Beach Profile Modification and Sediment Transport by Ice: An Overlooked Process on Lake Michigan

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ABSTRACT

In the winters of 1989 and 1990 field studies of ice zonation, ice sediment content, coastal profile adjustments, sediment entrainment by ice, and ice rafting were carried out along the coast of southern Lake Michigan, quantifying the effect of lake ice on coastal processes and sediment transport. Coastal lake ice includes a belt of mobile brash and slush ice and a stable nearshore-ice complex (NIC). The NIC consists of an icefoot and a sequence of ice ridges founded on offshore bars with intervening ice lagoons. This complex can be developed and partly, or completely, destroyed several times during a single winter. Multiple winter coastal profiles illustrate both erosion and deposition consistent with displacement of wave energy from the shoreface to the ice-ridge face. Sediment concentrations indicate that the NIC and the belt of brash and slush contains 180 to 280 t (113 to 175 m$^3$) of sand per kilometer of coast. This static sediment load is roughly equivalent to the average amount of sand eroded from the bluffs and to the amount accumulating in the deep lake basin each year. Sediment is being rafted alongshore in the mobile brash and slush at rates of 10 to 30 cm/sec. Applying conservative estimates of sediment loads to the drifting ice suggests that 0.35 to 2.75 x 10$^3$ t/day could be transported alongshore and around obstacles such as groins. The processes associated with the development, maintenance and destruction of the NIC do not protect the coast. Rather, shoreface erosion is enhanced as severe winter wave energy is displaced from the beach to the shoreface and coastal ice entrains and transports sediment alongshore and offshore.

ADDITIONAL INDEX WORDS: Coastal erosion, coastal processes, ice rafting, coastal ice, lake ice, beach protection.

INTRODUCTION

As part of an effort to understand erosion processes affecting the coast of southern Lake Michigan (BARNES, 1990), this study assesses the role of lake ice as an agent of sediment transport and coastal modification. Many previous Great Lake coastal studies focused on the nearshore ice regime and its qualitative influence on the lakebed and shoreline; however, quantitative studies are lacking.

Sea ice is known to affect the bottom topography of high-latitude coastal-marine environments (BARNES et al., 1988; KOVACS and SODHI, 1980; McCANN and CARLISLE, 1972; HEQUETTE and BARNES, 1990) and the shoreline of subarctic regions (DIONNE, 1979). In the Great Lakes, most of the recent literature on coastal ice is focused on its role in beach protection (O'HARA and AYERS, 1972; MARSH et al., 1973, 1976; DAVIS, 1973; SEIBEL et al., 1976; EVENSON and COHN, 1979), its role in erosion (BAJORUNAS and DUANE, 1967; MINER and POWELL, 1991), and on ice morphology as it relates to lakebed morphology (DAVIS, 1973; SEIBEL, 1986). Several studies describe the nearshore ice regime, its development, and eventual decay (KIVISILD, 1970; EVENSON and COHN, 1979). This report discusses ice zonation, coastal profiles in the presence of ice, and sediment content in the coastal ice of southern Lake Michigan (Figure 1) based on detailed field and laboratory data contained in MCCORMICK et al. (1990). Using these data we describe and quantify the ice processes that influence winter coastal processes and speculate on the potential for coastal erosion from ice related processes.

Setting

The surficial coastal deposits of southern Lake Michigan are underlain by eroding Holocene and Pleistocene glacial units that crop out in coastal bluffs and on the lakebed (LINEBACK et al., 1979;
The underlying glacial unit, the Wadsworth Till, is composed primarily of silty clay with an average sand content of 7% (Lineback et al., 1979). These glacial units are the major source of beach sediments.

The beaches and nearshore deposits are composed of sand with small admixtures of gravel, forming linear deposits a few meters thick, and a few hundred meters wide (Shabica et al., 1989; Wood et al., 1988). These deposits are perched atop glacial units which are exposed at the lakebed in water depths of 5 to 10 m off the coast of Illinois and Indiana (Foster and Colman, 1990).
Figure 2. Southern Lake Michigan climatology: (a) average monthly water surface temperatures adjusted from ship observations, (b) ice conditions, (c) winter wind regime, (d) seasonal distribution of wind, and (e) monthly wave heights and directions from ship observations and weather buoys. Modified after Saulesleia (1986).
The beaches are bordered by varied nearshore slopes that normally feature one or more bars at depths to 5 ft (WOOD and WEISHAR, 1984).

The Lake Michigan ice cover develops from north to south (RANDY, 1971; ASSEL et al., 1983; BOLSenga, 1988), and from the more rapidly cooling shallow edges (SAULESLEJA, 1986) to deeper parts of the lake (Figure 2a and b). Coastal ice usually begins to form in December and persists until March. However, the central part of the lake is generally ice free throughout the winter (Figure 2b).

The peak intensities of wind and wave energies coincides with the period of ice cover, thereby providing abundant energy for coastal sedimentary processes influenced by ice. Prevailing northerly and westerly winter winds (Figure 2c and d) normally have velocities of 22 to 35 m/sec at the southern end of the lake (SAULESLEJA, 1986; WOOD et al., 1988). During summer, waves caused by prevailing southerly winds average less than 1 m in height (Figure 2c and e); during late fall and winter, waves are commonly from 1 to 2 m in height; whereas storm waves reach heights of more than 3 m (Figure 2e; WOOD and WEISHAR, 1984).

The prevailing westerlies (Figure 2c and d) cause the strongest surface currents to develop along the eastern shore (AYERS et al., 1958; ALLENDER, 1977). Because the southern part of the lake has its greatest fetch to winds and waves from the northern quadrants, net southerly littoral transport prevails along both the western and eastern coasts of the lake (Hough, 1935; Chrzastowski, 1990).

**Ice Terminology**

We use the ice terminology from KIVISILD (1970) and Seibel (1986), paralleling usage for coastal ice in the arctic-marine environment (Rex, 1964; Dionne and Laverdiere, 1972; McCann and Carlisle, 1972). We follow the common arctic usage of "icefoot" from Wright and Priestley (1922), the subarctic usage of Dionne (1973), and the introductory usage on the Great Lakes of Zumberge and Wilson (1953) for the linear ridge of ice formed on the beach at the shoreline. We use the phrase, nearshore-ice complex (NIC), introduced by Seibel et al. (1976), to identify the unique association of fast-ice features observed along the coast in southern Lake Michigan.
rafting is the term used to define drifting ice of any size or shape carrying sediment.

