Available online at www.sciencedirect.com
SCIENCE DIRECT®
Marine Geology 203 (2004) 95–107
MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS
www.elsevier.com/locate/margeo

Flocculation and sedimentation on the Po River Delta

J.M. Fox[a,*], P.S. Hill[a], T.G. Milligan[b], A. Boldrin[c]

[a] Department of Oceanography, Dalhousie University, Halifax, NS, Canada B3H 4J1
[b] Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, NS, Canada B2Y 4A2
[c] Istituto di Scienze Marine – ISMAR, Biologia del Mare – C.N.R., Castello 1364/A, 30122 Venice, Italy

Received 4 November 2002; accepted 9 September 2003

Abstract

With the goal of improving understanding of the effect of flocculation on the formation of fine-grained deposits on continental shelves, hydrographic profiling, in situ imaging of suspended matter, and collection of surficial sediment samples were conducted at the Po River Delta in June 2001. These data show that during medium flow conditions (1920 m^3/s), sedimentation occurs rapidly immediately offshore of the main distributary, Po della Pila. Rapid sedimentation is promoted by large rapidly sinking flocs forming in the river well upstream of the mouth. The delivery of fine sediment to the seabed at the mouth of the Po is sufficient to overwhelm the erosive effects of waves and currents, leading to accumulation of mud in water depths as shallow as 4 m. On cross-shelf transects 2 km north and south of the mouth, however, suspended sediment supply from the river is reduced to the point that mud accumulates only seaward of the 8-m isobath. Along the central transect, suspended sediment concentration decreases rapidly seaward of the 6-m isobath where the emergence of a more organic-rich population of flocs along a mid-water density interface is suggested. Energetic activity along the 15-m isobath likely promotes resuspension with the potential for removal of material from the delta. Further investigation of floc properties, namely the relationship of floc size to settling velocity, is necessary to establish the degree to which the suspension is flocculated during transport and deposition.

Keywords: aggregation; delta; floc; freshwater; Po River; sedimentation

1. Introduction

The removal of fine sediment from buoyant plumes occurs rapidly (Nelson, 1970; Drake, 1976; Wright, 1977). Stokesian settling velocities of clays are minuscule and cannot account for the proximal deposition of such particles. The ability of fine particles to deposit rapidly is made possible by the process of particle flocculation (Kranck, 1973, 1980), which occurs via inter-particle collision followed by adhesion. Collectively, fine particles in a floc sink more quickly than they would as single grains, effectively increasing removal rates (Syvitski et al., 1985; Hill et al., 2000). Empirically, flocculation does not appear to depend strongly on particle size, so deposits formed by deposition of flocs are poorly sorted (Kranck and Milligan, 1991). The poor sorting

* Corresponding author. Fax: +1-902-494-3877.
E-mail address: jfox@phys.ocean.dal.ca (J.M. Fox).

0025-3227/03/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0025-3227(03)00332-3

typical of muds complicates the process of extracting an environmental record of the conditions leading to deposition based on analysis of particle size. The complication arises from the fact that particles can arrive at the seabed as single grains, with well documented physical properties, or as flocs, which because of their fragility and attendant difficulties in sampling them, have less well constrained physical properties. Progress in interpretation of fine-grained deposits has been fostered by increased understanding of the role of flocculation in deposition (McCave et al., 1995; Milligan and Loring, 1997) and by continuing efforts to document the properties of flocs as well as their rates and mechanisms of formation.

Flocculation has been inferred to be important in deposition from plumes in numerous systems (Drake, 1972, 1976; Eisma and Kalf, 1984). However, direct observations of flocs on the continental shelf are limited to a few systems. Flocculation was postulated as necessary to explain the observed deposits off the Amazon (Gibbs and Konwar, 1986; Kineke et al., 1991; Berhane et al., 1997) and Eel (Geyer et al., 2000; Hill et al., 2000) river systems. These two systems are quite different oceanographically. The Amazon is the world's largest source of water (Gibbs, 1972; Kuehl et al., 1996) and second largest source of sediment to the sea (Milliman and Meade, 1983). The receiving shelf is broad, with sediment dispersal being affected by large tidal and coastal currents as well as moderate wave action (Gibbs and Konwar, 1986; Geyer et al., 1996). Although the Eel River system is comparatively smaller in scale, episodes of high sediment discharge arise from short, intense flood events (Wheatcroft, 2000). Flooding of the Eel is closely related to storm events, so sediment is introduced onto the shelf during periods of energetic wave action, resulting in a flood deposit which resides seaward of the flood plume (Traykovski et al., 2000). The Eel shelf is narrow with a high gradient at the shelf boundary.

Although the Amazon and the Eel shelf offer some contrasts for exploring environmental controls on floc deposition, they are both high energy environments. Numerous settings where mud deposits, such as sheltered coastal inlets and epicontinental seas, are lower energy. Because flocculation is affected by energy (Hill et al., 2001; Berhane et al., 1997), a fuller understanding of floc deposition requires data from lower energy continental shelves than the Amazon and Eel river systems. The Po delta is an ideal study site for a number of reasons.

The Po-receiving basin is a low-energy environment relative to both the Amazon and Eel systems. The Po empties onto a low gradient, shallow shelf of the Northern Adriatic Sea, and is subject more to circulatory wind forcing than to wave action (Kourafalou, 1999). Due to a low bathymetric gradient, minor storm activity can deeply penetrate the water column and easily initiate resuspension events (Matteucci and Frascari, 1997). The Po has been the focus of ongoing sedimentological research (Nelson, 1970; Boldrin et al., 1988; Matteucci and Frascari, 1997), and flocculation has been invoked as an important factor in sedimentation and the development of fine-grained deposits on the Po Shelf, yet direct observations of flocs are lacking. Size distributions of sediment beneath the buoyant plume were shown to be poorly sorted, implicating flocculation as an important removal mechanism (Boldrin et al., 1988). Observations of rapid settling of resuspended material have fostered suggestions that bottom boundary layer (BBL) sediments are highly flocculated (Matteucci and Frascari, 1997).

