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Effects of Bentonite Clay on Sediment Erosion Rates

PURPOSE: This technical note (TN) details analysis of the effects of varying amounts of bentonite clay on the erosion rates of mud (topsoil), sand, and a mixture of both. The presence of clay, even in small amounts, can dramatically change the erosion properties of sediment. This work was performed as part of the DOER work unit Estimating Vertical Variation in Erodibility and Deposition Rates of Mixed Sediments in the Nearshore Placement focus area. The final goal of all research associated with this DOER work unit is to develop methods of associating sediment erosion rates to material bulk properties.

BACKGROUND: Contaminated bottom sediments can be a significant source of contamination to the overlying water, especially during storms. However, in most cases the major negative impact of contaminated bottom sediments is on the benthic organisms and subsequent biomagnification to the food chain. In situ capping of these sediments is one solution to these problems and has been accomplished in many locations (Palermo et al. 1998a; Palermo et al. 1998b). The success of capping depends to a large extent on the stability of the capping material, i.e., on the erosion rates of the material as a function of the applied shear stress due to wave action and currents. But erosion rates also depend on the bulk properties of the sediment. If this dependence were quantitatively known, more stable capping materials could be better selected by choosing sediments with appropriate mineralogy or other bulk properties.

In cases where sediments are not contaminated, it is still often important to understand the erosion rates of these sediments. Regulatory agency approval for a dredged material placement site often requires an understanding of dispersion (caused by erosion and subsequent transport) of that material. Also, it is beneficial to understand the material's erosion characteristics before considering it as a source for beach nourishment via nearshore placement. At present, costly and time-consuming site specific tests are required to determine the erosion potential of many dredged materials. A quantitative understanding of the effects of bulk properties on erosion potential would significantly reduce time and cost associated with the tests required for site approval.

Bulk properties which significantly affect erosion rates include bulk density, particle size (both mean and distribution), mineralogy, organic content, volume of gas in the sediments, salinity of the pore waters, oxidation and other chemical reactions, and time after deposition. Some work has been done on the effects of each of these properties, but there is not a quantitative understanding of, or ability to predict, the effects on erosion rates of most of these properties, especially in combination. In particular, little is known quantitatively about the effects of different minerals. It is qualitatively known that the addition of small amounts of clay minerals can have a significant effect on sediment bulk properties and erosion rates (see, for example, Mitchner and Torfs 1996). However, this has rarely been quantified.

In a previous study (McNeil et al. 2000), laboratory experiments were performed to determine erosion rates of a proposed capping material as affected by consolidation and gas generation. In this investigation, the erosion rates of the capping material alone as well as over a base sediment were measured as a function of depth in the sediments, shear stress, and consolidation time. Gas was present due to the degradation of organic matter in the cap and base, and this significantly affected the erosion rates. The base sediment used in these experiments was organic-rich natural sediment from the Grasse River, MI. Consolidation times varied from 1 to 128 days, while shear stresses varied from 0.2 to 6.4 N/m^2. The capping material was a well mixed 50/50 mixture by volume of topsoil and sand. The topsoil was used because it was readily available and had a grain size distribution and mineralogy consistent with what is found in the field. For the topsoil, the mean particle size was 35 μm (note: 1000 μm = 1 mm); the organic content was 3.3 percent; and the mineralogical composition was predominantly quartz, feldspar, and illite with only trace amounts of smectite. For the sand (pure quartz), the mean particle size was 214 μm, and the organic content was 0.03 percent. Representative results of this investigation follow.

The work described in this TN extended the study by McNeil et al. to include the effects on erosion rates of adding small amounts of bentonite to the capping material. Erosion rates were then measured as before as a function of depth, shear stress, and consolidation time. Bulk properties were also determined. Bentonite is a clay material primarily composed of montmorillonite, a member of the smectite family of clay minerals. The reason bentonite was selected as the additive is that it is the most cohesive of the common clays and, because of this, should have the most effect on erosion rates. Previous research on clay added to a sand have indicated that even small amounts of clay (3 percent) will significantly increase the critical shear stress for initiation of erosion (Mitchner and Torfs 1996; Torfs 1997). The present study will include analysis of even smaller amounts of added clay, as low as 0.5 percent.

For comparison with the proposed capping material, similar experiments were done with the topsoil and the sand as capping materials, both without and with added bentonite. All experiments were done with the capping material over a base sediment in order to more adequately simulate real conditions. The base material selected was an organic-rich natural sediment. Erosion rates for each capping material were determined as a function of depth, shear stress, percent bentonite added, and consolidation time. A complete listing of the experiments for the different combinations of bentonite additions and consolidation times that were analyzed is shown in Table 1.

A report summarizing all of the data obtained has been prepared (Jin et al. 2000). This data set is quite extensive. To illustrate effects more simply, a representative subset of the data is discussed in detail here. In the following section, the experimental procedures are briefly presented. In the third section, the experimental results are presented and discussed. A summary and concluding remarks are given in the final section.

EXPERIMENTAL PROCEDURES: Tests were done with capping materials consisting of the 50/50 mixture, the topsoil, and the sand. The base for each cap was reconstructed sediment from the Grasse River in New York. Its mean size was 45 μm, the organic content was 2.0 percent. Mineralogical tests indicated that it was composed primarily of quartz, feldspar, and illite, with almost no smectite (similar to the topsoil). For each test, the base sediment was first thoroughly mixed, poured into a coring tube, and then allowed to consolidate. After three days, the base

Table 1. Parameters for Which Bulk Properties and Erosion Rates Were Determined*

Percent Bentonite	Consolidation Time, days							
	1	2	4	8	16	32	64	128
50/50 Mixture Topsoil and Sand								
0	X	X	X	X	X	X	X	X
0.50		X		X		X		X
1		X		X		X		X
2	X	X	X	X	X	X	X	X
4		X		X		X		X
8		X		X		X		X
16		X		X		X		X
Topsoil								
0		X		X		X		X
0.50		X		X		X		X
1								
2		X		X		X		X
4		X		X		X		X
Sand								
0	X					X		
0.50		X		X		X		X
1								
2		X		X		X		X
4		X		X		X		X

* Three sediments with bentonite additions up to 16 percent and consolidation times from 1 to 128 days were investigated.

sediment was reasonably firm, approximately 15 cm thick, and there was little suspended sediment in the overlying water. Bentonite, obtained from Fisher Scientific as a laboratory-grade powder, was then added to the capping material in amounts from 0 to 16 percent by volume. This material was thoroughly mixed and slowly poured into a coring tube containing the base sediment so as to minimize mixing of the capping material and base sediment. After a few days of consolidation, the thickness of the capping material was approximately 15 cm. Both layers then consolidated with time with the local densities and thickness of each layer changing with time due to water migration as well as gas generation and migration. For each capping material, multiple identical cores were prepared. They were then sacrificed at intervals for the erosion measurements. Erosion rates were measured by means of Sedflume. McNeil et al. (1996) provides details of the Sedflume apparatus and procedures. For each core, erosion rates were measured as a function of depth in the core and at shear stresses ranging from 0.2 to 12.8 N/m^2.

To assess the parameters that affect sediment erosion, the bulk properties of density, water content, and volume of gas for the cap and base were determined as a function of depth. Bulk densities were measured nondestructively at different time intervals after the sediments were poured and also immediately before each erosion test. Since little sediment is needed for determining the water content and volume of gas, small amounts of sediment were removed from each core at intervals during the erosion tests to determine these parameters as a function of depth. By this procedure, erosion rates and bulk properties were determined from the same core.

Bulk densities were measured by means of the density profiler (Gotthard 1997; Roberts et al. 1998). This device uses a gamma radiation emitter, ^{137}Cs, as a radiation source and measures the attenuation of the radiation as it is transmitted horizontally through the sediments. The accuracy in the measured density is estimated to be ± 0.01 g/cm^3. The horizontally transmitted radiation is measured as the emitter traverses the core in a vertical direction. This traverse speed was set at 3.3×10^{-3} cm/sec (2 mm/min). Because of statistical fluctuations of the radiation, this output was averaged over time (or distance traversed). In the present case, data were averaged over 1 cm to both reduce the fluctuations in the data and to illustrate trends more simply.

The density profiler measures the actual density of the sediments, ρ, which includes solids, water, and any gas present. The standard procedure (e.g., see Hakansen and Jansson 1983) for measuring sediment density measures the density, ρ*, of the sediments due to solids and water and ignores the presence of gas. In the present experiments, both densities were measured. From these two quantities, the fractional gas volume, v_g, can be shown to be

