Relationships between core recovery, coring systems, and sedimentary lithology for scientific ocean drilling

Helen F. Evans

Introduction

The Ocean Drilling Program (ODP) and its successor programs, the Integrated Ocean Drilling Program and the International Ocean Discovery Program (IODP), have cored more than 455 km (282 miles) throughout the world's ocean basins over the past 33 years. From this, more than 325 km of core has been recovered. The recovery percentage is dependent on a variety of factors including the coring system used, the lithology cored, weather conditions, and sea state. To minimize the impact of the latter two factors, favorable weather windows are sought for scheduling expeditions. The lithology and coring system are highly interdependent and so one must choose the most favorable coring system for the specific lithologies to be encountered in order to optimize core recovery.

Understanding how core recovery relates to the IODP coring systems used in different sedimentary lithologies is thus an important part of preparing proposals and operational planning for expeditions. In this technical report, extensive data sets available from IODP operations and collected sediment cores are compiled to compare core recovery, lithology, and bulk density data to allow a better understanding of the possible outcomes when coring. Specifically, results from Integrated Ocean Drilling Program Expeditions 320 through International Ocean Discovery Program Expedition 376 are used because the coring systems used during these expeditions are comparable with those available today.

The four following coring systems are considered:

> **Advanced Piston Corer (APC)**: A hydraulically actuated piston corer used to recover relatively undisturbed sediments in very soft oozes to firm but unconsolidated sedimentary formations.
>
> **Half-Length Advanced Piston Corer (HLAPC)**: Similar to the APC used to recover relatively undisturbed cores from short intervals of soft sediment between harder layers and to extend the depth of a piston core hole into firmer sediments than can typically be achieved using the APC.
>
> **Extended Core Barrel (XCB)**: A coring system that relies on rotation of a retractable cutting shoe in front of four rotary bits. The system is generally used in firm sediments to partially lithified sedimentary rock.
>
> **Rotary Core Barrel (RCB)**: A rotary coring system used in medium to hard sediments and sedimentary rock.

For more detailed information on the IODP coring systems see http://iodp.tamu.edu/tools/index.html.

Core recovery and bulk density data are available in the LIMS database, and the average core recovery and bulk density by coring type are given in Table T1. Recovery data were averaged and the standard deviation calculated by site and core type. The core recovery data were then divided into the lithology groupings and the average and standard deviation calculated by core type. The number of cores included in the calculation is also given. Cores with >120% recovery were not included in the calculations. Bulk density data from moisture and density (MAD) measurements were divided by site, lithology, and core type before the average and standard deviation were calculated.

Methods

Percent core recovery and bulk density data used in this study were downloaded from the LIMS (http://web.iodp.tamu.edu/LORE/) and JANUS (http://iodp.tamu.edu/janusweb/) databases. Percent core recovery data were compiled by site. Cores with >120% recovery were assumed to be spurious (e.g. core expansion, fall-in) and removed. Average percent recovery and standard deviations were calculated by site for each of the four coring types (APC, HLAPC, XCB, or RCB) (see Appendix Table AT1).

(Note that for HLAPC the letter "F" is usually used to denote the use of the HLAPC; however, for Expeditions 341 and 346, when the system was first introduced, the letter "H" was used for both the APC system and the HLAPC system).

Lithological information for each of the sites was compiled from the various site reports (http://publications.iodp.org/) or, if these were not yet available, from the site summaries available on the IODP webpage for each expedition. A brief description of the lithology at each site is included in Table AT1. The lithologies were divided into 6 broad groups (see below). Each site was assigned to a lithologic group based on the major or dominant lithology at the site. If a site had significantly different lithologies downhole it was divided by lithologic unit (using units assigned shipboard), and individual units were assigned to a lithology group. For the sites assigned according to lithologic unit, the average and standard deviation were re-calculated using only the cores assigned to each unit (see Table AT1).

The average percent recovery was calculated for each lithology group and core type along with the standard deviation and the number of cores included in the calculation. These data are summarized in Table T2. The detailed data is presented in Appendix Table AT2. The percent recovery data are presented in a series of histogram plots with binned increments of 5% (Figure 1A–1W).

Bulk density data from shipboard MAD measurements (e.g., Blum, 1997) were also downloaded from JANUS and LIMS, and the same lithological groupings were applied. Bulk density measurements <1 g/cm^3 were removed. Bulk density data were then averaged by site (Table AT1), lithology, and core type, and standard deviation was calculated (appendix Table AT3). The number of bulk density measurements included is given (Table T2) and the data are presented in a series of histogram plots with binned increments of 0.1 g/cm^3 (Figure 2A–2W).

Lithological groupings

The sedimentary lithologies were divided into groups by the dominant or major lithology at each site. Some sites were assigned by lithologic unit or groups of units if the lithologies differed significantly. The summary spreadsheet lists the lithology that each site has been assigned to. The glacial sediment grouping is unusual in that it contains many lithologies that could fall into other groups. To increase the number of measurements included in the siliceous lithology group, diatom ooze lithologies in the glacial grouping that could be easily separated (Expedition 318, Site U1357) were also included in the siliceous group.

Basic descriptions of the lithologies can be found in the summary spreadsheet. For full descriptions of the lithologies refer to the *Proceedings* volume for that expedition.

Pelagic carbonate oozes

Nannofossil ooze, chalk, foraminiferal ooze, and calcareous oozes.

Silts, clays, sands

Clays, muds, sands, silts with varying amounts of biogenic material, tephras, fine turbidites, and deep-sea clays. Sandstones, siltstones, claystones, mudstones—potentially well-lithified.

Shallow-water carbonates

Floatstone, grainstone, rudstone, wackestone, packstone, and dolostone, lithified or unlithified.

Siliceous oozes

Diatom ooze, radiolarian ooze, and diatomite.

Volcaniclastics

Volcaniclastic sediments or tuffs, may contain clasts, ash, and turbidites, with varying amounts of biogenic material.

Glacial

Limited to expeditions off Antarctica (Expeditions 318 and 374) and Alaska (Expedition 341). Silts, clays, muds, and sands. Some calcareous oozes. Interbedded diatom oozes, diamict, clasts/dropstones, and glacial till. These sediments are sometimes lithified even at shallow depths.

Results

In general, sediments become more lithified with depth, bulk density increases, and the type of coring system used generally changes from APC-HLAPC-XCB-RCB. However, operational and time constraints sometimes require that the RCB system is used in place of the APC.

Average percent recovery decreases from the APC coring system, where it is in the 90%–100% range, through the HLAPC system to XCB and RCB, where it ranges 30%–70%. Standard deviation around the average increases significantly for the XCB and RCB coring systems, indicating a much wider range of recovery values, as shown by the histograms in Figures F1A–F1W.

Pelagic carbonate oozes and chalks are the lithology group with the best average recovery regardless of coring system (Figures F1A, F1B, F1C, F1D; Table T2).

Silts, muds, and clays have high percent recovery with the APC/HLAPC coring systems (100.1% and 94.9%, respectively) but drop significantly with XCB and RCB (63.4% and 33.9%, respectively) (Figures F1E, F1F, F1G, F1H). Unlithified thick sands are difficult to core and have poor recovery; however, this is not well represented in the dataset.

Shallow-water carbonates are recovered well using the APC (97.6%) and HLAPC (94.9%) but are recovered poorly using either the XCB (36.8%) or the RCB (32.2%) (Figures F1I, F1J, F1K, F1L).

Siliceous oozes are recovered well with the APC system (101.0%) but not with the XCB (49.0%); however, this a relatively small data set (48 data points). The average percent recovery (80.3%) for the siliceous ooze RCB category calculated from cores drilled at a single site, Expedition 371 Site U1511, which cored diatomite (Sutherland et al., 2019) (Figures F1M, F1N, F1O).

Both volcaniclastic sediments (Figures F1P, F1Q, F1R, F1S) and glacial sediments (Figures F1T, T1U, F1V, F1W) were well recovered using the APC (100.6% and 96%, respectively) and the HLAPC (100.7% and 90.9%, respectively), whereas the XCB system (27.6% and 31.6%, respectively) obtained significantly lower average recovery. Recovery using the RCB increased for both sediment types (volcaniclastic: 66.0%; glacial: 41.5%).

Generally, the average bulk density increases with depth in the hole and therefore through the sequence of coring systems. In the pelagic carbonate oozes and chalks group, the average bulk density increases from APC coring to HLAPC then decreases for XCB coring and then increases again for the RCB (Figures F2A, F2B, F2C, F2D).

Higher average bulk density for sediments does not generally equate to an increase in percent core recovery. This is because factors other than bulk density of the sediment contribute toward recovery (e.g., grain size, porosity, cementation/cement type, and coring system).

Acknowledgments

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References

Blum, P., 1997. Physical properties handbook. *ODP Tech. Note,* 26. doi:10.2973/odp.tn.26.1997

Sutherland, R., Dickens, G.R., Blum, P., Agnini, C., Alegret, L., Bhattacharya, J., Bordenave, A., Chang, L., Collot, J., Cramwinckel, M.J., Dallanave, E., Drake, M.K., Etienne, S.J.G., Giorgioni, M., Gurnis, M., Harper, D.T., Huang, H.-H.M., Keller, A.L., Lam, A.R., Li, H., Matsui, H., Morgans, H.E.G., Newsam, C., Park, Y.-H., Pascher, K.M., Pekar, S.F., Penman, D.E., Saito, S., Stratford, W.R., Westerhold, T., and Zhou, X., 2019. Site U1511. *In* Sutherland, R., Dickens, G.R., Blum, P., and the Expedition 371 Scientists, *Tasman Frontier Subduction Initiation and Paleogene Climate*. Proceedings of the International Ocean Discovery Program, 371: College Station, TX (International Ocean Discovery Program). https://doi.org/10.14379/iodp.proc.371.108.2019

Table T1. Summary of core recovery and bulk density by coring type.

Coring system	Number of cores (N)	Average recovery (%)	Number of bulk density measurements (N)	Average bulk density (g/cm^3)
APC	5,740	100.2	10,179	1.63
HLAPC	1,710	95.1	1,848	1.86
XCB	2,619	56.9	5,151	1.84
RCB	3,385	49.9	8,483	2.07

Table T2. Average core recovery by lithology and coring system.

