Hydrobiologia **176/177**: 111–124, 1989.
P. G. Sly and B. T. Hart (eds) Sediment/Water Interaction.
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Sediment dispersion: part 2, characterisation by size of sand fraction and percent mud

P. G. Sly
Environment Canada, Canada Centre Inland Waters, POB 5050, Burlington, Ontario, L7R 4A6, Canada

Key words: sediment texture, sand size, percent mud, dispersion, Liverpool Bay, River Mersey

Abstract

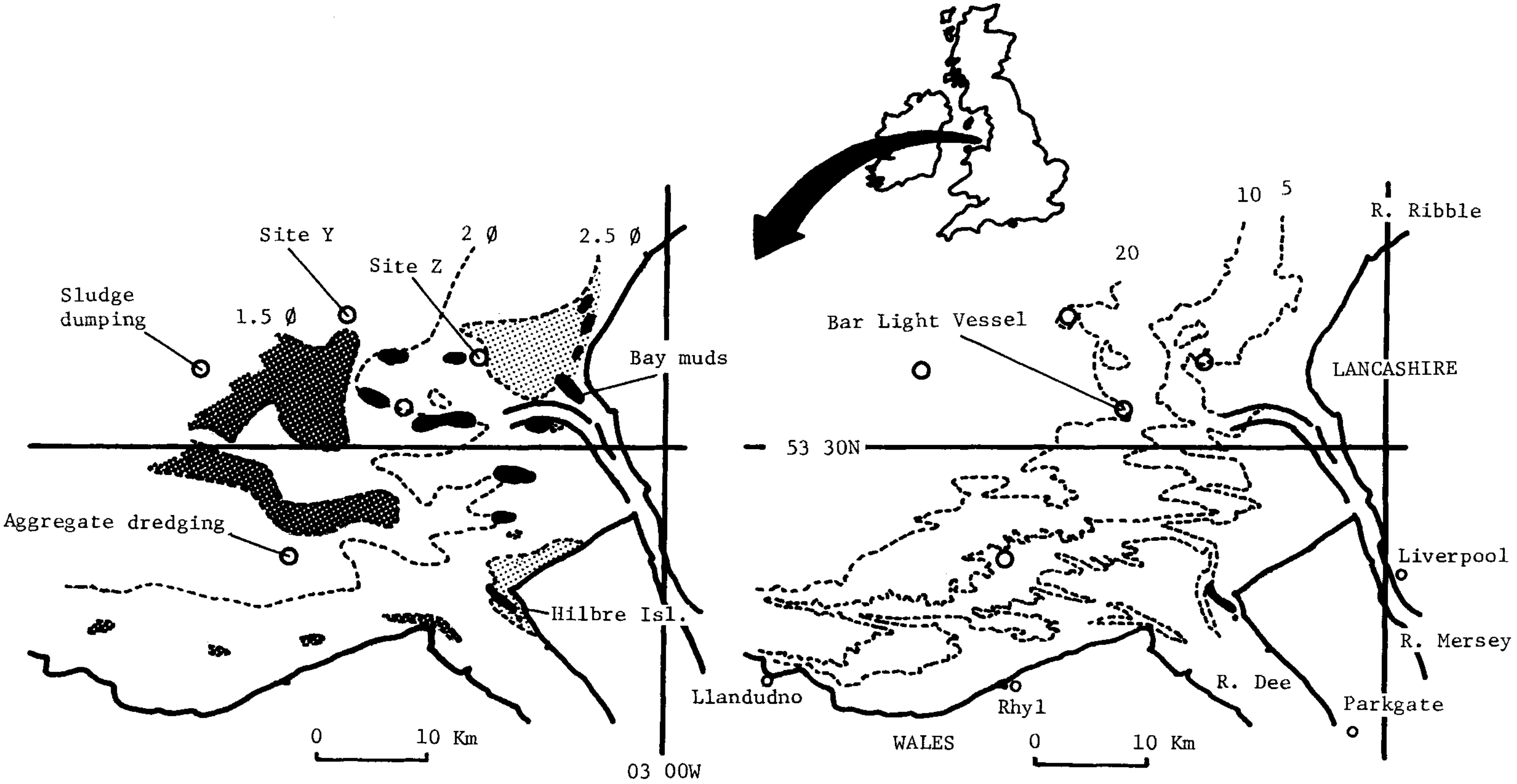
In part 2 of this contribution, examples are drawn from the River Mersey and Liverpool Bay illustrating the use of simple statistical parameters to describe dispersion of sands and muddy sediments. The River Mersey and Liverpool Bay, eastern Irish Sea, were sites of intensive studies on the dispersal of dumped harbour mud and sewage sludge during the mid 1960's–70's. The combined effects of strong tidal scour, wave action and shoreward near-bed residual drift result in shoreward transport of large volumes of sand in the bay. Large amounts of mud (silt/clay mixtures) oscillate in the river estuary, and naturally derived and dumped muds also move shoreward in the bay. Unpublished historic geochemical data have been combined with reprocessed particle size data and both have been used to reassess sedimentological techniques for defining transport and dispersal pathways. River and bay muds have similar size compositions, but river muds have excess Cd > V > U > As = Zn relative to bay muds. The lower relative concentrations of heavy metals in the bay are thought to reflect desorption and degradation of organic matter from the river. Trends in sediment distribution data based on the means of the sand size fraction, alone, provide sensitivities comparable to those of higher order moment measures and are usually easier to interpret than full size spectrum analyses.

Introduction

Sediment research continues to demonstrate the diversity of complex sedimentary environments (Walker, 1984) and now, more than ever, there is a need to simplify methods and interpretations so that the utility of underlying concepts remains easily understood and widely applied. The topic of sediment dispersion is covered by a contribution in two parts.

In the first part (Sly, this volume), attention has been drawn to the silt/clay ratio as a diagnostic feature of fine sediments, and Great Lakes' data have been used to provide examples as a basis for interpretation. In the second part of this contribution, the focus is widened to include sands and muddy sediments and their use as a means of substantiating dispersal of both naturally derived and introduced materials.