$$v_g = \frac{\rho^* - \rho}{\rho^*} \tag{1}$$

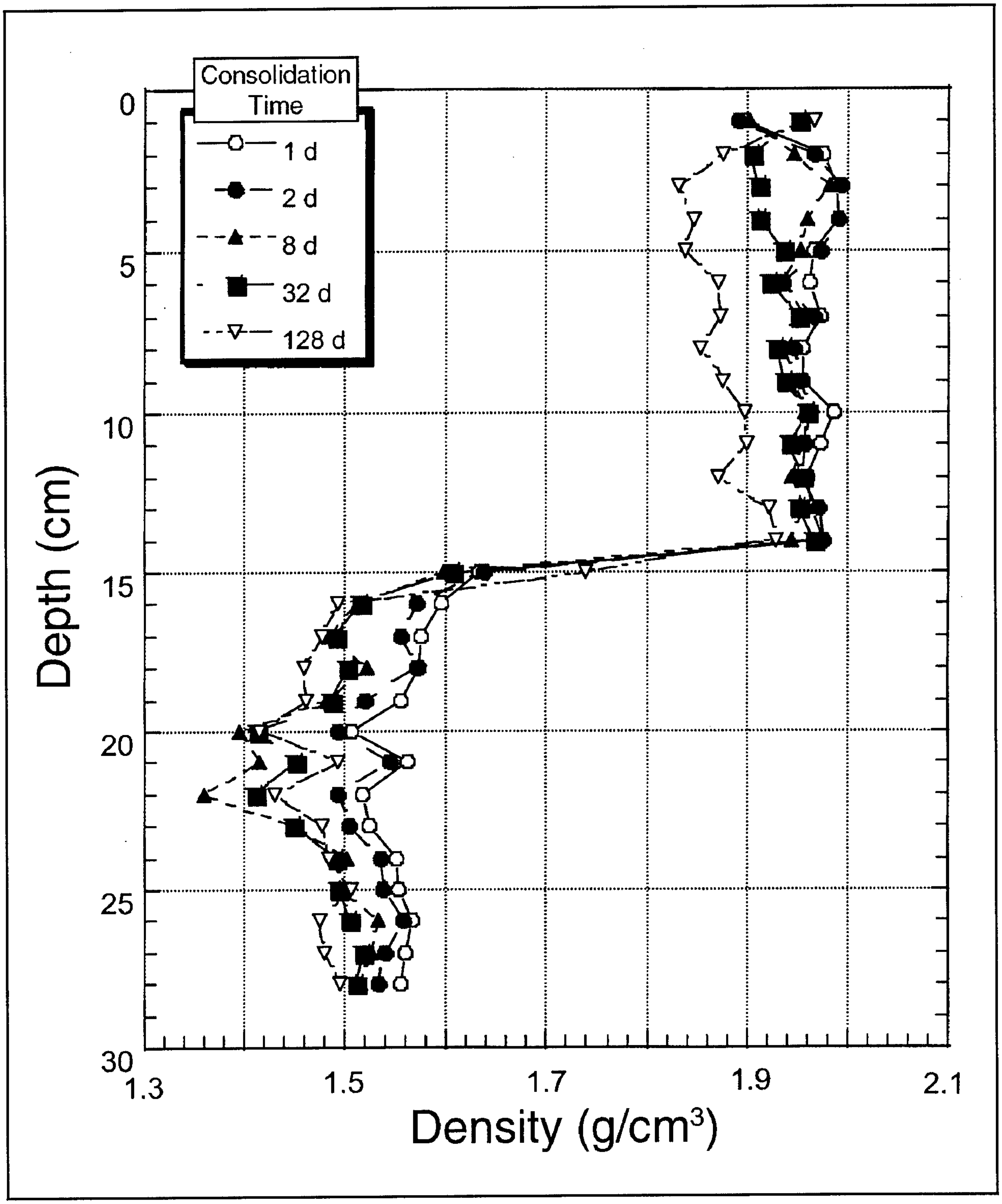
This equation was used to determine v_g as a function of depth.

Particle size distributions and mean particle size were determined by use of a Malvern particle sizer. Total organic carbon of the sediments was measured at the University of California, Santa Barbara, Marine Science Analytical Laboratory using the Environmental Protection Agency (EPA) standard method (EPA 1983). The mineralogy of the sediments was approximately determined by means of X-ray powder diffraction by Reed Glasmann (Willamette Geological Service, Philomath, OR).

RESULTS AND DISCUSSION: In the previous study by McNeil et al. (2000), bulk properties and erosion rates of the 50/50 capping material with no added bentonite were determined. A brief summary of this data will be given here as a base for comparison when bentonite is added to this same capping material and also for comparison with the topsoil and sand caps.

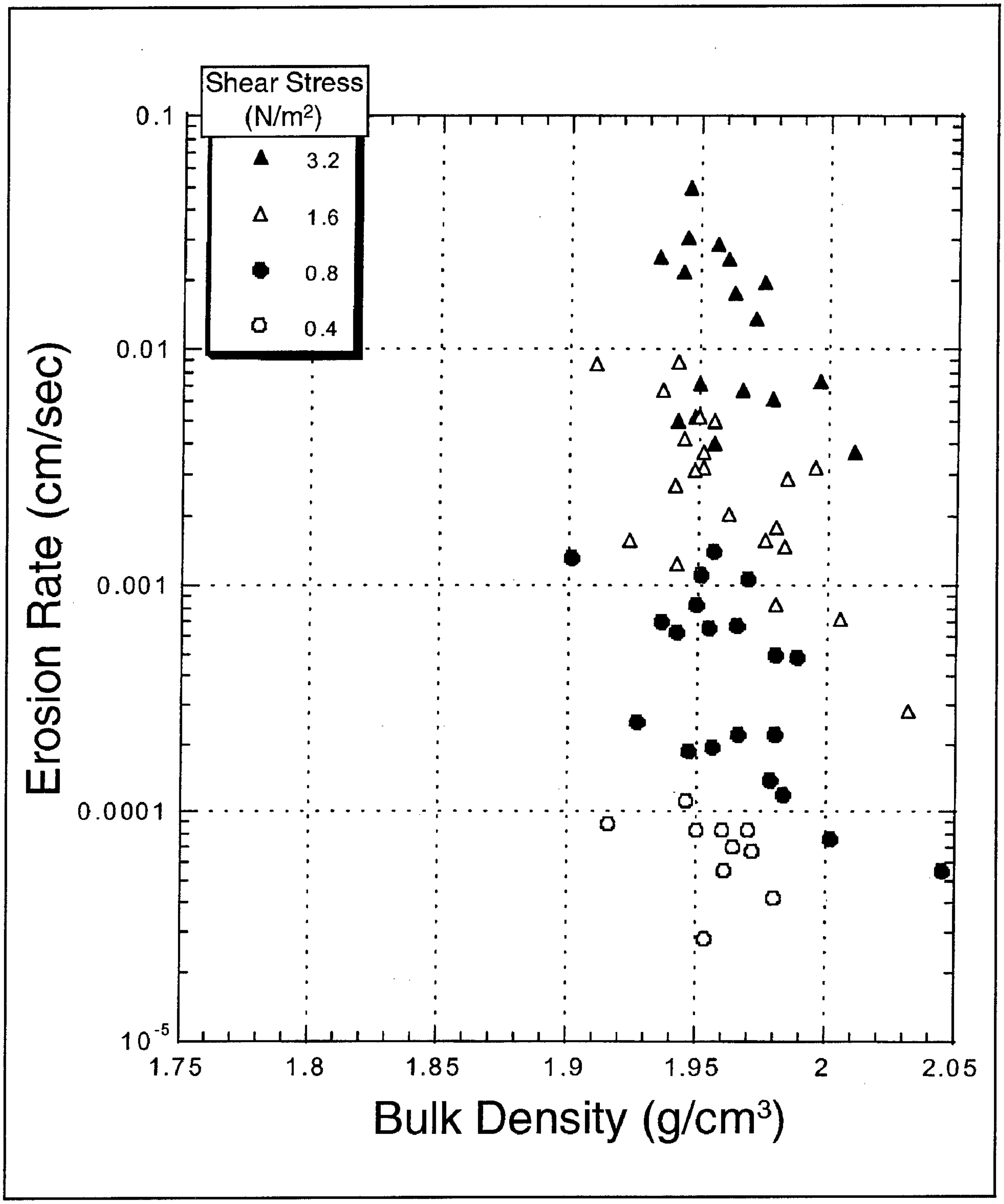
For the 50/50 capping material with no added bentonite, the measured densities in the cap and base are shown in Figure 1a as a function of depth at consolidation times of 1, 2, 8, 32, and 128 days. The capping material, which was more coarse and noncohesive than the base sediment, had a higher density (between 1.8 and 2.0 g/cm^3) than did the base sediment (between 1.35 and 1.6 g/cm^3). The densities in both layers generally decreased monotonically with time due to gas generation, despite the time effects of self-weight consolidation.

The density of the solid-water matrix, ρ*, was also determined as a function of depth and time. From ρ and ρ*, the gas fraction was determined from Equation 1. The gas fraction in both layers increased with time until a reasonably steady state was reached by 128 days. At this time, it was much higher in the base sediment (maximum of 14 percent) than in the cap (maximum of



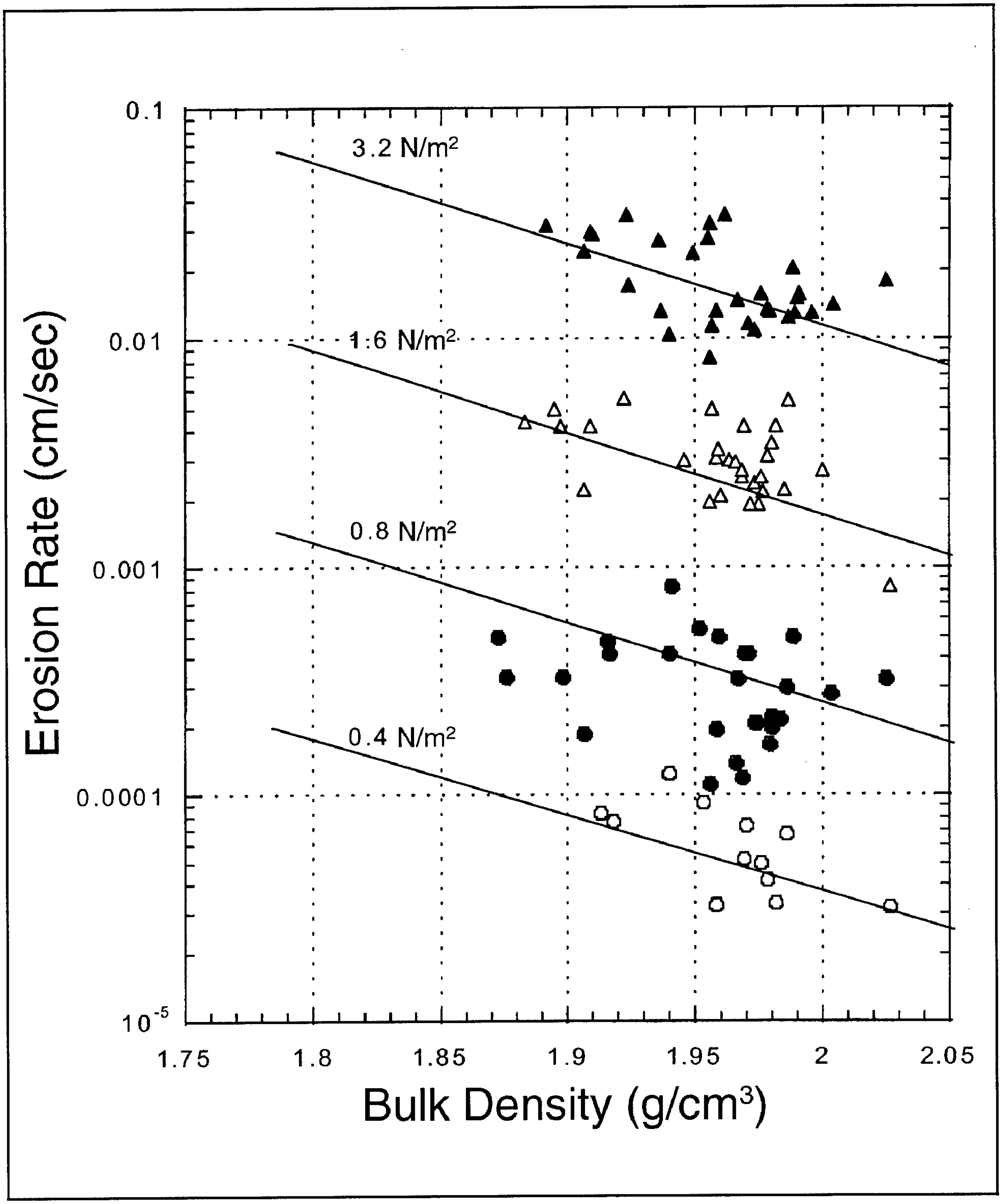
a. Bulk density as a function of depth at times after deposition of 1, 2, 8, 32, and 128 days for both the capping material and base sediment

