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Boston Harbor Sediment Study

U.S. Army Corps of Engineers
New England District

Jesse Roberts, Rich Jepsen, Charles Bryan, and Mike Chaplin

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Abstract

Experiments have been done in order to determine the erodibility of two composite sediments from the Boston Harbor as a function of consolidation and shear stress. For both sediments at all shear stresses, erosion rates were strong decreasing function of density. For each sediment, the erosion rate was approximated as a function of shear stress (τ) and bulk density (ρ) as $E=A\tau^n\rho^m$ where, A, n, and m are sediment specific, experimentally determined constants. In addition, sediment bulk properties of in-situ cores from each site were analyzed and determined to be similar to those found for their respective site composite sediments.

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1. Introduction

In this study, the erosion rates of two reconstituted sediments from the Boston Harbor have been determined as a function of density and shear stress by means of a high shear stress sediment erosion flume at Sandia National Laboratories. One sediment was from the CAD cell called the Open Cell and one was an area near the CAD cell called the Mid Channel. For all cores bulk density was determined as a function of depth and consolidation time. Sediment cores were eroded to determine erosion rates as a function of density and shear stress. In addition, an in-situ core from each site was analyzed for bulk density, particle size, mineralogy, and organic content as a function of depth.

In the following section, descriptions of the high shear stress sediment erosion flume and experimental procedures are given. The results of laboratory studies for the reconstituted sediments are presented in section 3, while the laboratory studies for the in-situ cores are presented in section 4. The fifth section discusses the reconstituted and in-situ laboratory results, and the summary and concluding remarks are given in the final section.

2. Experimental Procedures

The information in this section is partially based on the articles by Jepsen et al (1997a), and Roberts (1998).

2.1 Description of the High Shear Stress Sediment Erosion Flume

The High Shear Stress Sediment Erosion Flume is shown in Figure 1 and is essentially a straight flume, which has a test section with an open bottom through which a rectangular cross-section coring tube containing sediment can be inserted. The main components of the flume are the coring tube; the test section; an inlet section for uniform, fully-developed, turbulent flow; a flow exit section; a water storage tank; and a pump to force water through the system. The coring tube, test section, inlet section, and exit section are made of clear acrylic or polycarbonate so that the sediment-water interactions can be observed. The coring tube has a rectangular cross-section, 10 cm by 15 cm, and can be up to 1 m in length.

Water is pumped through the system from a 120 gallon storage tank, through a 5 cm diameter pipe, and then through a flow converter into the rectangular duct shown. This duct is 5 cm in height, 10 cm in width, and 200 cm in length; it connects to the test section which has the same cross-sectional area and is 15 cm long. The flow converter changes the shape of the cross-section from circular to the rectangular duct. The flow is regulated by a three-way valve so that part of the flow goes into the duct while the remainder returns to the tank. Also, there is a small valve in the duct immediately downstream from the test section which is opened at higher flow rates to keep the pressure in the duct and over the test section at atmospheric conditions.

At the start of each test, the coring tube is filled with reconstructed sediments. The procedure for preparing the reconstructed sediments in the laboratory will be described later. The coring tube and the sediment it contains are then inserted into the bottom of the test section. An operator moves the sediment upward using a piston which is inside the coring tube and is connected to a mechanical jack and then driven by a variable-speed controller. By this means, the sediments can be raised and made level with the bottom of the test section. The speed of the jack movement can be controlled at a variable rate in measurable increments as small as 0.25 mm.

Water is forced through the duct and the test section over the surface of the sediments. The shear produced by this flow causes the sediments to erode. As the sediments in the core erode, they are continually moved upwards by the operator so that the sediment-water interface remains level with the bottom of the test and inlet sections. The erosion rate is recorded as the upward movement of the sediments in the coring tube over time.

2.2 Hydrodynamics

For the flow rates of interest, it can be shown that fully developed turbulent flow exists in the test section. Turbulent flow through pipes has been studied extensively, and empirical functions have been developed which relate the mean flow rate to the wall shear stress. In general, flow in circular cross-section pipes has been investigated. However, the relations developed for flow through circular pipes can be extended to non-circular cross-sections by means of a shape factor. An implicit formula relating the wall shear stress to the mean flow in a pipe of arbitrary cross-section can be obtained from Prandtl's Universal Law of Friction (Schlichting, 1979). For a pipe with a smooth surface, this formula is

$$\frac{1}{\sqrt{\lambda}} = 2.0\log\left[\frac{UD\sqrt{\lambda}}{\nu}\right] - 0.8\,(2.1) \qquad (2.1)$$

where U is the mean flow speed, ν is the kinematic viscosity, λ is the friction factor, and D is the hydraulic diameter defined as the ratio of four times the cross-sectional area to the wetted perimeter. For a pipe with a rectangular cross-section, or duct, the hydraulic diameter is

$$D = 2hw/(h + w) \qquad (2.2)$$

where w is the duct width and h is the duct height. The friction factor is defined by

$$\lambda = \frac{8\tau}{\rho U^2} \qquad (2.3)$$

where ρ is the density of water and τ is the wall shear stress. Inserting Eqs. (2.2) and (2.3) into Eq. (2.1) then gives the wall shear stress τ as an implicit function of the mean flow speed U.

For shear stresses in the range of 0.1 to 10 N/m^2, the Reynolds numbers, UD/ν, are on the order of 10^4 to 10^5. These values for Reynolds numbers are sufficient for turbulent flow to exist for the stresses of interest in this study. For flow in a circular pipe, turbulent flow theory suggests that the transition from laminar to turbulent flow occurs within 25 to 40 diameters from the entrance to the pipe. Since the hydraulic diameter of the duct pipe is 6.8 cm, this suggests an entry length of approximately 170 to 270 cm. The length of the duct leading to the test section is 180 cm and is preceded by a 20 cm flow converter and several meters of inlet pipe. These arguments along with direct observations indicate that the flow is fully turbulent in the test section.

2.3 Core Preparation

In order to gain insight on how sediment consolidation parameters (namely bulk density or water content of the sediment) affect erosion rates, reconstituted sediments were prepared in the laboratory. To obtain different bulk densities for the sediments taken from the Open Cell and Mid Channel sites for the erosion tests, sediment cores were prepared as follows. Approximately 30 gallons of wet sediments were placed in 35 gallon cylindrical tanks and mixed until the sediment-water mixture was homogeneous.

The sediment mixtures were then poured into 30 cm coring tubes. These cores were allowed to consolidate for 2, 5, 10, 30, 60, 90, and 120 days.

2.4 Measurements of Sediment Erosion Rates

The procedure for measuring the erosion rates of the sediments as a function of shear stress and depth was as follows. The sediment cores were prepared as described above and then moved upward into the test section until the sediment surface was even with the bottom of the test section. A measurement was made of the depth to the bottom of the sediment in the core. The flume was then run at a specific flow rate corresponding to a particular shear stress. Erosion rates were obtained by measuring the remaining core length at different time intervals, taking the difference between each successive measurement, and dividing by the time interval.

In order to measure erosion rates at several different shear stresses using only one core, the following procedure was generally used. Starting at a low shear stress, the flume was run sequentially at higher shear stresses with each succeeding shear stress being twice the previous one. Generally about three shear stresses were run sequentially. Each shear stress was run until at least 1 to 3 mm but no more than 2 cm were eroded. Also, each shear stress was run for a minimum of 20 seconds and a maximum of 10 minutes. This defines the minimum and maximum erosion rates measured by the high shear stress sediment erosion flume to be 1.67×10^{-4} and 0.1 cm/s respectively. The time interval was recorded for each run with a stop watch. The flow was then increased to the next shear stress, and so on until the highest shear stress was run. This cycle was repeated until all of the sediment had eroded from the core. If after three cycles a particular shear stress showed a rate of erosion less than 10^{-4} cm/s, it was dropped from the cycle; if after many cycles the erosion rates decreased significantly, a higher shear stress was included in the cycle.

2.5 Measurements of Critical Shear Stress for Erosion

A critical shear stress can be quantitatively defined as the shear stress at which a very small, but accurately measurable, rate of erosion occurs. In the present study, this rate of erosion was chosen to be 10^{-4} cm/s; this represents 1 mm of erosion in approximately 15 minutes.

2.6 Measurements of Sediment Bulk Properties

For the analysis of the sediment bulk properties duplicate cores were made that were prepared the same as the rectangular. The core sleeves of these analysis cores were made from 7.6 cm inner diameter thin acrylic tubes of the same length as the rectangular cores.

In order to determine the bulk density of the sediments at a particular depth and consolidation time, the sediment analysis cores were frozen, sliced into 2.5 cm sections, and then weighed (wet weight). They were then dried in the oven at approximately 75°C for 2 days and weighed again (dry weight). The water content W is then given by

$$W = \left(\frac{m_w - m_d}{m_w} \right) \tag{2.4}$$

where m_w and m_d are the wet and dry weights respectively. A volume of sediment, V, consists of both solid particles and water, and can be written as

$$V = V_s + V_w \tag{2.5}$$

where V_s is the volume of solid particles and V_w is the volume of water. If the sediment particles and water have densities ρ_s and ρ_w respectively, the water content of the sediment can be written as

$$W = \frac{\rho_w V_w}{\rho V} \tag{2.6}$$

where ρ is the bulk density of the sediments. A mass balance of the volume of sediment gives

$$\rho V = \rho_s V_s + \rho_w V_w \tag{2.7}$$

By combining Eqs. (2.5), (2.6), and (2.7), an explicit expression can be determined for the bulk density of the sediment, ρ, as a function of the water content, W, and the densities of the sediment particles and water. This equation is

$$\rho = \frac{\rho_s \rho_w}{\rho_w + (\rho_s - \rho_w)W} \tag{2.8}$$

For the purpose of these calculations, it has been assumed that $\rho_s = 2.6$ gm/cm^3 and $\rho_w =$ 1.0 gm/cm^3.

