ELOSD - Sand Transport

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C. Brian Trask

DIFFERENTIAL TRANSPORT OF FALL-EQUIVALENT SAND GRAINS, LAKE ONTARIO, NEW YORK[1]

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ABSTRACT: Fractions composed of grains having uniform fall velocity (equivalent to 2 ϕ quartz) were extracted from beach sands collected along the eastern end of Lake Ontario, New York. Heavy-liquid separations and point counts were performed on these fall-equivalent velocity splits to obtain relative abundances of hornblende, augite, hypersthene, garnet, magnetite, and quartz-density lights.

Heavy minerals decrease in abundance in the direction of transport, and the degree to which any particular mineral lags behind another lighter mineral is a simple function of the mineral's effective-density ratio. Our results appear to confirm that heavy minerals are less transportable than fall-equivalent lights, an effect that may result from differential entrainability, transport within different zones of the beach, or both.

INTRODUCTION

The eastern shore of Lake Ontario provides an ideal natural environment in which to study progressive sorting of light and heavy minerals during longshore transport. Sedimentologically, the system is relatively simple and well understood. Sand-beach stretches for 25 km from the Salmon River to Stony Point (Fig. 1), interrupted only by occasional inlets that connect the open lake with lagoons behind an otherwise continuous barrier. Because the orientation of the beach is north-south (normal to the approach of longest-fetch waves), littoral drift at a particular locality can be in either direction, but the long-term balance favors northward transport. Reversals affect mostly the region north of the inlet to North Pond.

In the present study, we examine down-drift changes in abundance ratios of minerals within a particular fall-velocity fraction. These changes can be related to textural trends and known transport directions in ways that may have applications to the analysis of ancient dispersal patterns. They also provide insight into the nature of hydraulic equivalence in the littoral environment.

EQUIVALENCE

Sedimentologists commonly characterize grains in terms of fall velocity. The special appeal of fall velocity is that it represents a balance between grain weight, which offers resistance to transport, and hydrodynamic drag, which is chiefly responsible for entraining grains and keeping them in motion. In general, we expect that the faster a grain settles through still water, the less easily it will be moved by currents.

Fall equivalence has sometimes been used as an approximation to *transport equivalence,* especially when grains of different-density minerals are being compared. Nevertheless, fall equivalence is an imperfect measure of transportability because grain transport in a natural system is different from free fall in still water. Some of the differences are geometric (grain orientation and packing, for example), whereas others are related to flow conditions near the bed (effects of shearing flow, the viscous sublayer, nonuniform distribution of turbulence near the bed, entrained sediment). It is important, therefore, to distinguish between fall equivalence and transport equivalence.

Unfortunately, transport-equivalence relationships are elusive. They prevail only in the context of some natural environment that generally cannot be reproduced in the laboratory. Furthermore, different relative transportabilities (and different equivalence relationships) may occur on different scales and at different times, even within a particular environment.

Rittenhouse (1943) attempted to identify transport-equivalent ("hydraulically equivalent") sizes of various minerals in Rio Grande sediment by determining the size-grade pairs of light and heavy minerals that most nearly maintained constant abundance ratios among samples of bed material. The abundance ratios themselves (multiplied by 100) were termed hydraulic ratios. Barring differential destruction, hydraulic ratios were expected to remain constant in the downstream direction until sediment of a different character was introduced from another source. Conversely, changes in hydraulic ratios could (at least in principle) be used to document differential destruction of particular minerals or the influx of sediment from tributary streams. McMaster (1954) used hydraulic ratios to help define sediment sources and transport directions on beaches along the New Jersey shoreline.

Our study did not involve identification of transport-equivalent fractions or use hydraulic ratios as defined by

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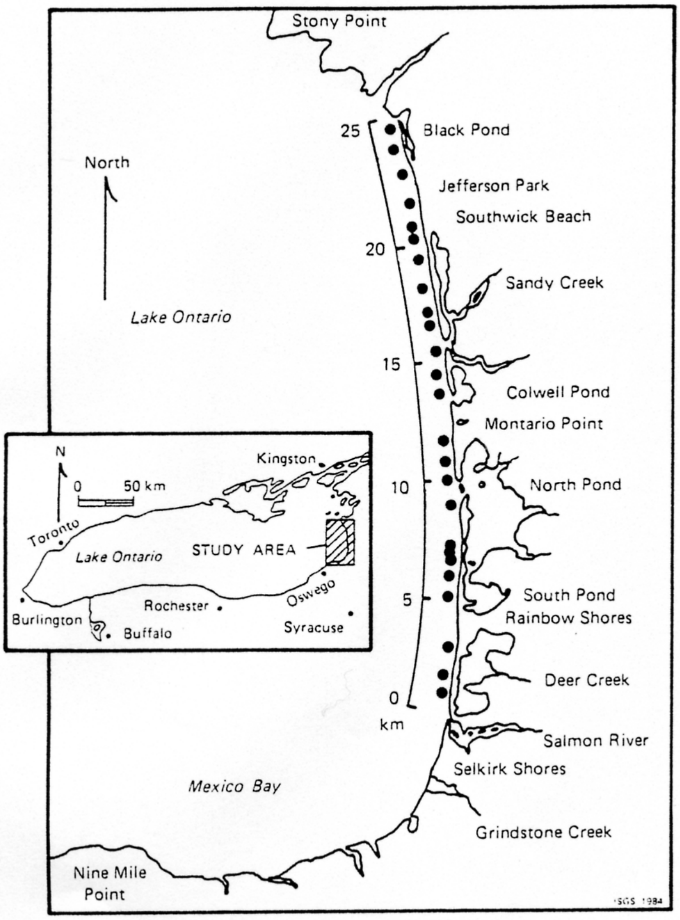

FIG. 1.—Index map. Scale shows distance in km north of Salmon River inlet. Dots show locations of samples for which mineral ratios were determined.

