

A QUANTITATIVE MODEL OF THE DISPERSAL OF DETRITAL INPUTS AND MINOR COMPOSITIONAL COMPONENTS IN LAKE MICHIGAN SEDIMENTS

Andrew R. B. Zimmerman and Robert M. Owen*

Department of Geological Sciences
The University of Michigan
Ann Arbor, Michigan 48109-1063

ABSTRACT. This study involves the development and application of mathematical models which are used to ascertain the sources, distribution, and fate of sedimentary material entering Lake Michigan. Major compositional end-members are identified by a modified Q-mode factor analysis procedure, and estimates of the relative amount of each end-member in each sample are obtained by linear programming. Four factors account for 93.8% of the total variance. These are interpreted as representing the inputs of fine-grained (Factor 1), and coarse-grained (Factor 2) detrital minerals, manganous carbonate (Factor 3) and non-manganous carbonate (Factor 4) to the lake sediment. Significant linear correlations between the relative amount of each compositional end-member and the grain-size distribution for each sample support these interpretations. Contour plots of end-member distributions suggest that the sediment chemistry of Lake Michigan is primarily influenced by regional-scale physical processes. In a revised version of the model, the distribution of minor sediment components (ferromanganese oxyhydroxides and siliceous plankton tests) are examined. Each model accounts for approximately 90% of the measured elemental concentrations in lake sediment. We conclude that this modeling approach is a viable method for determining the distribution of sedimentary inputs in large lacustrine basins, and may also be useful in monitoring the dispersal pathways of coastal erosion products or chemical pollutants.

INDEX WORDS: Detritus, Lake Michigan, mathematical models, lake sediments, geochemistry, erosion, beach erosion.

INTRODUCTION

The complex interactions between the physical, geochemical, and biological processes within a depositional basin typically produce spatial differences in sediment composition. These differences can range in degree from those which are pronounced and readily discernable, as in the case of nearshore vs. deep-sea sediments, to those which are very subtle, as in the case of foreshore vs. back-shore beach sediments. Whatever the scale of comparison, investigators have found that analytical approaches designed to identify and quantify compositional differences in contemporaneously deposited sediments can provide useful information concerning both the sources and the processes which control the distribution of sedimentary material. Quantitative analysis of differences in sediment properties have been employed, for example, to discriminate between the dispersal of

coarse and fine-grained sediments on continental shelves (e.g., numerous studies cited in Swift *et al.* 1972), to correlate the composition of ocean basin sediments with generic sources of sedimentary material (Bostrom *et al.* 1973, 1974; Heath and Dymond 1977; Dymond 1981; Leinen and Piasias 1984; Chen and Owen 1989), to determine compositional variations in the distribution of surficial lacustrine sediments (Kemp and Thomas 1976; Sly 1975, 1978; Thomas *et al.* 1972, 1973, 1976), and to delineate areas of potential economic mineral enrichment from landmasses adjacent to coastal embayments (Owen 1980, 1987).

The present study involves the development and application of quantitative models of sediment dispersal in Lake Michigan, in which sediment geochemical properties are used to ascertain the sources and distribution of sedimentary material in the lake. Our intent is to identify the major types of geochemically distinct sediments, to relate these to different source areas, and to examine their dis-

*Author to whom correspondence should be addressed.

persal patterns in terms of the extant physical transport processes within the lake. Information of this sort also has practical value, inasmuch as it should augment our understanding of the fate of various chemical pollutants and coastal erosion products which enter the lake.

The modeling approach employed here is based upon a factor analysis of sediment geochemical data. Several authors have used some form of factor analysis in the study of lacustrine sediments (Thomas *et al.* 1972; Potter *et al.* 1975; Dean and Gorham 1976a,b; Cahill, 1981), particularly in cases where the number of samples and measurements are relatively large (e.g., see discussion in Jones and Bowser 1978). We have used a recently developed Q-mode factor analysis technique which is specifically designed to estimate the composition of geochemical end-members in sedimentary mixtures (Leinen and Piasias 1984). This approach has not previously been applied to lacustrine sediments, but has been used successfully to correlate sediment composition in a broad expanse of the Southeast Pacific Ocean (the Nazca Plate) to specific geochemical sources (Leinen and Piasias 1984) and to discriminate between the compositions of proximal and distal hydrothermal sediments (Olivarez and Owen 1989). Given the obvious differences between marine and freshwater environments in terms of the size of the depositional basin, the sources of sedimentary material, the kinds and relative intensities of depositional processes, and the degree of homogeneity in sediment grain sizes, a second objective of this study is to evaluate the viability of applying this modeling approach to large lacustrine systems.

We chose Lake Michigan for this study because there is an extensive literature concerning the physical limnology and sediment chemistry of the lake, and the geology of the surrounding drainage basin. This can be used to evaluate the model results. The regional geology of the Lake Michigan drainage basin consists of exposed rocks of the Canadian shield to the north, and Paleozoic formations of carbonate, sandstone, and shale, often overlain by glacial till, along the eastern and western lake margins. Excellent reviews of the geology of the Lake Michigan region may be found in Hough (1958), Sly and Thomas (1974), Cahill (1981), and Rea *et al.* (1981).