Particle sizes and particle size distributions were determined by use of a Malvern Mastersizer S particle sizing package for particle diameters between 0.05 and 900 μm. All sediment samples had particle sizes less than 900 μm. Approximately 5 to 10 grams of sediment was placed in a beaker containing about 500 mL of water and mixed by means of a magnetic stir bar/plate combination. Approximately 1 mL of this solution was then inserted into the sizers sampling system and further disaggregated as it is re-circulated through the sampling system by means of a centrifugal pump. The sample was allowed to disaggregate for five minutes on the stir plate and an additional five minutes in the recirculating pump sampling system before analysis by the sizer. To ensure complete dissagregation and sample uniformity the sediment samples were analyzed multiple times and repeated in triplicate. From these measurements, the distribution of grain sizes and mean grain sizes as a function of depth were obtained.

The dry sediment was crushed into powder and then weighed. Approximately 5 mL of 10% hydrochloric acid was added to every 1 gram of dry sediment (Tye et al, 1996). The sample was again dried in the oven at 75°C, and analyzed in an UIC, Inc. Model CM5014 CO_2 Coulometer to determine the total organic carbon content of the sediment.

The mineralogies of the sediments were determined by means of X-ray powder diffraction using a Bruker, AXS Model D8 Advance X-ray Diffractometer. Samples were crushed to a size of about 10 μm before being measured by X-ray diffraction.

3. Results for Laboratory Consolidation and Erosion Tests

Tests were done to determine erosion properties for two sediments retrieved from the Boston Harbor with respect to consolidation and bulk density. The two sites are identified as Open Cell and Mid Channel. Each site was individually mixed into a homogeneous composite prior to testing.

3.1 Bulk Properties

Particle size, bulk density, organic content, and mineralogy of each of the two composite sediment mixtures were measured. The size distributions for each composite are shown in Figure 2. The mean particle size was 99.8 and 35.7 μm for the Open Cell and Mid Channel sediments respectively. The organic content for the composite mixture was 3.02 % for Open Cell, 2.23 % for Mid Channel. The mineralogy of each composite and a summary of all sediment properties is shown in Table 1. Particle size, organic content, and mineralogy were constant with depth for each composite core. Bulk density was the only parameter that was a variable in each core.

Bulk density was determined as a function of depth for 30 cm core lengths. Consolidation times were between 2 and 120 days for each core. Densities were determined by measuring the water content of each core in 2.5 cm increments. Sediment bulk densities are shown in Figure 3a for Open Cell and Figure 3b for Mid Channel. For all cores, the bulk density generally increases with depth and consolidation time. The bulk density for the Open Cell sediments ranged between 1.45 g/cm^3 and 1.58 g/cm^3 for up to a 120 day consolidation time. The Mid Channel sediments had a bulk density range of 1.38 to 1.51 g/cm^3. The Mid Channel sediments were less dense and smaller (i.e. lesser mean particle size) than the Open Cell sediments. In general, sediments with smaller mean particle sizes will be less dense than those with a larger mean particle size. However, this is not always the case, other important considerations are mineralogy and organic content.

3.2 Erosion Rates

Erosion rates as a function of shear stress and depth were obtained for cores at consolidation times between 2 and 120 days. Erosion rates were measured for shear stresses of 0.5, 1.0, 2.0, and 4.0 N/m^2. The erosion rates for the lower shear stress of 0.5 N/m^2 could only be reasonably measured for the upper portion of the cores and for short consolidation times. This is because erosion either does not occur or is so slow that it would take hours to days to erode a measurable amount of sediment. Likewise, the 4.0 N/m^2 shear could not be tested at all depths because it eroded low bulk density areas too fast for the operator to accurately measure erosion rates.

All of the data for erosion rates as a function of bulk density for shear stresses of 0.5, 1.0, 2.0, and 4.0 N/m^2 are shown for each core in Figures 4a and 4b for site composites Open Cell and Mid Channel respectively. A large decrease in erosion rate as the bulk density increases can be seen at all shear stresses. This has also been seen in previous experiments by Jepsen et al (1997a, 1997b, 1998) and Roberts et al (1998) for other natural and pure quartz sediments in similar laboratory tests. In general, the data can be approximated by an equation of the form

$$E = A\tau^n\rho^m \tag{3.1}$$

where E is the erosion rate (cm/s), τ is the shear stress (N/m^2), ρ is the bulk density (g/cm^3), and n, m, and A are constants. The constants are shown in Table 2 for each composite. For each shear stress, the erosion rate as a function of bulk density is shown as a straight line which demonstrates that the above equation represents the data quite well and also that the erosion rate is a unique function of shear stress and bulk density. This relationship (with different constants) has been shown to successfully describe seven other natural and many synthetic sediments (Jepsen et al, 1997a, 1997b and 1998, and Roberts et al, 1998).

3.3 Critical Shear Stress

The critical shear stress can also be determined as a function of bulk density. From Eq. (3.1), the shear stress, τ, can be defined as the critical shear stress, τ_{cr}, by setting the erosion rate, E, to 10^{-4} cm/s. Solving for τ_{cr} as a function of bulk density gives

$$\tau_{cr} = \left[\frac{E}{A}\right]^{\frac{1}{n}} \rho^{\frac{-m}{n}} \tag{3.2}$$

By substituting 10^{-4} cm/s for the erosion rate and the constants n, m, and A for each sediment into the above equation, one obtains a general relation for the critical shear stress. Substituting the constants listed in Table 2 for each sediment shows that the critical shear stress increases rapidly with small increases of bulk density.

Since tests were done for most of the shear stresses at erosion rates down to 10^{-4} cm/s , Eq. (3.2) is well supported by experimental data. However, Eq. (3.2) can also approximate the data for erosion rates less than the defined 10^{-4} cm/s erosion rate for the critical shear stress. Although erosion rates less than 10^{-4} cm/s may be difficult to measure accurately, the curves plotted in Figures 4a and 4b that are described by Eq. (3.1) could be extrapolated to lower erosion rates. This would allow the critical shear stress to be defined for an erosion rate of 10^{-5} cm/s as well. For example, Figures 5a and 5b show the critical shear stresses (defined for erosion rates of 10^{-4} and 10^{-5} cm/s) as a function of bulk density as determined from Eq. (3.2) for the Open Cell and Mid Channel composites respectively.

4. Results for Laboratory Studies of In-Situ Cores

Tests were done to determine sediment bulk properties for three in-situ sediment analysis cores retrieved from the Boston Harbor. The three sites are identified as Control 1 (retrieved near the Mid Channel site), and T31 and T33 (retrieved near the Open Cell site). The in-situ cores were not analyzed for erosion rate because they were divided into sections, on sight, prior to shipping with the intention of only doing bulk analysis. This is because a whole in-situ core cannot be shipped without significant agitation and detriment to the bulk properties. Therefore, erosion rate properties of in-situ cores must be done on sight.

Particle size, bulk density, organic content, and mineralogy of the in-situ site Control 1 and T31 were measured. For the T33 site, bulk density was the only bulk property measured. The bulk properties of each sediment core were measured with depth and recorded in 7.6 cm increments from the surface (0 cm) to a depth of 45.7 cm.

4.1 Bulk Properties for In-Situ Site: Control 1

The bulk density (Figure 6a) increased from 1.37 g/ cm^3 to 1.4 g/cm^3 for the first 11 cm in depth. Then the bulk density remained constant between 1.39 g/cm^3 and 1.41 g/cm^3 for the remainder of the core. The mean particle size (Figure 6b) was 105 μm at the surface; it then decreased and remained relatively constant between 11 cm and 35 cm ranging from 43 μm to 51 μm in size. At the bottom the mean particle size decreased further to 33 μm in size. The organic content (Figure 6c) was 4.3% at the surface; it then decreased and remained relatively constant for the rest of the core ranging from 2.2% to 2.7%. The mineralogy was qualitatively constant with depth and is shown in Table 1 along with a summary of all sediment properties.

4.2 Bulk Properties for In-Situ Site: T31

The bulk density (Figure 7a) generally increased with depth throughout the core ranging from 1.35 g/cm^3 to 1.68 g/cm^3 with local decreases in bulk density near 20 cm and 42 cm depths. The particle size (Figure 7b) was largest at the surface near a size of 103 μm; it then decreased almost linearly to a depth of 20 cm reaching a value of 65 μm. The mean sized then increased and stayed relatively constant throughout the remainder of the core ranging between 80 μm and 89 μm in size. The organic content (Figure 7c) at the surface was approximately 3.2%; it then decreased and remained relatively constant between about 12 cm and 35 cm ranging from 2.1% to 2.8%. The organic content increased at the bottom to its highest value of about 4%. The mineralogy was constant with depth and is shown in Table 1 along with a summary of all sediment properties. The mineralogy for the Control 1 and T31 sites were nearly identical, the major difference was that there was more quartz at the T31 site.

4.3 Bulk Properties for In-Situ Site; T33

The bulk density (Figure 8) was smallest at the surface (1.5 g/cm^3); it then increased significantly at a depth of 12 cm. The bulk density remained constant for the rest of the core (ranging from 1.71 g/cm^3 to 1.77 g/cm^3) except for a local increase in the density at a depth of 27 cm to a value of 1.85 g/cm^3.

5. Discussion of Results

The following compares the bulk properties of the composite sediments and their related in-situ cores. Also discussed and compared is the erosion behavior of the two composite sediments.

5.1 Bulk Properties: In-Situ vs. Composite Sediments

The composite sediment identified as Mid Channel and the in-situ core retrieved near the Mid Channel site identified as Control 1 showed a general similarity in their bulk properties. First, Although the particle size of the surface layer of Control 1 sediment was relatively coarse, the remainder of the core had similar size distributions and mean particle size as that determined for the Mid Channel composite (Table 1 & Figures 2 & 6b). Second, except for an increase in organic content at the top and bottom of the Control 1 core, the organic content was similar to that determined for the Mid Channel composite (Table 1 & Figure 6c). Finally, the two sediments existed in the same density range and had nearly identical mineralogical properties. Therefore, the studies performed on the composite sediments are relevant to field conditions and using the consolidation time vs. density plot for the Mid Channel composite (Figure 3b), one could estimate how long ago the field sediments were deposited. However, laboratory consolidation studies were conducted for a maximum of 120 days as shown in Figure 3b. Therefore, the information contained in Figure 3b is best suited to give estimations of in-situ sediment consolidation history for residence times less than 120 days.