The opportunity to make observations of flocs in the Po plume began with a major flooding of the river in October 2000. As part of the Office of Naval Research EUROSTRATAFORM program, extensive coring and hydrography was subsequently conducted to locate and investigate the resultant flood deposit beginning in December 2000. In June 2001, we joined the research group on board the *Sarom VIII* to make floc observations in the plume seaward of the 10-m isobath. It quickly became apparent that sedimentation under the moderate-to-low discharge of the Po in June was inshore of the 10-m isobath. An opportunity was provided by Istituto di Scienze Marine – Biologia del Mare (ISMAR-BM) to use a smaller vessel for 1 day to make observations in shallower waters. Thus, three transects were occupied in front of the main river mouth. The results from the three transects coupled with results from water samples collected upstream of the river mouth suggested that flocculation was occurring in the river prior to discharge. In October 2000, additional floc observations were made upstream of the mouth to investigate the possibility of floc formation in the Po. So, while not extensive, the observations provide direct support of long-standing hypotheses regarding the role of flocculation in Po sedimentation. These observations also provide insight into other low-energy systems. Herein, the results of floc observations near the mouth of the Po River are reported and used to assess the importance of flocculation for fine-grained sediment deposition in the system.

2. Materials and methods

2.1. Overview

The Po River is the most important fluvial system in Italy. The catchment basin receives input from the Alps to the north and west and from the Appenine mountain range to the south. The Po is used as a source of water as well as being a receiver of waste passing through the country's most industrialized regions. The river travels eastward carrying an estimated annual sediment load of 20 million tonnes (Nelson, 1970). The Po is the greatest contributor of riverine input to the Northern Adriatic Sea, significantly controlling budgets of dissolved and particulate materials (Matteucci and Frascari, 1997). Human manipulation and redirection of the river flow since 1600 AD have resulted in the formation of the present-day delta (Gandolfi et al., 1982). Five distributary channels discharge from the delta with roughly three quarters of the flow passing through the Pila mouth located at the apex (Fig. 1).

The sampling effort involved profiling of the water column, and collection of in situ suspended sediment photographs, water samples, and surficial sediment samples. On June 3, water samples were collected from bridges in the delta plain (Fig. 1). On June 7, sixteen stations along three transects were surveyed directly offshore, north, and south of the Pila mouth from the Istituto di ISMAR-BM research vessel *Mysis* (Fig. 1). The survey took place during ebb tide. At each station, a Benthos 373 plankton silhouette camera (Kranck et al., 1992) was deployed, followed by a hydrographic profiling package including an Idronaut Srl. model Ocean Seven 316 CTD, a Seapoint transmissometer, and a Seapoint fluorometer. Water samples were collected at the surface and 0.8 m above the seabed via a tethered Niskin bottle tripped by a messenger. An Ekman grab was used to collect surficial bottom sediment samples.

River discharge in late May and early June was declining, but rose following a thunderstorm that occurred on June 3 (2470 m^3/s). Maximum discharge as a result of storm activity occurred on June 4 (2510 m^3/s) and continued to decline, with a resultant discharge of 1920 m^3/s on June 7. Daily mean discharge data were provided by the gauging station at Pontelagoscuro (Regione Emilia-Romagna, 2001).

From the resultant 107 images, estimates of median floc size, in situ floc size distribution, and floc volume concentration were made. Total suspended matter concentration (TSM) and total inorganic concentration calculations were performed on the water samples, and disaggregated inorganic grain size (DIGS) distributions and geometric mean diameter (GMD) were determined from both the water and surficial sediment samples. Water samples collected along the three transects were also analyzed for particulate organic carbon (POC) content and carbon/nitrogen ratios.

2.2. Median floc Size (d50)

Median floc size ($d50$) was estimated by image analysis as outlined in Hill et al. (2000). It was calculated as $\sqrt{(4/\pi)A_{50}}$, where A_{50} is the median floc area of a given image. The depth of field of each image was 4.0 cm. Prior to analysis, images were re-photographed using a Fuji FinePix S1 Pro digital SLR generating high resolution (3040 × 2016 pixels) jpeg-image files. Grey scale thresholding was user defined due to high-exposure variability between low- and high-concentration images. The lower particle detection limit of the camera is 125 μm, thus, images do not represent the full spectrum of matter in suspension.

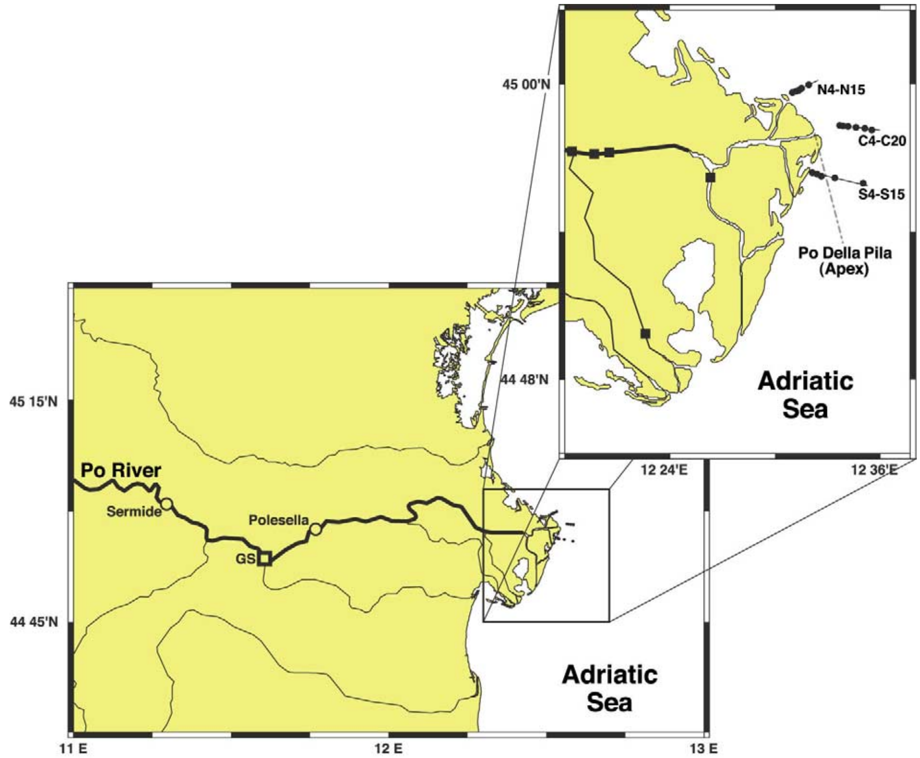

Fig. 1. Site Map of the study area. Stations are identified by a location letter [*N*orth, *C*entral, *S*outh] and a number representative of the station depth (4, 6, 8, 10, 15 m for all transects; 20 m for the central transect only). The gauging station (GS) at Pontelagoscuro is marked by an open square. Filled squares indicate water sample locations within the delta plain.

Discarded images include those containing resuspended bottom sediments as well as images containing schlieren, which are swirling filaments of different water types that cause significant light refraction. Schlieren typically appear at the interface of fresh and salt water. In both cases, the view of particles in suspension was obscured, thereby preventing proper analysis.