Rittenhouse (1943), but rather focused on the departures of transport equivalence from fall equivalence. That such departures exist has been known for some time. Hand (1967) found that, in general, heavy minerals in New Jersey beach sands were too fine (i.e., they settled too slowly) to be fall-equivalent with the associated quartz, although mean sizes of minerals varied among samples in such a way that they appeared to reflect hydraulic equivalence. Moreover, the light and heavy minerals in sands from associated dunes seem adjusted to eolian transport; they showed similar systematic depatures from fall equivalence provided the depositing medium was presumed to be air.

Slingerland (1977) has suggested that the observations reported by Hand (1967) might reflect availability of particular grain sizes rather than sorting based upon hydraulic equivalence. Clearly, the role of hydraulic sorting must be evaluated using methods that are insensitive to source area limitations. The present study accomplishes this by examining trends in abundance ratios of various minerals *within a particular fall-velocity fraction*. Abundance ratios determined in this way should not be influenced by characteristics of the overall grain-size distributions (e.g., coarse or fine, well-sorted or poorly sorted) of the samples. Furthermore, these ratios are unaffected by whether the availability of a particular mineral in the fraction in question happens to be high or low compared with availability of the same mineral in other velocity ($\approx$ size) fractions.

Unlike the Rittenhouse hydraulic ratios, our mineral abundance ratios within a particular velocity fraction are not expected to remain constant; fall equivalence does not guarantee transport equivalence. However, changes in the down-transport direction should be smooth and systematic, and should provide measures of the degree to which transportability is controlled by factors other than fall velocity. As with hydraulic ratios, of course, dissimilar material from a new source would be expected to produce abrupt changes in abundance ratios.

CHARACTER AND HISTORY OF THE EASTERN SHORELINE

From near the mouth of the Salmon River (Km 0), a broadly arcuate sand beach extends northward for 25 km to the bed-rock headlands of Stony Point (Fig. 1). For most of its length the beach consists of barriers and spits backed by marshes, lagoons, and estuaries. Active dunes (less than about 6 m high) commonly occur on the barriers, and in several places heavily vegetated, inactive dunes reach 20 m or more in height.

The shoreline of Lake Ontario is experiencing transgression that began about 10,500 years ago when the St. Lawrence Valley became free of ice and the present lake outlet was established (Karrow et al. 1961). Rise in lake level has occurred because the bed-rock sill that controls the outlet has been rebounding more rapidly than the rest of the lake basin. This Holocene transgression accounts for the rialike configuration of the mainland coast behind the barriers of the eastern shore. A further consequence of rising lake level has been the development of a transgressive sand sheet over the entire "shelf" region along the eastern end of the lake (Sutton et al. 1970, 1974). This sand sheet extends about 3 km offshore to a "shelf" edge in water about 15 m deep.

The overall picture is of a relatively narrow barrier system migrating eastward in response to rising lake level. As in many comparable marine-barrier systems, recession of the lakeward margin is compensated by growth of the landward margin through storm washover and eolian processes. True tidal deltas do not develop because the Great Lakes are essentially tideless, though sieches with amplitudes of several tens of centimeters and periods of about 6 hr are common (Bolduc 1974; Cohn 1974; Simpson and Anderson 1964). Waves and storm-generated currents also sweep sand landward through inlets. Fine sediment and organic material accumulate in marshes fringing the back of the barrier. In the face of barrier encroachment and sediment infilling, open-water lagoons are maintained by the continuing rise in lake level.

LONGSHORE SEDIMENT TRANSPORT

Along the eastern end of Lake Ontario, there are few opportunities for sediment input except by littoral drift from the south (Sutton et al. 1974). Bluffs of erodible drift are known to supply significant quantities of sediment along many other parts of the Lake Ontario shoreline, but along the eastern shore, north of the Salmon River, bluffs are of minor significance. Moreover, the presence of a Holocene sand sheet indicates that offshore is a region of net sedimentation that precludes derivation of much sediment through subaqueous (shoreface) erosion, except perhaps at times when portions of the shelf sand sheet are temporarily removed to permit erosion of underlying material. Finally, broad marshes or mud-floored lagoons (freshwater estuaries) that function as effective sediment traps preclude appreciable fluvial input of sand.

The consensus of most workers has been that beach sand along the eastern shore is supplied primarily by littoral drift from the south (Casey et al. 1973; Canada Centre for Inland Waters 1973; Sutton et al. 1974). This is consistent with the known eastward movement of sediment along the southern shore of Mexico Bay (Sutton et al. 1974), and with the fact that bed-rock headlands and deep coves associated with the outlet to the St. Lawrence River preclude introduction of much sand by littoral drift from the north.

Sutton et al. (1974) based their conclusion of northward transport on an observed northward decrease in mean grain size accompanied by improved sorting and decrease in abundance of heavy minerals. These observations are consistent with the northward migration of Salmon River and Grindstone Creek inlets (U.S. Beach Erosion Board 1954) and with short-term studies using tracer sands (Nugent et al. 1975).

Nevertheless, persistent northward transport is best established for the southern part of the eastern shoreline. North of the inlet to North Pond, drift directions are more variable (Casey et al. 1973). Ultimate derivation of the more northerly beach sand by littoral drift from the south is, of course, not precluded by this finding. However, directional trends might well be expected to become less pronounced toward the northern "dead end" as short-term reversals become relatively more important.

TEXTURE

Methods

We collected two sets of beach foreshore samples for textural analysis to provide background for the study of mineral ratios. Thirty-one "June" samples were obtained between 3 June and 2 July 1974, toward the end of an erosional cycle that had produced an extremely narrow beach. Distance between sampling stations was about 1 km. Sixty-two "autumn" samples, spaced approximately at 0.5-km intervals, were collected during the period 14 September to 15 October 1974. The beach at this time was in an accretionary phase and up to 100 m wide.