In-situ core T33 retrieved near the Open Cell composites sediments (further away than T31) did not share similar bulk densities with the Open Cell and was therefore not further investigated. In-Situ core T31 retrieved near the Open Cell shared similar bulk properties with the Open Cell. A unique characteristic of the Open Cell sediment was its distinct bimodal particle size distribution, also present in the T31 sediment but less pronounced. The fine-grained portion of the sediment is very similar to that found in the Mid Channel (Figure 2). Also, the size distribution shows clearly that 100-200 μm sand has been mixed in with the sediment in the Open Cell. The majority of the T31 sediment had a particle size comparable to the Open Cell composite especially at the surface where the composite sample was taken, with an exception at a depth of 20 cm where there was a significant decrease in the particle size. The organic content, mineralogy, and the bulk density ranges for both sediments are similar and overlap. Therefore, the studies performed on the composite sediments are relevant to field conditions and using the consolidation time vs. density plot for the Open Cell composite (Figure 3a), one could estimate the residence time of recently deposited sediments (i.e. less than 120 days).

5.2 Consolidation and Erosion Properties for the Composite Sediments

For the Mid Channel composite the sediment consolidation was relatively slow with time although after 60 days the consolidation seemed to slow significantly. For the Open Cell composite, consolidation was quicker and slowed considerably by 30 days. The reason for the faster consolidation of the Open Cell sediments was probably due to the larger mean particle size, which increases the ability for the pore water to be expelled.

The mineralogy for the Open Cell and Mid Channel are qualitatively similar, although by using quantitative techniques it was seen that the Open Cell had approximately 1.5 times more quartz than the Mid Channel. This is most likely due to the large sand content in the Open Cell.

The dependence of erosion on bulk density was greater for the Mid Channel composite sediments which is quantitatively seen as the steeper slope or greater negative m value seen in Table 2. The m value in equation 3.1 can be viewed as a measure of the cohesiveness of the sediments where non-cohesive sediments being attributed with an m value of zero and increasingly negative values attributed to more cohesive sediments. Therefore the Mid Channel sediments can be viewed as more cohesive than the Open Cell sediments. Since the organic content and qualitative mineralogy are similar, the increase in cohesivity is most likely a result of the smaller mean particle size of the Mid Channel sediment. Again, from review of the particle size distributions (Figure 2) the decrease in mean particle size is a result of the decrease in the quartz mineral constituent above 100 μm.

6. Summary and Concluding Remarks

By means of the experiments described here, the effects of sediment bulk density on erosion rates were measured for two composite sediments from two locations in the Boston Harbor. From these experiments, the following was determined. (1) The bulk density of the sediments generally increases with depth and time. (2) For each sediment and shear stress, the erosion rate is a unique function of bulk density and decreases as the bulk density increases. (3) For each sediment, the erosion rate can be approximated as $E=A\tau^n\rho^m$ where, A, n, and m are sediment specific, experimentally determined constants.

In addition, an in-situ core from each site was analyzed for bulk density, particle size, mineralogy, and organic content as a function of depth. The bulk properties of these cores proved to be similar to those found for the their respective site composite sediments. Therefore, the studies performed on the composite sediments are relevant to field conditions and may be used to predict present and future erosion properties of those sediments in the Boston Harbor.

7. References

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Table 1. Summary of all Sediment Bulk Properties

Sediment Name	Bulk Density Range (g/cm^3)	Mean Particle Size (μm)	Mean Organic Content (% by mass)	Mineralogy (Minerals listed in descending amount)
Open Cell	1.45-1.58	99.8	3.02	1) Quartz, 2) Muscovite, 3) Albite, 4) Chlorite, 5) Microcline
Mid Channel	1.38-1.5	35.7	2.23	Same as above
Control 1	1.37-1.41	55.1	2.80	Same as above
T31	1.35-1.68	83.7	2.84	Same as above
T33	1.50-1.85	-	-	-

Table 2. Constants for Equation 3.1 for the two composite sediments

Sediment	n	m	A
Open Cell	3.25	-75	3.35×10^{10}
Mid Channel	3.55	-103	1.32×10^{12}

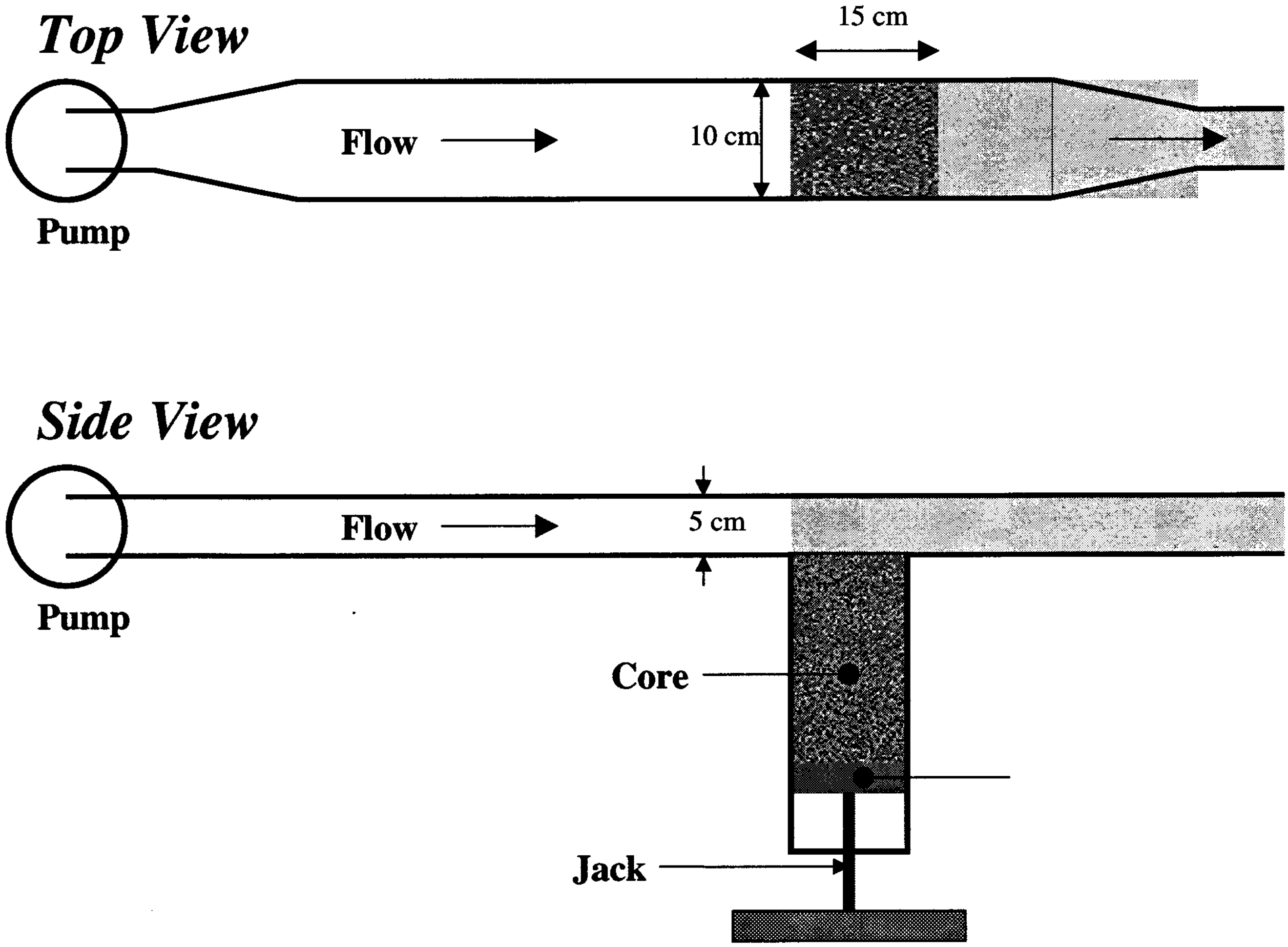

Figure 1. High Shear Stress Flume schematic.

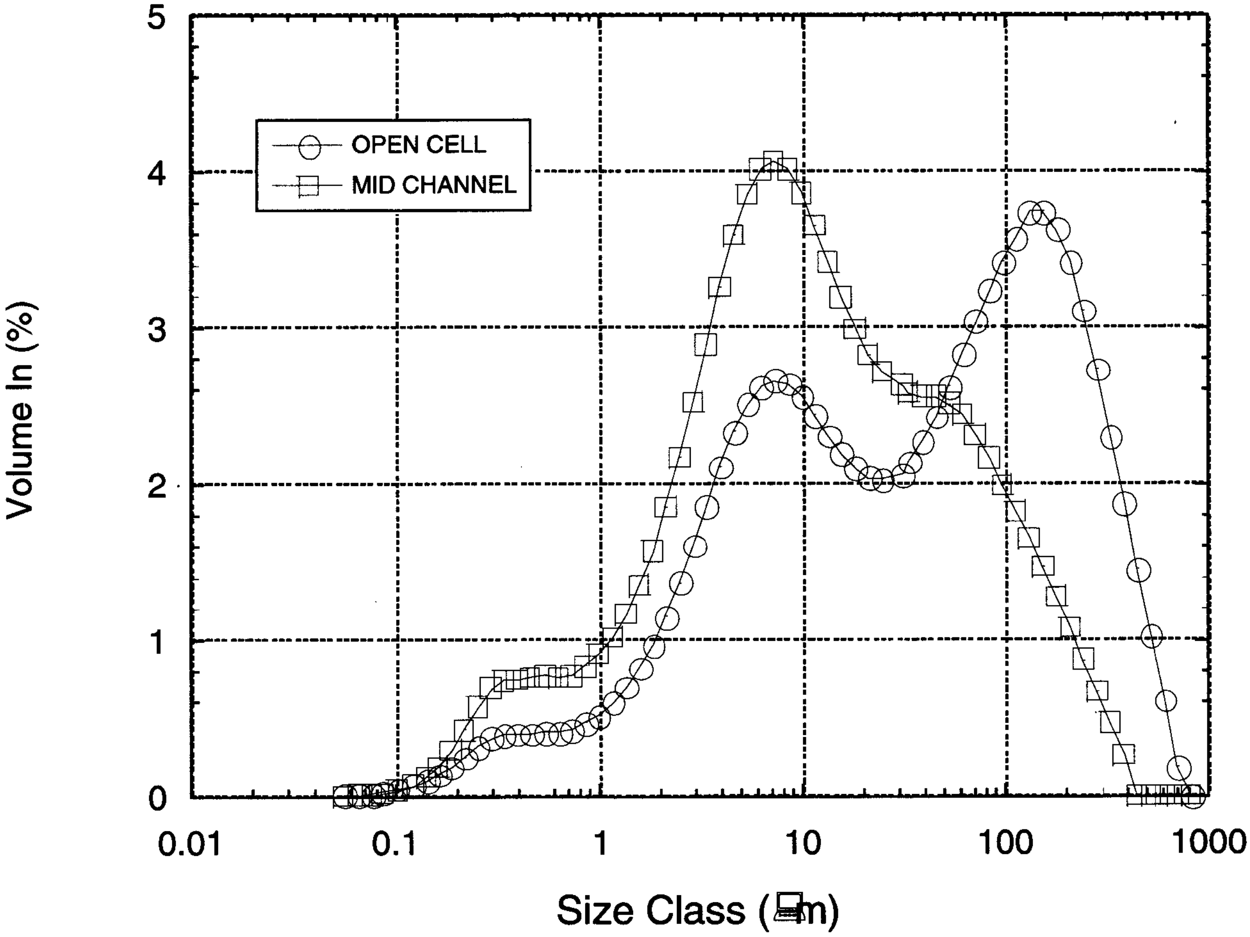

Figure 2. Particle size distribution for Open Cell and Mid Channel composites.