*2.3. Large particle volume concentration (*LPVC*)*

LPVC was used to quantify the abundance of large material identified in the images. Estimates of LPVC were calculated for each image under the assumption that all identified objects, whether organic or inorganic, represent solid entities. Volumes for each object were determined from equivalent spherical diameter. Total volume concentration is the sum off all particle volumes divided by the total image volume, which is the product of the area of interest (AOI) and the depth of field. The values were multiplied by a factor of 10^6 and are reported as parts per million (ppm). Typical AOI for images ranged from 1000–3000 mm^2. When LPVC values were on the order of 100, typical particle counts per unit area were 0.6 with absolute particle counts in the range of 600–1800. Therefore, data are not prone to error due to small sample size. For certain images, the lack of discrimination between living and non-living ‘particles’ makes a strict quantitative interpretation of LPVC difficult.

2.4. DIGS distribution

Total suspended sediment concentration was determined by filtering a known volume of water through an 8-μm nitrocellulose filter. DIGS distribution analysis was performed on filter samples and surficial sediment samples using a Coulter Counter Multisizer IIe (Milligan and Kranck, 1991).

Total inorganic concentration was calculated via low-temperature ashing and hydrogen peroxide digestion to eliminate the filter and organic material from suspension (Milligan and Kranck, 1991). Samples were then suspended in a known volume of saline solution (1% NaCl), disaggregated with a Misonix ultrasonic probe, and passed through the Multisizer. Suspended DIGS distributions are expressed as volume ppm, as a function of size. Surficial sediment DIGS are expressed as equivalent weight percentage based on the total solid mass analyzed. Comparison of the suspended sediment distributions to surficial sediment distributions is possible by normalizing each suspended sediment distribution by the total solid inorganic volume of each sample.

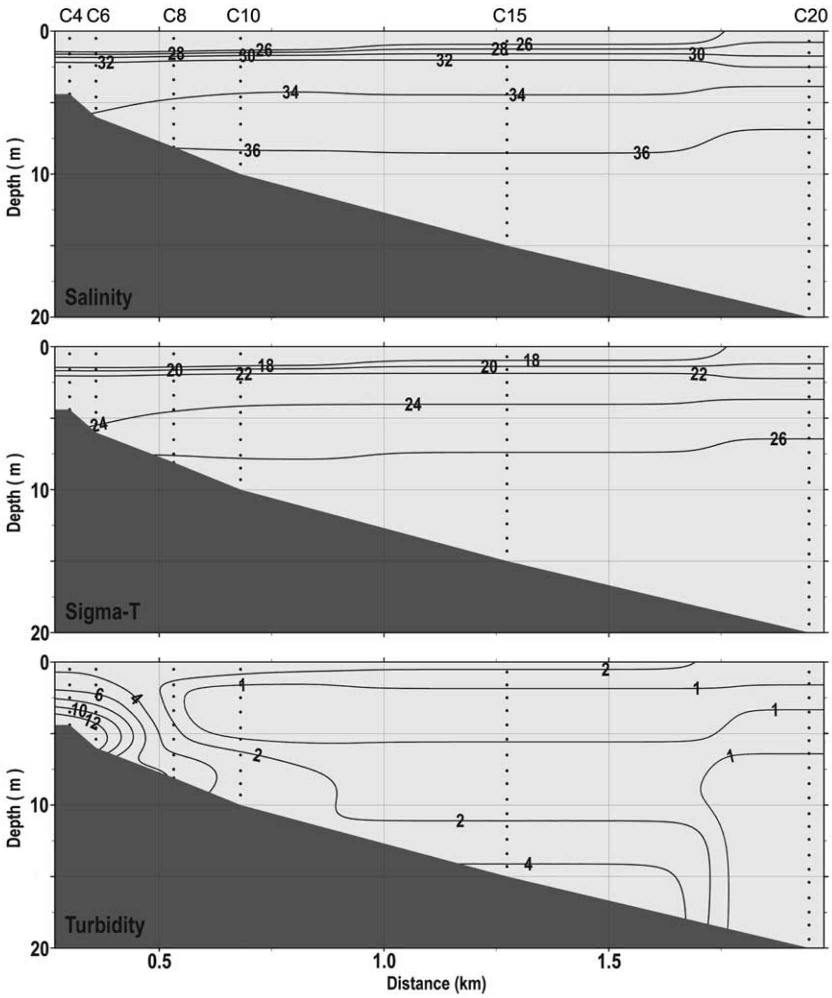

Fig. 2. Contours of salinity (psu), Sigma-T (kg/m^3), and turbidity (a.t.u.) are plotted along the central transect. Stations are identified at the top of the figure with corresponding data points marked by solid circles. The water column is salinity stratified with fresher Po water flowing over more saline Adriatic water. Adriatic water encroaches on the delta to 6.5 m water depth with the bulk of sediment in suspension deposited by C6.

2.5. GMD

GMD expressed in micrometers for a normalized DIGS distribution is calculated as follows:

$$GMD = 2^{\left[-\sum_{i=1}^{nclass}\Phi(i)P(i)\right]} \times 1000 \quad (1)$$

In 1, $\Phi(i) = (-\ln d(i))/(\ln 2)$, where $d(i)$ is the nominal diameter of size class i and $P(i)$ is the relative proportion of material of size class i to the total material analyzed.

2.6. Carbon and nitrogen content

For BBL water samples along the three transects, organic carbon and nitrogen content were determined through the use of freeze-dried filter samples in a Carlo Erba model 1106 CHN analyzer following the method of Sharp (1974). The freeze-dried filters were treated with 1% HCl solution to remove inorganic carbon. Samples were placed into a sample rod and 5–10 mg of oxygen donor was added. The sample rod was then intro-