Lake Michigan can be subdivided by its bathymetry (Fig. 1) into four distinct regions: the relatively large northern and southern basins which are separated by the mid-lake high, the northern straits

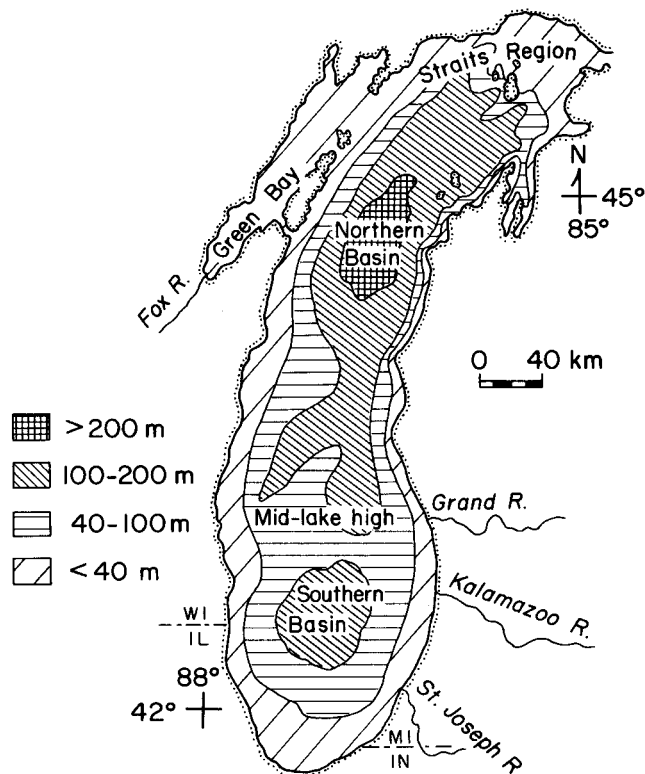


FIG. 1. Generalized bathymetry of Lake Michigan (adapted from Cahill 1981) showing the northern and southern basin, mid-lake high, northern straits region, and Green Bay.

region, and Green Bay (Hough 1958). The general surface circulation pattern of Lake Michigan consists of two large counter-clockwise gyres centered on each of the large basins (Callender 1969). The strongest currents are known to occur in the straits region, as well as along the southeast and western margins of the lake. Seasonal upwelling is predicted to occur offshore of these areas of strong currents (Ayers *et al.* 1958).

METHODOLOGY

Data Set

The geochemical data set used for our sediment dispersal models was developed by Richard Cahill of the Illinois State Geological Survey (Cahill 1981), who measured 50 different geochemical and textural parameters for 286 surficial sediment samples collected from throughout Lake Michigan. Of these, we selected 150 samples for this

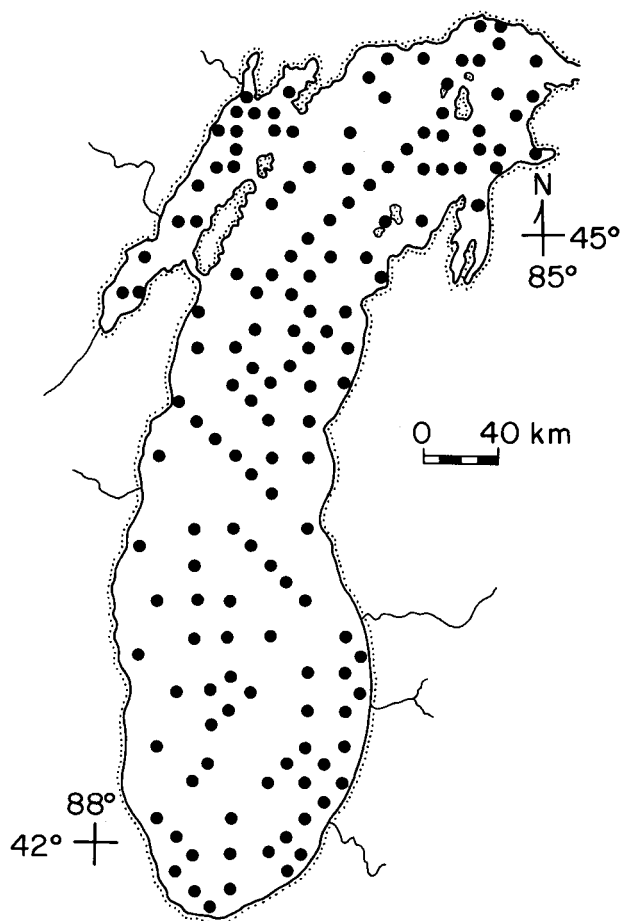


FIG. 2. Locations of the surficial sediment samples used in this study (adapted from Cahill 1981).

study so as to ensure broad, even coverage of the whole lake (Fig. 2). Detailed information regarding the shipboard procedures and analytical methods employed is given in Cahill (1981).

The following parameters were selected as input variables for the sediment dispersal models developed by this study: Si, Al, Fe, Mg, Ca, Mn, Ba, Cu, Ni, Na, K, and C_{org} (organic carbon). These parameters are considered to have the greatest potential for defining geochemical end-members, inasmuch as they account for a major portion of the variability in the data set developed by Cahill (1981) and because of their known associations with the various common mineralogical phases which occur in Lake Michigan (Moore 1961, Strong and Eadie 1978, Rea and Pigula 1979, Rea *et al.* 1981, Cahill 1981).

Sediment Dispersal Model

Our modeling approach is based on the assumption that the sediments present within a depositional basin are typically mixtures of inputs from different source areas. Moreover, the relative amounts of sedimentary material contributed from each source area are likely to vary from point to point within the basin, depending upon how the extant wave and current regimes have distributed the material from each source area. The goal of the sediment dispersal model is to deconvolute sediment compositions such that the relative amounts of each major compositional end-member present in each sample are determined for any sampling point within the basin. Once this information is obtained, it is a straightforward task to prepare contour maps or plots which depict the dispersal pattern of each compositional end-member. A quantitative approach to this problem involves combining mathematical techniques capable of (1) isolating a set of sediment parameters which can serve as characteristic identification tags or "tracers" for each end-member, and (2) determining the relative amount of each end-member in each sample within any given mixture of end-members.

The major compositional end-members in Lake Michigan sediments were identified using the Q-mode factor analysis technique of Leinen and Piasias (1984). This technique includes a vector rotation procedure which effectively converts factor scores into realistic estimates of the geochemical composition of each end-member that has been identified. Although this technique will generate enough factors to account for 100% of the variance within the data set, it is not likely that all of these factors are of geological significance. We have chosen to use only those factors which account for more than 2% of the total variance within the data.