Figure 1. 50/50 mixture of topsoil and sand (with no added bentonite) (Sheet 1 of 3)



b. Erosion rates as a function of density, ρ*, with shear stress (N/m^2) as a parameter. Cap over base. Inset legend indicates values for different shear stresses

Figure 1. (Sheet 2 of 3)



c. Erosion rates for capping material with no base sediment as a function of ρ^* with shear stress (N/m^2) as a parameter

Figure 1. (Sheet 3 of 3)

4 to 6 percent). This was primarily due to the coarser and less cohesive nature of the capping material, which allowed gas to percolate more easily through the cap than through the base.

For each core, erosion rates were measured as a function of depth. Since the densities, ρ and ρ^*, were also measured as a function of depth, the erosion rates can then be determined as a function of ρ and ρ^*. From previous work with sediments when no gas was present (and therefore $\rho = \rho^*$), it has been demonstrated that the relation between erosion rates and ρ can be approximated by

$$\begin{aligned} E &= A\tau\rho^m \qquad && \tau > \tau_{cr} \\ E &= 0 && \tau \le \tau_{cr} \end{aligned} \tag{2}$$

where E is the erosion rate (cm/sec); τ is the shear stress (N/m^2); ρ is the bulk density (g/cm^3); A, n, and m are constants, and τ_{cr} is the critical shear stress for initiation of transport (N/m^2). This equation has been shown to be a valid approximation for sediments with a wide range of properties in both laboratory and field experiments (Jepsen, Roberts, and Lick 1997; Lick and McNeil 2000). It shows the effects of hydrodynamics (dependence on τ) and consolidation (dependence on ρ where ρ depends on time after deposition). The parameters A, n, and m are different for each sediment and depend on the bulk properties of the sediment, not including ρ. This equation is somewhat different than the standard equation used for cohesive sediment transport where an erosion rate is a function of the excess shear stress (τ - τ_{cr}), not the applied shear stress. This standard equation works well for noncohesive sediment and cohesive sediment at low shear stress, but does not match recent data for cohesive sediment at high shear stress. Equation 2 does match the data for cohesive sediment erosion at high shear stress (Roberts et al. 1998; Gailani et al. 2001).

When gas is present, ρ and ρ^* are not equal. In this case, the use of ρ^* rather than ρ in the previous equation gives a better approximation to E (McNeil et al. 2000), but other effects caused by the presence of gas also are present so that this relation is not as good a predictor as when there is no gas.

For the present case, erosion rates are shown in Figure 1b as a function of ρ^* with shear stress (N/m^2) as a parameter. For comparison, Figure 1c shows a similar plot for this same capping material alone, with no base. The straight lines in Figure 1c are approximations given by Equation 2 with $A = 31.2$, $n = 2.74$, and $m = -16$. It can be seen that Equation 2 approximates the data in Figure 1c quite well (note that the lines are not best-fit lines, but rather an average of best-fit lines that will produce parameters for Equation 2, while Figure 1b shows more scatter. The probable reason for this is the effects of additional gas from the base sediment, i.e., gas migrates through the base sediment into the capping material and has an effect on the cap which is in addition to the effects of gas generated in the cap. This effect is to stiffen the sediment matrix and hence lower erosion rates. Consistent with this hypothesis is the fact that, for each shear stress, the smaller erosion rate data in Figure 1b occurs at large consolidation times when more gas is present and propagating. Despite the scatter in Figure 1b, the straight lines in Figure 1c can also be used as a reasonable approximation to the data in Figure 1b.

As an extension to these experiments, bentonite in the amounts of 0.50, 1, 2, 4, 8, and 16 percent by volume was added to the 50/50 capping material. Bulk properties and erosion rates for these sediments were then determined in a similar manner to that previously described. As an example, erosion rates for 2 percent-added bentonite are described here. Erosion rates for other bentonite additions will be summarized in the following paragraphs.

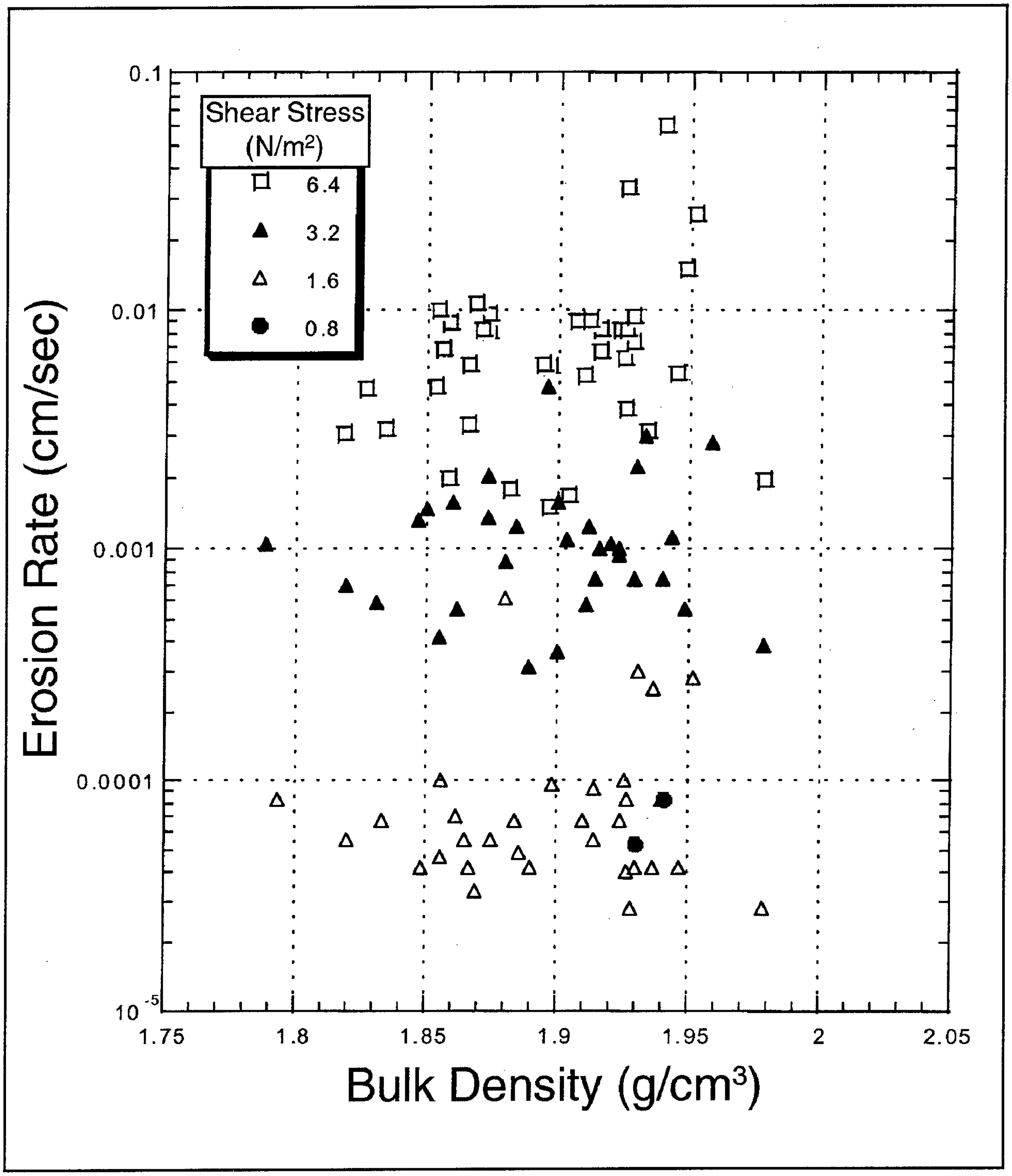
For the 50/50 capping material with 2 percent added bentonite, erosion rates for all tests (1-128 days) are shown in Figure 2a as a function of ρ with shear stress as a parameter. Although general trends are clear, the data are somewhat scattered. The dependence of these data on bulk parameters can be improved and clarified (1) by eliminating small-time (thixotropic) effects that are not associated with bulk parameter change and (2) by plotting the resultant data as a function of ρ^*. Thixotropic effects are a change in characteristics of a material with time without changes in other bulk properties (Jell-O solidification over a period of a few hours is an example of a thixotropic effect). The time scales of thixotropic effects for the sediments in this study are predominately on the order of hours to 1 day.

Erosion rate data for 1 day of consolidation time are shown in Figure 2b. By comparison with Figure 2a, it is quite clear that 1-day erosion rates are significantly higher than those for longer consolidation times. This can be attributed to thixotropic effects which are short-time (generally occurring within consolidation times of 1 or 2 days) and cause reductions in erosion rates without concomitant changes in other bulk properties such as density. This thixotropic effect was generally present in these experiments for all sediments with added bentonite; there are indications that this effect is also present in other sediments, probably because of the clays present in those sediments (Teeter 2000). Thixotropic phenomena are well known in soil mechanics (e.g., see Mitchell 1993), but the effect of thixotropy on sediment erosion has not been well quantified.