Samples were obtained from the swash zone by inserting a 6.5-cm-diameter tube into the beach to a depth of 15 cm, then transferring the contents to plastic bags. Samples were coded by a colleague so they could be processed in random, blind sequence.

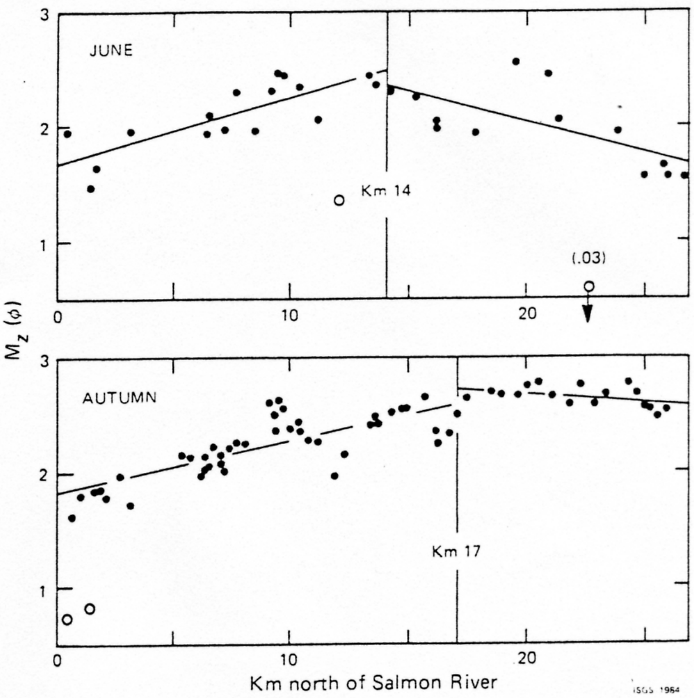

FIG. 2.—Change in mean grain size north of Salmon River inlet. Open circles represent datum points not included in regression analysis.

For mechanical analysis, we obtained a representative 30- to 50-g split from each bulk sample using a riffle splitter. As necessary, the subsamples were stirred in water and decanted to remove clay (present only in trace amounts) or treated with hydrogen peroxide to eliminate organic matter. They were then sieved using a ¼ ϕ screen interval. Summary statistics were calculated according to the equations of Folk and Ward (1957).

Results

Graphic mean grain size (M_Z) is plotted in Figure 2.

If two "outlier" points near Kms 12 and 22 are excluded, the June (erosional phase) samples range from 1.5 ϕ to 2.6 ϕ, evenly divided between fine sand and medium sand, and with a grand mean of 2.0 ϕ. (The anomalously coarse Km-22 sample was collected from a thin veneer of sand overlying gravel, close to a small till outcrop.)

Autumn samples (accretionary beach) were somewhat finer. Omitting two that were associated with gravel deposits near the extreme southern end (Km 0 and Km 1, both coarse sand), M_Z ranged from 1.6 ϕ to 2.8 ϕ. The grand mean was 2.3 ϕ, and 85 percent of the samples were fine sand.

Both sample sets show a clear northward decrease in grain size for the first 14 km. North of Km 14 (Colwell Pond), the June samples again coarsen. In the autumn data, the northward-fining trend persists to Km 17 (north of Sandy Creek inlet). Beyond Km 17 there may be northward coarsening, but the trend is weakly expressed. Sutton et al. (1974) show a grain-size pattern almost identical to that of our autumn samples.

in transport. Simple arithmetic decline requires that the mineral ratio go to zero within a finite distance.

Returning to the data of Figures 5 and 6, one can see that the slopes of the regression lines are related to the effective density ratios. The greater the effective density ratio, the greater the difference in transportability.

This relationship can be more fully evaluated by plotting the slopes C_t of the regression lines from Figures 5 and 6 against the log of effective density ratio (Fig. 7). When the data for mineral pairs involving quartz-density lights, hornblende, augite, hypersthene, garnet, and magnetite are then subjected to regression analysis with the best-fit line constrained to pass through the origin,

$$C_t = -.255 \log(\rho_H'/\rho_L'). \quad [3]$$

The correlation coefficient r is $-.96$. Without being forced to pass through the origin, the regression line misses the origin by a trivial amount. (Clearly, grains cannot be separated by density if they do not differ in density.)

Equations 1 and 2 can now be expanded:

$$\log R = \log R_o - .255 \log(\rho_H'/\rho_L')X \quad [4]$$

$$\log\left(\frac{R}{R_o}\right) = -.255X \log\left(\frac{\rho_H'}{\rho_L'}\right) \quad [5]$$

$$\frac{R}{R_o} = \left(\frac{\rho_H'}{\rho_L'}\right) - .255X \quad [6]$$

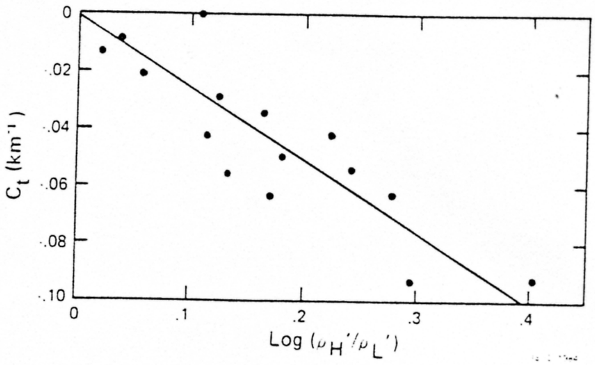

FIG. 7.—Relative transportability (expressed as C_t) as a function of log (effective density ratio). Regression constrained to pass through origin.

