerobic conditions prevail, and in embayments with swampy or peaty floors (Folger, 1972b).

Calcium carbonate is a negligible constituent of the sediments in the study area, with LOI values ranging from .04 to .72 percent. Under the petrographic microscope, neither carbonate minerals nor shells were observed in the sand fraction. Whether or not they have been derived from calcareous till, surface sediments in the open lake are non-calcareous because Lake Superior water is undersaturated with respect to carbonates. However, in late glacial sediments, carbonates were preserved as a result of rapid burial (Dell, 1978). Red till lining the south and north shores can be either calcareous and non-calcareous (Dell, 1971). Late glacial and early post-glacial sediments in the St. Louis Bay were treated with hydrochloric acid and found to be calcareous.

Mineralogy:

Clay minerals and heavy and light minerals were examined to determine the provenance of surface sediment in the harbor. As indicated by the mineral suite, sediments in the estuary are delivered from more than one rock type. Differential preservation may significantly distort the final percentages of mineral types found in the detritus, so it is impossible to specify the degree to which each formation influences the mineral assemblage.

Mineral constituents are derived from the Duluth Intrusive Complex, North Shore Volcanics and (meta)sediments of the Fond du Lac and Thomson Formations, as well as from till. Numerous studies of the bedrock mineralogy have been done, but none of this work has focused on the overlying till.

The percentage of heavy minerals in the sand fraction ranges between 1 and 9 percent. Grains are very angular for the most part, indicating that they have not traveled far from their sources. Clinopyroxene and orthopyroxene (4-22%), tremolite-actinolite and blue-green hornblende (8-29%), black opaques (3-42%), and rock fragments (20-33%) constitute the majority of grains in all slides (Table V). Large dark rock fragments are more abundant in Superior Bay slides and their abundance appears to be a function of grain size: sand from the ship channels in Superior Bay is coarser than sand in St. Louis Bay. Zircon, apatite, and magnetite (or ilmenite) are present in all samples. Epidote, biotite, tourmaline, and staurolite occur more often in the St. Louis River and Bay samples than in the rest of the slides. Garnet is more common in Superior Bay samples. Hematite is recognized both as indivi-

TABLE V

Heavy Minerals - Sand fraction (62.5 μm - 580 μm)

mple	9-22-1	9-22-12	9-23-6	9-23-16	9-24-3	10-17-9	10-17-11
heavy minerals	4.2	2.7	1.2	2.7	8.8	2.5	2.7
thic	28	33	30	29	18	20	25
aques	32	26	3	20	39	15	10
rnblende	4	7	20	8	14	20	29
emolite-actinolite	7	5	8	5	10	8	10
roxene	15	16	22	13	4	14	3
aurolite			1	1	2	3	
atite	2	<1	3	6	3	3	5
rnet		3		1	2	1	
rcon	5	4	4		3	6	6
matite				1	1	1	2
idote	2		2	2		1	
ained unidentifiables		<1	2	2		4	
artz		<1	4	3	4	4	8
agioclase	1			3			
otite						2	2
urmaline	3	3	1	1	1		1
isite							1
ssiterite				1			
hene				2			

dual grains and as a coating on other grains.

Several assemblages are implied from the collection of minerals identified. Hornblende, dominantly blue-green variety, together with epidote and staurolite, constitute a low grade metamorphic assemblage. Brown hornblende, zircon, biotite, and apatite characterize an acid igneous source. Tourmaline, rounded zircon and quartz are commonly from reworked sediments (Krumbein and Pettijohn, 1938).

About half of the light minerals are quartz, and the other half are very altered and stained beyond recognition. Twinned plagioclase and microcline are identified very rarely in the sediments, although the volcanic cliffs overlooking the harbor are rich in these feldspars. Apparent percentages of feldspar in sediment may be misleading in a provenance study because chemical and physical weathering are particularly severe on them. Steep igneous cliffs close to their detrital sink, as exist in the St. Louis River estuary, should provide the ideal setting for feldspar preservation.

Clay minerals identified are smectite, illite, and kaolinite-plus-chlorite (Table VI). Distribution maps (Fig. 13a,b,c) and ternary diagrams (Fig. 14a,b) illustrate patterns of deposition within the harbor.

Smectite constitutes 8 to 60 percent of the clay minerals (Fig. 14a). Very low values are limited to Superior Bay, and very high values are found consistently in the St. Louis River and Bay. Smectite is a common product of weathering of basic igneous rocks (Folk, 1974), such as are common in the study area.

The illite distribution also exhibits a subtle trend (Fig. 14b). In

TABLE VI

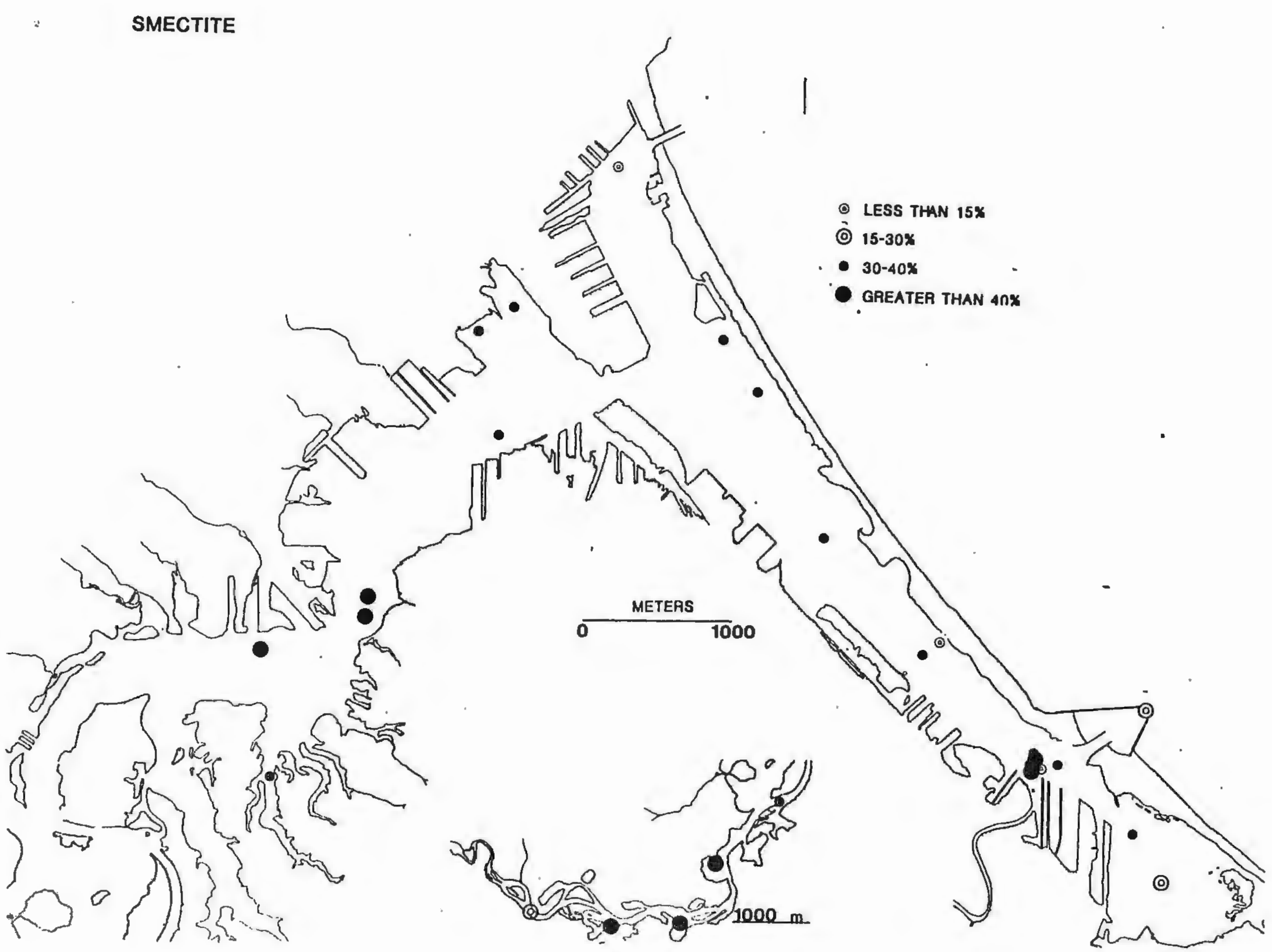
Clay Mineralogy

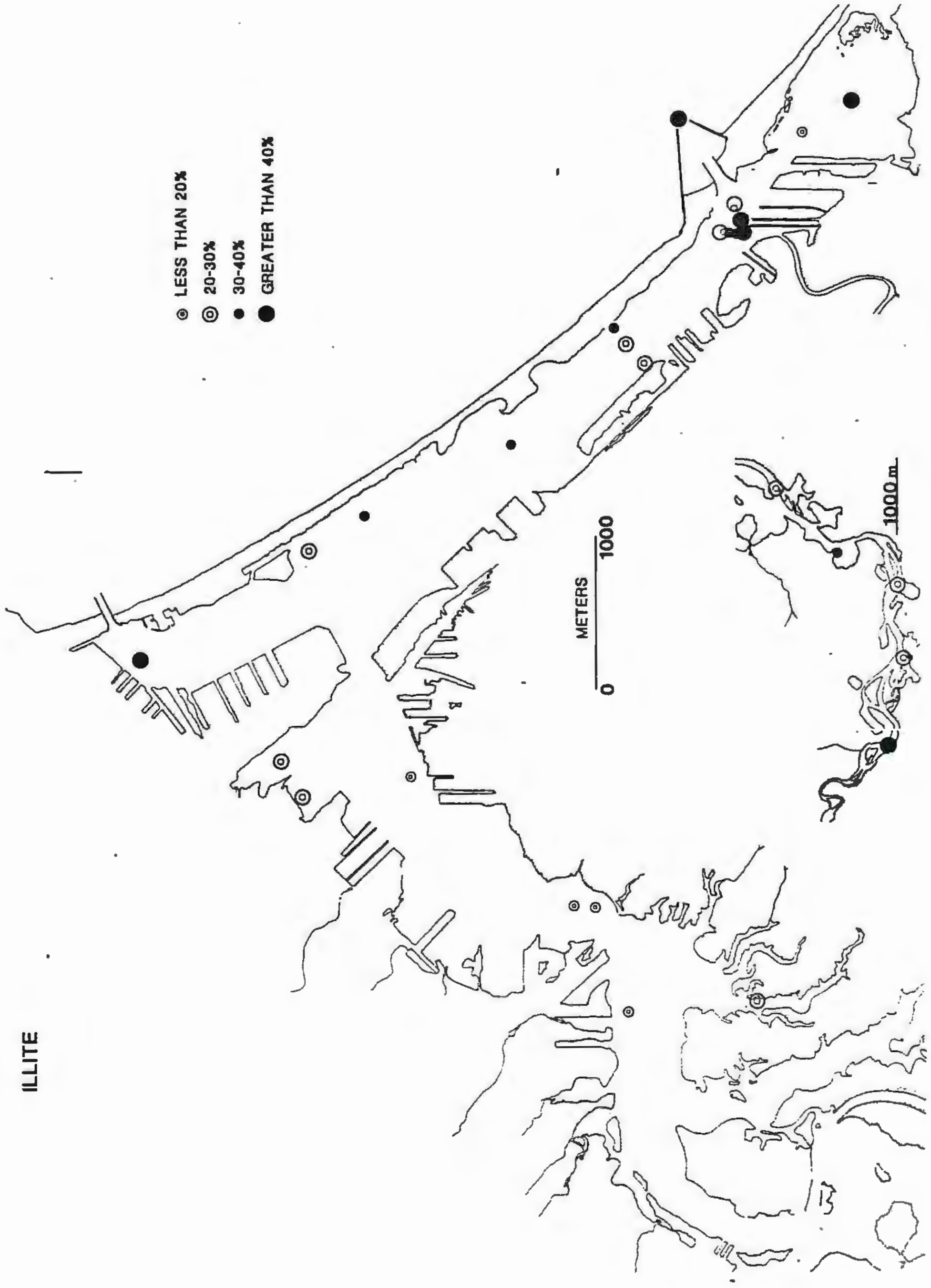
			Smectite	Illite	Kaolinite-plus-Chlorite	Kaolinite	Chlorite
9-22-80	2	(1)	48.52	37.44	14.04	8.41	6.42
		(2)	39.06	45.50	15.22		
	3		11.11	49.67	39.22	10.35	28.87
	4	(1)	25.18	21.73	53.09	21.83	11.53
		(2)	25.70	34.67	39.63		
		(3)	45.62	31.67	22.71		
		(4)	56.35	25.84	17.80		
	6	(1)	28.97	26.20	44.83	19.91	9.86
		(2)	48.52	37.44	14.04		
	7		49.90	31.28	18.82		
	8		33.48	25.34	41.18		
	12	(1)	24.28	44.28	31.43	22.46	11.16
		(2)	24.40	39.56	36.04		
9-23-80	7		7.83	46.08	46.08	18.32	27.64
	9		7.72	27.23	65.05	37.77	27.72
	11		40.65	22.45	36.90		
	13	(1)	18.72	29.10	52.17		
		(2)	10.10	32.58	57.32		
	18	(1)	23.66	35.17	41.17		
		(2)	51.72	15.56	32.72		
9-24-80	4		50.68	19.09	30.22		
	10	(1)	21.74	29.19	49.07	18.09	16.81
		(2)	64.63	14.58	20.74		
	19		41.42	23.47	35.12		
10-16-80	4		35.48	27.05	37.47		
	5		59.23	9.91	30.85		
	6		46.64	16.66	36.69		
	8		48.50	16.22	35.27		
10-17-81	1		58.78	16.54	24.68		
	2	(1)	28.58	45.50	25.92		
		(2)	29.78	41.71	28.51		
	4	(1)	40.28	36.14	23.59		
		(2)	26.23	35.96	37.81		
	5		34.74	32.26	33.00		
	6		21.99	44.50	33.50		
	8		49.15	28.39	22.46		
	9		52.22	27.20	20.58		
	10		44.73	34.54	20.72		
	11	(1)	35.37	28.87	35.76	27.48	9.55
		(2)	41.03	20.67	38.30		

Average values represented in clay mineralogy maps and graphs where duplicates were done. Kaolinite and chlorite values are the average percentage of K + Chl where duplicates were done.

Figure 13. Clay mineral distribution - (a) smectite, (b) illite, (c) kaolinite-plus-chlorite.

(a)


SMECTITE
◎ LESS THAN 15%
◎ 15-30%
● 30-40%
● GREATER THAN 40%
METERS
0
1000
1000 m

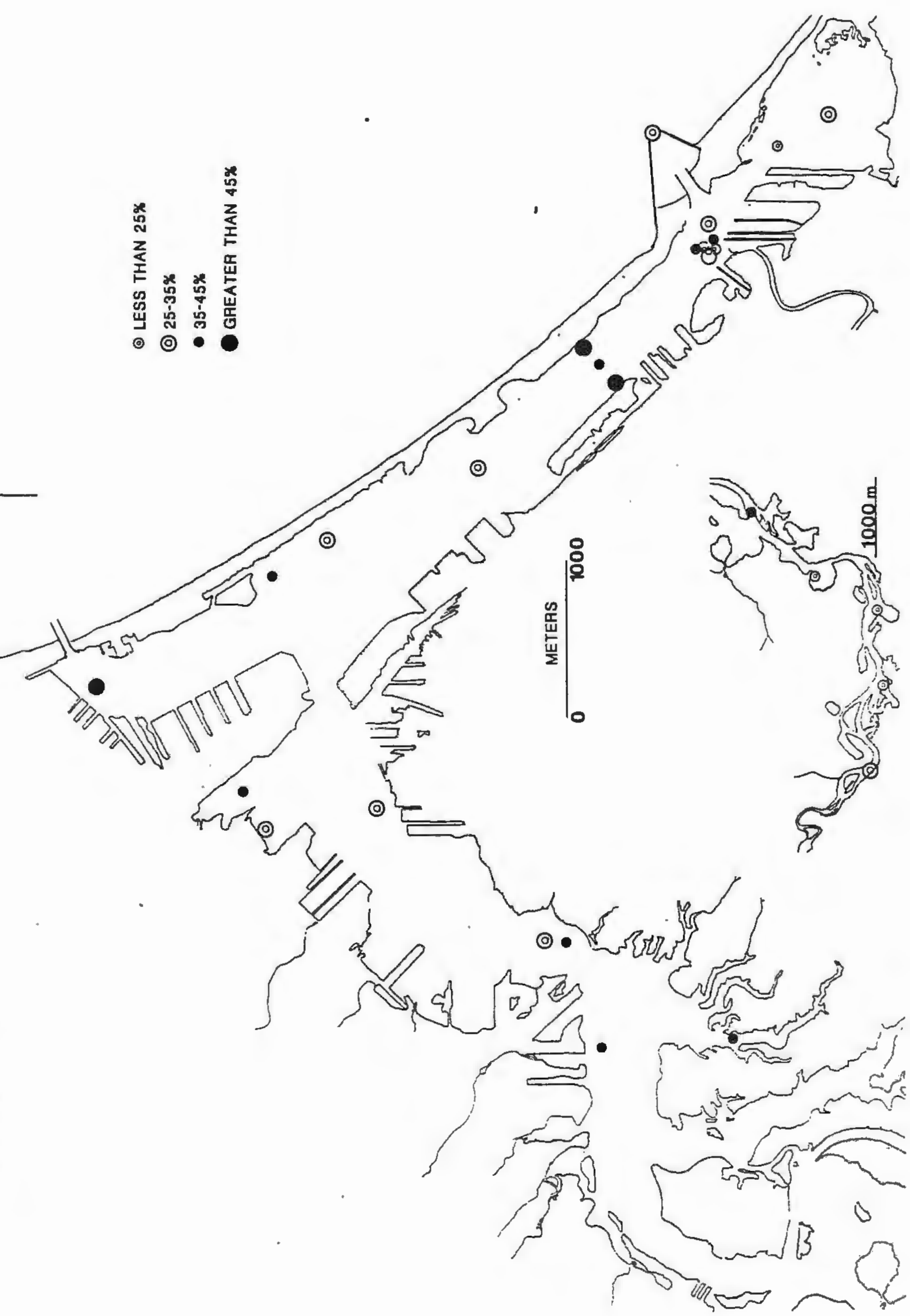


(b)

ILLITE

(c)

