

Cooperating Parties Group

**LOWER PASSAIC RIVER RI/FS
NEWARK, NEW JERSEY**

**APPENDIX M - ATTACHMENT E
SEDFLUME DATA ANALYSIS**

Prepared by:



E.1 Introduction

The Sedflume experiments involved erosion measurements on sediment cores from the LPRSA in 2005 (Borrowman et al, 2006) and provide information for the parameterization of the LPRSA ST model. Since the Sedflume experimental setup is designed to measure erodibility with depth into the bed, in combination with a spatially distributed sampling program, the Sedflume measurements can potentially provide information on the spatial and depth-dependent variations in erosion properties within the LPRSA. The LPRSA Sedflume experimental program, summarized in Borrowman et al, 2006 has been analyzed from this perspective. The following sections describe the sampling program and experimental setup, the analysis of the erosion measurements, and the resulting development of appropriate model inputs.

E.2 Core Locations and Experimental Setup

The sampling program for the Sedflume experiments consisted of cores collected from 14 locations (with duplicate cores at each location collected within 1-10 meters of each other) in the LPRSA in 2005. Figure 1 shows the locations where cores were collected as part of the Sedflume program. The cores were typically 30-60cm deep, with some cores collected from locations in the shallows and some within the former navigation channel. Six cores were collected from three locations up-estuary of RM 8 and twenty-two cores were collected at eleven locations between RM 0 and RM 8. The cores located between RM 0-8 were characterized by predominantly fine sediments whereas the cores between RM 8-17 were somewhat coarser. In addition to grain size distribution, the carbon content and bulk density profile of the sediments was also measured.

Figure 2 shows a schematic view of the Sedflume experimental setup. Borrowman et al (2006) provides a detailed description of the experimental setup and protocol summarized here. Briefly, the setup consists of a rectangular flume through which water is pumped at varying flow rates to impose varying shear stresses at the bottom of the flume. The bottom of the flume is also fitted with an opening to allow insertion of the cores collected from the field. The core is positioned such that the sediment-water interface is flush with the bottom of the flume. During the experiments, as sediments are eroded from the surface of the core due to the imposed shear stresses, the core is pushed upwards by means of a jack and piston arrangement so that the surface of the core is maintained flush with the bottom of the flume. A typical erosion experiment consists of a series of shear stress sequences (typically 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 4.5, 6.4, 8.0, 10.0, and 12.0 Pa) run through the flume. The depth of erosion (or lack thereof) corresponding to each imposed shear stress along with the time duration for which that shear stress is imposed is recorded and used to calculate the erosion rate associated with that shear stress. The upper and lower depths associated with the beginning and end of a given shear stress sequence is, for purposes of the analyses presented here, considered to be the depth-interval associated with that shear stress sequence. Accordingly, the terms shear stress sequence and depth-interval used in the text subsequently are meant to be analogous. The shear stress sequences are repeated for various depth intervals in the core to allow for measurement of the erodibility with depth

into the bed. The data from the Sedflume experiments therefore consists of pairs of erosion rate and shear stress with depth in the bed.

E.3 Erosion Rate Function by Shear Stress Sequence

Figure 3 through Figure 30 show the measured erosion rate (on Y-axis, in cm/s) as a function of the imposed bed shear stress (on X-axis, in Pa) for each of the shear stress sequences run for the various cores from the LPRSA. Core names correspond to the locations shown in Figure 1, with the A and B cores corresponding to the duplicate cores collected at each location. Each panel corresponds to a shear stress sequence with incrementally increasing shear stresses run through Sedflume. The value for variable d shown on each panel represents the starting depth of the depth-interval (in cm) spanning each shear stress sequence. The black circles represent shear stresses with reported erosion and plotted at the reported erosion rate. The red circles represent shear stresses with no measurable erosion rate and shown at the bottom of the Y-axis for plotting purposes. For instance, in the second shear stress sequence run in Core 01A ($d = 4.9$ cm, upper row, middle panel in Figure 3), the shear stress sequence started from 0.1 Pa, with no measurable erosion reported at this shear stress. Increasing the shear stress to 0.2 Pa and 0.4 Pa also did not result in any erosion. Erosion occurred only when shear stress was increased to 0.8 Pa, with erosion rate increasing with increasing shear stress.

The erosion function used to fit the Sedflume measurements is a power function of the shear stress:

$$E = A\tau^n \quad (1)$$

where E = erosion rate in cm/s and τ = bed shear stress in Pa. Parameters A and n are determined by a least-squares fit to the measured erosion rates in each shear stress sequence. The calculated values for parameters A and n are included on each panel.

In addition to the erosion rate function, the critical shear stress for erosion (τ_{cr}) is also commonly calculated from the Sedflume erosion measurements (Roberts et al, 1998). The approach involves the assumption that the critical shear stress for erosion is that shear stress which results in an erosion rate of 10^{-4} cm/s. Re-arranging Equation 1, the critical shear stress is calculated as:

$$\tau_{cr} = \left(\frac{10^{-4}}{A} \right)^{1/n} \quad (2)$$

The critical shear stress for erosion is calculated using Equation 2 using the parameters A and n calculated for given shear stress sequence, and is shown in each panel (value shown for variable τ_c).

The erosion rate functions for the individual depth-intervals and cores shown in Figure 3 through Figure 30 represent the raw erosion rate functions from the Sedflume experiments.

The majority of the depth-intervals show reasonable and expected trends, i.e. the erosion rate is a positive function of the imposed shear stress. However, certain depth-intervals such as the bottom-most depth-interval in core P01A (Figure 3) and the third depth-interval in core P14B (Figure 28) show a negative correlation between the erosion rate and the imposed shear stress; this may likely be a consequence of the variability inherent in the data and the fact that only two pairs of erosion rate and shear stress are available to develop the erosion rate function in this depth-interval. Another example of a questionable trend seen in the raw erosion rate functions is for the bottom-most depth-interval in core P01B (Figure 4). In this case, only one pair of erosion rate and shear stress is available which rules out the development of a credible regression function describing the erosion rate as a function of shear stress. Therefore, as described subsequently in the text, the erosion rate functions indicative of such questionable trends was not included in the development of model inputs as described subsequently.

E.4 Spatial and Depth-Dependent Patterns in Erodibility

The erosion rate functions fit for each shear stress sequence as described in the preceding section have been further analyzed and reviewed for spatial and depth-dependent patterns in erodibility. The approach consists of calculating the erodibility index, which is a measure of the erosion rate for a given core or depth interval relative to the erosion rate of the entire dataset. Accordingly, the erodibility index is calculated as:

$$EI = \frac{E_i}{\bar{E}} \quad (3)$$

where EI = erodibility index, E = cumulative erosion rate over a range of shear stresses as shown in Equations 4 and 5, subscript i indicates a given core or depth-interval (i.e. shear stress sequence), and the overbar indicates an average value for the entire dataset. The average erosion function for the entire dataset is calculated using Equations 6 and 7, as a logarithmic mean for parameter A and as an arithmetic mean for parameter n .

$$E_i = \sum_{\tau=0}^{\tau=x} A_i \tau^{n_i} \quad (4)$$

$$\bar{E} = \sum_{\tau=0}^{\tau=x} \bar{A} \tau^{\bar{n}} \quad (5)$$

$$\log \bar{A} = \frac{1}{N} \sum_{i=1}^{i=N} \log A_i \quad (6)$$

$$\bar{n} = \frac{1}{N} \sum_{i=1}^{i=N} n_i \quad (7)$$

where x is an environmentally realistic upper-bound on shear stress, and N is the number of cores or depth-intervals as appropriate.

E.4.1 Depth-Dependent Patterns in Erodibility

The erodibility index was calculated using Equation 3 for each depth-interval in each core relative to the overall dataset. Parameters A and n were first calculated for the entire dataset using Equations 6 & 7, with term N representing the number of depth intervals or shear stress sequences in the entire dataset. The parameters A and n thus calculated were used to calculate term $\bar{E}$ following Equation 5. Term E_i was calculated for the individual depth-intervals using the erosion rate function developed as described in Section E.3. Figure 31 shows the resulting erodibility index by depth, for each of the shear stress sequences run through Sedflume. The upper and lower bounds of the bars correspond to the core depth at the beginning and end, respectively, of given shear stress sequence. The calculated EI for each depth interval is also indicated within each bar. Red bars indicate depth-intervals where an EI was not calculated, typically due to the availability of either one or no shear stresses with measured erosion. Blue bars indicate a depth-interval where the erosion function was fit with only two points with pairs of shear stress and erosion rates. Such depth-intervals typically also coincide with highly variable EI values compared to depth-intervals above and below. For instance, the second depth-interval from the surface in core P02B which included only two data pairs of shear stress and erosion rate, shows erodibility about 5 orders of magnitude larger than the overall dataset. In contrast, the remaining depth-intervals in this core show lower erodibility than the overall dataset. Therefore, such depth-intervals with less than three pairs of shear stress and erosion rates were excluded from the analyses to calculate erosion properties for use in developing sediment transport model inputs. In general, for the predominantly cohesive cores (i.e. cores located between RM 0-8), considering only the shear stress sequences including three or more pairs of erosion rate and shear stress, comparing the surface-most and bottom-most depth-intervals shows that EI decreases with depth into the bed. That is, the erodibility or the erosion rate associated with a given shear stress decreases with depth into the bed. This is a reasonable and expected finding and likely reflects the effects of consolidation with depth in the bed. Exceptions to this general trend of decreasing erodibility from the surface to the bottom of the cores include cores P05B and P11B. This may partly reflect intra-core variability – for instance, cores P07B, P09B, P03A, etc. show EI that does not decrease monotonically from the surface to deeper depth-intervals. Although, the reason for this intra-core variability is unknown, the trend of decreasing erodibility from the surface to the bottom seen in the majority of the cores is a reasonable and expected pattern.

E.4.2 Depth-Dependent Patterns in Critical Shear Stress for Erosion

The critical shear stress for erosion was also reviewed for dependence with depth. Figure 32 through Figure 35 show the depth-profile of the critical shear stress for erosion calculated using the approach described by Equation 2 for the depth intervals corresponding to each shear stress sequence. For illustration purposes, to show the general trends with depth in the bed, a log-regression of the critical shear stress with depth is also shown with a red line in these figures. In general, for predominantly cohesive cores (i.e. cores located between RM 0-8), considering only the shear stress sequences including three or more pairs of erosion rate and shear stress, with the exception of a handful of cores (P05A, P06A, P09B, P11A, and P11B), the general trend is of increasing critical shear stress with depth in the bed. However, the critical shear stress in the individual depth-intervals do not always monotonically increase with depth in the bed. For instance, core P02A shows an increase in critical shear stress from the surface to the depth-interval between 11-14 cm, but a subsequent decrease up to the 24-28 cm depth-interval, followed by an increase up to the 40-44 cm depth-interval. The reasons for these vertical gradients (i.e. variability) are not known; this variability may also explain the apparent decrease in critical shear stress noted in a subset of cores. For instance, core P06A, despite an increase in critical shear stress when comparing the surface-most and bottom-most depth-intervals, shows a general trend of declining critical shear stress with depth, a trend likely related to the variability in critical shear stress within the individual depth-intervals. Nonetheless, the trend of increasing critical shear stress with depth noted in the majority of the cores is reasonable and explainable, and likely reflects the effects of consolidation with depth in the bed.

E.4.3 Spatial Patterns in Erodibility

The spatial pattern in erodibility was assessed using the erodibility index approach described previously. In this case an average value of the parameter A and n was calculated per core (using Equations 6 & 7, with term N representing the number of depth intervals in given core). The core-average A and n values were subsequently used to calculate a dataset average A and n using Equations 6 & 7, with term N representing the number of cores in the dataset. The core-average A and n values were used to calculate the cumulative erosion rate for each core using Equation 4, and the dataset average A and n were used to calculate the cumulative erosion rate using Equation 5, and the erodibility index calculated for each core using Equation 3. Figure 36 shows the resulting comparison of the inter-core EI for the cores collected between RM 0-8 (predominantly cohesive cores). However, there is no clear pattern evident between the various cores. EI is seen to vary over 2 orders of magnitude, with even the duplicate cores collected at a given location varying by an order of magnitude in some instances (e.g. cores 03A and 03B). The EI also does not show any trends with location within the LPR, organic carbon content, sand content, or bulk density. The magnitude of the variability, especially in the duplicate cores, is somewhat surprising. Similarly, the lack of a spatial pattern in erodibility and lack of a dependency with other variables such as grain size distribution, bulk density, or carbon content is also somewhat surprising.

E.5 Empirical and Calculated Critical Shear Stress for Erosion

As described previously, because of the Sedflume experimental protocol with a given depth-interval in the bed tested in a sequence of incrementally increasing shear stresses, some of the shear stresses may on occasion be too low to cause erosion. These shear stresses that are too low to cause erosion may be considered below the threshold for initiation of motion, in other words less than the critical shear stress for erosion for that depth interval. Therefore, the shear stresses with no measurable erosion provide information on the critical shear stress for erosion that can be compared against the critical shear stress for erosion calculated using Equation 2. This is illustrated using the same core and depth-interval described previously (the second depth interval for Core 01A). In this case, the lack of measurable erosion at shear stresses less than 0.4 Pa and with measurable erosion observed only at 0.8 Pa suggests that empirically the critical shear stress for erosion is a value greater than 0.4 Pa and less than 0.8 Pa. The lower bound of shear stress is referred to as the highest shear stress with no erosion (τ_0), and the upper bound of shear stress as the lowest shear stress with some erosion (τ_l). Comparison to the calculated critical shear stress (0.22 Pa) suggests that the calculated value under-estimates the empirical value by a factor of 2 to 4.

Figure 37 shows a comparison of the empirical and calculated critical shear stress for each of the shear stress sequences or depth intervals in the overall dataset. The empirical critical shear stress is bounded by τ_0 and τ_l (indicated by the horizontal bars), and for purposes of this comparison the empirical critical shear stress is calculated as the average of τ_0 and τ_l . Lines indicating perfect agreement (1X) between calculated and measured values, and under-estimation of measured values by several factors (2X, 4X, and 6X) are also included in Figure 37. This comparison shows that on average the calculated critical shear stress tends to be biased low compared to the empirical critical shear stress by up to a factor of 6. This bias has implications for the development and parameterization of the model and therefore the model calibration process has considered the range in τ_0 and τ_l in the development of the critical shear stress profile.

E.6 Summary and Model Inputs

The preceding sections described the Sedflume data and the erosion properties measured on the LPRSA cores. The erosion properties were analyzed for vertical and spatial heterogeneity. In general, the individual cores showed erodibility (as indicated by both erosion rate and the critical shear stress for erosion) decreasing with depth, a qualitatively reasonable expectation given that sediments at depth would be more consolidated than surficial sediments and therefore more resistant to erosion. However, spatially, the cores showed a high degree of variability with no apparent correlation with location within the LPR, organic carbon content, sand content, or bulk density; even duplicate cores taken at the same location showed a high degree of variability. Given this unexplained variability, and the lack of any objective criteria to map this variability in erosion properties to the entire LPR domain, the erosion properties measured in the individual Sedflume cores were averaged to develop a single set of parameters (referred to as the average core) for use in

the LPR/NB model. Only the cores collected in the predominantly cohesive portions of the domain (between RM 0-8) were used to develop the erosion properties of the average core.

The averaging process included first defining discrete depth-intervals for which the erosion properties are subsequently derived. The layering was chosen to preserve the depth-dependent erodibility noted in the data analyses in the preceding sections. Accordingly, depth-intervals between 0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm, 25-30 cm, and >30 cm were defined for the average core. Since the individual depth-intervals sampled in the Sedflume tests do not coincide with the depth-intervals defined for the average core, the measured A and n terms for the individual depth-intervals in a given core were first mapped to the depth-intervals defined for the average core using a length-weighted approach in log-space (for term A) and in arithmetic-space (for term n). Prior to this mapping, the dataset was filtered to exclude (1) shear-stress sequences with less than three measured pairs of erosion rate and shear stress, (2) exhibiting a negative functional relationship between erosion rate and shear stress, and (3) with correlation R^2 less than 0.8. The resulting A and n terms (in the individual cores and for each of the depth-intervals defined for the average core) were used to calculate a dataset average A and n for each of the depth-intervals defined for the average core using Equations 6 & 7, with term N representing the number of cores in the dataset.

Table 1. Erosion Properties Derived from Sedflume data

Depth Interval (cm)	A (cm/s)	n	τ_{Cr} (Pa)	
			Calculated ¹	Empirical ²
0 - 2.5	134×10^{-4}	2.14	0.1	0.25
2.5 – 5	62×10^{-4}	2.54	0.2	0.30
5 – 10	24×10^{-4}	2.71	0.31	0.83
10 – 15	24×10^{-4}	2.93	0.34	1.08
15 – 20	7.9×10^{-4}	3.25	0.53	1.02
20 – 25	4.4×10^{-4}	3.48	0.65	1.11
25 – 30	3.4×10^{-4}	3.39	0.69	1.03
>30	5.5×10^{-4}	2.79	0.54	1.57

¹ Calculated using Equation 2

² Calculated as the average of the highest shear stress with no erosion (τ_0), and the lowest shear stress with some erosion (τ_1)

Table 1 shows the erosion properties over depth for the average core developed from the Sedflume data. The decrease in the value of the A parameter is an indication of the reduced erodibility with depth into the bed. Table 1 also lists the calculated critical shear stress derived using Equation 2 and the averaged parameters A and n for each layer. Information on the empirical critical shear data from the individual shear stress sequences within each of the depth intervals is also included in Table 1 and was used to assess the bias between the calculated and empirical critical shear stress for erosion. Figure 38 shows the resulting comparison of the depth profile of the critical shear stress for erosion. The calculated critical shear stress is shown with black filled circles, the range between τ_0 (the highest shear stress within a given shear stress sequence with no observed erosion) and τ_l (the lowest shear stress within a given shear stress sequence with some observed erosion) for all the Sedflume shear stress sequences within a given depth interval is shown with grey bars, and the range and average of the empirical critical shear stress for erosion (calculated as the average of τ_0 and τ_l) is shown with red bars and red symbols respectively. The data show a large range (up to an order of magnitude) in the empirical critical shear stress for erosion in any given depth interval. The average empirical critical shear stress for each layer is shown in Table 1 and is seen to be about 1.5 to 3 times larger than the calculated values. The average empirical critical shear stress also increases with depth into the bed, increasing by a factor of 6, indicating the increasing strength of the bed with depth. This bias between the measured and calculated critical shear stresses, and also the range in the measured critical shear stress within a given depth-interval, was used as the basis of a calibration procedure used to develop model inputs for the critical shear stress profile. This calibration procedure and the resulting critical shear stress profile are described in Section 4.2.5 of the main body of this report.

The erosion properties of the average core were applied to the predominantly cohesive parts of the model domain: Newark Bay, the lower 7.8 miles of the LPR, the silt pockets above RM 8, and areas outside the former navigation channel above RM 8.3 in the LPR. Erosion properties for the predominantly non-cohesive parts of the domain (i.e., the areas within the navigation channel above RM 8, and all the areas above RM 13) were based on the values published in Roberts et al. (1998), which relates erosion properties to median diameter (D_{50}) of the sediments. The median diameter of the sediment bed in these areas was calculated using the initial conditions of bed grain size distribution developed for these areas.