DISCUSSION

We attribute the compositional trends within our (2 ϕ quartz-equivalent) fall-velocity fraction to progressive sorting. Multiple source areas could, of course, impose mineralogic differences, but in our study area this seems ruled out by the apparent simplicity of the transport system, the parallelism between compositional and textural trends, and the relative compositional uniformity of glacial deposits that provided the sand. Equally inadequate is differential attrition, given the known difficulty of abrading fine sand grains in water (Kuenen 1959, 1960), the small scale and low energy of the system, and the short length of time available.

If the observed variations among heavy minerals were imposed by either multiple source areas or differential attrition, then, similarly, strong variations would almost surely occur in the relative abundances of various light minerals as well. Examination of the light mineral fraction shows no such trends. Quartz, microcline, orthoclase, plagioclase, and carbonate grains all maintain relatively stable abundances along the eastern shore, despite the facts that these minerals differ widely in durability and generally would not be contributed in the same proportions from different source areas.

Our present results are better explained in terms of differential transport rates with denser grains moving alongshore less rapidly than fall-equivalent lights.

The implied departure of transport equivalence from fall equivalence may in part relate to difficulty of entrainment, as proposed by Hand (1967). Grains having equal fall velocities were presumed to travel similar distances during each brief transport (suspension) episode. But a heavy-mineral grain, because of its smaller size, has a geometric disadvantage that makes it less entrainable (and thus less transportable in terms of the overall transport process) than fall-equivalent light companions. The effect of relative size has been evaluated by Everts (1973) and Slingerland (1984), and relevant experiments involving heavy minerals have been conducted by Steidtman (1982). When bed forms are present, additional mechanisms come into play and complicate the situation, but variations in transport rates of heavies, vis-à-vis lights, are parallel to those during transport over a flat bed (Algeria 1983).

The foregoing model describes conditions within a single lane of "traffic," where all grains travel the same route and respond individually to the same set of environmental conditions. An alternative mechanism that could produce the same results involves segregation of grains according to their physical properties into different "traffic lanes" (Komar 1977). In the complex of environments that we call a beach, grains preferentially stored near the upper limit of swash, for example, may well move alongshore less rapidly than others which spend most of their time in the surf zone. The importance of this mechanism in the present context depends on how effectively grains having different densities but equal fall velocities can be segregated into different zones. It depends also on the relative amounts of sediment transported within each of these zones.

Strictly speaking, our results are compatible with either model. Both mechanisms must operate on most beaches, and we presume that the eastern end of Lake Ontario is no exception. But which dominates?

Although our data do not force a clear choice, a systematic relation between transport disadvantage and effective density follows naturally from the "single-lane" model. For the "multiple-lane" model to produce the trend seen in Figure 7, grains either must be segregated into "lanes" whose rate of longshore drift happens to be inversely proportional to effective density, or their residence time in slow and fast lanes must be partitioned according to effective density.

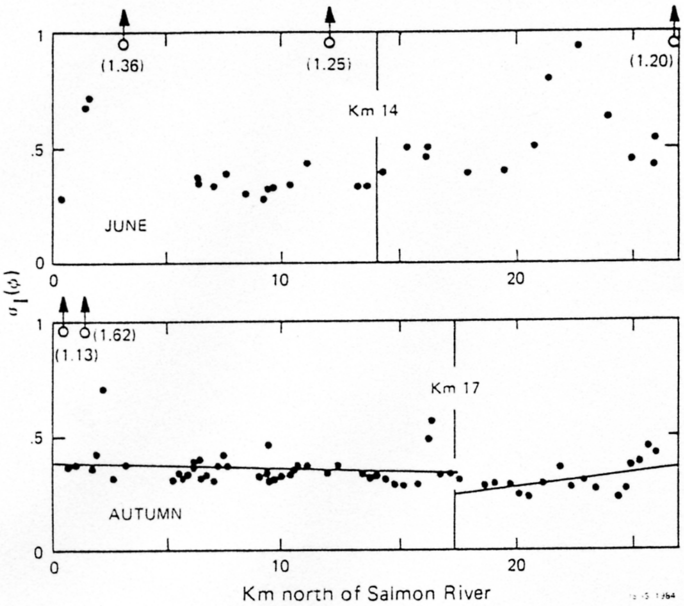

FIG. 3.—Change in standard deviation north of Salmon River inlet.

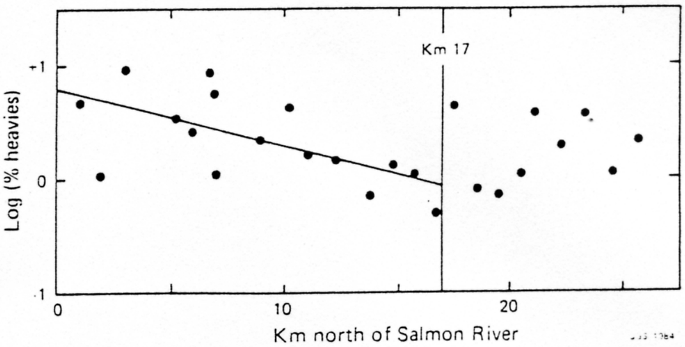

FIG. 4.—Change in heavy mineral abundance north of Salmon River inlet; 2 ϕ quartz-equivalent fraction.

Changes in grain size along a beach can reflect adjustment to differential wave attack (Goldsmith 1976). Within our study area, however, grain size appears unrelated to either offshore topography or expected wave energy (Trask 1976). The observed trends seem to be better explained in terms of progressive sorting during longshore transport. The June samples apparently represent two coastal cells (Trask 1976), with northward drift between Km 0 and Km 14 and southward drift between Km 14 and Km 26. In autumn, northward drift extended to Km 17, beyond which the preferred direction of longshore transport is uncertain, but probably southward.