In part 2, only two particle size characteristics have been chosen for principal discussion, these are the mean of sand size fraction (0 to 4 phi) and the percent mud content (material < 4 phi). Although these values are not sufficient to define all sedimentary conditions or characteristics, they are relatively easy to measure and understand, and they represent a powerful means of defining sedimentary regimes and dispersal. Historic data



(a) (b)

Fig. 1. Liverpool Bay: a) Distribution of sediments, mean phi size of sand fraction; b) Bathymetry, depth in metres.

describing modern sediments from Liverpool Bay and the River Mersey, UK, (Sly, 1966), are used to provide examples, and contemporaneous but unpublished geochemical data have been added to expand discussion.

Liverpool Bay is a triangular shaped body of water which lies within an area bounded by the coastlines of north Wales and Lancashire (Fig. 1). It is open to the Irish Sea both north and south of the Isle of Man. Three major rivers enter the bay through large estuaries (Dee, Mersey & Ribble). This shallow sea (< 30 m deep) and its drowned estuaries have formed as a result of shelf inundation by the post-glacial sea level rise, although, over the past several hundred years, sea level has remained generally stable (Sly, 1966; Gornitz & Ledédeff, 1987). The combined effects of wave erosion and tidal scour continue to erode glacial and post-glacial deposits and these provide a substantial source of material to be incorporated into the modern sedimentary regime. At present, little sand is contributed to the bay by inflowing rivers. The extent of nearshore sand movement in the bay, however, is dramatically shown by historic chart data (Fig. 2) and by port closures, such as at the village of Parkgate in the River Dee where navigation was lost over a 20–25 year period following the mid 1920's.

With westerly winds dominant over the bay, the fetch is generally limited to about 150 km or less; maximum recorded wave heights at the Bar Light Vessel are generally < 6 m, and 95% of all wave

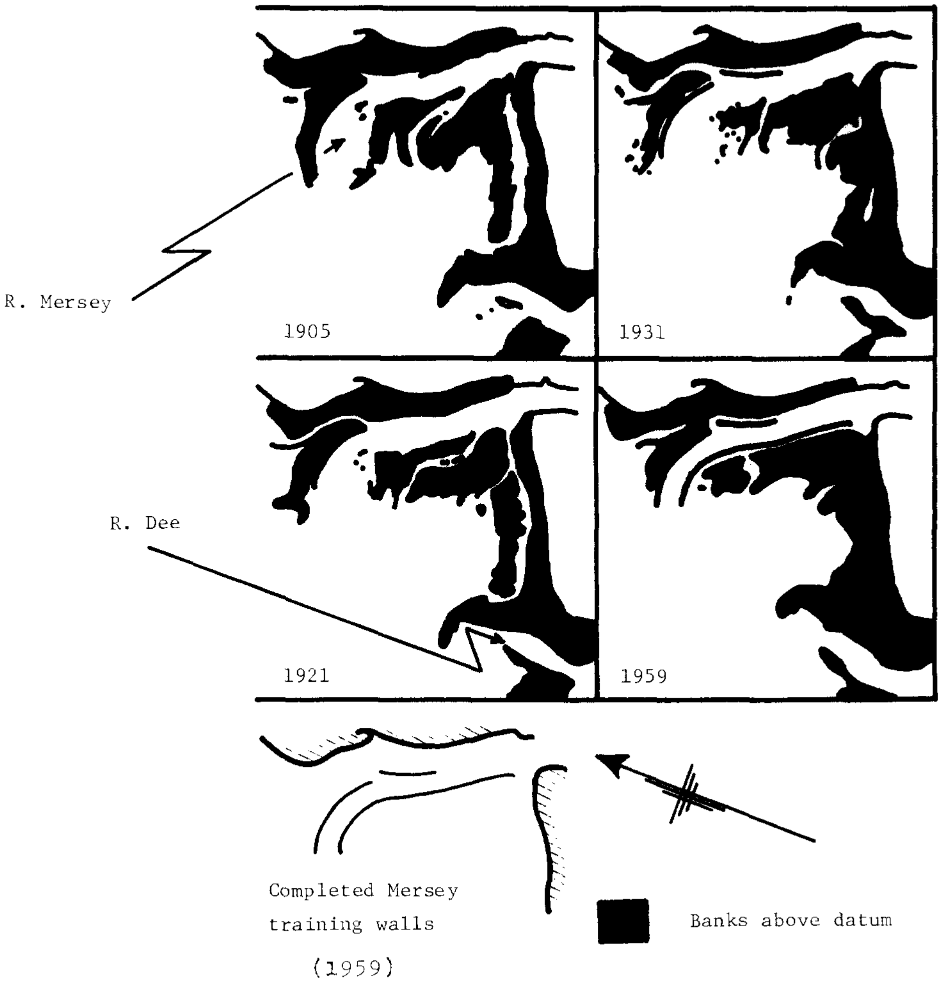


Fig. 2. Changes in bathymetry, Liverpool Bay (1905–1959), modified after DSIR (1938).

heights are less than 3 m. Steep and short period waves (< 6 secs.) are typical of the bay; the shoreline geometry and extensive bars and sand banks also result in locally confused nearshore wave conditions.

The tidal range is large, averaging about 5 m west of Llandudno and about 6 m at Liverpool; the maximum range at Liverpool is > 9 m. Tidal flow is strong, throughtout the area maximum surface currents exceed 1 $\mathrm{m/sec^{-1}}$ and can be > 3.5 $\mathrm{m/sec^{-1}}$ in constricted areas of the River Mersey. The direction of both flood and ebb currents is generally east–west but nearshore directions and velocities can be greatly modified by the bathymetry of channels, banks and bars; residual drift is usually shoreward (Halliwell, 1973).

Bay waters are not always well mixed and surface salinities are lowest in winter, reflecting both reduced salinity of the Atlantic inflow and increased discharge from rivers. At this time of year, Mersey water overlies oceanic water and may extend over most of the central part of Liverpool Bay (UKDOE, 1972). The influence of river discharge is least during the summer period.

Major cultural impacts

The construction of training walls beyond the mouth of the River Mersey took place between 1909–1957 with the object of stabilizing navigation channels; in addition, this had the effect of concentrating dredging activities required for port maintainance. During the late 1960's and early 1970's, harbour dredging amounted to about $15 \times 10^6 \mathrm{t/a^{-1}}$. Sand had to be removed regularly from the outer channel and from within the river, and mud was removed from the enclosed dock basins and their entrances. Almost all of the dredged material was dumped at Site Z (Fig. 1); Site Y received 'junk' from the docks (such as rubble, stone and metal).