Lithology	Carbonate ooze, chalk	Silt, clay, sand	Shallow-water carbonate	Siliceous ooze	Volcaniclastic	Glacial
APC cores (N)	1865	2331	454	401	305	384
Avg. recovery (%)	101.5	100.1	97.6	101.0	100.6	96.0
STDEV (%)	9.29	11.9	12.7	9.4	9.1	19.2
HLAPC cores (N)	154	934	434	0	17	172
Avg. recovery (%)	100.4	94.9	94.9	0	100.7	90.9
STDEV (%)	11.32	21	17.4	0	14.6	27.5
XCB cores (N)	598	1187	407	48	204	175
Avg. recovery (%)	75.9	63.4	36.8	49.0	27.6	31.6
STDEV (%)	33.2	40.5	37.3	41.7	28.8	32.8
RCB cores (N)	358	1628	490	22	340	547
Avg. recovery (%)	61.4	52.2	30.9	80.3	66.0	41.5
STDEV (%)	32.8	33.9	32.2	29.7	29.0	34.6

Table 3. Average bulk density (BD) data from MAD by lithology and coring system.

Lithology	Carbonate ooze, chalk	Silt, clay, sand	Shallow-water carbonate	Siliceous ooze	Volcaniclastic	Glacial
APC (N)	3267	4386	703	729	467	627
Avg. BD (g/cm3)	1.61	1.68	1.74	1.32	1.66	1.60
STDEV (g/cm3)	0.15	0.24	0.15	0.16	0.18	0.28
HLAPC (N)	195	982	419	-	53	199
Avg. BD (g/cm3)	1.78	1.88	1.87	-	1.65	1.93
STDEV (g/cm3)	0.10	0.18	0.12	-	0.07	0.19
XCB (N)	1223	2839	487	77	211	314
Avg. BD (g/cm3)	1.75	1.88	2.05	1.34	1.68	1.79
STDEV (g/cm3)	0.18	0.18	0.18	0.11	0.10	0.25
RCB (N)	737	4825	522	66	1274	1059

Avg. BD (g/cm3)	1.89	2.14	2.15	1.32	2.02	1.95
STDEV (g/cm3)	0.24	0.24	0.20	0.06	0.24	0.26

Appendix

Table AT1.

Summary of core recovery, bulk density, and lithology by coring type, Expeditions 320 through Expedition 375. Data include the total number of cores (#), average recovery (avg. recov., %), and standard deviation of recovery (STDEV, %) for each coring system along with bulk density (BD) number of data points (#), average BD (g/cm^3), and BD STDEV (g/cm^3) for each coring system. Additional spreadsheets in the workbook give the data broken down by major lithology.

Table AT2.

Core recovery data from each coring system used for calculations.

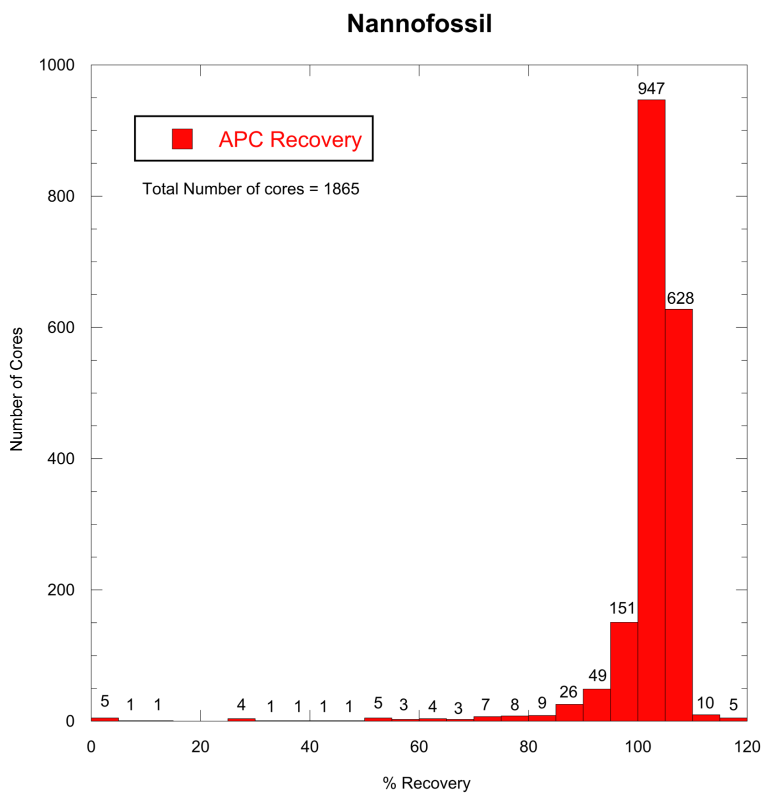
Table AT3.

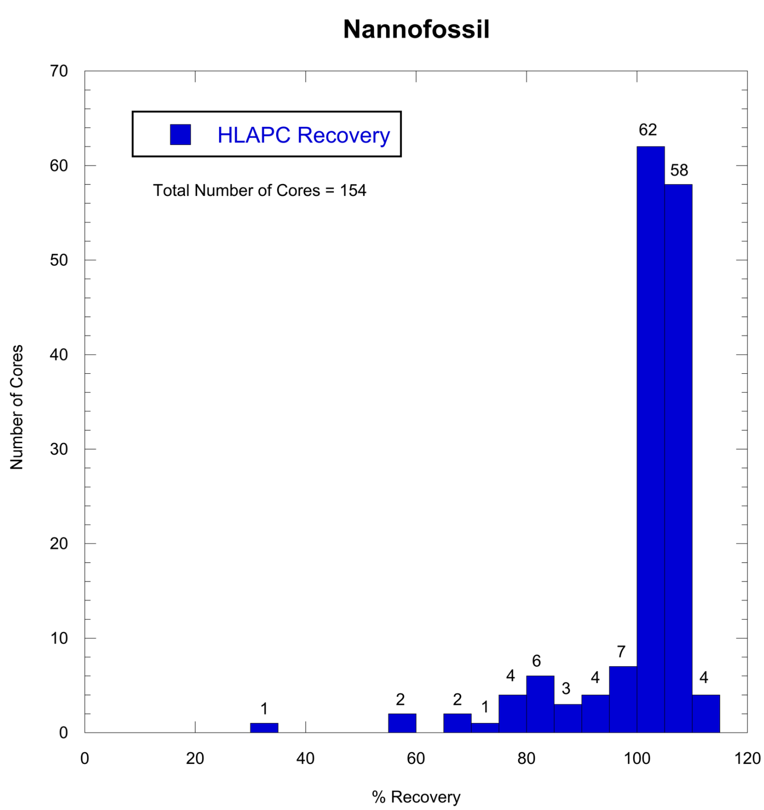
Bulk density data used for calculations.

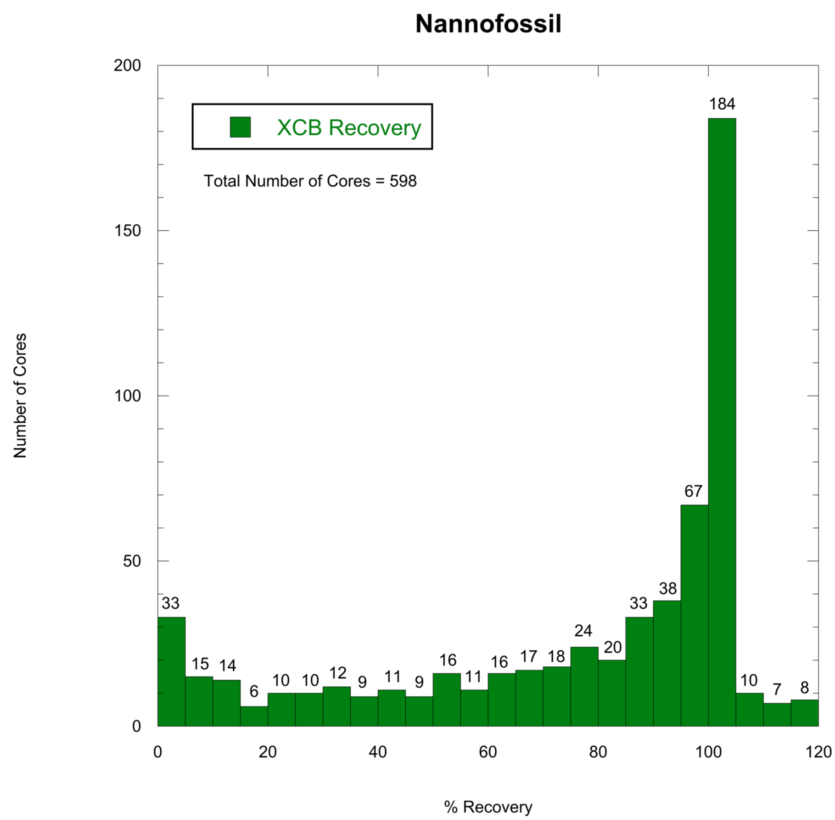
Figures

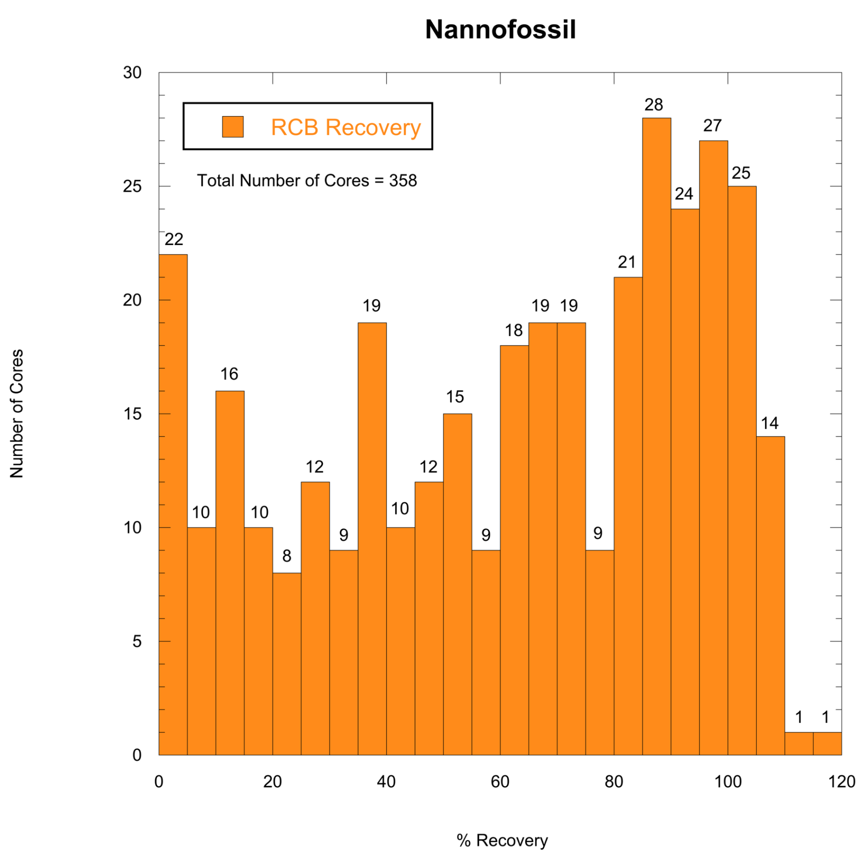
Figure F1. A–W. Histogram plots showing percent recovery data (from LIMS) split into bins of 5% against the number of cores in each bin. The percent recovery data is divided by coring type and lithology. Red = APC, Blue = HLAPC, Green = XCB and Orange = RCB.