Figure 3 shows Folk and Ward's (1957) inclusive graphic standard deviation, σ_I, which is an inverse measure of sorting. Most of our samples are well to very well sorted (Folk 1974), with autumn samples generally better sorted than June samples (mean $\sigma_I = 0.38\ \phi$ vs. $0.53\ \phi$). Both sets show so much scatter that interpretation is difficult. However, with prior knowledge that a discontinuity in mean grain size occurs at Km 17 in the autumn samples, one can perhaps detect a matching discontinuity in the corresponding plot of standard deviation.

MINERAL-ABUNDANCE RATIOS IN FALL-EQUIVALENT SPLITS

Methods

Because the textural data for autumn samples showed the greatest consistency and simplest trends, we examined these samples further in terms of mineral composition. Specifically, mineral-abundance ratios were determined in 25 of the 62 autumn samples, spaced approximately at 1-km intervals. A fraction having a fall velocity equivalent to 2 ϕ quartz was chosen for ease of mineral identification and because it contained a more varied population of heavy minerals than did finer fractions.

Grains fall-equivalent to 2 ϕ quartz were extracted using a water-filled settling tube 165 cm long by 7.3 cm inside diameter. The tube had previously been calibrated with quartz grains of known sieve size. Our calibration curve closely followed that of Gibbs et al. (1971) for settling of quartz spheres but was displaced slightly toward slower velocities, as should be expected for natural, nonspherical grains (Baba and Komar 1981).

Samples weighing 10 g were introduced at the top of the tube as sand-water slurries mixed by shaking in a small tube in the manner devised by Emery (1938). To disperse the grains as fully as possible and inhibit development of turbidity currents, the top 30 cm of water in the settling tube was churned just prior to sample release. After 51 to 53 seconds (depending on water temperature), a tap at a depth of 150 cm was opened for 2 sec to obtain a sample of fluid containing only grains having the fall velocity of 2 ϕ quartz.

We separated the 2 ϕ quartz-equivalent velocity "slices" into light and heavy mineral fractions using S-tetrabromoethane (s.g., 2.96 at 25°C), and weighed the fractions. Small, representative splits of these fractions were mounted on glass microscope slides with a thin smear of Lakeside cement.

Mineral identification was by standard optical techniques, including examination in oils introduced under a loose cover slip. We counted grains using a modified Fleet method (Fleet 1926; Galehouse 1969, 1971). All grains within each of several fields of view were identified until 200 grains had been counted. Additional nonopaque grains were then counted to provide a total of 200 nonopaque heavies (technique of Doeglas 1940).

Results

Heavy minerals within our 2 ϕ quartz-equivalent "slice" average 2.8 percent by weight, ranging from 0.5 percent to just under 10 percent. Their abundance decreases northward, and casual inspection of the data (Fig. 4) might suggest a simple, monotonic decrease across the full length of beach.

Close examination, however, reveals that the textural discontinuity previously identified at Km 17 can also be recognized in the data for heavy mineral abundance. There