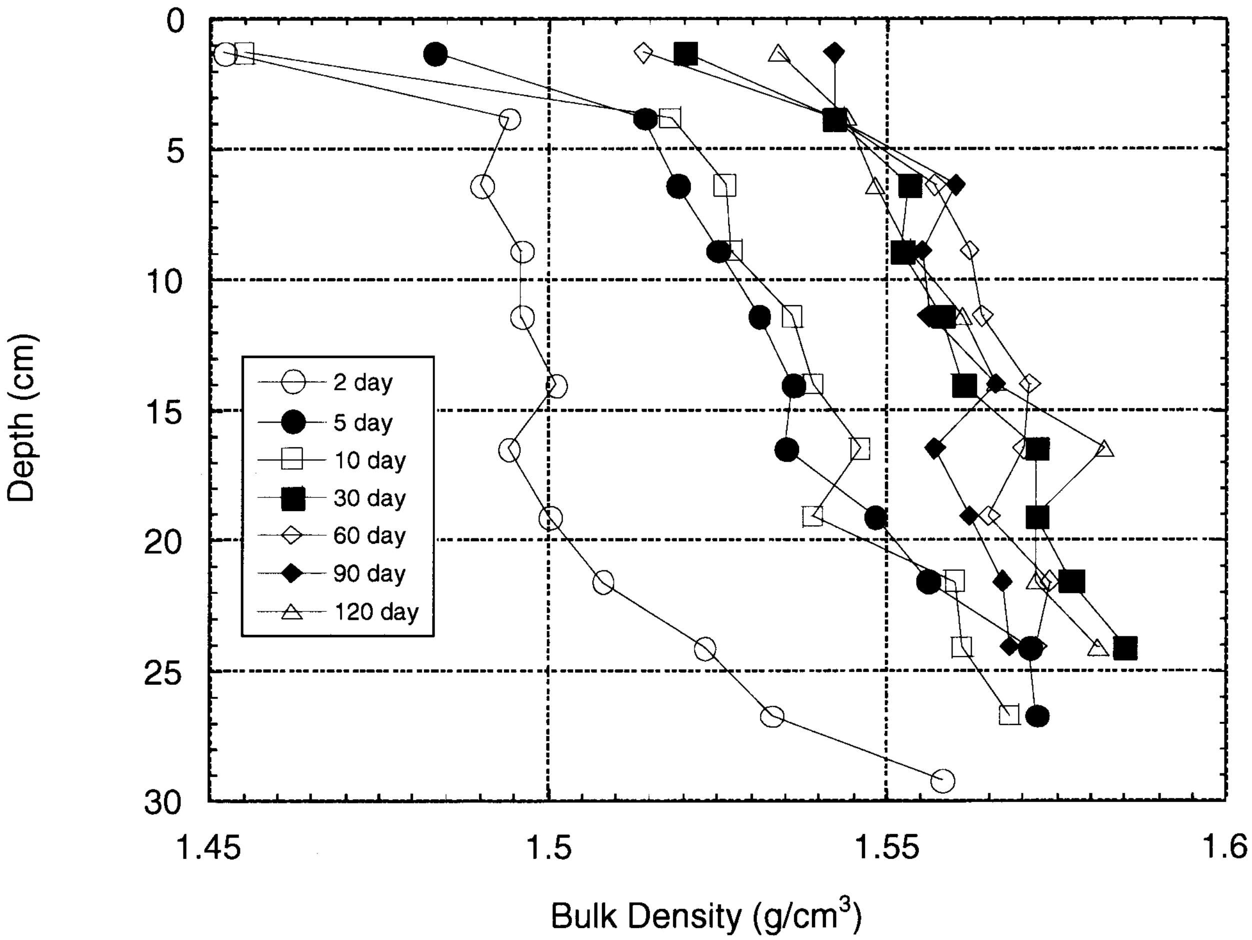

Figure 3a. Bulk density as a function of depth and consolidation time for Open Cell composite.

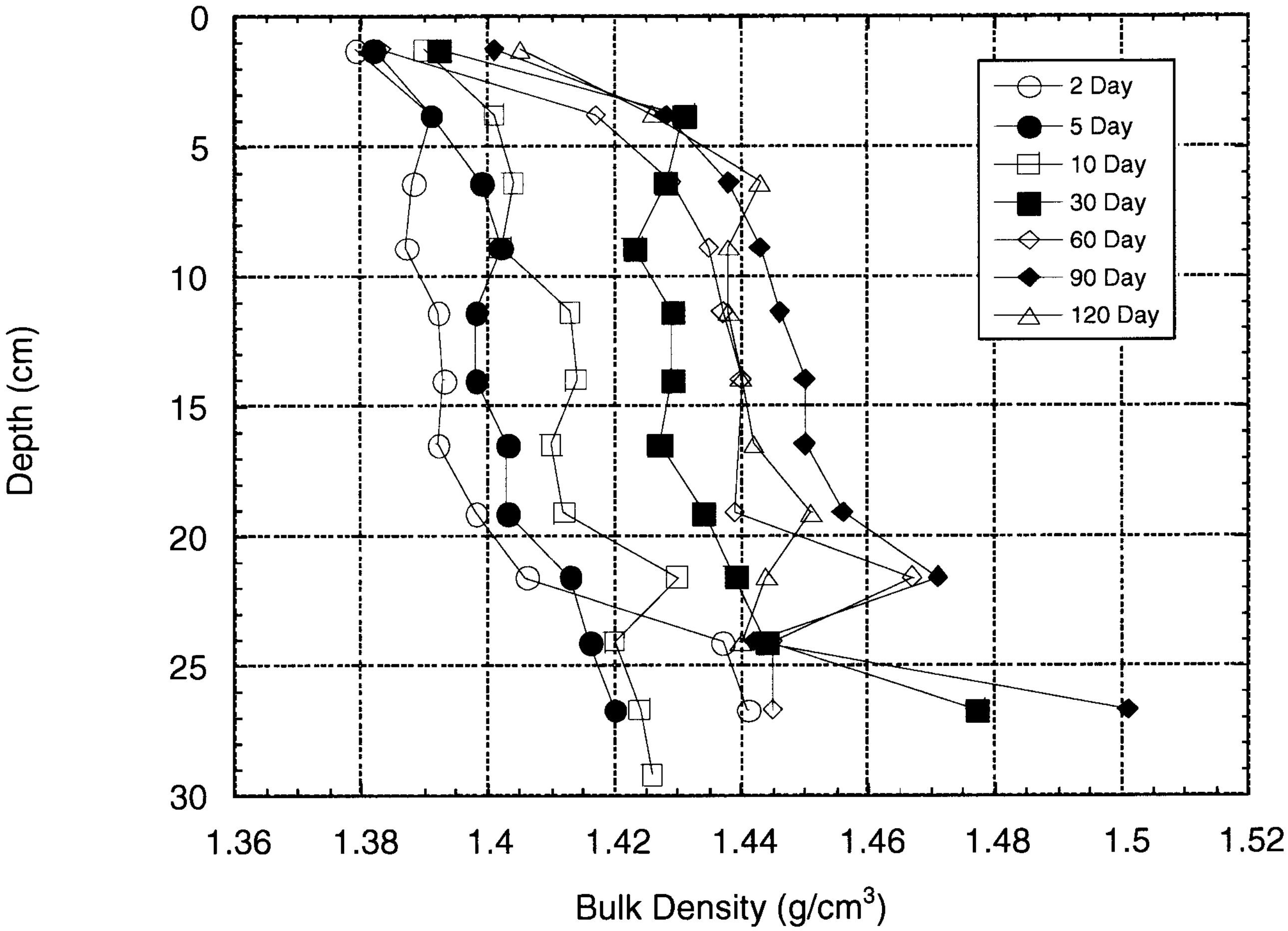

Figure 3b. Bulk density as a function of depth and consolidation time for Mid Channel composite.