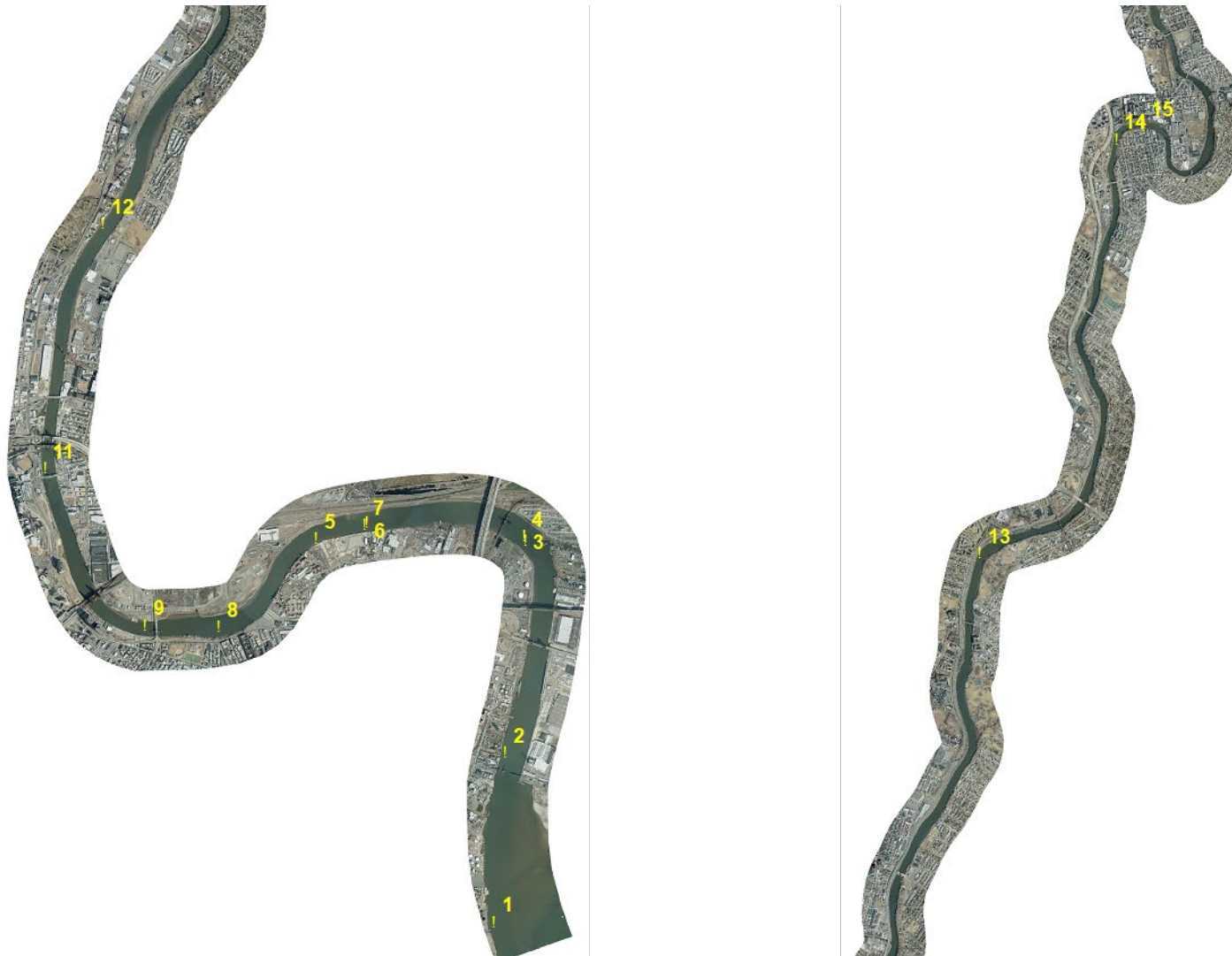


Figure 1. Locations of Sedflume cores.

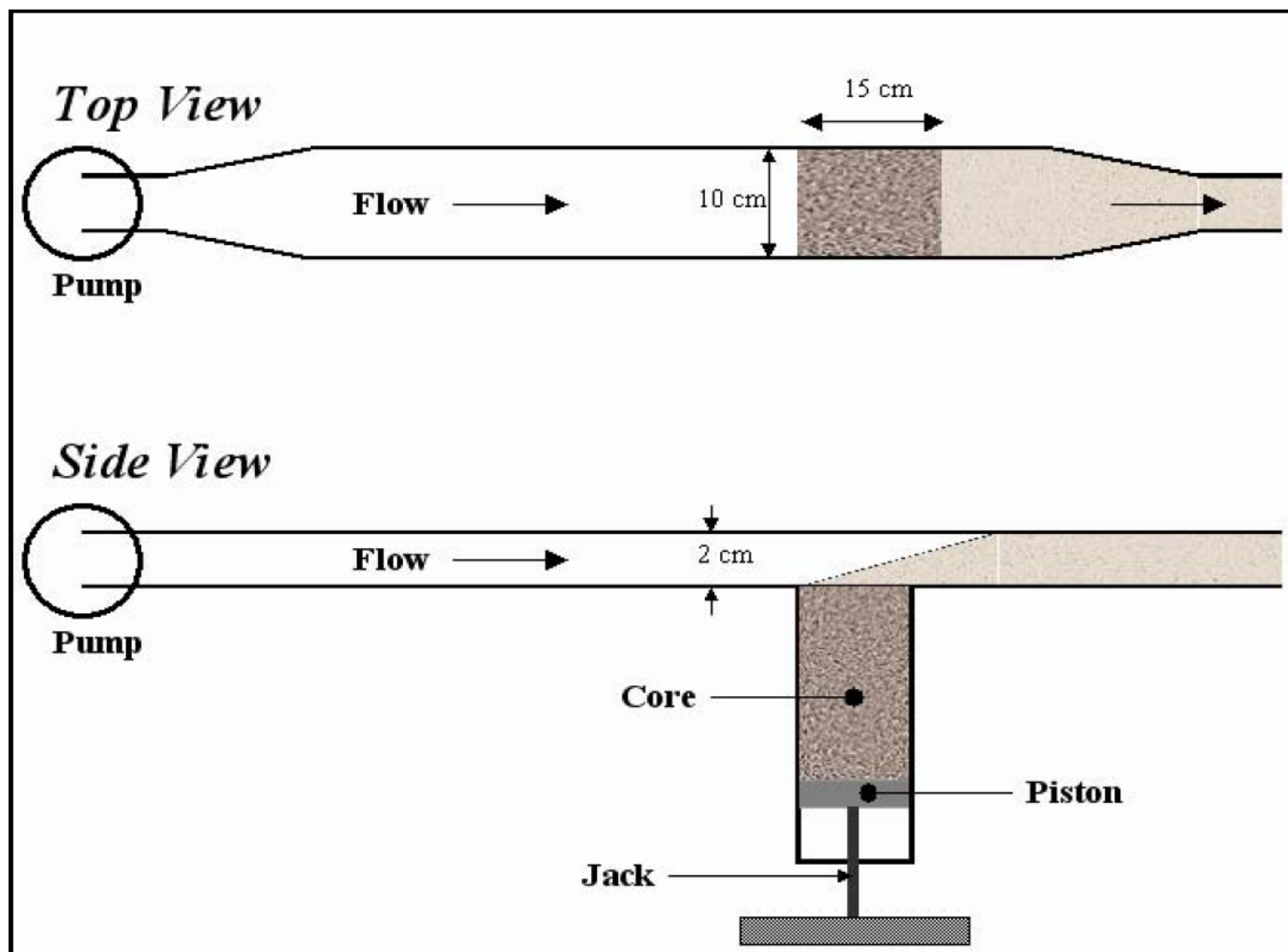


Figure 2. Schematic of Sedflume experimental setup (adapted from Borrowman et al, 2006).