As previously described and in prior studies, when gas is present in the sediments, E can be better approximated by Equation 2 when ρ^* rather than ρ is used as the independent variable. This is shown in Figure 2c, where $E = E(\rho^*)$ and erosion rate data for 1 day have been eliminated. The straight lines are approximations by Equation 2 with $A = 13.7$, $n = 3.26$, and $m = -21.3$. The approximation to the data by Equation 2 is quite good.

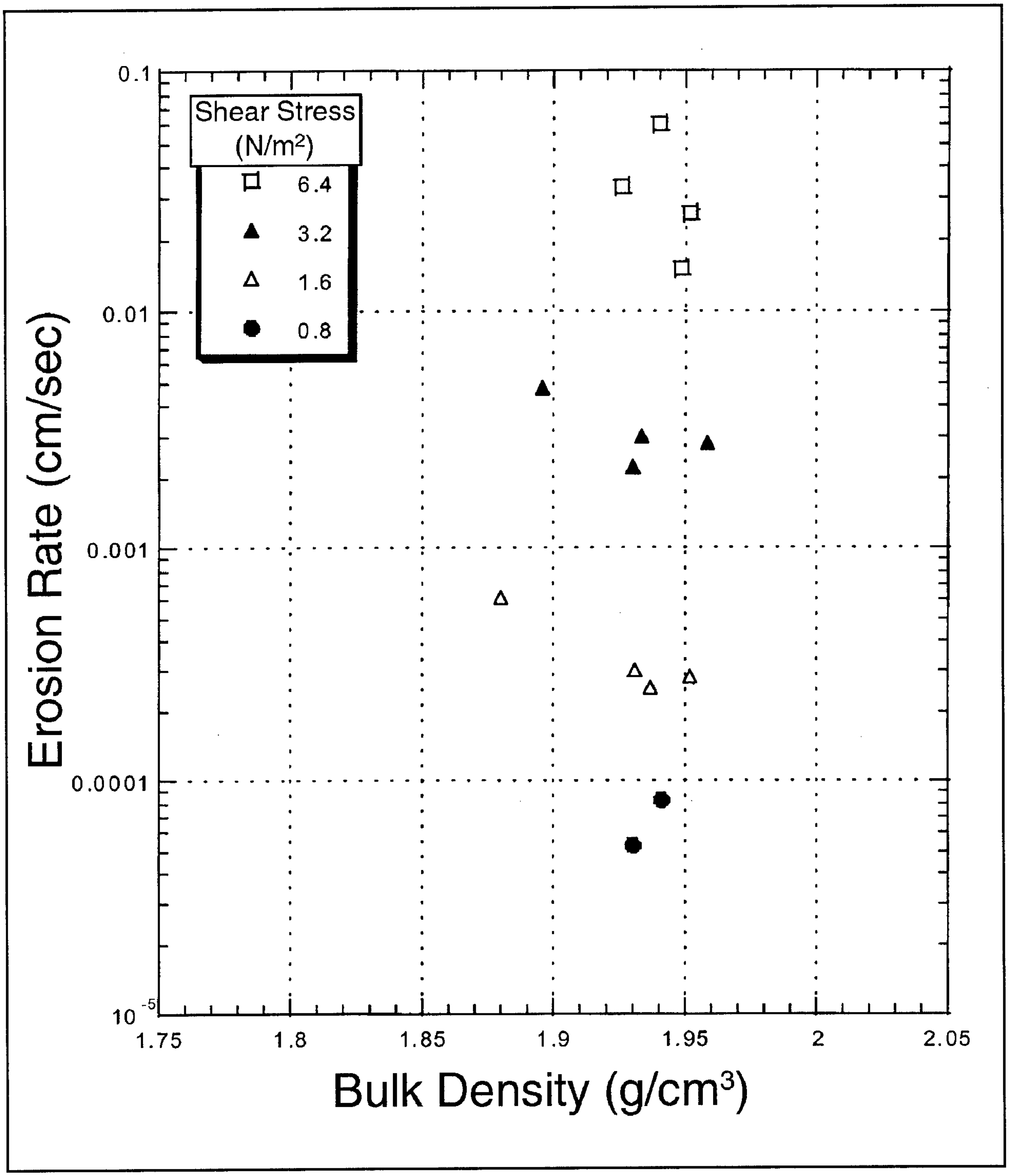
These data for 2 percent bentonite in Figure 2c should now be compared with Figure 1b and 1c for the 50/50 mixture with no bentonite. The effect of the addition of 2 percent bentonite on erosion rates is quite evident. This small amount of bentonite reduces erosion rates for each shear stress by more than an order of magnitude. Others (Mitchner and Torfs 1996; Torfs 1997) found similar results for 3 percent added clay (montmorillonite, a group of clays which includes bentonite). However, these papers only quantified the decrease in erosion rate in general terms.

Bulk properties and erosion rates were also determined for topsoil without bentonite and with bentonite additions of 0.50, 2, and 4 percent. The densities of topsoil with no added bentonite were smaller (1.54 to 1.8 g/cm^3) than those for the 50/50 mixture; gas contents were approximately the same. The decrease in density is because of less sand and therefore finer, more cohesive particles in the topsoil compared with the 50/50 mix. Erosion rates as a function of ρ^* are shown in Figure 3a. Comparison with Figures 1b and 1c indicates significantly lower erosion rates for the topsoil than for the 50/50 mixture.



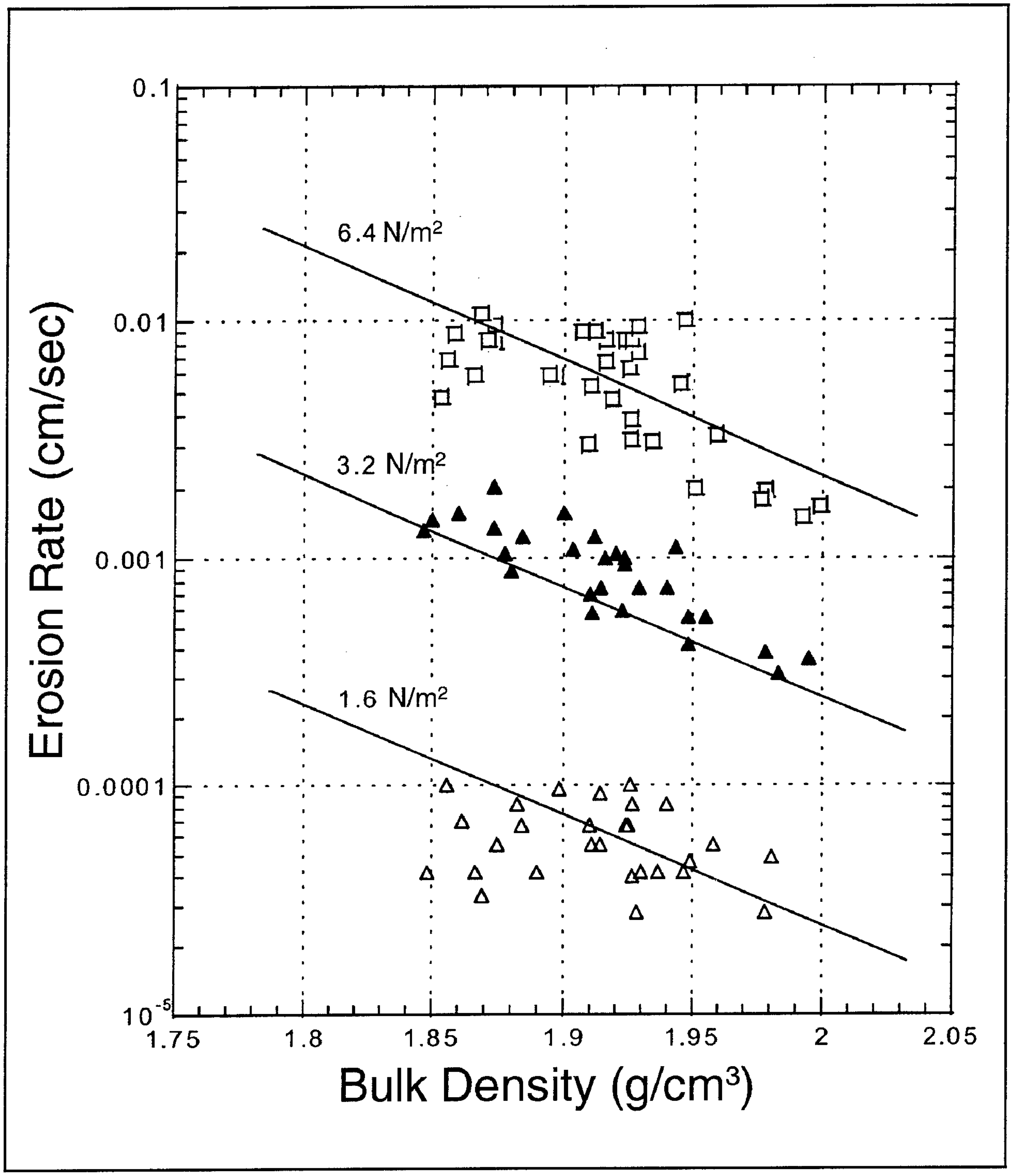
a. Erosion rates as a function of ρ with shear stress (N/m^2) as a parameter. Includes all consolidation times (1-128 days)

Figure 2. 50/50 mixture of topsoil and sand (with 2 percent added bentonite) (Sheet 1 of 3)