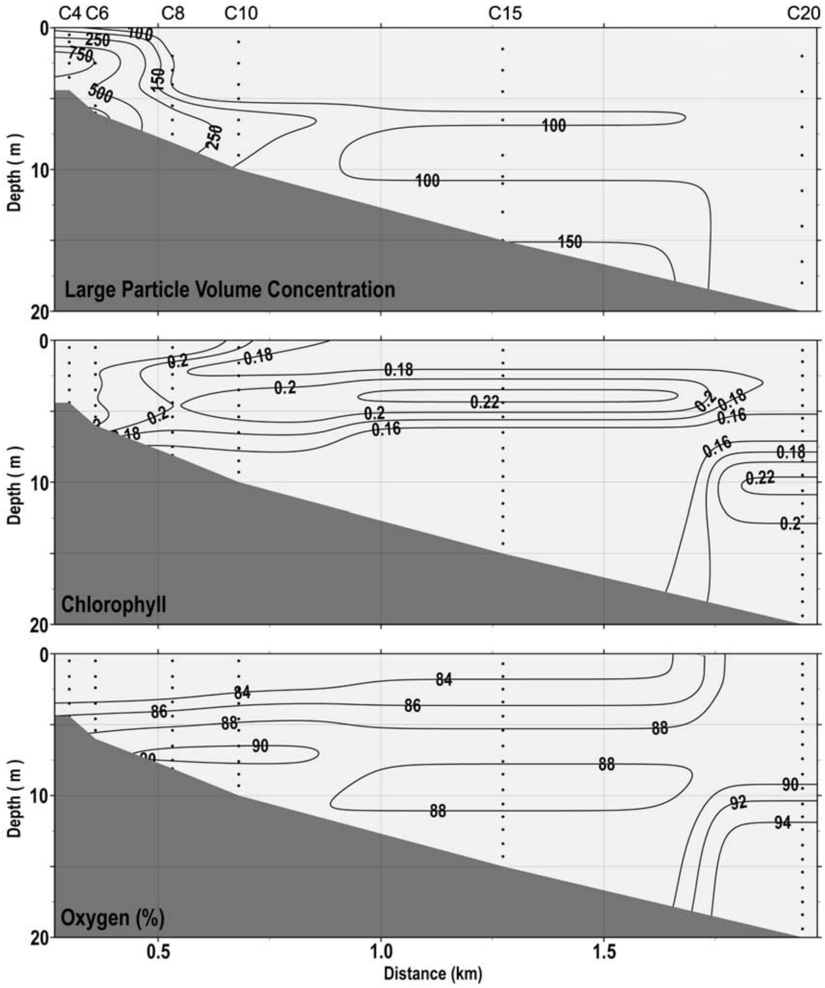

Fig. 3. Contours of LPVC, chlorophyll (a.f.u.), and oxygen saturation (%) are plotted along the central transect. Stations are identified at the top of the figure with corresponding data points marked by solid circles. Shoreward of 10 m depth, In the nearshore, the LPVC profiles are closely matched to turbidity profiles (Fig. 2). Beyond 10 m depth, a mid-water LPVC maximum is observed that is not clearly linked to a turbidity maximum. A region of high chlorophyll is observed at approximately 4 m extending from C10 through C15. A mid-water maximum oxygen % is observed through C15.

duced into the analyzer where the sample was combusted. The ratios of POC to TSM and carbon to nitrogen (C/N) were subsequently calculated.

3. Results

Hydrographic observations show a salinity stratified water column with fresher Po water flowing out over more saline Adriatic water (Fig. 2). A density front is observed at the contact of the $\sigma_t = 24$ isopycnal with the seabed near 6 m depth (Fig. 2). Water column structure is similar to that observed previously (Nelson, 1970; Boldrin et al., 1988). These authors described the water column as three-layered with bottom Adriatic water impinging on the Delta at depths less than 10 m. Associated with the density front near 6 m is a zone of turbidity near the seabed (Fig. 2). Turbidity and LPVC profiles are correlated in the nearshore showing both are low in surface waters at shallow stations, and then rapidly increase near the seabed (Figs. 2 and 3). For station C4, the image at 0.5 m possessed a LPVC of 10.3 ppm while the image at 2.5 m possessed the highest LPVC (1775 ppm), and the largest $d50$ (370 μm) and maximum observed aggregate size (>1000 μm) (Fig. 4). Similarly, Boldrin et al. (1988) observed a maximum TSM value near the seabed at 4 m. The low LPVC value at C4–0.5 m indicates that suspended material was capable of settling out of the top half-meter of the water column prior to the first station location. Along the northern and southern transects, LPVC and turbidity readings were on average an order of magnitude less than readings taken along the central transect indicating that the bulk of sedimentation was occurring directly offshore of the Pila mouth.

Correlation between turbidity and LPVC indicates that sediment is packaged primarily as flocs (Hatcher et al., 2001). The bulk of suspended material leaves the water column by station C6 (Figs. 2 and 3). Seaward of C6, turbidity and LPVC decrease rapidly (Figs. 2 and 3), likely because of the inability of waves to resuspend sediment during the relatively calm sampling periods. At the 15-m isobath, an increase in turbidity and LPVC are observed (Figs. 2 and 3), likely associated with the coastal current arising from the general cyclonic circulation of the Northern Adriatic Sea (Rizzoli and Bergamasco, 1983).

Seaward of the turbidity zone at 6.5 m is a midwater LPVC maximum along the $\sigma_t = 24$ isopycnal (Fig. 3). A zone of elevated chlorophyll resides above the region of elevated LPVC and elevated levels of oxygen saturation coincide with the LPVC maximum (Fig. 3). A corresponding layer of elevated turbidity is not observed.

Suspended sediments in the BBL at C4, C6 and C15 contain the lowest recorded proportion of

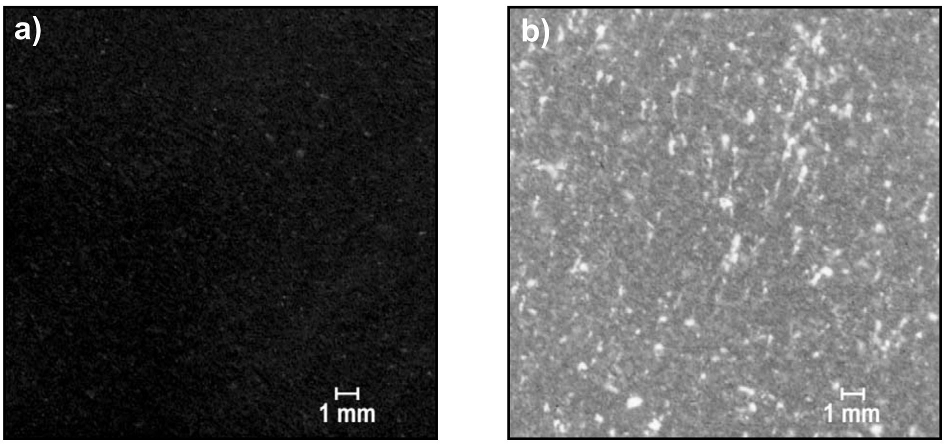

Fig. 4. Silhouette camera images from station C4 at (a) 0.5 m below surface and (b) 2.5 m below surface are displayed. There are no visible aggregates in image (a), while an abundance of material is visible in (b).