Nearshore-Ice Complex (NIC)

The typical NIC we observed is similar to that reported by Seibel (1986) and corroborates the earlier observations of Zumberge and Wilson (1953), Bryan and Marcus (1972), O'Hara and Ayers (1972), Evenson and Cohn (1979), and Marsh et al. (1973, 1976). This complex consists of fast-ice segments, including an icefoot and a lakeward sequence of ice ridges with intervening shore-parallel ice lagoons (Figures 3 and 4). At the shoreline, where the subaerial beach is initially exposed to wave swash at freezing temperatures, an icefoot is built of sediment and ice to a height of 0.5 m or more (Figure 5). The icefoot usually extends several meters onshore from the water's edge and is stratified with beach sediment. Immediately lakeward of the icefoot are one or more grounded ice ridges which are usually separated by ice-filled lagoons (Figures 3 and 4). The surface of the ice lagoons can be smooth or rough with relief from 10 to 30 cm (Figure 6) depending on the size of ice blocks crowded into the lagoon during formation. The water depths in the nearshore lagoons are less than a meter, and ice commonly extends nearly to the lakebed (Marsh et al., 1973).

Ice ridges are grounded, shore-parallel features, that are commonly composed of adjoining ice volcanos (Figure 4; Seibel et al., 1976; Fahnestock et al., 1973; Dozier et al., 1976) with steep, or even overhung, lakeward slopes and more gentle shoreward slopes (Figures 3, 4, and 6). Ridges are typically composed of millimeter-sized ice granules more or less frozen together (Bryan and Marcus, 1972). The submerged parts of these ridges are less indurated than the subaerial parts, except for isolated, enclosed ice blocks (O'Hara and Ayers, 1972; Bryan and Marcus, 1972). The ridges usually are about a meter high, but we observed heights of 5 to 7 m in some instances. O'Hara and Ayers (1972) report heights of 8 m.
A mobile zone of broken solid ice (brash) and masses of uncongealed ice crystals (slush) is commonly found at the shoreline or adjacent to the NIC. This belt thins lakeward (Figures 3 and 7); but inshore is thick enough to be in contact with the lakebed even at depths of a meter or more (Marsh et al., 1973). The width of the brash and slush belt commonly varies by a factor of two as the mobile zone moves alongshore. The outer edge of the belt may have a sinusoidal form with a wave length of 30 to 50 m (Figure 5).

**NIC Effects on Coastal Profiles and Sediment Entrainment and Transport**

To assess the erosional role of coastal ice, Bajorunas and Duane (1967) used repetitive surveys to find that erosion occurred lakeward of NIC ridges in water depths as much as 6 m. They attribute the erosion to the wave energy expended lakeward of the beach against grounded ice ridges. Although acknowledging that wave energy was displaced by the NIC, neither Marsh et al. (1973) nor Evenson and Cohn (1979) report significant erosion associated with the lakeward edge of the NIC.

Sediment-laden ice can originate as brash eroded from updrift NIC’s (Figure 5), as anchor ice, or ice balls which form in the swash and incorporate sediment during growth (Case, 1906; Bryan and Marcus, 1972; Marsh et al., 1973). Marsh and his co-workers (1973, 1976) noted qualitatively that the sediment content of the NIC decreased offshore, and was higher in the upper parts of ice ridges and lowest in the ice lagoons. Bryan and Marcus (1972) describe a complex, almost random, distribution of sediment within ice ridges. Evenson and Cohn (1979) obtained sediment concentrations of about 5 g/l (3 cm$^3$/l) from “relatively clean ice”. However, Fahnestock et al. (1973) report boulders as much as 20 kg. Recently, Miner and Powell (1991) estimate the amount of sediment incorporated by coastal ice by summing the sediment content of repetitively formed NIC’s along a shore-normal profile at Gillson Beach (Figure 1) through an entire winter season. They conclude that the cumulative ice mass at

Figure 5. Icefoot in and on frozen sediment near Dead River, Illinois (Figure 1): note fully developed icefoot with zones of floating brash-and-slush ice drifting in the surf zone.
Coastal Erosion by Ice

Figure 6. Inshore part of an NIC at Kohler-Andrae State Park, Wisconsin (Figure 1) showing the icefoot in the foreground, and an ice lagoon inshore of an ice ridge 1.5 to 2 m high.

this locale was 548 m$^3$/m of coast, which contained $5.9 \times 10^6$ g of sediment.

The final demise of the NIC in spring is well documented (O’HARA and AVERS, 1972; MARSH et al., 1973; DAVIS, 1973; EVENSON and COHN, 1979). The NIC is destroyed physically and/or by in situ melting, depending on temperature and wave conditions. In their study of the NIC in Lake Superior, MARSH et al. (1973) report a sequence of NIC decay reverse to its growth in which massive grounded offshore ridges were last to disappear. In southern Lake Michigan storm induced lake-level fluctuations and increased wave energies (Figure 2e) result in offshore and longshore ice drift and sediment rafting (O’HARA and AVERS, 1972; EVENSON and COHN, 1979). MINER (1989) estimated that over 90% of the NIC formed during winter was destroyed by waves and rafted from his study area in northern Illinois.

METHODS

Details of the methods used to study the NIC along with the data from coastal profiles, ice, and sediment samples, are given in MCCORMICK et al. (1990). Beach and ice profiles were surveyed during the winters of 1989 and 1990 at locations along the western and southern shores of Lake Michigan (Figure 1). At many locations, profiles overlie previously established transects (e.g. WOOD et al., 1988). An integrated, electronic distance-measuring transit aimed at a hand-held prism atop a survey rod provided accuracies of better than 0.10 m for horizontal and vertical distances. Profiles were referenced vertically to lake level at the time of the survey and, wherever possible, to bench marks. Bathymetric data, collected using a fathometer, was tied to the rod and transit surveys nearshore.

Ice samples were collected to determine sediment content, ice density, and sediment grain-size distribution. Samples of the NIC were obtained by combining the cuttings from several 15-cm ice auger holes, from drilled ice cores and, where the NIC was soft, from ice cores obtained by pushing an 8-cm plastic core tube into the ice. Samples of the unconsolidated brash and slush
were obtained with the plastic core tube or with a 20-cm diameter dip net. Beach and lakebed samples were obtained from the upper 2 cm of the sediment.