The population of the area surrounding Liverpool Bay is more than 5 million and many of the coastal municipalities discharge sewage effluent directly into the bay through outfall pipes. Other inland municipalities transport sewage to central points in Manchester and Salford (upstream from Liverpool) where effluents are combined and loaded into ships for offshore disposal. Sewage sludge (containing about 7% solids) was dumped into western Liverpool Bay (Fig. 1) at a rate of about $6 \times 10^5 \mathrm{t/a^{-1}}$ during the early 1970's (UKDOE, 1972). Both harbour materials and sewage sludge carried high TOD loadings, and elevated levels of heavy metals and persistent organic contaminants, as well as oils and greases. Cultural impacts in the bay are dominated by the River Mersey, and the combined effects of dumping and effluent disposal have lowered water quality. During the 1960's and 1970's, sand and gravel, for use in the aggregate industry, were recovered mostly from an area of about 45 $\mathrm{km^2}$ north of Rhyl (Fig. 1), at a licence limit of $1.2 \times 10^6 \mathrm{t/a^{-1}}$ (UKDOE, 1972).

Sand size particulates

The mean particle size of a total sediment sample is not usually the same as the mean of its sand size fraction. However, the two values become much closer in the mid sand size range where the influences of distal gravel or silt and clay size populations are least. This is reflected by the trend of standard deviation values which reach a minimum at the same point (Fig. 3). Peak kurtosis and the skewness divide (Sly *et al.*, 1983) share a similar point of coincidence in the mid sand size range. As interpreted by Sly *et al.* (1983), the third and fourth moment measures describe the presence of extremely well sorted sediments in which the inclusion of very small quantities of coarse or fine material will shift skewness values to − or + sign (respectively). The skewness divide is extremely sensitive to changes in particle size composition and it is an analog of the minimum shear velocity required to initiate motion of coehesionless particles. In effect, the shift from − to + skewness described a subtle change from erosion dominant to deposition dominant conditions (Hjulström, 1939). Under field conditions, the skewness divide reflects the interaction of a number of factors; in particular, the availability of

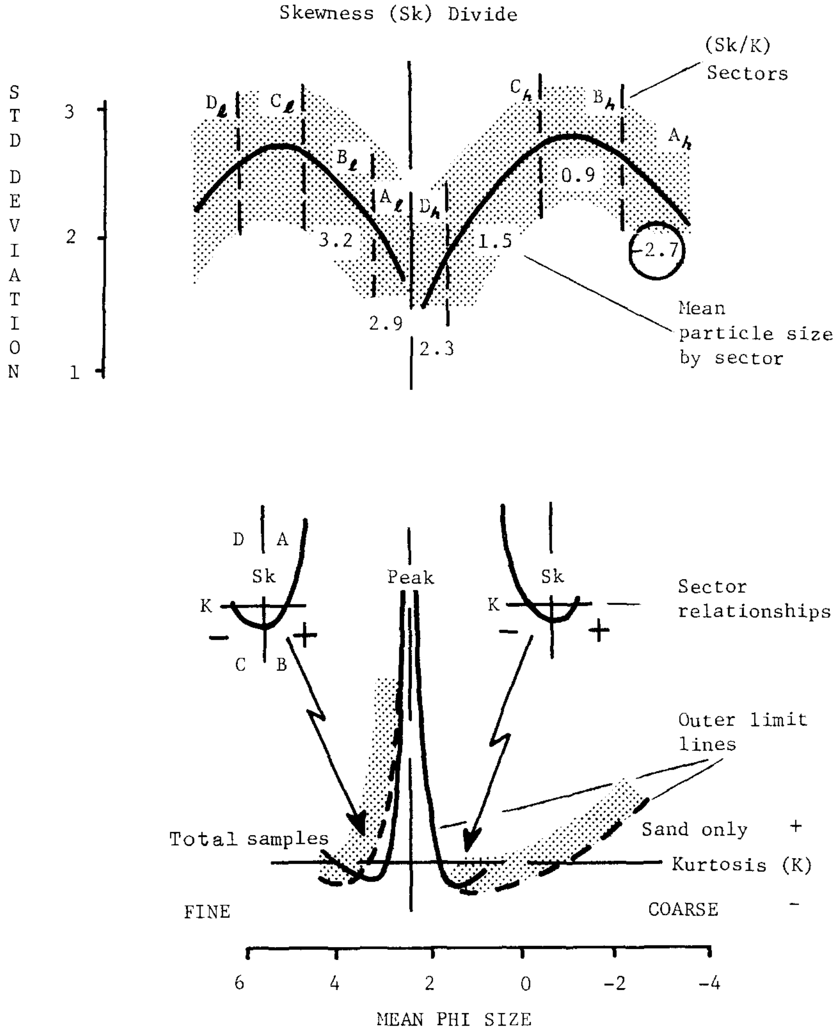


Fig. 3. Sediment moment measures and particle size relationships.

In the upper part of this figure, mean phi size is plotted over the standard deviation envelope, by discrete skewness (Sk) and kurtosis (K) sectors. The circled value records the mean of total samples, other values record the mean of sand fractions only.

In the lower part of this figure, relationships are shown between particle size and continuous distributions of skewness and kurtosis values. The solid line represents the outer limit line of total sample materials and the dashed line of sand fractions only.

particles of different size classes and the interactions of different flow regimes. This divide is therefore best thought of as a balance point where there will be slightly more influence by either erosional or depositional conditions.

The mean particle size of a total sediment sample is generally not a good correlate of hydraulic conditions characterised by near bed hydraulic shear velocities. There is no doubt, however, that sedimentary deposits of decreasing particle size do reflect a decrease in the energy of associated hydraulic regimes. The lack of a good correlation is due to the fact that although the smallest (coarse) particle size in a lag deposit is closely related to the maximum hydraulic shear velocity, the size of larger particles (which will predominate) is not so related. Thus, the bulk of larger particle sizes can distort relationships between total sample mean particle size and formative shear velocity. Similarly, entrapment of fines from a suspended load can alter the size composition of bed load deposits, again obscuring relationships between particle size (bed load) and shear velocity. By restricting mean size values to the sand class, the influence of unrelated distal size populations in relation to hydraulic shear velocity is substantially reduced.