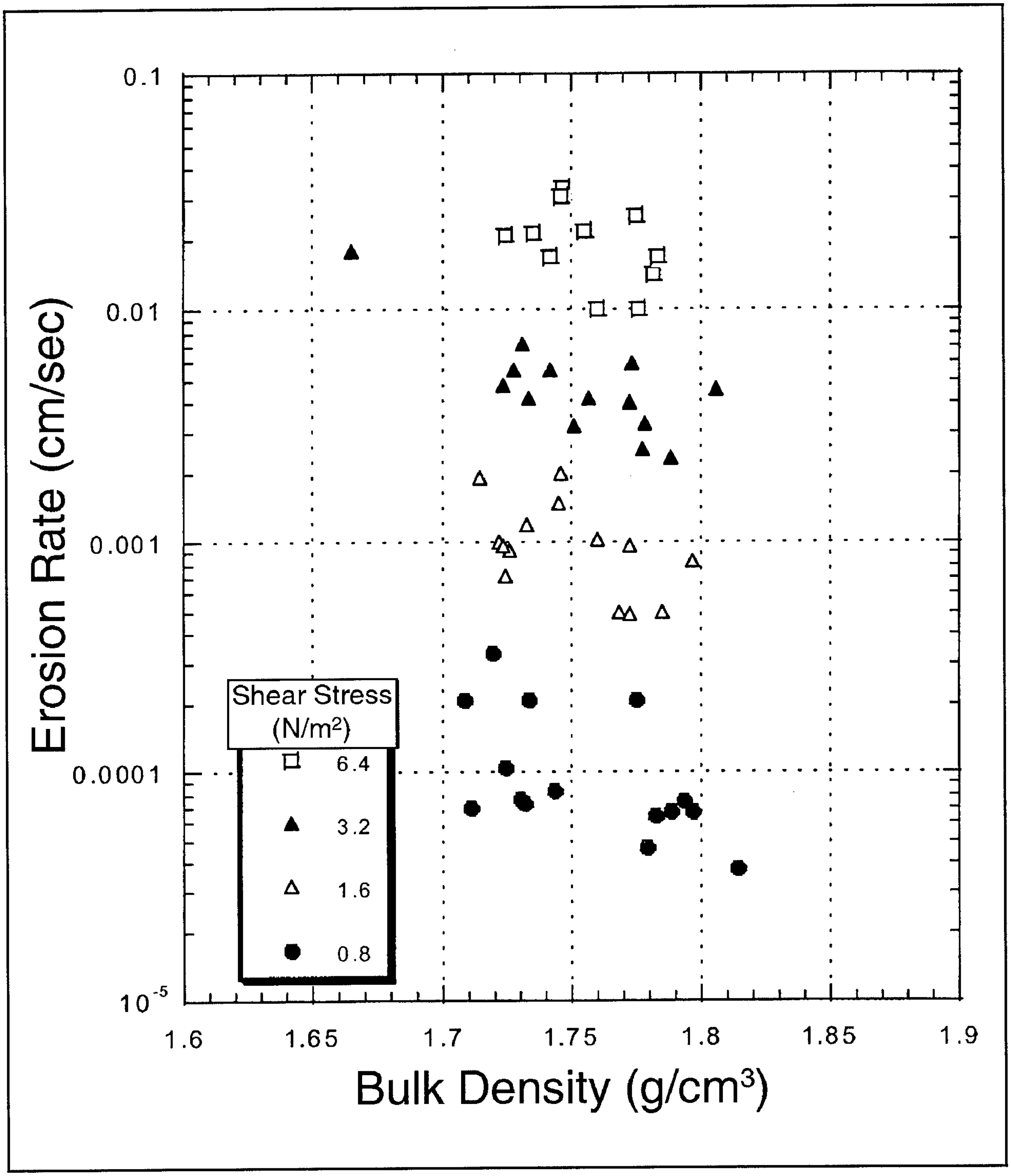
b. Erosion rates for 1 day consolidation time

Figure 2. (Sheet 2 of 3)



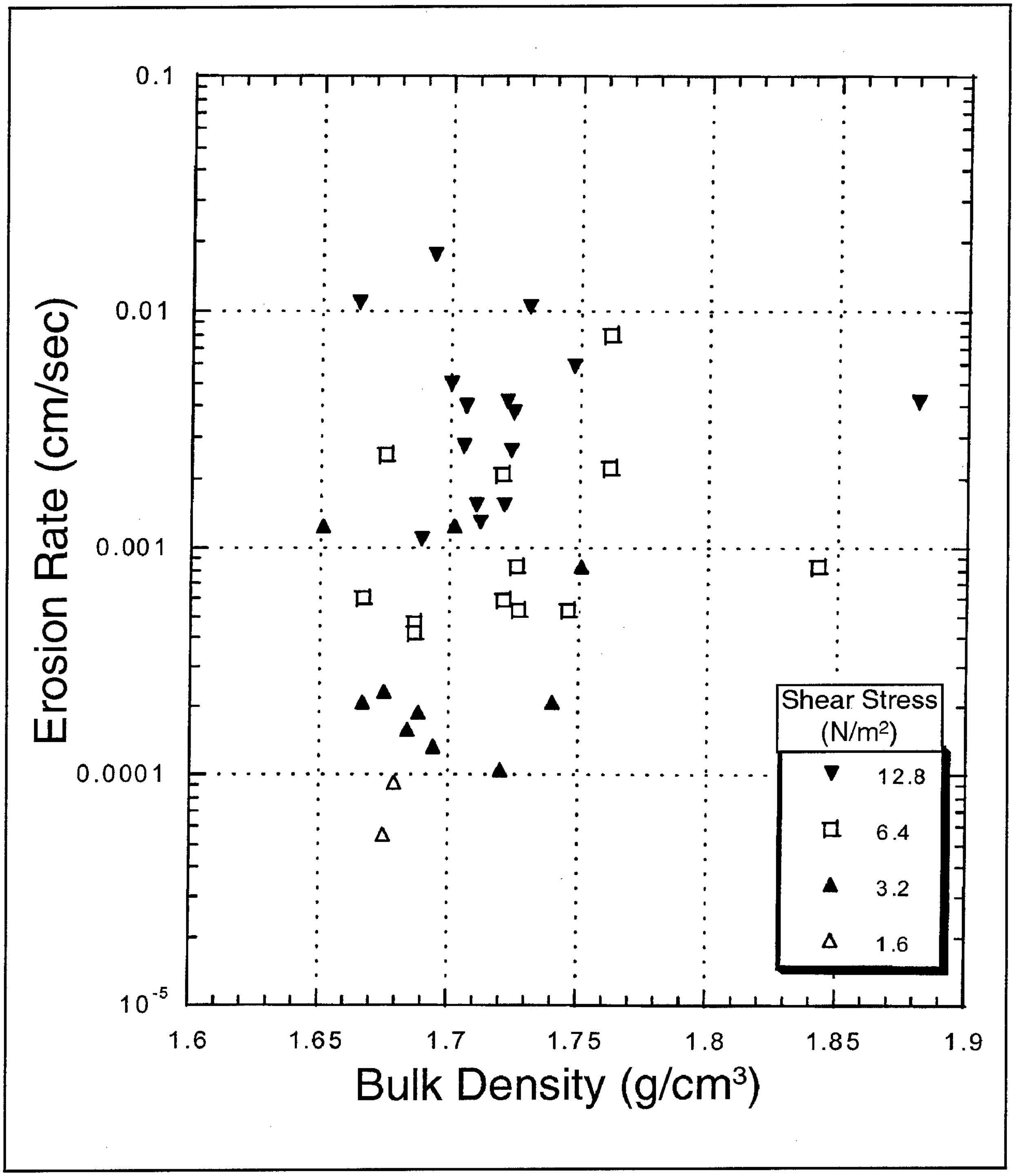
c. Erosion rates as a function of ρ* with shear stress (N/m²) as a parameter and 1 day data eliminated

Figure 2. (Sheet 3 of 3)



a. Topsoil with no added bentonite

Figure 3. Erosion rates as a function of ρ* with shear stress (N/m^2) as a parameter (Continued)



b. Topsoil with 2 percent added bentonite

Figure 3. (Concluded)

Erosion rates for the topsoil with 2 percent added bentonite are shown in Figure 3b. The data is somewhat scattered but, by comparison of Figure 3b with Figure 3a, a major decrease in erosion rates on the addition of 2 percent bentonite is evident, by more than an order of magnitude.

Bentonite in amounts of 0.50, 2, and 4 percent was also added to the sand. Erosion rates are shown in Figures 4a-4d. These sands were coarse and noncohesive compared with the topsoil and 50/50 mix. Because of this, their densities were relatively high and the variations in density were small. Also, the amount of gas in the sand cap tended to be relatively small so that ρ and ρ^* were approximately equal; the differences between the two densities is ignored in the following.

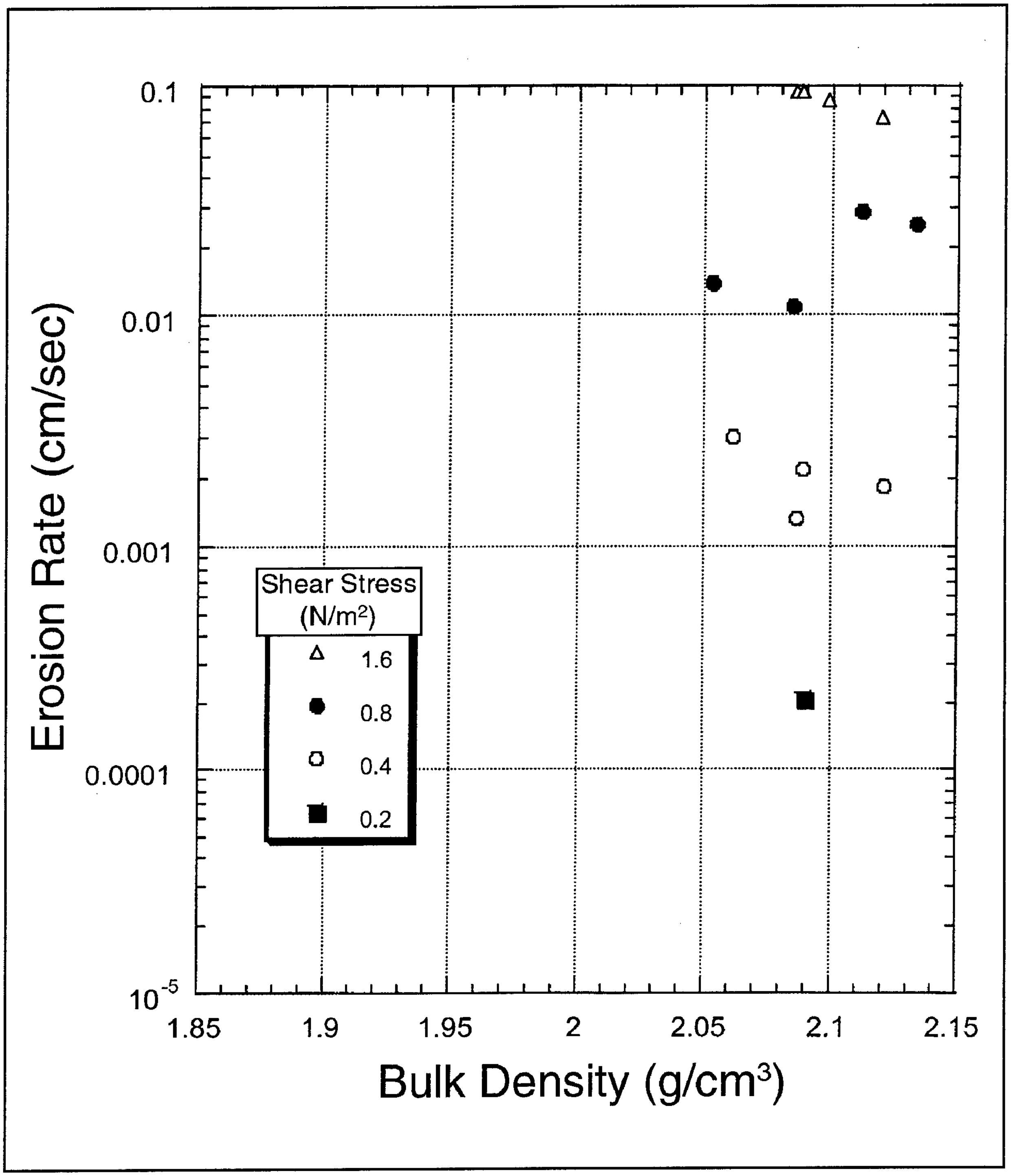
Erosion rates for sand with no added bentonite are shown in Figure 4a. Comparison of this figure with Figure 1b and 1c demonstrates that this sand is much easier to erode than is the 50/50 mix. For sand with 2 percent added bentonite, erosion rates are given in Figure 4b. The effect of 2 percent added bentonite is again seen to be quite significant with decreases in erosion rates of about two orders of magnitude, even greater decreases than for the 50/50 mix or the topsoil.