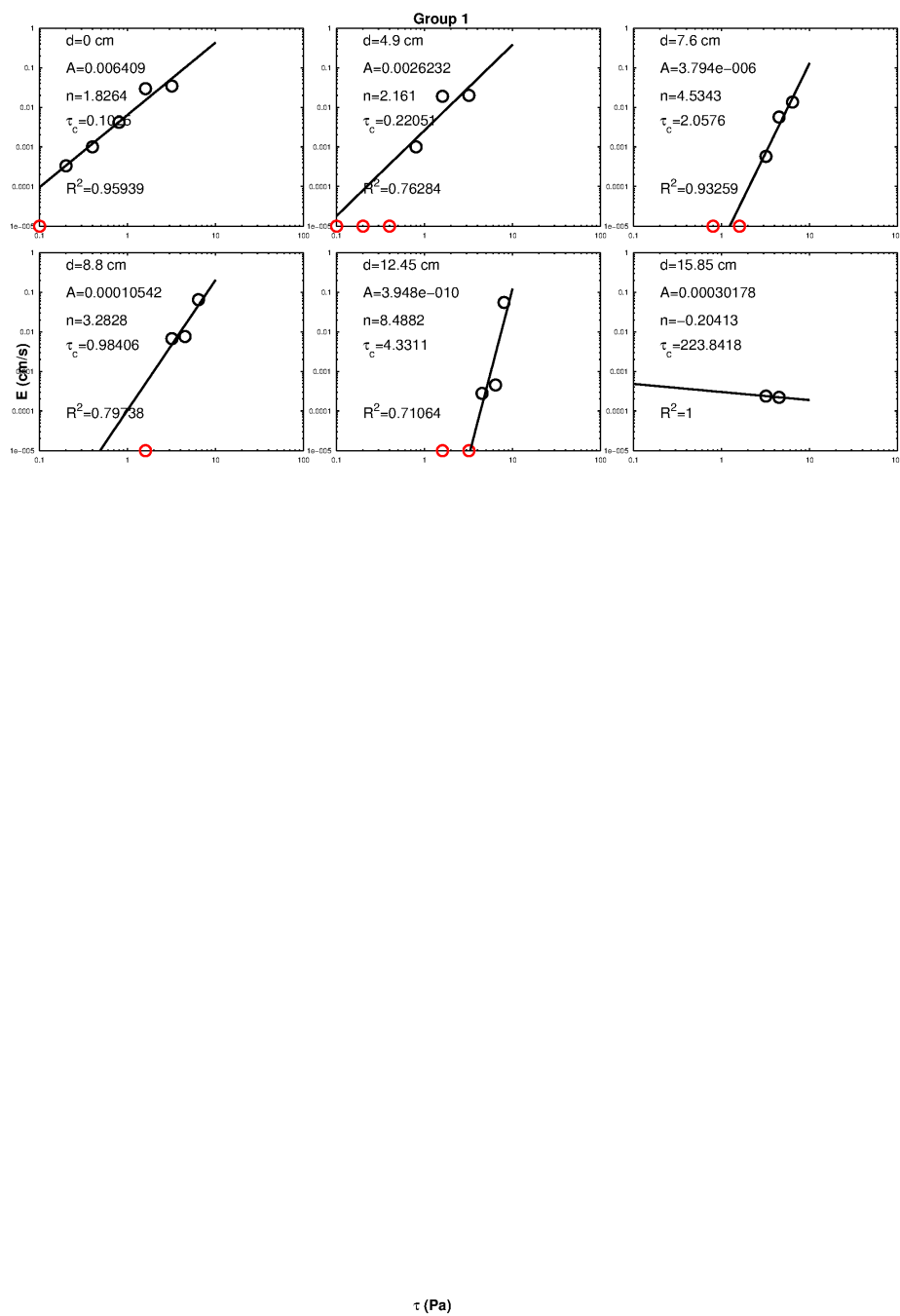


Figure 3. Measured erosion rate as function of shear stress for Core 01A

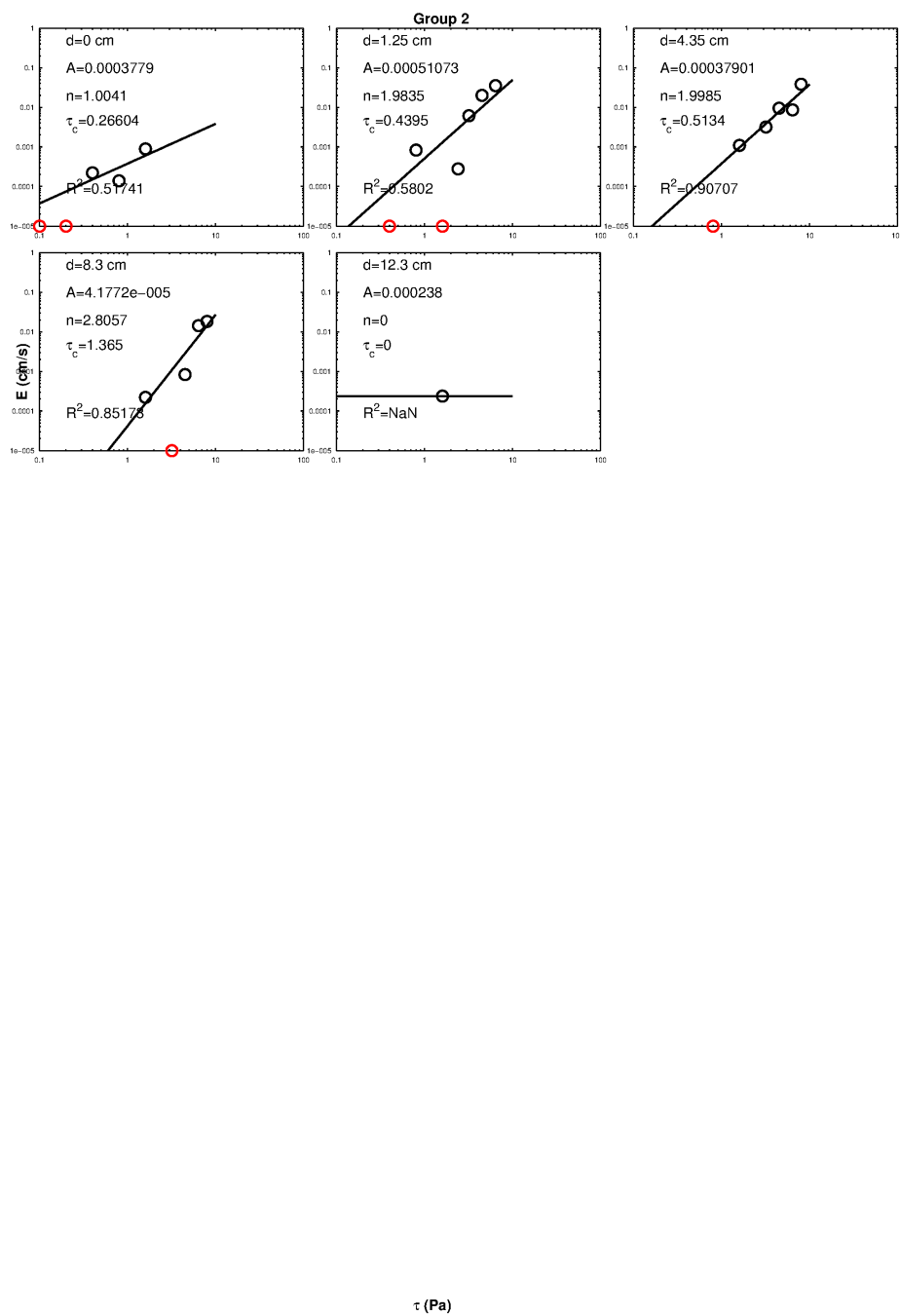


Figure 4. Measured erosion rate as function of shear stress for Core 01B

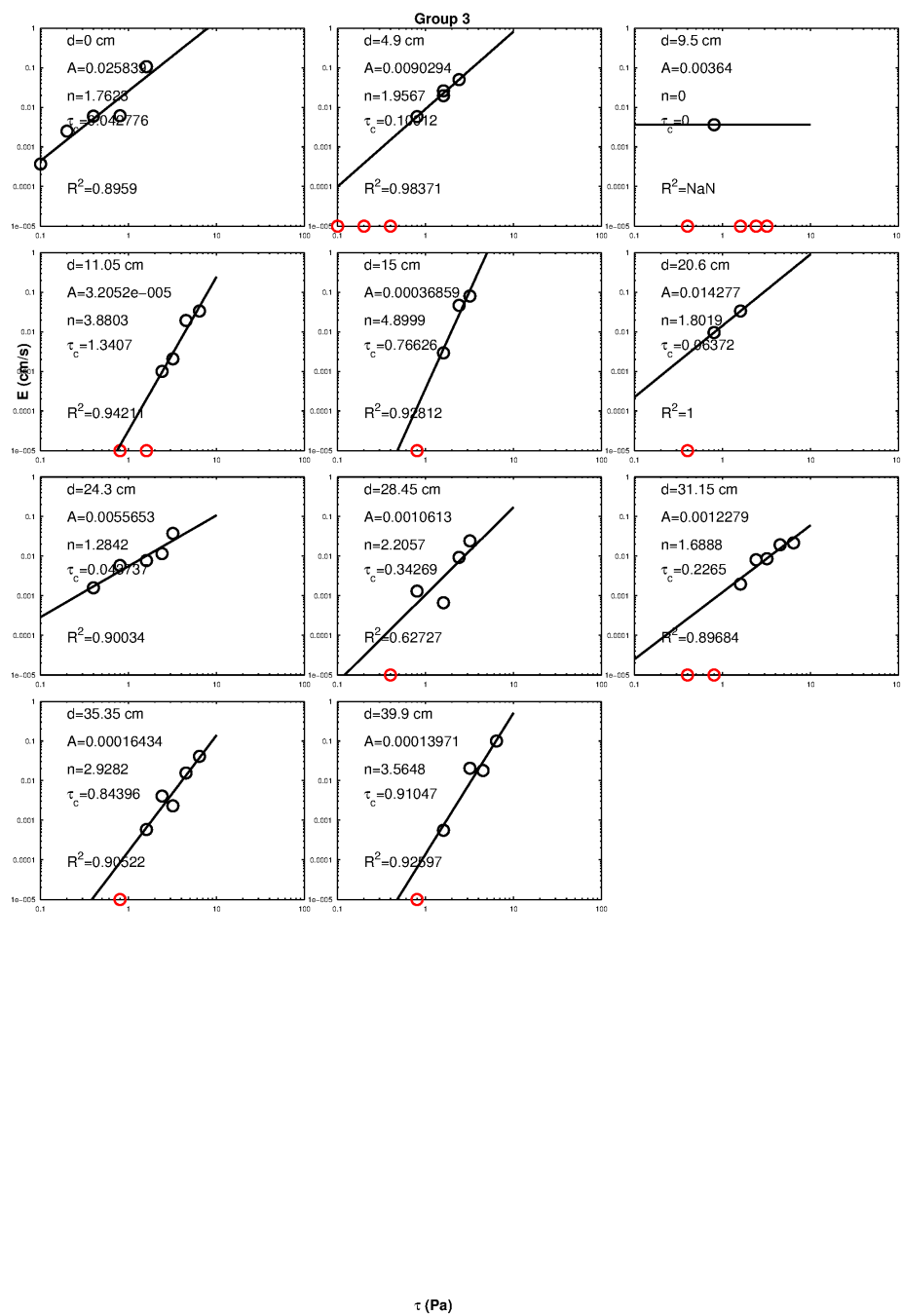


Figure 5. Measured erosion rate as function of shear stress for Core 02A

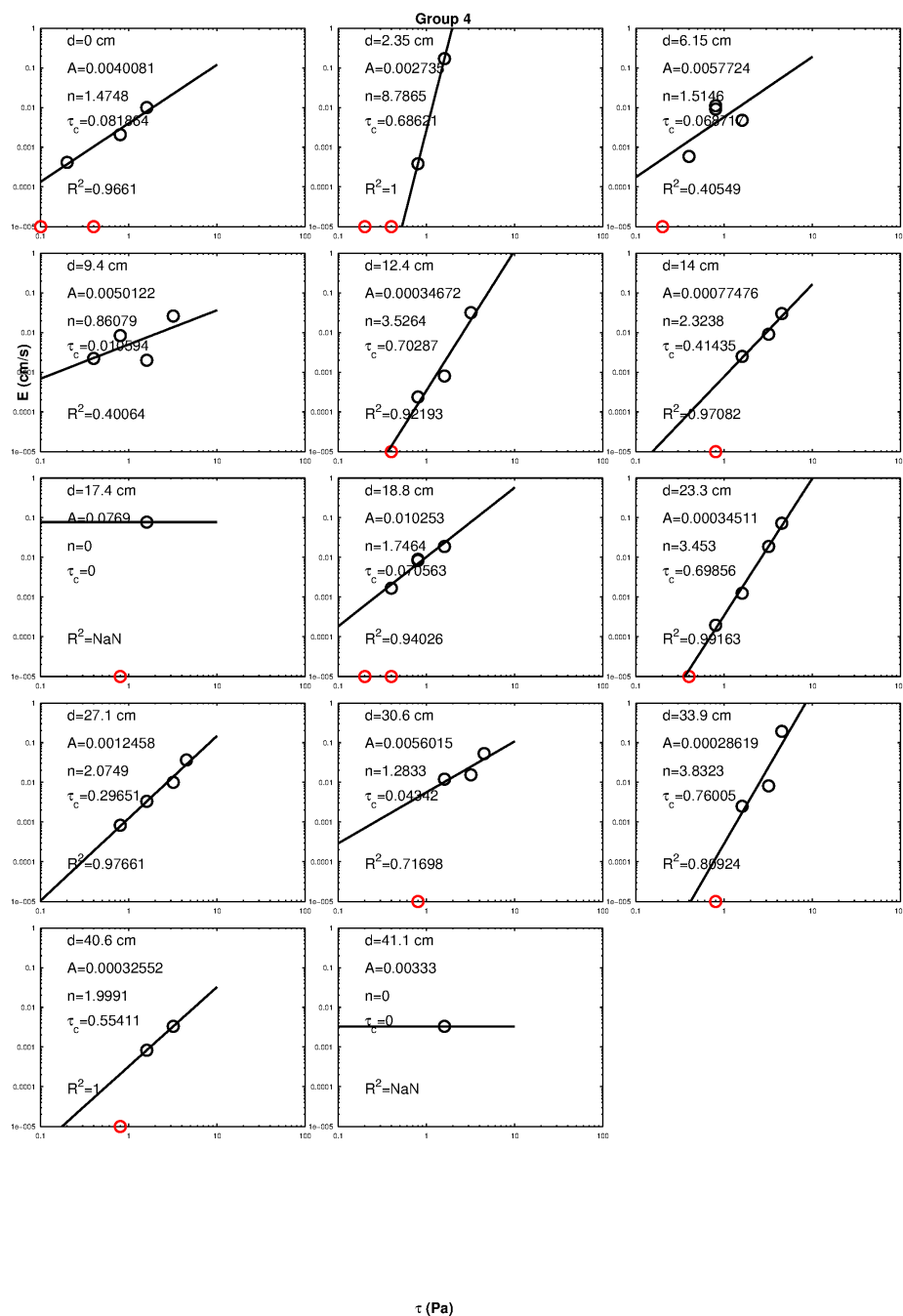


Figure 6. Measured erosion rate as function of shear stress for Core 02B

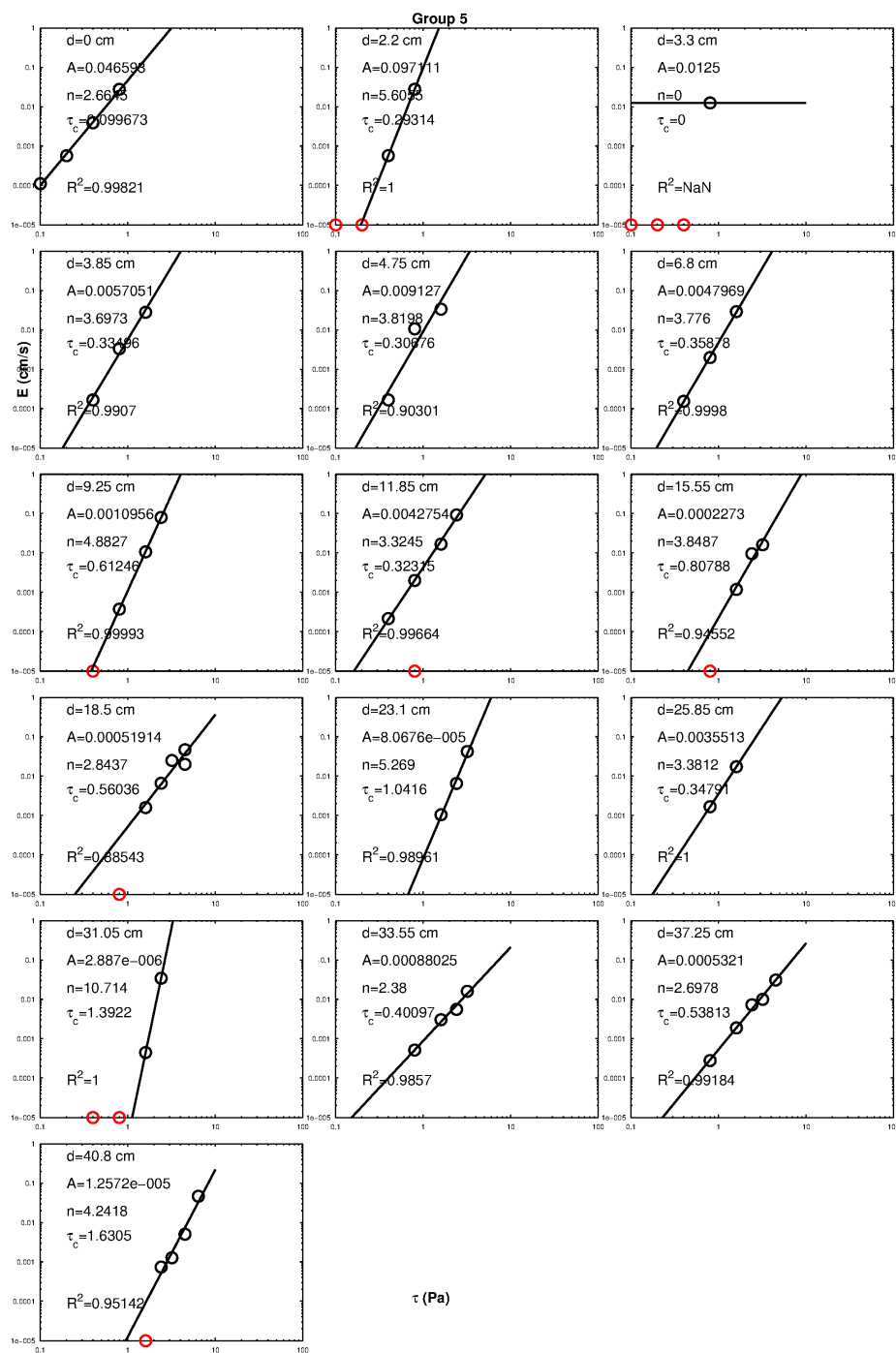


Figure 7. Measured erosion rate as function of shear stress for Core 03A

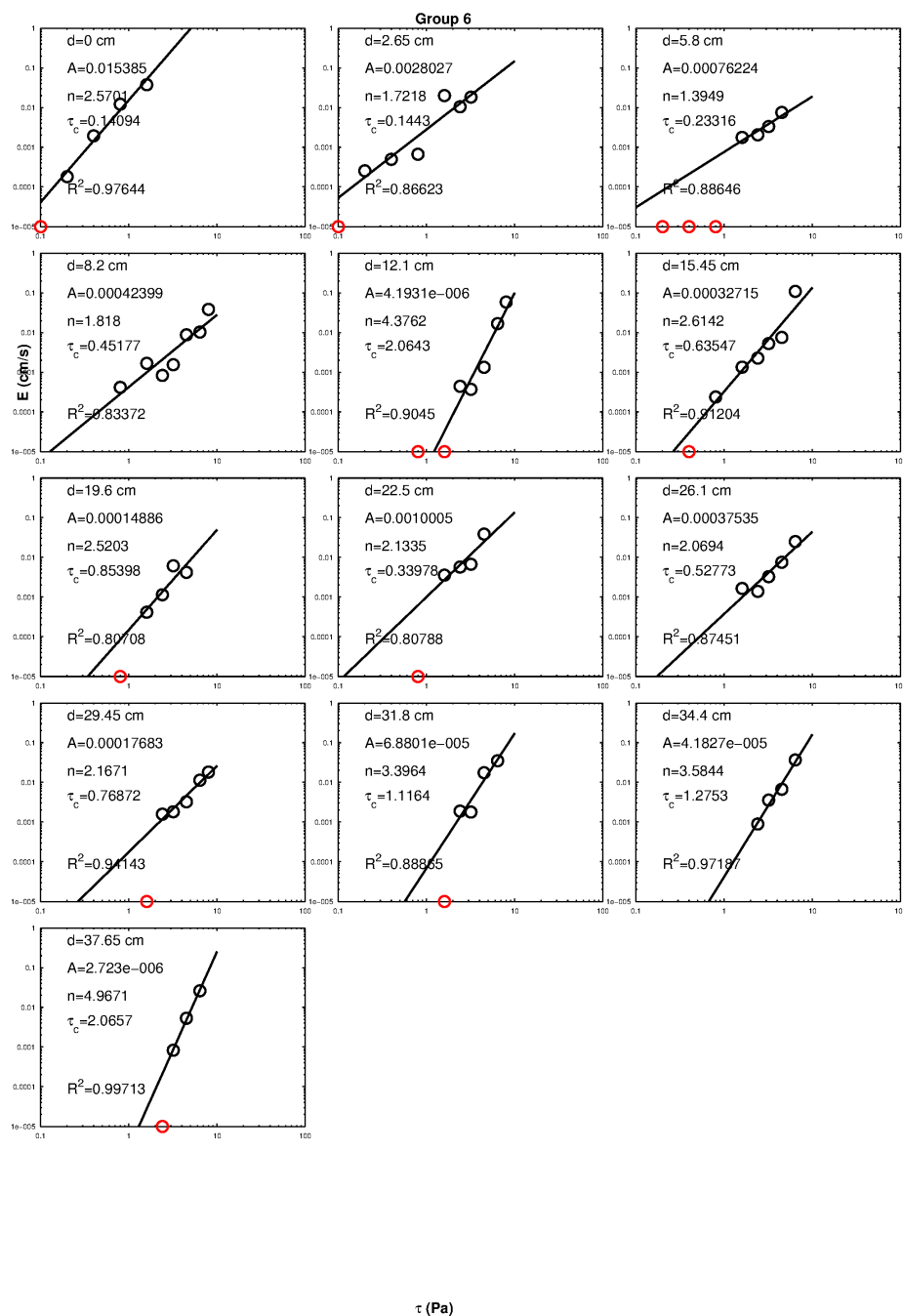


Figure 8. Measured erosion rate as function of shear stress for Core 03B

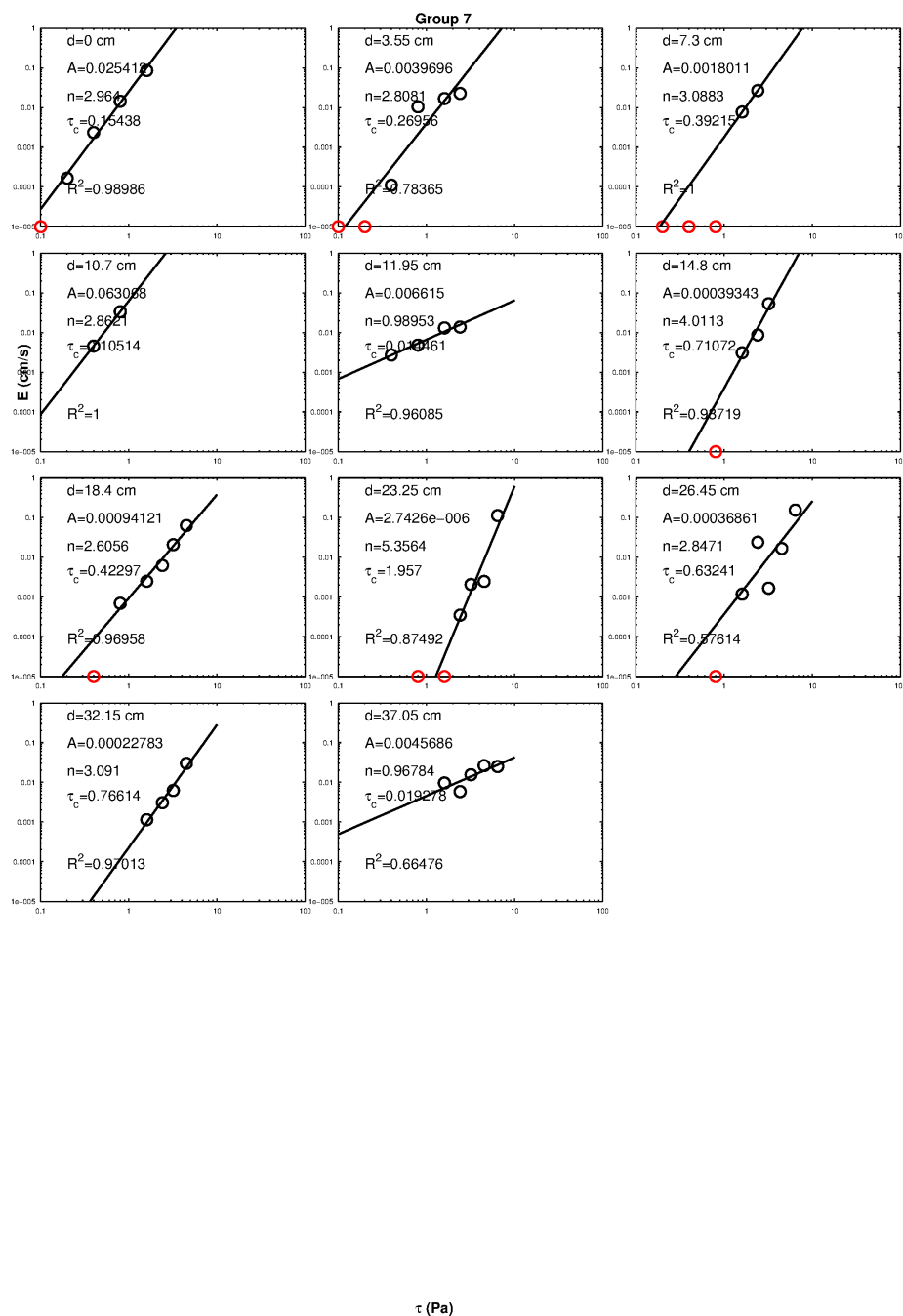