In addition, field observations included wading and diving observations, and television observations using a tethered remotely operated vehicle (ROV).

RESULTS

The NIC was similar at all our study sites (Figure 1); segments absent at some locations were often more fully developed at others. For example, during the initial stages of freezing, only a zone of brash and slush may exist. Subsequently the icefoot, ice ridges, and ice lagoons often occur between the coast and the zone of brash and slush.

The most complete and extensive NIC forms off shorelines with beaches exposed to intense storm waves. Where the shoreline is formed by engineered structures such as revetments, seawalls, and timber or steel sheet-pile bulkheads, the NIC was poorly developed or absent. In February 1989, the NIC was widest and most fully developed along the southeastern shore of the lake (Figure 4) and least developed along the western shore (Figure 5). During studies in February 1990, following a period of warm early winter temperatures, the NIC was absent in the southern part of the lake.

Coastal Profiles and the NIC

Beach and nearshore profiles show several ice and lakebed features that can be related to the NIC. Profile comparisons of shore-normal profiles...
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(Barnes, 1990) indicate that ice ridges are associated with an underlying bar as noted by Seibert et al. (1976). However, the association is not exclusive; commonly there are more ice ridges than offshore bars.

A small but persistent feature of our winter coastal profiles is an erosional trough, commonly 10- to 15-cm deep, but as much as 50-cm deep and 2- to 3-m wide, at the lakeward edge of grounded ice ridges. This trough was first noted in 1989 while wading lakeward of the ice ridges at Illinois Beach State Park and Gillson Beach (Figure 1). At Point Beach State Forest, a shore-normal profile was repeated three times in a 4-day period (Figure 8). The initial 15-m wide NIC disappeared prior to the second survey, and the erosional trough filled. At the time of the third survey, a small 5-m wide NIC had formed along with a shallow erosional trough adjacent to the ridge (Figure 8).

A set of five profiles spaced 15-m apart and wading observations at Kohler-Andrae State Park show an uneven lakebed associated with the NIC and a trough inconsistently developed adjacent to the ice ridge (Figure 9). In addition, the waders noted shore-normal depressions 30- to 40-cm deep and approximately 1-m long associated with ice volcano re-entrants. On the central profile (Figure 9a, ML) a second trough is present under the NIC along the lakeward edge of the icefoot. This second trough has dimensions similar to the one observed on February 16 at Point Beach (Figure 8).

Other observations suggest that depressions lakeward of ice ridges are ubiquitous and are related to the underwater shape of the ice ridges adjacent to the troughs. Underwater video data collected with the ROV show a continuous linear trough 10- to 30-cm deep associated with a 2-m high ridge on the Indiana coast (WBR-1) and adjacent to 7-m high ridges at St. Joseph (Figure 1).

At the WBR-1 site, a new ice ridge intersected the lakebed at the deepest part of the trough as a nearly vertical wall, and an older ice ridge at St. Joseph sloped insshore as much as 3 m toward the trough axis. At the latter site, the trough contained irregular micro-relief of 10 cm which we interpret as ice-contact features.

Sediment Content of Ice

The sediment content of the different ice types varied considerably, although the averages from ice zone to ice zone, and year to year, were similar (Table 1). Concentrations ranged from less than 0.01 to 866 g/l; the latter value is associated with a fist-sized mass of ice and sediment rolling along the lakebed. Elsewhere, average sediment concentrations were highest in the icefoot (44 g/l) and drifting brash and slush (31 g/l) (Table 1). Values were lowest in lagoon ice and immobile brash and slush lakeward of the ice ridges. Lake water sam-

Figure 8. Repetitive coastal profiles at Point Beach State Forest, Wisconsin (Figure 1) showing the presence and demise of an erosional trough adjacent to an ice ridge. Local water level was 0 for our arbitrary datum on the 13th and about 0.3 m higher on the 16th.
samples contained very little sediment (0.03 g/l), and even less sediment was found in several offshore ice samples (0.003 g/l).

Submerged parts of the NIC and the adjacent brash and slush were saturated with water. This water, with its sediment (if any), was usually lost during sampling. However, when sampled, sediment concentrations in drain water were 10 to 100 times less than the concentrations retained in ice samples (Table 1).

In addition to measuring the average sediment content of several NIC’s, the distribution of sed-

Figure 9. Nearshore morphology at Kohler-Andrae State Park, Wisconsin (Figure 1), February 20, 1990. (a) Profiles of lakebed and beach indicating the location of lakebed troughs in relation to nearshore and offshore ridges. (b) Map showing location of profiles and major bars and troughs (dashed bands). Contour interval is 0.1 m.
iment within an individual NIC was studied at Point Beach in February 1990. A narrow but typical ice zonation had developed (Figure 8) and waves were breaking against the 1.2-m high ice ridge through a patchy 5-m wide belt of brash and slush. A profile of four shore-normal and four shore-parallel cores (Figure 10) indicated a sediment-rich surface layer 1- to 2-cm thick underlain by a mid-core, sediment-poor segment with dipping layers of sediment-stained ice. The bottom of the core is a mottled band of sediment-rich ice (Figure 11). ROV observations in 1989 of the un-

Table 1. Sediment concentration in Lake Michigan coastal ice (grams per liter of water plus sediment).