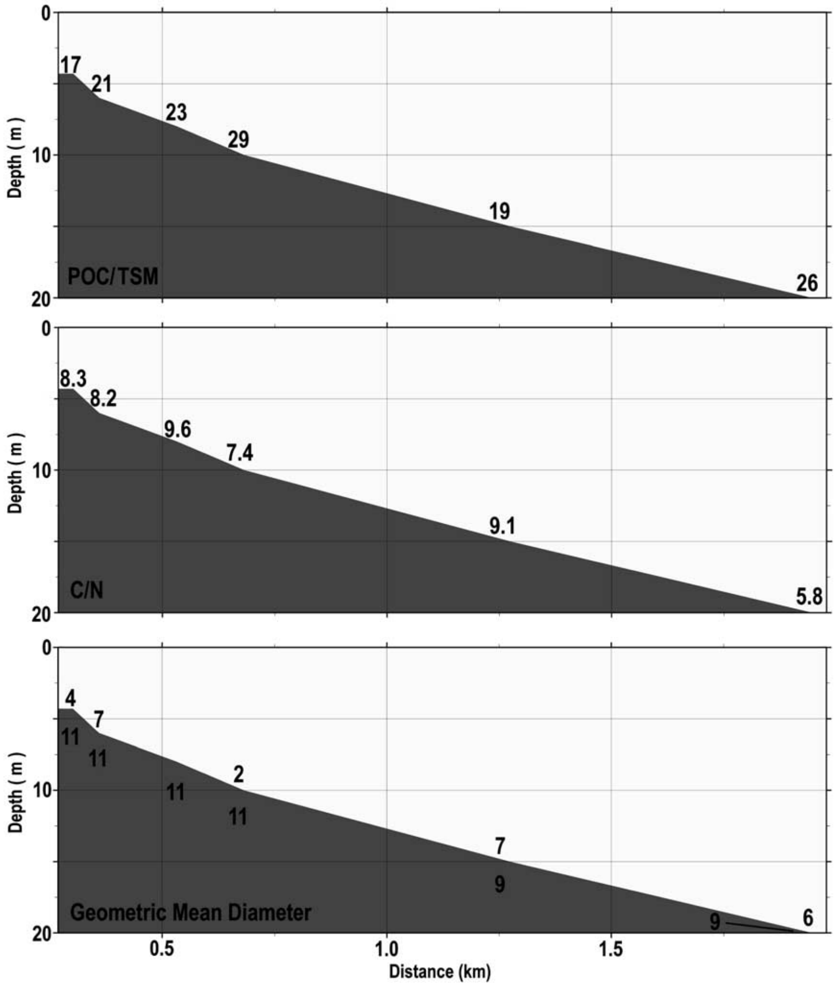

Fig. 5. POC to total suspended mass ratios (ppt), C/N ratios (mol), and GMD (μm) are plotted along the central transect. Surface and BBL data from 0.8 m above bottom. Surficial sediment data are included for GMD. BBL values at C4, C6, and C15 show POC/TSM minima and C/N ratio maxima. GMD maxima are observed in the BBL at C6 and C15. Resuspension near the 6-m and 15-m isobaths is inferred from these results.

organic material as well as relatively high C/N ratios, denoting an elevated degree of sedimentary degradation as well as a larger inorganic fraction (Fig. 5). Maximum GMD is observed in the BBL at C6 and C15, suggesting greater resuspension at these sites (Fig. 5).

4. Discussion

Nelson (1970) attributed rapid loss of sediment from suspension at the Pila mouth of the Po River to sedimentation of coarse silt and sand from river waters that flow over the wedge of saline Adriatic water that impinges on the delta. The areal expansion of the plume as it enters the sea reduces its speed and energy, eliminating the ability to transport coarse material. Boldrin et al. (1988) observed enriched fine fractions in size distributions from the BBL and the seabed at depths of 15–25 m. Based on these observations, Boldrin et al. hypothesized that rapid sediment loss at the Po mouth was due to floc formation and sinking. This study provides direct support for the Boldrin et al. hypothesis with in situ observations of flocs in the waters of the Po Delta.

In the absence of flocculation, well-sorted distally fining bottom sediment distributions would exist offshore of the river mouth (Wright, 1977). Poorly sorted DIGS distributions are observed. Thus, the suspended matter must be flocculated. This inference is consistent with the rapid removal of sediment from surface waters. Rapid removal of material suggests that the degree of flocculation is high and that any subsequent transport of deposited material occurs in the BBL.

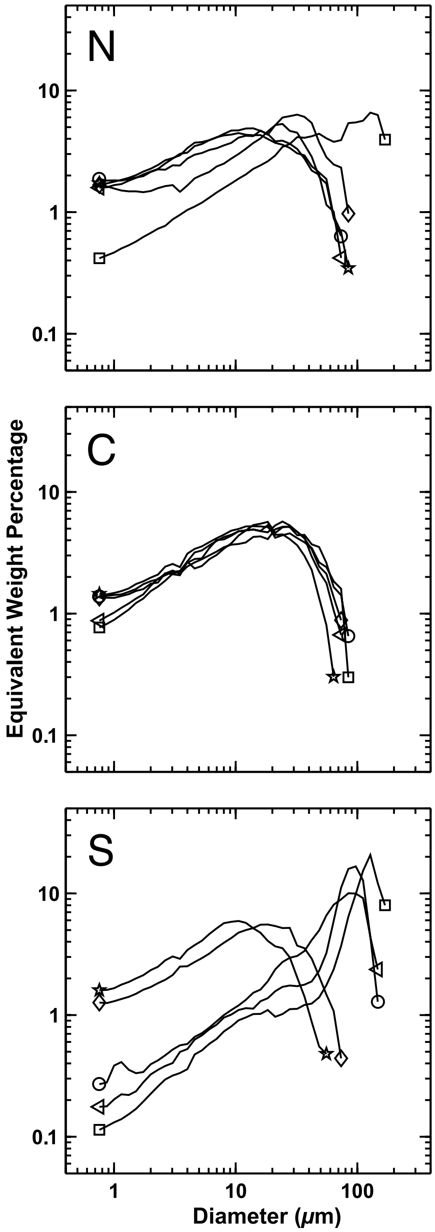

Fig. 6. DIGS distributions are plotted for surficial sediment samples collected along the northern, central, and southern transects respectively. Corresponding depths are indicated by the following symbols: 4 m = square; 6 m = triangle; 8 m = circle; 10 m = diamond; 15 m = star. Offshore evolution of DIGS shows a defined sand–mud transition at 8 m for the northern and southern transects as the distributions shift from coarse modal distributions to poorly sorted distributions. The central transect remains poorly sorted cross-shelf, with mud present on the seabed at 4 m depth. The lack of a distinct sand–mud transition is attributed to elevated sediment concentration near the river mouth.