KAOLINITE PLUS CHLORITE



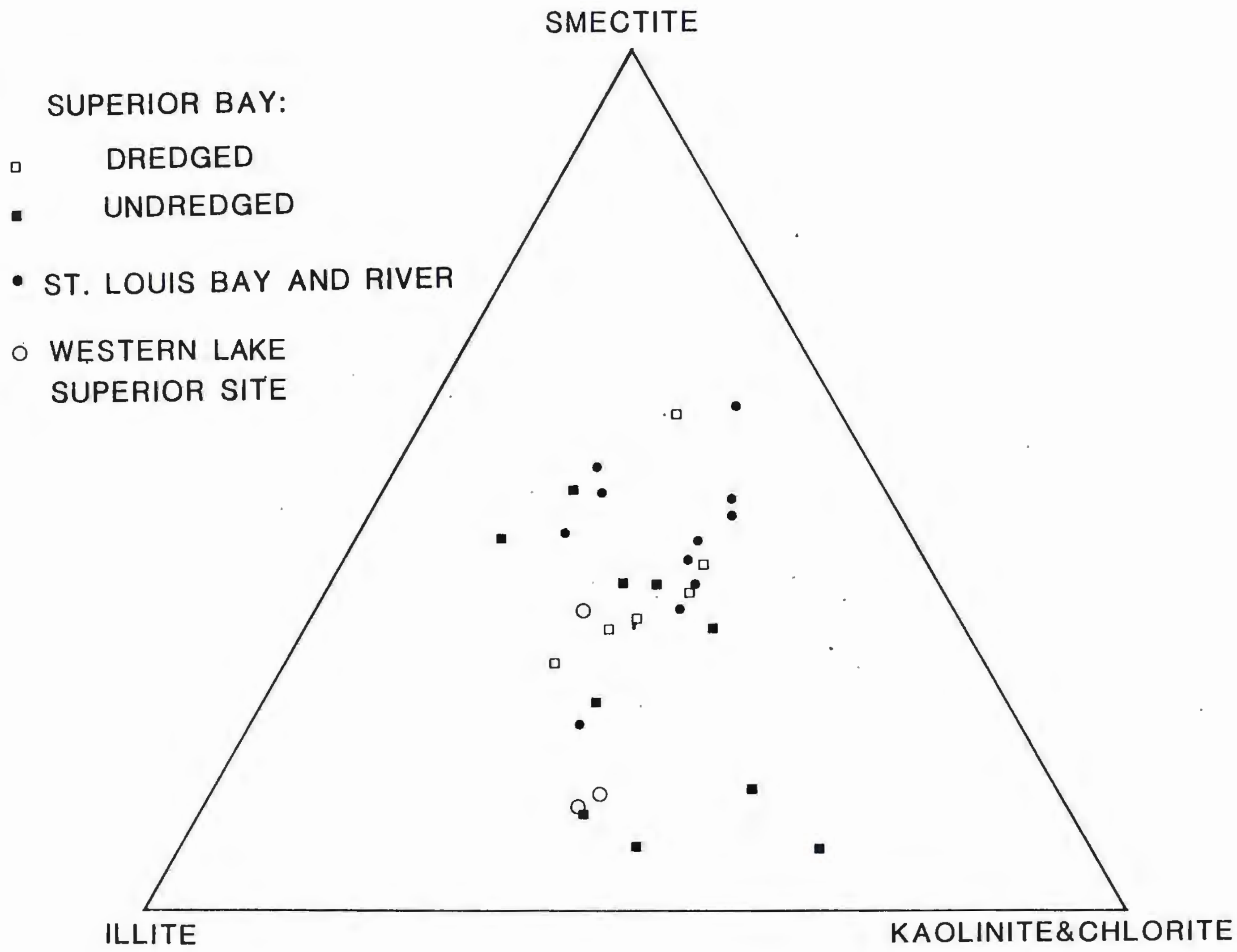


Figure 14a. Clay mineralogy with respect to location.

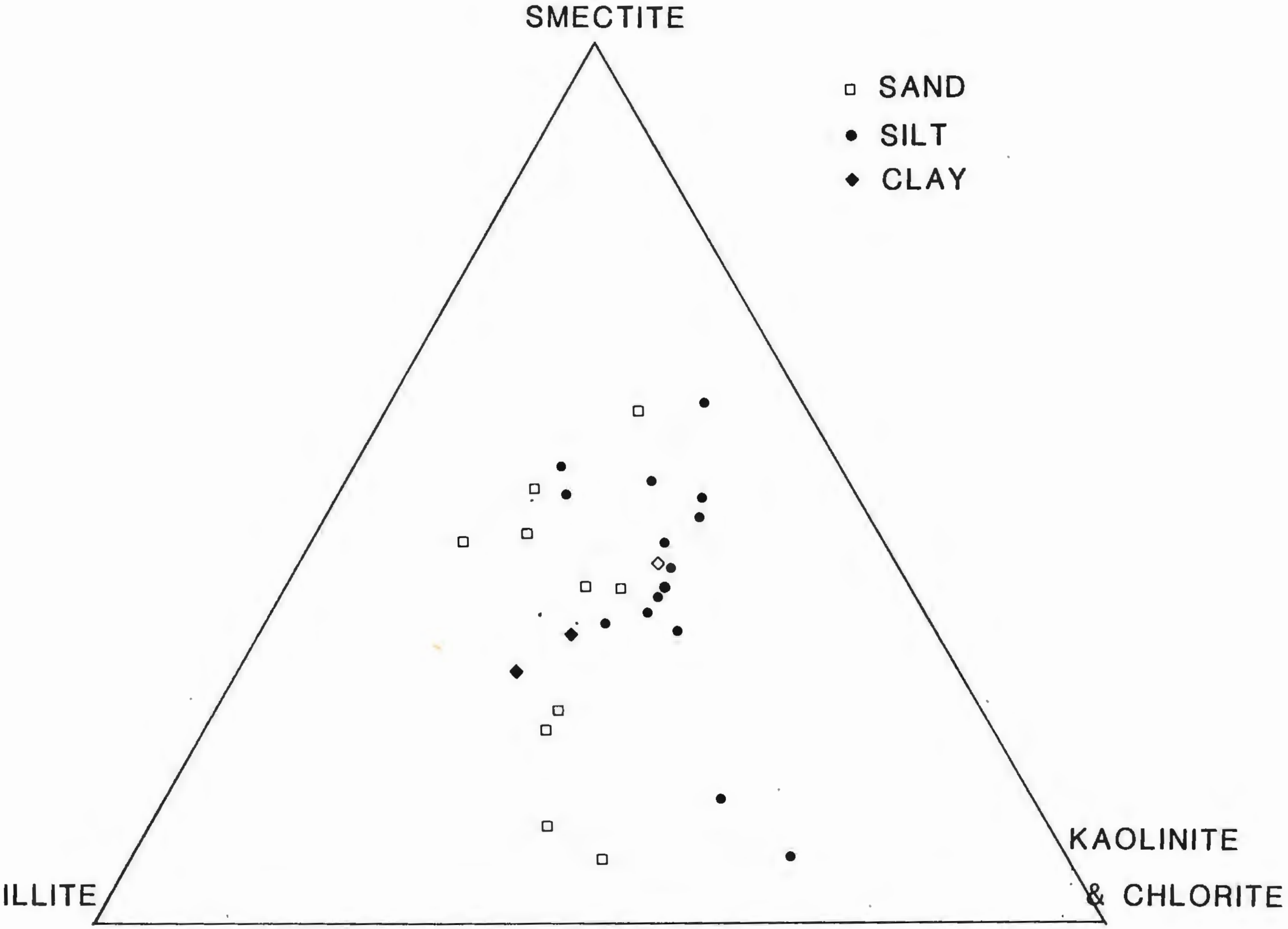


Figure 14b. Clay mineralogy with respect to grain size.

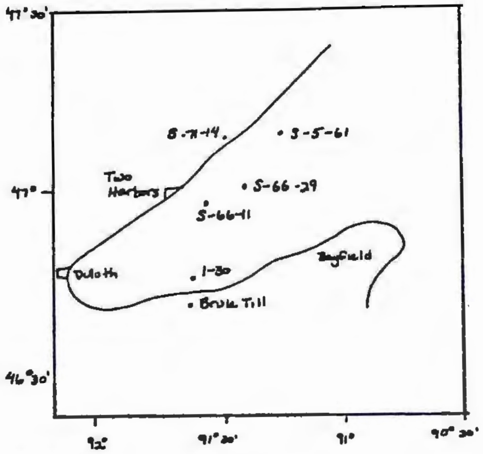
St. Louis Bay, illite ranges from 9 to 29 percent. Throughout Superior Bay, and at the mouths of the Nemadji and St. Louis Rivers, illite constitutes a higher than average percentage of the clay minerals. Disaggregation of older clay bearing beds, such as in the Fond du Lac Formation, may be the predominant origin of illite.

Kaolinite-plus-chlorite compose 14 to 50 percent of the clay minerals and are variable throughout the harbor (Fig. 14c). Chlorite may be derived from glacial till, decomposition of montmorillonite in the soil or from weathering of low-grade metamorphic rocks in the drainage basin (Folk, 1974). Similarly, kaolinite may be derived from several sources.

Grain size may be one control on clay mineral distribution. In general, the relative percentage of kaolinite-plus-chlorite increases in samples that are primarily silt, while the relative percentage of illite increases in coarser sediment (Fig. 15). Differential settling may in part explain the distribution of kaolinite-plus-chlorite in the Duluth-Superior Harbor. Kaolinite-plus-chlorite are washed farther from their river source, while illite settles more rapidly and hence closer to its area of input.

Depositional patterns of clay minerals within the Duluth Harbor may also reflect open lake influence. Relatively low percentages of smectite may be the result of dilution with open lake clays containing low smectite.

The sparse data available on clay mineralogy offshore (Dell, 1971), however, revealed that smectite makes up 51-58 percent of the clay minerals. Local sources are the third influence of clay mineral deposi-



Clay mineralogy of sample S-66-29:

Depth in Core	Smectite	Illite	Kaolinite	Chlorite
0-10 cm	35	38	8	17
50-60 cm	12	50	6	32
96-98 cm	13	47	7	32

Mineralogy of fine sand (.053-.25 mm) fractions:

Sample	S-5-61		S-66-29		Brule till	S-71-4	1-30
Depth in Core	1402-1433 cm	0-10 cm	120-130 cm	460-500 cm		(till)	(till)
Opaques	29.5	73.5	54	26.5	41.5	8	71
Pyroxene	57	19	33	56.6	45	80	19
Hornblende	5.5	2.5	4.5	10.5	5.5	7.5	3
Garnet	X		6	X	X	X	X
Altered greenstone	X		X		X		X
Epidote	X			X	X	X	X
Tremolite-actinolite	X		X	X	X	X	
Apatite	X		X	X	X	X	X
Zircon	X			X	X		X
Tourmaline	X		X	X		X	X
Chlorite			X		X		
Biotite					X	X	
Hematite							
Rutile					X		
Clino-zoisite					X		X
Sphene			X		X		
Dolomite	X			X			

(from Dell, 1972)

Figure 15. Mineralogy of selected samples from western Lake Superior, after Dell (1972).

tional patterns. The low relative percentage of illite is lowest in St. Louis Bay, perhaps implying dilution there by local sources.

Clay mineral assemblages in marine embayments are in most cases attributed to the combined effects of circulation and source (Feuillet and Fleischer, 1980; Hathoway, 1972). Flocculation, which is much more important in saline environments, and diagenesis, usually important only when subsurface analyses are to be performed, may also influence the final mineral suite in some cases, but these probably are minor processes in a young (Holocene), freshwater environment.

The absence of very distinct patterns of clay mineral distribution at any location implies a uniform influence of all sources on clay mineralogy in the harbor.

Comparison with open lake mineralogy:

Dell (1971) examined mineralogy in 2 cores, 1 grab sample, and 2 shoreline till samples from the western arm of Lake Superior (Fig. 15). Values of clay minerals were adjusted in order to make comparisons between relative percentages of clay minerals within the harbor and those from the open lake: in Dell's data, vermiculite and mixed layer clays were eliminated, and expandable clays were compared with smectite.

Clay mineralogy in the uppermost postglacial layer of offshore sediment was described for only one of Dell's locations, S-66-29. Subsamples from three depths within the core were examined. Smectite measures 12 to 35 percent, illite constitutes 38 to 50 percent, and kaolinite-plus-chlorite compose 25 to 39 percent of the clay minerals in the core. The average composition of Dell's sample is plotted on Figure

14a, and shows it to be within the range of harbor clay mineralogy. This supports the conclusion previously stated that the sources have fairly uniform clay mineralogy, or at least that they cannot be distinguished on the basis of clay mineralogy. More analyses of clay mineralogy offshore are warranted, however.

Dell analyzed the grab sample and till samples for heavy mineralogy (Fig. 15). Opaques make up 71 percent of the mineral assemblage in the grab sample, pyroxene 19 percent, and hornblende 3 percent. Till samples from the north and south shores were very different from each other: opaques and pyroxenes each represent about half of the heavy minerals from the south shore; pyroxenes represent 80 percent of those on the north shore, 10 times greater than the opaque abundance. Hornblende remains the same on both shores (5-8%). Accessory minerals include garnet, epidote and apatite in all samples. Tremolite-actinolite, zircon, tourmaline, chlorite, biotite, rutile, zoisite, sphene and dolomite are also identified.

Harbor sediment is more similar mineralogically to the till and grab samples on the south shore of the lake than to those from the north shore, except at the Duluth entry. Where opaques are less common and pyroxenes are more abundant than in south shore till, more comparable to Dell's till sample from the north shore (but only in these respects). Accessory minerals identified in the open lake are similar to those in the St. Louis River estuary, with the exception of rutile and dolomite. Neither dolomite nor any other carbonates were identified in the sand fraction of the harbor.

Subsurface Data

Borehole Stratigraphy:

The deepest borehole penetration in Superior Bay is only 14 m (Fig. 16a,b). Borings from the Arrowhead and Interstate Bridge sites spanning St. Louis Bay and from the U.S. Steel Works near Spirit Lake have penetrated as much as 61 m of subsurface (Fig. 16d,f). The sediment types observed in the boreholes consists of brown sand, red clay, sand/silt, peat, silt and coarse sand/gravel. Till, which is up to 400 m thick in western Lake Superior (Wold *et al.*, 1982) and lacustrine clay form the bluffs lining the estuary.

The lowest unit, brown sand, is found at a depth of 45-60 m in the deep borings from St. Louis Bay (Fig. 16d,f). Sedimentation rate and thickness of this unit are unknown. The brown sand is presumably associated with till because it contains gravel and infrequent boulders.

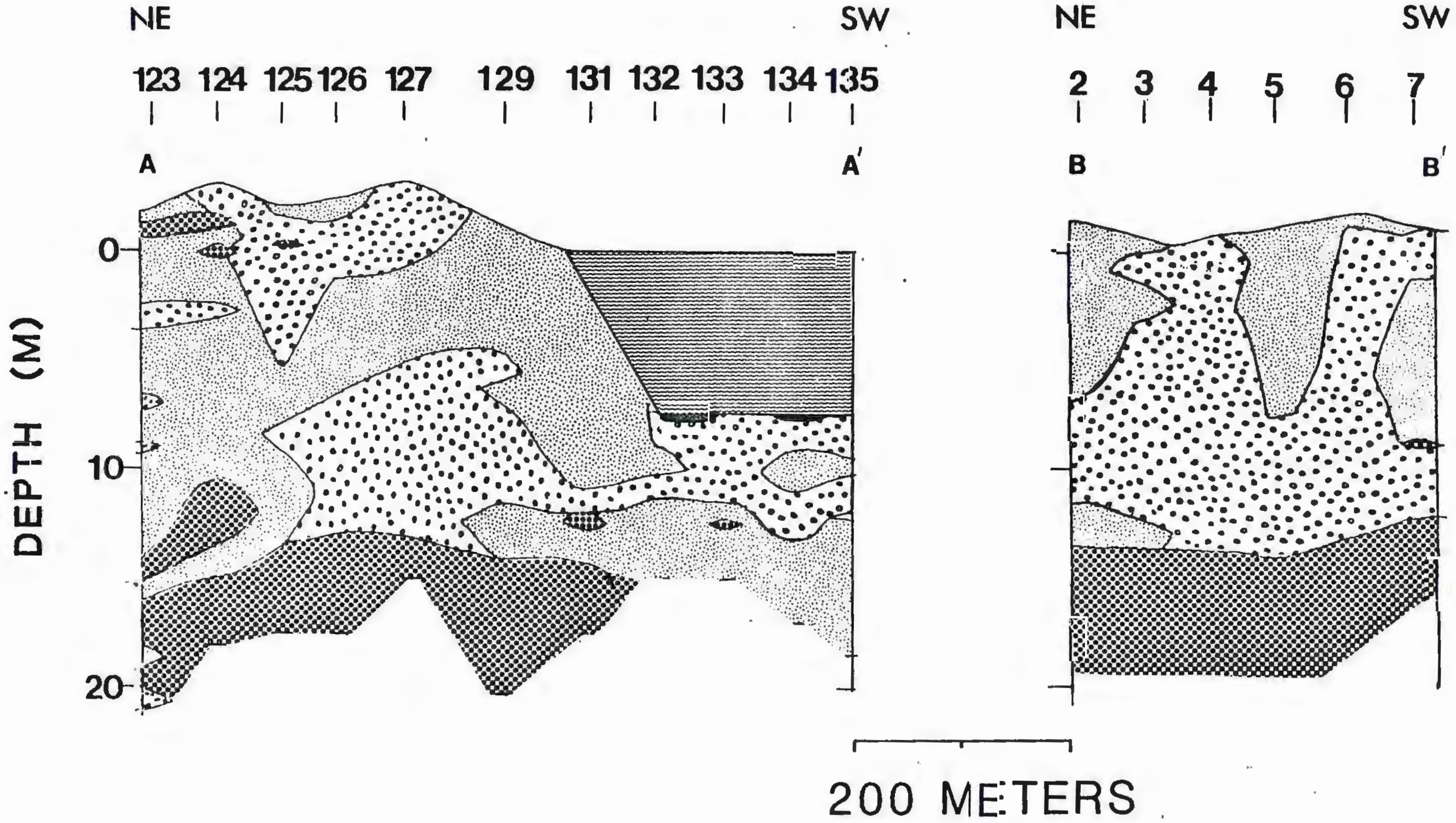
The depth at which red clay begins varies from one part of the harbor to another. At the Superior Entryway the top of the clay layer lies at 12-13.5 m below lake level (Fig. 16a). In St. Louis Bay (Fig. 16f), the top of this stratum dips from 9-12 m depth at the Minnesota shoreline, to 18 m depth at the Wisconsin shoreline. Thickness of the unit varies from 6 to 18 m, usually about 12 m. Clay is described as varved in some borehole logs from Superior Bay. The strata above the clay are much more heterogeneous from one part of the study area to another.