Figure 9. Measured erosion rate as function of shear stress for Core 04A

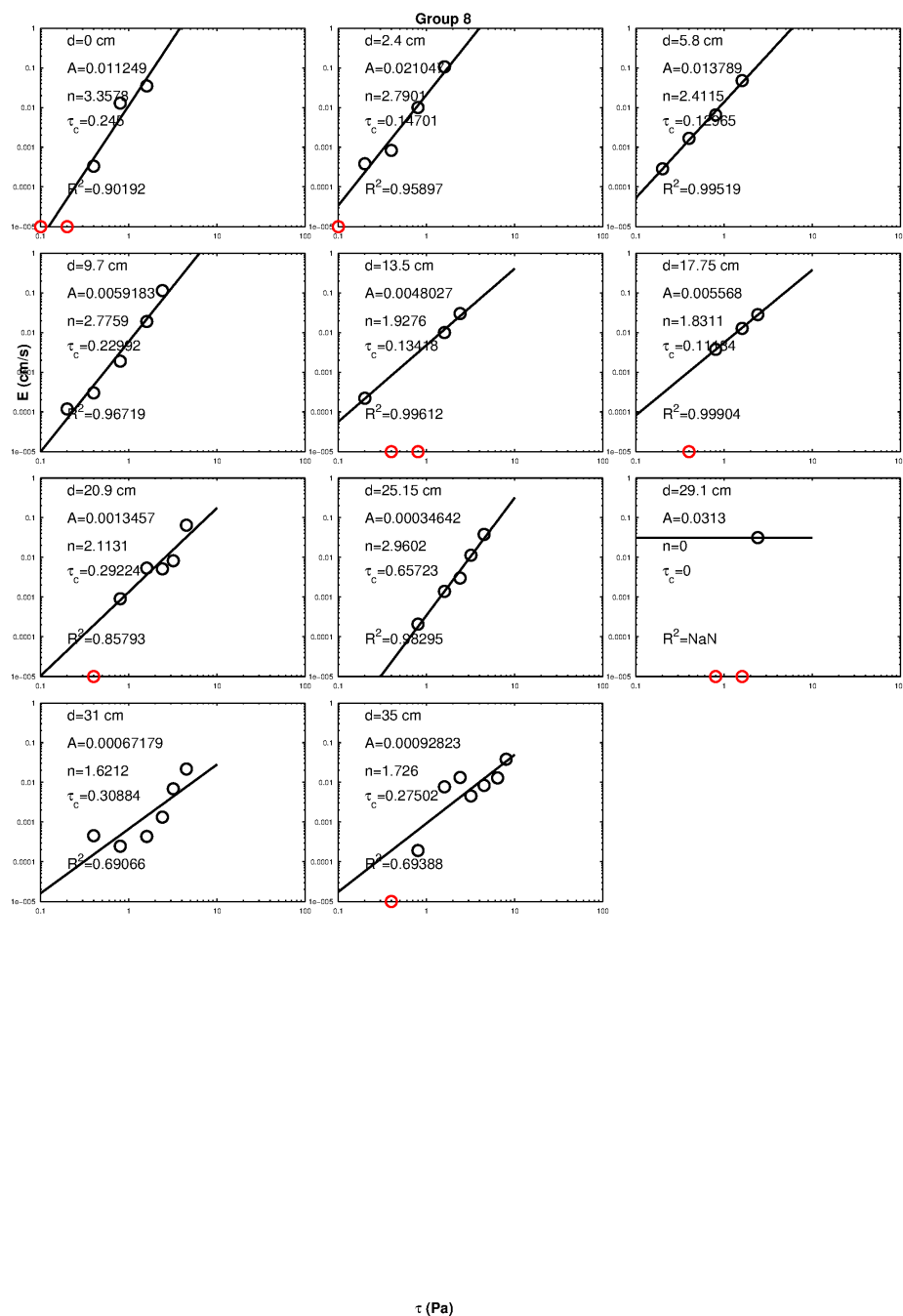


Figure 10. Measured erosion rate as function of shear stress for Core 04B

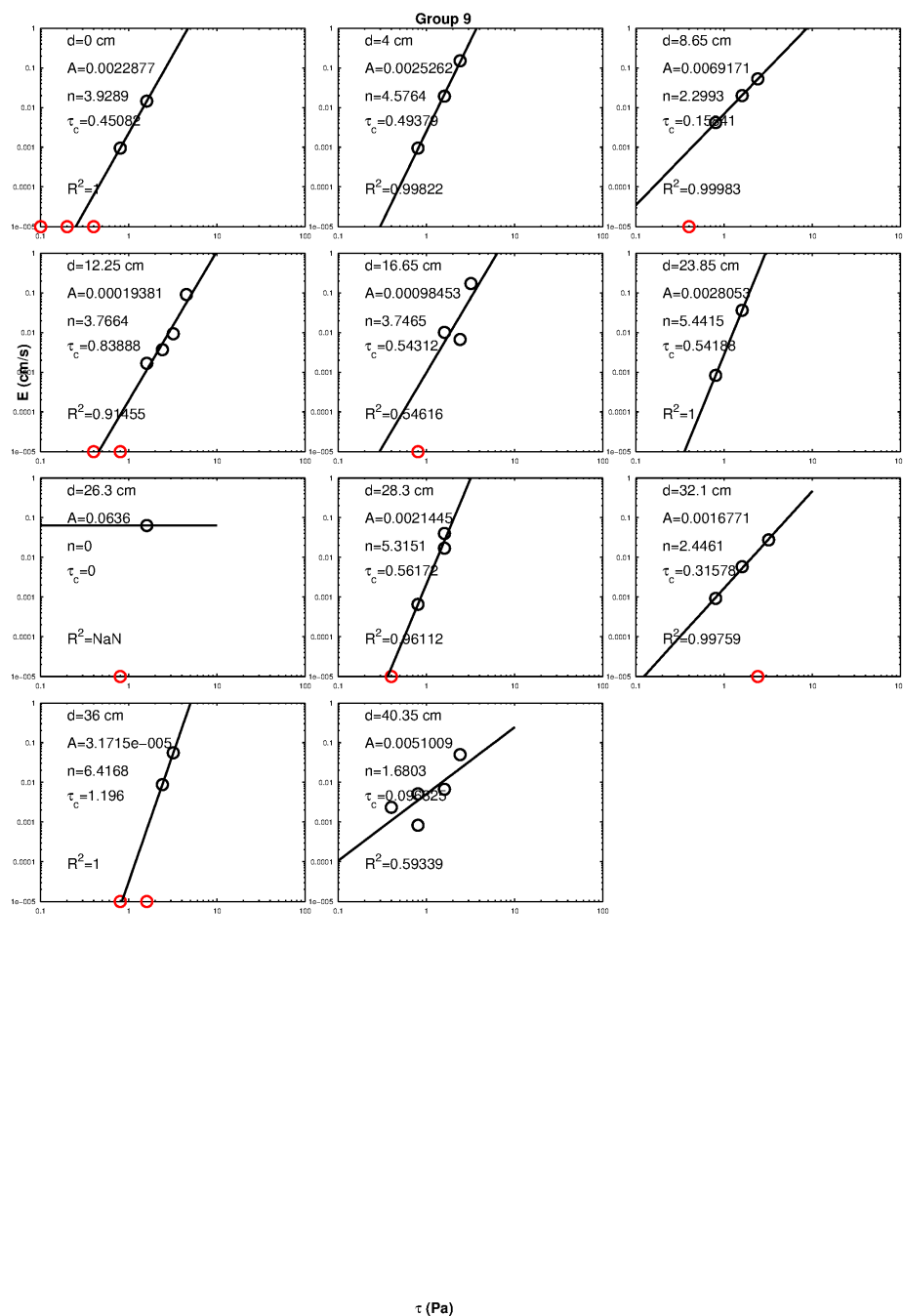


Figure 11. Measured erosion rate as function of shear stress for Core 05A

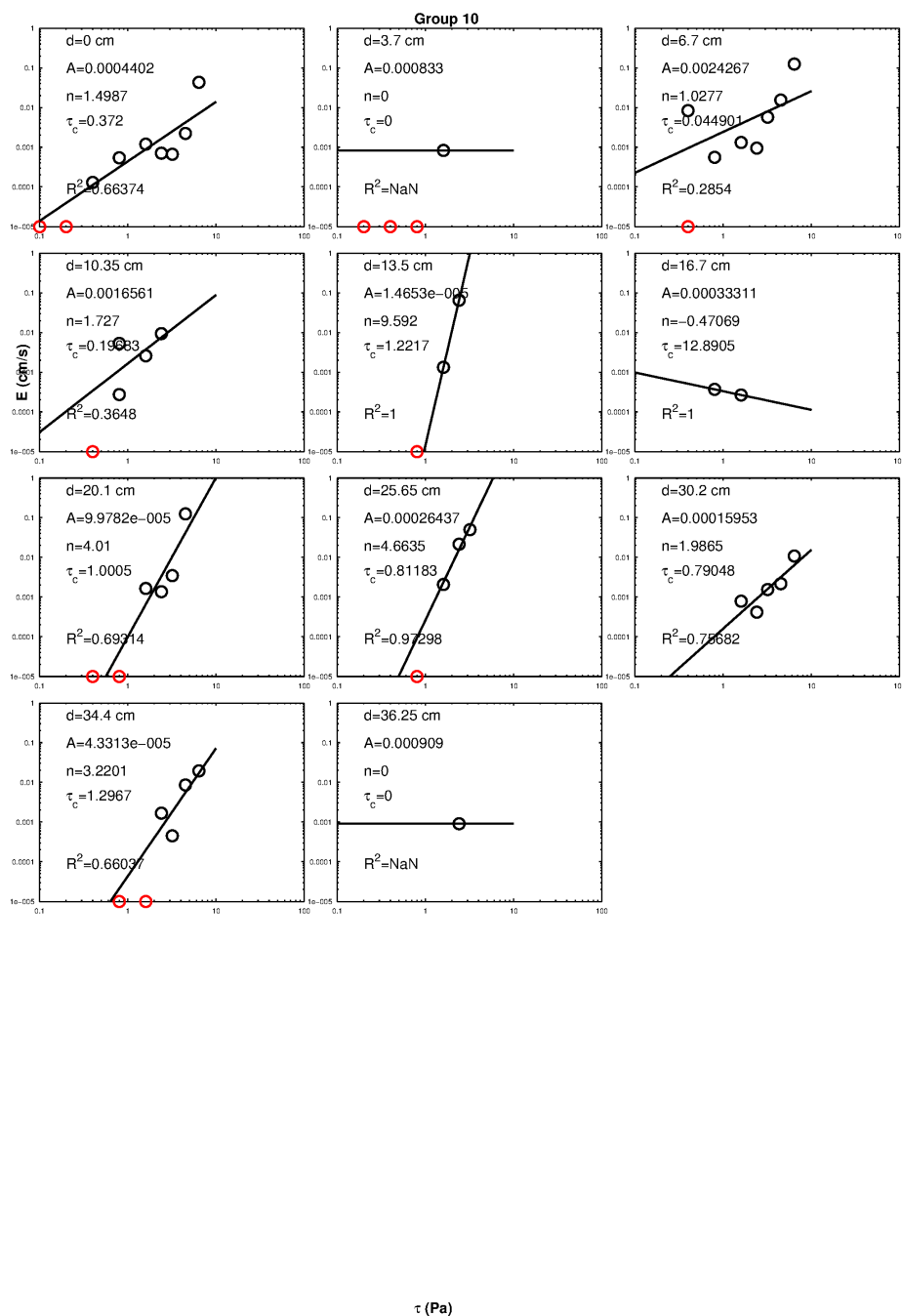


Figure 12. Measured erosion rate as function of shear stress for Core 05B

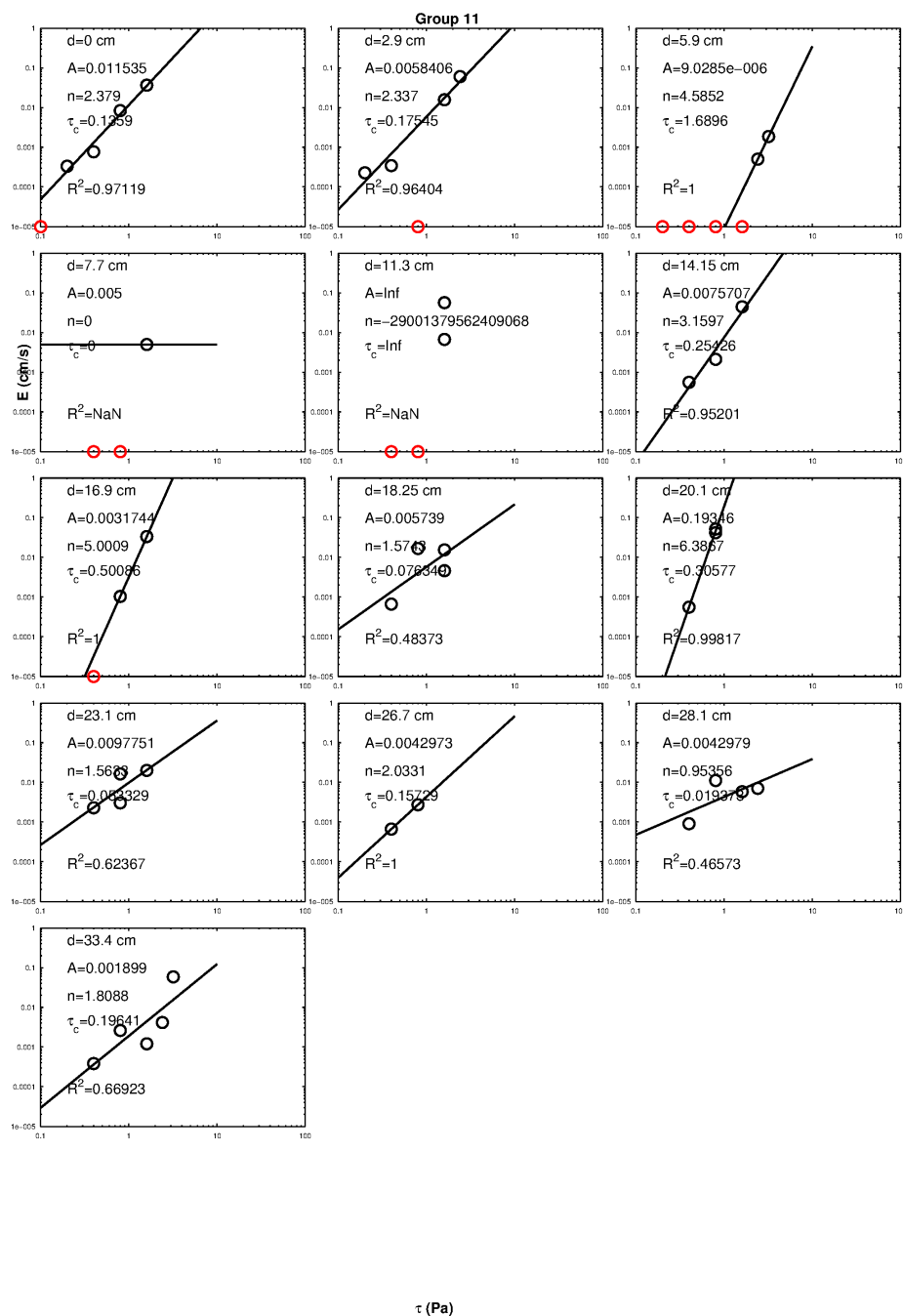


Figure 13. Measured erosion rate as function of shear stress for Core 06A

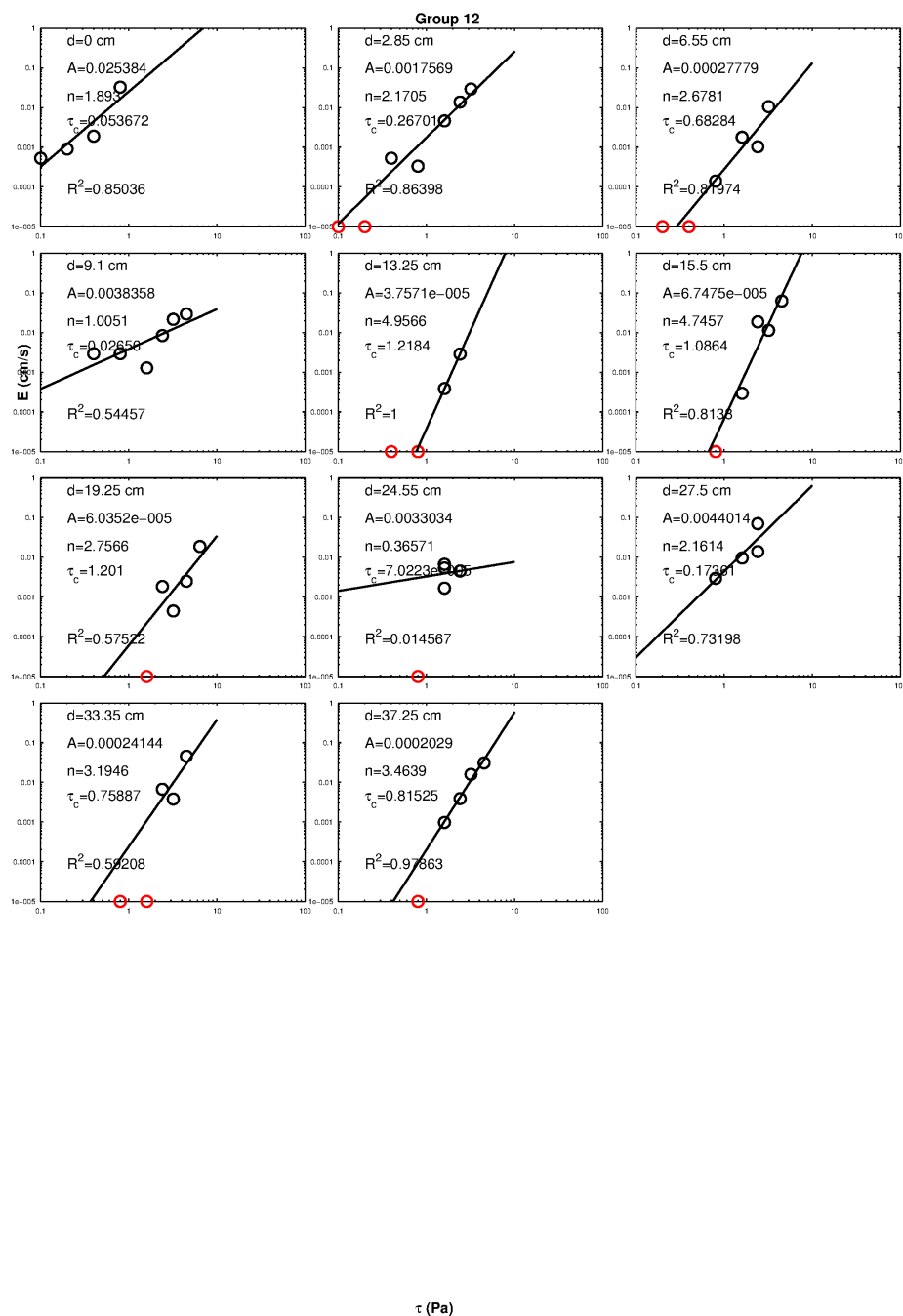


Figure 14. Measured erosion rate as function of shear stress for Core 06B

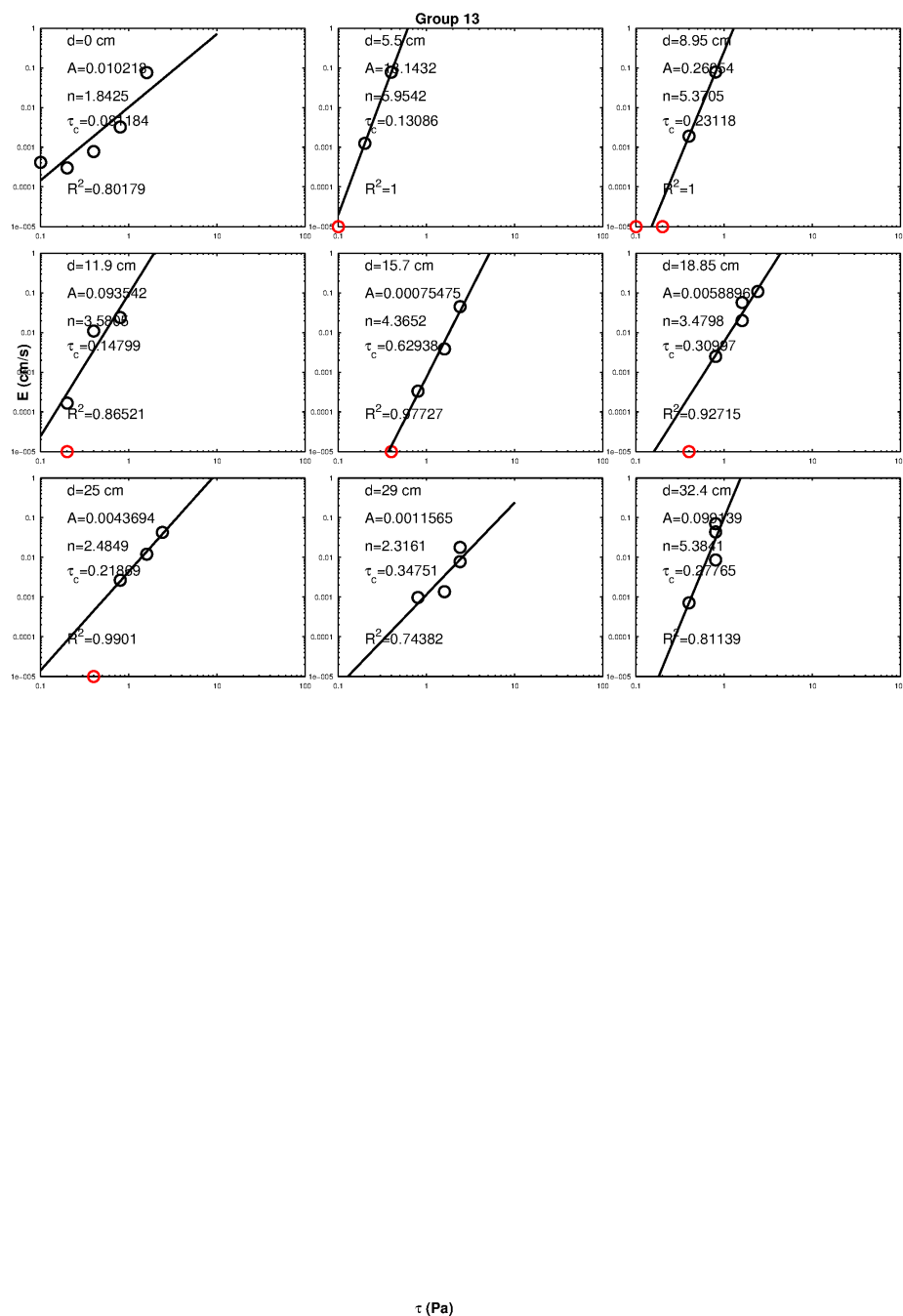


Figure 15. Measured erosion rate as function of shear stress for Core 07A