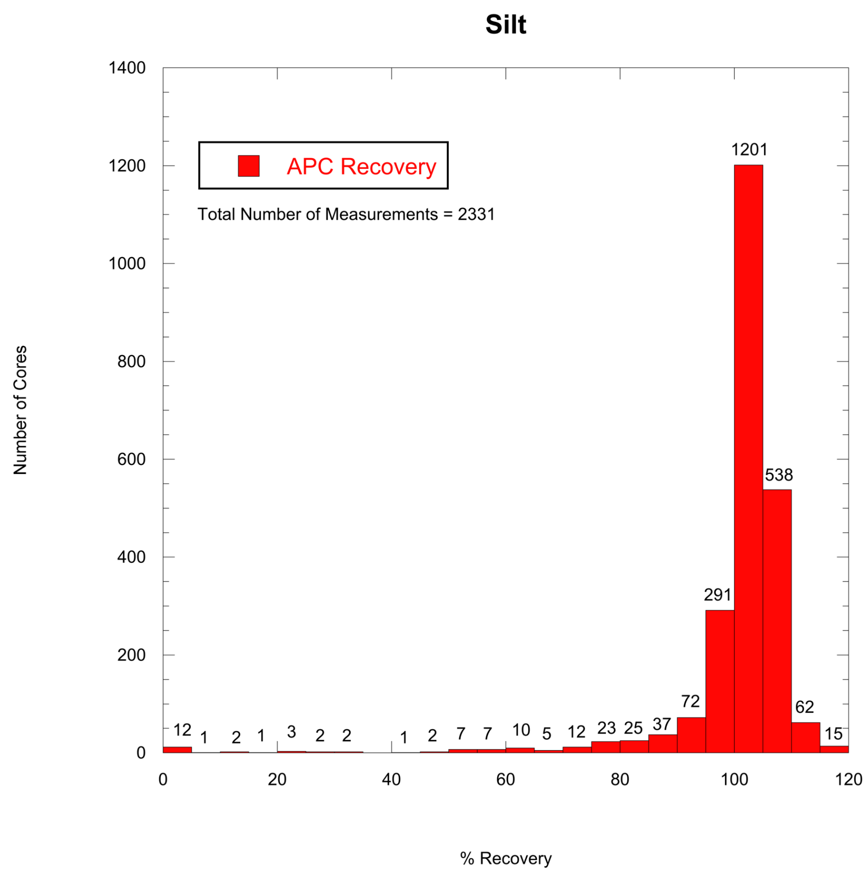
Figure F2. A–W. Histogram plots showing bulk density data (from LIMS) split into bins of 0.1 g/cm^3 against the number of measurements in each bin. The bulk density data is divided by coring type and lithology. Red = APC, Blue = HLAPC, Green = XCB and Orange = RCB.

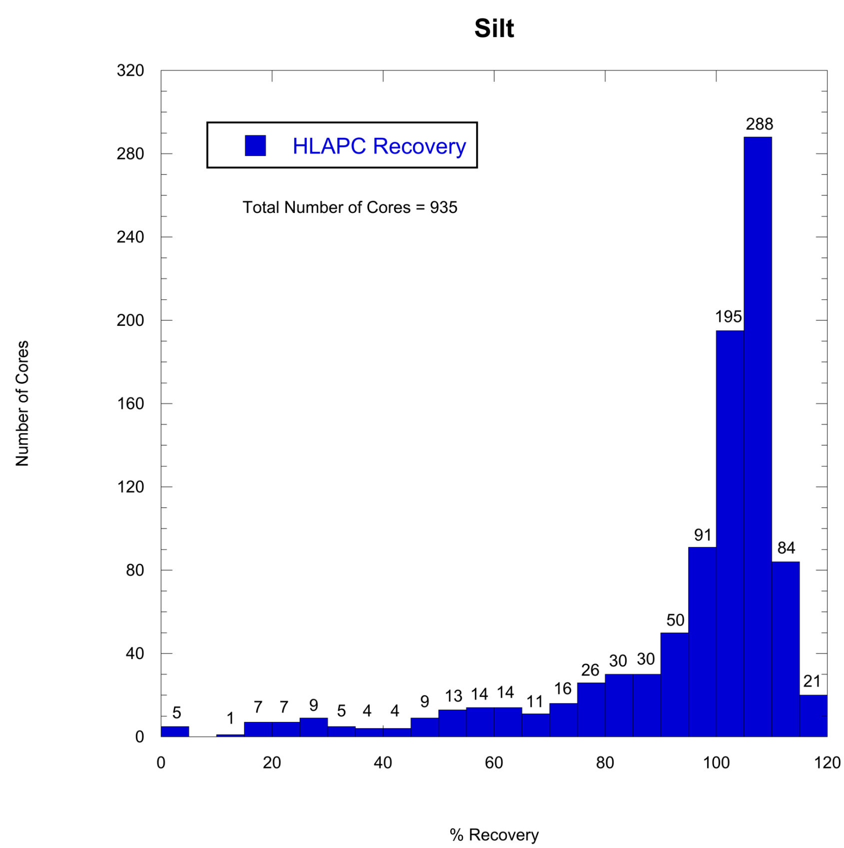

Nannofossil
APC Recovery
Total Number of cores = 1865
Number of Cores
% Recovery
5
1
1
4
1
1
1
1
5
3
4
3
7
8
9
26
49
151
947
628
10
5


Nannofossil
HLAPC Recovery
Total Number of Cores = 154
Number of Cores
% Recovery
1
2
2
1
4
6
3
4
7
62
58
4


Nannofossil
XCB Recovery
Total Number of Cores = 598
Number of Cores
% Recovery
0
50
100
150
200
0
20
40
60
80
100
120
33
15
14
6
10
10
12
9
11
9
16
11
16
17
18
24
20
33
38
67
184
10
7
8


Nannofossil
RCB Recovery
Total Number of Cores = 358
Number of Cores
% Recovery
0
5
10
15
20
25
30
0
20
40
60
80
100
120
22
10
16
10
8
12
9
19
10
12
15
9
18
19
19
9
21
28
24
27
25
14
1
1


Silt
APC Recovery
Total Number of Measurements = 2331
Number of Cores
% Recovery
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
12
1
2
1
3
2
2
1
2
7
7
10
5
12
23
25
37
72
291
1201
538
62
15


Silt
HLAPC Recovery
Total Number of Cores = 935
Number of Cores
% Recovery
320
280
240
200
160
120
80
40
0
0
20
40
60
80
100
120
5
1
7
7
9
5
4
4
9
13
14
14
11
16
26
30
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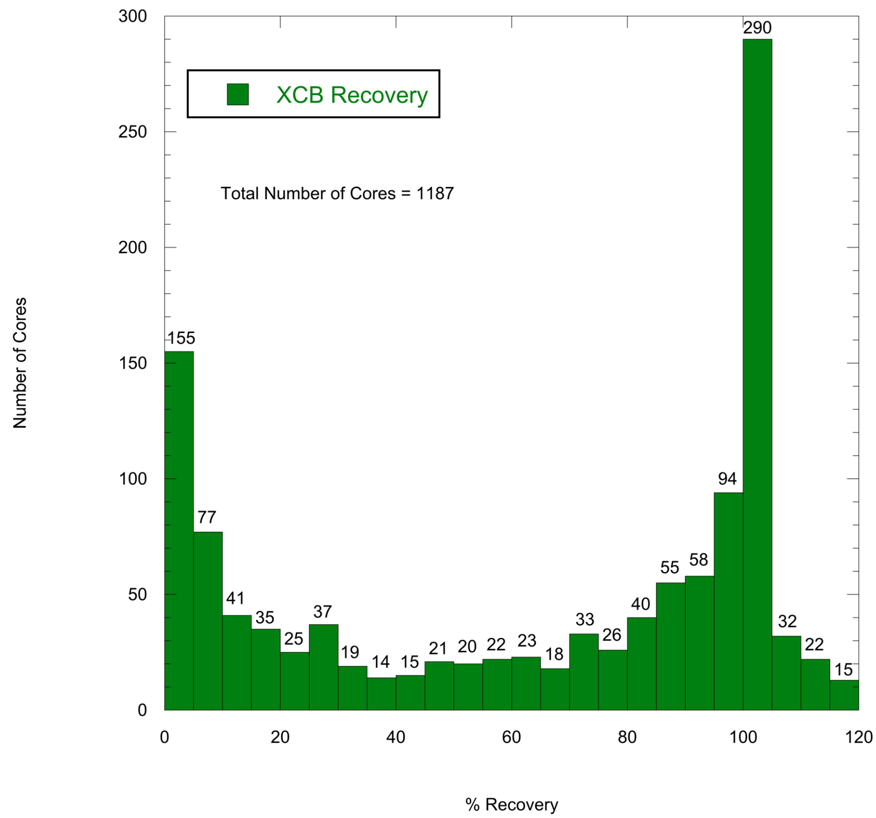
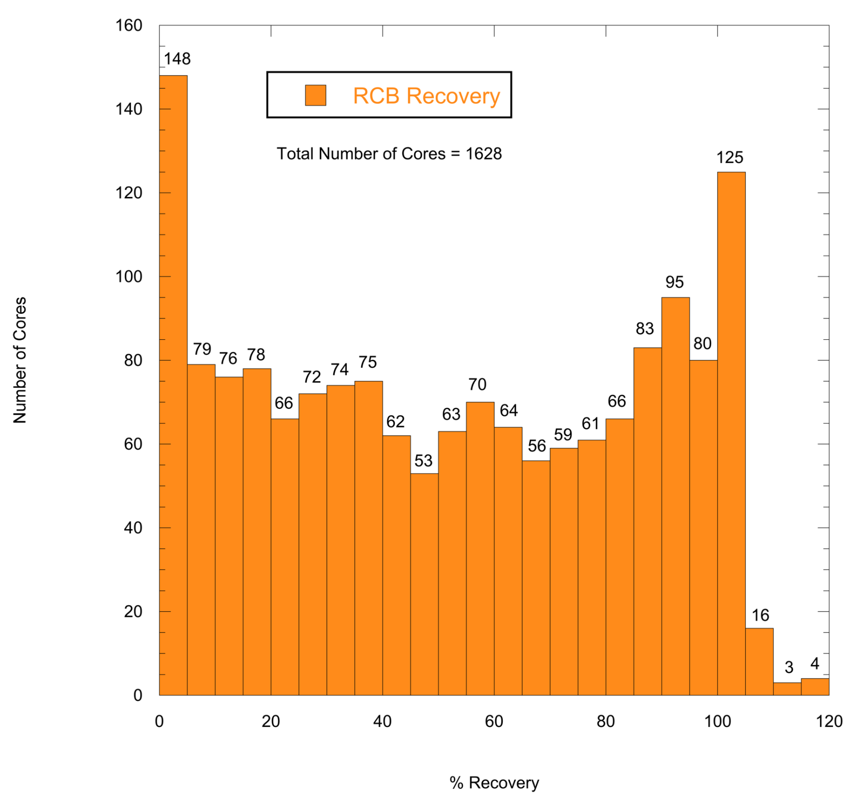
50
91
195
288
84
21