Overlying the clay is a sand unit of variable texture. At the Superior entryway and on Rice's Point, medium to coarse sand and gravel make up at least the upper 9 m of the natural sediment column (Fig.

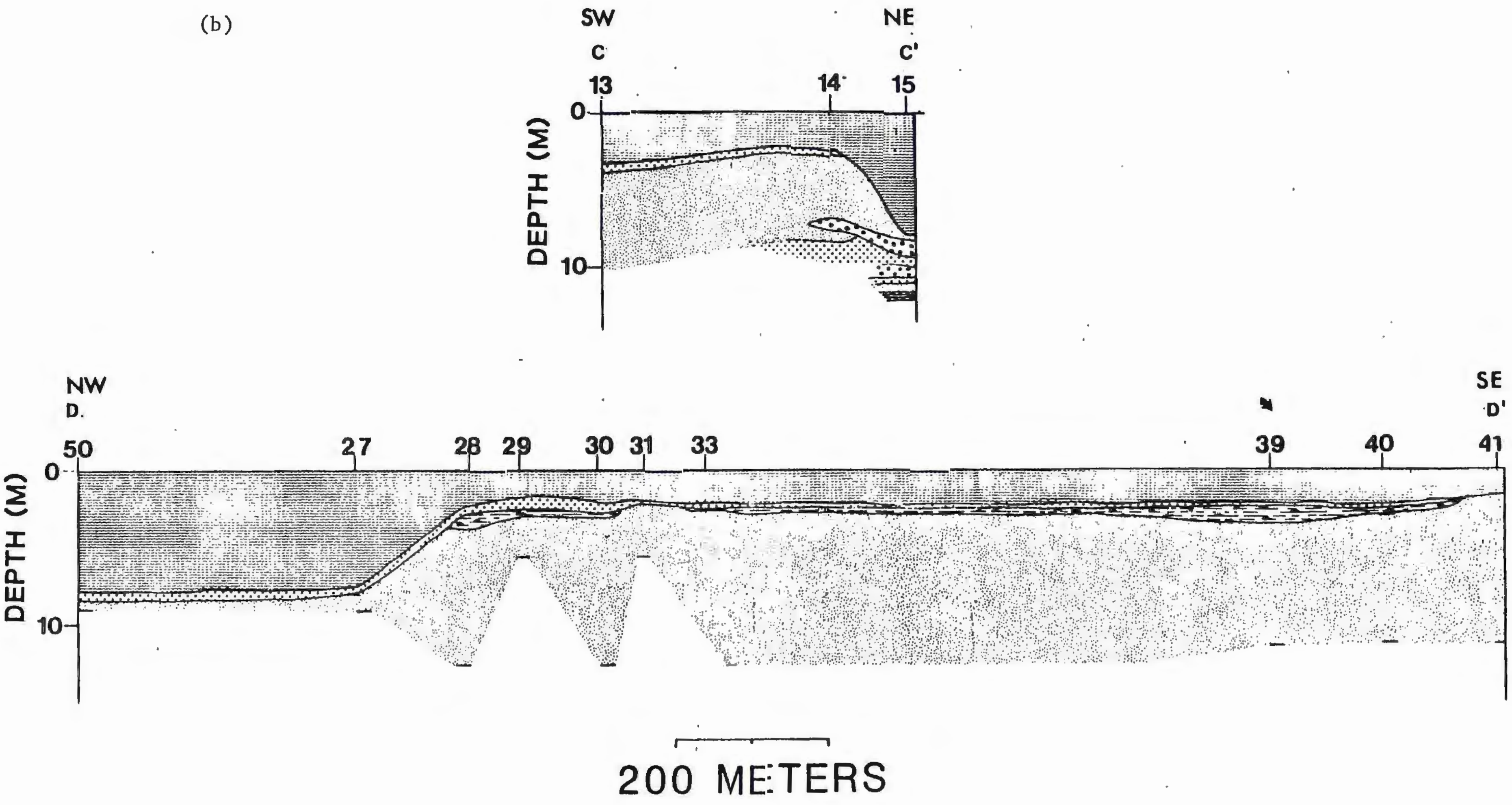
Figure 16. Stratigraphic sections drawn from engineering borehole logs. (a) Superior Entryway (A-A', B-B'); (b) Superior Front Channel (C-C'), Duluth Harbor Basin and East Gate Basin (D-D'); (c) Rice's Point (E-E'); (d) Interstate (Blatnik) Bridge Site (F-F'); (e) 21st Avenue West Channel (G-G'), Howards Bay (H-H'), Minnesota Channel (J-J'); (f) Arrowhead Bridge Site (I-I'); and (g) U.S. Steel Works (K-K').

KEY	
⁙	gravel, sandy gravel, coarse sand
▒	medium-fine sand, silty sand
░	silt, sandy silt
□	clayey silt, silty clay
▦	clay
▥	peat, silty peat
▤	water
▨	fill
▓	rip-rap

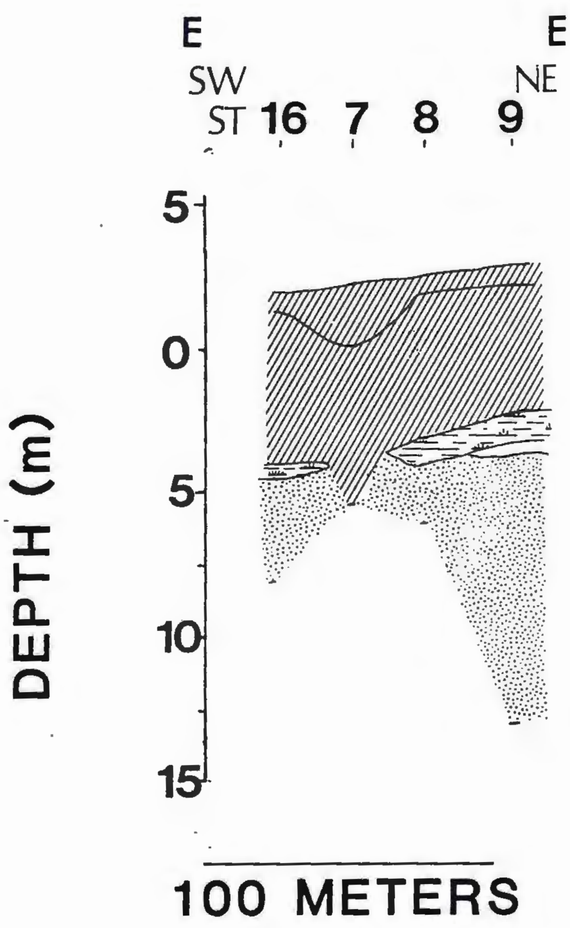
(a)


NE
SW
123
124
125
126
127
129
131
132
133
134
135
A
A'
NE
SW
2
3
4
5
6
7
B
B'
0
10
20
DEPTH (M)
200 METERS

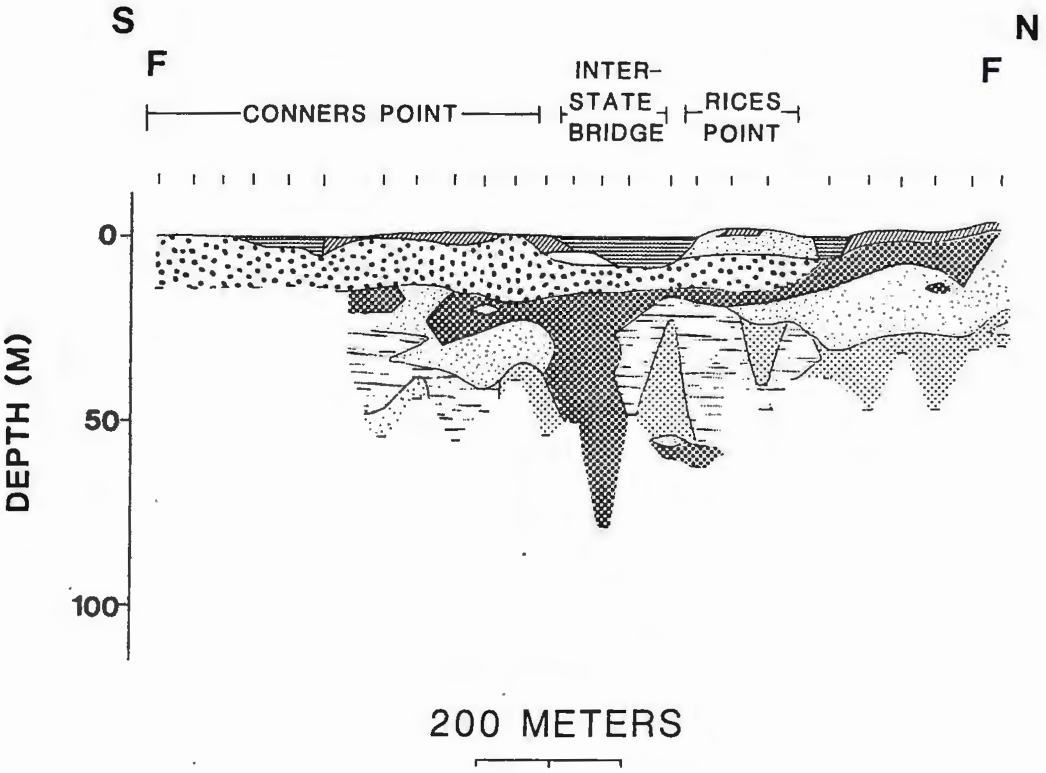
(b)


SW
C
13
14
15
NE
C'
0
10
DEPTH (M)
NW
D
50
27
28
29
30
31
33
39
40
41
SE
D'
0
10
DEPTH (M)
200 METERS

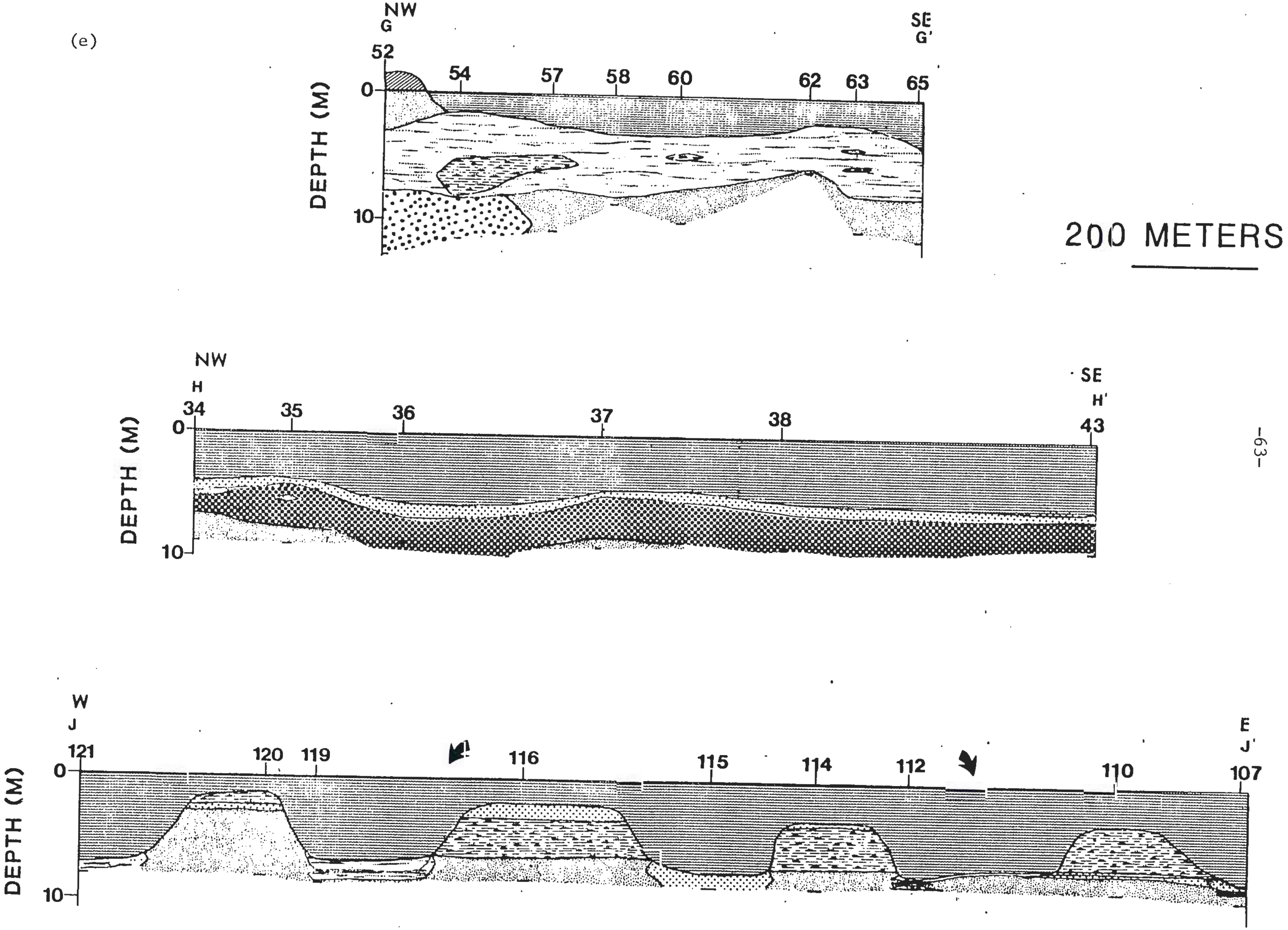
(c)

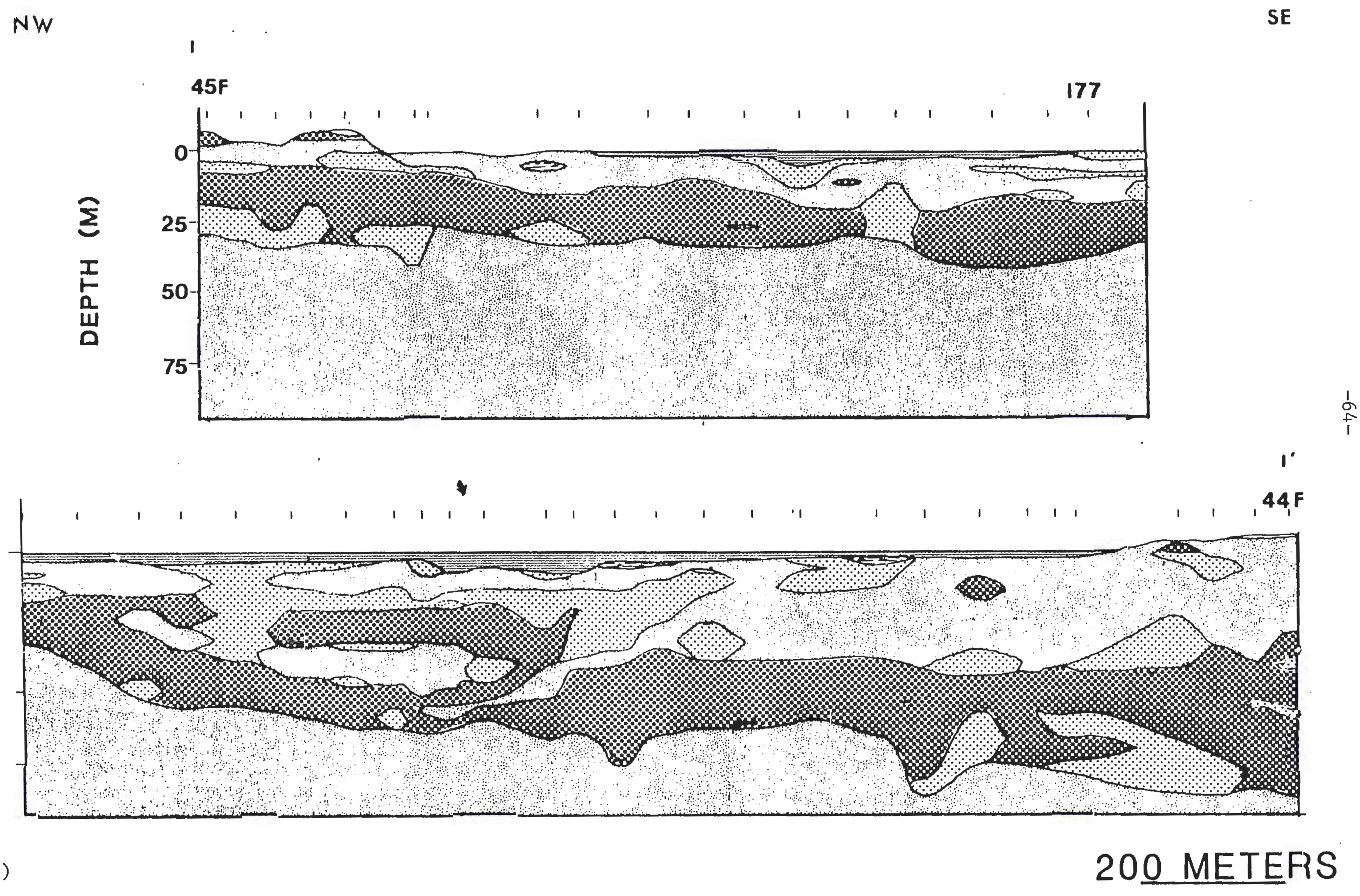


(d)