<table>
<thead>
<tr>
<th>Location</th>
<th>1989 Avg. g/l (No. of samples)</th>
<th>1990 Avg. g/l (No. of samples)</th>
<th>Avg. g/l</th>
<th>Range g/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Icefoot</td>
<td>39.2 (4)</td>
<td>53.5 (2)</td>
<td>44.0</td>
<td>9.2-59</td>
</tr>
<tr>
<td>Ice lagoons</td>
<td>10.7 (1)</td>
<td>1.8 (2)</td>
<td>4.7</td>
<td>1.8-10.7</td>
</tr>
<tr>
<td>Ice ridges</td>
<td>11.2 (6)</td>
<td>15.8 (9)</td>
<td>14.0</td>
<td>1.0-44</td>
</tr>
<tr>
<td>Weighted avg.</td>
<td>21.3 (11)</td>
<td>19.5 (13)</td>
<td>20.3</td>
<td>1.0-59</td>
</tr>
<tr>
<td>Fast ice</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brash pieces</td>
<td>34.8 (4)</td>
<td>28.0 (4)</td>
<td>31.4</td>
<td>3.4-92</td>
</tr>
<tr>
<td>Slush</td>
<td>11.1 (6)</td>
<td>18.2 (6)</td>
<td>17.0</td>
<td>0.3-97</td>
</tr>
<tr>
<td>Weighted avg.</td>
<td>20.6 (10)</td>
<td>22.1 (10)</td>
<td>21.4</td>
<td>0.3-97</td>
</tr>
<tr>
<td>Mobile brash/slush ice</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immobile brash/slush</td>
<td>1.0 (10)</td>
<td></td>
<td></td>
<td>0.01-2.0</td>
</tr>
<tr>
<td>Lake water</td>
<td>0.03 (1)</td>
<td>0.59 (17)</td>
<td>0.56</td>
<td>0.01-2.3</td>
</tr>
<tr>
<td>Anchor ice</td>
<td></td>
<td>45.0 (4)</td>
<td></td>
<td>25-73</td>
</tr>
<tr>
<td>Sediment laden ice blocks</td>
<td>445 (3)</td>
<td>130 (5)</td>
<td>248</td>
<td>28-866</td>
</tr>
<tr>
<td>Selected offshore ice</td>
<td>0.22 (6)</td>
<td>20.3 (2)</td>
<td>5.2</td>
<td>0.003-21</td>
</tr>
<tr>
<td>NIC (EVENSON and CORN, 1979)</td>
<td>5 (2)</td>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

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derwater sections of ice ridges also showed increased sediment content near the lakebed.

The effectiveness of wave overwash in incorporating sediment into the NIC was evaluated at Point Beach. The surficial 10 cm of ice was scraped from a 0.5-m² ice-ridge area actively overwashed at intervals of less than 1 minute, and a core was taken (Sample 49; Figures 10 and 11). An hour later, after 1 to 2 cm of ice had accumulated, the same site was re-cored (Core 58). The amount of the sediment in the upper 10 cm of the core (Figure 11) had doubled due to the overwash of water and ice.

Slush ice, formed in shallow water prior to the formation of the NIC, contains high concentrations of sediment. At Neshotah Beach (Figure 1) masses of sediment-laden slush (97 g/l—the highest value recorded for slush) occurred at the shoreline. Sediment-laden slush masses filled the water column 7 to 8 m out from the shore. At first glance the presence of ice was not obvious as the ice took on the appearance of water and was not damping the small (10 to 20 cm) waves except within a meter of the shoreline. The slush and brash accumulations observed lakeward of a substantially developed NIC had notably less sediment (Table 1).

Sediment Textures

The sediment entrained in the NIC and drifting slush and brash consisted primarily of well-sorted, medium-grained (0.25 mm) beach sand (Figures 11 and 12); a few samples contained a bimodal admixture of coarse sand and gravel, especially the ice samples from Illinois beaches (Barnes et al., 1990). The textural character of the sediments from the ice and the adjacent lakebed are essentially the same. Small quantities of silt- and clay-size material were observed in both the water samples and offshore ice samples (Table 1). A comparison of composite textural histograms from nine representative samples of the NIC with modern lakebed sediments from water depths between 13 and 95 m (Colman and Foster, 1990), show a common mode of medium to fine
sand (Figure 12). Core samples, however, are less well sorted than the ice samples.

Ice Drift

In 1989 and 1990, shore-parallel drift of brash and slush was dominated by southerly transport (Table 2). Measured rates were as much as 60 cm/sec and one estimate was 100 cm/sec (2 kn). Measurements were obtained on brash blocks traversing a measured distance just outside the NIC. We believe that the average rates of 19 cm/sec and 35 cm/sec for the 2 years of observation are reasonably representative of ice transport. The variability in ice drift velocity from the inner to
Table 2. Rate and direction of ice drift in Lake Michigan.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location (see Figure 1)</th>
<th>Direction</th>
<th>Rate (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 a.m. IL Beach, S.P.</td>
<td>E</td>
<td>*&lt;~2</td>
<td></td>
</tr>
<tr>
<td>13 a.m. IL coast</td>
<td>S</td>
<td>Not measured</td>
<td></td>
</tr>
<tr>
<td>13 a.m. Gillson Beach</td>
<td>S</td>
<td>Not measured</td>
<td></td>
</tr>
<tr>
<td>14 a.m. Lake St., IN</td>
<td>E</td>
<td>*~5 “slow”</td>
<td></td>
</tr>
<tr>
<td>17 p.m. IN MI border</td>
<td>S</td>
<td>~15</td>
<td></td>
</tr>
<tr>
<td>22 p.m. Gillson Beach</td>
<td>S</td>
<td>25 “0.5 kns”</td>
<td></td>
</tr>
<tr>
<td>22 a.m. IL Beach S.P.</td>
<td>S</td>
<td>100 “2 kns”</td>
<td></td>
</tr>
<tr>
<td>23 a.m. IL Beach S.P.</td>
<td>S</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>23 p.m. Wind Pt.</td>
<td>S</td>
<td>Not measured</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>S</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>

| 1990 |
| 13 0900 Pt. Beach | N | 26 |
| 13 1040 Pt. Beach | S | 60 |
| 14 0800 Pt. Beach | S | 21 |
| 14 1430 Algoma | S | 18 (5 obs.) |
| 15 1130 Two Creeks | S | 36 (3 obs.) |
| 15 1730 Two Creeks | S | 30 |
| 16 1000 Pt. Beach | S | Not measured |
| 16 p.m. Algoma | — | 0 |
| 16 p.m. Sheboygan | — | *0 |
| 17 p.m. Kohler-Andrae | S | 33 (2 obs.) |
| 17 a.m. Wisconsin coast | S | *0 |
| 19 a.m. Kohler-Andrae | E | *~2 |
| Average | S | 19 |

* Estimated rate

outer part of the brash and slush zone (e.g., Figure 7) was not measured, however the variability seemed to be related to the concentration of ice. High concentration of brash-and-slush impeded movement of the ice along the inshore part of the

brash-and-slush zone where the zone abutted the shore or an ice ridge.