Aqueous sediments can be separated into two groups, those which are in quasi-equilibrium with hydraulic conditions and those which are anomalous (e.g. ice-drop, mixed-layer or relict deposits). Based on skewness/kurtosis values, which are particularly sensitive to distributions in the tails of size distributions, it has been possible to differentiate between the two groups (Sly, 1984). Sediments which are close to the outer limit line (Fig. 3) are likely to be in near equilibrium, those away from the line are anomalous. The skewness/kurtosis sector sequence D_l–A_l (l, low energy) and D_h–A_h (h, high energy) reflects increasing levels of hydraulic energy and the skewness divide (between A_l and D_h) marks the point of minimum erosion velocity. The total sample mean particle size and the sand only mean particle size (based on 227 near equilibrium samples) are given for each sector in Fig. 3. Providing spherical hydraulic equivalent particle size data are used (Fig. 4), the mean size values of the sand only sector data should be near universal for equilibrium sediments. These restricted mean sand size data are more closely related to hydraulic shear velocities than the total sample size data. However, they are likely to be directly related only when the mean particle size is coincident with the break-point in size-frequency curves, which characterizes the intercept between traction and

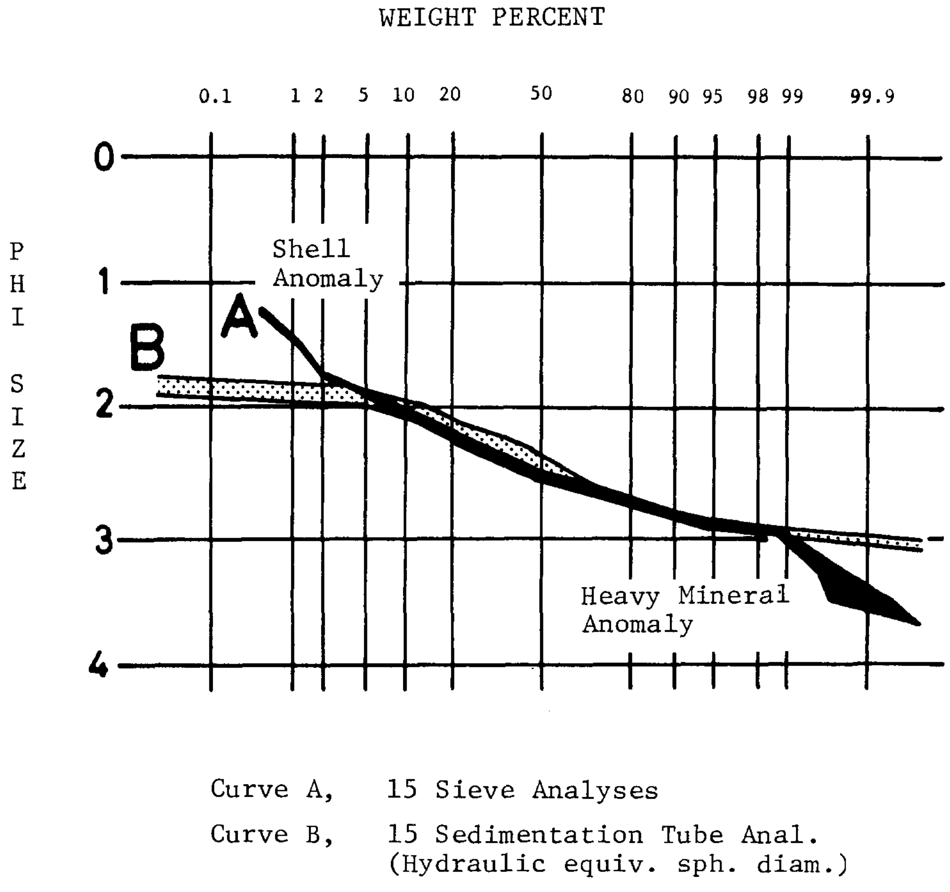


Fig. 4. Comparison of size analyses: sedimentation tube gives size in relation to hydraulic spherical equivalent diameter, sieve analyses distort the tails of size distributions.

intermittent suspension loads (Middleton, 1976). In exploration of this latter point, the relationships between mean sand sizes (range 1.1–3.3 phi) and break-points (range 0.3–2.8 phi) have been analysed by regression on 236 samples in which break-points were identifyable, from Liverpool Bay and the River Mersey. On the assumption that the break-point is directly related to hydraulic shear, close linear relationships between mean particle size of the sand class and shear velocity are strongly suggested by r = 0.83.

It is therefore proposed that mean particle size of the sand class is a better correlate of active hydraulic conditions than mean particle size of a total sediment sample, and, further, that distributions of mean sand size data will be valuable indicators of the dispersal of sediments containing significant quantities of sand. Based on the example data, sediments with a sand class mean finer than about 1 phi and a mean coarser than about 3.2 phi have high sand contents; the content of sand in samples coarser than 1 phi and finer than 3.2 phi is typically less than 10% of the total sample.

Muds

Because the formation of bottom sediments composed of sub sand size material usually occurs under non-erosional hydraulic conditions, the mean size of mud particles has long been used to characterise this depositional environment. The method provides a valuable means of describing sediment distributions where a decrease in mean particle size relates to lower hydraulic shear velocities. However, due to complex interactions between electrolytes, particle concentrations and turbulence, generally described by the process of flocculation, relationships between mean particle size of bed material and near bed hydraulic shear velocity are not consistent. Further, as a result of fixation by benthic suspension feeders particulates which would otherwise remain in suspension may be incorporated into bottom deposits.

Plots of the relationships between total sample mean particle size and the silt/clay ratio (silt/clay boundary taken as 8 phi. Sly, this volume) demonstrate that the data are poorly correlated at total sample means which fall within the coarse and mid silt sizes. Deposits having total sample means within this range are typical of flocculent conditions, or of areas in which the influence of shifting water masses result in the accumulation of mixed sediments; mixed sediments effectively integrate short term changes in hydraulic regime which only become apparent where temporal scales are more extended, as with varve formation. At finer total sample mean particle sizes relationships to the silt/clay ratio become well correlated (Sly, this volume) and this is because; at low concentrations of fine material, deposition of suspended material conforms closely to Stoke's Law in which settlement is characterised by the behaviour of discrete grains. Thus, a detailed understanding of the significance of deposits of sub sand size material requires not only definition of total sample mean particle size but also their silt and clay contents.