S
F
N
F
CONNERS POINT
INTER-STATE BRIDGE
RICES POINT
0
50
100
DEPTH (M)
200 METERS

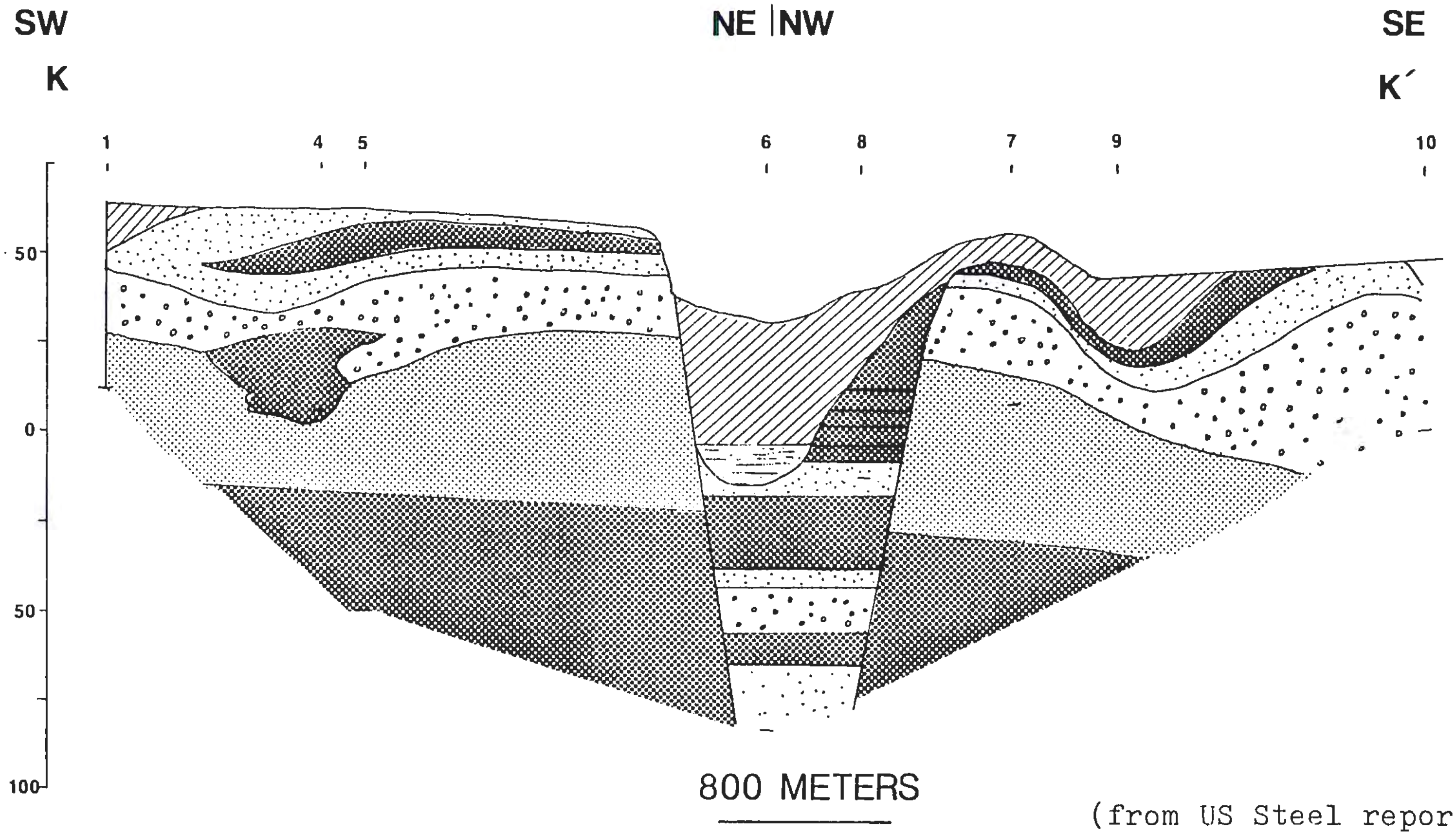
(e)


NW
G
52
54
57
58
60
62
63
65
SE
G'
DEPTH (M)
0
10
200 METERS
NW
H
34
35
36
37
38
43
SE
H'
DEPTH (M)
0
10
W
J
121
120
119
116
115
114
112
110
107
E
J'
DEPTH (M)
0
10



(f)

(g)



(from US Steel report)

16a,c), whereas the subbottom sand in Superior and St. Louis Bays contains a significant proportion of silt (Fig. 16b,e,f).

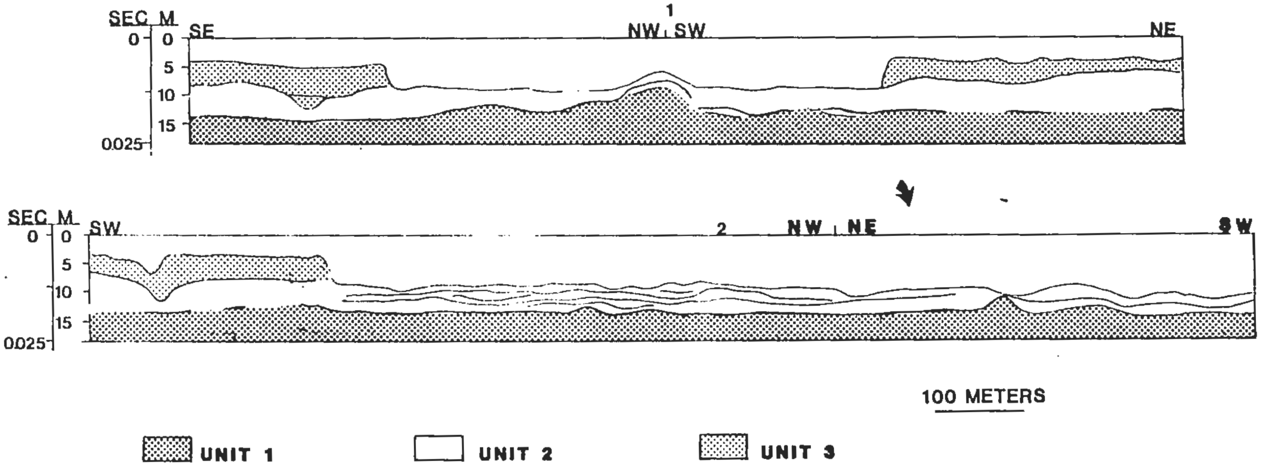
Several lenses of peat and organic rich silt lie above and within the sand layer. Peat extends across the shoreline flats adjacent to Minnesota Point (D-D') and St. Louis Bay (J-J') and is buried by nearly 6 m of fill on the margins of Rice's Point (Fig. 16c), but it is entirely absent from the ship channels. Even in areas of similar water depths, peat is laterally discontinuous. Silt is the dominant sediment on the estuary floor (Fig. 8).

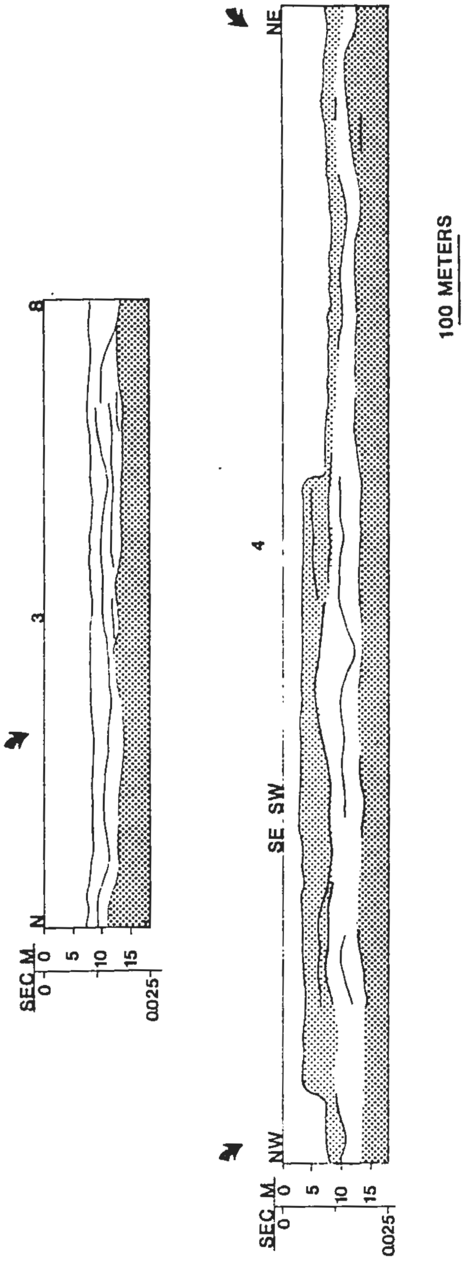
Seismic Profiles:

The quality of the seismic records is poor. Reflectors are very faint and inconsistent. Despite their lack of clarity, some trust may be placed in the seismic records because reflectors can be correlated with lithologic changes, but unfortunately, there are 2 problems with this correlation. (1) Borehole stratigraphy has been altered, and (2) profiles intersect stratigraphic sections at only 2 locations (indicated with arrows on the line drawings and cross sections). Therefore, the seismic results must be considered tentative.

Three stratigraphic units are recognizable on the subbottom profiles (Fig. 17). The lowest, or basement reflector, lies between 10.5 and 12 m below water level. Neither the base of the unit nor internal reflectors within the unit are discernible, so the thickness cannot be resolved from the acoustic records. Throughout the profiles, the bottom reflector is fairly continuous and flat lying and never breaches the overlying unit. Glaciolacustrine clay is found underlying postglacial

Figure 17. Seismic profile line drawings.




SEC M
0
5
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SEC M
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NE
100 METERS

sediment at similar depths in borings from the Superior Front Channel and at the Superior Entryway, so Unit 1 is interpreted to be this sediment type.

The unit overlying the basement reflector, unit two, is characterized by lateral interruptions, varying thickness, and discontinuous internal reflectors that dip in numerous directions. The main reflector, which delineates the top of the stratum, is discernible more clearly in the shoreline flats, usually almost on a level with the channel floor. The sediment of unit two is primarily sand and appears on the profiles to outcrop on the channel floor, although a thin layer of silt overlies it. It is likely that dredges have eliminated a portion of the stratum. Unit 2 is 2.5-5 m thick.

Unit 3, the uppermost unit, is visible only in the shallow-water flats of the estuary floor. Abrupt disappearance of this unit in the channels may indicate that it has been removed largely by dredging. This is interpreted to be primarily silt or silty clay. Internal reflectors are less frequent in unit 3 than in unit 2.

Relation of Stratigraphy to Changing Lake Levels:

Subsurface lithologic changes in the Duluth-Superior Harbor reflect the Holocene history of changing water levels in Lake Superior (Fig. 18). About 11,500 ybp, when glacial ice first began to melt away from the western shore of Lake Superior (Farrand, 1962), glacial outwash and ice-contact deposits were laid down. These are brown sand and gravel at the base of the deep boreholes.

A deep proglacial lake, Glacial Lake Duluth, was formed, with its

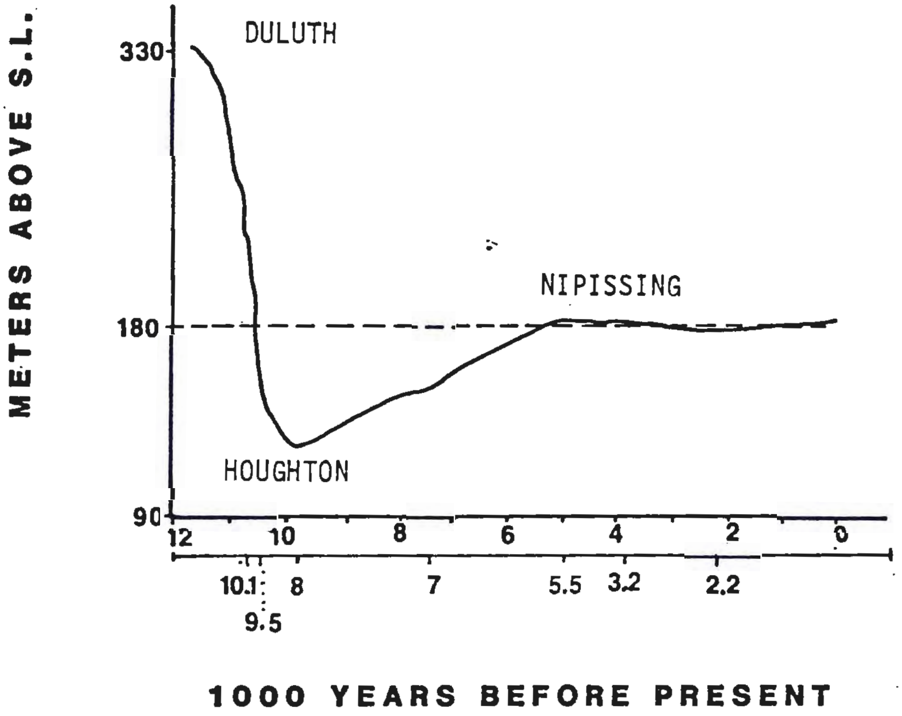


Figure 18. Curve of lake level vs. time, after Farrand (1960). Upper line of dates are those assigned by Farrand, lower line are revisions by Saarnisto (1975).

surface 150 m above lake level today. As the ice lobe melted, a series of progressively lower proglacial lakes filled the western Superior Basin between 11,000 ybp and 9500 ybp (Saarnisto, 1975) as outlets to the north and east were uncovered, and in response to temporary stillstands of the waning ice. Red clay is associated with the proglacial lake stages in the western basin. Interfingering and interbedded silt lenses within the red clay record either minor fluctuations in lake level, or variations in sediment source area. As lake level dropped, first silt, and then (probably) nearshore beach sands were deposited.

About 9500 ybp the entire Superior Basin became free of ice and the Lake Minong Stage came into existence. Water in the western arm of the lake was approximately 40 meters below present level and was controlled by a morainic threshold at the Sault St. Marie outlet. When the drainageway was eroded down to bedrock, water in the Lake Superior Basin attained its lowest elevation, 70 meters below present. This was the Lake Houghton stage of about 8000 ybp (Saarnisto, 1975).

During the Lake Houghton stage, the lake margin receded from the western shore, and standing water in the location of the St. Louis River estuary disappeared. The St. Louis River, fed by water from glacial lakes Aitkin and Upham (Wright, 1976), cut its valley through previously deposited sediment, exposing outwash at the base of a deep gorge. Sedimentation in the embayment area was very irregular primarily due to changing courses of the meandering river.

The Nipissing transgression was initiated after the Houghton Stage and culminated about 5500 ybp. During this time, water level rose about 78 m to a position above the modern waterline, in response to crustal upwarping of the principle outlets, first the St. Mary's River, and later North Bay. Water inundated the St. Louis River valley, establishing an estuary, while open lake beach sand continued to be deposited on the open-lake shores of the present location of Superior, Wisconsin. Rice's and Connor's Points may have been formed during this time. (Spit development is discussed later.)

It is not possible to define the boundary between beach sand and estuarine infill in the St. Louis Bay, despite the expectation that nearshore sands should be better sorted. This is probably for the following reasons: (1) the magnitude of coastal winnowing processes was too small to promote well sorted beach sands, either because lake level was changing too rapidly, or because the existing topography/bathymetry minimized the effect of the waves; (2) beach sands were removed from the estuary by slope erosion and river downcutting; and (3) beach sands were deposited over such irregular topography that they are not revealed as discrete and continuous beds but rather as lenses within estuarine sediments.

After the Nipissing stage, lake level fell in response to outlet downcutting and upwarping. Although the change in water level was relatively minor, probably no greater than 8 m (assuming that the deepest occurrence of peat indicates the draining of water from the harbor, it had an important effect on the sedimentation and morphology of the Duluth-Superior Harbor. Again the St. Louis River had the opportunity to flow through older beds, but this time the downcutting was much less severe, as stream erosion was not aided by the sediment-free water provided by the glacial lakes, as occurred during the earlier low water period. A layer of peat developed on the floor of the drained estuary, and the outer set of spits grew at the mouth of the river.

It was probably during this (post-Nipissing) time that Minnesota and Wisconsin Points evolved, forming Superior Bay as it exists today and creating a much quieter environment there. (Mechanisms of spit development are discussed below.) Peat and silt deposition, initiated at a later date in Superior Bay than in St. Louis Bay, signal the detachment of the outer bay from the open lake. It is usually assumed that a subsurface layer of peat implies moist but not flooded conditions, otherwise burial of the peat would be impossible.

However, the peat on the southern extent of Rice's Point (E-E') is clearly the product of dredge disposal. This area was covered with wetland vegetation prior to the development of the port. When the outer ship channels were dredged, spoils were used as fill to build-up Rice's Point, so the plant cover was buried under about 6 m of sediment. This explanation may also be valid for the peat in the flats along St. Louis Bay, where dredge spoils from the adjacent channels were dumped.

Using the time table and curve for lake level change (Fig. 18) established by Farrand (1960) and revised by Saarnisto (1975), and measuring sediment thicknesses described in engineering borehole logs, rough sedimentation rates can be calculated for the lithologic units: (1) sedimentation rate of the brown sediment cannot be calculated because thickness is not known, (2) red lacustrine clay, usually about 20 m thick, is associated with elevated lake levels between 11,000 and roughly 10,000 ybp, indicating a sedimentation rate of 2 cm/yr, (3) the thickness of the sand/silt, channel fill unit in the main river channel is up to 36 m, deposited from the onset of slowly rising lake level until it fell once again after the Nipissing stage, a period not exceeding 2500 years, or 1.4 cm/yr. Deposition probably occurred at a different rate in the "proto" Superior Bay. The lower contact of the sand is seen only at the Superior Entryway (because boreholes within most of Superior Bay do not penetrate clay), and the upper contact is seen only in Superior Bay, so unit thickness cannot be determined. Assuming that a long depositional hiatus records the time when the outer harbor was dry, and that a majority of the material laid down prior to draining was subsequently eroded, the sand layer was deposited between about 6000 and 3000 ybp. (4) After the water level maximum of Lake Nipissing, a layer of peat developed over the floor of the inner bay in response to falling lake level, reaching a thickness of 1.5-3.0 m over a maximum period of 3300 years. The calculated sedimentation rate for the peat in the inner bay is 0.4 to 0.9 cm/yr. In the newly formed outer bay, peat accumulated to a thickness of about 1.2 m. If the sedimentation rate was the same as that in the inner bay, then the time interval for peat deposition was between 1600 and 3000 years (depending on the age of the outer spits).

Cross sections presented in Figure 16 were useful in illustrating environmental changes, but some of the borehole data were outdated at the time of writing. For example, sections A-A', C-C', D-D', G-G' and H'H' were described in the 1950's and 1960's, but subsequent dredging has altered the stratigraphy where they were located.

Comparison of St. Louis River Embayment and Marine Estuaries

Similarities between marine and Lake Superior estuarine and nearshore settings can be considered in terms of physical dimensions, recent geological history, circulation, and sedimentation.

Minnesota Point is the longest freshwater spit in the world, 11.7 km, but it is small compared to oceanic barriers which may be as much as ten times larger (Dolan *et al.*, 1980). Likewise, Superior Bay is relatively small compared to marine lagoons. Offshore bathymetric zones and their corresponding sedimentary environments are also compressed in the lake environment. The western arm of the lake, extending several kilometers offshore, corresponds to the oceanic continental shelf. Onshore, sand dunes on Minnesota Point, up to 3-6 m high, are similar in height to dunes on oceanic shorelines.

Dimensions of an estuarine interior in a marine setting are linked to regional topography, bathymetry (Emery, 1967), and tidal range (Folger, 1972a). Larger estuaries are promoted on wide, flat coastal plains and/or where the tidal range is high and the sediment yield is low. In contrast, high relief, a narrow coastal plain, copious sediment supply and low tidal range stunt estuarine growth. The St. Louis River embayment has traits common to both large and small marine estuaries. It is bounded by high relief on one shore and moderate relief on the other, and it has a low sediment supply, narrow coastal plain and seiche oscillations of low amplitude, typically between 15 and 23 cm (Stortz and Sydor, 1980).