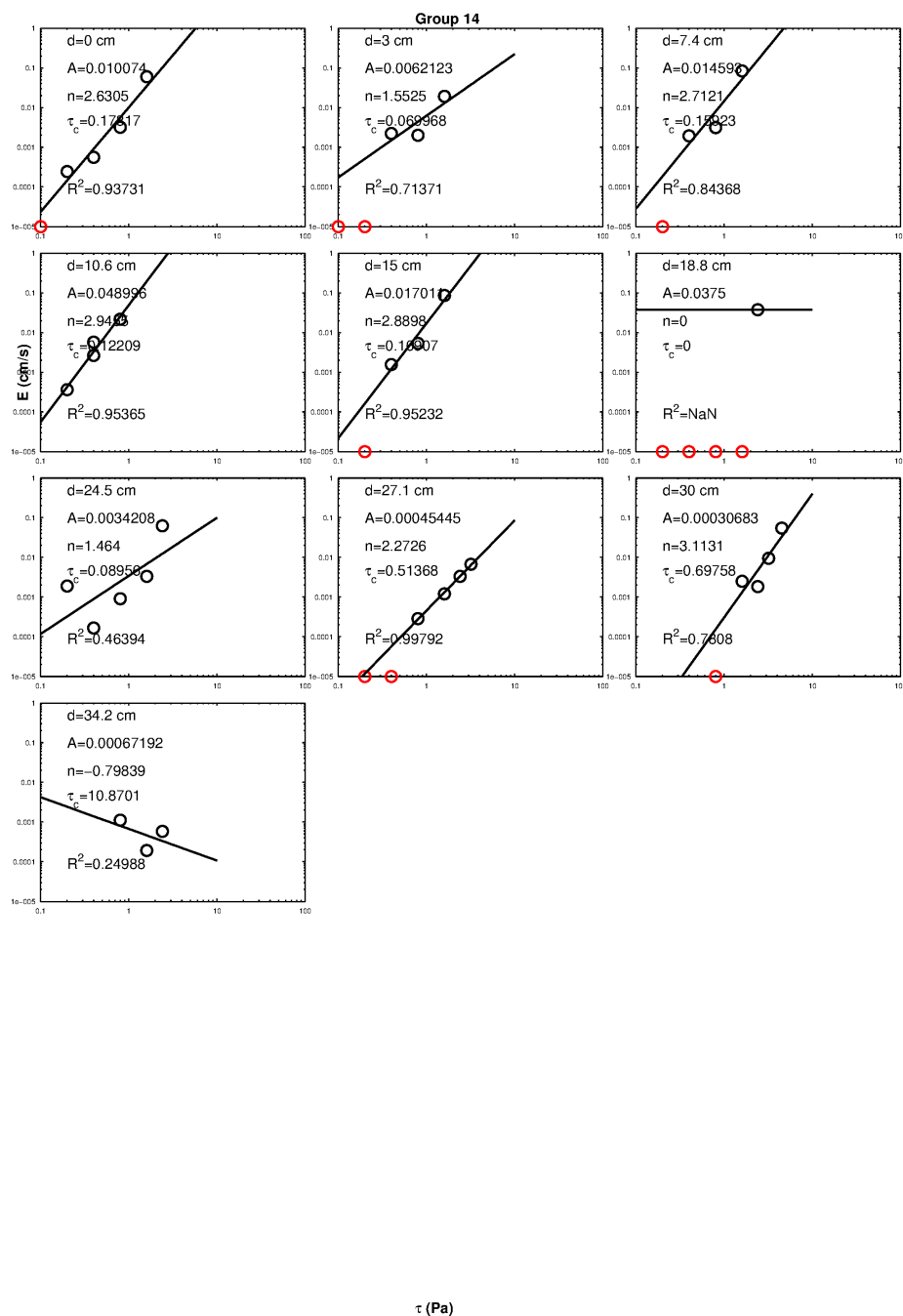


Figure 16. Measured erosion rate as function of shear stress for Core 07B

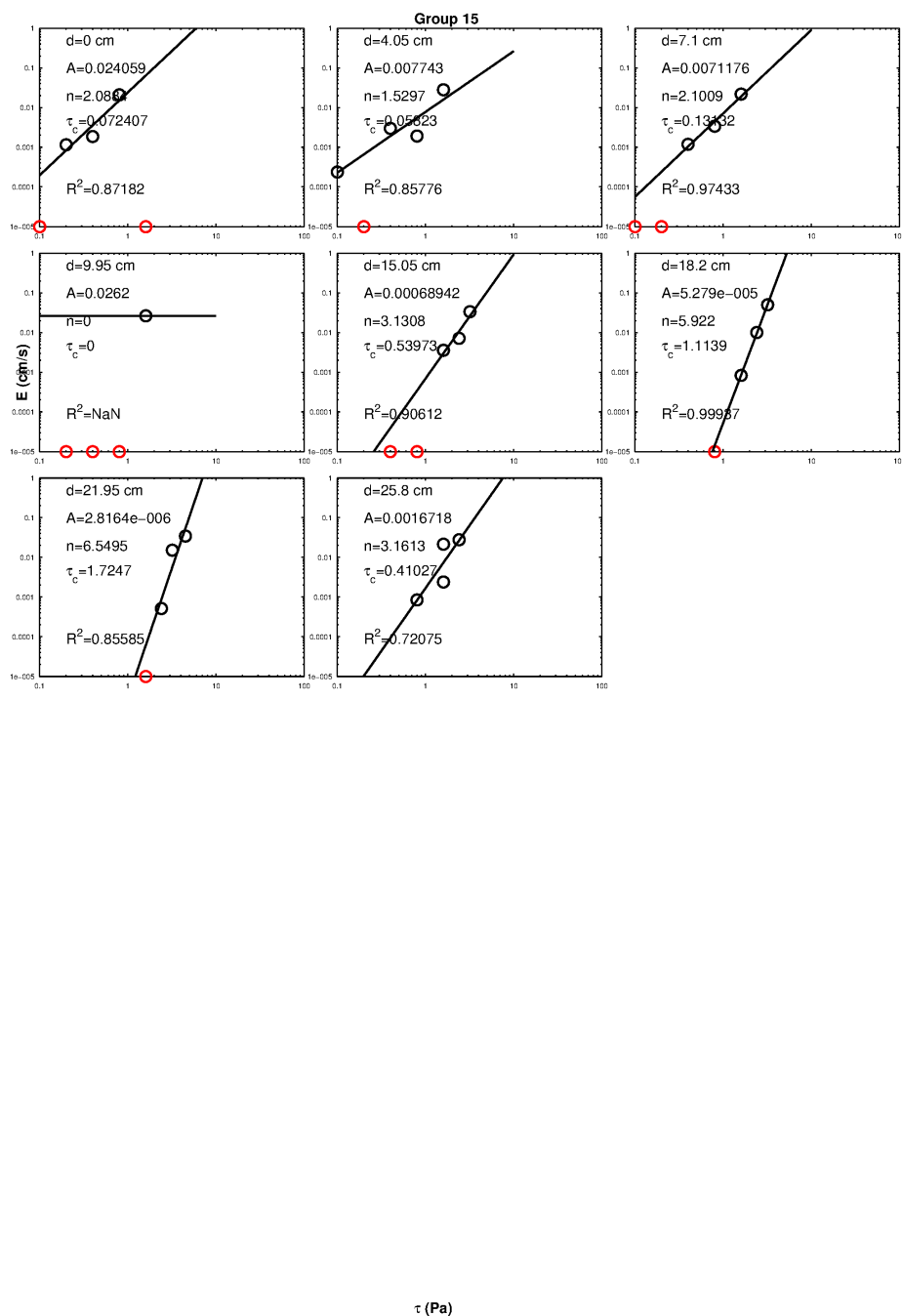


Figure 17. Measured erosion rate as function of shear stress for Core 08A

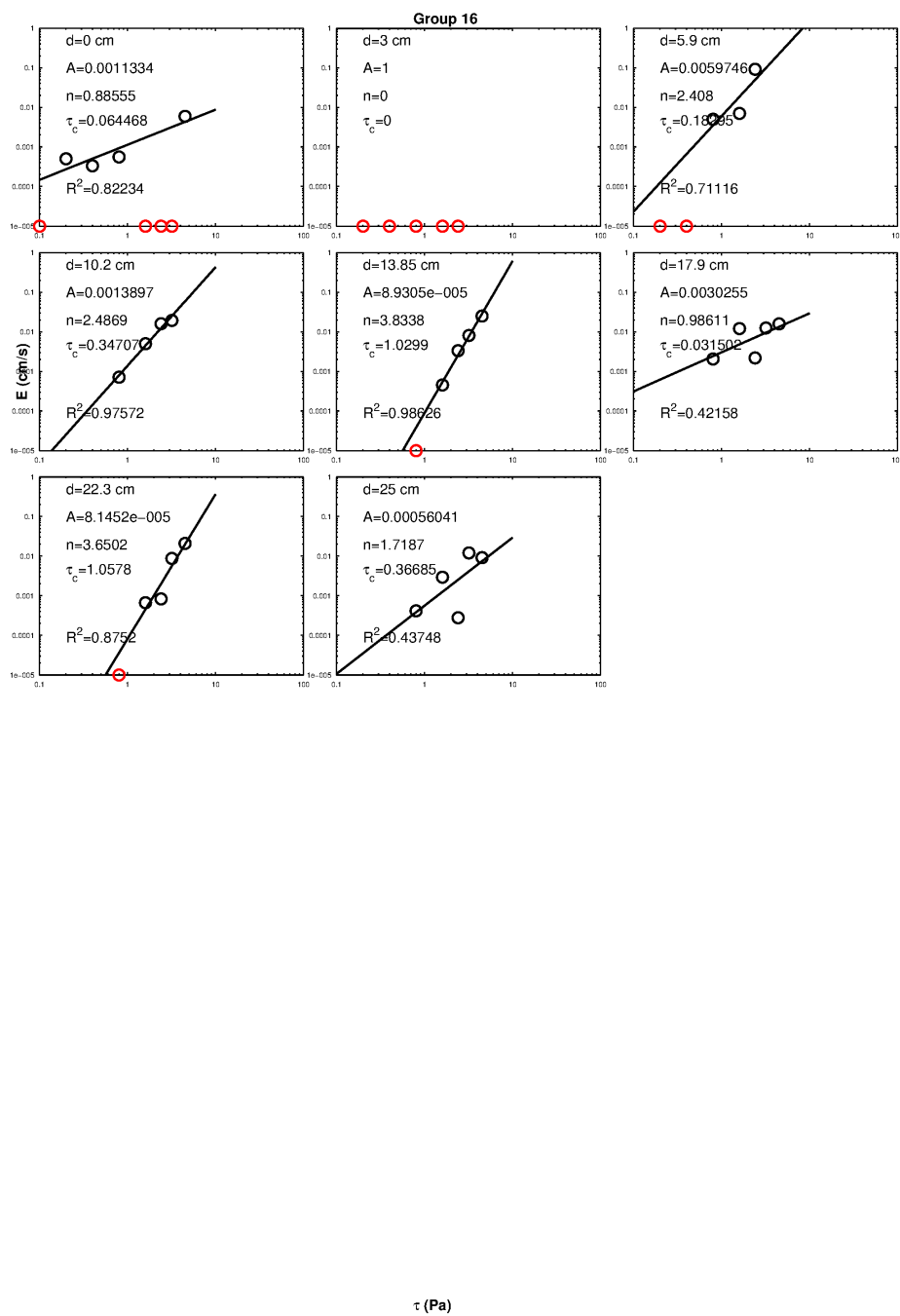


Figure 18. Measured erosion rate as function of shear stress for Core 08B

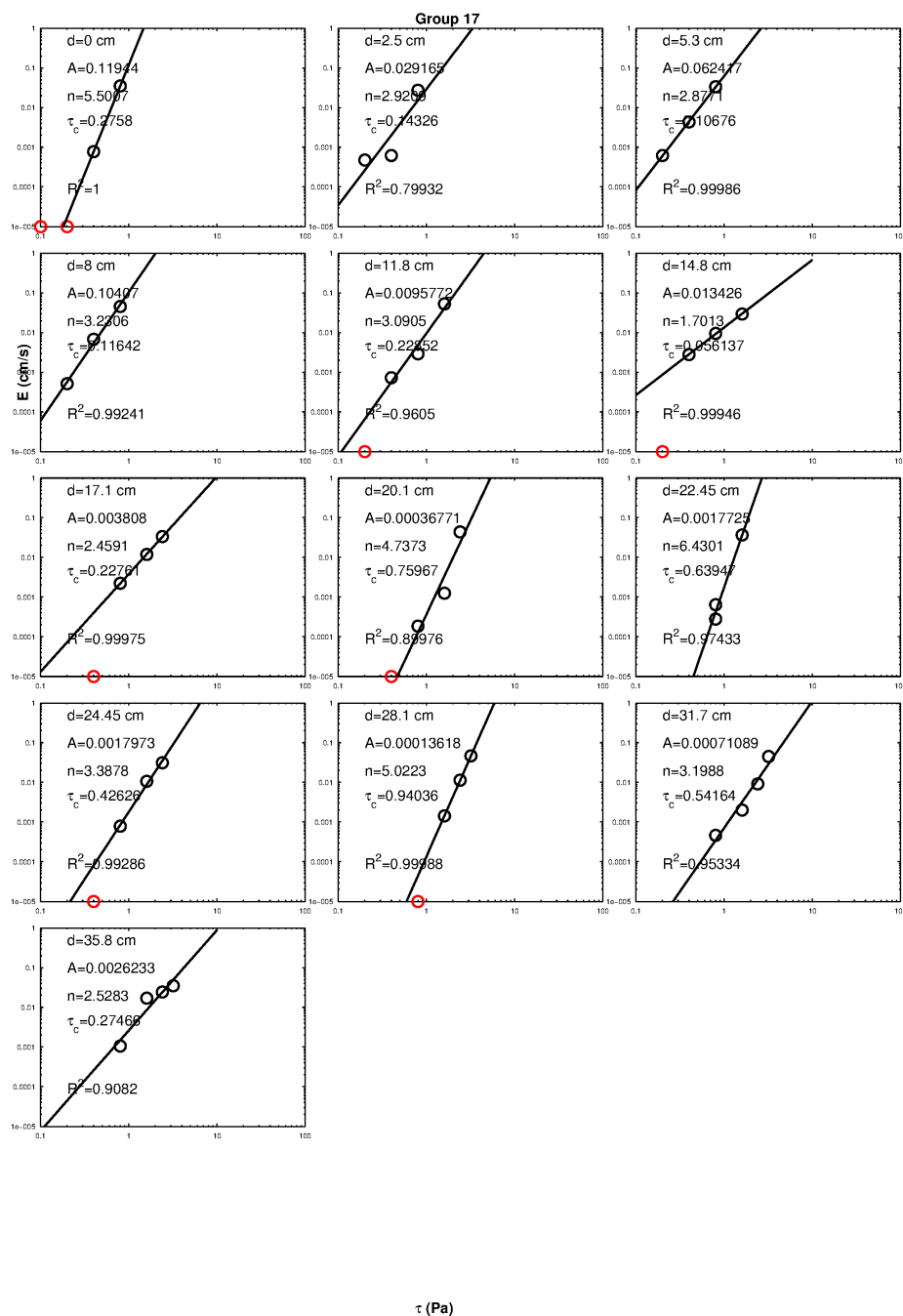


Figure 19. Measured erosion rate as function of shear stress for Core 09A

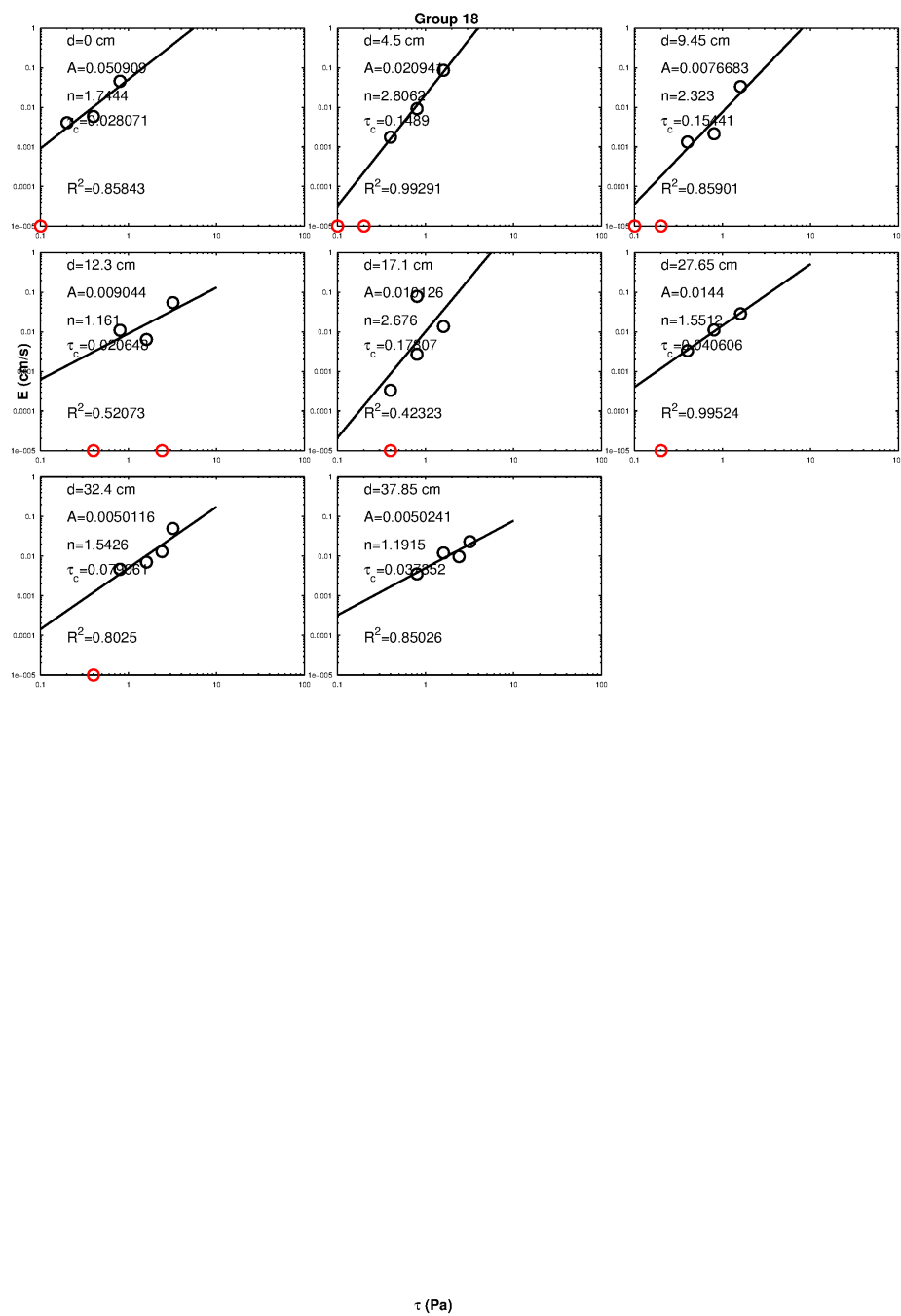


Figure 20. Measured erosion rate as function of shear stress for Core 09B

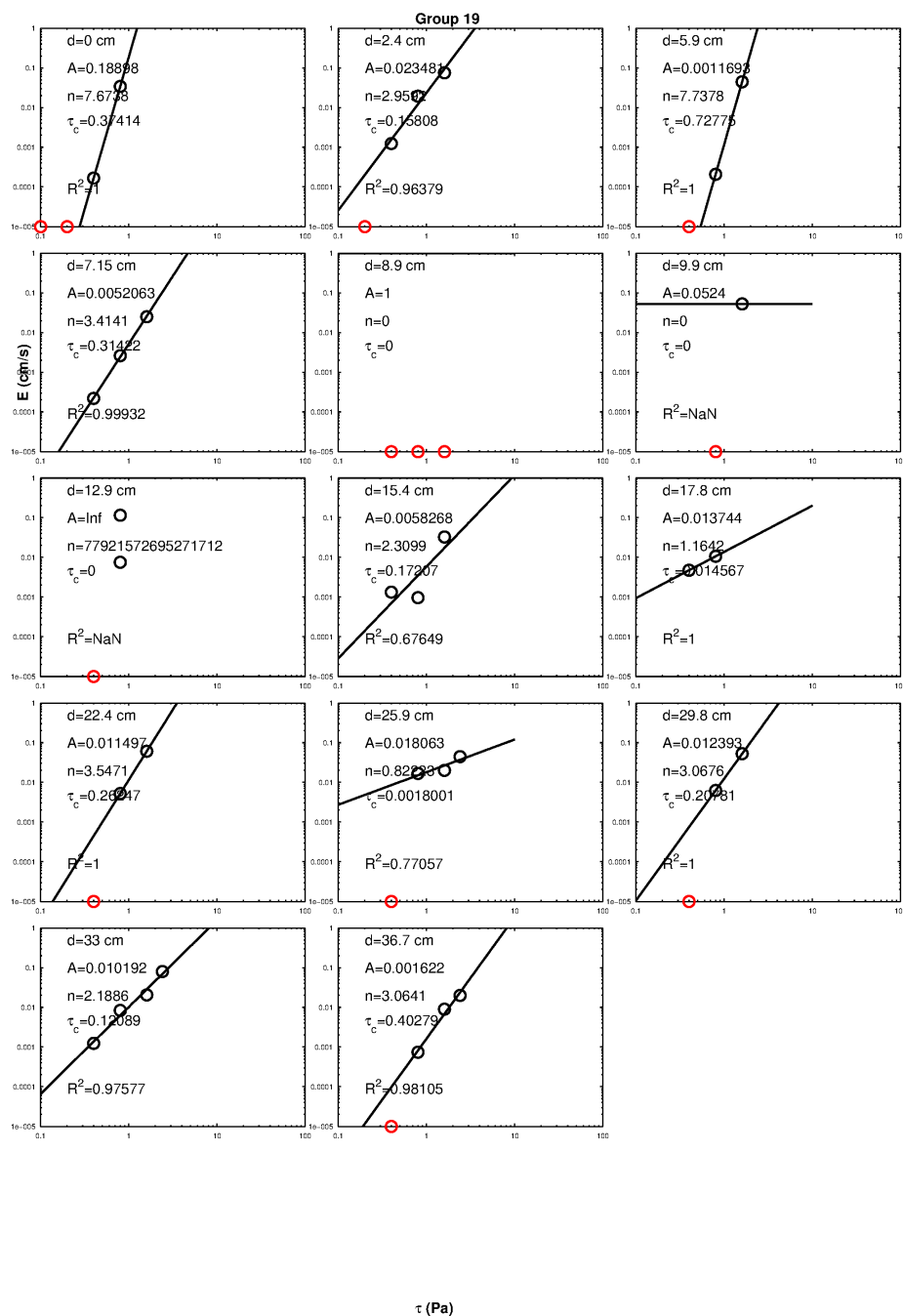


Figure 21. Measured erosion rate as function of shear stress for Core 11A