Once the number and composition of the end-members are determined, the next step is to obtain a quantitative estimate of the relative amount of each end-member in each sediment sample. Because the sediment samples are regarded as simple mixtures, the bulk composition of each sediment sample is assumed to consist of some linear combination of end-member compositions. Consequently, each sample can be represented mathematically as a system of n equations (n = the number of individual geochemical parameters used to identify the compositional end-members) in m

unknowns (m = the number of major compositional end-members that are present) of the form:

$$\begin{aligned} S_{p1} &= k_1 E_{1p1} + k_2 E_{2p1} + \dots + k_m E_{mp1} + R_{p1} \\ S_{p2} &= k_1 E_{1p2} + k_2 E_{2p2} + \dots + k_m E_{mp2} + R_{p2} \\ &\vdots \\ S_{pn} &= k_1 E_{1pn} + k_2 E_{2pn} + \dots + k_m E_{mpn} + R_{pn} \end{aligned}$$

where $S_{p1}, S_{p2}, \dots, S_{pn}$ = the measured concentrations of parameters $p_{1,2}, \dots, p_n$ in the sample;

E_{1p1}, \dots, E_{mpn} = the concentrations of parameters p_1, \dots, p_n in the compositional end-members E_1, \dots, E_m determined by factor analysis;

k_1, k_2, \dots, k_n = unknowns whose magnitudes for each sample reflect the relative contributions (decimal percent) of each compositional end-member in that sample; and,

$R_{p1}, R_{p2}, \dots, R_{pn}$ = residual terms reflecting the fact that each equation is inexact due to sampling error, analytical error etc.

These systems of equations are usually overdetermined ($n > m$) in sediment geochemical applications and optimum solutions can be obtained using linear programming methods (Gass 1975, Chvatal 1983). The major advantage of obtaining a linear programming solution is that certain physical constraints can be incorporated into the mathematical calculations (Dymond 1981, Heath and Dymond 1981). For example, the linear programming solution specifies that no compositional end-member can have a negative contribution to the total composition of a sediment sample.

The residual terms associated with each system of equations represent the difference between the linear programming estimate and the actual concentration of each element in the sample. The optimum solution for each system of equations is that for which the residual terms are minimized. Since a "perfect" modeling solution would account for 100% of the measured concentration for each element, we have evaluated the validity of our models by calculating a mean residual percent for each element (i.e., the mean residual for each element divided by the mean elemental concentration).

Finally, a graphic illustration of sediment dispersal patterns is obtained by constructing contour plots of the relative distribution of each compositional end-member in the lake basin. These plots were constructed manually using grid values estimated by calculating the weighted average of nearest observations. We note that we deliberately avoided using any of the several commercially

TABLE 1. Varimax factor score matrix. Factor loadings are expressed in units of standard deviation from the mean of a hypothetical variable.

Variable	Factors			
	1	2	3	4
Si	-0.139	0.744	0.034	0.002
Al	0.279	0.132	0.017	0.096
Fe	0.327	0.102	-0.016	0.005
Mg	-0.004	-0.052	0.326	0.480
Ca	-0.144	-0.041	0.414	0.611
Mn	0.239	0.001	0.812	-0.476
Ba	0.167	0.398	-0.088	0.027
Cu	0.438	-0.096	-0.095	0.052
Ni	0.510	-0.003	-0.164	0.038
Na	0.004	0.393	0.106	0.136
K	0.209	0.261	-0.063	0.116
Corg	0.368	-0.154	-0.051	0.351
% variance	31.7	33.5	13.5	15.2

available contouring programs for this purpose: our experience has been that these often produce erratic results which are artifacts of the program design. Davis (1973) discussed the inherent problems associated with the design of contouring programs.

RESULTS AND DISCUSSION

Factor Analysis Model

The Q-mode factor analysis determined that four factors account for 93.9% of the total variance within the data. A varimax factor score matrix of the factor loadings on each chemical parameter is known in Table 1, and the corresponding scores for each compositional end-member which resulted from the vector rotation of the original factors are shown in Table 2. The goodness-of-fit statistics (Table 3) for the linear programming solution indicate that this model accounts for more than 90% of the measured concentrations of Mg, Ca, and Mn, and more than 97% for most of the remaining geochemical parameters.

Factor 1, which represents 31.7% of the total variance in the data, is interpreted as a fine-grained detrital and organic matter end-member. The interelement ratios and relatively high Al, K, Na, and Mg concentrations in this end-member are indicative of a mixed assemblage of clay minerals rather than a specific common clay or shale. The rela-

TABLE 2. Compositions of reference axes (compositional end-members) after the rotation of original factors.

Variable	Factor compositions ($\mu\text{g/g}$)			
	1	2	3	4
Si	26130	391665	246717	277717
Al	115119	6879	14046	21207
Fe	80548	3486	6527	10162
Mg	30198	1402	30659	27880
Ca	895	2774	63045	55289
Mn	67566	1855	45412	0
Ba	2036	338	120	433
Cu	232	0	4	25
Ni	218	5	0	24
Na	4961	1687	2547	2699
K	46560	5010	3517	10534
Corg	40638	0	2507	9132
% variance	31.7	33.5	13.5	15.2
% cumulative variance				93.9

TABLE 3. Goodness-of-fit statistics for linear programming. The "goodness-of-fit index" is that percent of an element's geochemical abundance which is explained by our model. Model 1 involves only those factors determined by factor analysis. Model 2 includes, additionally, two minor sediment component end-members.

Variable	Goodness-of-fit index (%)	
	Model 1	Model 2
Si	100.0	100.0
Al	99.8	97.1
Fe	99.9	90.1
Mg	92.4	91.1
Ca	90.4	89.6
Mn	90.5	87.9
Ba	97.9	87.2
Cu	77.4	85.4
Ni	98.4	89.8
Na	98.6	98.5
K	98.3	95.0
Corg	97.4	89.9

tively low Si/Al ratio (0.277) of this factor suggests the presence of gibbsite ($\text{Al}(\text{OH})_3$) in the clay mineral assemblage, and is indicative of relatively high flow rates for waters passing through the unconsolidated soils surrounding the lake (Berner 1971).