DISCUSSION

Development of the NIC

Bryan and Marcus (1972) note that the formation of a Great Lakes NIC requires: (1) freezing air and water temperatures; (2) large bodies of water; (3) onshore winds and storm waves; and (4) a supply of brash and slush. These conditions occur in southern Lake Michigan repeatedly during the winter months (Figure 2; O'Hara and Ayers, 1972; Miner and Powell, 1991) and the associated processes of sediment entrainment, rafting, and profile adjustment occur to varying degrees each time these conditions are met. In addition, winter erosion and transport are slightly enhanced by the increased viscosity of extremely low water temperatures (Grant and Madsen, 1979). We believe that erosion is greatly enhanced by the abrasiveness of ice crystals on the lakebed and their buoyancy in the water column.

Brash and Slush Ice

The presence and interaction of the innocuous, mobile brash-and-slush zone is conspicuous at all
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stages of NIC development. A brash-and-slush zone of variable width both exists before an NIC develops (Figure 5), and after an NIC is destroyed. As ice forms, brash and slush congeals into the icefoot, ice ridges, and ice lagoons. Sediment is ubiquitous in frozen slush, anchor ice, and broken pieces of NIC that make up this zone, resulting in a great potential for sediment rafting. We believe that this nearly submerged, often visually inconspicuous ice zone, which is easily overlooked, transports a major part of the ice rafted sediments.

Icefoot

A frozen beach is the first coastal ice feature to form, usually a week or more before lake temperatures drop to freezing. The ice-bonded surface may be undercut by waves, resulting in an erosional scarp. Thin slabs of ice-cemented sand are dislodged by the undercutting and distributed along the beach (O'HARA and AVERS, 1972; DAVIS, 1973; NIELSEN, 1988). As lake waters cool to freezing, frazil and slush ice, rich in sediment, form in the swash zone. The uncongealed material is readily driven against the coast in a seaway, rubbing against the lake bed and supplying ice and sediment to build the icefoot through overwash (Figure 5). Continued accretion of brash and slush (often derived from up-drift NIC’s) builds a sediment-laden icefoot of horizontal layers. Commonly, the resulting icefoot is several meters wide and the offshore edge is an ice ridge a meter or more high (DAVIS, 1973; Figures 8 and 10). Once built, the icefoot stops sediment motion on the beach and focuses wave energy on its offshore edge. With changing wind and temperature conditions, the icefoot can be destroyed and rebuilt several times through the winter (MINER and POWELL, 1991; DAVIS, 1973).

Ice Lagoons

Continued ice formation and longshore drift in the presence of waves moves brash, slush, and entrained sediment, both alongshore and against the icefoot, dampens waves, and ultimately fills the entire water column out to the first bar with unconsolidated ice (Figures 5 and 8). Wave energy is consumed as they break on offshore bars and propagate through shoreward-thickening brash and slush (Figure 7). Lower wave energies in the ice lagoon between the icefoot and the first bar are indicated in lower sediment concentrations (Table 1). Lower values may result from sediment being dislodged from ice interstices by wave trains passing through unconsolidated slush (KEMPFFMA et al., 1989).

Ice Ridges

Once sufficient brash and slush accumulates inshore, wave energy is focused almost entirely on the offshore bar, pushing, piling, spraying, and overwashing slush, brash, and entrained sediments into an ice ridge (Figures 3 and 6). The intensification of wave energy on the bar causes increased sediment resuspension, enriching the sediment content of the ice ridges (Table 1). Repeated overwash of water and ice enables sediment to be “filtered”, concentrating sediment in the upper parts of the ridge (Figure 11; O'HARA and AVERS, 1972). The outer edge of the growing ice ridge is commonly a vertical scarp that reflects a portion of the incoming wave energy (Figures 8 and 9a). During periods of ice-ridge erosion or decay (usually in the absence of a fringing brash and slush zone), ice volcano re-entrants and slumped ice-ridge sections are common (Figures 3 and 4; DAVIS, 1973; DAVIS et al., 1976; SEIBEL et al., 1976). MARSH et al. (1973) noted that the location of ice ridges varied by a maximum of only 16 m over three consecutive winters; this variation is less than the seasonal shifts noted in offshore bar crests (WOOD and WEISHAR, 1984).

Effect of NIC on Coastal Profile

When the NIC is developed, the focus of wave energy is shifted offshore by the NIC. Because MARSH et al. (1973) and EVENSON and COHN (1979) found little change in profiles inshore of 2 m through the winter, they attributed a protective role for the NIC. EVENSON and COHN (1979) comment, “Even the largest, most destructive winter waves (60% of the yearly wave energy occurs during the winter on Lake Ontario) are forced to expend their energies against the protective ice barrier mantling the beach”. However, earlier studies by ZUMBERGE and WILSON (1953) suggest that the ice cover, although “mantling the beach”, affects the coastal profile offshore, a conclusion later supported by the work of BAJORUNAS and DUANE (1967). Our own studies also document a change in coastal profiles following the formation of an NIC (Figure 13; BARNES et al., 1990).

Modified bottom profiles suggest that the redirected wave energy results in lakebed scour and mobilization of sediments. Sediment is then available for longshore and offshore transport by currents or ice and for incorporation into the NIC. A systematic offshore development of successive
ice ridges (Figure 4) and associated lakeward displacement of wave energy and resulting sediment mobilization could explain the winter offshore displacement of bars noted by Wood and Weishar (1984).

Our profile data document the consistent development of a small erosional trough of 20 to 40 cm adjacent to the icefoot and offshore of ice ridges (Figures 8 and 9) even with low (< 0.5 m) wave action. This suggests ice is important in focusing wave energy at the lakebed and provides a mechanism for the small scale nearshore erosion, observed by Nielsen (1988) and attributed to coastal ice processes.

Underwater video and wading observations confirm a rough bottom owing to ice-keel gouging and current scour in the vicinity of ice keels. A roughened lakebed will absorb increased wave energy as the profile seeks to re-establish equilibrium in the spring. Wood and Weishar (1984) noted the presence of ephemeral nearshore bars in the spring that might have been produced by scour underneath and around ice blocks. We conclude that the development of the erosional trough and ice roughened lakebed indicate displacement and refocusing of wave energy by the NIC.

NIC Reworking and Demise

The NIC is continually being reworked by winter storms. Its loosely frozen mass of brash and slush is easily integrated and disintegrated by waves. Concurrent freezing conditions often preclude significant melting and release of entrained sediment as the NIC is physically reworked. We observed such an event after the NIC at Point Beach was profiled on February 13, 1990 (Figure 8) when winds shifted from onshore to shore parallel. By the following morning, lake level had risen and the NIC had disappeared except for drifting brash and a small frozen beach scarp at the shoreline. Two days later a narrow NIC had reformed under continued freezing conditions and higher water levels. Miner and Powell (1991) document similar NIC cycles in Illinois associated with offshore winds, including several where only the outer part of the NIC was lost.