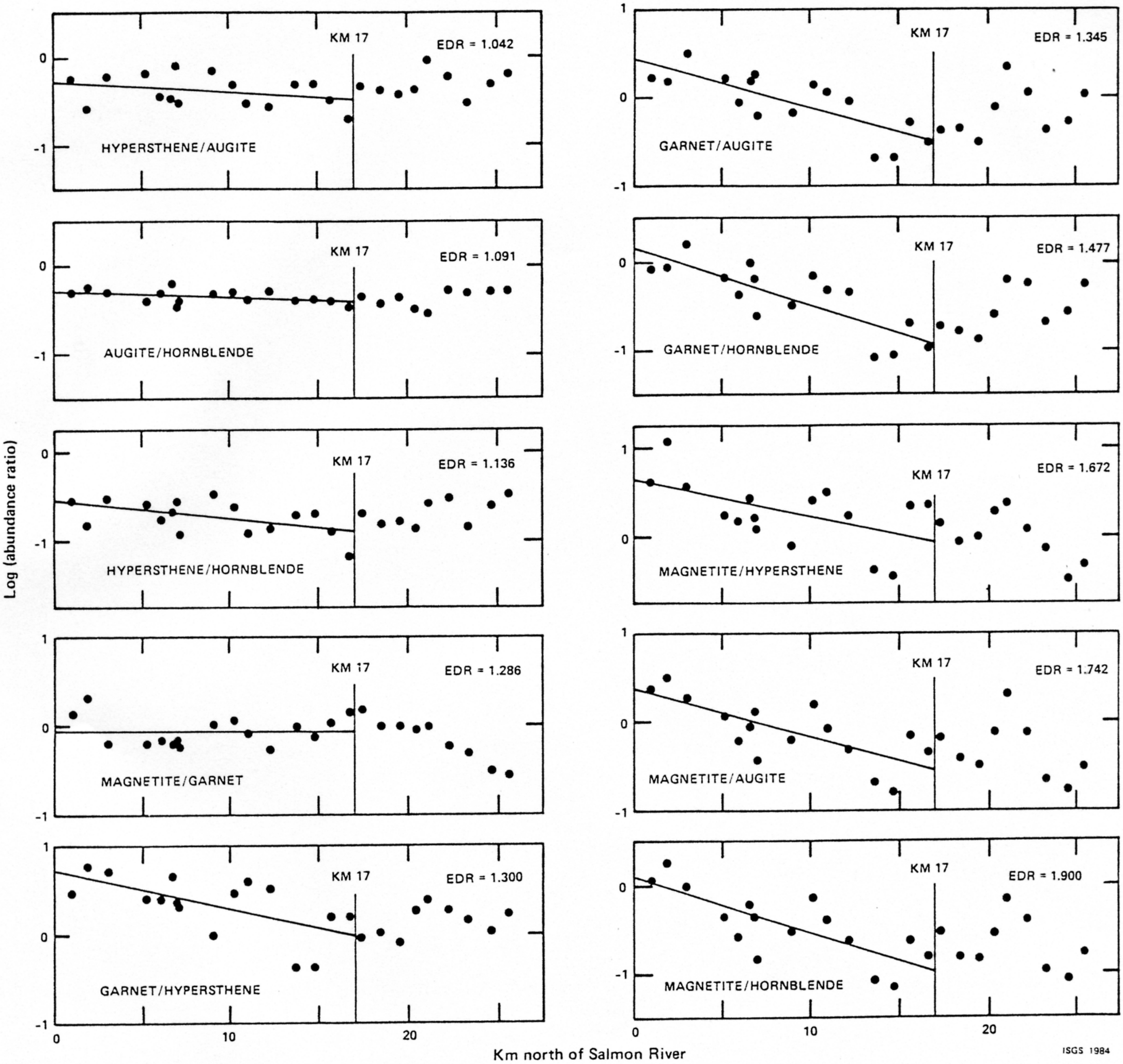

FIG. 6.—Change in abundance ratios (heavy/light) north of Salmon River inlet; 2 ϕ quartz-equivalent fraction. Individual heavy minerals are compared with other heavy minerals.

where simple linearity might be expected (Km 0 to Km 17).

3) With arithmetic scales, slopes of regression lines range wildly across several orders of magnitude, depending on whether the particular heavy mineral is being compared with an abundant companion (e.g., quartz) or one whose abundance is comparable with its own (another heavy mineral).

All these pratical problems vanish when semilog plots are used.

Using the logs of abundance ratios can also be justified in terms of the process being represented. Suppose, for example, that the effect of 10 km of transport is to halve the ratio of Mineral A to Mineral B. It then seems reasonable to expect this ratio to be halved again by another 10 km of transport, and so on, indefinitely. On semilog paper, not only will the results graph as a straight line, but the slope of that line will be independent of the initial abundances of either mineral. Furthermore, deposition is a probabilistic phenomenon, wherein some individual grains of every mineral are bound to continue indefinitely is progressive depletion of heavy minerals in the down-drift direction, which implies that heavies are less readily transported by littoral drift than are fall-equivalent lights. Consistent with the textural data, samples from north of Km 17 do not continue this well-defined trend, nor do they suggest an independent trend of their own.

"Heavies," of course, are a mixed bag whose average density depends on what minerals are present in what proportions. Moreover, unless the relative abundances of different mineral species remain constant during transport, their resulting average density will almost certainly change with distance.

For this reason, we undertook to determine the relative abundances of five particular minerals within the heavy mineral fraction: hornblende (density 3.20), augite (3.40), hypersthene (3.5), garnet (4.25), and magnetite (5.18). In assigning densities, we took account of the varieties common in local glacial deposits, from which most of the sand was derived. (Other heavy minerals present in our samples included apatite, epidote, kyanite, monazite, rutile, sillimanite, sphene, topaz, tourmaline, tremolite-actinolite, zircon, zoisite, ilmenite, leucoxene, and hematite.)

Abundance ratios of particular heavy minerals with respect to quartz-density lights are shown in Figure 5, and ratios determined for various heavy mineral pairs are in Figure 6. Within each figure, plots are ordered according to the effective density ratios of minerals being compared. Effective density ρ' is equal to grain density less fluid density, and the effective density ratio is ρ_H'/ρ_L', where subscripts identify the heavier and lighter minerals of a pair.

In every instance, these data suggest the same discontinuity at Sandy Creek that was revealed by textural analysis and reflected in heavy mineral abundance. Between Salmon River inlet and Sandy Creek (Km 0 to Km 17), the heavier of two minerals in any pair decreases northward in the direction of littoral drift, but beyond Km 17 the abundance ratios behave erratically and seem unrelated to trends farther south. Because our focus will be on changes that occur during transport, the data from north of Km 17 need not be considered further.

Regression lines computed for the reach between Salmon River inlet and Sandy Creek (Figs. 5 and 6) show the down-drift changes in mineral composition that occur within our 2 ϕ quartz-equivalent fraction. These can be expressed mathematically as follows:

$$\log R = \log R_o + C_t X \quad [1]$$

$$R = R_o \times 10^{C_t X}, \quad [2]$$

where R is the abundance ratio computed with respect to another mineral, R_o is the initial abundance ratio, C_t is a coefficient of transportability (generally negative), and X is the distance of transport. The value of C_t depends on the particular mineral pair being considered and expresses the relative transport disadvantage of the heavier mineral. It is in fact the slope of the appropriate regression line (Figs. 5 and 6). In our analysis, C_t has dimensions km^{-1} because X is expressed in km.