The second major distinction concerns recent geological history, specifically the geological chronology and mode of formation of estuaries on marine coasts and around Lake Superior. Estuaries are ephemeral features; they are so abundant worldwide because of the relatively recent and rapid rise in sea level, so pre-glacial coasts probably contained many fewer estuaries than modern ones (Russel, 1967; Curray, 1969). Contours that define the walls and floor of marine estuaries were carved during Wisconsin glaciation, when sea level was lowered by as much as 130 m. This exposed large portions of the continental shelf, and rivers cut their channels into a new source of unconsolidated sediment. Between 16,000 ybp and 6000 ybp, glacial meltwater replenished the oceanic supply of water, flooding the incised river valleys.

Concurrently, water level changes were taking place in the Lake Superior basin, but with the opposite trend. During ice retreat, a series of proglacial lakes formed. Lake level fell in response to the uncovering of lower outlets, reaching a maximum depression at 75 m below today's level. It was during this time that the St. Louis River channel was cut. Inundation initially occurred when one of the main outlets at North Bay rebounded, forcing water level to rise about 5500 ybp (Saarnisto, 1975). Therefore many estuaries lining the continental shelves predate the original St. Louis River Estuary by several thousand years.

The third major distinction between marine and lacustrine estuarine systems is the mode of formation. Pritchard and Carter (1971) classified marine estuaries by their formational characteristics. According to his scheme and other characteristics described by Curray

(1969), the study area is a combination of two types: St. Louis Bay is a drowned-river-valley estuary and Superior Bay is a bar-built estuary. In St. Louis Bay, sedimentation has not kept pace with lake water encroachment in the region. Its general shape is that of a river valley, characterized by a triangular cross section, extensive mudflats (predating settlement), sinuous central channel, and modification of spits at its mouth (Rice's and Connor's Points). In Superior Bay a sufficient supply of sediment was available to build a bar across the river mouth (Minnesota Point), and sedimentation was able to keep pace with inundation. Other characteristics of a bar-built estuary seen in Superior Bay are that depths seldom exceed a few meters, and current velocities diminish rapidly with distance from the inlet (Stortz and Sydor, 1980).

Circulation is the fourth major distinction. Circulation in the St. Louis River estuary is radically different from that in a marine estuary. A marine estuary acts as a mixing zone for saline and fresh water. Segregation of the two water masses is inherent due to density differences, and promotes a system of two layer flow. Circulation is driven by tidal, river, and wind currents. Density, basin shape, and the domination of one water source over the other determine the manner in which stratification will develop, and the direction of net mass water movement (Schubel, 1971; Dyer, 1973, 1979). In the freshwater system of the St. Louis River estuary, the effect of density stratification is minimized. Water temperature and turbidity are the only causes of density differences between the river and lake water masses. Tides are negligible in the St. Louis River estuary, which also makes it different from a marine system. Circulation in the estuary is driven by river inflow, seiche oscillations, and wind currents. Specific measured and calculated velocities are listed in Figure 19.

For comparison, in estuaries along the Gulf of Mexico, a low energy coast, tidal range is low. Currents rarely exceed 50 cm/sec and waves are significant only during hurricanes. Sediment supply in the Gulf is abundant (Folger, 1972a; Rusnak, 1964; Shephard, 1955).

The fifth major distinction regards sedimentation and sediment distribution. Circulation and stratification effects on sedimentation in the marine environment are explained by Dyer (1973, 1979). In general, suspended particulate matter is carried downstream by river currents and returned upstream, mixed with oceanic sediment. If the river is the dominant agent for water transport, sediment accumulation increases with proximity to the river mouth. Where tides are dominant, mixing is vigorous at both the river mouth and tidal inlets. Deposition is concentrated in the mid-estuary region and lag deposits are found in the river bed and entrance channels.

The natural sediment distribution in the St. Louis River estuary (Fig. 8) closely mimics that found in Gulf coast embayments, where clay and silt predominate on the channel floor, grading into sand along the margins, and very coarse material is limited to inlets (Folger, 1972a). (More specific sediment characteristics of marine estuaries were compared in the discussion of surface sediments in the harbor.)

TABLE 1. Calculated currents for various channels of interest.

Maximum Upstream, Average, and Maximum Downstream Speeds (cm/sec)

Location	No Seiche	3.0 cm Seiche Max Up	3.0 cm Seiche Av	3.0 cm Seiche Max Down	15.0 cm Seiche Max Up	15.0 cm Seiche Av	15.0 cm Seiche Max Down
Superior Entry*	1.6	-7.9	2.0	11.5	-30.4	1.9	34.6
Duluth Entry*	2.0	-16.6	1.9	19.4	-41.9	2.5	45.8
Superior Front Channel*	0.6	-3.0	1.1	5.0	-11.8	1.2	14.1
Duluth Harbor Basin	0.3	-2.1	0.4	2.7	-5.3	0.5	6.1
Blatnik Bridge*	2.7	-17.1	3.4	22.3	-45.4	3.7	50.0
Sewage Plant	2.5	-15.6	3.2	20.5	-42.0	3.4	45.7
Coal Dock	1.2	-7.7	1.6	10.0	-20.6	1.6	22.1
Cross Channel	0.1	-0.9	-0.0	0.8	-1.9	0.0	1.8
North Channel*	1.5	-9.0	1.9	11.8	-24.4	2.0	25.7
South Channel	1.4	-5.1	2.1	8.8	-19.0	1.8	20.8
Arrowhead Bridge*	1.7	-8.4	2.7	12.6	-26.5	2.5	28.2
Drills*	2.0	-6.4	3.0	11.3	-23.2	2.6	24.7
Oliver Bridge	2.0	-1.5	2.7	6.5	-8.9	2.7	11.9
Fond du Lac*	17.8	14.3†	15.6	16.7	11.9†	15.5	18.5

*Insitu current measurements made in channel.
†Flow does not reverse at this location.

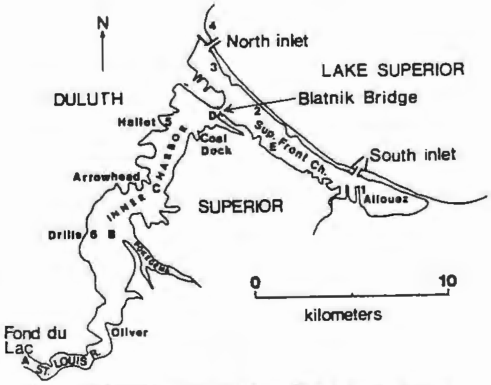


FIG. 1. Duluth-Superior harbor. Water level stations are indicated by numbers, current meter stations by letters.

Figure 19. Current velocities and locations, from Stortz and Sydor (1980).

Sedimentary Processes in the Duluth-Superior Harbor

Sedimentation in the Duluth-Superior Harbor is governed by the shape of the basin and its effect on seiche and river currents, by currents generated by ship propellers, and by surface waves.

The seiche is the dominant driving force for mass transport in the lower St. Louis River and harbor (Stortz and Sydor, 1981). In the absence of a seiche, water movement is dominated by discharge from the St. Louis River, which averages 30 m^3/sec (measured at several locations within the embayment and at Fond du Lac), with flow velocities of 1-3 cm/sec in a lakeward direction (in most channels in the harbor). At high seiche conditions, the current is up to 20 times greater (Stortz and Sydor, 1981; Fig. 19). Currents are greatest at constrictions in the waterways, particularly in the harbor entryways and in the opening between the inner spits.

Currents generated by ore boats may be much faster than most seiche currents. Ship wash is restricted primarily to the navigable channels, but in some of these areas it probably surpasses seiche currents in impact upon sedimentation. Fuehrer *et al.* (1981) derived the following equations to study the impingement of ship-induced velocity on harbor floors:

(1) $V_o = 1.6\ nDK_T$

where V_o = induced jet velocity from the propeller at ship speed = 0 (same units of length as used for D),

n = propeller speed in revolutions per second,

D = propeller diameter, and

K_T = thrust coefficient at ship speed = 0. K_T is a function of thrust, speed, and diameter of the propeller, and density of the fluid in which the propeller is operating (see Comstock, 1967, p. 386).

If K_T is not known, the following equation can be used:

(2) $V_o = 1.48\ P_D{}^{1/3}/D^2$ (Blaauw and van de Kaa, 1978)

where P_D = installed engine power in kW and D = propeller diameter in meters.

The induced jet velocity is used to calculate the velocity as it translates to the harbor floor:

(3) $V_{B_{max}} = V_o E(hp/D)^{-1}$

where $V_{B_{max}}$ = maximum bottom velocity at ship speed = 0,

hp = distance from the center of the propeller to the channel bottom, and

E = a coefficient that is a function of stern size and shape, and rudder arrangement.

Fuehrer <u>et</u> <u>al</u>. (1981) used their results to determine the size of rip-rap needed to maintain stability of a channel floor, by means of the following equation:

(4) $V_{B_{max}} = B\ \ d_{50}\ g\ \frac{\rho_s - \rho}{\rho}$

where d = average diameter of rip-rap stones,

g = gravity,

ρ_s = stone density,

ρ = water density, and

B = a coefficient which is a function of stern type and rudder arrangement and is the limiting condition for incipient rock movement.

Equations 2, 3 and 4 were applied to the case of an ore boat cruising in the Duluth-Superior Harbor. The largest ships entering the harbor (300 m long) usually have two propellers, each measuring 5 to 6 m in diameter sitting in an upright position (Ralph Bertz, U.S. Steel Fleet Headquarters, pers. comm.). Speed limits restrict ship speed to about 9 knots (15.8 km/hr). At this speed, propellers revolve at as little as 30 rpm, except maneuvering into piers where they may accelerate to 70 rpm, and installed engine power is at most 5000 HP (3730 kw) (Bertz, pers. comm.). Minimum clearance between the hull and channel bottom is 76 cm, so the distance between the center of the propeller and channel floor is about 3.76 m. The coefficient E is 0.25 for an inland ship with tunnel stern and twin rudder gears; B is 1.25 for a ship with a central rudder, found by experiment (Fuehrer et al., 1981). Grain density of sediment is taken as 2.65 g/cm^3. Under these conditions, the induced jet velocity (V_o) = 63.74 cm/sec, the maximum bottom velocity ($V_{B_{max}}$) = 25.43 cm/sec, and the largest grain size sediment moved is 2.76 mm.

The rip-rap size calculated by Fuehrer's method agrees reasonably well with the grain size estimated from the modified Sunborg (1956) diagram (Miller et al., 1981) under similar velocity conditions (Fig. 20). The Sunborg diagram defines zones of sedimentation and erosion by observed movement of sediment of a specific size when subjected to a water velocity measured 100 cm above the bed. A current velocity of about 80 cm/sec is required to initiate transportation of gravel (2mm in

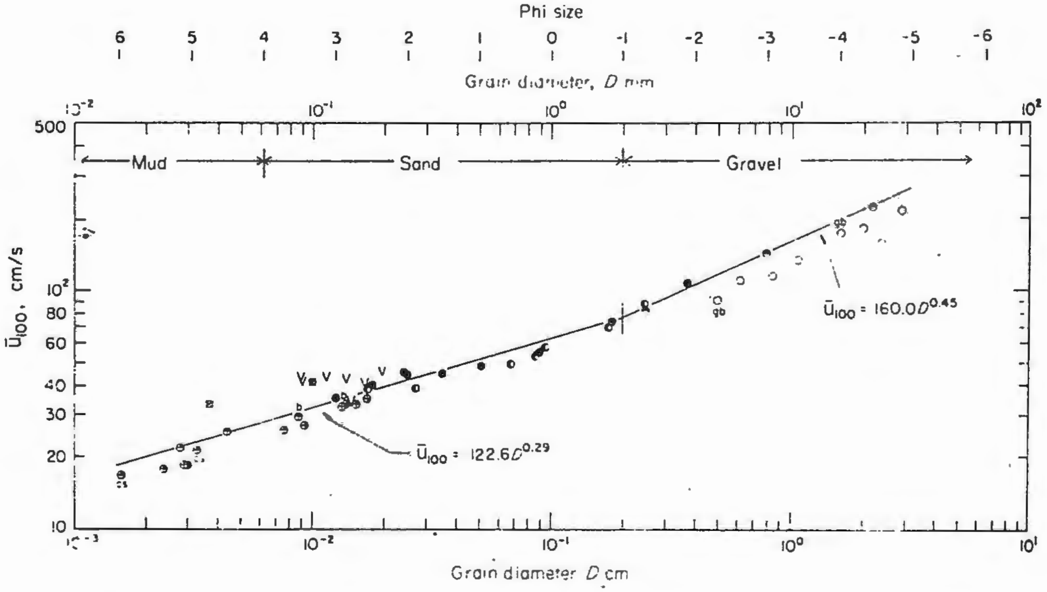


Fig. 6. The grain diameter D versus the flow velocity 100 cm above the bed u_{100} necessary for threshold for quartz density material in water of temperature 20 C. (modified from Sundborg 1956)

Figure 20. Modified Sunborg diagram, from Miller *et al.*, 1977.

diameter) and a current of 30 cm/sec is capable of transporting fine sand ($<$ 0.1 mm).

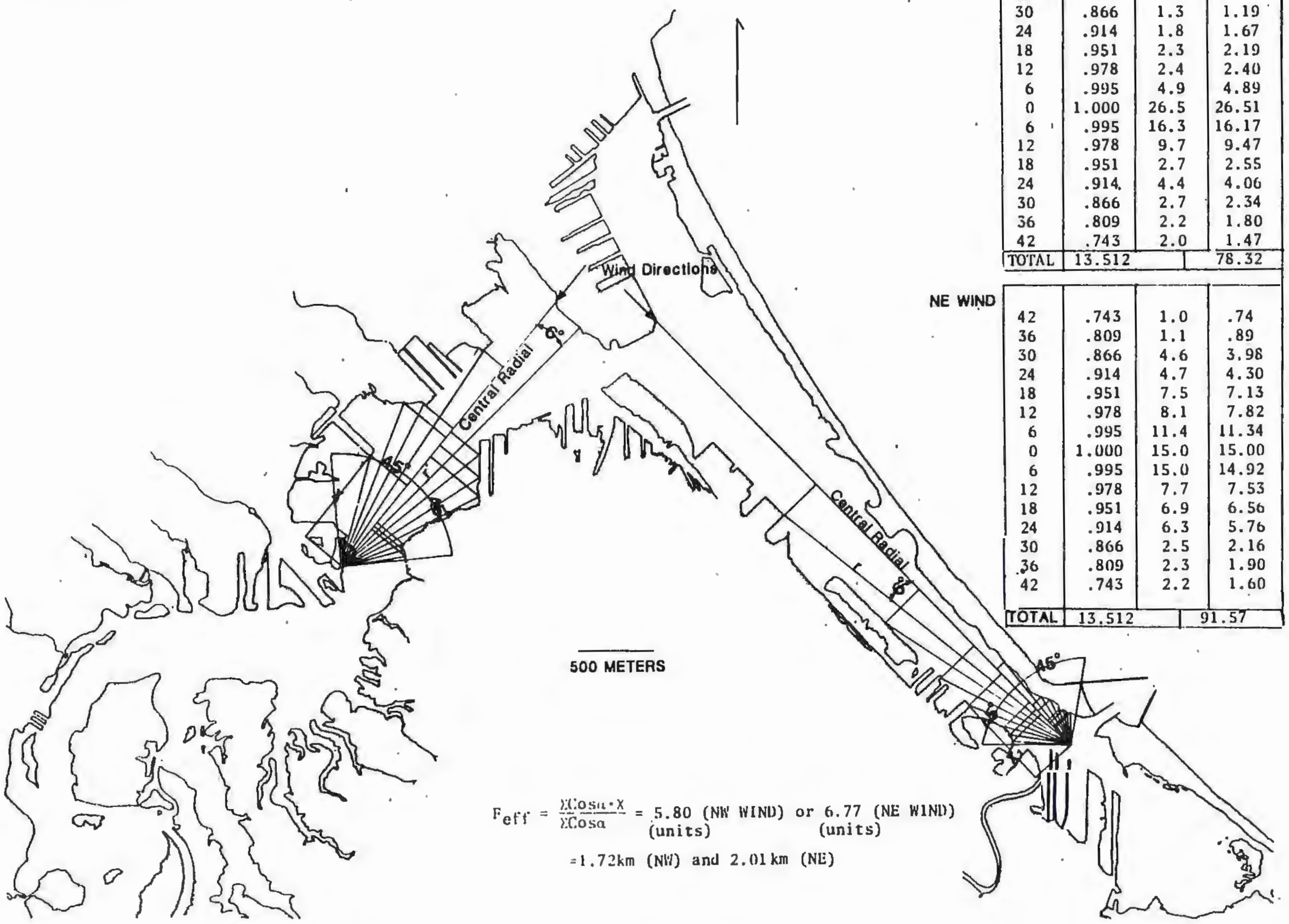
Wind generated waves are an important means of sediment transport only in very shallow water. Effective fetch and wind speed were used to determine grain size of the largest bottom sediment particles transported under conditions typical of the harbor, after Johnson (1980). Maximum effective fetch was estimated by a method described by the U.S. Army Corps of Engineers Coastal Research Center (1977). Radials were constructed from a designated wind direction at 6° intervals up to 45° and extended to intersect the shore. The cosines of all the angles were multipled by their respective distances in the direction of the wind, the totals summed, and then divided by the sum of the cosines of all the angles (Fig. 21).

Northwest and northeast winds were chosen for 2 reasons: (1) They parallel the long axes of Superior and St. Louis Bays, respectively, and (2) the prevailing winds are usually from the west-northwest or northwest, and storm winds usually approach from the northeast (U.S. Coast Guard Office, Duluth, pers. comm.). The average of the 2 fetches, 1865 m, was used because the individual fetch values differed by less than 300 m.

Average wind velocities for individual months over the past 30 years range between 11 knots in August to 14 knots in April (National Weather Service, Duluth, pers. comm.). The greatest wind speed in the last 30 years was recorded in April 1958 at 82.5 knots (at the Duluth Airport).