The reworking of the NIC is significant as rafted sediments are permanently removed from their original site of incorporation, and the coasts are repeatedly re-exposed to new sediment-entrainment events. Rafted sediment that moves alongshore will commonly become part of a newly forming, downdrift, NIC. Rafted sediment may also be moved offshore. Reimnitz et al. (1991) report remnant NIC ice containing coarse beach sediment as much as 5 km offshore.

Breakup begins when the icefoot melts, releasing most of the entrained sediment with little transport. Above freezing temperatures and transport diminish the width and thickness of the brash and slush zone. In the absence of wave dampening brash and slush, ice ridges are breached and lagoons break up, leaving remnants of grounded ridges (Figure 3). Ice inshore of the ridges is hindered from drifting offshore and longshore, thus restricting sediment raifing. The destruction of the large offshore ice ridges provides erosional products that raft sediment alongshore and offshore, depending on wind direction, strength and duration. The destruction is often storm related (O'Hara and Ayers, 1972; Marsh et al., 1973) and long distance ice sediment transport around obstacles may result.

During the breakup, when the NIC and adjacent ice may be in motion, bottom contact by ice is inevitable, and sediment will be gouged in the direction of ice motion. If the brash and slush is porous, additional sediment may be captured during gouging (Barnes et al., 1988). However, the prevalence of weakly solidified masses of frozen brash and slush minimizes ice gouging in southern Lake Michigan in contrast to the way ice contact gouges the bottom in the arctic (Barnes et al., 1988) and in Lake Erie (Grass, 1984). Wallowing blocks of brash and NIC remnants traveling in the longshore wave zone (Figure 5) further enhance sediment transport by intensifying flow at the bed (Reimnitz and Kempema, 1982). However, we have no data that quantify these processes.

Sediment Entrainment by Ice

The primary processes entraining sediment in ice are frazil formation, anchor ice formation, and wave splash-and-overwash. Secondary entrainment occurs by basal adfreezing, aeolian processes, and runoff. Basal adfreezing of sediment requires that the grounded ice become a sub-freezing, heat sink at the lakebed. These conditions are commonly met in the icefoot (Figure 5), but elsewhere the subaqueous portion of NIC is flooded with water and therefore, is not a sub-freezing heat sink. The other secondary processes were also insignificant during our studies and have been studied by other workers (Davis, 1973; Evenson
Frazil ice formation nearshore is a primary process of sediment incorporation into lake ice (KEMPEMA et al., 1989). This process leads directly to the moderate to high values of sediment noted in slush ice samples (Table 1). Therefore the greatest potential for sediment entrainment occurs where turbulence near the lakebed is high during freezing; in the swash zone and where waves interact with ice ridges (Figure 5). Once entrained by frazil formation, wave overwash and spray becomes the prime method of adding sediment to the NIC during icefoot and ice-ridge construction (O'HARA and AVERS, 1972; DAVIS, 1973). This results in higher sediment concentrations in icefoot and ice-ridge samples and an offshore decrease in concentration (MARSH et al., 1976) punctuated by higher values in the ridges.

The pumping action of waves carrying sediment into and out of the NIC has been described as an important mechanism for sediment enrichment (ACKERMAN et al., 1990). If true, the intermittently submerged part of the ridges subjected to the most intense pumping should contain the most sediment. This is not the case; rather, the increase in sediment concentration occurs at the ridge overwash surface, as demonstrated over a one-hour period when wave overwash raised sediment concentrations on the ridge surface (cores 49 and 58, Figure 11).

The formation of sediment-rich, anchor-ice masses is a mechanism of sediment entrainment of unknown importance in the lake. Our observations suggest that slush is often indistinguishable from anchor ice found on the lakebed, and both contain similar sediment concentrations (Table 1). The lake conditions during which we observed anchor ice included calm, sub-freezing weather, shallow water (< 1 m), and a narrow NIC. These conditions suggest that the formation of anchor ice does not require vigorous water-column turbulence, the precursor suggested by KEMPEMA et al. (1989).

Sediment Transport

Coastal-lake ice affects sediment transport in three major ways. First, sediment incorporated in the NIC is removed during midwinter by reworking and during the spring by disintegration. Second, brash-and-slush zone rafts sediment almost continuously. Lastly, wave and current transport of sediment is modified by the displacement of the surf zone to the lakeward margin of the NIC. Our data supports quantitative observations on the first two mechanisms, and qualitative speculations on the last.

Sediment Concentrations in Coastal Ice

Measured melt water sediment concentrations (Table 1) need to be adjusted for ice density to compute sediment concentrations in the NIC. Solid lake ice has densities approaching 0.8 to 0.9, but the air- and water-filled interstices of the NIC, expand the range to 0.22 and 0.93 (BRYAN and MARCUS, 1972; MINER, 1989). Our single 1989 ice density measurement of 0.48, when applied to all 1989 samples (Table 3), underestimates the NIC sediment content. In 1990, mean ice density values for unconsolidated slush and brash were 0.40, while values for the ice-ridge and ice-lagoon samples were 0.6.

Volume estimates of the NIC (Table 3) are based on aerial observations combined with field measurements and profiles (Figures 8 and 9). Brash-and-slush thickness and volume are estimated from wading and diving observations indicating a wedge-shaped accumulation of ice that thins to zero offshore. The resulting regional values of coastal ice volume for our two years of study, 39 and 18 m$^3$/m of coast, are more than an order of magnitude less than the 548 m$^3$/m obtained by MINER and POWELL (1991) at a localized study site (Gillson Beach). Our values are low, since only a single period during the season long growth and modification of the NIC was measured. We believe seasonal and regional NIC ice volumes in southern Lake Michigan are higher than we measured but less than that observed at the local site studied by MINER and POWELL (1991).