Silt



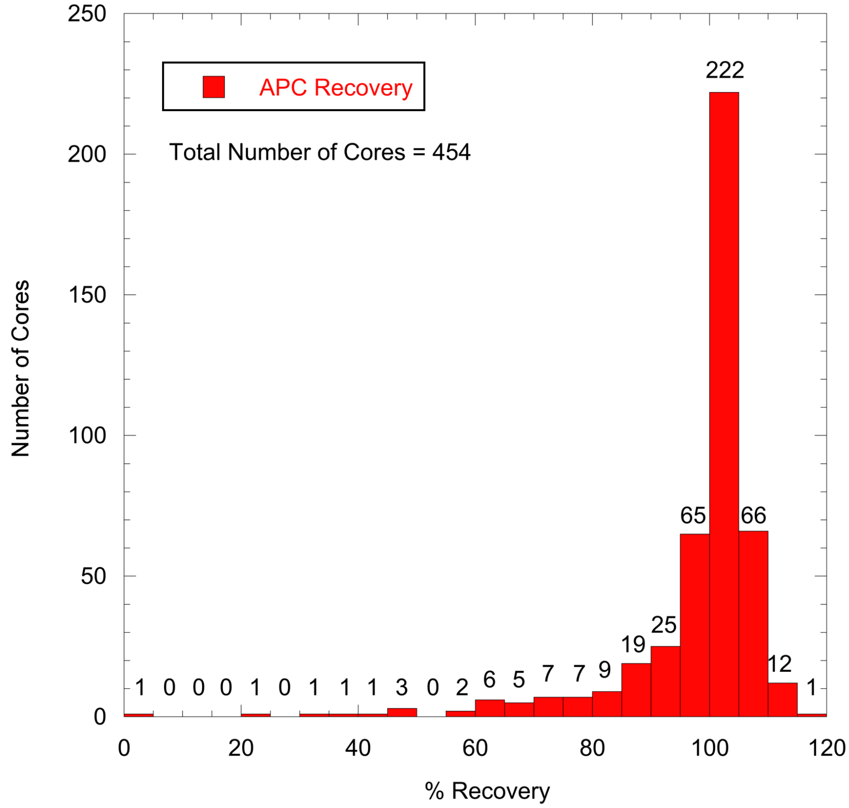
XCB Recovery
Total Number of Cores = 1187
Number of Cores
% Recovery
0
50
100
150
200
250
300
0
20
40
60
80
100
120
155
77
41
35
25
37
19
14
15
21
20
22
23
18
33
26
40
55
58
94
290
32
22
15

Silt

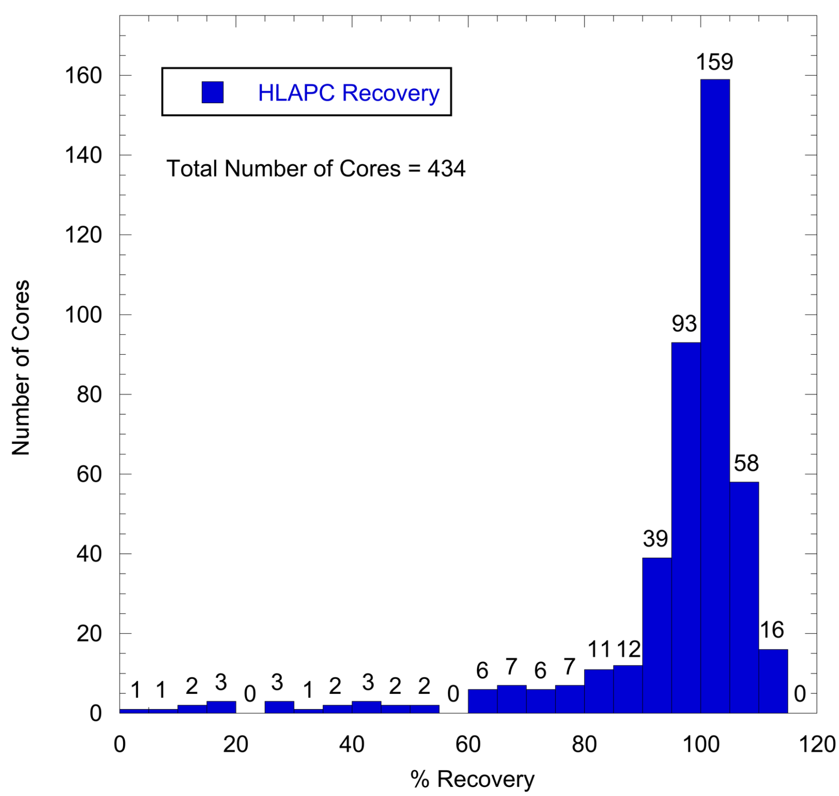


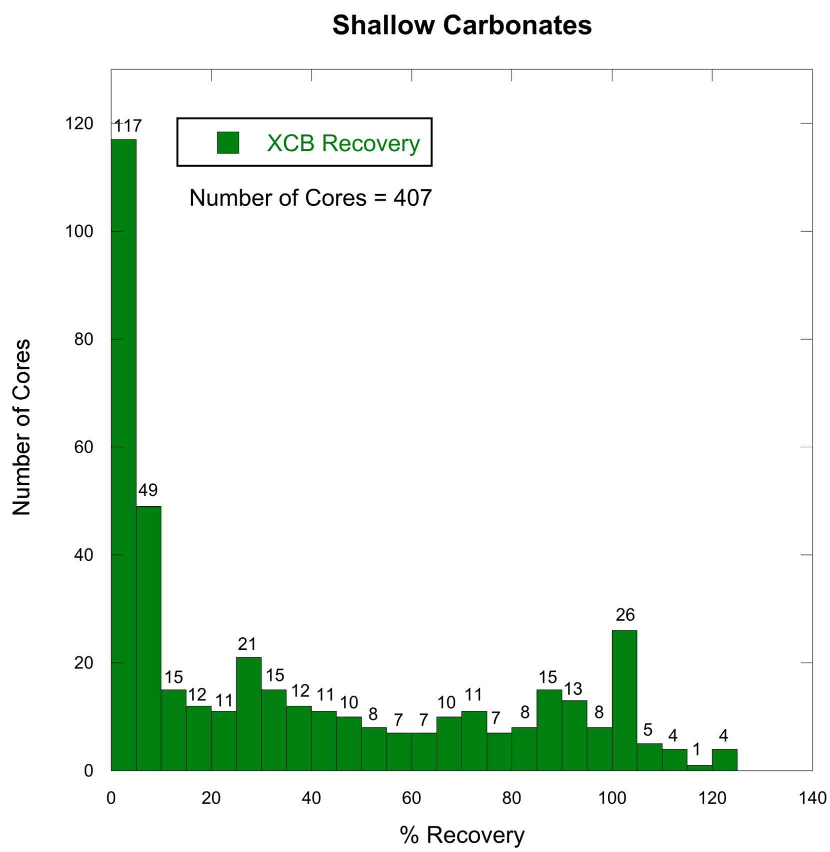
RCB Recovery
Total Number of Cores = 1628
Number of Cores
% Recovery
0
20
40
60
80
100
120
140
160
0
20
40
60
80
100
120
148
79
76
78
66
72
74
75
62
53
63
70
64
56
59
61
66
83
95
80
125
16
3
4