A 12 knot wind has the capacity to transport coarse sand ($\leq$ 1.4 mm diameter) in 0.5 m deep water, but only very fine silt ($\leq$ .005 mm) in

EFFECTIVE FETCH



NW WIND

α	Cosα	X_1	X_1Cosα
42	.743	.9	.71
36	.809	1.1	.90
30	.866	1.3	1.19
24	.914	1.8	1.67
18	.951	2.3	2.19
12	.978	2.4	2.40
6	.995	4.9	4.89
0	1.000	26.5	26.51
6	.995	16.3	16.17
12	.978	9.7	9.47
18	.951	2.7	2.55
24	.914	4.4	4.06
30	.866	2.7	2.34
36	.809	2.2	1.80
42	.743	2.0	1.47
TOTAL	13.512		78.32

NE WIND

α	Cosα	X_1	X_1Cosα
42	.743	1.0	.74
36	.809	1.1	.89
30	.866	4.6	3.98
24	.914	4.7	4.30
18	.951	7.5	7.13
12	.978	8.1	7.82
6	.995	11.4	11.34
0	1.000	15.0	15.00
6	.995	15.0	14.92
12	.978	7.7	7.53
18	.951	6.9	6.56
24	.914	6.3	5.76
30	.866	2.5	2.16
36	.809	2.3	1.90
42	.743	2.2	1.60
TOTAL	13.512		91.57

$$F_{eff} = \frac{\Sigma \mathrm{Cos}\alpha \cdot X}{\Sigma \mathrm{Cos}\alpha} = \underset{\text{(units)}}{5.80} \text{ (NW WIND) or } \underset{\text{(units)}}{6.77} \text{ (NE WIND)}$$

$$= 1.72\text{km (NW) and } 2.01\text{km (NE)}$$

Figure 21. Calculation of effective fetch for northwest and northeast winds.

4 m of water. Coarse sand in 4 m deep water can be transported by a 50 knot wind and granule sized particles (2-4 mm) are moved at a depth of 2 m.

Currents generated by seiches, ships, and waves affect sedimentation to varying degrees in different areas of the harbor. In the inlets, seiche currents reach maximum speeds of 30-45 cm/sec, leaving lag deposits of cobble and gravel. Current velocities are even greater at the Blatnik Bridge constriction, where 90-98% of the bottom is coarse sand. Ship traffic also influences grain size in the inlets.

Directly inside the Duluth Ship Canal in the Duluth Harbor Basin seiche currents are greatly diminished, although grain size remains primarily cobble, gravel, and sand (greater than 90%). Grain size there reflects current velocities produced by ship traffic. Resuspended sand and gravel usually resettle in the channels from which they were stirred, accumulating at the edges of the channels where turbulence is reduced (Stortz and Sydor, 1981). Silt settles closer to the Superior entryway than to the Duluth Ship Canal, because more ship traffic passes through the latter.

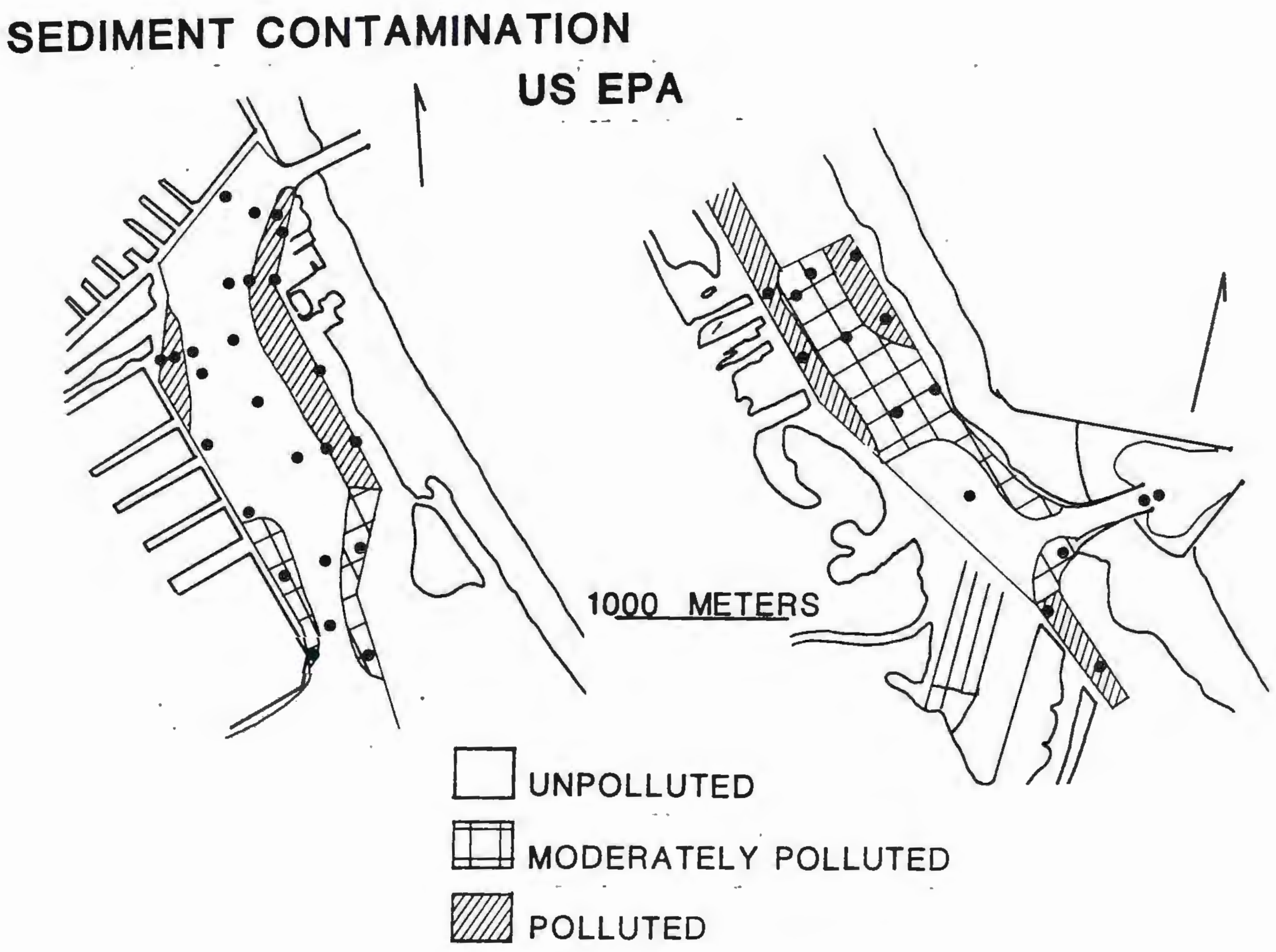
Similar low seiche current velocities measured in the Superior Front Channel control grain size there (silt), because ship traffic is light. Closer to Superior Entryway, at the mouth of the Nemadji River, sediment is predominantly sand despite the high suspended sediment concentration; this relation should imply that the river input contains a large percentage of silt and clay. Ore ships pull out of the coal docks in reverse, stop, then turn their propellers on at full thrust, forcing the resuspension of a plume of sediment behind the stern. This action serves to winnow out fine sediment. Sand next to some piers in St. Louis Bay may be accounted for in the same way.

In St. Louis Bay channels, calculated and measured maximum current velocities are about 1/2 the magnitude of those in the constricted waterways. Ship traffic is light, and sediment is predominantly silt, both within and outside of the ship channels.

From Fond du Lac to Spirit Lake (Oliver Bridge) river currents are strong enough to prevent deposition of silt or clay on the river bed, although measured velocities are lower than those in St. Louis Bay where the substrate is silty. The reason for this size distribution is that current speed in the river is much faster during spring runoff and large storms than is the seiche current in St. Louis Bay.

Wind-driven waves are responsible for well sorted sand along the shorelines of both Superior and St. Louis Bays. There may also be a difference in the mean grain size between shallow and deep areas outside of the ship channels, but the data are not detailed enough to confirm this assertion.

Current velocity and grain size distribution correlate with contaminated sediment zones, as determined by the U.S. Environmental Protection Agency (1975, 1976). Bulk sediment analysis of surface and short core samples taken from the ship channels of Superior Bay revealed areas that are polluted, moderately polluted, and unpolluted (Fig. 22). Criteria for drawing these boundaries were based on definitions assigned to the categories that take into account both nutrient and metallic parameters, because sampling and analytical methods vary from one location to the next.



US EPA CRITERIA FOR SEDIMENT CLASSIFICATION

	UNPOLLUTED	MODERATELY POLLUTED	HEAVILY POLLUTED
Volatile Solids	< 5%	5%-8%	>8%
COD	< 40,000	40,000-80,000	>80,000
TKN	< 1000	1000-2000	>2000
Oil and Grease (Hexane Solubles)	< 1000	1000-2000	>2000
Lead	< 40	40-60	>60
Zinc	< 90	90-200	>200
Mercury	< 1.0		>1.0
Ammonia	< 75	75-200	>200
Cyanide	< 0.10	0.10-0.25	>0.25
Phosphorous	< 420	420-650	>650
Iron	< 17,000	17,000-25,000	>25,000
Nickel	< 20	20-50	>50
Manganese	< 300	300-500	>500
Arsenic	< 3	3-8	>8
Cadmium	*	*	>6
Chromium	< 25	25-75	>75
Barium	< 20	20-60	>60
Copper	< 25	25-60	>60

*Lower limit not established
Measurements are in mg/kg dry weight unless otherwise specified.

Fig. 22. Pollution map of ship channels in Superior Bay near the entryways. (USEPA)

Very high energy areas with lag deposits, such as those in and very near the entryways are classified unpolluted. Channel margins receive fine sediment resuspended by ship propellers, and so they are moderately polluted or polluted.

CHAPTER IV

SPIT FORMATION AND SHORELINE CHANGES

Formation of the Spits

The two sets of peninsulas outlining the Duluth-Superior Harbor are barrier spits that are direct analogues to their marine counterparts. Barrier islands and spits on marine coasts are formed by (1) vertical growth or emergence of offshore bars (de Beaumont, 1845; Johnson, 1919; Cooke, 1968, 1971; Otvos, 1970a,b, 1981), (2) inundation or submergence of coastline ridges (McGee, 1890; Hoyt, 1967, 1968a,b, 1970) or (3) spit progradation by littoral drift or by self generation (Aubrey and Gains, 1982), with subsequent inlet incision (Gilbert, 1845; Fischer, 1968). No single method is exclusively acknowledged and multiple causality is favored by many textbooks, summarized by Schwartz (1972). Any of these models may be used to adequately explain the genesis of the spits at the head of Lake Superior.

Emergence can occur in two ways. Incoming waves agitate sediment from the shelf floor, which accumulates in the form of an offshore, submarine bar where waves break and wave energy is dissipated (Fig. 23a). If bars are generated while water in the lake is elevated, such as during a proglacial lake stage, then they will break the surface when the water recedes (Fig. 23a). There is evidence of a submarine bar 4 m high about 5 km east of Duluth, however, neither the circumstances of formation nor the orientation is known at this time (T.C. Johnson, 1982, pers. comm.).

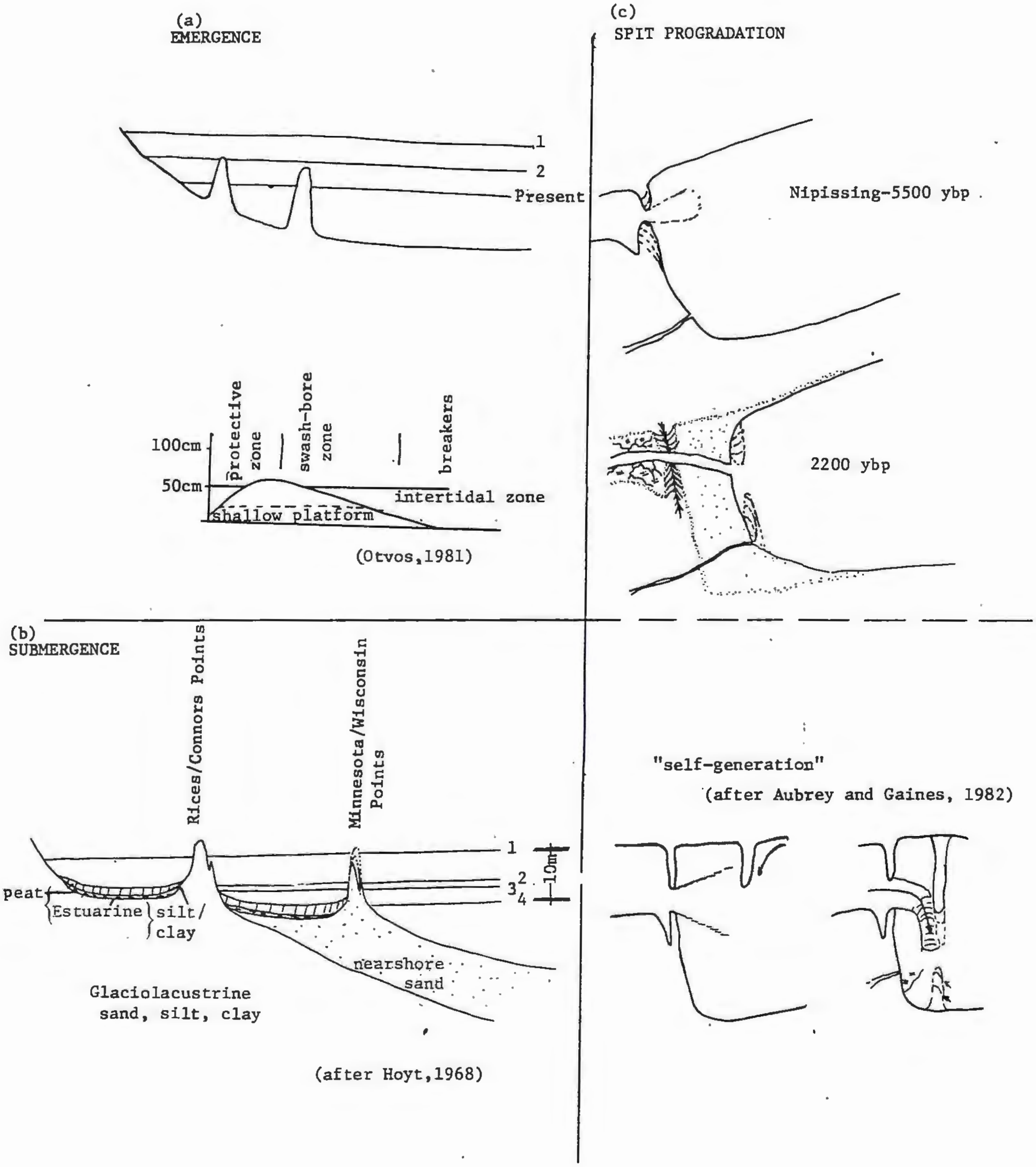


Figure 23. Formation of barrier islands and spits.

Emergence may also take place without a drastic change in water level (Otvos, 1981). First, a shallow platform must evolve, usually in the form of an ebb tidal delta (river delta in the lake) or by means of longshore current aggradation. Next, a subtidal shoal accretes onto the platform, its height determined by the hydrodynamic regime, the presence of a nearshore shallow bottom and the availability of a sufficient sand supply. Growth from subtidal to intertidal elevation requires the presence of a wave bore, which delivers sand to the "lee" side of the shoal, landward of and protected from the erosive breaker zone. Otvos (1982) observed this process during fair weather conditions, although others suggested that storm conditions and subsequent subsidence of high water were prerequisites to bar emergence (Cooke, 1968). Bar emergence in this manner requires a wave bore, unlikely to be found in lakes (Fig. 23a).

The second model for the origin of the two sets of spits incorporates the ridge-engulfment hypothesis. As lake level dropped after the Nippising stage, water stabilized at two different elevations. At each level, wind formed dunes, coupled with swash formed beach ridges, created topographic highs along the shoreline, 6-9 m high. When lake level rose, the areas behind both sets of ridges were flooded, the ridges being high enough that they remained subaerial. The inner dune and beach ridge formed Rice's and Connor's Points; the outer ridge became Minnesota and Wisconsin Points (Fig. 23b).

The third mechanism for barrier island formation is by means of spit progradation. Loy (1962, 1963) proposed that both sets of spits grew as lateral extensions of the south shore because sand is absent on the north shore. He speculated that when water level stabilized about 5000 ybp (by Farrand's chronology, 1962) at a level similar to that of today, growth of the inner spit commenced. When the spit reached the north shore, St. Louis Bay was sealed, to be re-opened during a later surge of the river. After the Nipissing stage, water level dropped to a new lower stillstand, and the inner points were abandoned. The outer spit was initiated from the south shore, grew to the north shore, and was re-opened at a weak point corresponding to a former channel of the Nemadji River. When lake level rose about 2000 ybp accretion rates were great enough to prevent the outer spits from drowning (Fig. 23c).

Spit progradation does not necessitate sealing in order for sediment from the south shore to reach the north shore. Inlet bypassing of sediment is a common albeit poorly understood process (Bruun, 1978). Another source of sand for the outer spit may have been the dry lake bed, exposed when water receded from the western shoreline, 8000 ybp. The nature and direction of modern currents in the western arm of the lake were modeled by Diehl _et al_. (1979), and may be useful in determining the direction from which sand was transported to the head of the lake (Fig. 24).

After it has formed initially, a spit may also prograde by means of "self generation" (Aubrey and Gaines, 1982). A low tidal range and small tidal prism are required for spit elongation in this manner. When a barrier island or spit overlaps with a headland, the ebb (or river) current is re-channeled, becoming sub-parallel to the mainland shoreline. As the bar grows, flow is further restricted, accelerating erosion in the new river channel. The scoured material accumulates in the

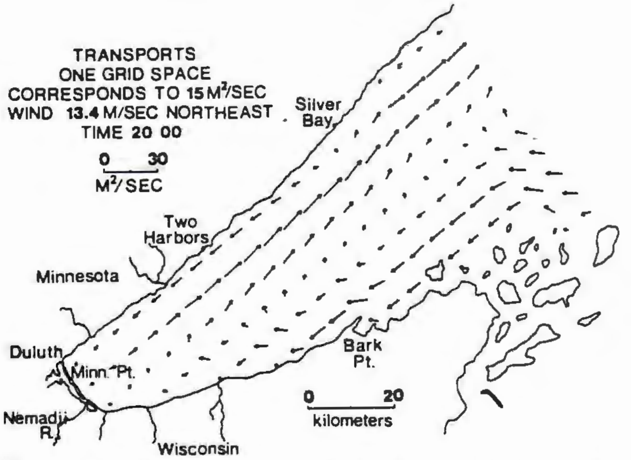


Fig. 1. Calculated transports in extreme western Lake Superior for northeast wind conditions at Duluth, Minnesota.