Certain trace metals are commonly incorporated into the clay fraction of sediments by biochemical

uptake, ion-exchange, or adsorption (e.g., Stumm and Morgan 1981), and Fe, Ni, Mn, and Cu are probably enriched in this end-member (above-normal clay mineral concentrations) due to these processes. Other (possibly anthropogenic) metals such as Pb, Zn, Co, and As exhibit a highly coherent geochemical behavior in fine-grained lake sediments (Owen and Mackin 1980) and are likely associated with this end-member in the form of metal-humic complexes (Shimp *et al.* 1970, Baker-Blocker *et al.* 1975, Filipek and Owen 1978). The association of organic material with this factor is evident from the high concentration scores for C_{org} and Ba (an element commonly associated with organic residue: Dymond 1981, Schmitz 1987).

The highest concentrations of Factor 1 are found in the quiescent deep parts of Lake Michigan's three depositional basins (Fig. 3), where it represents up to 30% of the total sediment composition in the northern and southern basins and in Green Bay, while it is least abundant where water depths are shallow and in the upper straits region (i.e., in high energy environments). The highest nearshore concentrations of this end-member occur in the southeast portion of Lake Michigan, which receives drainage from the Grand, Kalamazoo, and St. Joseph rivers. Fluvial inputs of both natural and anthropogenic materials from the Fox River probably account for the high concentrations of this end-member in Green Bay.

Factor 2, which represents 33.5% of the total variance of the data, is highly concentrated in Si (39%). This end-member is interpreted as a coarse-grained sediment component. The inter-element ratios of factor 2 are very similar to those of a fairly "clean" quartz sandstone. Thus the Si should be present mainly as quartz (SiO_2), while Al, K, and Na in this end-member are likely due to the presence of feldspar minerals which are also a significant mineralogical component of Lake Michigan sands (Pigula *et al.* 1977). Mineralogical studies of Lake Michigan surficial sediment have reported overall compositions of up to 61% quartz and 12% feldspar (Callender 1969, Rea and Pigula 1979).

The distribution of Factor 2 is greatest along the shorelines, at the mid-lake topographic high, and in the northern straits region where it comprises more than 60% of the total sediment composition (Fig. 4). A good correlation exists between the distributions of Factor 2 and known regions of consistent and vigorous surface current circulation (Ayers *et al.* 1958). These results are consistent

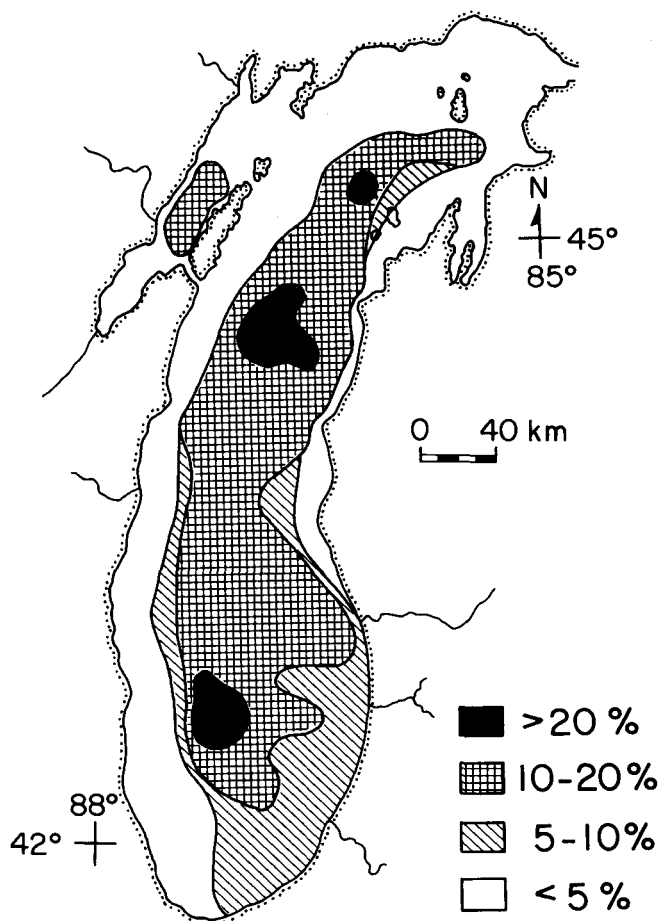


FIG. 3. Percent distribution of Factor 1 (fine-grained clay minerals and organic matter).

with measurements of 60% to 90% sand composition in most of northeastern Lake Michigan (Moore 1961) and other sand distribution studies in the lake (Hough 1935, Callender 1969), and they suggest that Factor 2 represents coarse-grained sediments deposited in shallow high energy environments where smaller-grained particles are removed by winnowing.

Factors 3 and 4 account for 13.5% and 15.2%, respectively, of the total variance of the data. Both factors contain high concentrations of Ca and Mg, suggesting an association with carbonate minerals, while the concentrations of Si, Al, and K in these factors suggest they may also include minor amounts of detrital aluminosilicates. We do not consider that ferromanganese nodules and coatings, the insoluble oxide and hydroxide phases of Fe and Mn, are responsible for the Mn concentra-