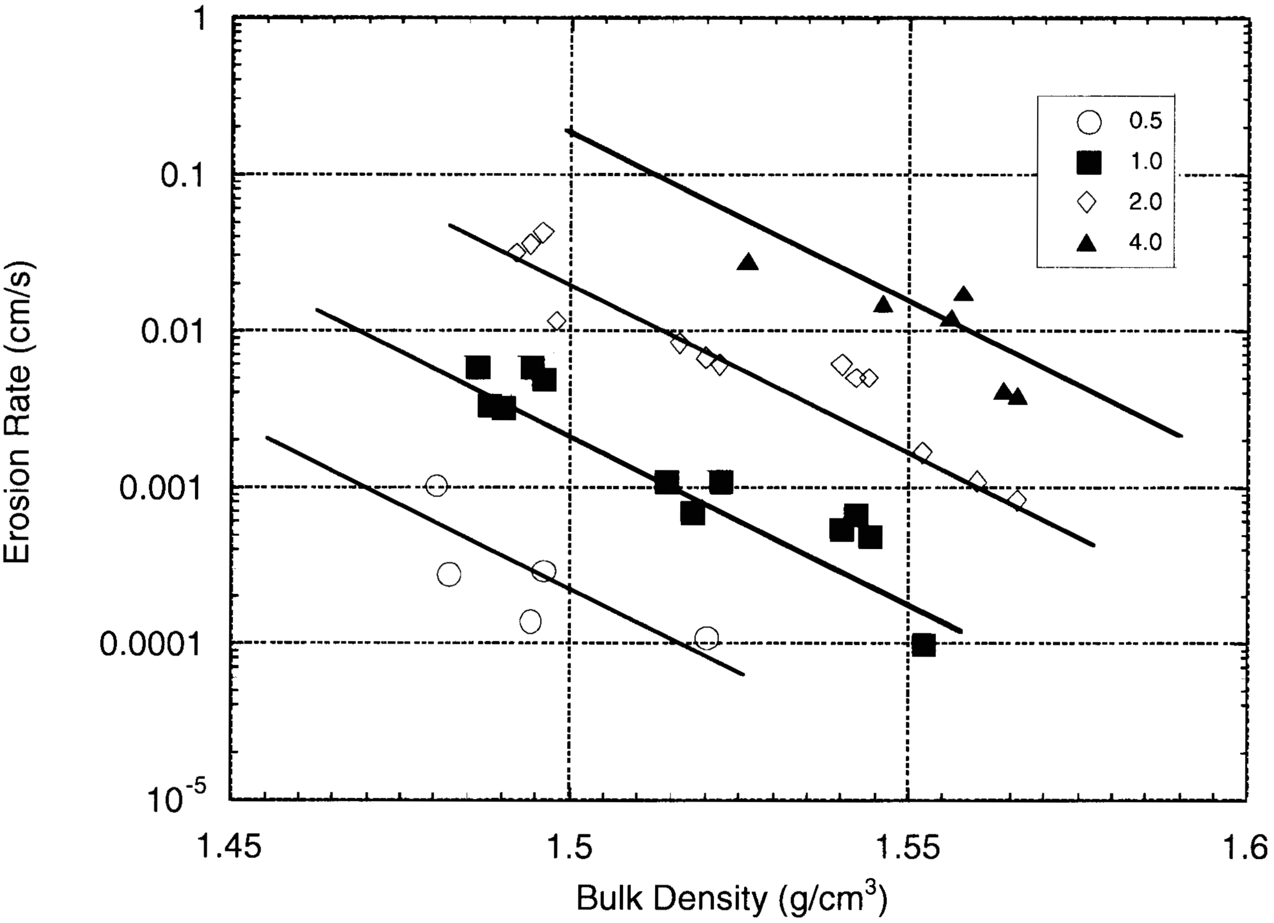

Figure 4a. Erosion rate vs. bulk density and shear stress for Open Cell composite. Shear stresses of 0.5, 1.0, 2.0 and 4.0 N/m^2 are shown.

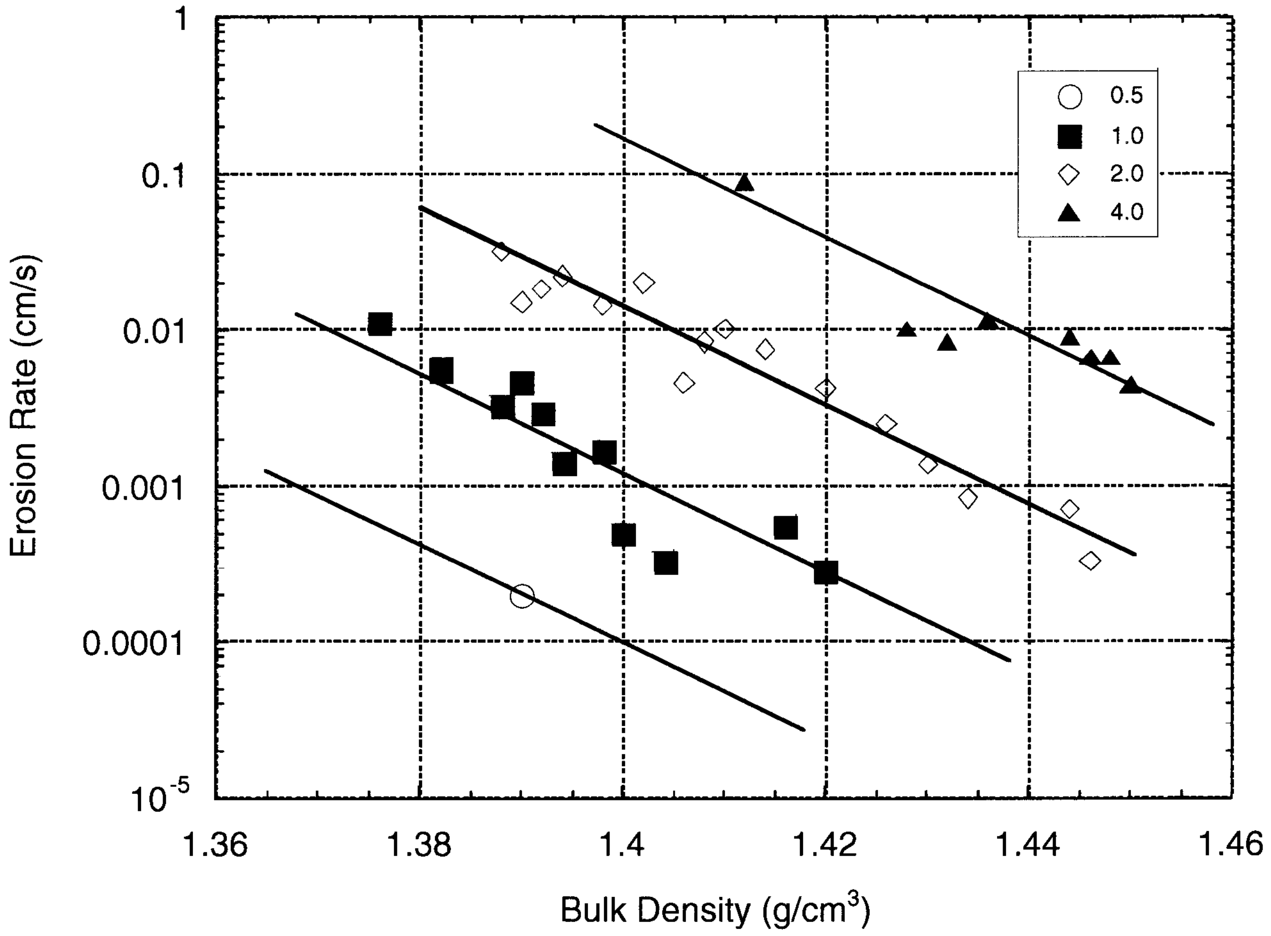

Figure 4b. Erosion rate vs. bulk density and shear stress for Mid Channel Composite. Shear stresses of 0.5, 1.0, 2.0 and 4.0 N/m^2 are shown.

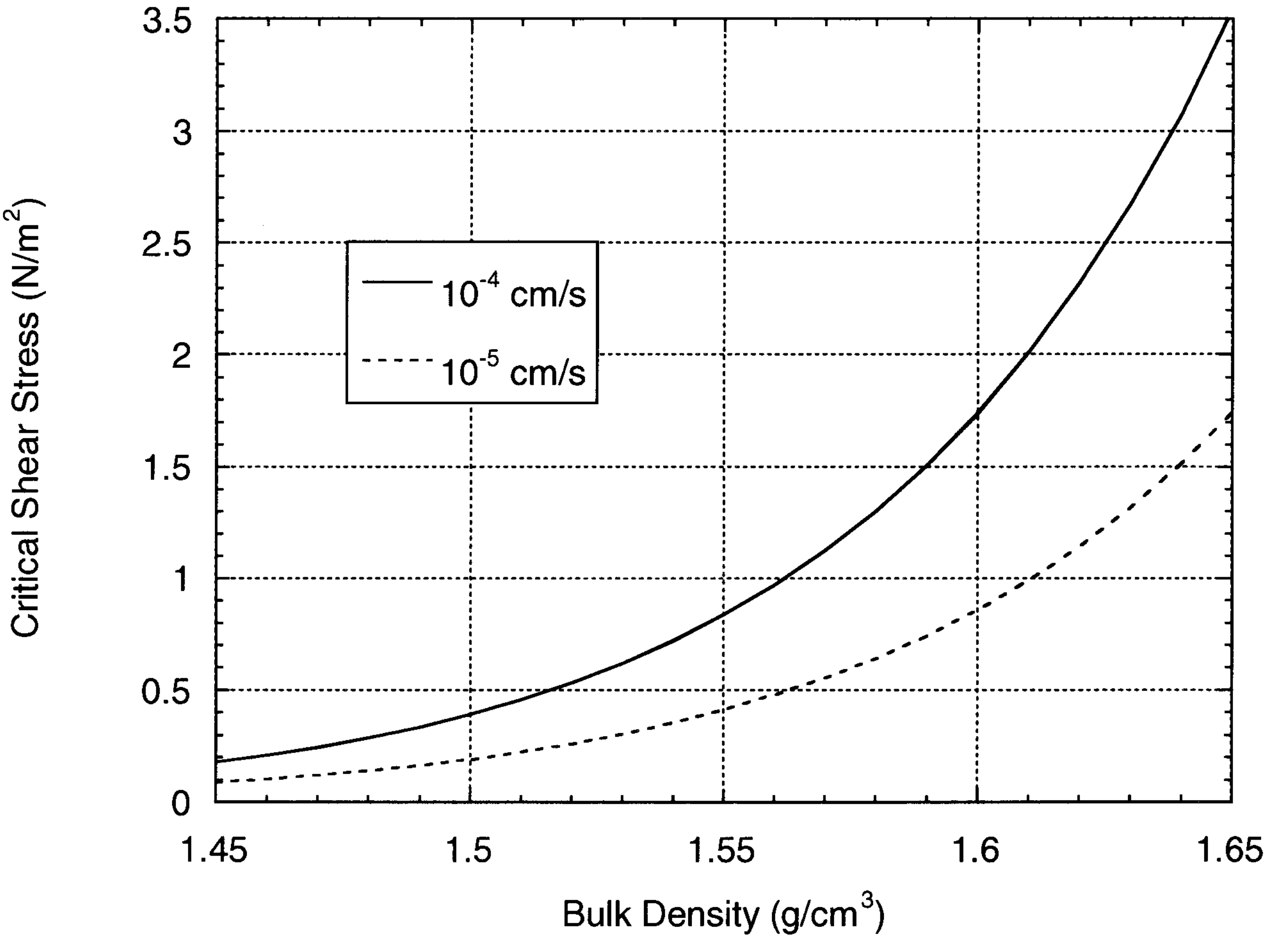

Figure 5a. Critical shear stresses as a function of bulk density for Open Cell composite.