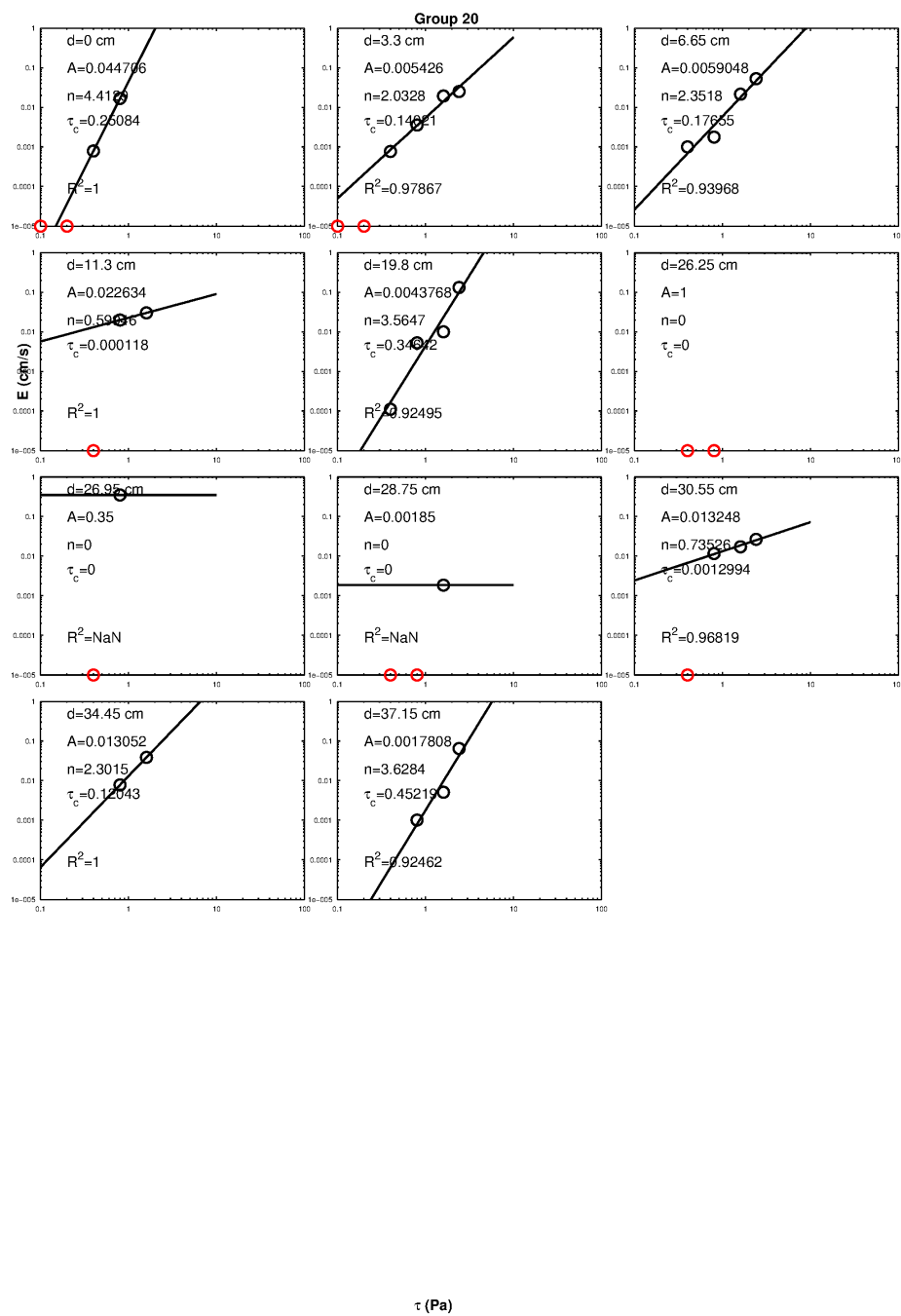


Figure 22. Measured erosion rate as function of shear stress for Core 11B

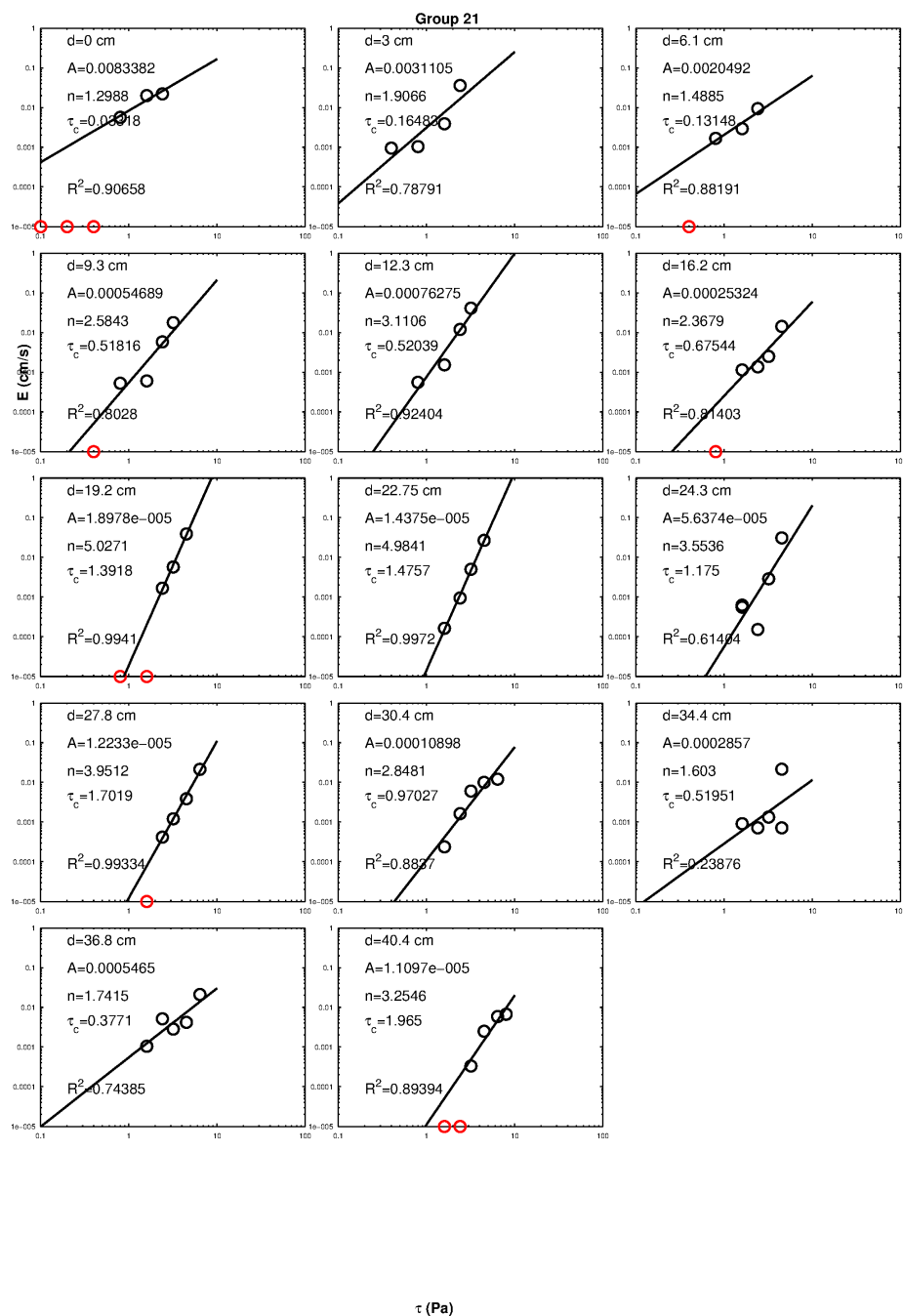


Figure 23. Measured erosion rate as function of shear stress for Core 12A

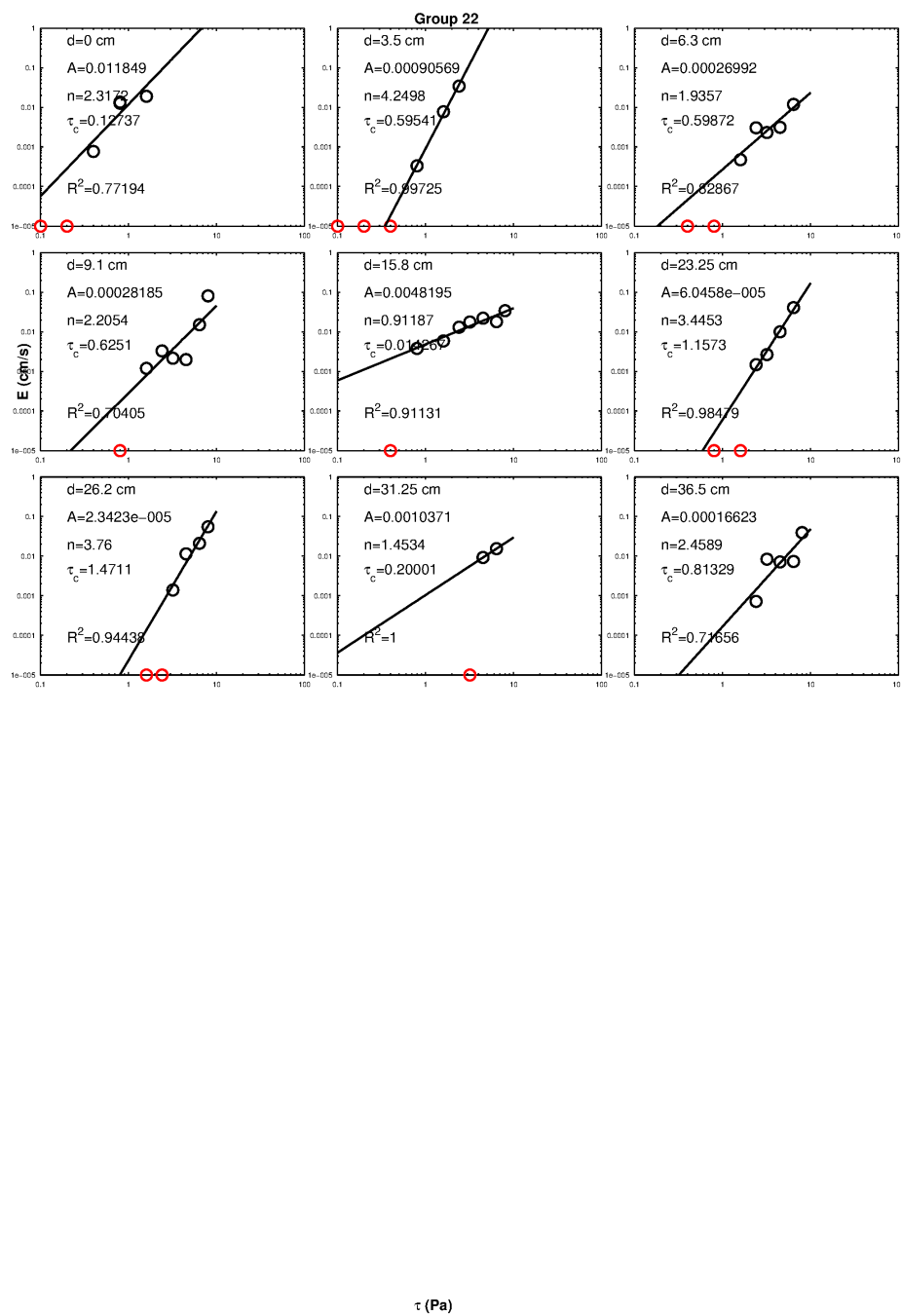


Figure 24. Measured erosion rate as function of shear stress for Core 12B

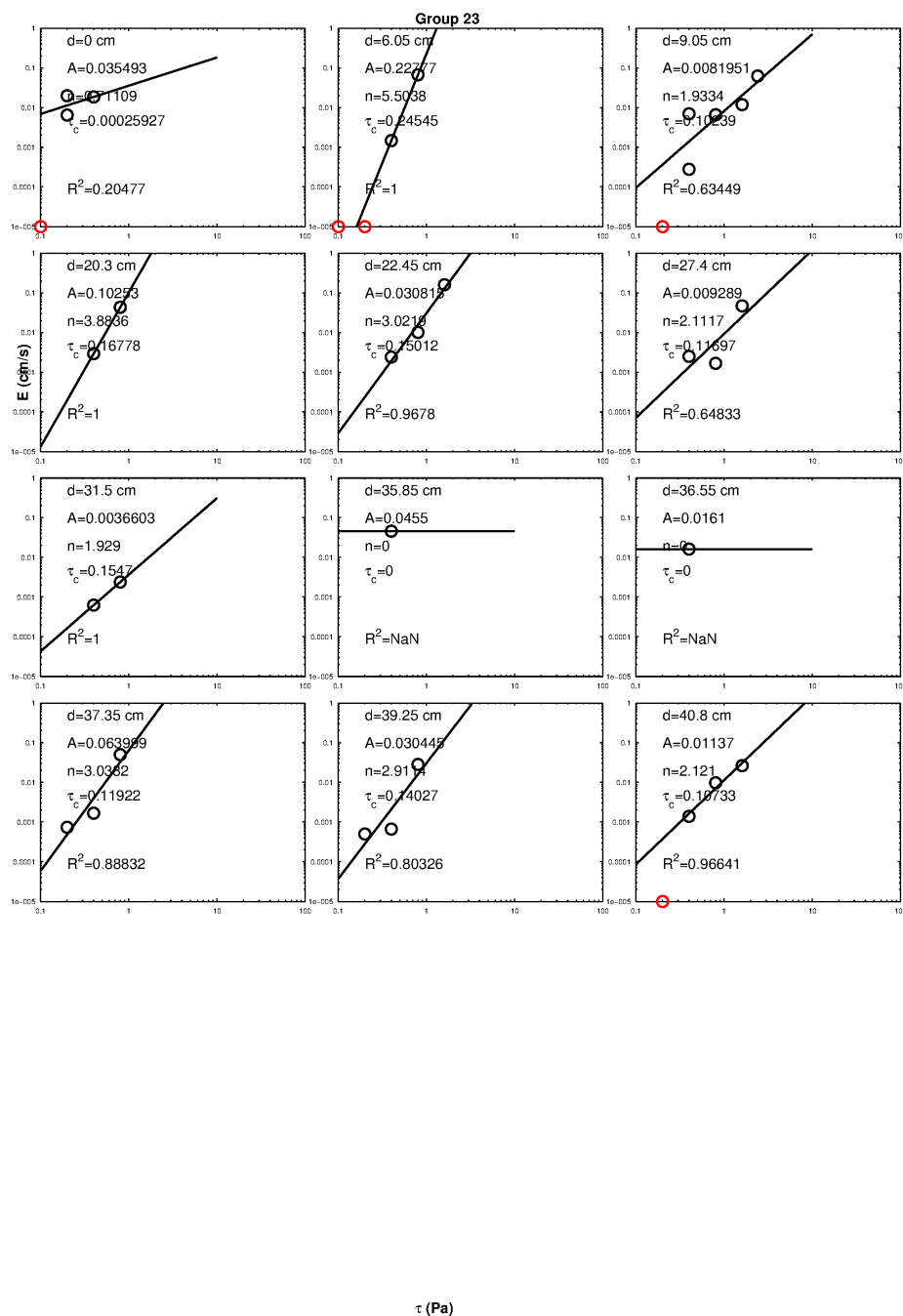


Figure 25. Measured erosion rate as function of shear stress for Core 13A

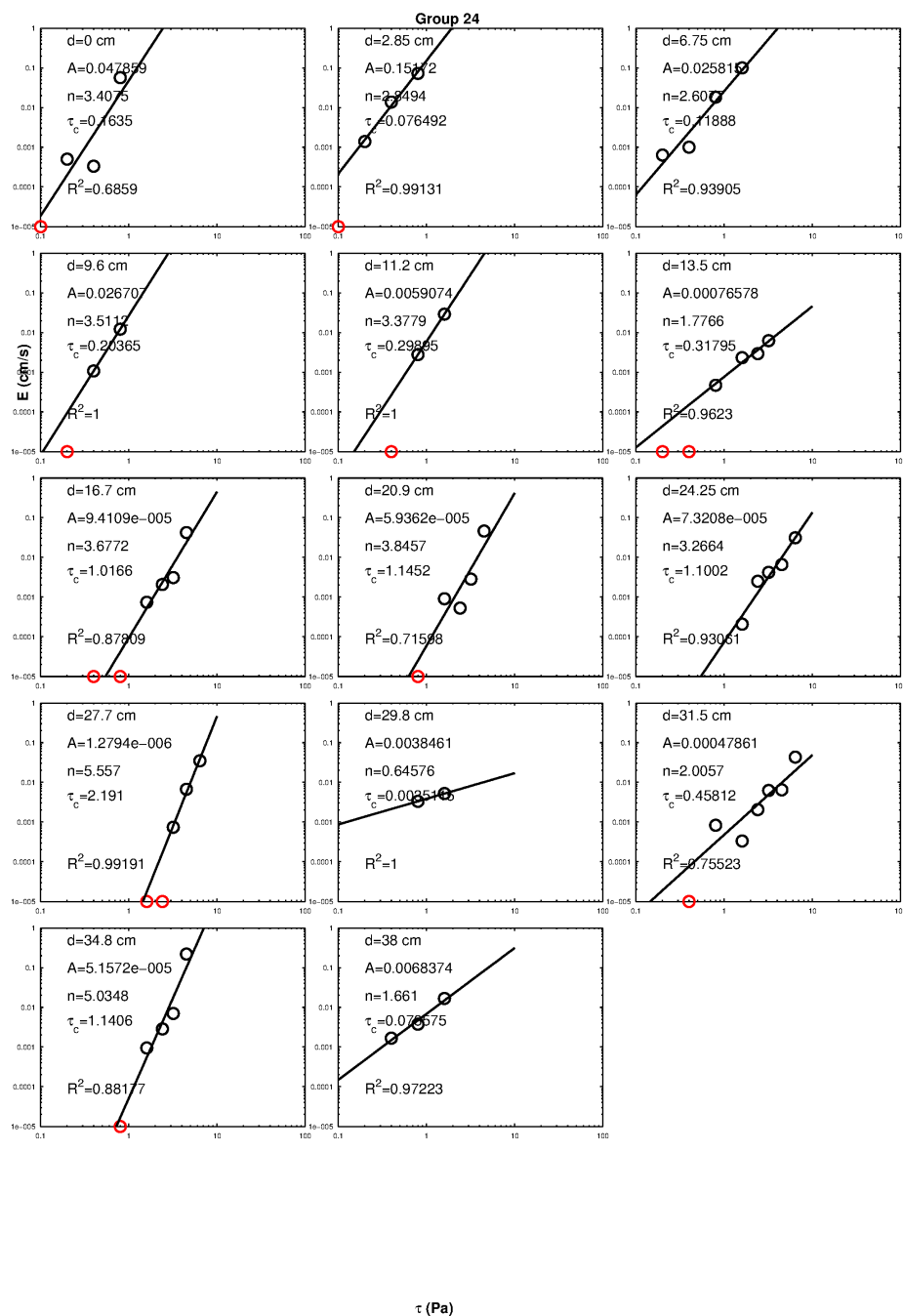


Figure 26. Measured erosion rate as function of shear stress for Core 13B

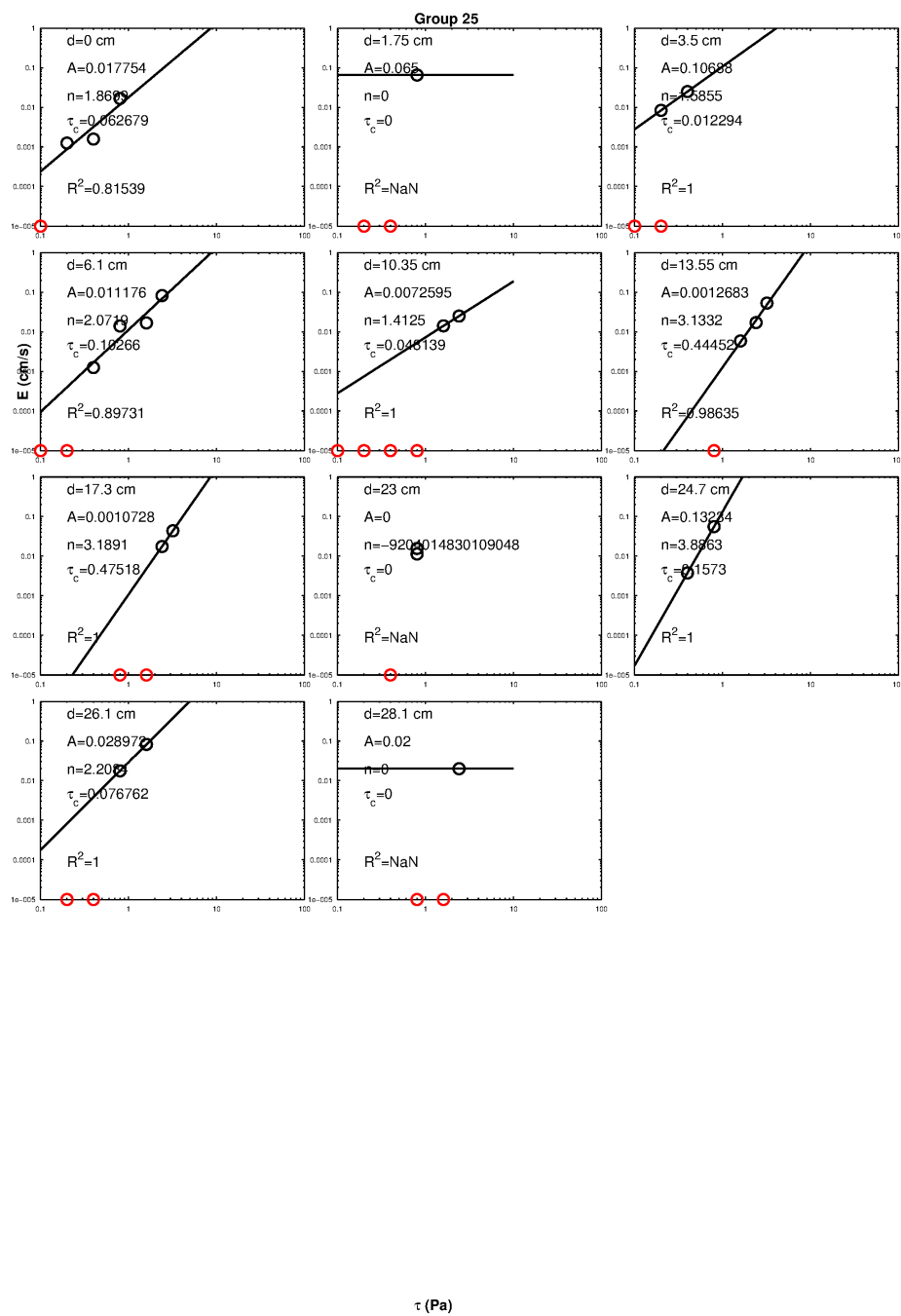


Figure 27. Measured erosion rate as function of shear stress for Core 14A

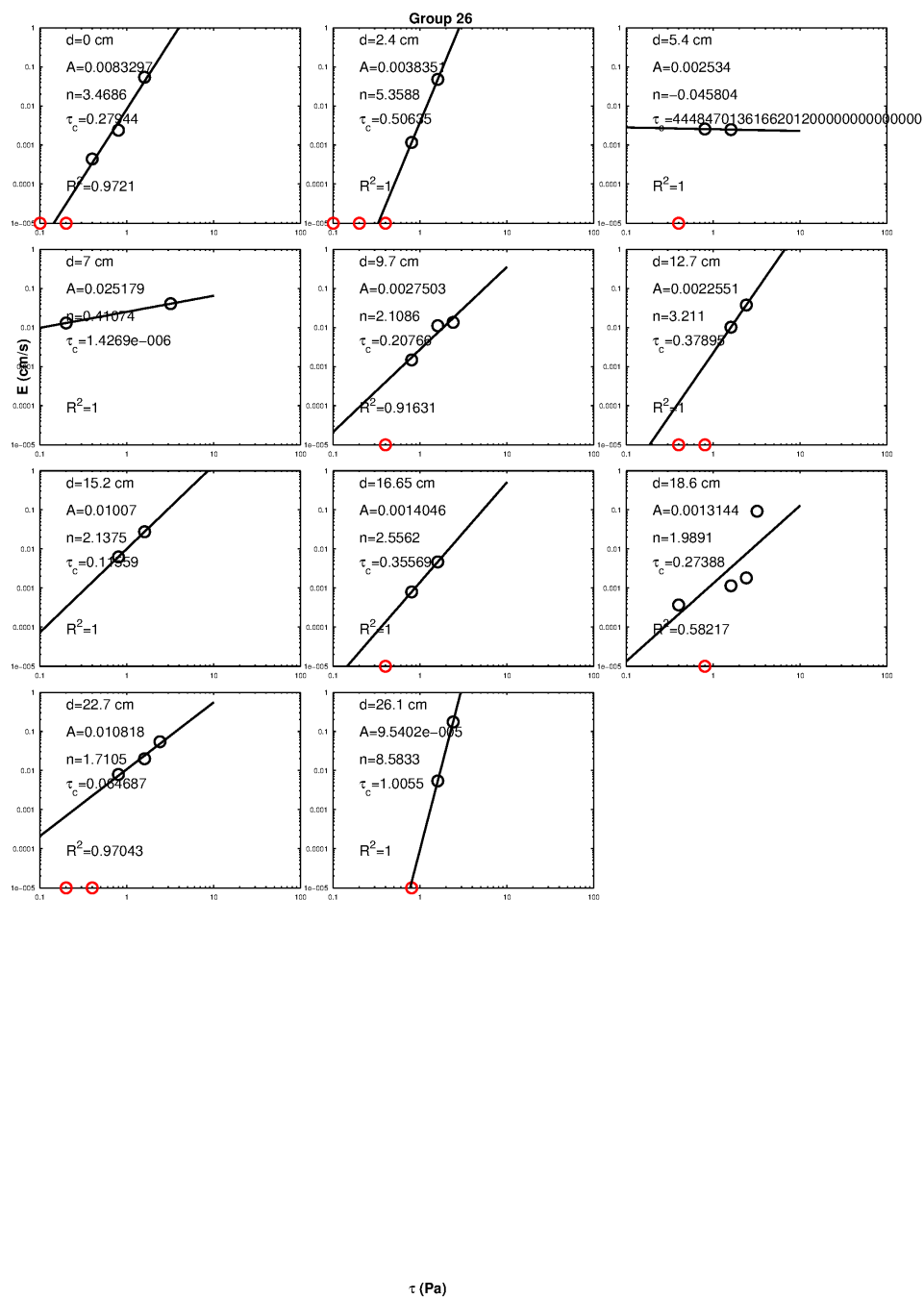