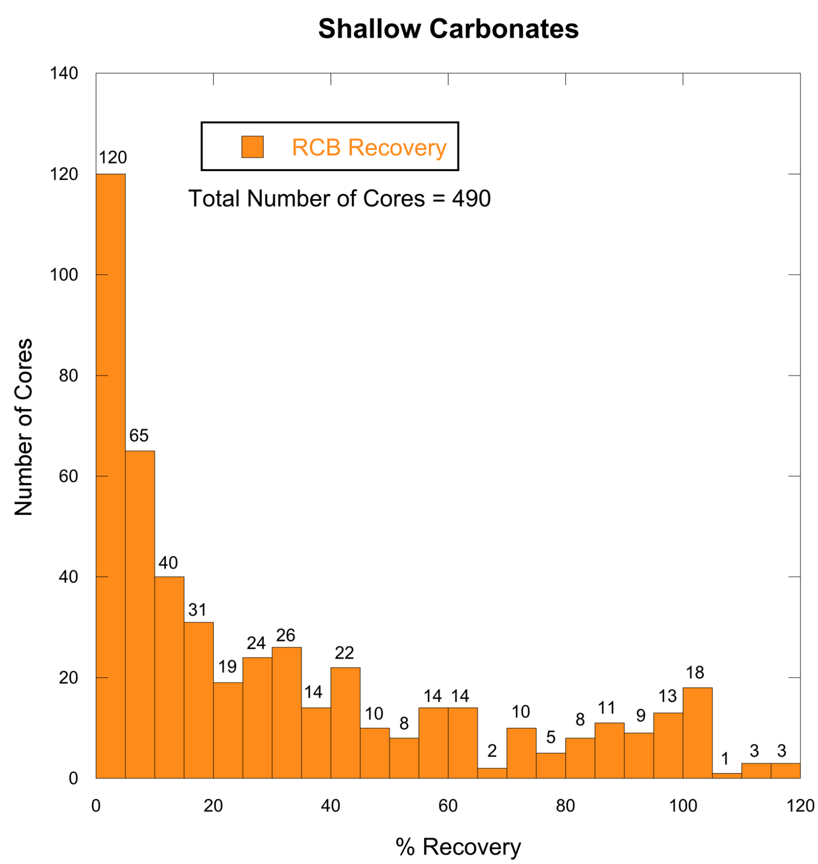
Shallow Carbonates

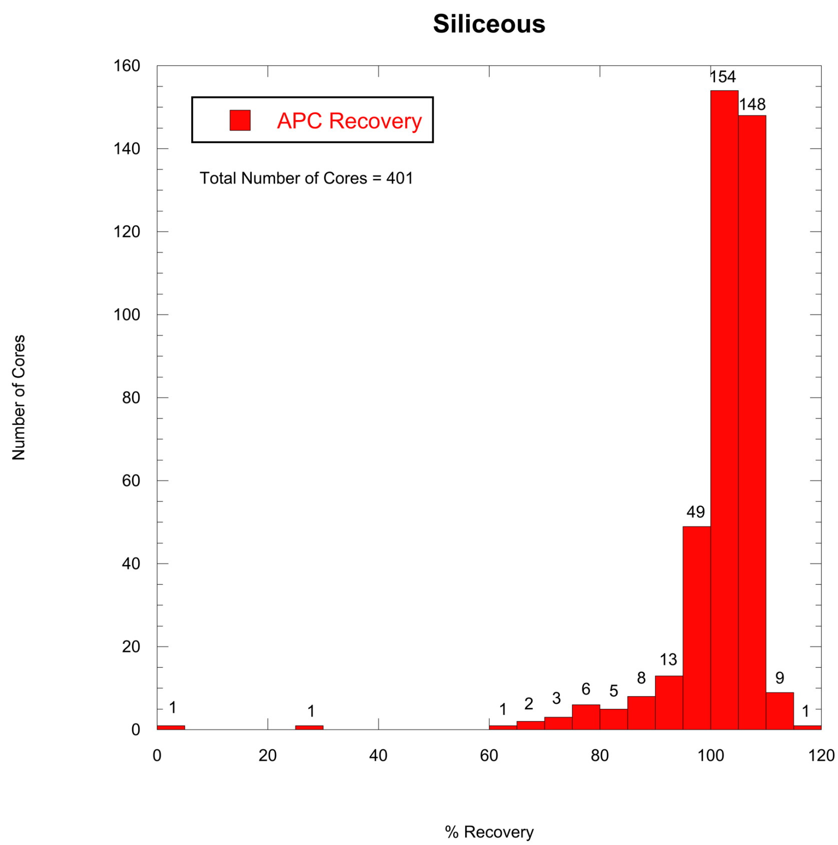


Shallow Carbonates

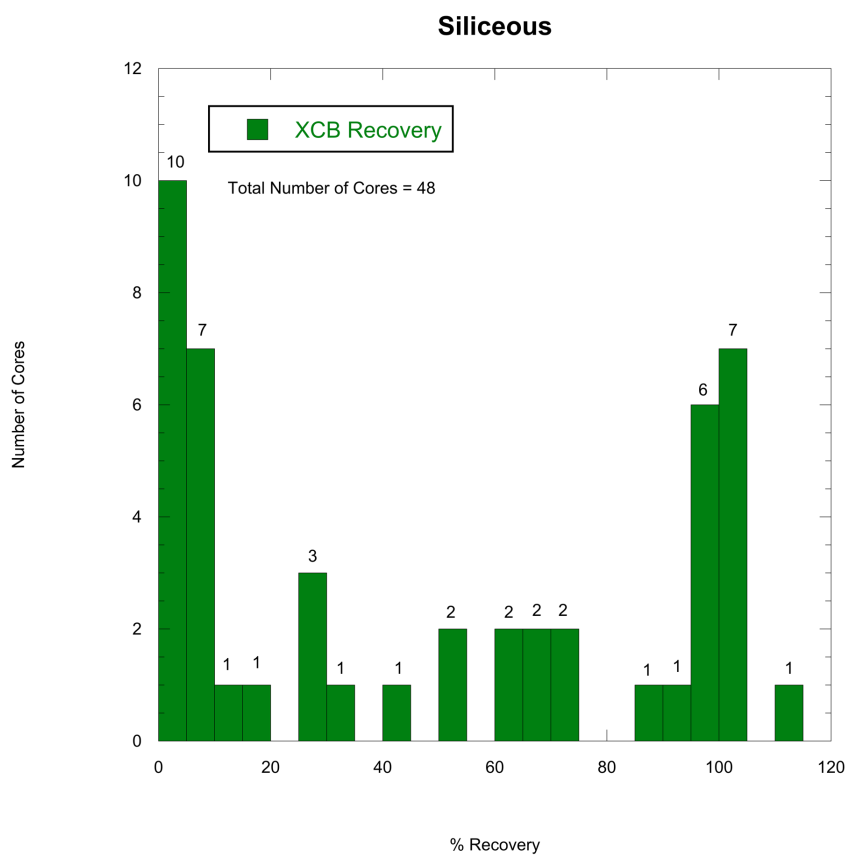



Shallow Carbonates
XCB Recovery
Number of Cores = 407
Number of Cores
% Recovery
0
20
40
60
80
100
120
140
117
49
15
12
11
21
15
12
11
10
8
7
7
10
11
7
8
15
13
8
26
5
4
1
4


Shallow Carbonates
RCB Recovery
Total Number of Cores = 490
Number of Cores
% Recovery
0
20
40
60
80
100
120
140
120
65
40
31
19
24
26
14
22
10
8
14
14
2
10
5
8
11
9
13
18
1
3
3

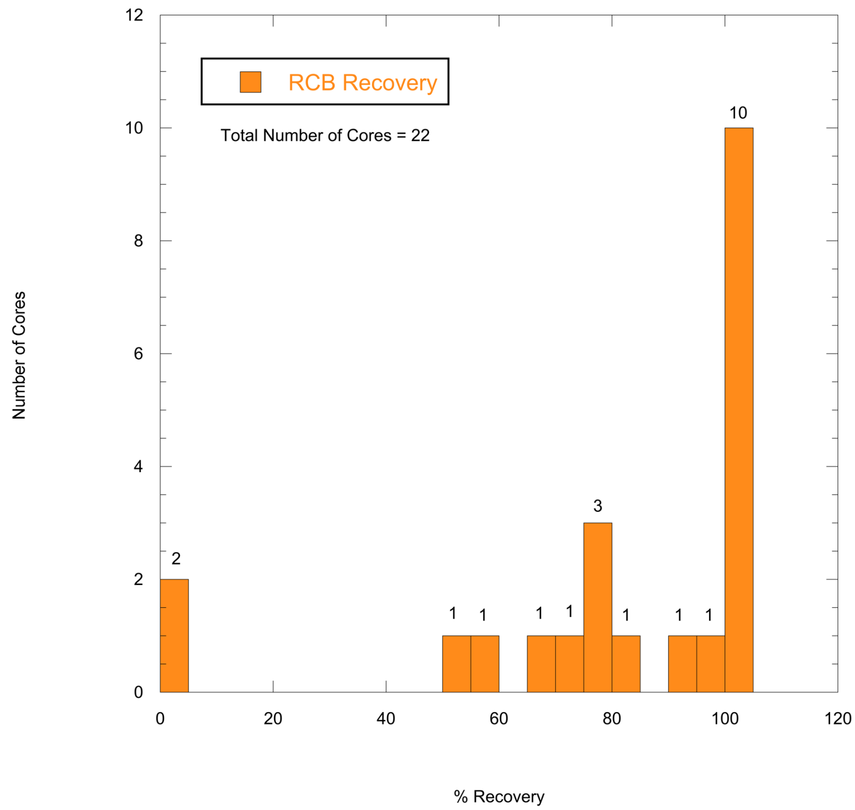


Siliceous
APC Recovery
Total Number of Cores = 401
Number of Cores
% Recovery
0
20
40
60
80
100
120
140
160
0
20
40
60
80
100
120
1
1
1
2
3
6
5
8
13
49
154
148
9
1

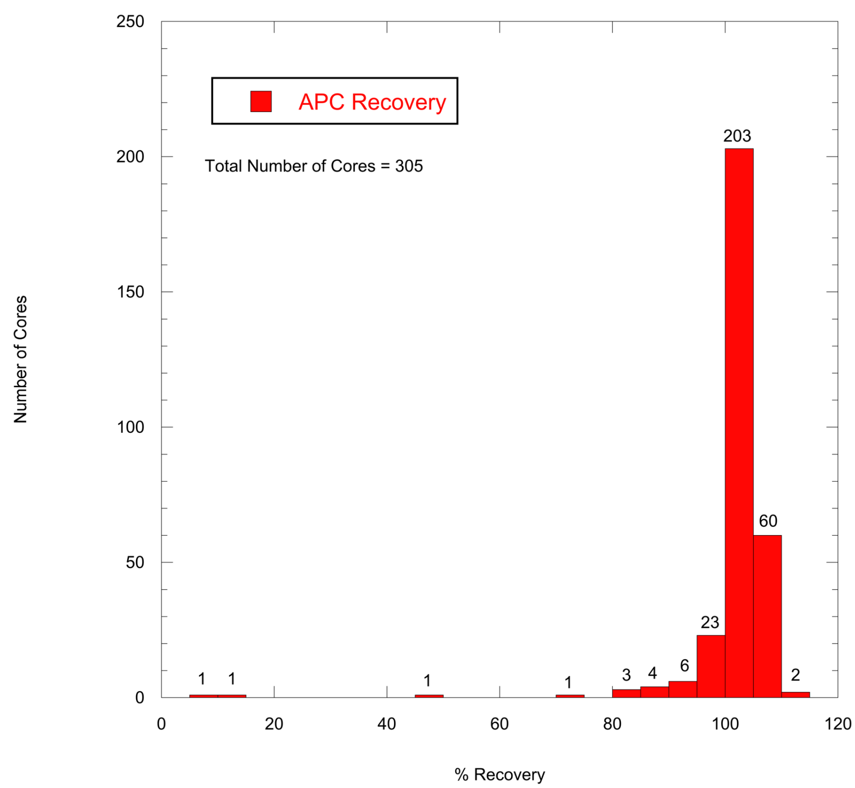


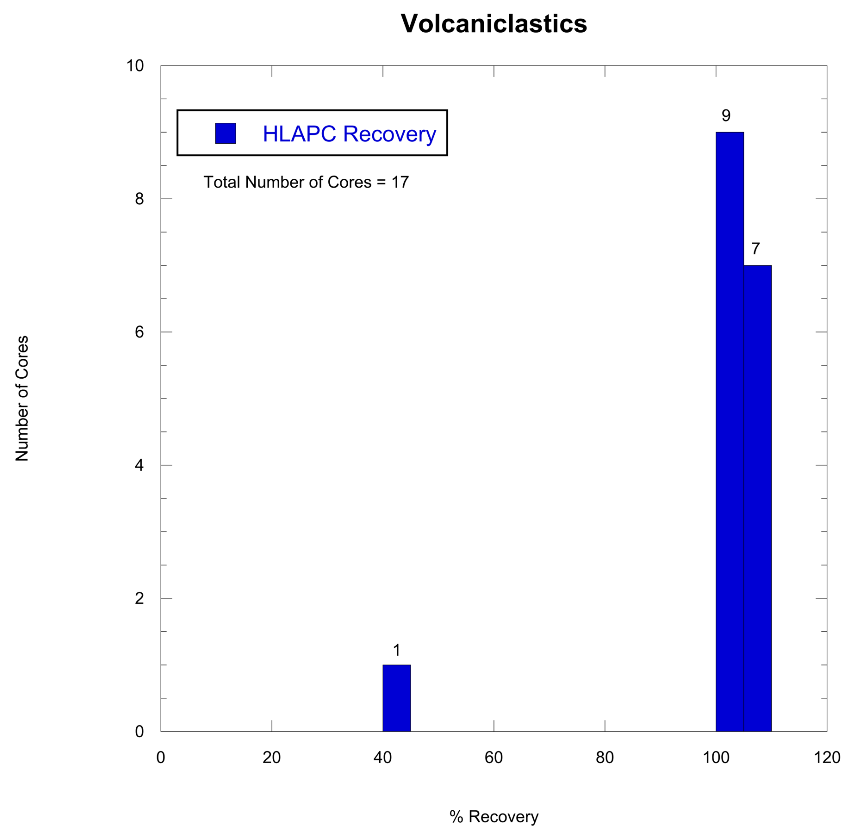
Siliceous
XCB Recovery
Total Number of Cores = 48
Number of Cores
% Recovery
0
2
4
6
8
10
12
0
20
40
60
80
100
120
10
7
1
1
3
1
1
2
2
2
2
1
1
6
7
1