Under the influence of decreasing hydraulic shear there is a generally continuous decrease of grain size, and, as noted in the example data, there is already a significant amount of mixed silt and clay in samples having a sand only mean size in the < 3.2 phi range. In Sly (this volume), it has been shown that mixtures of sand, silt and clay are typical of rapidly flocculating sediments, or of sites where settlement occurs from suspensions in which the dominance of sand or silt fluctuates. Where sand is effectively absent (< 5%) from mud deposits, the sediments are usually characterised by fine silts and clays whose accumulation has been dominated by the behaviour of discrete particles.

Therefore, the combination of percent mud content with mean particle size of sand only data should provide a means of defining dominant hydraulic conditions within a given survey area. However, there is no direct relationship between hydraulic shear and the mean size or percent mud composition of flocculating suspensions, although there is a relationship between this velocity and the mean size of very fine silty clays.

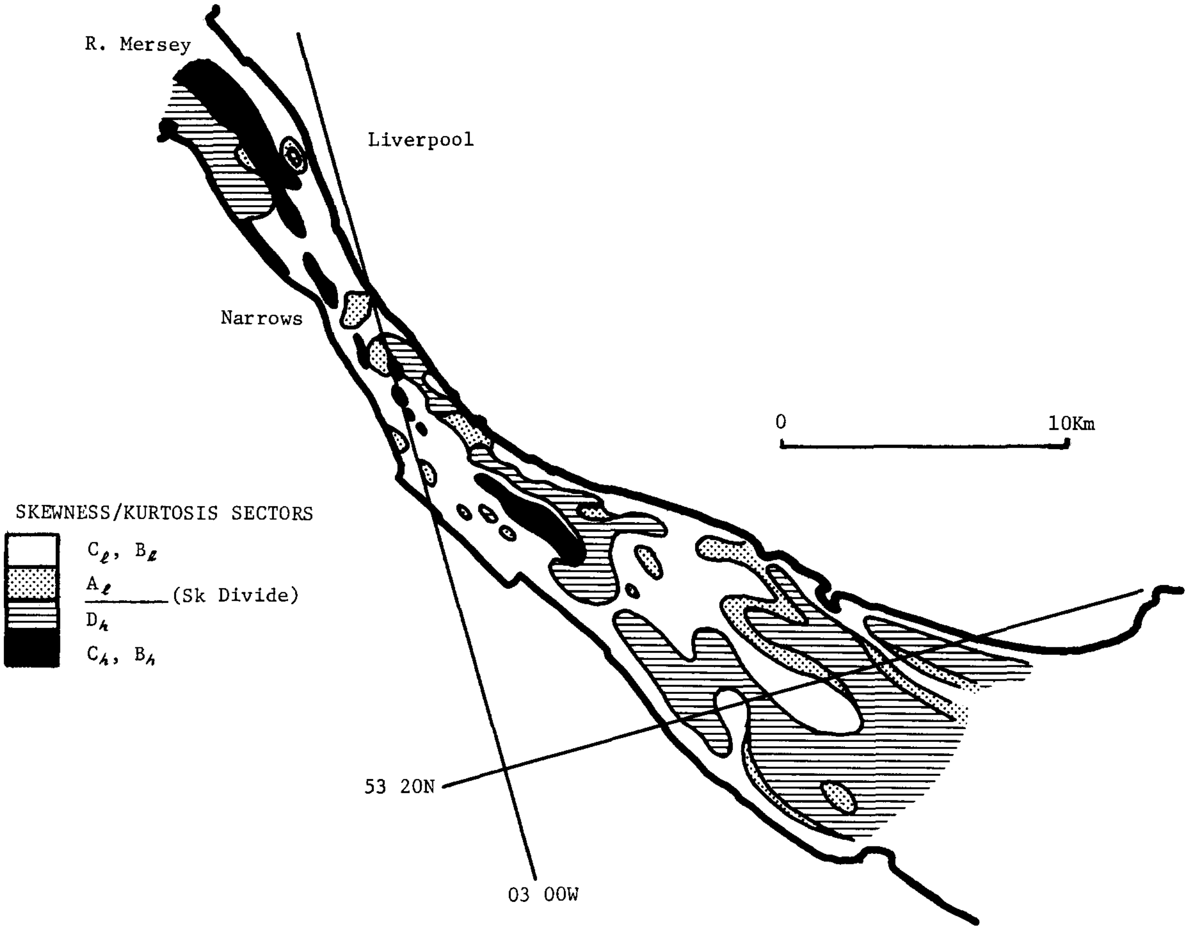


Fig. 5. Distribution of sediment types in the Mersey estuary, based on Sk/K sector relationships.

Application to example data

Figure 5 illustrates the distribution of sediment types within the estuary of the River Mersey. Sectors B_h–D_h characterise erosional lag gravels, gravelly sands and medium sands, under conditions of decreasing hydraulic shear. Sectors A_l–C_l characterise depositional sands and sandy muds, also under conditions of decreasing near bed shear. Figure 6 shows the distribution of the mean particle size of sand only from the same sample locations. Close comparison of these two figures is made possible by assuming that the boundary between sectors D_h/A_l correlates with a size of about 2–2.5 phi.

Figures 5 and 6 identify the presence of high energy coarse sediment at both north and south ends of the Narrows where flood and ebb current velocities rise to near maximum values as the width of the river cross section is reduced. Lobes of relatively coarse (sector D_h) material appear to be roughly related to channel form in the inner estuary and similar though less prominant features occur in the sand size data. The differences between ways in which the two figures characterize sediments of the inner estuary are not incompatible. In effect, the coarser and more residual components are most stable, and are most closely related to channel forms (where current velocities are greatest). Features in the mean size distribution data of the inner estuary are minimal and there is little difference in the erodea-