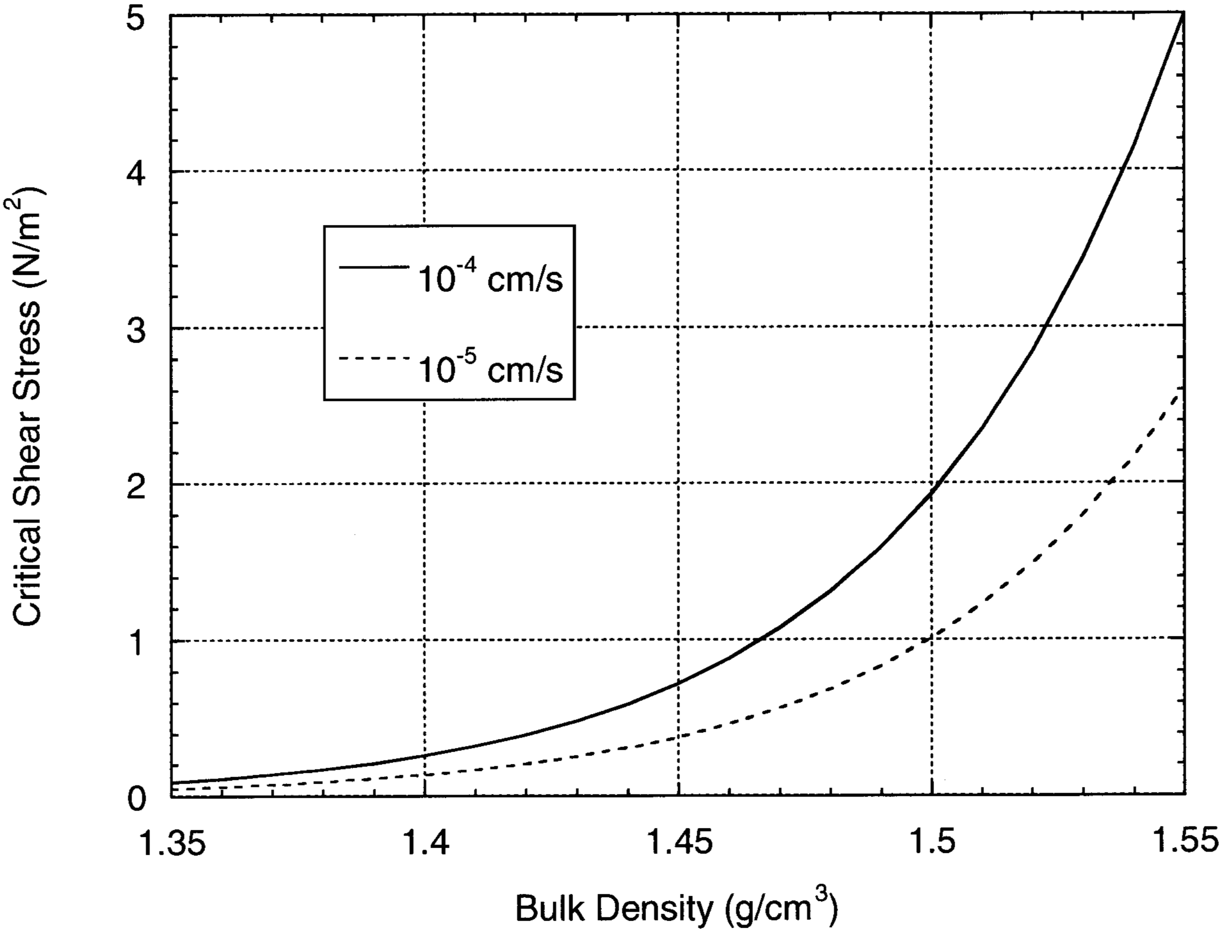

Figure 5b. Critical shear stresses as a function of bulk density for Mid Channel composite.

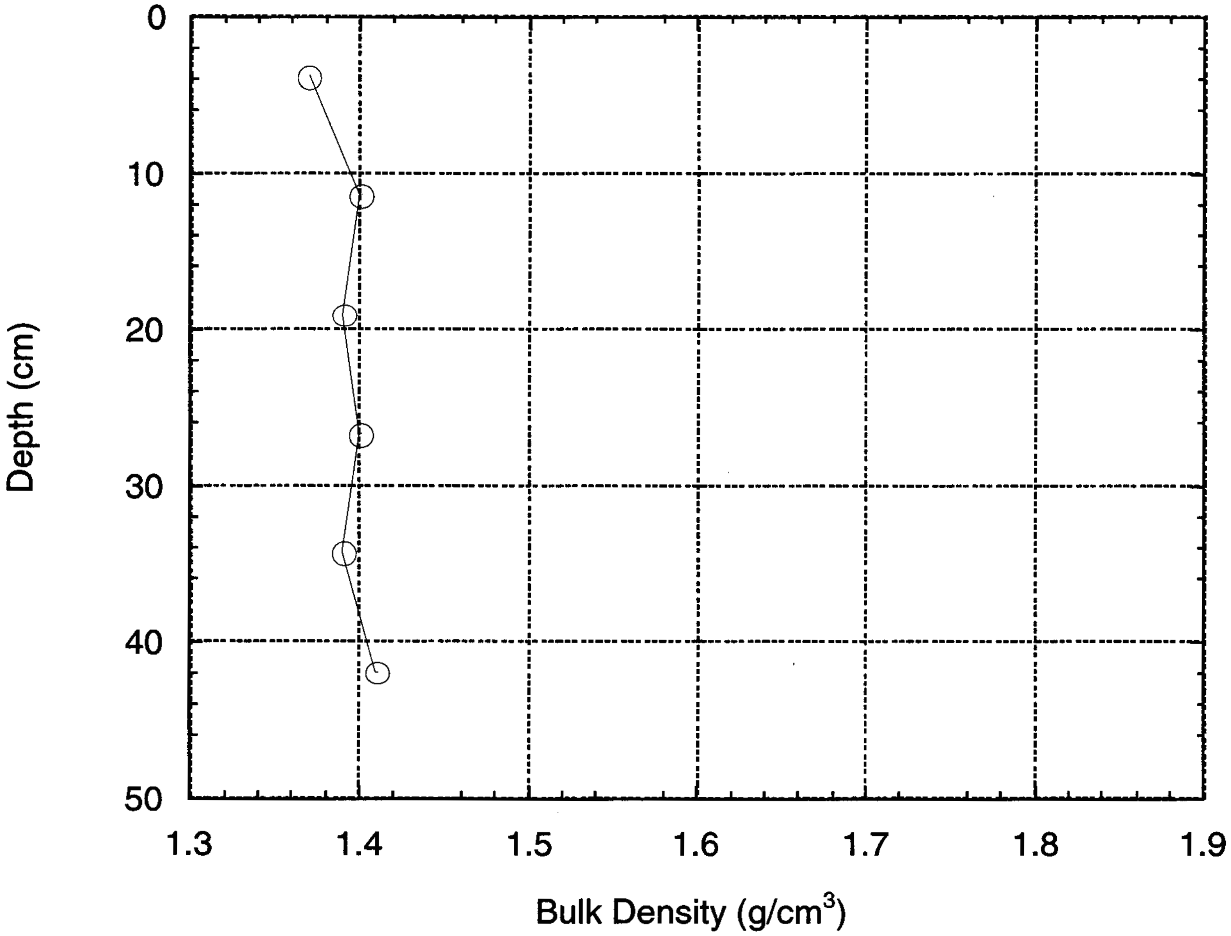

Figure 6a. In-situ core, Control 1. Bulk density as a function of depth.

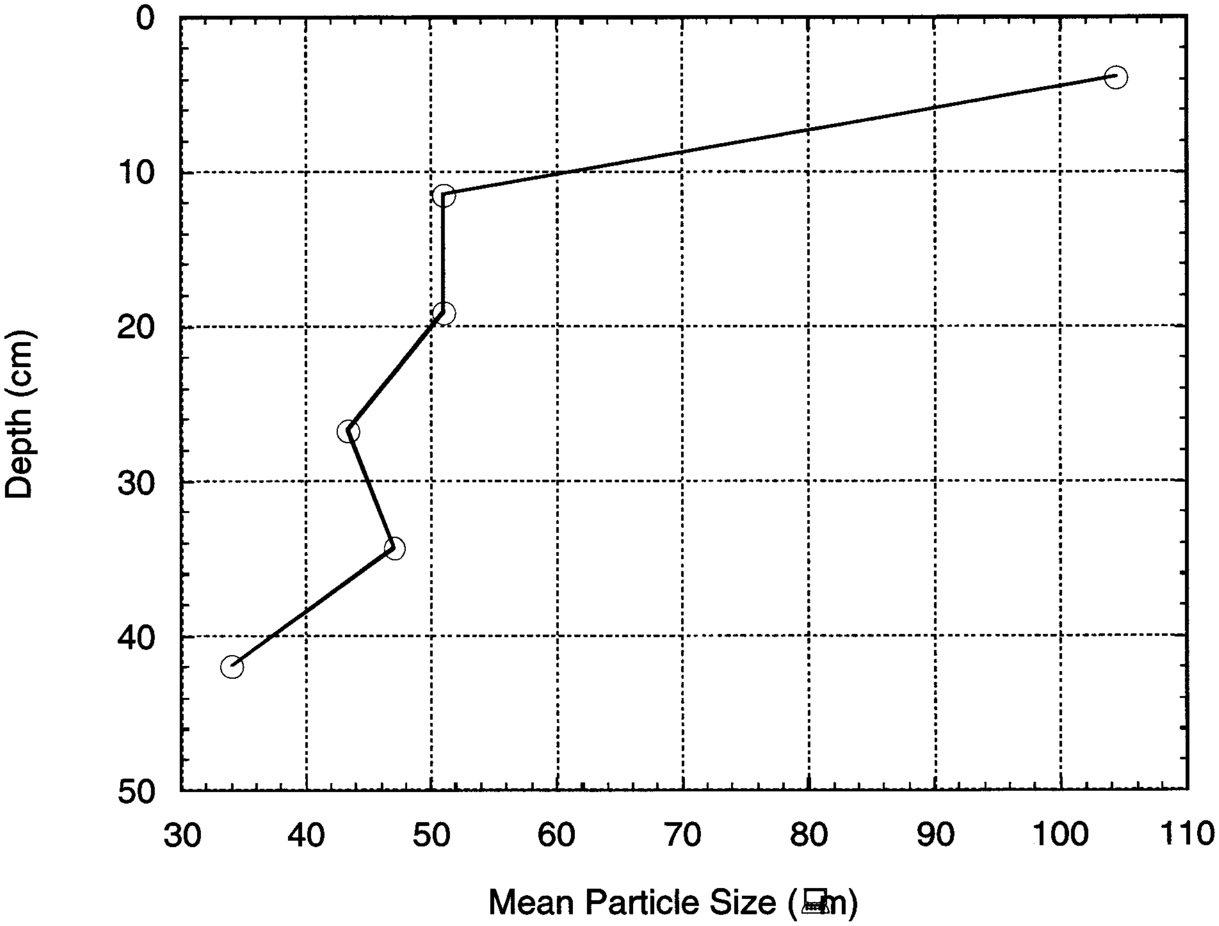

Figure 6b. In-situ core, Control 1. Mean particle size as a function of depth.