Figure 28. Measured erosion rate as function of shear stress for Core 14B

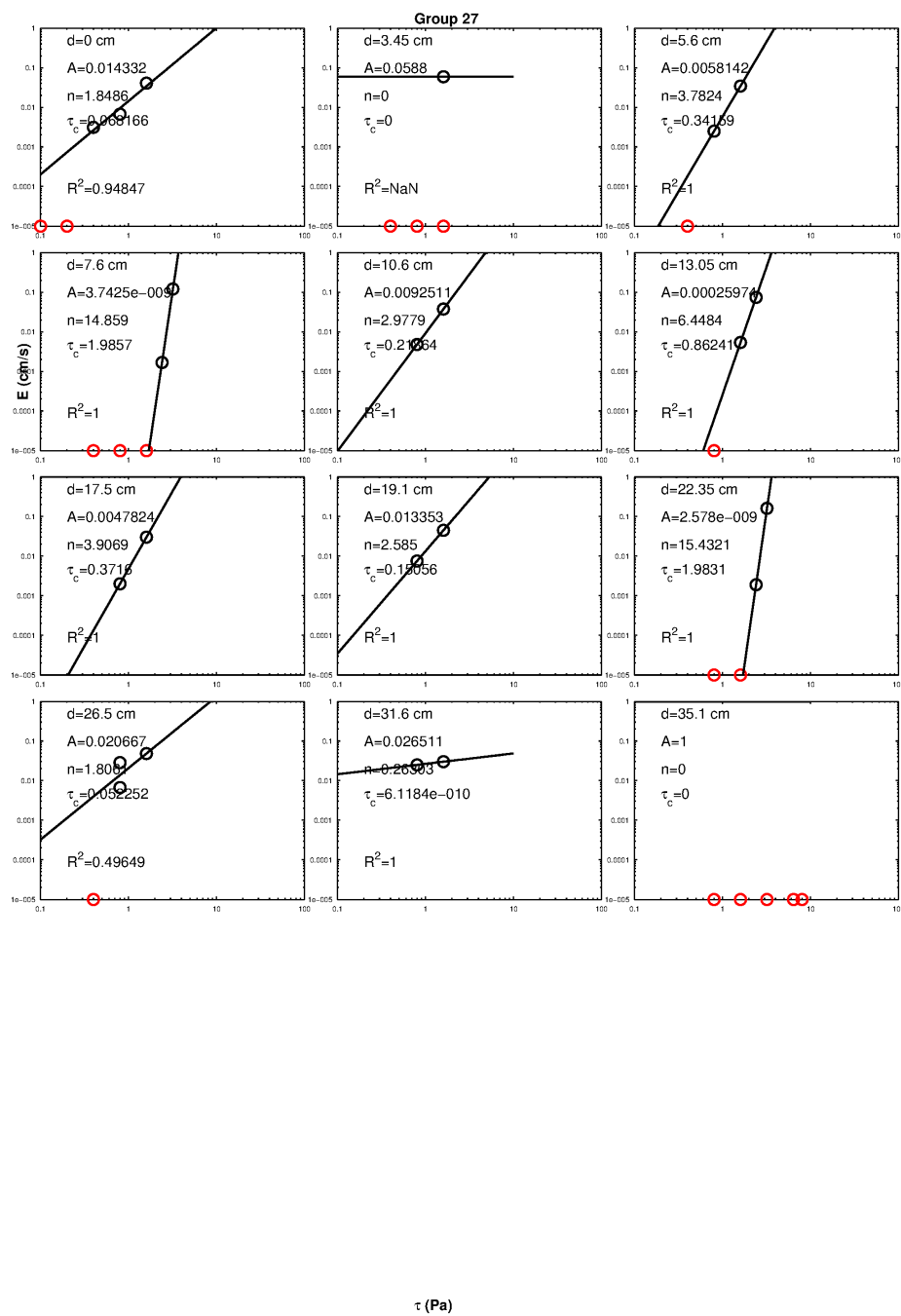


Figure 29. Measured erosion rate as function of shear stress for Core 15A

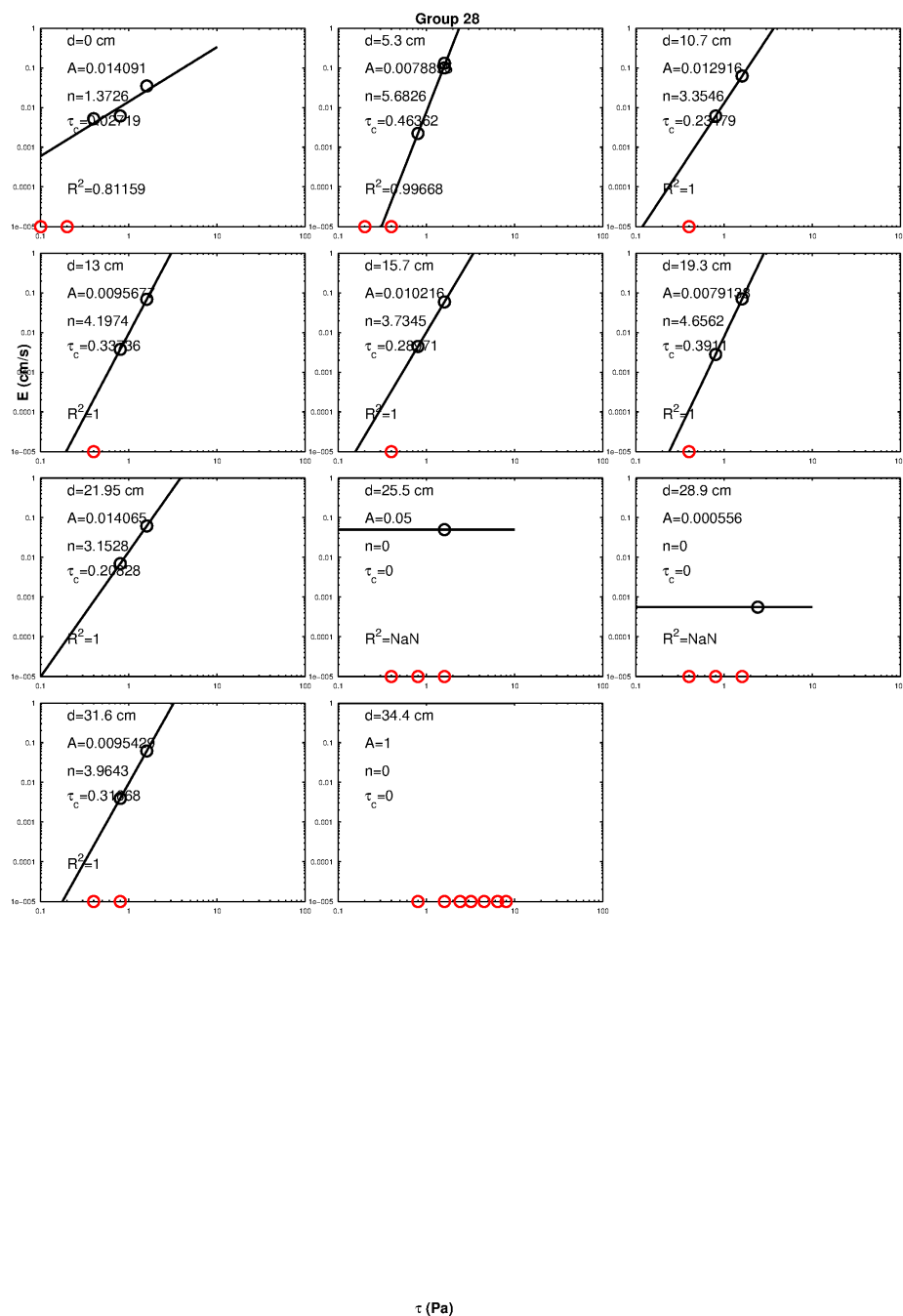


Figure 30. Measured erosion rate as function of shear stress for Core 15B

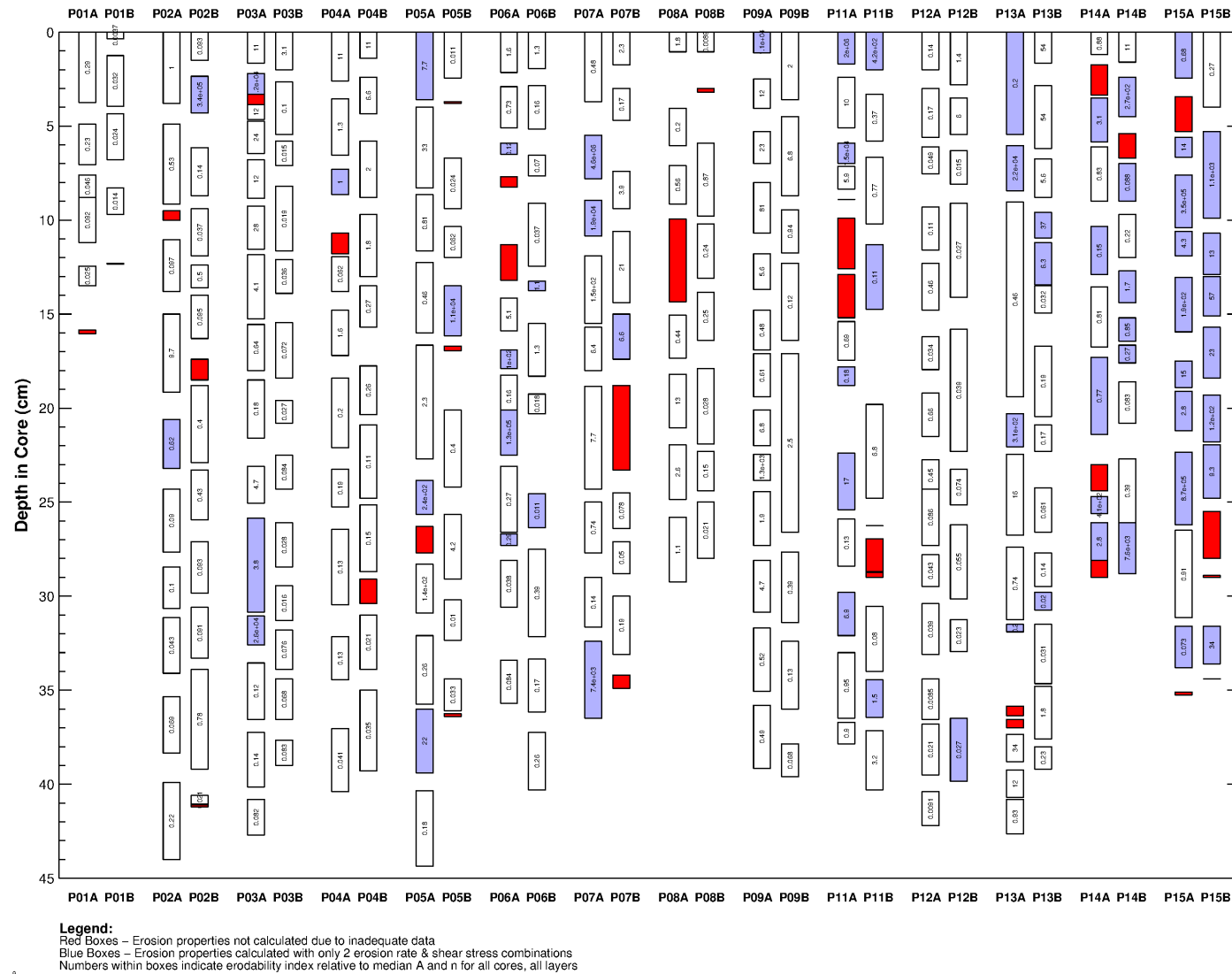


Figure 31. Erodibility index by depth (for each core) relative to entire dataset.

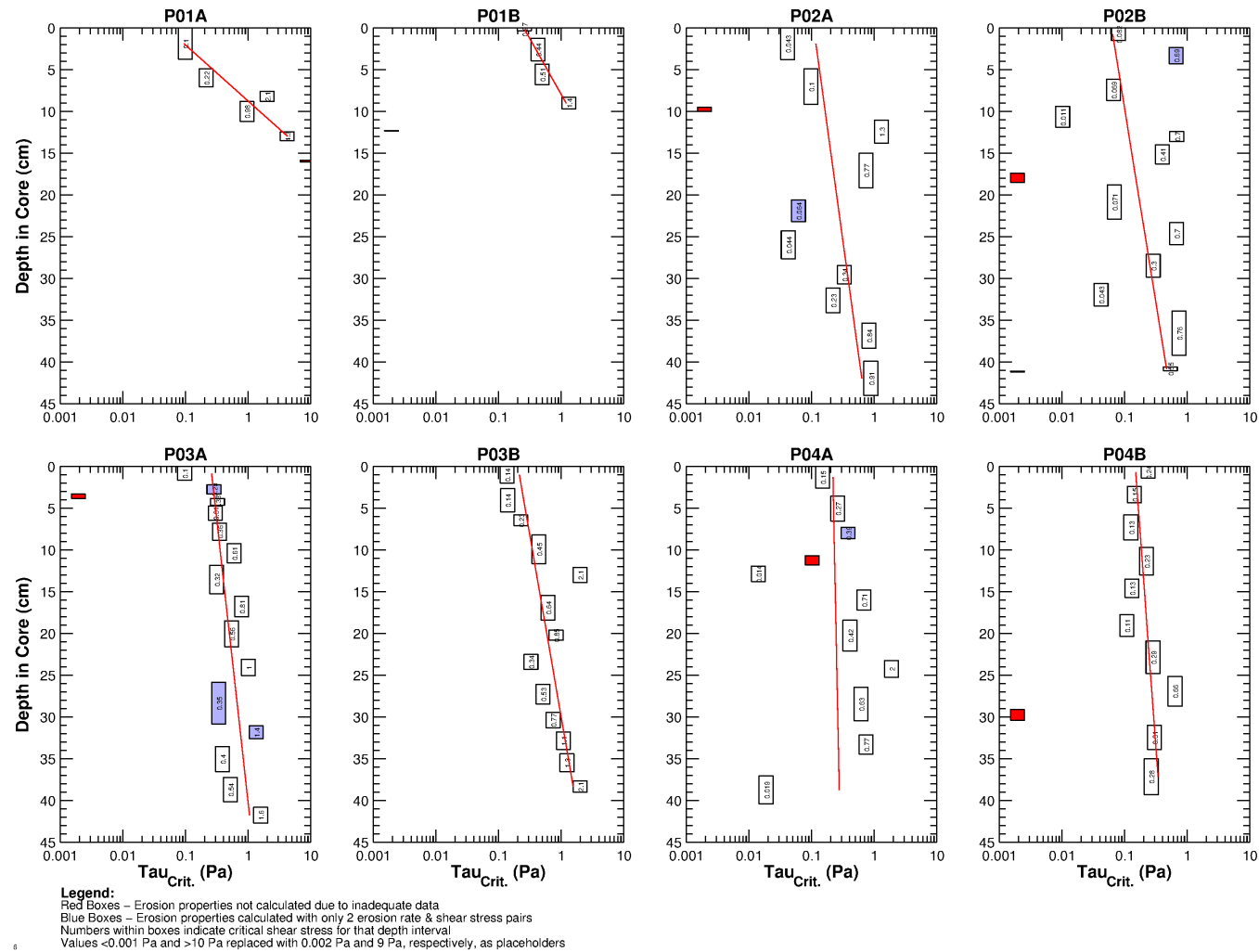


Figure 32. Depth-profile of calculated critical shear stress for erosion. Red line indicates a log-regression using data from depth-intervals with more than two pairs of erosion rate and shear stress; used only to indicate the general trend of critical shear stress with depth.