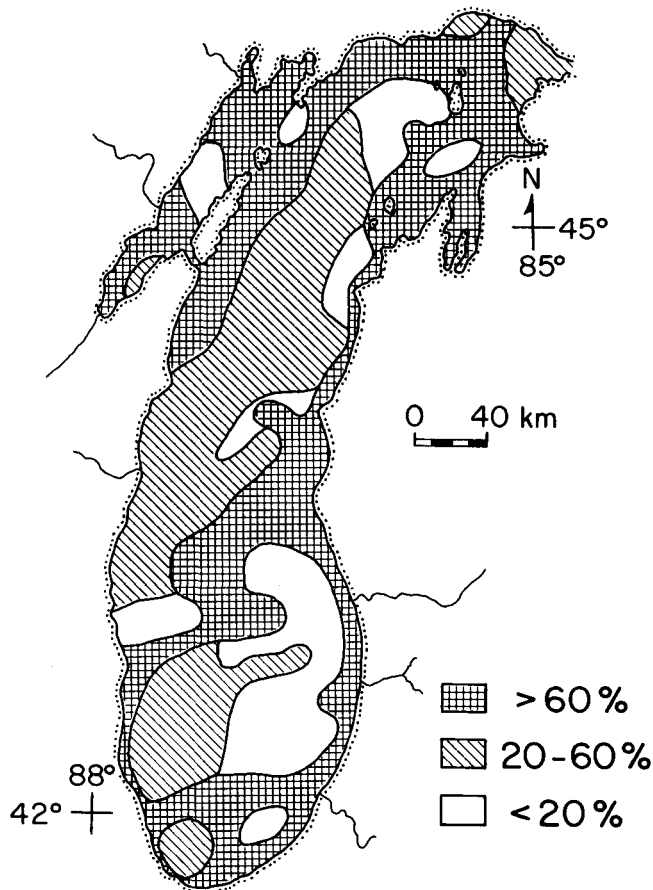


FIG. 4. Percent distribution of Factor 2 (coarse-grained detrital minerals, primarily quartz and feldspar).

tions in Factor 3. Factor 3 is a significant component of the sediment in southern portions of the lake (Fig. 5), where manganese nodules have not been observed, while there is virtually no Factor 3 sediment component in Green Bay, where ferromanganese nodules are most commonly found (Rossmann and Callender 1969, Edgington and Callender 1970, Cahill 1981). In addition, Fe and Ni, which are often associated with the oxide and hydroxide phases of Mn, are only minor constituents of Factor 3. For these reasons, we interpret Factors 3 and 4 as representing, in part, a carbonate sediment component which has been subdivided into a manganous carbonate end-member (Factor 3) and a non-manganous carbonate end-member (Factor 4). The manganese carbonate end-member is probably rhodochrosite (MnCO_3), which is believed to be a thermodynamically favored reaction product during the diagenesis of

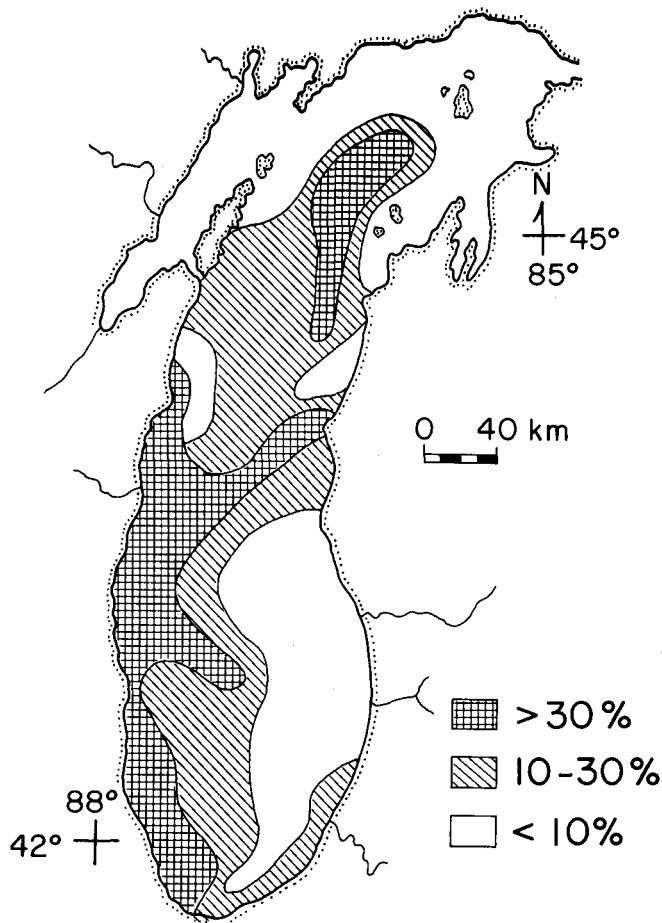


FIG. 5. Percent distribution of Factor 3 (Mn-carbonates). See also the distribution of non-Mn-carbonates (Fig. 6).

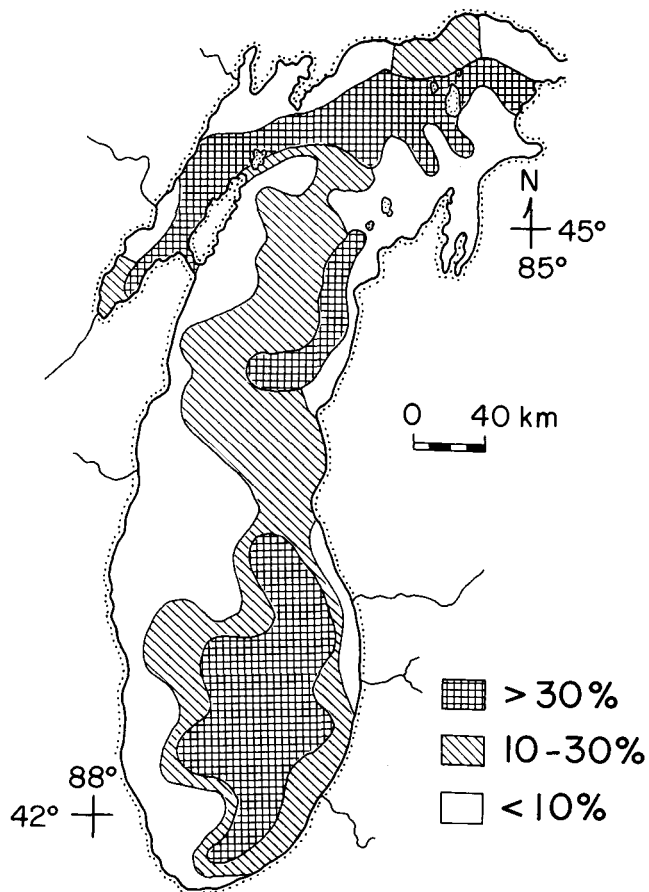


FIG. 6. Percent distribution of Factor 4 (non-Mn-carbonates). See also the distribution of Mn-carbonates (Fig. 5).