Along the central transect, surficial sediment size distributions are poorly sorted from 4 m to 15 m. In contrast, a sand–mud transition is observed in distally fining cross shelf size distributions 2 km to the north and south (Fig. 6). Retention of fine-grained material in the nearshore is controlled by the suspended concentration near the seabed, settling velocity, and the limiting shear stress provided by wave and tidal current energies (McCave, 1972). While the three transects are subject to comparable energy regimes, only the central transect, directly offshore of the river mouth, receives enough rapidly settling flocs to overwhelm the erosive power of waves and currents.

Because of the rapid sedimentation observed in June, it was hypothesized that flocs may have been present in the river before it reached the sea. Others have observed freshwater flocs in temperate climates (Weilenmann et al., 1989; Droppo and Ongley, 1994), thus the floc camera was deployed from several bridges across the Po to test the hypothesis (Fig. 1). Abundant flocs were found in the river far upstream of the delta. Photos from Polesella and Sermide exhibit a mean LPVC of 668 and a median size of 266 μm in waters with salinity less than 0.5 psu (Fig. 7).

The rapid removal of material is in part due to the fact that flocs arrive at the salt/fresh water interface pre-formed. Observations of flocs in freshwater have been made previously in many

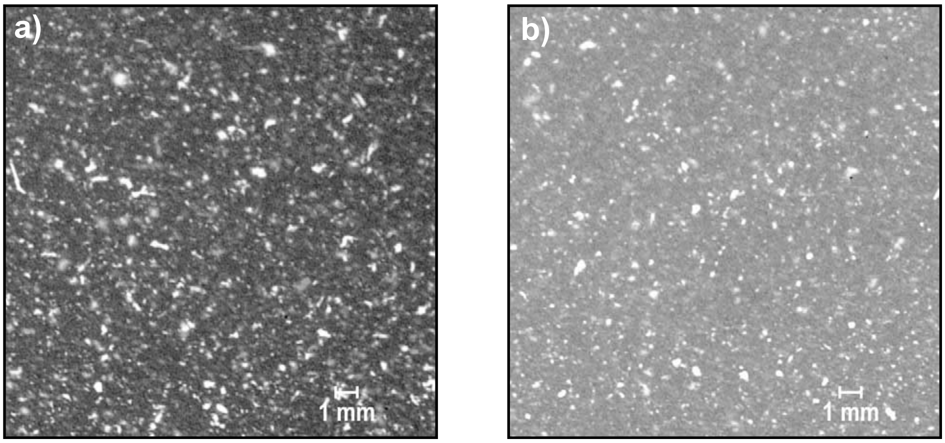

Fig. 7. Silhouette camera images from (a) Sermide and (b) Polesella are displayed. Aggregates possess a median size of 266 μm in waters of less than 0.5 psu. The images clearly document the presence of flocs in fresh water in the Po River.

different environments (Eisma, 1986; Walling and Moorehead, 1989; Weilenmann et al., 1989; Droppo and Ongley, 1994; Slattery and Burt, 1997). A certain balance of organic material and ionic species is necessary for freshwater flocculation to occur. Droppo and Ongley (1994) noted three ingredients essential for freshwater flocculation: decaying detrital material, diatoms, and bacteria that excrete polymeric fibers. Multivalent ionic species are known to be efficient at promoting flocculation (van Olphen, 1963; Droppo and Ongley, 1994; Elimelech et al., 1995), with Ca^{2+} and Mg^{2+} ions being the most effective (Tsai et al., 1987; Tiller and O'Melia, 1993). In a study examining the chemical composition of suspended material in Po waters, biogenic material was found to constitute $6.8 \pm 6.9\%$ of total solids mass, and Ca^{2+}, Mg^{2+} were shown to be the major ionic constituents in Po waters in both the dissolved and particulate phases respectively (Pettine et al., 1994). Thus, the chemical conditions that facilitate freshwater floc formation are present in the Po.

Surficial sediment DIGS distributions along the central transect follow the same general trend as river DIGS distributions, but they are enriched in coarse silt and fine sand (Fig. 8). The similarity among suspended sediment size distributions in the river and surficial sediment size distributions on the central transect suggests that sediment deposits primarily as flocs (Kranck, 1993). The slight enrichment of seabed samples in coarse silt and fine sands likely reflects the contribution of bedload transport to the deposit. Nelson (1970) states that 23% of the material in suspension is coarse with additional supply via bedload transport.

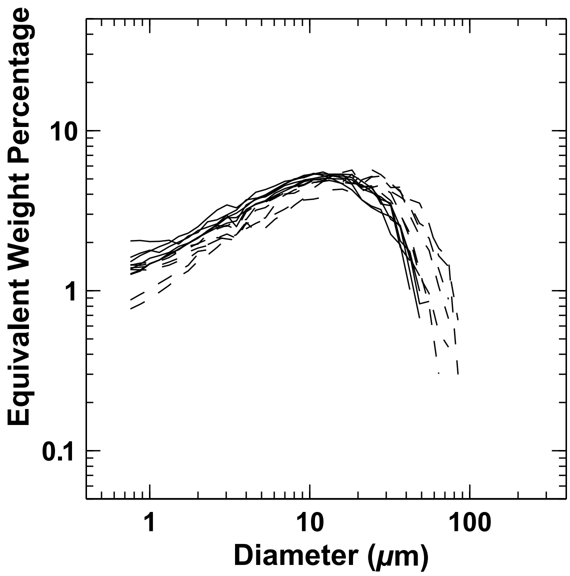

Fig. 8. A comparison is made of DIGS distributions of material in suspension from bridges within the delta plain (solid lines) and surficial sediment samples along the central transect (dashed lines). The surficial sediment samples are similar to suspended sediment samples in the river. They are comparatively enriched in coarse material which is attributed to bedload transport within the river.

The LPVC maximum along the $\sigma_t = 24$ isopycnal may comprise a new population of flocs created by the biological input from above and horizontal mixing along the interface from the seabed. Although the values for oxygen saturation along the interface are not as large as those considered biologically favorable by Boldrin et al. (1988), they are amongst the highest values reported in this study and reside directly underneath the highest levels of chlorophyll (Fig. 3). The density gradient may serve to stall sinking particles, promoting aggregation. The lack of scattering of light as observed by the turbidity meter may be due to a comparatively larger proportion of organic material which does not scatter light to the extent of inorganic fine-grained particles. This is shown by a low turbidity at the location of maximum chlorophyll count (Figs. 2 and 3). More irregularly shaped aggregates, which are likely composed primarily of loose organic material (Kranck and Milligan, 1991) appear in corresponding in situ photos.