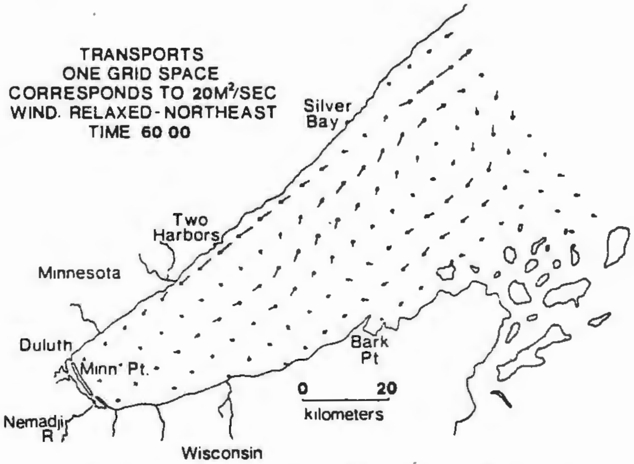


Fig. 3. Transport pattern after a northeasterly storm.

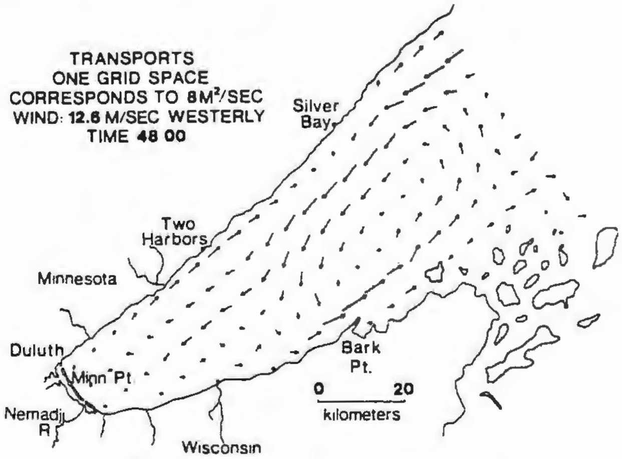


Fig. 5. Transports for a westerly wind.

Figure 24. Transports in western Lake Superior, from Diehl (1977).

form of a channel-margin linear bar along the barrier side of the inlet. Growth of the barrier ceases where the coastline changes, e.g. at the south shore or where the Nemadji River enters the lake. Littoral drift may also be contributed to the island, aiding barrier stabilization. This method cannot be used for the formation of the inner set of spits in Duluth-Superior Harbor, because there is no headland overlap there (Fig. 23c).

Alteration of barriers is primarily by means of sediment transfer in a net direction either toward or away from the mainland shore (Dillon, 1970; Hayden and Dolan, 1979). Seaward or lakeward migration requires an overabundance of sediment. Lakeward migration is promoted by an insufficient sediment supply. By constantly replacing sand from the seaward to the landward face through inlets and by overwash and eolian processes, the barrier "walks over itself," and ultimately becomes welded to the mainland. This process is active on most marine coastal barrier islands today and may have been important in Lake Superior as well. From historic events related by Minnesota Point residents, it seems that catastrophic inland migrational events did take place before the spit was widened:

> "In the winter of 1876, winds blew away a whole section of the dune. A part of the account of Mr. John A. Bardon describing this case of massive wind erosion is quoted below.
>
> > 'There was an Indian Cemetery on Minnesota Point, just west of the old lighthouse. It was situated on a rather higher portion of this sandy Point. The 60-mile Northeaster began to tear away the loose sand, and, of course blew it into the Bay and across to the Superior side, where it practically filled what was then a swamp lying between the present Daisy

> Flour Mill and the Nemadji River. It actually blew away the entire cemetery down to a depth of probably six feet or more, thus removing the five acres of surface'
>
> Minnesota Point was nearly breached in a storm just east of the present amusement park at the place referred to as the "barrens". Storm waves washed over this section of the point until, according to Mrs. Bachand, one could almost canoe across it. This section of the point has since been protected by an artificial ridge of quarried rocks." (from Loy, 1962).

It would be difficult to trace the distance or rate that Minnesota and Wisconsin Points have migrated since they were established, because they were not charted before 1825, and that chart contained little detail. It was very soon after the earliest navigational map was drafted in 1861 that the points underwent deforestation and development. Deforestation, the initial disruption, may have accelerated inland sediment transfer temporarily. Overwash and eolian sediment transfer processes are counteracted by sand replacement to the beach front from which it blew, and by revegetation projects which have been carried out in an effort to stabilize the sand dunes (Lydecker, 1980). Dredging reduces the amount of bottom sediment that enters through the inlets and overland. Littoral drift replenishes the store of sediment that has been displaced inland; this effect is diminished. The spits would have become narrower, but dredge disposal in the nearshore zone of the lake has widened them (see Historic Shoreline Changes).

The other major process that modifies barrier islands is the opening of new inlets. Inlets may be opened from either the open marine (lake) or mainland side of the barrier, by means of a tidal storm or river flood surge, respectively, over topographically lower areas of the barrier. When cut from the seaward (lakeward) side, narrow barriers are more susceptible to breaching than are wider barriers backed by extensive tidal flats; when the surge is caused by river flooding, the wider barriers are more likely to be effected as overflow is channeled down streams in the flats and through the barrier (Pierce, 1970). Again, historical accounts indicate that Minnesota Point may have been subject to breaching from the open lake.

Historic Shoreline Changes

Industrial development within the last century has changed the physiography of virtually the entire harbor. Natural changes have been occurring synchronously. The ensuing series of maps illustrate shoreline changes from 1861-1977 (Fig. 25).

In 1861 the harbor was lined with trees on almost all shores (Plate II, Fig. 25a). Wetland vegetation was extensive in Allouez Bay, at the mouth of the Nemadji River, on the Superior Bay sides of Minnesota and Rice Points, in Howards Bay, on Grassy Point, in Spirit Lake, and along the banks of the St. Louis River. Superior was the only major settlement, and a few structures were clustered on the Minnesota shore of St. Louis Bay and in the vicinity of what is now Fond du Lac. The only inlet was opposite the city of Superior. The tip of Wisconsin Point recurved into Superior Bay.

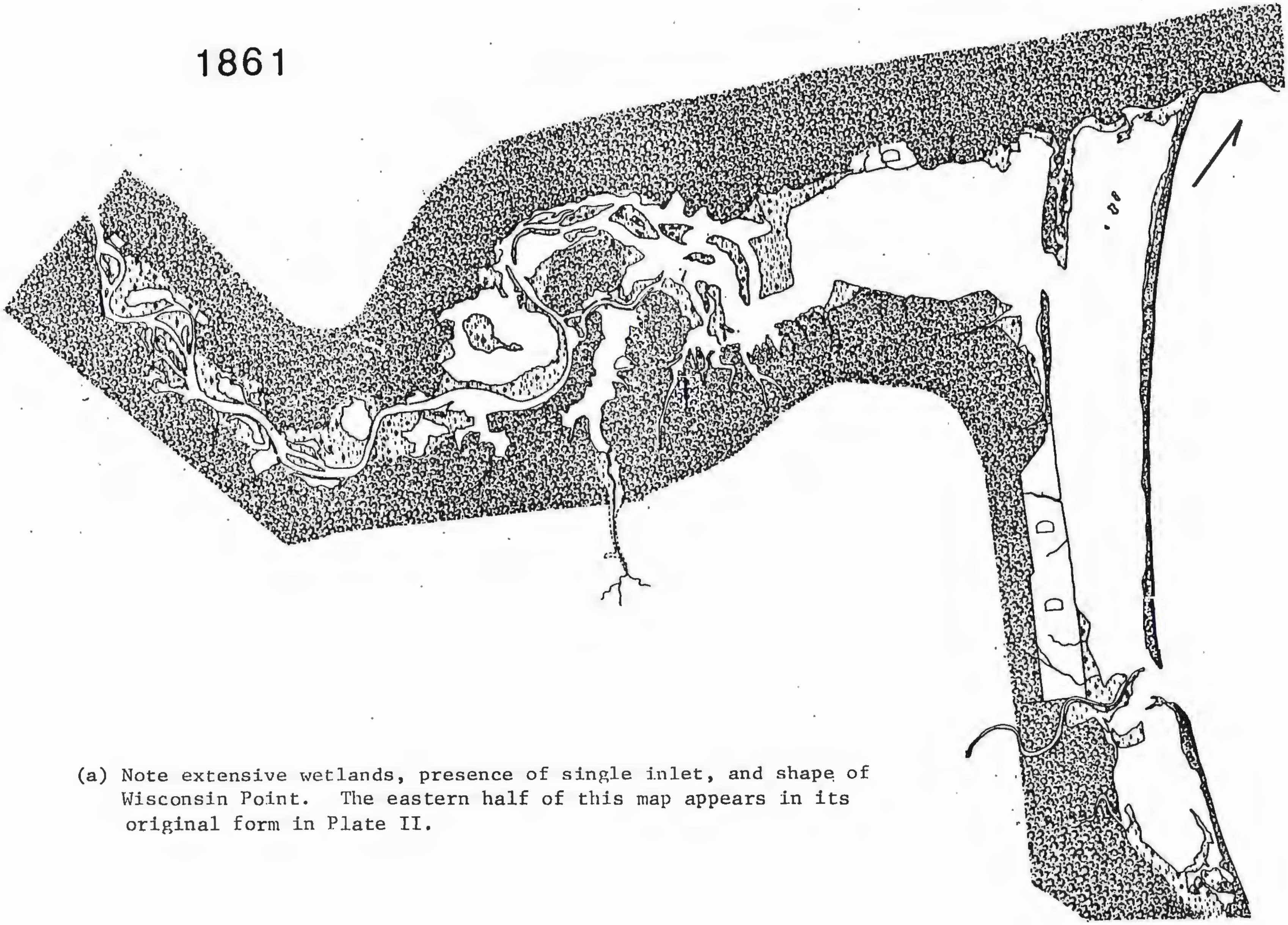
Breakwaters, 600 m long, were constructed at the Superior Entry in 1869 to a depth of 12 m (Fig. 25b). Subsequently, facilities were erected at Superior to accommodate shipping business. Two years later the Duluth Ship Canal was excavated, originally 2.5 m deep and 15 m wide

Figure 25. Historic shoreline changes.

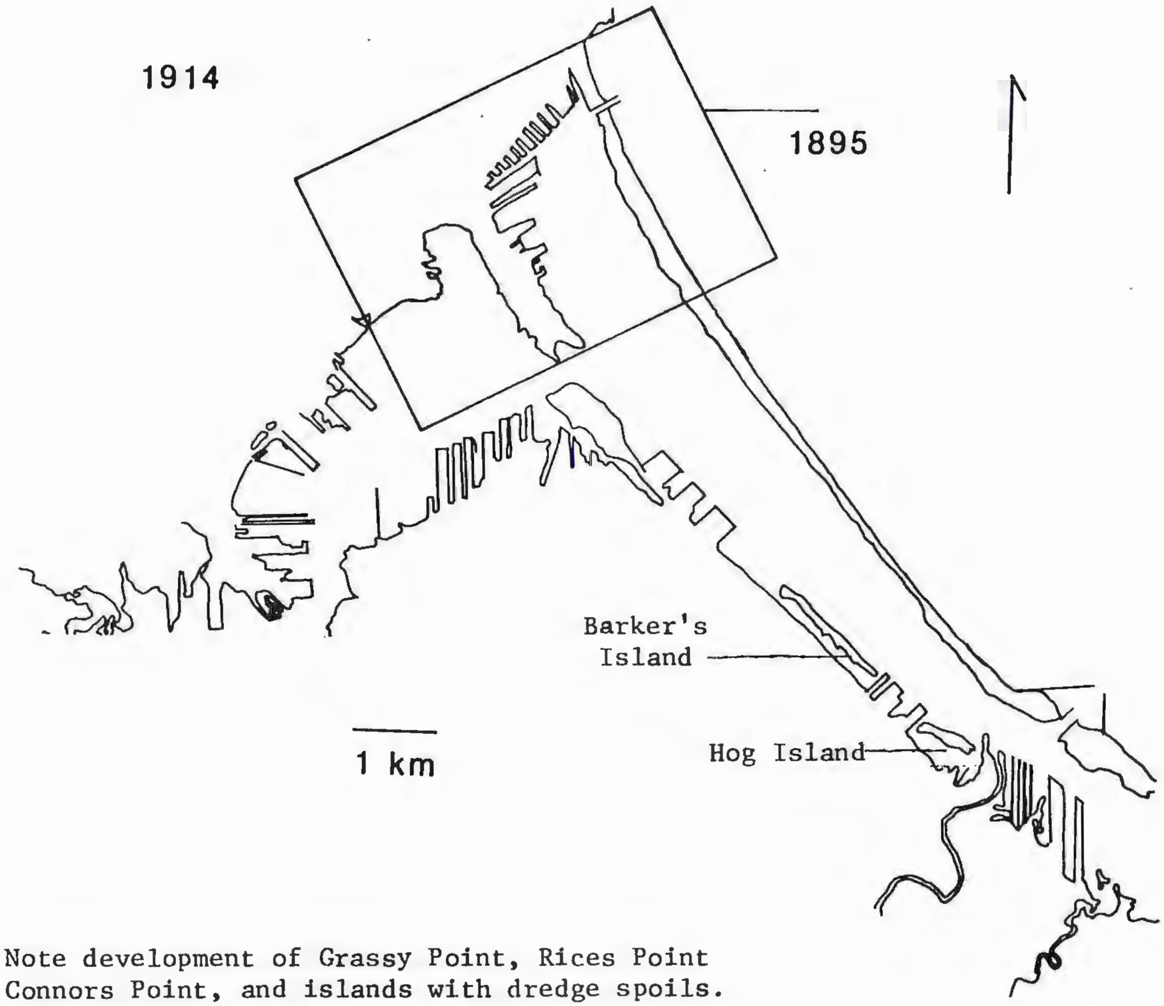
KEY

▨ tree cover
⌂ residential
▦ industrial
▩ wetland
▭
░ dunes/ grasses
■ beach sand

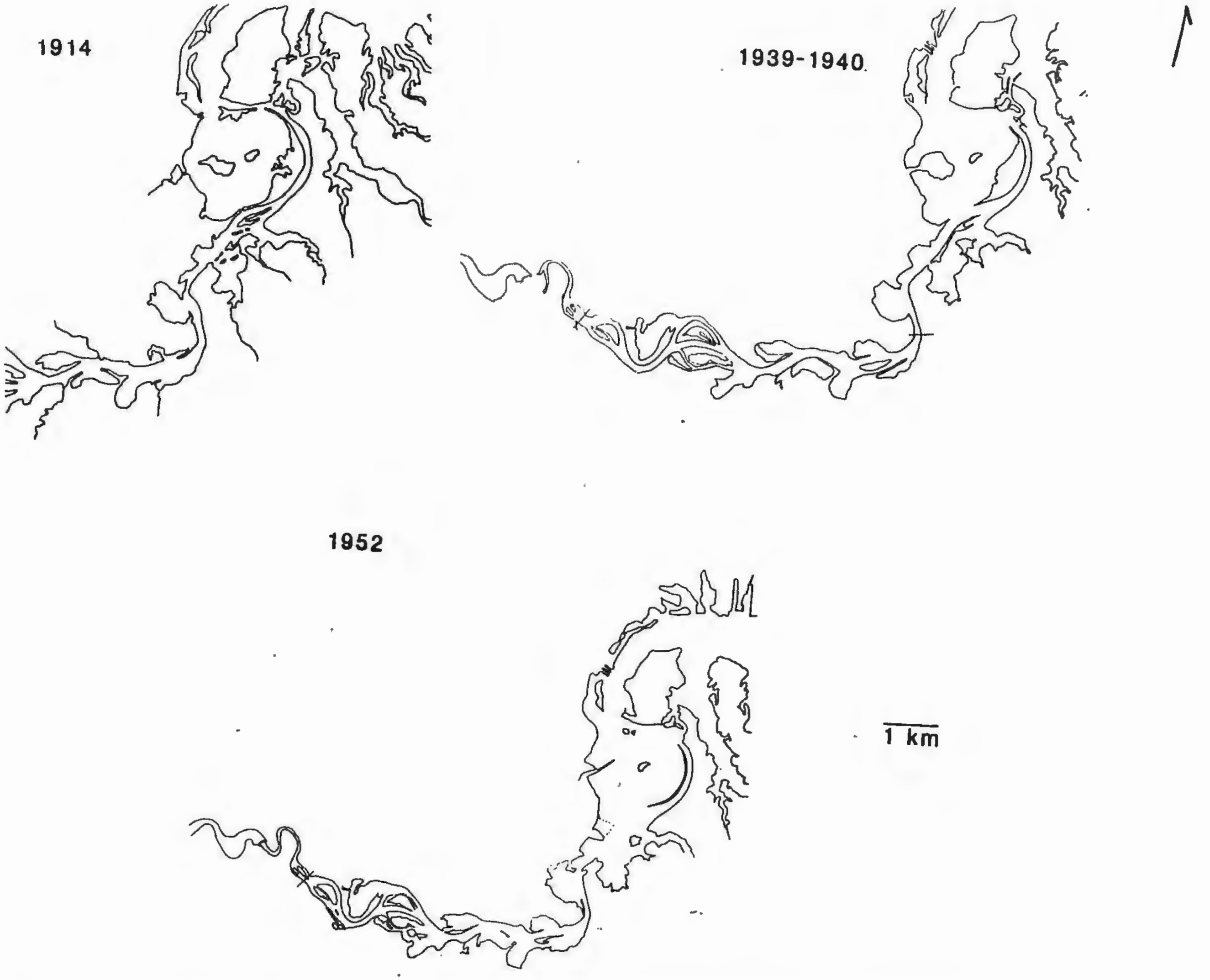
1861



(a) Note extensive wetlands, presence of single inlet, and shape of Wisconsin Point. The eastern half of this map appears in its original form in Plate II.