Mn in lacustrine sediments (Robbins and Callender 1975). Previous studies have reported geochemical evidence for the occurrence of rhodochrosite in Lake Michigan sediments (Filipek and Owen 1978, 1979). The high concentrations of Mg in both of these factors suggest that dolomite is a major constituent of the carbonate material being eroded into the lake. Callender (1969) has reported that as much as 17% of the surficial sediment is composed of dolomite vs. 3% for calcite.

The relative concentrations of Factor 3 (Fig. 5) and Factor 4 (Fig. 6) are greatest in intermediate depth intervals. Erosion of exposed Paleozoic limestone and dolomite formations is probably the dominant source of the carbonate sediments in the northern lake region. The major rivers which drain into the lower lake region also erode Paleozoic car-

bonates and calcareous glacial tills (Callender 1969) and deposit carbonaceous sediment throughout the rest of the lake. The distribution of the manganous carbonate end-member (Fig. 5) corresponds to many regions in which reducing conditions exist (Cahill 1981) and is consistent with the proposed diagenetic origin of manganous carbonate.

Some carbonate sediments in the lake may result from authigenic processes. For example, the concentration of dissolved Ca is greatest in the southeastern portion of the lake (Ayers *et al.* 1958). Whittings have also been observed in this portion of the lake (Strong and Eadie 1978), and Factor 4 is a dominant sediment component here. It is doubtful, however, that authigenic carbonate formation is a major sediment source, because many have

noted the existence of chemical conditions which are corrosive toward carbonates (Kemp and Dell 1976, Rea and Pigula 1979, Graham and Rea 1980).

Critique of Factor Analysis Model

The compositional end-members which result from the Q-Mode factor analysis of Lake Michigan sediment geochemical data differ significantly from those which are typically obtained from similar analyses of deep-sea sediments. For example, previous applications (Dymond 1981, Leinen and Piasias 1984, Chen and Owen 1989) of this approach to deep-sea sediments have commonly extracted compositional end-members which, on the basis of their highly characteristic inter-element ratios, display a simple one-to-one correspondence with specific generic geochemical source materials (e.g., detrital, hydrothermal, biogenous, etc.). In contrast, the compositional end-members for Lake Michigan all appear to reflect a mixed assemblage of minerals from multiple detrital sources, although there is a close correspondence between each of these end-members and relative depositional energy levels in the lake. This result is similar to what has been observed for nearshore marine sediments (e.g., Calvert 1976), and suggests that first-order bulk sediment compositional variations in the Lake Michigan basin are not the result of geochemical processes, but instead are primarily a reflection of the effects of hydrodynamic sorting of sediment grains by the extant wave and current regime. This assertion is supported by the observed relationship between the relative amount of each compositional end-member that is present vs. the grain-size distribution for the Lake Michigan samples. A highly significant linear correlation ($p < 0.005$) exists between % Factor 1 and clay-sized grains, % Factor 2 and sand-sized grains, and % Factor 3 + 4 and silt-sized grains (Fig. 7). These relationships are also consistent with our interpretations of the compositional significance of each of the factors. Sedimentologists have long recognized that the combined effects of weathering, erosion, and transport of detrital grains result in a segregation of different mineralogical groups, such that sand-sizes are dominated by quartz and feldspars, silt-sizes by carbonates, and clay-sizes by clay minerals (Moore 1961, Folk 1973, Sly and Thomas 1974, Filipek and Owen 1979, Rea *et al.* 1981, and many others).

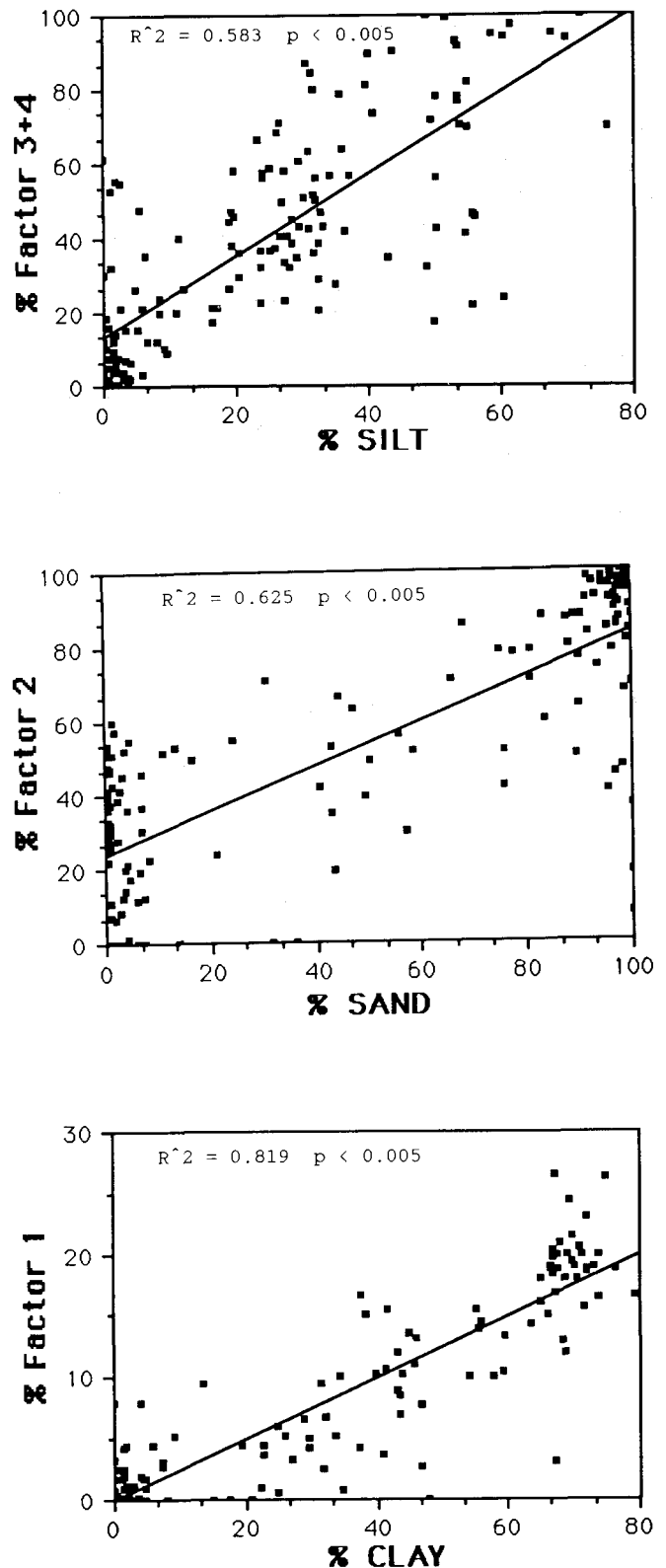


FIG. 7. Correlation between compositional end-members and sediment grain-size classes.