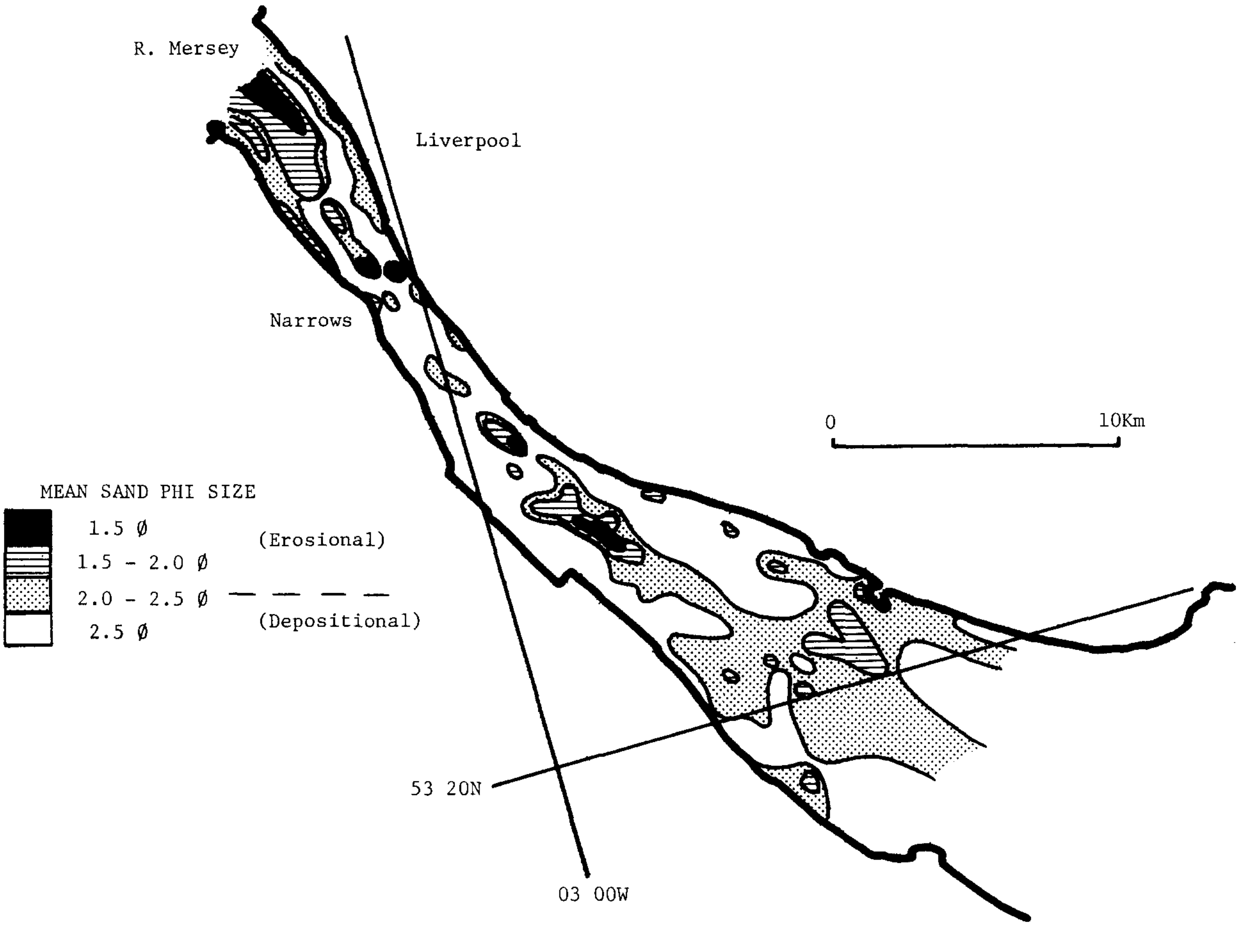


Fig. 6. Distribution of sediment types in the Mersey estuary, based on mean phi size of the sand fraction.

bility of these sediments; the lack of synoptic sampling has also obscured more subtle variations which may occur in temporally discrete data. There is some fining towards the innermost parts of the estuary. However, perhaps the most interesting point to be drawn from the sand size data is that within the Narrows, where current velocities are highest, the bed is covered by fine sandy silt and silty sand. In this section of the river, maximum bed velocities exceed 1 m/sec^{-1} (Halliwell & O'Connor, 1965) and, normally, coarse residuals or exposed bedrock would be expected to occur. However, concentrations of suspended sediment are extremely high in the river, with maximum values reaching 2000 ppm or more. Under these conditions, flocculation is very rapid at slack water and even though most material is resuspended during the following tidal cycle a portion of the material remains on the bed. The presence of coarse residuals partly covered by mud attests to this formative origin. A positive balance in the suspended sediment flux allows coarse material to remain uncovered at each end of the narrows.

The distribution of the mean sand size fraction of Liverpool Bay sediments is shown in Fig. 1 and, contrary to the usually anticipated relationship between water depth and particle size, the bay sediments become coarser with increasing water depth. This relationship has been produced by the effects of post-glacial sea level rise. The finer sand fractions have been winnowed away from source deposits and have migrated shoreward, largely in response to the combined