Regions of elevated turbidity in the BBL at C6 and C15 may arise from sediment resuspension, which likely promotes biodegradation of sedimentary organic matter (Aller, 1998). This hypothesis is supported by corresponding values of low organic content and high C/N ratios, which indicate an elevated degree of sedimentary degradation, and by observed variability in GMD calculated from DIGS distributions. The surficial sediments underlying suspended GMD maximums at C6 and C15 possess GMDs greater than that in the BBL, so the seabed likely serves as the source for the observed increase (Fig. 5). In deltaic environments, rapid and efficient cycling of organic material is promoted by resuspension (Aller, 1998). Elevated C/N and GMD at 6 and 15 m may indicate, therefore, that resuspension was active along the central transect at C6 and C15 during sampling. At 6.5 m, resuspension may have occurred at the front between Adriatic waters and Po-freshened mid-waters. Resuspension along the 15-m isobath may result from along-shelf current activity, reflected by a consistent increase in TSM and GMD at all three 15-m stations (data not shown). This resuspended material is likely entrained in the current and removed from the delta.

The presence of flocs in the Po River system is now firmly established, but the degree of flocculation is not known. Determination of a floc size vs. settling velocity relationship would permit calculation of floc fraction, a representation of the proportion of floc mass to total mass (Syvitski et al., 1995; Dyer and Manning, 1999; Curran et al., 2002). With this knowledge, new mechanistic interpretations of the environmental conditions of deposition eventually will emerge.

5. Conclusions

In past studies, rapid sedimentation was observed seaward of the Pila mouth of the Po River (Nelson, 1970; Boldrin et al., 1988). The present study not only corroborates those observations, it also confirms previous hypotheses of floc settling by providing direct observations of flocs in the water column. Maximum observed floc size was in excess of 1000 μm, with the bulk of suspended material removed from the water column by 6 m depth. Sedimentation offshore of the river mouth is rapid and immediate, sufficient to clear the top 0.5 m of the water column above the 4-m isobath. Rapid clearance and deposition occurs in part due to the packaging of fine sediment into flocs in the river itself, well upstream of the freshwater/seawater interface.

Acknowledgements

This study was supported by the U.S. Office of Naval Research contracts N00014-97-1-0160 and N00014-99-1-0113, by the EURODELTA Project contract UEN.EVK3-CT-2001-20001, and by ARPA Veneto (Environmental Protection Regional Agency), a division of the Italy-Slovenia INTERREG II Research Project founded by EU. Special thanks is given to ISMAR-CNR-Italy and, in particular, Stefano Miserocchi, for his time and effective guidance on tracking down additional data. Thanks are also given to Andrew Stewart and Brent Law in the Particle Dynamics Laboratory at the Bedford Institute of Oceanography for conducting particle size analysis. Prep-

aration of the transect figures was carried out using Ocean Data View software designed by Reiner Schlitzer (http://www.awi-bremerhaven.de/GEO/ODV).

References

Aller, R.C., 1998. Mobile deltaic and continental shelf muds as suboxic, fluidized bed reactors. Mar. Chem. 61, 143–155.

Berhane, I., Sternberg, R.W., Kineke, G.C., Milligan, T.G., Kranck, K., 1997. The variability of suspended aggregates on the Amazon contiental shelf. Cont. Shelf Res. 17, 267–286.

Boldrin, A., Bortoluzzi, G., Frascari, F., Guerizoni, S., Rabitti, S., 1988. Recent deposits and suspended sediments off the Po Della Pila (Po River, main mouth), Italy. Mar. Geol. 79, 159–170.

Curran, K.J., Hill, P.S., Milligan, T.G., 2002. Fine grained suspended sediment dynamics in the Eel River flood plume. Cont. Shelf Res. 22, 2537–2550.

Drake, D.E., 1976. Suspended sediment transport and mud deposition on continental shelves. In: Stanley, D.J. and Swift D.J.P. (Eds.), Marine Sediment Transport and Environmental Management. John Wiley and Sons, New York, pp. 127–158.

Drake, R.L., 1972. A general mathematical survey of the coagulation equation. In: Hidy, G.M. and Brock, J.R. (Eds.), Topics in Current Aerosol Research, volume 3 (Part 2). Pergamon Press, New York, pp. 203–376.

Droppo, I.G., Ongley, E.D., 1994. Flocculation of Suspended Sediment in rivers of Southeastern Canada. Water Res. 28, 1799–1809.

Dyer, K.R., Manning, A.J., 1999. Observation of the size, settling velocity, and effective density of flocs, and their fractal dimensions. J. Sea Res. 41, 87–95.

Eisma, D., 1986. Flocculation and de-flocculation of suspended matter in estuaries. Neth. J. Sea Res. 20, 183–199.

Eisma, D., Kalf, J., 1984. Dispersal of Zaire river suspended matter in the estuary and the Angola basin. Neth. J. Sea Res. 17, 385–411.

Elimelech, M., Gregory, J., Jia, X., Williams, R.A., 1995. Particle Deposition and Aggregation – Measurement, Modelling and Simulation. Butterworth Heinemann, Woburn, MA.

Gandolfi, G., Mordenti, A., Paganelli, L., 1982. Composition and longshore dispersal of sands from the Po and Adige Rivers since the pre-Etruscan age. J. Sediment. Petrol. 52, 797–806.

Geyer, W.R., Beardsley, R.C., Lentz, S.J., Candela, J., Limeburner, R., Johns, W.E., Castro, B.M., Soares, I.D., 1996. Physical oceanography of the Amazon Shelf. Cont. Shelf Res. 16, 575–616.

Geyer, W.R., Hill, P., Milligan, T., Traykovski, P., 2000. The structure of the Eel River plume during floods. Cont. Shelf Res. 20, 2067–2093.

Gibbs, R.J., 1972. Water Chemistry of the Amazon. Geochim. Cosmochim. Acta 36, 1061–1066.

Gibbs, R.J., Konwar, L., 1986. Coagulation and settling of Amazon River suspended sediment. Cont. Shelf Res. 6, 127–149.

Hatcher, A., Hill, P.S., Grant, J., 2001. Optical backscatter of marine flocs. J. Sea Res. 46, 1–12.