Revised Model: Distribution of Minor Components

Another key difference between the application of the Factor Analysis Model to deep-sea vs. lacustrine systems concerns the ability of the model to extract reasonably accurate compositional end-members which represent minor sedimentary components. Both deep-sea and lacustrine sedimentary mixtures tend to be dominated by a single major compositional component; biogenous material (biogenic CaCO_3 or opaline SiO_2) in deep-sea sediments, and detrital material in lacustrine sediments. Each also typically contains a small number of minor components which, collectively, amount to only a few percent of the total sediment mass. However, accurate factor analysis estimates of the composition of the minor components are difficult to obtain because their effect on variations in the bulk sediment geochemistry is overwhelmed by the dominant component. Marine geochemists can avoid this problem by mathematically removing the effect of the dominant component (e.g., by converting the entire data set to a carbonate-free and/or opal-free basis before performing the factor analysis). This correlation is possible because both biogenic carbonate and opaline silica have the characteristics of being chemically simple, essentially uniform in composition, and easily measured. In contrast, there is no simple and straightforward way to completely remove the effect of the dominant detrital component in lacustrine studies, although this can be achieved to some extent by converting data to a quartz-free basis (e.g., Thomas *et al.* 1973).

Previous investigations of Lake Michigan sediments indicate the presence of two minor components which are not reflected in our factor analysis results: siliceous plankton debris (e.g., diatom tests) (Stoermer and Yang 1969, 1970), and an authigenic ferromanganese oxyhydroxide phase (Rossmann and Callender 1969, Edgington and Callender 1970). We have attempted to examine the distribution of each of these minor components in Lake Michigan by developing a revised sediment dispersal model. In the revised model, we designated an end-member composition for each of the two minor components based on analyses reported in the literature (Table 4), and then recalculated a linear programming solution for each sample using the four compositional end-members determined by the factor analysis plus these two designated end-members.

TABLE 4. Estimated end-member compositions of minor sedimentary components. Fe/Mn = authigenic ferromanganese oxyhydroxide (adapted from Cronan 1980); Bio-Si = siliceous planktonic debris (adapted from Dymond 1981).

Variable	Estimated Compositions ($\mu\text{g/g}$)	
	Fe/Mn	Bio-Si
Si	53890	360000
Al	11600	720
Fe	230000	360
Mg	3700	0
Ca	12000	0
Mn	105000	8
Ba	9100	720
Cu	360	18
Ni	350	14
Na	0	2000
K	0	500
Corg	1000	20000

Although the amount of error associated with each parameter in the revised model is generally somewhat greater (Table 3), the revised model still accounts for at least 85–90% of the bulk composition of Ca, Mn, Ba, Cu, Ni, and C_{org} , and more than 90% of all other parameters. Contour plots (Figs. 8–9) of the concentrations of the two minor components are generally consistent with available information concerning the distribution of these phases in Lake Michigan. The predicted high levels of ferromanganese oxyhydroxides (Fig. 8) in Green Bay and in the northern and central part of the lake agree with previously documented occurrences of these deposits (Rossmann and Callender 1969, Edgington and Callender 1970, Cahill 1981). Similarly, the highest concentrations of the siliceous planktonic debris end-member (Fig. 9) correspond well with regions where surface currents are strong and upwelling may occur (Ayers *et al.* 1958). Fertilizer runoff from agricultural areas in Wisconsin may also contribute to increased productivity in surface waters and an increase in biogenous deposits along the western margin of the lake. The areas of highest concentration of both minor components in the southern portion of the lake are similar, and probably reflect zones of Fe and Mn enrichment resulting from the remobilization of these elements during organic diagenesis (Jones and Bowser 1978).

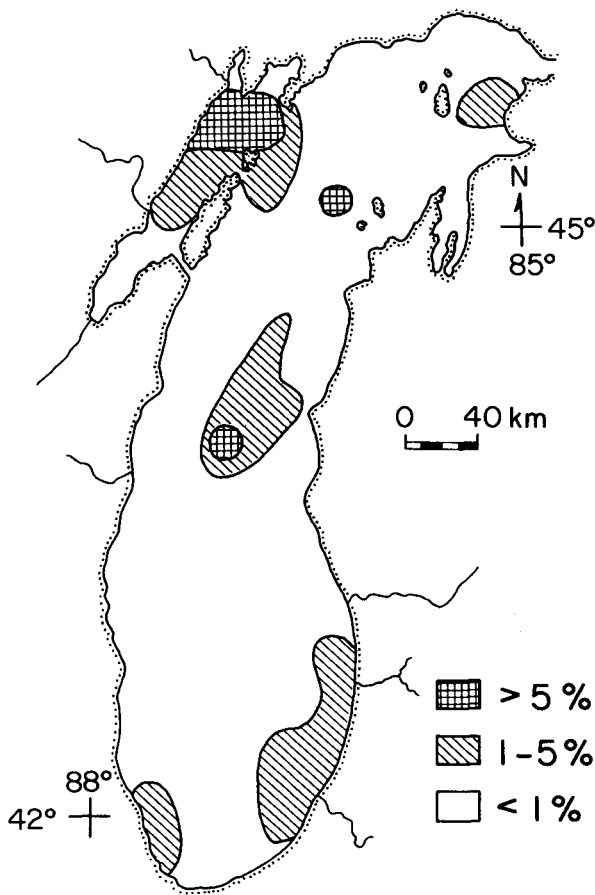


FIG. 8. Percent distribution of the minor ferromanganoous end-member as determined by the revised model.