For 4 percent added bentonite, erosion rates as a function of density are shown in Figure 4c (2 days consolidation time) and Figure 4d (8, 32, and 128 days consolidation time). By comparison of these two figures, the thixotropic effect on erosion rates is again evident with decreases in erosion rates by factors of 2 to 6. Figure 4d demonstrates a further decrease in erosion rates by more than another order of magnitude compared with 2 percent added bentonite (Figure 4b).

Because of the dependence of erosion rates on density and the variations in densities from one capping material to another, it is difficult to compare results for different sediments and to isolate and quantify the effects of added bentonite from the previous data. For this purpose, summary plots have been prepared as follows. For each capping material, percent added bentonite, and shear stress, erosion rates have been averaged over all densities (or consolidation times). This summary data should not be used for modeling studies or predictions because of the significant dependence of E on ρ which is excluded in this type of summary; nevertheless, the plots clearly show the average effects of bentonite on erosion rates. This averaged data is shown in Figures 5a-5c for the 50/50 mix, the topsoil, and the sand capping materials, respectively.

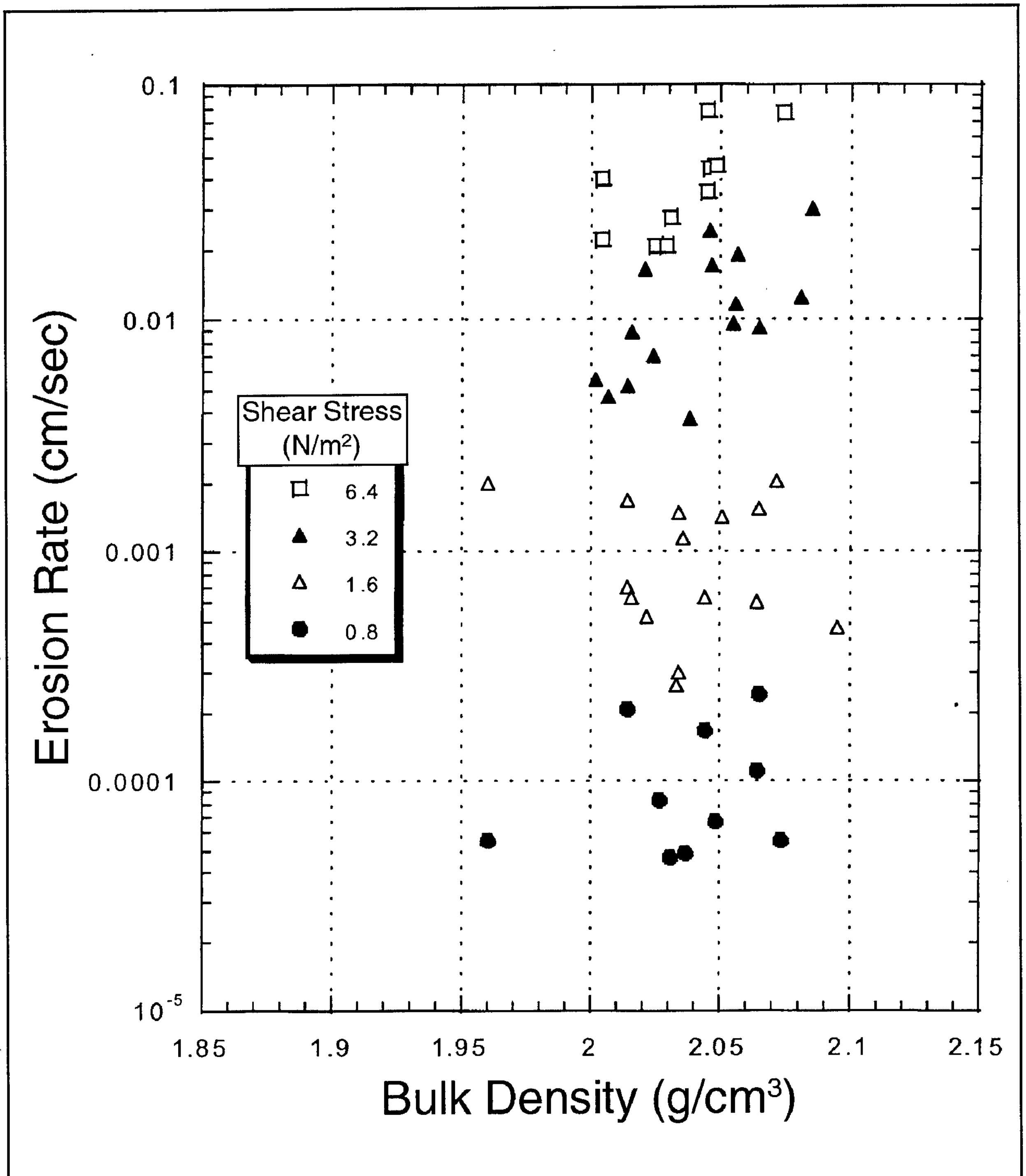
Figure 5a demonstrates that the effect of adding bentonite to the 50/50 mix is quite dramatic with decreases of 5 ($\tau = 6.4$ N/m^2) to 50 ($\tau = 1.6$ N/m^2) for 2 percent added bentonite and decreases of almost 50 ($\tau = 6.4$ N/m^2) to 250 ($\tau = 3.2$ N/m^2) for 4 percent bentonite. Erosion rates were also determined for 8 percent and 16 percent added bentonite. Decreases in erosion rates were again substantial but the rate of decrease was somewhat less than for the lower bentonite percentages. For example, a 16 percent addition of bentonite caused a decrease in erosion rates by almost three orders of magnitude.

Figure 5b shows that the topsoil without and with low bentonite additions is more difficult to erode than the 50/50 mix, but that the effect of adding bentonite is again quite significant. However, the addition of bentonite seems to have less of an effect than for the 50/50 mix. This may be due to the fact that the topsoil has more clay initially. This clay is primarily illite, chlorite, and vermiculite rather than bentonite or another smectite. However, the presence of this clay fraction may act to reduce the effect of the added bentonite.