The choice of semilogarithmic plots to display mineral-

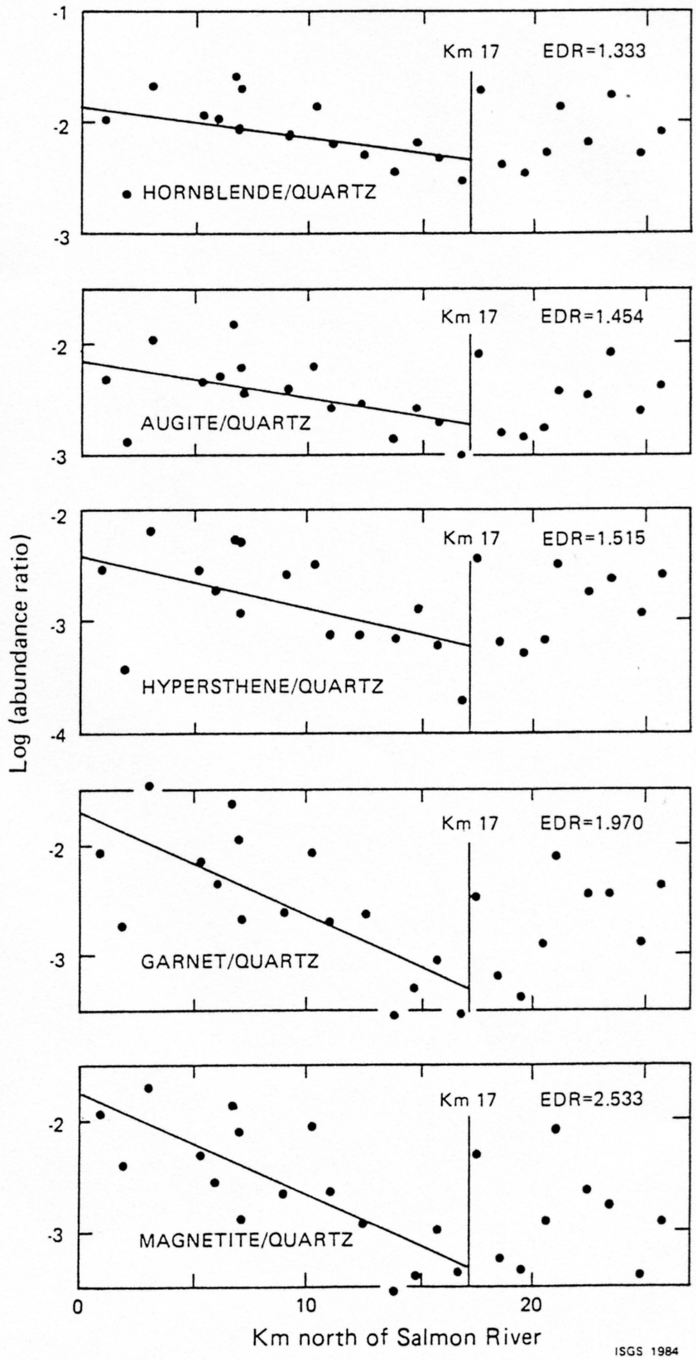

FIG. 5.—Change in abundance ratios (heavy/light) north of Salmon River inlet; 2 ϕ quartz-equivalent fraction. Individual heavy minerals are compared with quartz-density lights. EDR = effective density ratio.

abundance ratios was based in part on practical considerations but, more importantly, on arguments relating to the physical meaning of the graphs. Several observations suggest that our practice is an appropriate one:

1) Arithmetic plots of the same data are highly heteroschodastic, that is scatter increases as the magnitude of the plotted values increases.
2) Arithmetic plots are consistently curvilinear in regions

We prefer a middle ground. While the reality of multiple lanes must be acknowledged, we suspect that transport within the surf zone is volumetrically so important as to dominate. Our trends can then be understood as consequences of differential transportability within the surf zone (essentially a "linear" model). Material swept onto the foreshore may be biased as a sample of surf-zone sediment, but it should nonetheless reflect the same compositional trends.

Preservation of Trends

Down-transport decrease in mean grain size and improvement in sorting are so ordinary that they might seem to call for no further discussion, explanation being required only when there is a reversal of these familiar trends (for example, Bradley et al. 1972). If heavy minerals are known to be less transportable than fall-equivalent lights, then depletion of heavies in the down-drift direction seems equally reasonable.

However, sedimentologic trends, whether textural or compositional, do not automatically follow from the fact that some constituents travel more rapidly than others. In a flume where sediment and water are continually recycled together, the equilibrium bed will be uniform for its entire length even though different fractions travel at different speeds. The same is true for beach sediment in "through" transport between points A and B, A being a source and B a sink, provided enough time has elapsed so that the slowest-moving sediment fraction can have traveled the full distance (Pettijohn and Ridge 1932).

Differential transport rates can be translated into trends if sediment is lost en route, that is, the transport path functions also as a line sink. The textural and compositional trends between Salmon River inlet and Sandy Creek may therefore owe their development to sediment storage (net deposition) on the beach itself or loss to the offshore zone. Neither mechanism, of course, could produce longitudinal gradients of any type if all components of the sediment were equally transportable.

The beach storage alternative might seem indicated by the fact that our autumn samples (the ones used for mineralogic analysis) were collected following a period of beach accretion. However, this accretion was due almost entirely to seasonal offshore/onshore redistribution of sand that occurs on Great Lakes shorelines, much as it does along marine beaches (Davis and Fox 1972; Davis et al. 1972). It did not result from import of large quantities of new sediment from the south. Indeed, the narrowness of the barriers is evidence that the beach has not been characterized by net accretion and widening, at least through the latter part of the Holocene. The better alternative is that sand is continually being lost offshore—that it is being "left behind" during transgression to nourish and extend the shelf sand sheet.

Short-term fluctuations in longshore transport occur (June vs. autumn textural data), but they involve small quantities of surficial sediment that cannot much affect the bulk character of the beach. We interpret the observed textural and compositional trends not as products of a single season, but as reflections of gradients developed over hundreds, if not thousands, of years, in response to persistent transport and depositional patterns.

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REFERENCES

ALGERIA, S. A., 1983, Relative transportability of sand grains as a function of size and density determined for various bed states in a laboratory flume [unpubl. M.S. thesis]: Syracuse Univ., 190 p.

BABA, J., AND KOMAR, P. D., 1981, Measurements and analysis of settling velocities of natural quartz sand grains: Jour. Sed. Petrology, v. 51, p. 631–640.

BRADLEY, W. C., FAHNESTOCK, R. K., AND ROWEHAMP, E. T., 1972, Coarse sediment transport by flood flows on Knik River, Alaska: Geol. Soc. America Bull., v. 83, p. 1261–1284.

BOLDUC, P., 1974, Point Petre storm surges simulation: Proc. 17th Conf. Great Lakes Res., pt. 1, p. 358–368.

CANADA CENTRE FOR INLAND WATERS, 1973, Great Lakes shore erosion studies, a progress report, March 1973: CCIW Paper No. 11, 10 p.