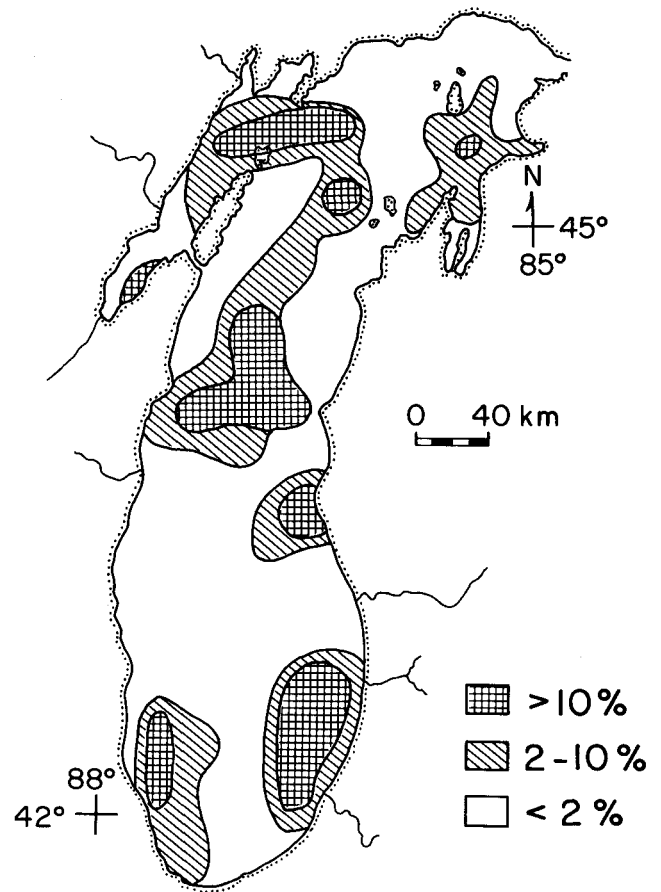


FIG. 9. Percent distribution of the minor biogenous end-member (mainly siliceous planktonic debris) as determined by the revised model.

SUMMARY AND CONCLUSIONS

The Q-mode factor analysis results determined in this study of lacustrine sediments differ significantly from those which typically have been obtained when this modeling approach is used to examine the distribution of compositional end-members in deep-sea sediments. These differences illustrate the relative importance of physical vs. geochemical processes in controlling sediment composition in different depositional environments. Deep-sea sediments accumulate in a highly uniform, low energy depositional environment that is far removed from most source areas. Individual grains reaching deep-sea basins from non-biogenous sources represent the remaining clay-sized fraction of material from detrital,

volcanogenic, and hydrothermal sources after larger grains have been removed during the early stages of eolian and hemipelagic transport processes. The biogenous fraction also includes fine-grained material composed of the microscopic tests of marine plankton. A factor analysis of bulk sediment geochemical data from these well-sorted sediments typically results in compositional end-members which directly correspond to the characteristic compositions of material from specific sources.

Lake Michigan sediments, on the other hand, are largely derived from a mixture of detrital sources (e.g., glacial till) which initially contribute a multi-modal distribution of grain sizes. These grains undergo size segregation via hydrodynamic sorting during transport, and are ultimately deposited, according to grain size, across the spectrum

of depositional environments that exist in the lake. In this case, each of the end-member compositions determined by the factor analysis corresponds to a grain-size fraction that is deposited in a specific depositional environment.

There is relatively little compositional variation within the detrital fraction of deep-sea sediments. Individual grains within this fraction typically have undergone an extensive amount of chemical weathering, and the average composition of this fraction is very close to that of shale (Piper 1974). However, chemical weathering is minimal in the northern temperate climate region of Lake Michigan, and the composition of detrital grains in the lake sediments reflects the entire range of lithologies found in the parent source rocks. No single mineralogical composition is representative of this range of compositions, and thus it is not possible to remove the effect of the dominant detrital component from the geochemical data in order to highlight the role of minor sedimentary components. Our revised sediment dispersal model attempts to overcome this problem by incorporating assumed compositions for minor sedimentary components into the set of compositions which represent the geochemical end-members in Lake Michigan sediments. We conclude that this is a viable approach, inasmuch as our revised model predicts distribution patterns for minor sedimentary components (ferromanganese oxyhydroxides and siliceous planktonic tests) which closely resemble those which have been observed for these components.

The sediment dispersal models developed here provide a composite "picture" of how the integrated surface effects of wave action, longshore transport, surface and bottom currents, and upwelling events produce significant compositional gradients in the sediment chemistry of Lake Michigan. Obvious practical applications for this modeling approach include its use in estimating the dispersal pathways of the products of coastal erosion and of chemical pollutants entering the lake. For example, it has been estimated that over 60% of the material presently entering Lake Michigan is in the sand-sized fraction (Monteith and Sonzogni 1976), and that most of this input is due to coastal erosion (Rea *et al.* 1981). The dispersal pattern determined for the coarse-grained quartz and feldspar assemblage (Factor 2) in this study is probably a reasonable first-order approximation of the fate of this material. Similarly, an accurate assessment of the impact of chemical pollutants on the biogeochemical cycles of an aquatic system requires a

knowledge of how these substances are distributed within the system. Many common pollutants in the Great Lakes, such as heavy metals (Cahill 1981, Rygwelski 1984), petroleum by-products (Meyers 1984), and polycyclic aromatic hydrocarbons (Eadie 1984) are rapidly incorporated into the solid phase, either because of their inherently low solubilities or because they exhibit a high affinity for adsorption onto particulate matter. These pollutants are typically associated with clay minerals and organic matter (Shimp *et al.* 1970, Filipek and Owen, 1978, Cahill 1981), and their dispersal pattern in Lake Michigan should be similar to that shown for the fine-grained (Factor 1) compositional end-member determined in this study.

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