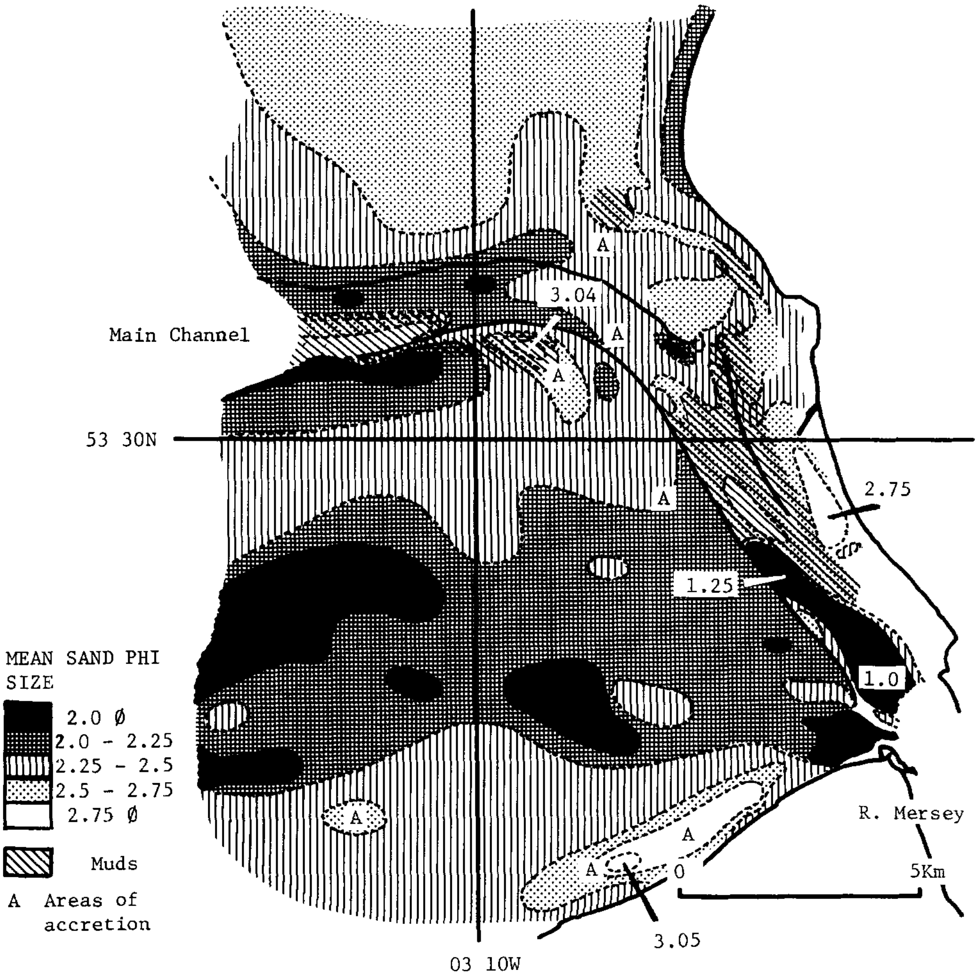


Fig. 7. Sediment distribution patterns at the mouth of the River Mersey, based on mean phi size.

influence of rising water levels and wave action. The major channels of the River Dee and the River Mersey are generally reflected by lobes of coarse sediment that extend toward the present shoreline. At depths of 5–10 m the complex of modern bars and channels is superimposed on the most mobile components of the sand size fraction (of about 2 phi and slightly finer). Muds are virtually absent from all areas coarser than 2 phi.

Figure 7 shows the outer channel of the River Mersey in greater detail and, in particular, the distribution of muds relative to the mean particle size of the sand fraction. The muds are mostly associated with the main channel and occur both within and outside it. Within the channel, flow conditions are similar to those of the Narrows; outside the channel, velocities are much reduced. As in the river, the muds represent a net depositional flux from the suspended load at sites where accumulation by way of rapid flocculation is not quite compensated by erosional scour. The accumulation of muds near the east shore occurs under conditions of lower flow velocities and is likely enhanced by biogenic fixing. The presence of the muds, more or less contiguous with those within the river estuary, provides strong evidence that much of this suspended load oscillates in and out of the estuary on a continuing basis.

Assessment

Based on the preceding summaries, it is necessary to assess whether or not the parameters of mean sand size and percent mud provide adequate descriptors of the movements of natural sediments, dispersals of dumped harbour dredgings and sewage sludge, or the impact of aggregate recovery. Each issue is separately assessed.

Evidence from the highly conformable sand size data imply that virtually all areas of the bay are subject to sediment reworking. This observation can be established by calculating the maximum horizontal shear velocity close to the sediment/water boundary layer; the formulation is: $\mu m = \pi\ Hs/(Ts\ \mathrm{Sinh}\ (2\pi\ d/Ld)$, Sheng & Lick (1979), in which μm = velocity, Hs = significant wave height, Ts = significant period, d = local depth, $Ld = L\ \tanh\ (2\pi/Ld)$, and $L = (gTs^2\ 2\pi)$.

With a fetch of about 120 km, wave heights of 2.5/3 m and periods of 5–6 sec, $\mu m\ =\ 20\ \mathrm{sec}^{-1}$ at 25 m depth. This is sufficient energy to move sand particles of ≤ 1 phi. With additional influence from current flow, coarser particulates can be eroded from coehesionless sediments. The interactions between wave action and current flow enforce a strong shoreward component to bed and saltation (intermittent traction) load transport and virtually all of the bay is subject to potential sediment reworking. Generally the coarser lag deposits in the deeper parts of the bay have been subject to winnowing for the greatest length of time. The time lag between changes in large scale bed form adjustment and changing hydraulic conditions (eg. sea level rise) is partially characterized by the lack of exact fit between isopleths of mean sand size and bottom contour. In addition, bedform is also influenced by the availability of particle size supply and elevation of sites of accumulation may not occur if the quantity of fines is not sufficient. These points, and the greater influence of variable wind/wave activity, further explain the instability of bank and channel structures which characterise the nearshore zone.

Sample spacing of the example data set was designed to describe large scale distribution patterns in the bay and resolution of small scale structures is lacking. Similarly, because of temporal variations, a lack of more nearly synoptic data makes it impossible to detail sediment transport at depths of $<$ 5–10 m where bed form change is most active. Certainly, the mean particle size of the sand fraction is sensitive enough to demonstrate short term changes in sediment transport, erosion and deposition. However, it is questionable whether interpretations of short term sediment fluctuations are useful in the context of many non-equilibrium conditions, especially where limitations imposed by particle size availability can mask responce to hydraulic change. Rather, it seems more useful to define areas of potential mobility or stability; in this regard it is clear that sediments of 2–2.5 phi mean size are most easily reworked and are therefore most mobile. On the other hand, well defined channel forms and associated coarse sediments, or accumulations of fines, as noted in Fig. 7, characterise areas where dominant hydraulic regimes remain stable. Sediment distribution patterns show that particle dispersal results from the combined interactions of sediment transport and size selective deposition. Directions of material transport under multidirectional flow are poorly characterised by size distribution data, alone, although gradients between particle size isopleths may be used to reflect net transport.

Most of the materials derived from harbour dredging are dumped at Site Z (Fig. 1) and the size of sand particulates from both the river and outer channel dredging sites ranges between 2–3 phi. This is close to the size range of naturally occurring sediments at the dump site and the presence of limited sediment accumulations (local elevation of the sea bed a little shoreward of the dump site is 1–2 m) implies that much of the introduced material becomes incorporated into the natural dispersal pattern at this site. Particle size anomalies south and west of site Z likely reflect minor residuals associated with the allochthonous inputs. Several patches of mud also occur south and west of the dump site but based on physical characteristics there is no way of establishing their relationships to dumping, estuarine flow or marine sources. However, the presence of fine sand mixed with the muds indicates that they are likely flocculent materials of relatively local derivation.

The lack of large mud deposits in the area of offshore sewage sludge disposal is clear evidence that these fine particulates do not remain permanently deposited at this dump site, rather they become widely dispersed and incorporated into the eastward residual drift within the bay.