CASEY, D. J., FISHER, W., AND KLEVENO, C. O., 1973, Lake Ontario environmental summary 1965: U.S. Environmental Protection Agency, Region II, Rochester Field Office, 85 p.

COHN, B. P., 1974, Accretion and erosion of a Lake Ontario beach, Selkirk Shores, New York [unpubl. M.S. thesis]: Syracuse Univ., 173 p.

DAVIS JR., R. A., AND FOX, W. T., 1972, Coastal processes and nearshore sand bars: Jour. Sed. Petrology, v. 42, p. 401–412.

DAVIS JR., R. A., FOX, W. T., HAYES, M. O., AND BOOTHROYD, J. C., 1972, Comparison of ridge and runnel systems in tidal and non-tidal environments: Jour. Sed. Petrology, v. 42, p. 413–421.

DOEGLAS, D. L., 1940, The importance of heavy mineral analysis for regional sedimentary petrology: National Research Council, Committee on Sedimentation, Report 1939–1940, Exhibit G, p. 102–121.

EMERY, K. O., 1938, Rapid method of mechanical analysis of sands: Jour. Sed. Petrology, v. 8, p. 105–111.

EVERTS, C. H., 1973, Particle overpassing on flat granular boundaries: Am. Soc. Civil Engineers Proc., v. 99, no. WW4, p. 425–438.

FLEET, W. F., 1926, Petrological notes on the Old Red Sandstone of the West Midlands: Geol. Mag., v. 63, p. 505–516.

FOLK, R. L., 1974, Petrology of sedimentary rocks: Austin, Texas, Hemphill Publishing Co., 182 p.

FOLK, R. L., AND WARD, W. C., 1957, Brazos River bar: a study in the significance of grain-size parameters: Jour. Sed. Petrology, v. 27, p. 3–26.

GALEHOUSE, J. S., 1969, Counting grain mounts: number percentage vs. number frequency: Jour. Sed. Petrology, v. 39, p. 812–815.

GALEHOUSE, U. J. S., 1971, Point counting, *in* Carver, R. E., ed., Procedures in Sedimentary Petrology: New York, Wiley Interscience, p. 385–407.

GIBBS, R. J., MATTHEWS, M. D., AND LINK, D. A., 1971, The relationship between sphere size and settling velocity: Jour. Sed. Petrology, v. 412, p. 7–18.

GOLDSMITH, V., 1976, Wave climate models for the continental shelf: critical links between shelf hydraulics and shoreline processes, *in* Davis Jr., R. A., and Ethington, R. L., eds., Beach and Nearshore Sedimentation: Soc. Econ. Paleontologists Mineralogists Spec. Pub. 24, p. 24–47.

HAND, B. M., 1967, Differentiation of beach and dune sands using settling velocities of light and heavy minerals: Jour. Sed. Petrology, v. 37, p. 514–520.

KARROW, P. F., CLARK, J. R., AND TERASMAE, J., 1961, The age of Lake Iroquois and Lake Ontario: Jour. Geology, v. 69, p. 659–667.

KOMAR, P. D., 1977, Selective longshore transport rates of different grain-size fractions within a beach: Jour. Sed. Petrology, v. 47, p. 1444–1453.

KUENEN, P. H., 1959, Experimental abrasion 3. Fluviatile action on sands: Am. Jour. Sci., v. 257, p. 172–190.
———, 1960, Experimental abrasion of sand grains: Norden, 21st International Geological Congress, pt. 10, p. 50–53.
MCMASTER, R. L., 1954, Petrography and genesis of the New Jersey beach sands: New Jersey Dept. of Conservation and Economic Development, Geologic Series, Bull. 63, 239 p.
NUGENT, R., CALKIN, P. E., AND STEPHENS, J., 1975, Interim report of coastal studies along eastern Lake Ontario and the St. Lawrence River: Watertown, NY, St. Lawrence-Eastern Ontario Commission, 55 p.
PETTIJOHN, F. J., AND RIDGE, J. D., 1932, A textural variation series of beach sands from Cedar Point, Ohio: Jour. Sed. Petrology, v. 2, p. 76–88.
RITTENHOUSE, G., 1943, Transportation and deposition of heavy minerals: Geol. Soc. America Bull., v. 54, p. 1725–1780.
SIMPSON, R. B., AND ANDERSON, D. V., 1964, The period of longitudinal surface seich of Lake Ontario: Proc. 7th Conf. Great Lakes Res., v. 369–381.
SLINGERLAND, R. L., 1977, The effects of entrainment on the hydraulic equivalence relationships of light and heavy minerals in sands: Jour. Sed. Petrology, v. 47, p. 753–770.
———, 1984, Role of hydraulic sorting in the origin of fluvial placers: Jour. Sed. Petrology, v. 54, p. 137–150.
STEIDTMAN, J. R., 1982, Size-density sorting of sand-size spheres during deposition from bedload transport and implications concerning hydraulic equivalence: Sedimentology, v. 29, p. 877–883.
SUTTON, R. G., LEWIS, T. L., AND WOODROW, D. L., 1970, Near-shore sediments in southern Lake Ontario, their dispersal patterns and economic potential: Proc. 13th Conf. Great Lakes Res., p. 308–318.
SUTTON, R. G., LEWIS, T. L., AND WOODROW, D. L., 1974, Sand dispersal in eastern and southern Lake Ontario: Jour. Sed. Petrology, v. 44, p. 705–715.
TRASK, C. B., 1976, Mineralogy, texture, and longshore transport of beach sand, eastern shore of Lake Ontario [unpubl. Ph.D. dissert.]: Syracuse Univ., 306 p.
U. S. BEACH EROSION BOARD, 1954, Selkirk Shores State Park, N.Y., Beach Erosion Control Study: House Doc. No. 343, 83rd Congress, 2nd Session, 32 p.