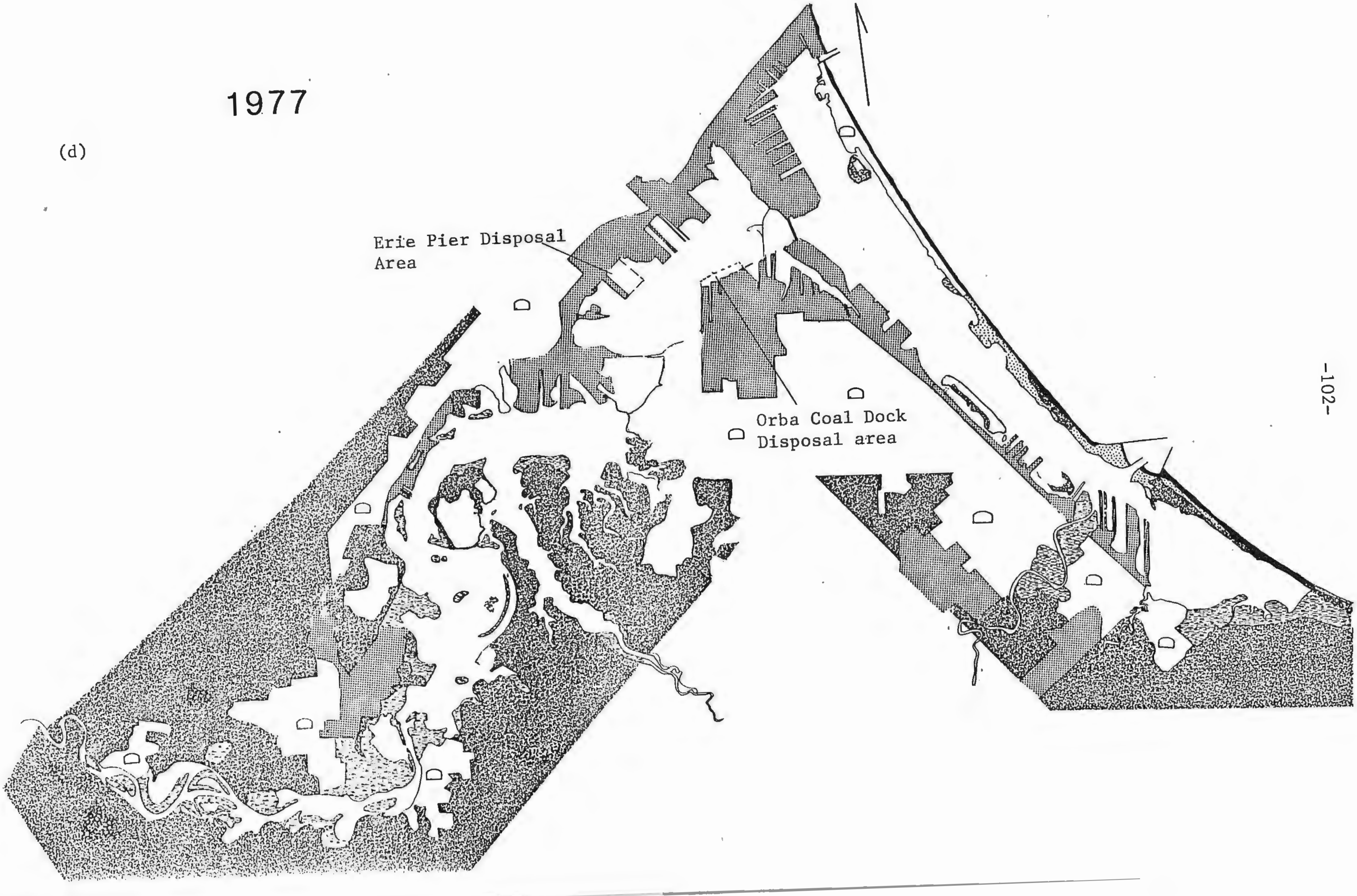
(b) Note development of Grassy Point, Rices Point Connors Point, and islands with dredge spoils.



(c) Spirit Lake and lower St. Louis River, illustrating water inundation.

1977

(d)



(Loy, 1962). Numerous wharves were built at the base of Duluth in response to the new access at the northern end of the bay.

Waterways were dredged between 1873 and 1939 (Loy, 1962) About one-half of the dredged material was used as fill on marshy shorelines in order to make them stable enough to support additional docks. The other half of the dredge spoils were dumped lakeward of Minnesota Point and caused the spit to widen by up to 60 m in some places.

Dredged spoils were also used to build small islands in the harbor. The earliest of these islands (later called Hog Island) appears on the 1914 chart immediately north of the Nemadji River (Fig. 25b). By 1939 Hearding and Barkers Islands were established and Hog Island was enlarged (Fig. 25c).

Flooding, as well as dredging and dredge disposal, have been responsible for wetland disappearance over the past 120 years. Water in the southwest part of Lake Superior is becoming deeper at a rate of 23 cm/century due to isostatic rebound which is greater at the northeast part of the lake basin than near Duluth (Kite, 1972). Low elevation marshy areas are affected most severely.

The most distinct example of water inundation is in Spirit Lake. Spirit Island was actually the limb of a larger island, but the two are now disconnected. The foot of Kilchis Meadow (name taken from an 1825 map) was attached subaerially to the Minnesota shoreline. Several other smaller lakes along the St. Louis River banks were enclosed within marshes in 1861, but today they appear open to the river. This observation extends only as far upriver as 1-2 km below Fond du Lac (Fig. 25c).

Shoaling has also altered the bathymetry of the harbor. In 1861, the deepest section of the river channel averaged 4.5 to 9 m, and 2.5 to 3.3 m were typical depths in the remainder of the bays. Today, isolated depressions, 4 to 5 m deep, coincide with the deepest part of the river, and areas outside of the dredged channels average 0.3 to 1 m shallower than they did a century ago.

Shoaling in the harbor is not an accurate measure of natural sedimentation rate. A portion of shoaling results from resettling of sediment that was resuspended from the channel floor by ships, and also from dredge disposal on the shoreline flats. Disposal sites in the harbor include the diked-in Erie Pier, an on-land site at the Orba Coal Dock, an area near the 21st Avenue West channel, Nettleton slip, and the Lakeshead Materials Storage Facility (Fig. 25d).

Another facet of shoreline development in the harbor involves bridge construction. Three railroad bridges spanned the harbor by 1914, and a network of tracks extended around Duluth and Superior. The original Interstate Bridge, stretching between Rices and Connors Points, and the Arrowhead Bridge, between Grassy Point and Superior, was built in the 1920's. The Blatnik Bridge replaced the first Interstate Bridge in the early 1960's. The new Arrowhead Bridge is under construction today to reduce traffic on the old Arrowhead Bridge.

CONCLUSIONS

The ultimate purpose of studying sediment characteristics, sedimentation processes, and changes with time is to determine where sediments are accumulating in the Duluth-Superior Harbor. This knowledge will supplement the sparse data on sediment pollutants, assist the search for other contaminated areas and help to assess the anthropogenic impact on the area.

Grain size, organic carbon, heavy mineral and clay mineral analyses reflect the energy distribution of the estuary. Seiche and river currents and the manner in which they are affected by basin morphology, jet streams produced by ship propellers, and (to a lesser extent) wind generated waves, all have distinct effects on sediment characteristics. The lower St. Louis River estuary can be divided into two sedimentary environments: erosional and depositional (Fig. 26).

The erosional facies is a high energy environment. Lag deposits result from strong river currents (e.g., in the river bed), from seiche currents where they are accelerated in constrictions (e.g., entryways, inlet between the inner spits), and from excessive velocities generated by ship propellers (e.g., Duluth Harbor Basins and southernmost Superior Harbor Basin). Organic carbon concentration is extremely low in these areas of very coarse grained sediment. Lithic fragments constitute a relatively large portion of the sand, and illite is relatively abundant in the clay fraction.

Most of the estuary is a depositional environment. The lower St. Louis River including the Duluth-Superior Harbor is primarily a sink for

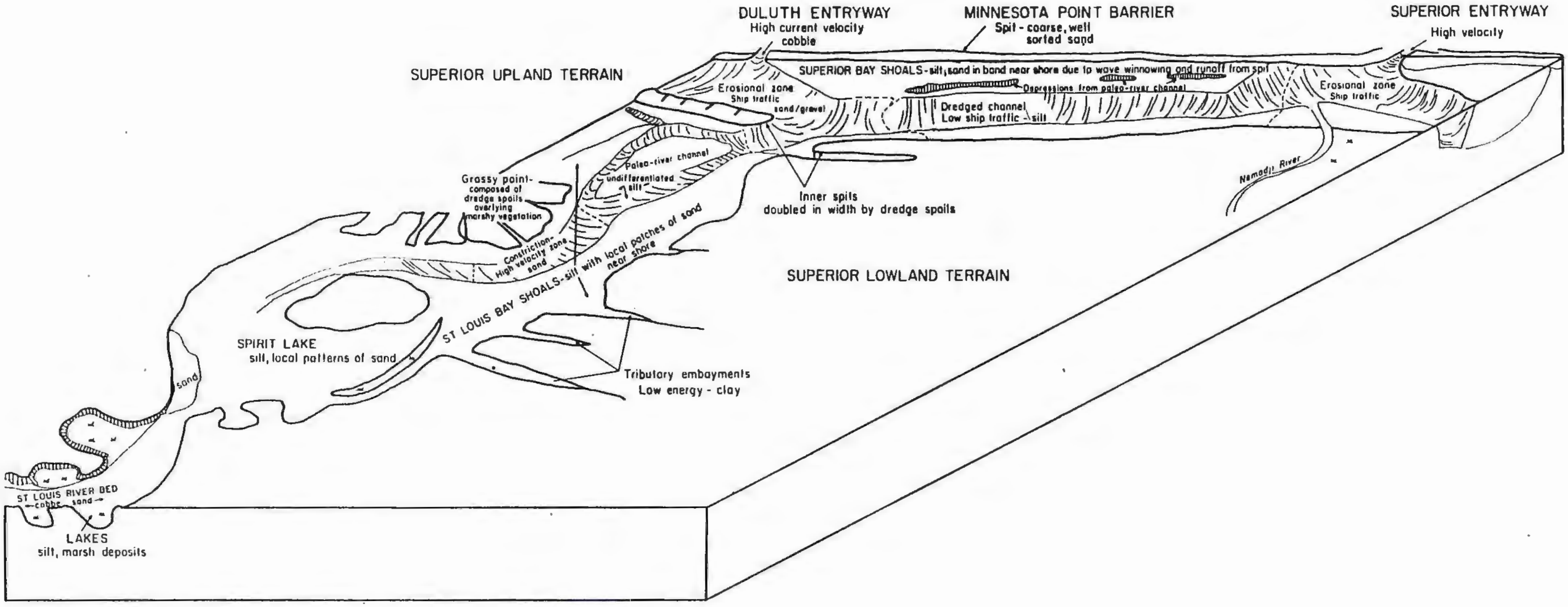


Figure 26. Sedimentary environments in the Duluth-Superior Harbor.

sediment brought to it by the Nemadji and St. Louis Rivers and by aeolian processes. Silt is the dominant sediment in the study area. Sand is often found on the nearshore estuary floor, a result of winnowing of fine sediment by wind generated waves. In St. Louis Bay these sands are poorly sorted and fine-grained and contain a much greater percentage of silt and clay size particles than do the sands in Superior Bay. Clay fills some of the embayments along St. Louis Bay and depressions outside of the ship channels. Organic carbon content increases with decreasing grain size. Relative concentrations of kaolinite and chlorite increase in silt- and clay-sized sediments.

The major conclusions of this study are relevant to data on sediment chemistry obtained by the U.S. Environmental Protection Agency (1975, 1976). Unpolluted sediments correspond to the erosional areas, whereas polluted sediments occupy depositional zones in Superior Bay.

Holocene history was traced from the time of deglaciation of Lake Superior through today by means of stratigraphic sections, aerial photographs and historic charts. Duluth-Superior Harbor evolved after a series of proglacial lakes disappeared from the Lake Superior basin after the Late Wisconsin glacial maximum. The modern shape of the estuary resulted from a low lake level, when the St. Louis River carved a gorge several meters deep through glacial lacustrine sediment. The continual rise of water in the southwestern limb of the lake caused by isostatic rebound is evident on maps from the past century.

Use of the harbor for large scale commercial shipping began about 120 years ago. Excavation of a second inlet, construction of docks around the shorelines, extensive dredging of the ship channels, filling in of wetlands and deforestation are some of the products of human development. All of the above activities have affected sedimentation in the Duluth-Superior Harbor.

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APPENDIX I

INSTRUCTIONS FOR ORGANIC CARBON MEASUREMENT ON TOTAL CARBON ANALYZER

Oceanography International Model 0524B

I. Preparation (At least 4 replicates of each sediment, standard and blank ampule should be made because ampules break easily.)

A. Sediment Samples:

1. Dry approximately 1 g of sediment in oven at 100°C for about 3-4 hours.
2. Grind sample with mortar and pestal to a fine powder and return to oven for about 1 hour.
3. Weigh sediment. The amount of sediment used for analysis should contain about 60 μg of carbon. Example: If it is estimated from loss on ignition or educated guess that a sample contains roughly 3 percent carbon, then the suggested sediment size is

   $$60\ \mu g/.03 = 2000\ \mu g, \text{ or } 2.0\text{ mg of sample}$$

   However, because of weighing error, measurement made on less than 2.5 mg may be inaccurate.
4. Weigh 10 ml ampules. Caution must be taken not to contaminate the ampule with moisture from hands.
5. Carefully add sediment to ampule.
6. Add 5 ml distilled water.

B. Standards:

Standards of known organic carbon concentrations are prepared with potassium acid phthalate ($KHP=KHC_8H_4O_4$). Glucose and several other organic compounds may also be used.

KHP molecular weight: 204.22

Atomic mass carbon: 12

96 g carbon/204.22 g KHP = 1 g carbon/2.1273 g KHP

1. Dissolve 2.1273 g KHP in 1000 ml distilled water to obtain a solution of 1000 mg carbon/liter.
2. Dilute this solution to varying concentrations. Take into account the approximate range of TOC in the sediment under investigation and prepare standard solutions to bracket by a wide margin the range of concentrations in the sediment.
3. Pipette 5 ml standard solution into ampule.
4. Go to Step D.

C. Blanks

1. Pipette 5 ml distilled water into ampule.
2. Go to Step D.

D. From this point on, standards, blanks, and sediments are treated in a similar manner.

1. Add 1 ml of 6% (V/V) phosphoric acid.
2. Add 1 ml distilled water to wash neck of ampule.
3. Allow samples to sit for 1/2 hour. (During this time, the purging/sealing module should be turned on to warm up.)
4. Add approximately 0.2 g potassium persulfate ($K_2S_2O_8$) oxidizing agent.
5. Rinse neck again with 2 ml distilled water.
6. Total liquid in each ampule should be 9 ml.

(Sealing and analyzing are just briefly summarized here because specific mechanics of turning on and off instruments will vary with different units and are usually explained in their corresponding instruction manuals.)

II. Sealing

A. Ampules are purged with O_2 until the oxidizing agent is completely used up, driving off the inorganic CO_2. Takes about 6 minutes.

B. Ampules are sealed in a flame.

C. Ampules are heated in oven at 100°C for 12 hours.

III. Analysis

A. Top of the sealed ampule is broken off in a vacuum.

B. As N_2 is used to force CO_2 from the ampule into the analyzer, a number of "counts" are recorded on the Horiba PIR 2000 Readout Unit.

C. The "count" values of the blanks are averaged and then subtracted from standard and sediment values. Blanks are considered to be noise from background TOC that is inadvertently added to the sediment and standards.

D. A curve of standard concentrations (either in mg carbon per liter or µg per ampule) vs. standard "count" values is plotted. By comparing a sediment sample's "counts" to the number of "counts" yielded by the standards, this curve is used to determine the amount of carbon contained in sediment ampules. The absolute amount is then converted to a percentage by comparison with the original weight of sediment enclosed in the ampule.

Suggestion: An analysing session may take several hours during which time the instrument may drift, i.e., yield two different readings for an identical amount of TOC, depending on whether the subsample was run at the beginning or end of the session. For the most accurate results, groups of ampules should be split up to be run at different times during the analyzing session. A group comprises all ampules containing either a single sediment sample, a single known concentration of carbon, or blanks.

APPENDIX II

Cross Section	Location	Obtained from/title of report if known
A-A'	Superior Entryway	U.S. Army Corps of Engineers (U.S.A.C.E.) Duluth, Minnesota
B-B'	Superior Entryway	U.S.A.C.E.
C-C'	Superior Bay	U.S.A.C.E.
D-D'	Superior Bay	U.S.A.C.E.
E-E'	Rice's Point	Braun Engineering Testing, Hibbing, MN
F-F'	Rice's and Connor's Points, Site of Interstate Bridge	Howard, Needles, Tammen and Bergendorff Consulting Engineers, 1957, Duluth- Superior Interstate Bridge Project IN390-3(1), Subsurface Exploration Report
G-G'	St. Louis Bay, behind Rice's Point	U.S.A.C.E.
H-H'	Howards Bay, behind Connor's Point	U.S.A.C.E.
I-I'	St. Louis Bay, Arrowhead Bridge Site	Wisconsin Department of Transportation, 1978, Arrowhead Bridge subsurface investigation report, U.S. Highway 2 over St. Louis Bridge, Project I.D. 8680-01-02 Structure B-16-38, Superior, Wisconsin-Duluth, Minnesota
J-J'	St. Louis Bay	U.S.A.C.E.
K-K'	U.S. Steel Works, Adjacent St. Louis River	Barr Engineering Company, 1981, Soil and Ground Water Investigation U.S. Steel Corporation's Duluth Works, Minneapolis, Minnesota Report obtained from Minnesota Pollution Agency, Division of Solid Waste, St. Paul, Minnesota

APPENDIX III

List of Aerial Photos and Historic Charts

YEAR	TITLE	SCALE	AGENCY/AUTHOR	OBTAINED FROM	USED IN THIS STUDY
1825					
1861	St. Louis River from the mouth in Superior Bay to the head of St. Louis Bay	1:16000	Meade, Hearding Graham, Casgrain	Duluth Historical Society	X
1861	St. Louis River from the head of St. Louis Bay to Fond du Lac Village	1:16000	Meade, Hearding Graham, Casgrain	Duluth Historical Society	X
1895	Duluth, Minnesota	1:62500	USGS	Univ. Minn. map library	X
1902	Map of soundings in the St. Louis River from Grassy Point to the upper end of Spirit Lake	1:62000		Duluth Historical Society	
1914	Plot of St. Louis River at proposed bridge site - Twp. 48N Rg. 15W	1:72000		Duluth Historical Society	
1871	Track survey of the River St. Louis	1:49300	Collins Bayfield	Duluth Historical Society	
1917	Superior, Wisconsin-Minnesota	1:62500	USGS	Univ. Minn. map library	X
1930	Duluth-Superior "Twin Ports"	1:26000	Compiled by McGill & Warner Company	Univ. Minn. map library	
1939-1940	Aerial photos		ASCS (?)	Univ. Minn. map library	X
1952	Aerial photos		ASCS (?)	USGS-Natioal Cartographic Information Service - Rawings, MO	
1977	Aerial photos		Mark Hurd aerial surveys		X

The Duluth Historical Society owns a few additonal but less revealing maps which are not mentioned here.