Applying sediment concentrations (Table 1) to entire segments of the NIC (Table 3) is justified as samples were obtained from the entire thickness of the NIC, and lateral similarity is suggested from the cores (Figure 11). When this is done, the regional, “average” NIC contained nearly 0.28 t of sediment per meter of coast in 1989 and 0.18 t in 1990 (Table 3); values remarkably smaller than the 5.9 t reported by MINER and POWELL (1991) from their localized study site. Due to the large ice volumes, more than half the sediment is contained in the ice-ridge and -lagoon complex, even though sediment concentrations are higher in the icefoot. Although the ice volume of the 1990 NIC is about half of that in 1989, the estimated sediment content is only slightly less (Table 3).
Table 3. Volume and sediment content of coastal ice in southern Lake Michigan.

<table>
<thead>
<tr>
<th>Location</th>
<th>Icefoot Width (m)</th>
<th>Icefoot Thickness</th>
<th>Ridges and Troughs Width</th>
<th>Ridges and Troughs Thickness</th>
<th>Brash and Slush Width</th>
<th>Brash and Slush Thickness</th>
<th>Stable Adjacent Ice Width</th>
<th>Stable Adjacent Ice Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL Beach S.P. 2/12</td>
<td>15</td>
<td>0.6</td>
<td>None</td>
<td>None</td>
<td>1*</td>
<td>0.1*</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Ft. Sheridan</td>
<td>4*</td>
<td>0.75*</td>
<td>None</td>
<td>None</td>
<td>5</td>
<td>0.3*</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>IL Beach S.P. 2/22</td>
<td>1.5</td>
<td>0.15</td>
<td>None</td>
<td>None</td>
<td>10</td>
<td>0.2*</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Wilmette</td>
<td>12</td>
<td>0.1</td>
<td>40</td>
<td>1</td>
<td>5</td>
<td>0.1*</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Lake St.</td>
<td>14</td>
<td>0.1</td>
<td>50</td>
<td>0.6</td>
<td>None</td>
<td>None</td>
<td>&gt;20</td>
<td>0.4*</td>
</tr>
<tr>
<td>WBR-1</td>
<td>0</td>
<td>0</td>
<td>38</td>
<td>0.3</td>
<td>None</td>
<td>None</td>
<td>&gt;20</td>
<td>0.5</td>
</tr>
<tr>
<td>WBR-3</td>
<td>5</td>
<td>0.2</td>
<td>15</td>
<td>0.4</td>
<td>None</td>
<td>None</td>
<td>&gt;50</td>
<td>0.5</td>
</tr>
<tr>
<td>UM-6 Pier St.</td>
<td>12</td>
<td>0.4</td>
<td>91</td>
<td>1</td>
<td>None</td>
<td>None</td>
<td>&gt;260</td>
<td>0.3</td>
</tr>
<tr>
<td>Grand Mere</td>
<td>6</td>
<td>0.2</td>
<td>25</td>
<td>0.5</td>
<td>None</td>
<td>None</td>
<td>&gt;220</td>
<td>0.3</td>
</tr>
<tr>
<td>UM-7 Chalet</td>
<td>7</td>
<td>0.5</td>
<td>35</td>
<td>0.7</td>
<td>None</td>
<td>None</td>
<td>&gt;260</td>
<td>0.4</td>
</tr>
<tr>
<td>Average</td>
<td>8.5</td>
<td>0.29</td>
<td>42</td>
<td>0.64</td>
<td>5.3</td>
<td>0.18</td>
<td>&gt;138.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Ice vol. m³/m of coast</td>
<td>2.47</td>
<td>27.9</td>
<td>9.19</td>
<td>&gt;55.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total ice vol. m³/m</td>
<td>38.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice density</td>
<td>0.48 (1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sed. cntnt. g/l Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Sed. cntnt. g/l</th>
<th>Sed. cntnt. kg/m of coast</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL Beach S.P. 2/13</td>
<td>39.2</td>
<td>46.5</td>
</tr>
<tr>
<td>Ft. Beach S.P. 2/16</td>
<td>11.0</td>
<td>142.6</td>
</tr>
<tr>
<td>Kohler-Andrae</td>
<td>20.6</td>
<td>90.9</td>
</tr>
<tr>
<td>Neshotah</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>Algoma 2/14</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Two Creeks 2/15</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ice vol. m³/m of coast</td>
<td>1.15</td>
<td>-</td>
</tr>
<tr>
<td>Total ice vol. m³/m</td>
<td>18.4</td>
<td>14.35</td>
</tr>
<tr>
<td>Ice density</td>
<td>18.4</td>
<td>14.35</td>
</tr>
<tr>
<td>Sed. cntnt. g/l Table 1</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>Sed. cntnt. kg/m of coast</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>Total kg/m²</td>
<td>180.2 (equivalent to 113 m³/km²)</td>
<td></td>
</tr>
</tbody>
</table>

* Estimate from field notes
** Sediment content [ice vol. × ice den. = water vol.] sed. cntnt.(g/l) = kg/m of coast ÷ 1.6 = m³/m of coast

Note: g/l is same as kg/m²

This similarity indicates that the higher concentrations of sediments are localized in the inshore part of the NIC, the portion that was present both years.

Rates of Sediment Transport

The longshore transport rates of brash and slush can be estimated from rates of drift (Table 2), ice volume (Table 3), and sediment content (Table 1). On this basis, transport was 2.75 × 10³ t/day in 1989 and 0.35 × 10³ t/day in 1990. Kempema and Reimnitz (1991) estimate a minimum transport by slush and brash of 0.18 × 10³ t/day, or at least 13% of the potential wave and current transport. However large a component of sediment transport, ice rafting does not require constant sediment resuspension by waves. Additionally, rafting can easily detour sediments around coastal obstacles at very low drift velocities and can raft grains across deep water, allowing for long transport trajectories. As a result, ice transport is likely to result in permanent removal of materials from the littoral zone.

Long-term littoral transport (which includes both ice and wave and current transport) noted by Chrzastowski (1990) suggests yearly rates of 78 × 10³ m³/yr or 125 × 10³ t/yr at (1.6 bulk density) or an average daily transport of 0.34 × 10³ t, which is of the same order of magnitude that we noted for brash-and-slush transport. Data are unavailable to estimate the number of days ice transport occurred and, because of the lack of
data on wave-and-current transport when an NIC is present, are unavailable to provide a definitive estimate of the relative effect of ice transport on littoral transport.