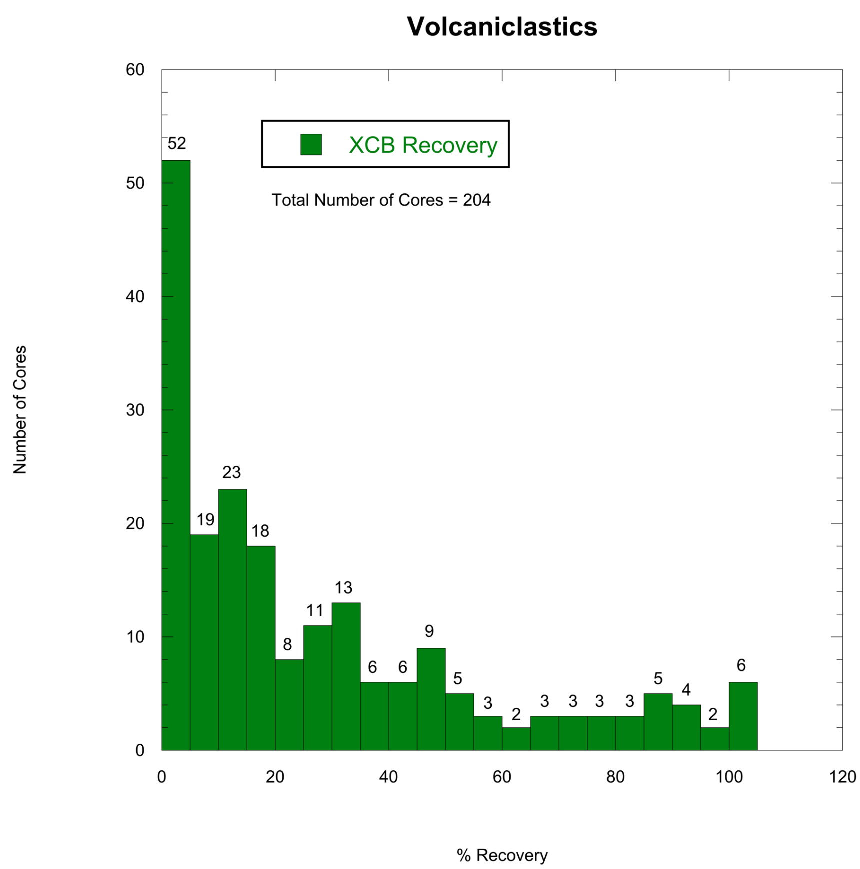
Siliceous

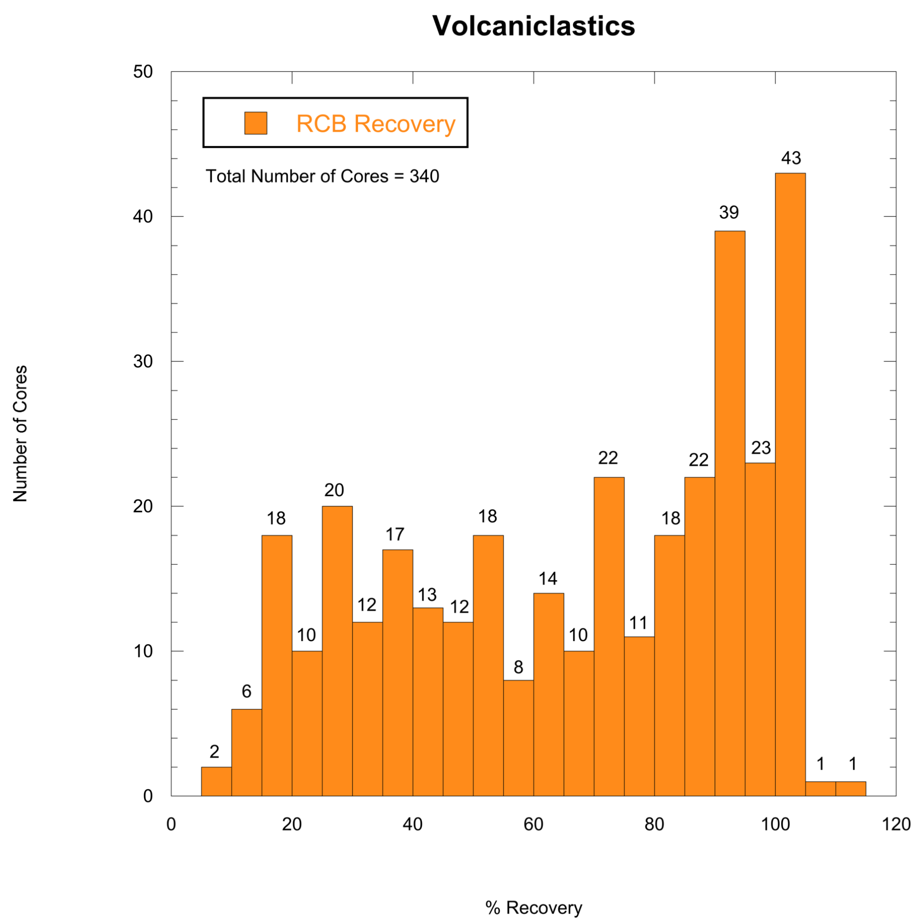


Volcaniclastics




Volcaniclastics
HLAPC Recovery
Total Number of Cores = 17
Number of Cores
% Recovery
0
2
4
6
8
10
0
20
40
60
80
100
120
1
9
7


Volcaniclastics
XCB Recovery
Total Number of Cores = 204
Number of Cores
% Recovery
0
10
20
30
40
50
60
0
20
40
60
80
100
120
52
19
23
18
8
11
13
6
6
9
5
3
2
3
3
3
3
5
4
2
6