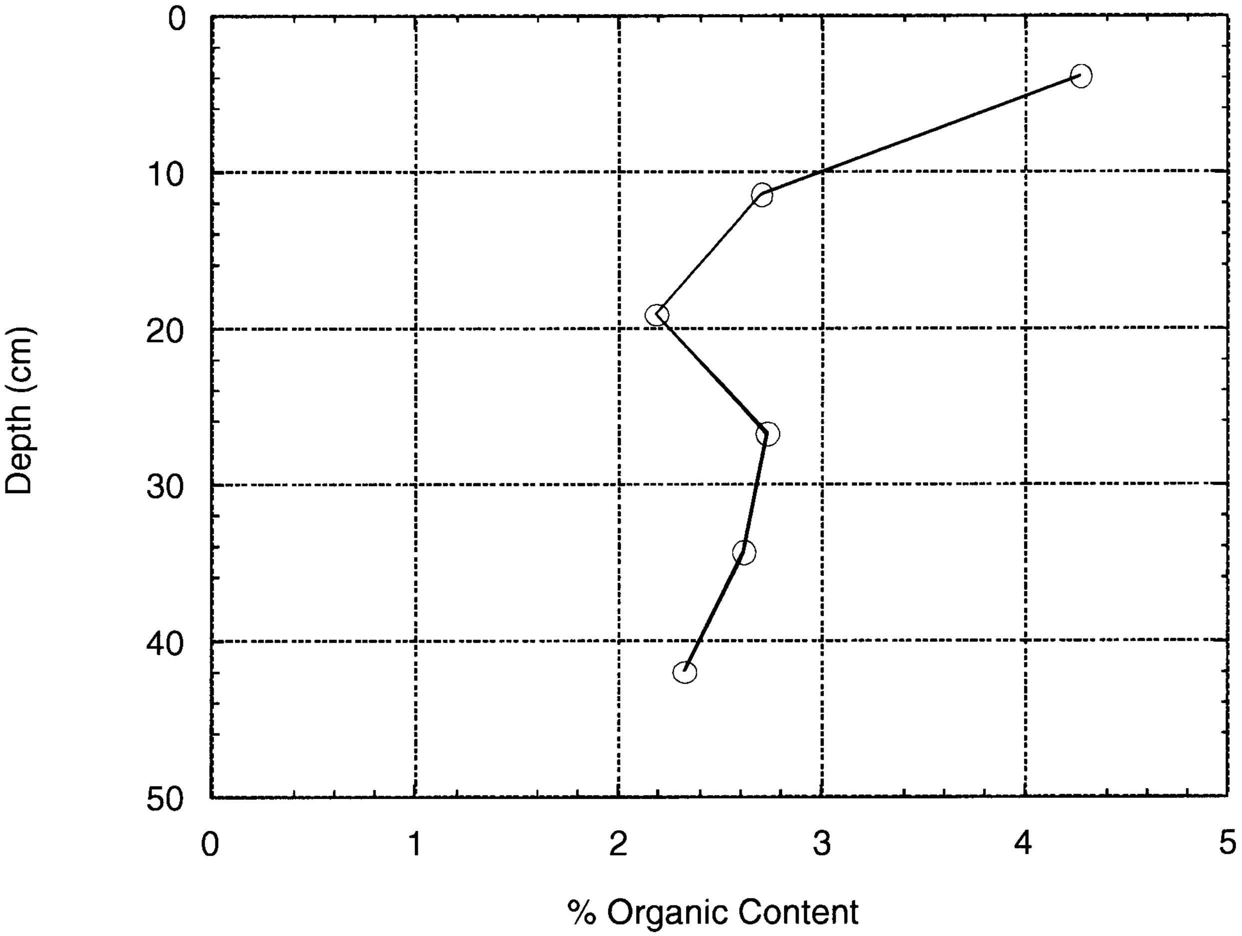

Figure 6c. In-situ core, Control 1. Organic content as a function of depth.

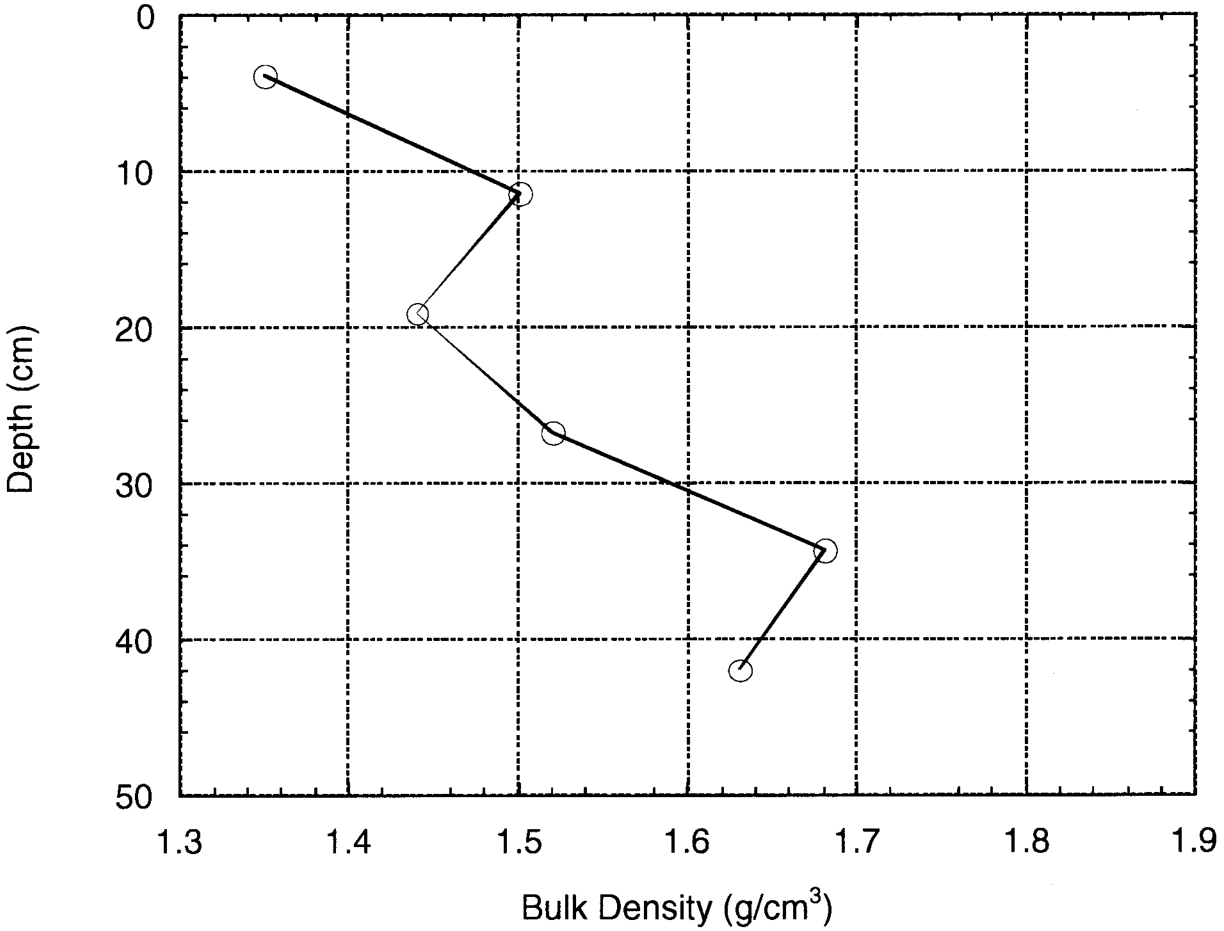

Figure 7a. In-situ core, T31. Bulk density as a function of depth.