Although sampling densities were not designed to assess the impact of aggregate recovery on bottom sediments, anomalies of slightly coarser material can be identified in the general area of the dredging licence (Fig. 1). These anomalies may be explained as dredging impacts but they could be related to natural features, and more detailed studies would be required to address this possibility.

Geochemical characteristics

Compositionally, the sands and sandy gravels of Liverpool Bay are very similar to equivalent size materials from Cardigan Bay (Moore, 1968), except that Ca, Mg, and Sr are higher in Liverpool Bay where they reflect the influence of local carbonate bedrock. The Cardigan Bay area, on the west coast of Wales, is essentially free from industrial and municipal contamination and provides a useful background comparison for the Liverpool Bay area. By contrast, most of the heavy metals analysed in sediments from the River Mersey were at noticeably higher concentrations than in Liverpool Bay.

Selected geochemical characteristics are summarized in Table 1. Columns 1 and 3 list elemental concentrations of bay sediments after quartz correction (Thomas, 1972) to compensate for slight compositional differences. Column 1 describes sector A_1 sediments (mobile, medium size sands with minor contents of mud); column 3

Table 1. Summarized geochemistry of Liverpool Bay and River Mersey samples.

PARAMETER	Bay (Sector A_1)	River/Bay (Sector A_1)	Bay (Mean of Mud Samples)	River (B_1)/Bay Mud	River (C_1)/Bay Mud
Sand	89.3	0.8	–	–	–
Silt	8.6	2.5	38	1	1.5
Clay	–	N/A	7.8	1.7	2.3
Si	84	0.9	76.6	1	1
Ag	0.7	1.2	1.0	1	1.1
As	6.3	2.8	14.8	1.3	1.3
Cd	1.0	3.3	1.8	2.1	2.1
Co	12.0	0.8	13.8	1	1
Cr	130	1	176	1	1.4
Cu	23.7	2.0	99.2	0.6	0.6
Hg	547	2.1	1286	1.2	1.2
Mo	2.7	0.5	2.6	0.7	0.8
Ni	19.3	0.9	23.9	1.1	1.1
Pb	58	1.5	99.2	1.1	1.1
U	0.6	1.1	0.2	1.5	1.6
V	43	1.5	54.3	1.6	1.6
Zn	96.7	2.5	270	1.3	1.3
COLUMN	(1)	(2)	(3)	(4)	(5)

Note: Sand, Silt and Clay as percentages;
Si as %: other elements as ug/g^{-1}; except Hg, as ng/g^{-1};
All metals quartz corrected, all values as means based on 227 samples.

describes the composition of bay muds (Figs. 1 and 7). Column 2 provides a comparison of size equivalent river and bay samples by the ratio of river/bay values. In columns 4 and 5, river/bay ratios express sector B_1 (muddy sands) and sector C_1 (sandy muds) compositions relative to the bay muds. With the exception of Co, Cr, Mo and Ni, river sands have higher metal contents than bay sands; the reason for this is likely that many of the metals are associated with the silt size fraction which is noticeably higher in the river sediments. This tends to be supported by the major element composition (not shown in this table) in which river and bay concentrations of Al, K, Mg, Na, P and S are virtually identical, although Fe and Ti are slightly greater in th river sediments (both ratios 1:1.2) and Ca and Mn contents are lower (both ratios 1:0.7). The Fe and Ti anomaly seems to be related to heavy mineral contents and the Ca anomaly is related to higher contents of broken shell material in bay sediments (see also, Fig. 4). The differences in Mn values likely reflect redox conditions and the formation of grain coatings on bay sediments; the DO of bay waters is generally higher than that of the estuarine waters (UKDOE, 1972).

After quartz correction, there is almost no difference in contents of Ag, Co, Ni and Pb in either bay or river muds; Cr, however, shows a relationship with the finer silt-clay particle size fractions. Most of the other metals are at higher concentrations in the river sediments (irrespective of silt or clay content) and the ratios of relative enrichment (river/bay mud values) follow the order $Cd > V > U > As = Zn > Hg$; both Cu and Mo concentrations are highest in the bay sediments. Based on observations by Fernex *et al.* (1986) and Förstner *et al.* (1986) it is suggested that, as degradation of organic matter and desorption take place, mobilization occurs ($Cd > Hg$) and this reduces the metal content of particulates in the bay waters. It is not known how the Cu or Mo are associated with particulate matter (likely with the organic fraction), but neither seem to be particularly mobile within the bay environment. Unless evidence is found to suggest that these two elements are largely derived from sources in the bay, it is unlikely that particle dilution plays a major role in changing the relative composition of bay muds, relative to the geochemistry of river muds.

Based upon these geochemical data, it is not possible to define the exact movements of harbour muds dumped in the bay. It seems most likely, however, that river muds (as suspended particulates) oscillate in and out of the Narrous with tidal flow, and that the portion of dumped material which goes back into suspension (as a result of reworking by wave action and current flow) will follow local patterns of residual drift. Some of the dumped mud from harbour dredgings will be reincorporated into the suspended load of the river. During the period of time between dumping and re-entry into the river system, quantities of some heavy metals are lost to the dissolved phase by mobilization ($Cd > Hg$). Noticable though inconsistent gradients in metal concentrations of bottom muds likely indicate an increasing dominance of riverine particulates in the bay deposits closest to the river mouth. The relative contents of many heavy metals therefore provide an expression of temporal exposure to bay conditions. The effect of the training walls along the outer channel of the River Mersey is to entrain much of the river mud during tidal oscillations. Muds which are dispersed in the bay and which return to the river are mostly carried over the banks in suspensions of much lower concentrations during the flood cycle.

Conclusions

Regional studies of sediment dispersal are usefully served by sedimentological analyses yet, despite sophisticated methodologies, major limitations restrict the extent to which sediment characteristics can reflect governing hydraulic conditions. This being the case, it is argued that mean size of the sand fraction and a measure of the content of silt + clay (mud) are adequate to describe the most significant conditions regarding movement and deposition of sediments. Sediment distribution data reflect conditions where well defined erosional or depositional conditions persist as a dominant hydraulic regime. Distributions of sediments composed of size fractions which respond to minimum erosion velocities may reflect net transport; however, they are best described as areas where sediment mobility is greatest and channel and bank stability is least. Depending upon site specific conditions, geochemical data may enhance interpretations based upon sand size and mud content parameters.

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