Ice heavily laden with sediment is a minor but conspicuous component of drifting ice and, when insufficiently buoyant to drift on the surface, an inconspicuous transport component of unknown importance rolling on the lakebed. The high sediment concentrations in selected sediment laden and dirty ice samples (Table 1) suggest these components may contain a major part of the sediment moved by ice. However, because of the patchy and often submerged occurrence of heavily laden ice, a satisfactory estimate of transport of this component cannot be made. This implies that the average values represented in Table 1 contain only a part of the sediment available for transport by ice. Perhaps these heavily laden ice blocks represent extreme sediment transport events comparable to storms.

Potential for Coastal Erosion by Ice

Sediment contained in the NIC is rafted away during breakup (O'Hara and Ayers, 1972; Marsh et al., 1973) resulting in shoreface erosion. Miner (1989) reported that the 71% of NIC volume loss occurred during periods of high waves and occurred too rapidly to be attributed to melting. He concludes that more than 90% of the sediment trapped in the NIC was rafted from his study site. If rafting removed all the sediment we observed in the NIC in 1989 and 1990 (Table 3), then 280 t and 180 t, respectively, would have been removed from each kilometer of coast. Sediments can be rafted to nearby coastal sites or, as suggested by Miner and Powell (1991) and Reimnitz et al. (1991), to sites on the southern and eastern shores of the lake.

Evidence for offshore ice transport is seen in lake-basin cores that contain ice-rafted sand and occasional pebbles in a fine-grain (hydraulically derived) matrix (Hough, 1958; Lineback et al., 1979; Colman and Foster, 1990). The amount of sediment rafted offshore by ice is estimated from the occurrence of sand in cores where hydraulic and turbidity current processes are not responsible for the observed sand. Cores obtained by Lineback et al. (1979) and Colman and Foster (1990) contain mud, deposited since the start of the Nipissing Transgression 10.3 ka, with an average of 5% ice-rafted sand. The textural similarity of 1989 and 1990 NIC sediment with the sand at the top of these cores (Figure 12) indicates that the coastal sand is a plausible source and ice rafting a possible mechanism. The relatively poorer sorting of sediment in core samples compared to the ice probably indicates the influence of other supply mechanisms for finer sediments.

An estimation of ice rafting from the NIC to the basin assumes that the sand fraction in cores from the southern part of the lake (shaded in Figure 1) is derived from the adjacent coasts. This assumption is supported by prevailing north-westerly winds (Figure 2), prevailing southerly coastal currents (Table 2), and an anti-clockwise surface circulation gyre (Allennder, 1977) confining ice and any rafted sediment to the southern basin. The volume of the sand fraction in the postglacial sediments (estimated from the map of Foster and Colman, 1990) amounts to $1,600 \times 10^6$ m$^3$ or about $2,500 \times 10^6$ t (at a bulk sediment density of 1.6 g/cc). This amount would require an annual ice-rafted contribution of $250 \times 10^6$ t to the basin. This contribution is equivalent to
removing 0.83 t from each meter of coast in the region (~300 km coastline). Removing the 0.23 t/m of coast contained in our average NIC (Table 3) would supply an insufficient quantity of ice rafted material. Several other sources must also supply sand to the deep basin. Additional sand could be carried offshore from: (1) multiple NIC growth and decay episodes (using total season NIC sediment content values, Miner, 1989) indicates that 5.4 t/yr/m of coast would be available from some sections of coast), (2) rafting from the brash-and-slush ice zone when the NIC is static (Reimnitz et al., 1991), (3) ice rafting from outside of the study area, and (4) non-ice processes.

The sediment supplied by bluff erosion to a segment of the coast suggests the potential magnitude of ice rafting. We dismiss longshore transport, assuming losses are replaced from updrift. The glacial units in the Illinois bluffs are eroding at an estimated rate of 4.2 m³/yr/m of coast (Jibson et al., 1990) or 6.7 t/yr/m. Assuming a 10% sand content for the bluffs (R. W. Jibson, oral communication, 1990) gives a sand supply of 0.67 t/yr/m. This value is of the same order of magnitude as the amount incorporated each year in the NIC and as the amount needed to supply the ice-rafter component of the deep-basin sediments (Figure 14). Given the mechanisms cited above as a first approximation, it is reasonable to suggest that ice rafting alone is sufficient to remove as much material from the coastal zone as is supplied to it by bluff erosion and deliver it to the deep basin.

CONCLUSIONS

A distinctive nearshore-ice complex (NIC) repeatedly develops along the coast of southern Lake Michigan between December and March. The growth of the NIC does not diminish the coastal effect of waves, however it does force the waves to expend their energy further lakeward, where multiple ice ridges localized atop offshore bars act as ephemeral seawalls. These barriers erode and modify the adjacent lakebed due to the effects of winter storm waves, resulting in a rough spring lakebed profile.

The bulk of coastal sediment entrainment by ice occurs from frazil and anchor ice processes which are most effective in shallow water. Once entrained, sediments are further concentrated by dynamic wave processes that build the icefoot, ice volcanos, and ice ridges of the NIC by piling slush and brash against the coast and the lakebed. Wave energy is focused at the outer edge of the NIC and additional sediment is mobilized and entrained. Given these processes, narrow and recurring NIC’s will incorporate more sediment than will wide and/or stable NIC’s.

Once entrained in ice, greater quantities of sediment are rafted alongshore than are rafted offshore. However, conservative estimates suggest that NIC’s entrain sufficient quantities of coastal sands to account for the coarse ice-rafted sediment found in post-glacial sediments in the deep lake basin. The quantities entrained are also similar to the amount supplied by bluff erosion in northern Illinois.

In a previous study Davies et al. (1976) concluded: “Fortunately for coastal residents, the protection that ice affords comes at the most desirable time of year, when storms are both severe and common”. We believe that this statement is misleading, because significant erosion and transport is associated with the growth and decay of the NIC. More specifically, ice processes affect the morphology and sediment budget of the central shoreface and ice rafting removes significant quantities of sediment. These factors almost certainly affect the observed long-term response of beaches, bluffs, and coastal engineering structures.

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ering and interpreting the data included in this report. These workers include M. Chrzastowski, J. Haines, R. Hunter, G. Meadows, T. Reiss, and W. Wood. Tau Rho Alpha's patient and skillful efforts produced the interpretive diagram used in Figure 3. The input of M. Chrzastowski, J. Dingler, J.-C. Dionne, M. Ovetz, and an anonymous reviewer helped to improve the manuscript.

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