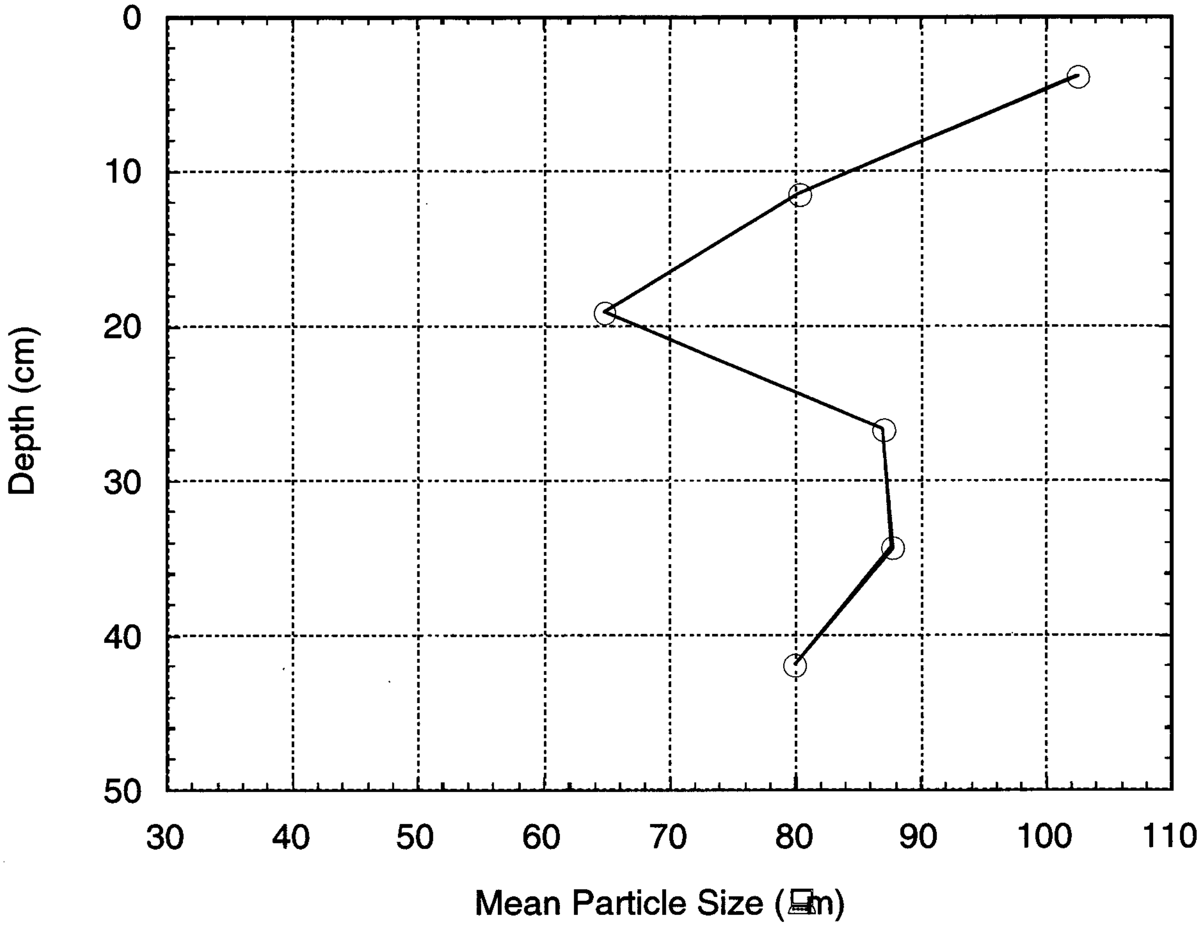

Figure 7b. In-situ core, T31. Mean particle size as a function of depth.

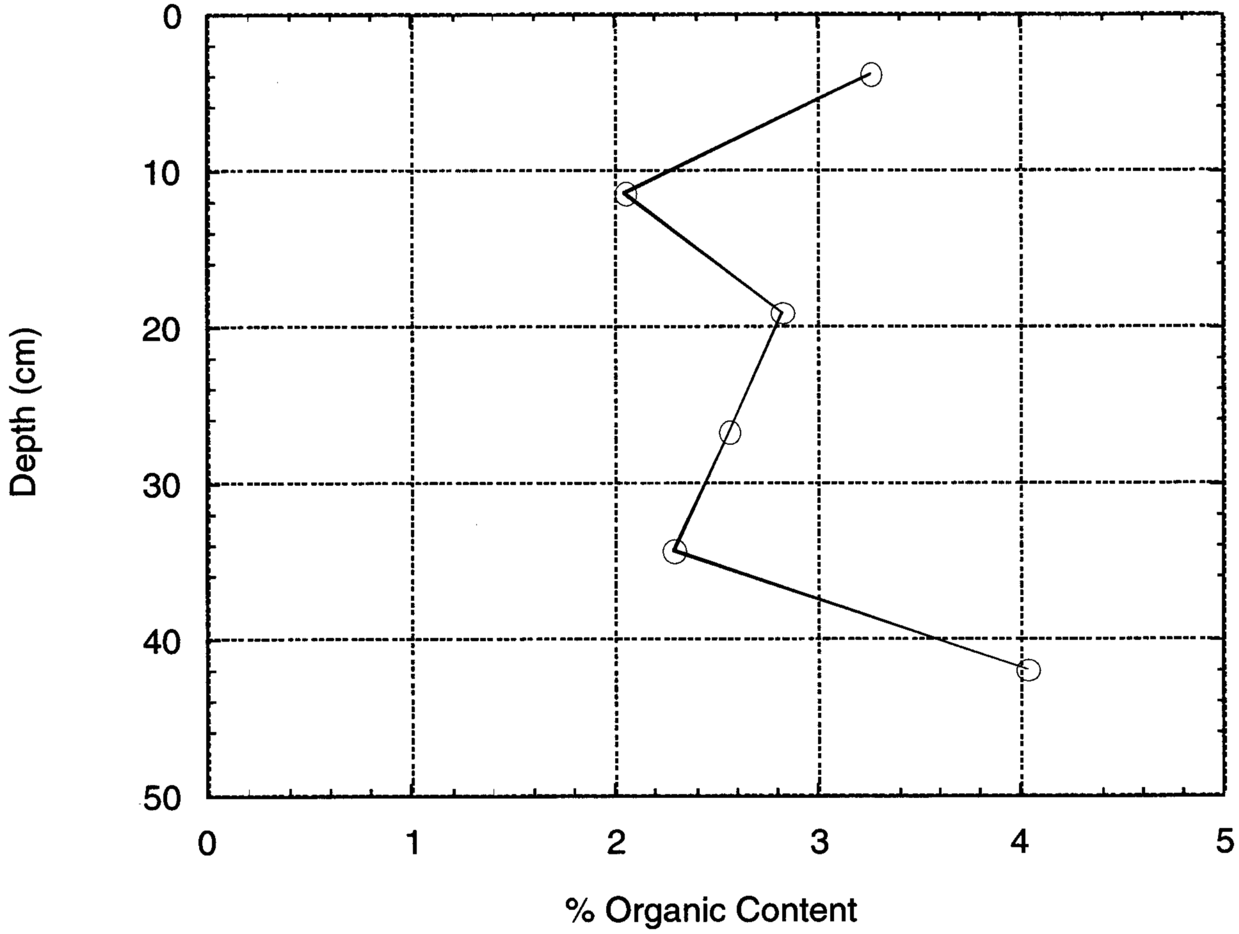

Figure 7c. In-situ core, T31. Organic content as a function of depth.

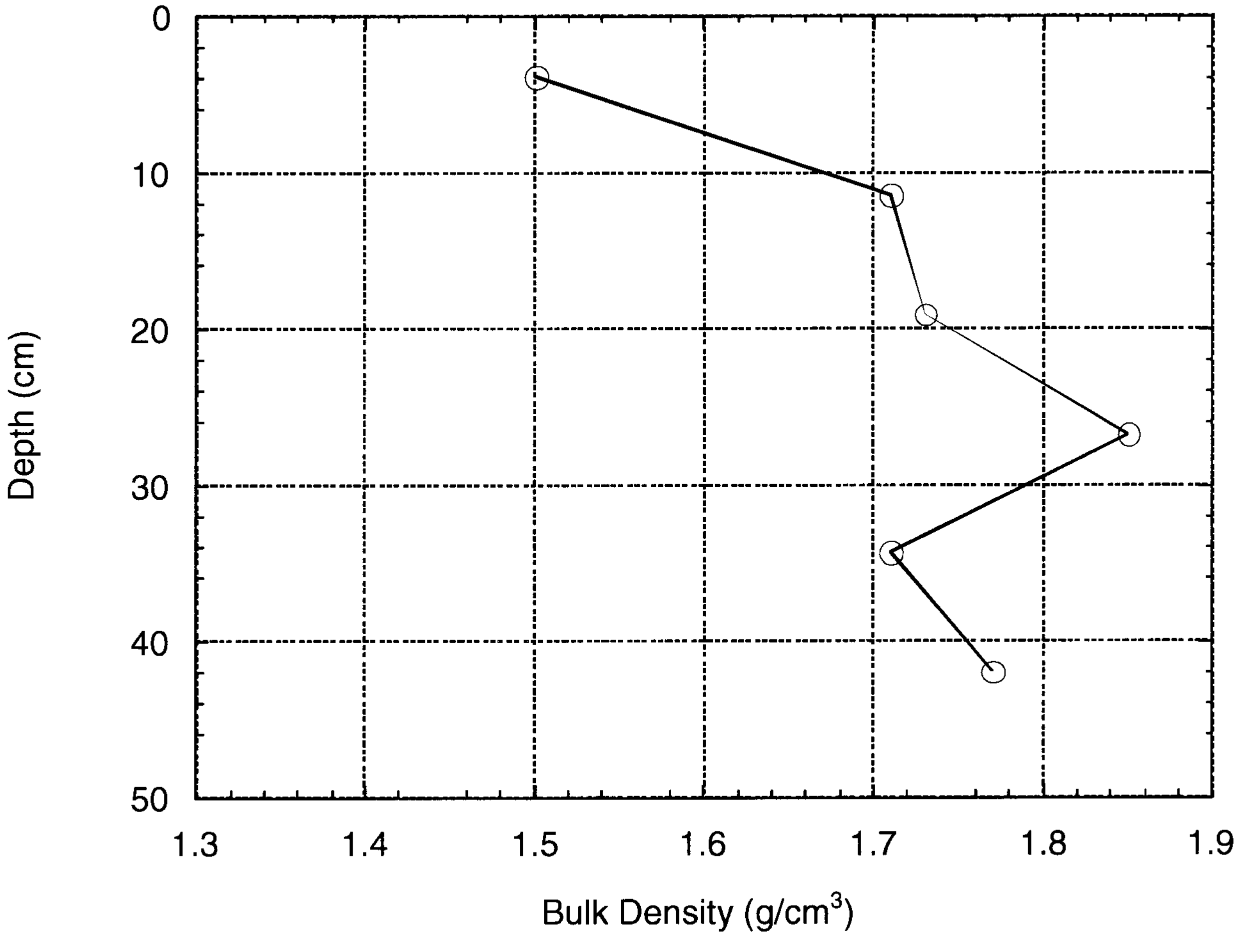

Figure 8. In-situ core, T33. Bulk density as a function of depth.

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