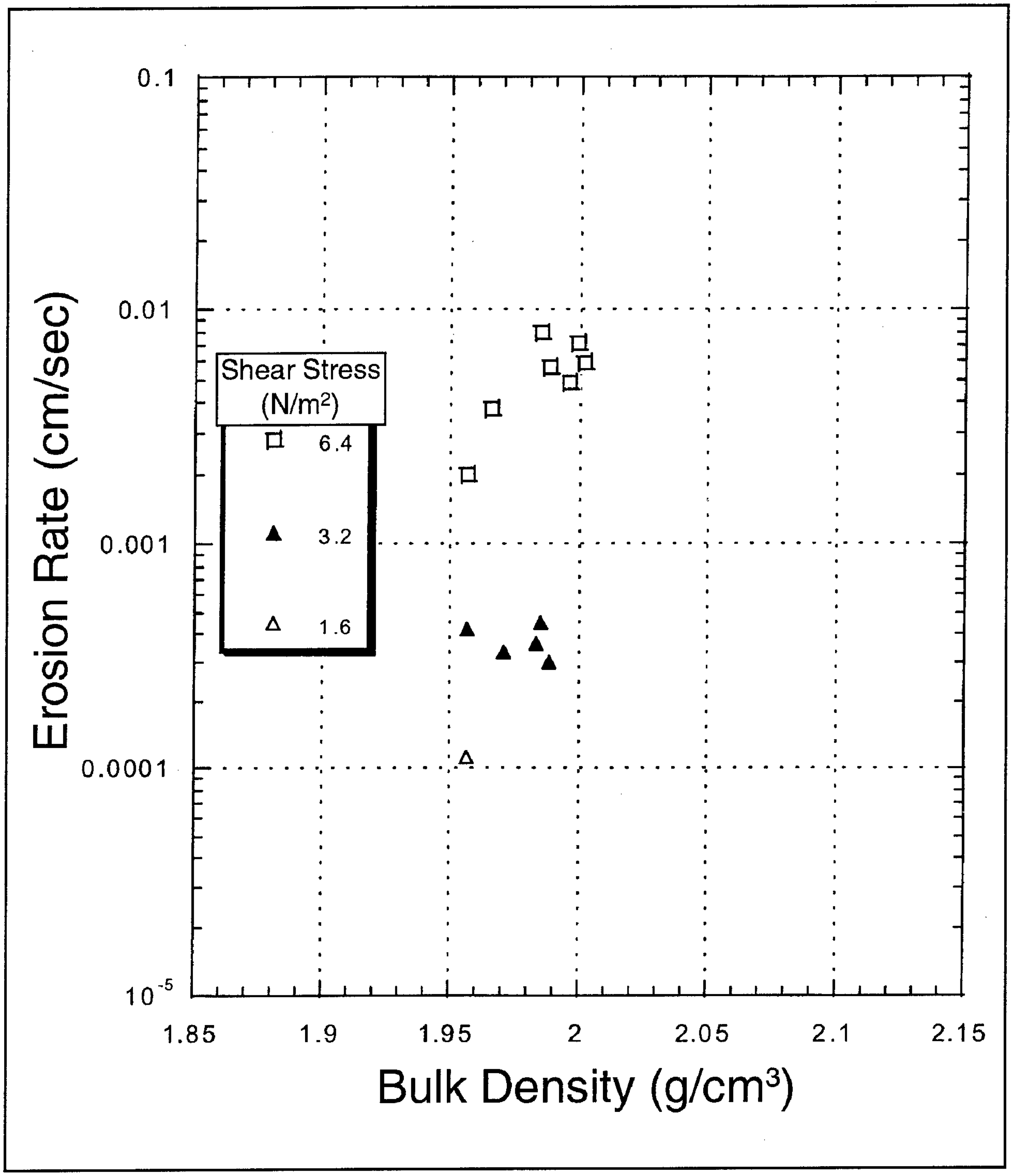
a. Sand with no added bentonite

Figure 4. Sand erosion rates as a function of ρ with shear stress (N/m^2) as a parameter (Sheet 1 of 4)



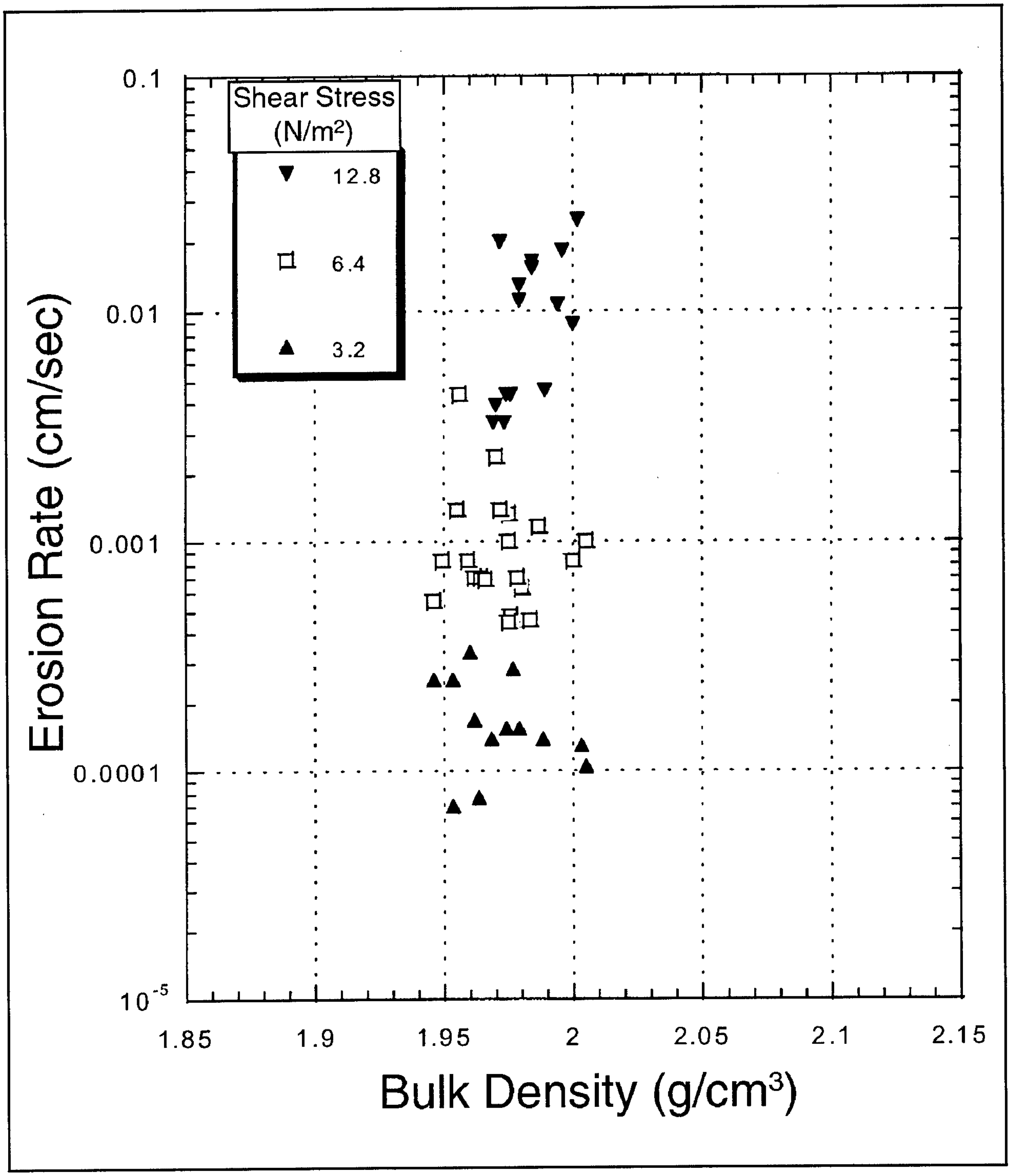
b. Sand with 2 percent added bentonite

Figure 4. (Sheet 2 of 4)



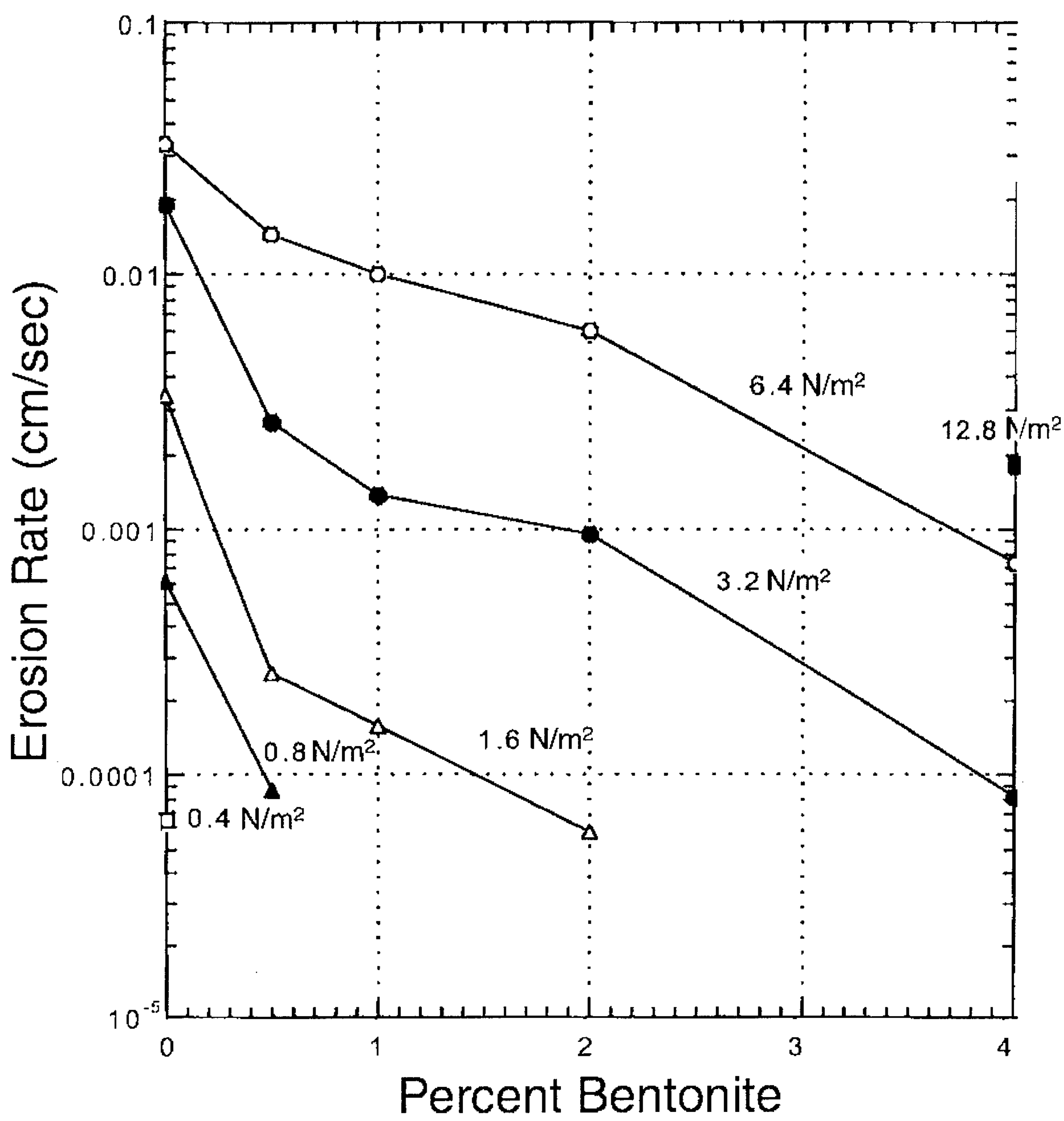
c. Sand with 4 percent added bentonite, consolidation time of 2 days

Figure 4. (Sheet 3 of 4)