Volcaniclastics
RCB Recovery
Total Number of Cores = 340
Number of Cores
% Recovery
0
10
20
30
40
50
0
20
40
60
80
100
120
2
6
18
10
20
12
17
13
12
18
8
14
10
22
11
18
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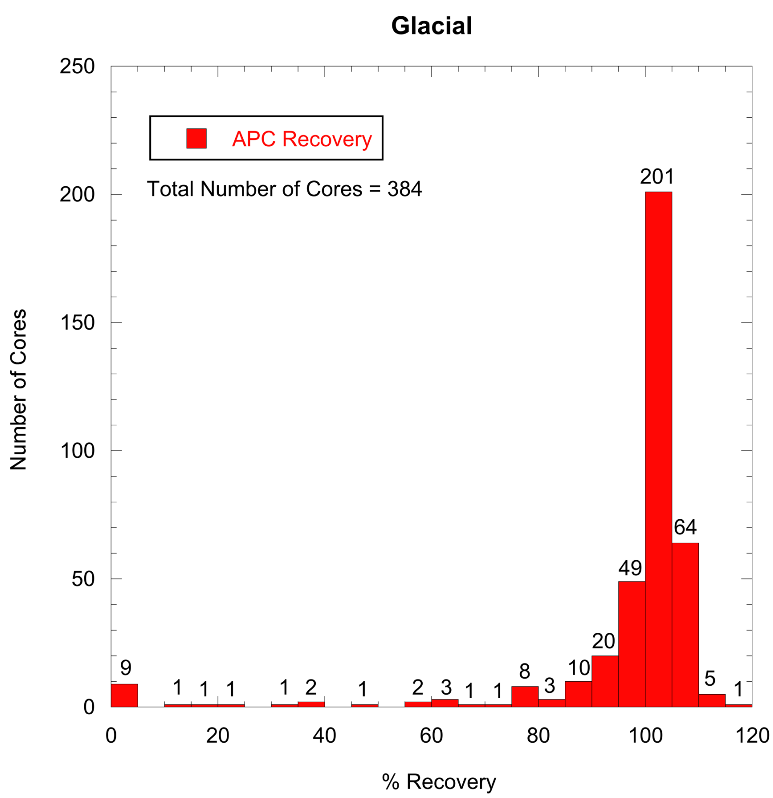
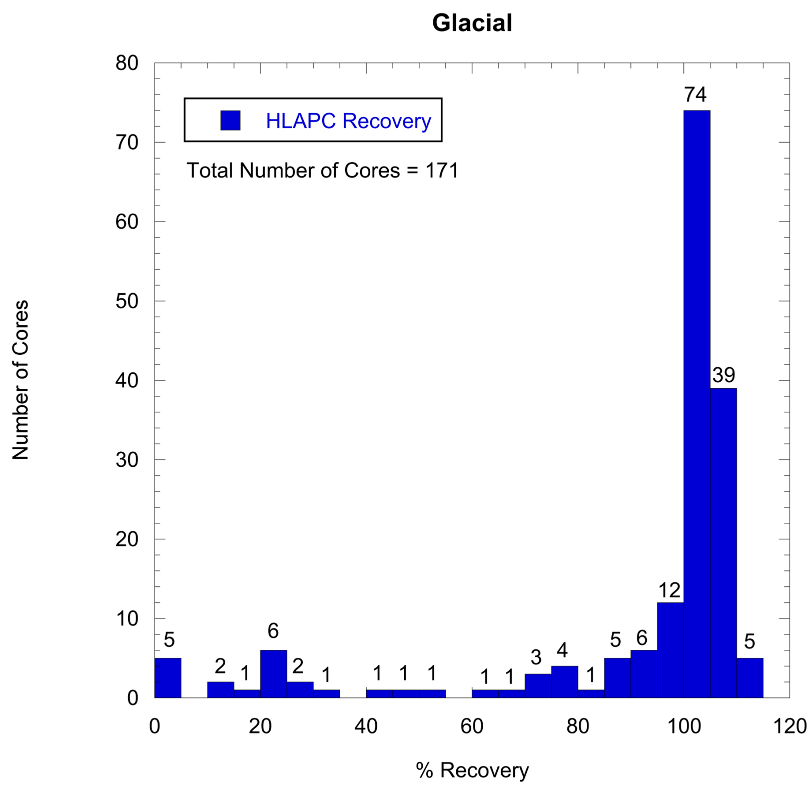
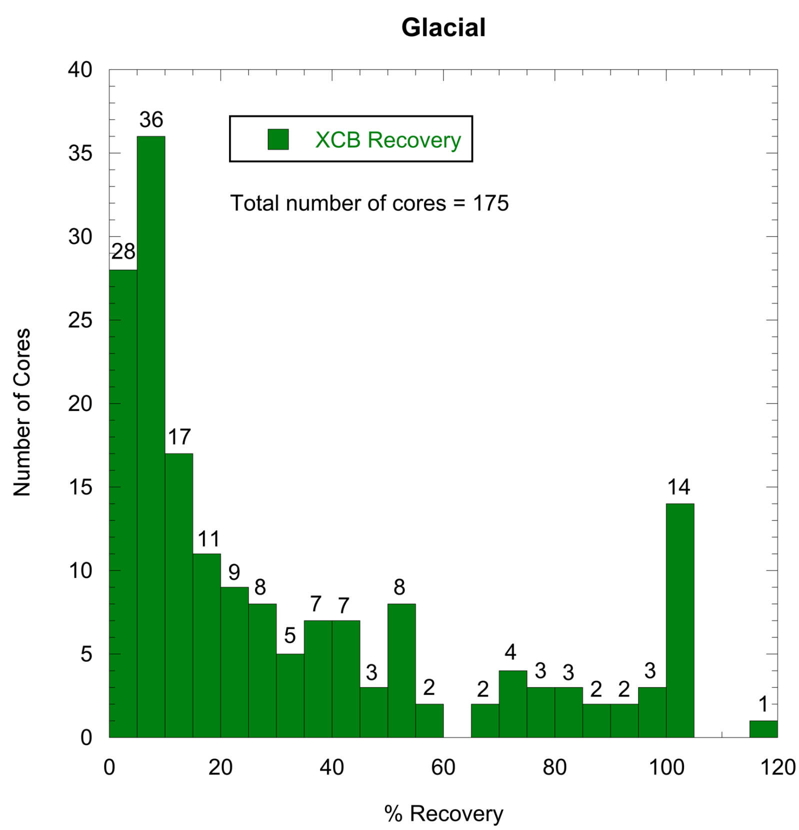
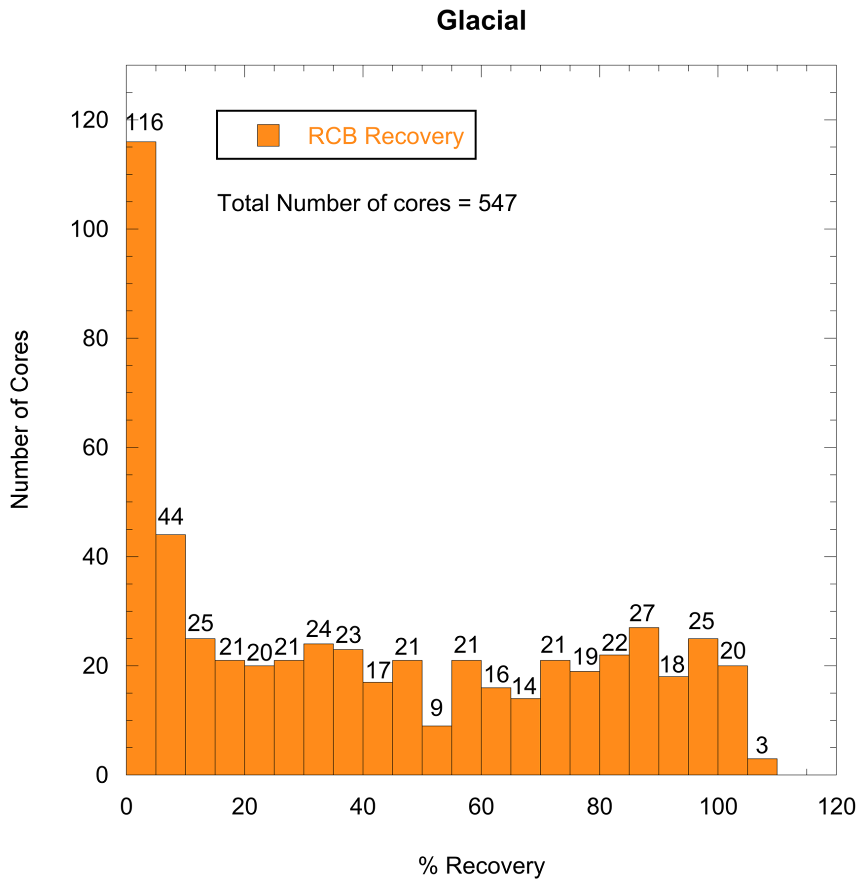
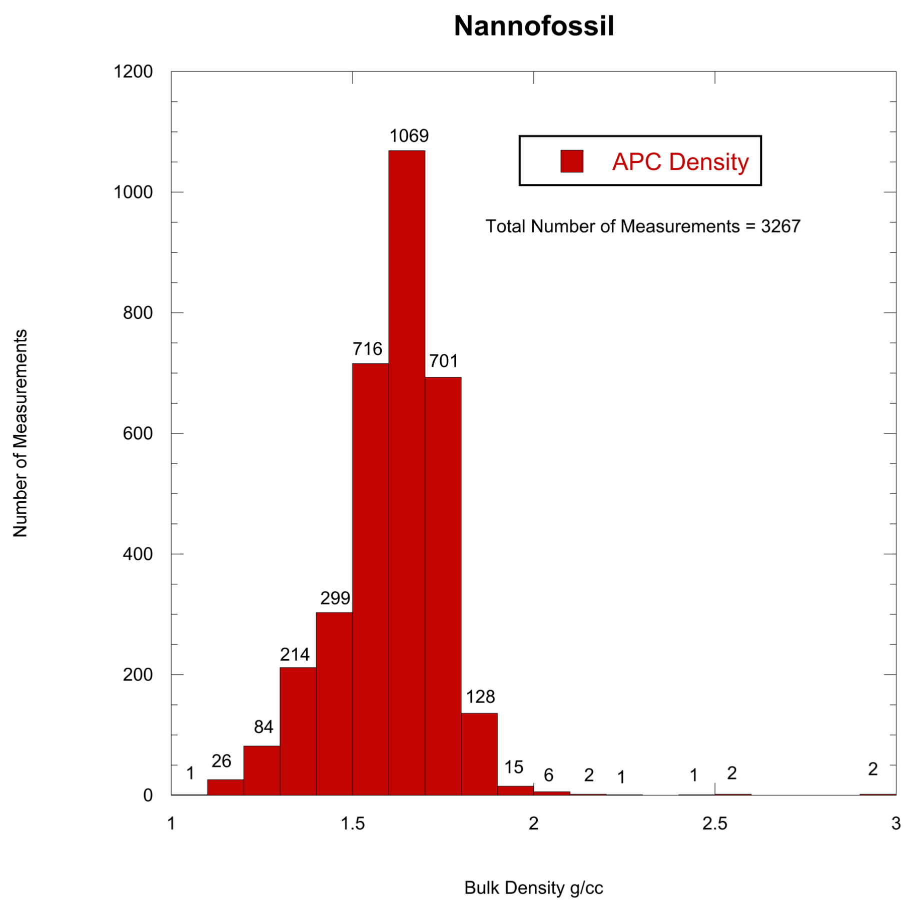
39
23
43
1
1

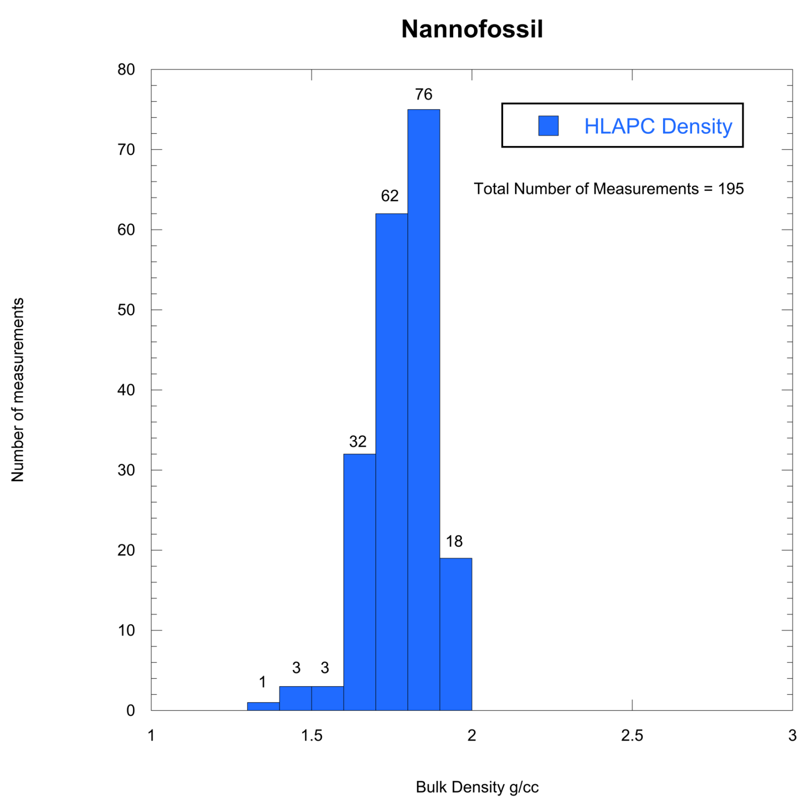

Glacial
APC Recovery
Total Number of Cores = 384
Number of Cores
% Recovery
0
50
100
150
200
250
0
20
40
60
80
100
120
9
1
1
1
1
2
1
2
3
1
1
8
3
10
20
49
201
64
5
1


Glacial
HLAPC Recovery
Total Number of Cores = 171
Number of Cores
% Recovery
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
5
2
1
6
2
1
1
1
1
1
1
3
4
1
5
6
12
74
39
5