Hill, P.S., Milligan, T.G., Geyer, W.R., 2000. Controls on effective settling velocity of suspended sediment in the Eel River flood plume. Cont. Shelf Res. 20, 2095–2112.

Hill, P.S., Voulgaris, G., Trowbridge, J.H., 2001. Controls on floc size in a continental shelf bottom boundary layer. J. Geophys. Res. 106, 9543–9549.

Kineke, G.C., Sternberg, R.W., Cacchione, D.A., Kranck, K., Drake, D.E., 1991. Distributions and Characteristics of Suspended Sediment on the Amazon Shelf. Oceanography, Feature (April), 21–26.

Kourafalou, V.H., 1999. Process studies on the Po River plume, North Adriatic Sea. J. Geophys. Res. 104, 29963–29985.

Kranck, K., 1973. Sediment deposition from flocculated suspensions. Nature 246, 348–350.

Kranck, K., 1980. Experiments on the significance of flocculation in the settling of fine-grained sediment in still water. Can. J. Earth Sci. 17, 1517–1526.

Kranck, K., 1993. Flocculation and sediment particle size. Arch. Hydrobiol. Suppl. 75, 266–309.

Kranck, K. and Milligan, T., 1991. Grain size in oceanography. In: Syvitski, J.P.M. (Ed.), Principles, Methods, and Application of Particle Size Analysis. Cambridge University Press, pp. 332–345.

Kranck, K., Petticrew, E., Milligan, T.G., Droppo, I.G., 1992. In situ particle size distributions resulting from flocculation of suspended sediment. In: Mehta, A.J. (Ed.), Nearshore and Estuarine Cohesive Sediment Transport, Coastal and Estuarine Studies Series, v. 42. American Geophysical Union, pp. 60–75.

Kuehl, S.A., Nittrouer, C.A., Allison, M.A., Faria, L.E.C., Dukat, D.A., Jeager, J.M., Pacioni, T.D., Figueiredo, A.G., Underkoffler, E.C., 1996. Sediment Deposition, accumulation, and seabed dynamics in an energetic fine-grained coastal environment. Cont. Shelf Res. 16, 787–815.

Matteucci, G., Frascari, F., 1997. Fluxes of suspended materials in the North Adriatic sea (Po prodelta area). Water Air Soil Pollut. 99, 557–572.

McCave, I.N., 1972. Transport and Escape of Fine-Grained Sediment from Shelf Areas. In: Swift, D.J.P., Duane, D.B. and Pilkey, O.H. (Eds.), Shelf Sediemnt Transport: Process and Pattern. Dowden, Hutchinson and Ross, Inc., Stroudsburg, PA, pp. 225–248.

McCave, I.N., Manighetti, B., Robinson, S.G., 1995. Sortable silt and fine sediment size/composition: Parameters for palaeocurrent speed and palaeoceanography. Paleoceanography 10, 593–610.

Milligan, T.G. and Kranck, K., 1991. Electro-resistance particle size analyzers. In: Syvitski, J.P.M. (Ed.) Principles,

Methods and Applications of Particle Size Analysis. Cambridge University Press, New York, pp. 109–118.
Milligan, T.G. and Loring, D.H., 1997. The effect of flocculation on bottom sediment size distributions in coastal inlets and its implication for contaminant transport. Water, Air Soil Pollut., pp. 33–42.
Milliman, J.D., Meade, R.H., 1983. World-wide delivery of sediment to the oceans. Geology 91, 1–21.
Nelson, B.W., 1970. Hydrography, sediment dispersal, and recent historical development of the Po River Delta. In: Morgan, J.P. (Ed.), Deltaic Sedimentation: Modern and Ancient, pages 152–184. Soc. Econ. Paleontologists and Mineralologists, New York.
Pettine, M., Camusso, M., Martinotti, W., Marchetti, R., Passino, R., Queirazza, G., 1994. Soluble and particulate metals in the Po River: factors affecting concentrations and partitioning. Sci. Total Environ. 145, 243–265.
Regione Emilia-Romagna, 2001. Eutrofizzazione delle acque costiere dell' Emilia-Romagna. In: Emilia-Romagna-Rapporto annuale 2000. Regione Emilia-Romagna, Bologna.
Rizzoli, P.M., Bergamasco, A., 1983. The dynamics of the coastal region of the Northern Adriatic Sea. J. Phys. Oceanogr. 13, 1105–1130.
Sharp, J.H., 1974. Improved analysis for 'particulate' organic carbon and nitrogen from seawater. Limnol. Oceanogr. 19, 984–989.
Slattery, M.C., Burt, T.P., 1997. Particle size characteristics of suspended sediment in hillslope runoff and stream flow. Earth Surf. Process. Landf. 22, 705–719.
Syvitski, J.P.M., Asprey, K.W., Clattenburg, D.A., Hodge, G.D., 1985. The prodelta environment of a fjord: suspended particle dynamics. Sedimentology 32, 83–107.
Syvitski, J.P.M., Asprey, K.W., Le Blanc, K.W.G., 1995. In situ characteristics of particles settling within a deep-water estuary. Top. Stud. Oceanogr. 42, 223–256.
Tiller, C.R. and O'Melia, C.L., 1993. Physicochemical Aggregation and Deposition in Aquatic Environments. In: Buffle, J. and van Leeuwen, H.P. (Eds.), Environmental Particles (Volume 2). Lewis Publishers, Boca Raton, FL, pp. 354–383.
Traykovski, P., Geyer, W.R., Irish, J.D., Lynch, J.F., 2000. The role of wave induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. Cont. Shelf Res. 20, 2113–2140.
Tsai, C.-H., Iacobellis, S., Lick, W., 1987. Flocculation of fine-grained lake sediments due to a uniform shear stress. J. Great Lakes Res. 13, 135–146.
van Olphen, H., 1963. An Introduction to Clay Colloid Chemistry. Interscience Publishers, New York.
Walling, D.E., Moorehead, P.W., 1989. The particle size characteristics of fluvial sediment: an overview. Hydrobiologia 176/177, 125–149.
Weilenmann, U., O'Melia, C.R., Stumm, W., 1989. Particle transport in lakes: Models and measurements. Limnol. Oceanogr. 34, 1–18.
Wheatcroft, R.A., 2000. Oceanic Flood Sedimentation: A New Perspective. Cont. Shelf Res. 20, 2059–2066.
Wright, L.D., 1977. Sediment transport and deposition at river mouths: A synthesis. Geol. Soc. Am. Bull. 88, 857–868.