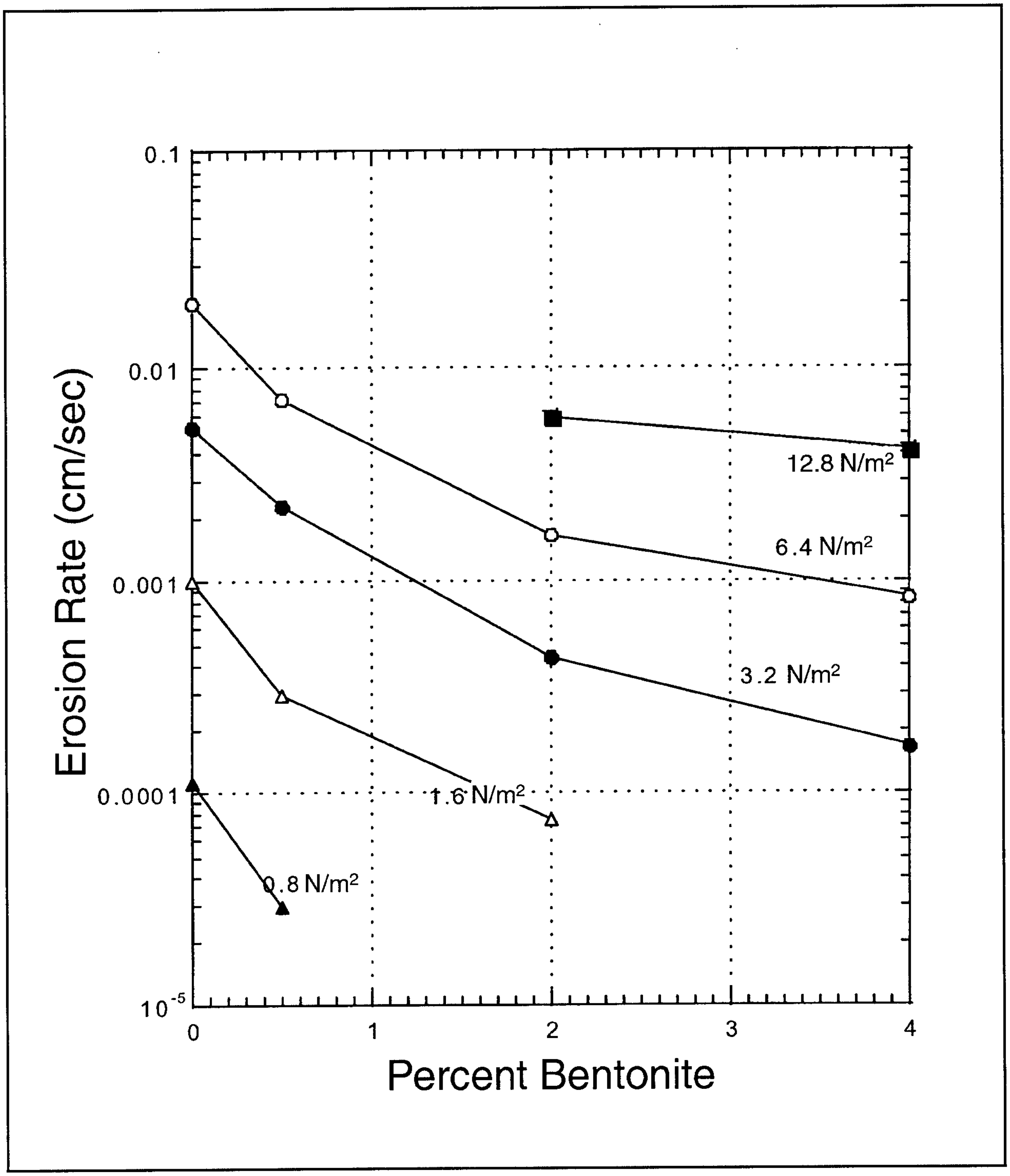
d. Sand with 4 percent added bentonite, consolidation times of 8, 32, and 128 days

Figure 4. (Sheet 4 of 4)



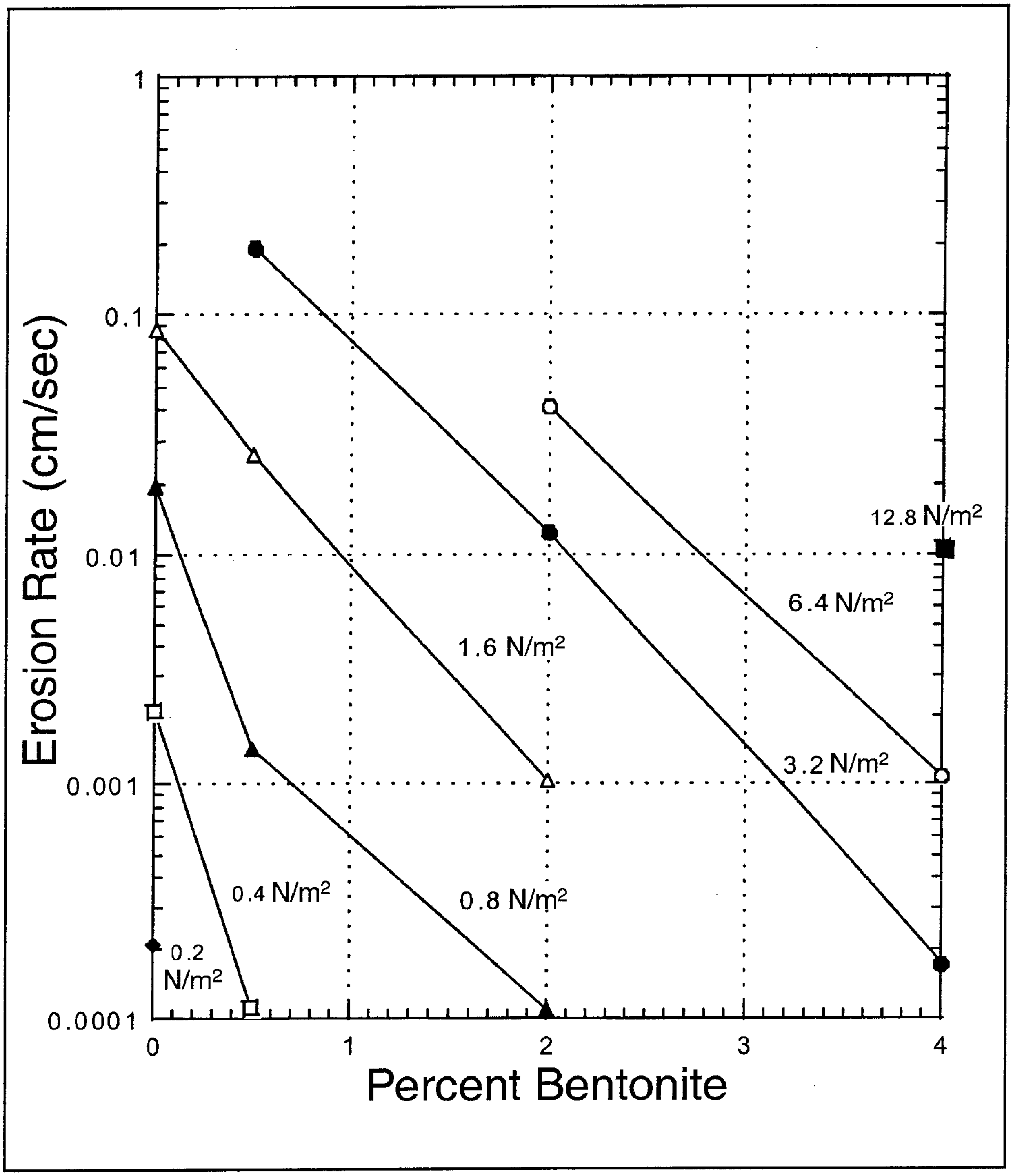
a. Parameter for a 50/50 mixture of topsoil and sand

Figure 5. Erosion rates averaged for all densities as a function of percent bentonite added with shear stress (N/m^2). Note the difference in the vertical scale between Figures 5a, 5b, and 5c (Sheet 1 of 3)



b. Parameter for topsoil

Figure 5. (Sheet 2 of 3)



c. Parameter for sand

Figure 5. (Sheet 3 of 3)

Erosion rates for the sand as a function of amount of added bentonite are shown in Figure 5c. (Note the difference in the vertical scale.) Here, the effects of adding bentonite are even greater than for the topsoil or 50/50 mix. For zero added bentonite, the sand is much easier to erode than the 50/50 mix or the topsoil. However, for 4 percent bentonite, it is only a little easier to erode than the other two. Decreases in erosion rates are almost two orders of magnitude for each 2 percent of added bentonite.

In previous work (Jepsen, Roberts, and Lick 1997; Gailani et al. 2001), erosion rates of reconstructed, well-mixed sediments from the Fox River in Wisconsin and an area offshore of Mobile, AL, were measured. It is interesting to note that the erosion rates of the 50/50 mix Fox Mobile, while the smectite content of the 50/50 mix Fox Mobile, i.e., as the smectite content increased the erosion rates decreased, similar to what has been demonstrated here for bentonite. Other factors such as particle size, organic content, gas content, and other bulk properties need to be considered before this relation can be considered to be valid for all applications and before it can be quantified.

SUMMARY AND CONCLUDING REMARKS: Small amounts of bentonite were added to a topsoil, a sand, and a 50/50 mix of the two. For each sediment and amount of added bentonite, erosion rates were determined as a function of depth, shear stress, and consolidation time. Without added bentonite, erosion rates were the largest for the sand and least for the topsoil. As bentonite was added, the erosion rates for each sediment decreased rapidly. For example, with the addition of 2 percent bentonite, erosion rates decreased by one to two orders of magnitude for each sediment and shear stress. This rate of decrease decreased as the amount of bentonite increased. The reductions in erosion rates were greatest for the sand and least for the topsoil.

Thixotropic effects (a reduction in erosion rates with time without changes in other bulk properties) on erosion rates were significant for consolidation times of 1 or 2 days, especially for the sediments with the larger amounts of bentonite. Without added bentonite, thixotropic effects were only evident for the topsoil and 50/50 mix (sediments which had some clay initially) but not for the sand. However, for the larger amounts of added bentonite, thixotropic effects were present in all three materials and were most evident for the sand.

Adding bentonite greatly reduces erosion rates for these three sediments and hence greatly enhances the stability of these sediments to erosion when used as a capping material. To generalize these results, the effects of bentonite on other sediments must be determined. The effects of other clay minerals on the erosion rates of sediments also need investigation. Bentonite is a very cohesive clay and the decrease in erosion for small amounts of other clays may be less dramatic.

An understanding of effects of mineralogy on erosion rates of clay mixed with other sediment will provide guidelines on the type of sediment most suitable for capping material. These data can also provide understanding of the dispersion potential of existing and proposed dredged material mounds.

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