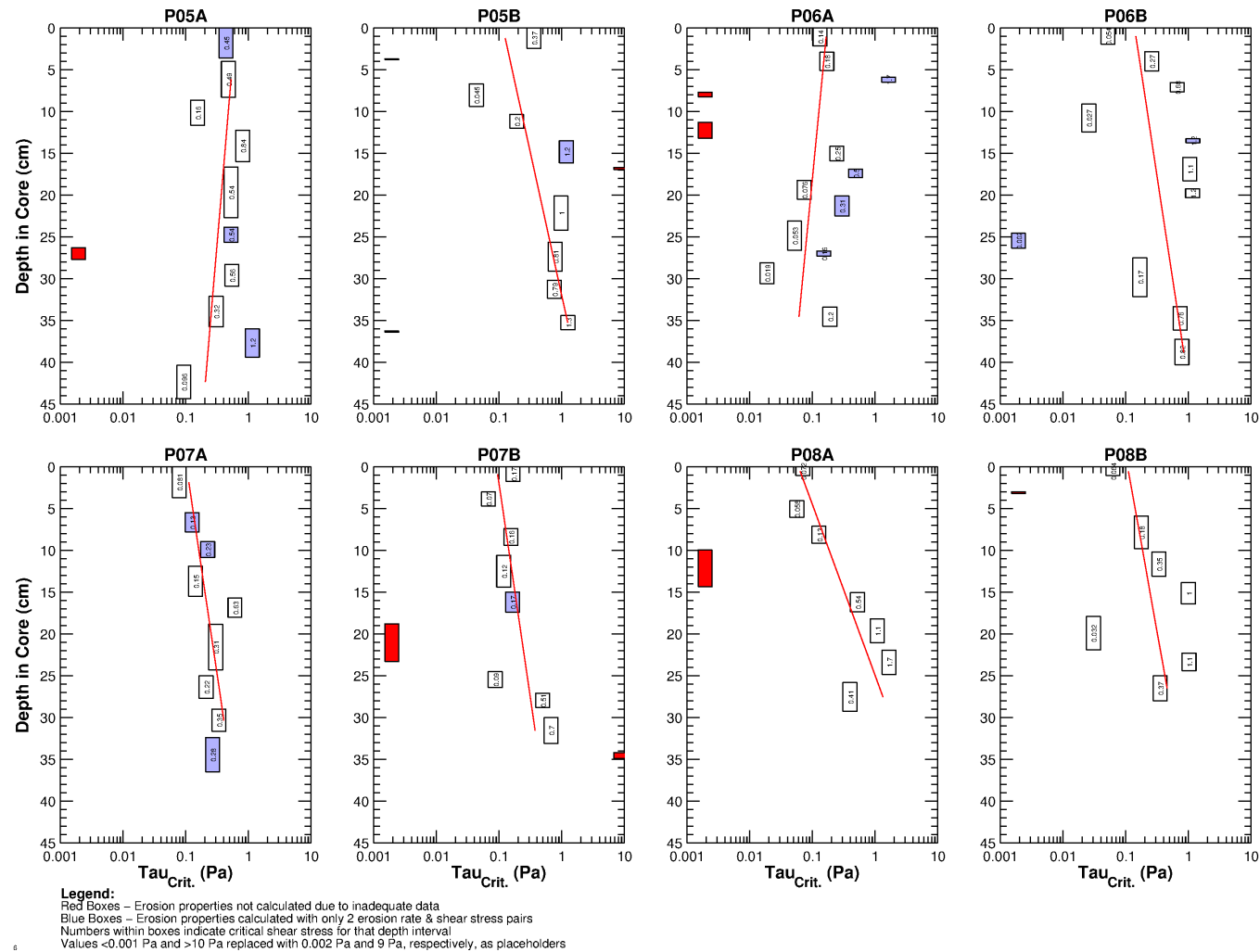


Figure 33. Depth-profile of calculated critical shear stress for erosion (Contd). Red line indicates a log-regression using data from depth-intervals with more than two pairs of erosion rate and shear stress; used only to indicate the general trend of critical shear stress with depth.

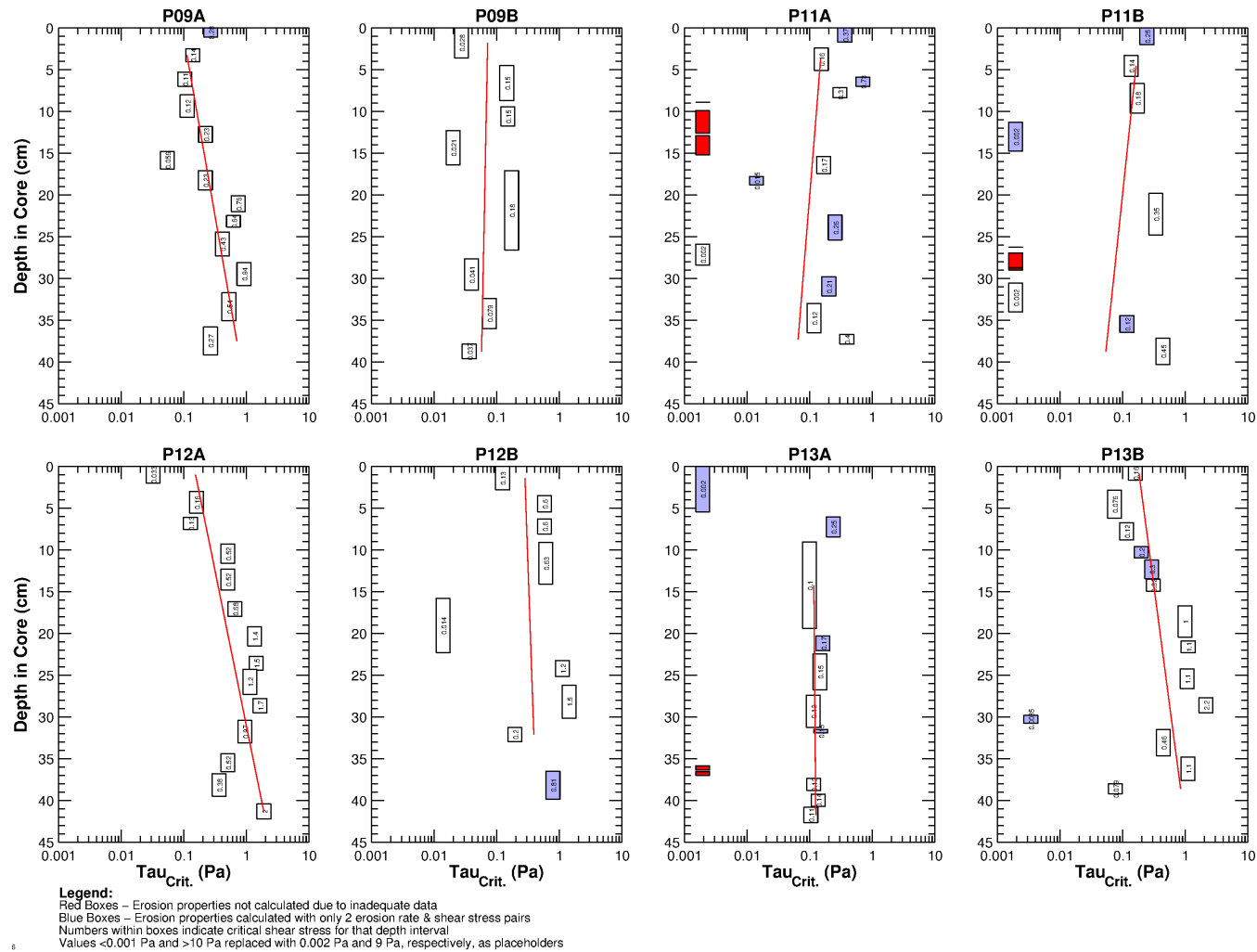


Figure 34. Depth-profile of calculated critical shear stress for erosion (Contd). Red line indicates a log-regression using data from depth-intervals with more than two pairs of erosion rate and shear stress; used only to indicate the general trend of critical shear stress with depth.

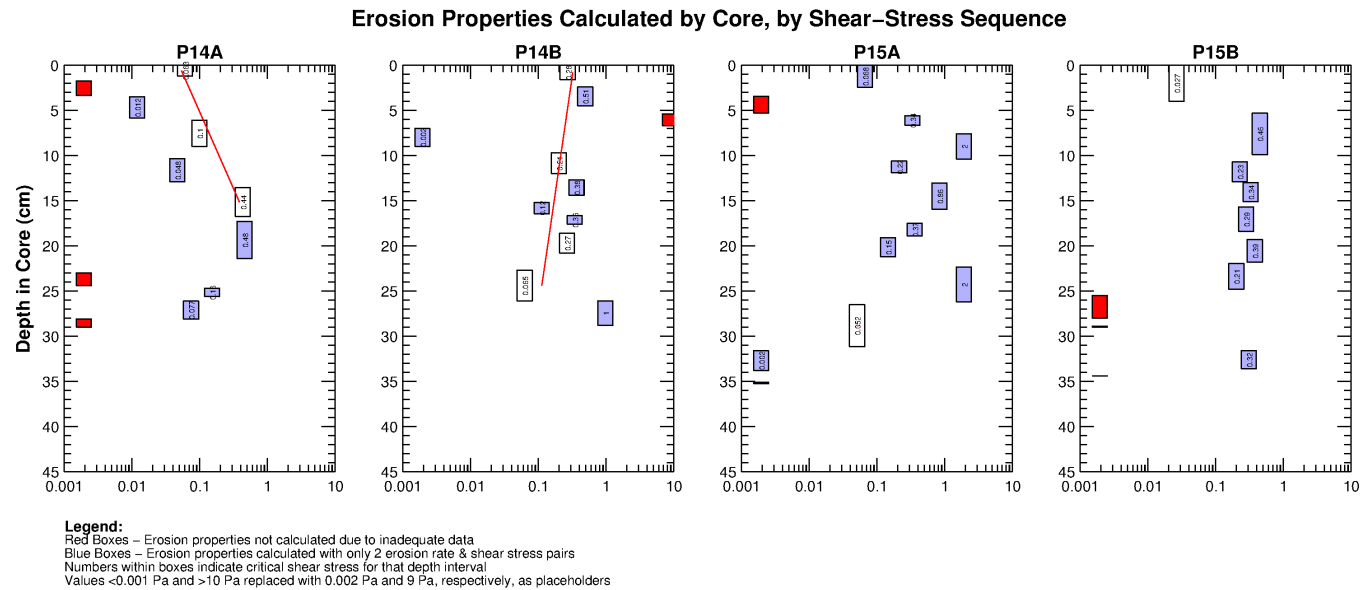


Figure 35. Depth-profile of calculated critical shear stress for erosion (Contd). Red line indicates a log-regression using data from depth-intervals with more than two pairs of erosion rate and shear stress; used only to indicate the general trend of critical shear stress with depth.

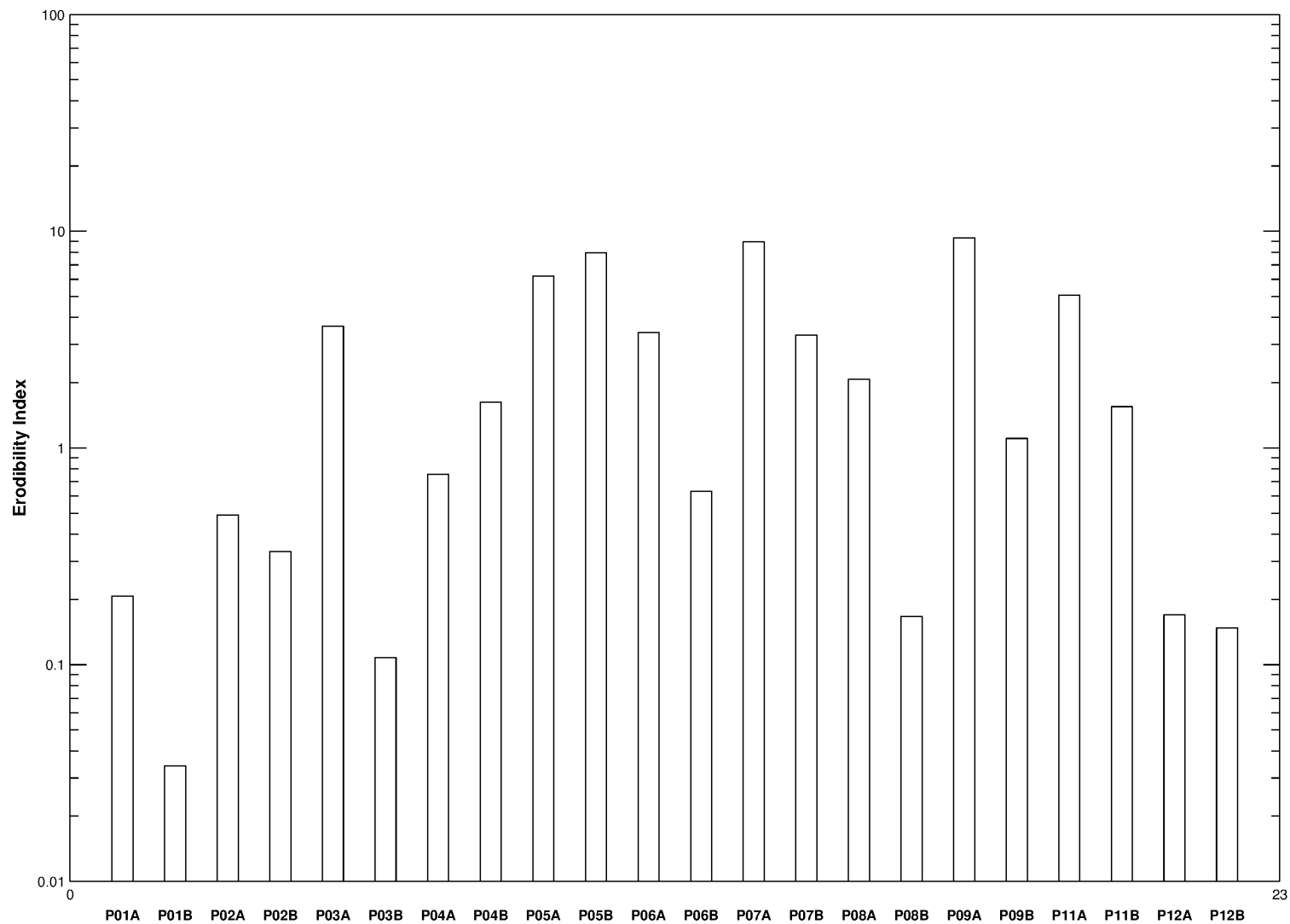


Figure 36. Erodibility index by core relative to entire dataset.

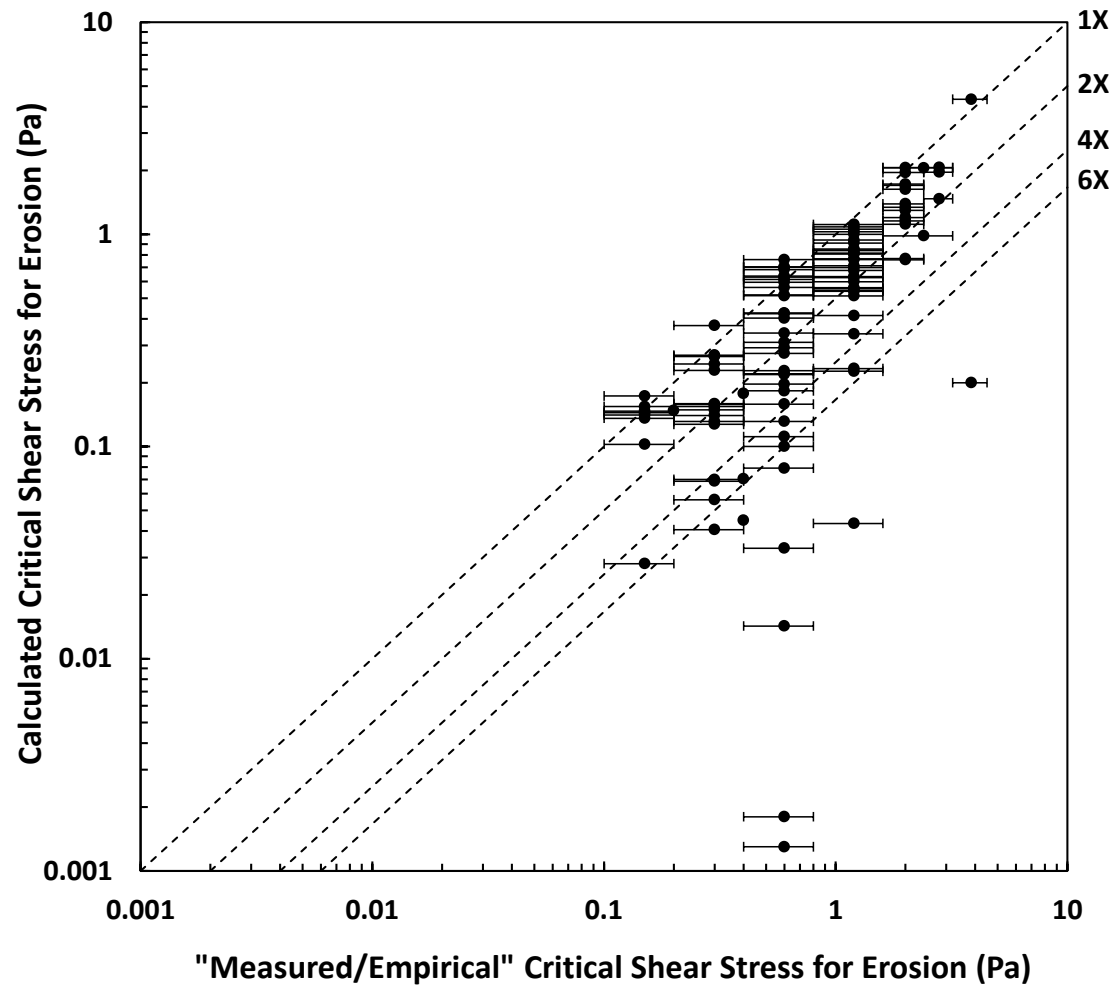


Figure 37. Calculated critical shear stress for erosion (corresponding to erosion rate of 10^{-4} cm/s) versus measured or empirical critical shear stress for erosion. Measured critical shear stress taken as the average of measured highest shear stress with no erosion and lowest shear stress with some erosion (range indicates the two values used in the computation of the average)

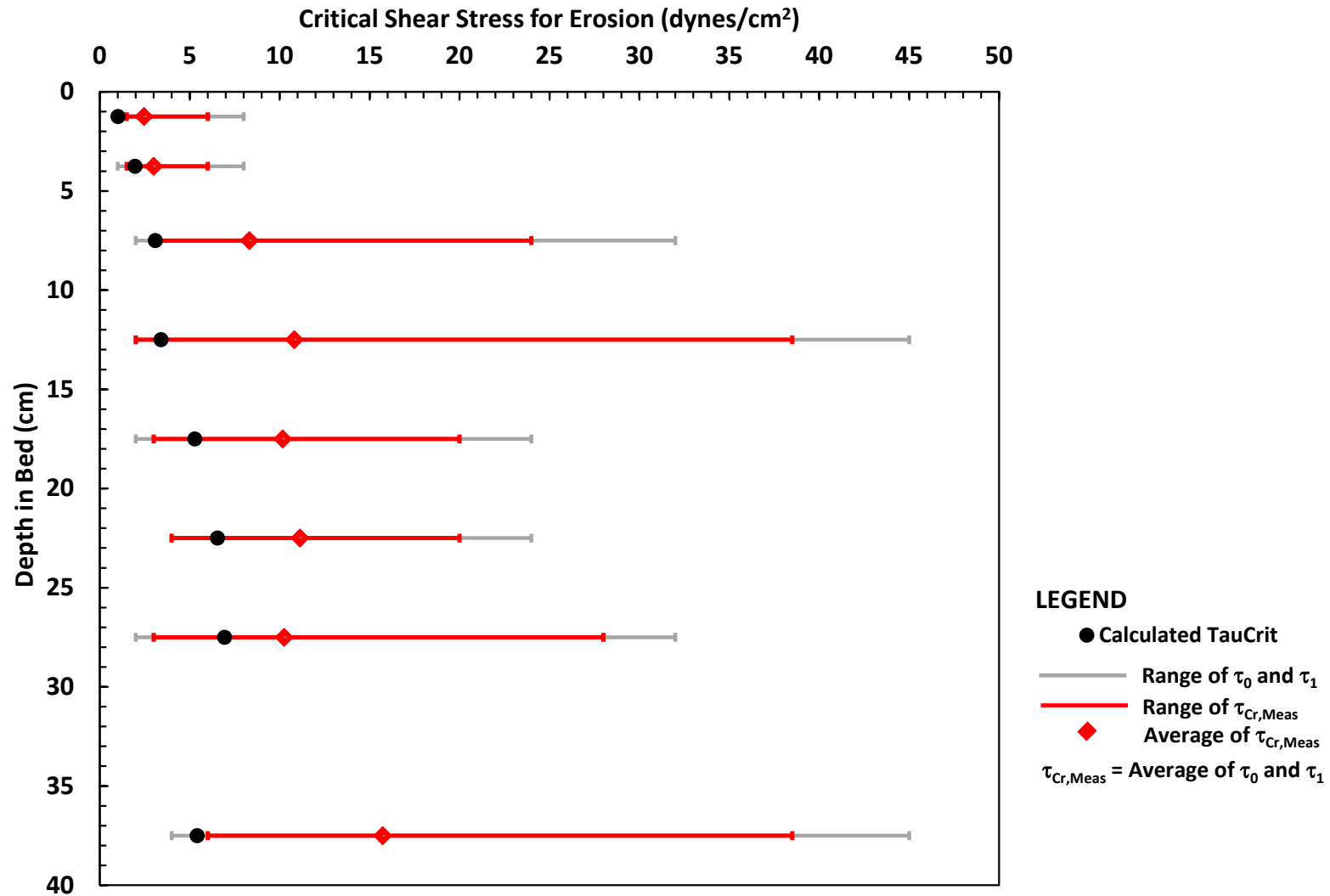


Figure 38. Depth profile of calculated critical shear stress for the average core, and measured critical shear stress for the depth intervals from the Sedflume experiments.