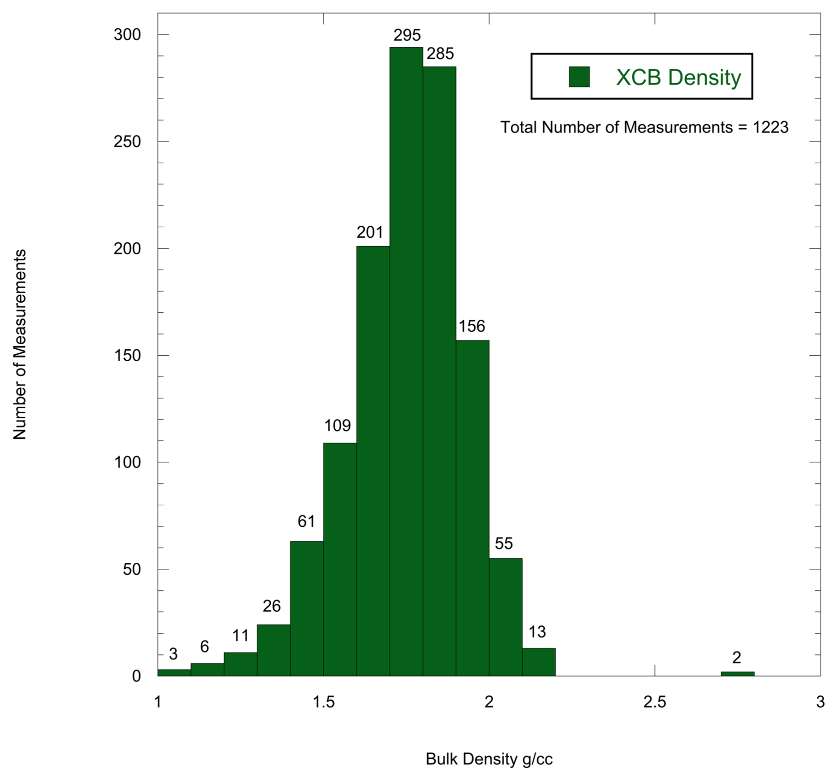

Glacial
XCB Recovery
Total number of cores = 175
Number of Cores
% Recovery
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120
28
36
17
11
9
8
5
7
7
3
8
2
2
4
3
3
2
2
3
14
1


Glacial
RCB Recovery
Total Number of cores = 547
Number of Cores
% Recovery
0
20
40
60
80
100
120
116
44
25
21
20
21
24
23
17
21
9
21
16
14
21
19
22
27
18
25
20
3

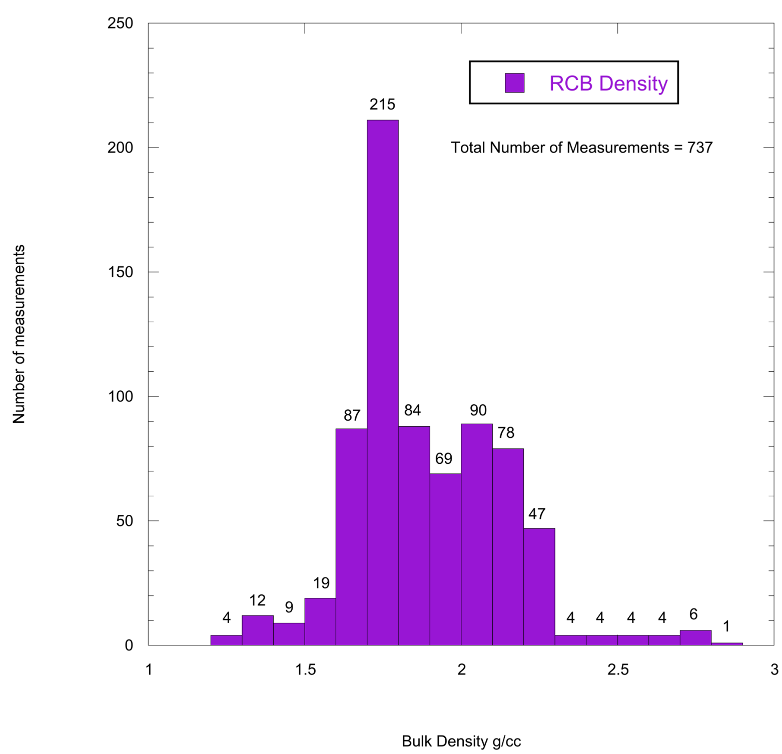

Nannofossil
APC Density
Total Number of Measurements = 3267
1069
716
701
299
214
128
84
26
1
15
6
2
1
1
2
2
Number of Measurements
Bulk Density g/cc
0
200
400
600
800
1000
1200
1
1.5
2
2.5
3

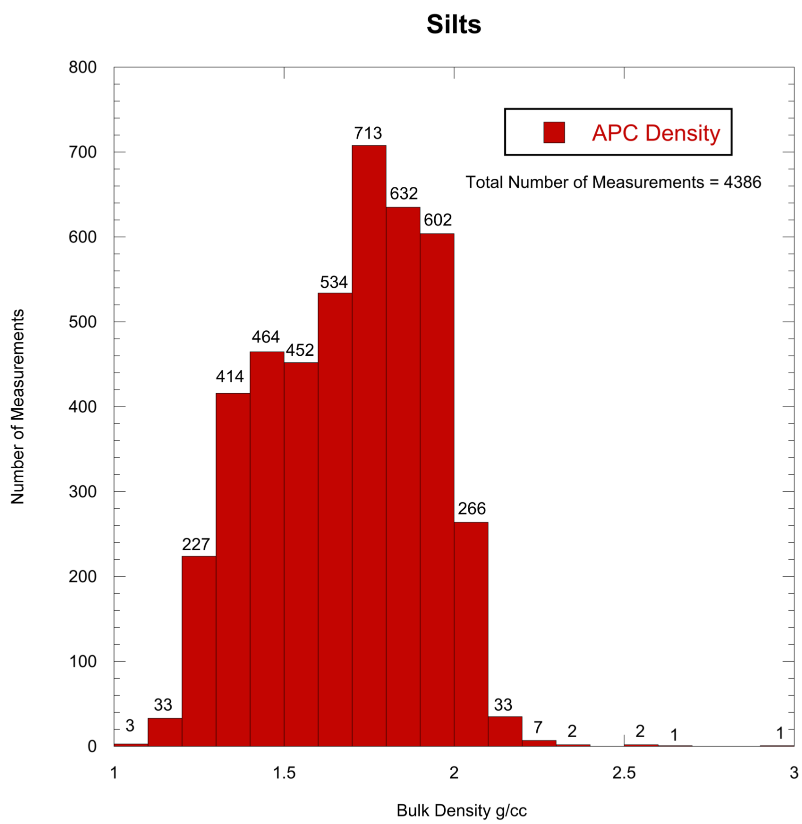

Nannofossil
HLAPC Density
Total Number of Measurements = 195
76
62
32
18
1
3
3
Number of measurements
Bulk Density g/cc
0
10
20
30
40
50
60
70
80
1
1.5
2
2.5
3

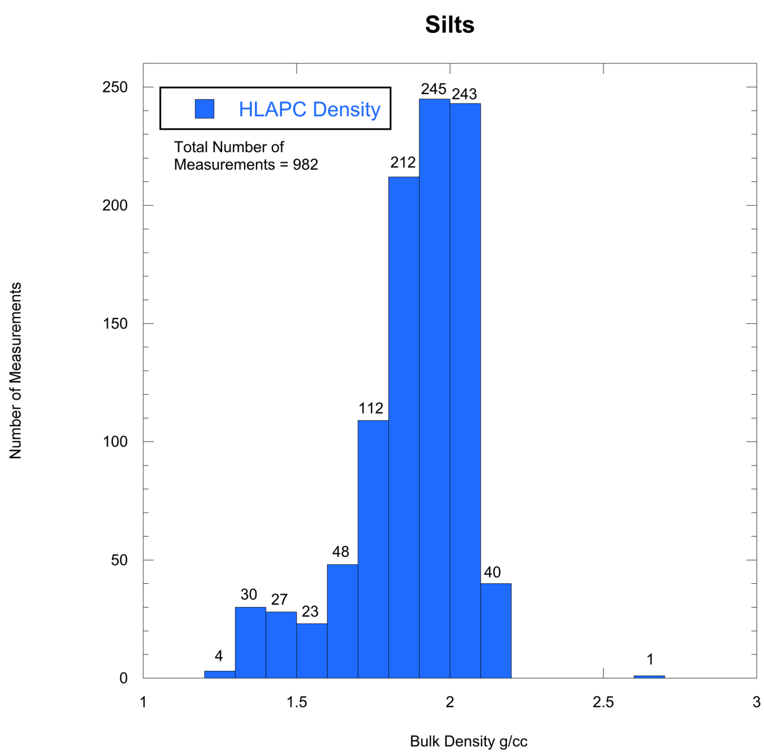
Nannofossil

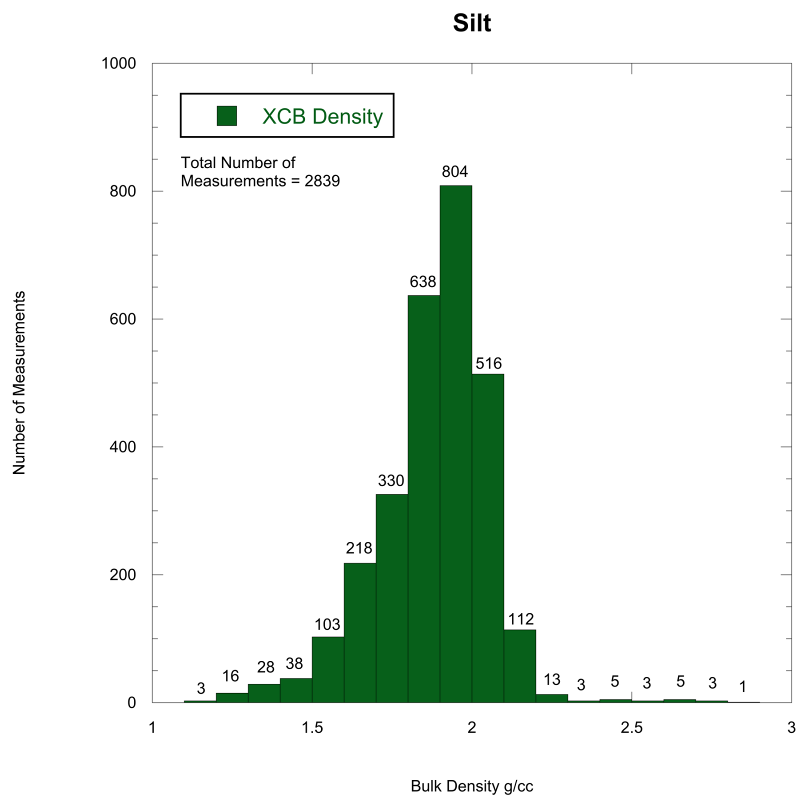


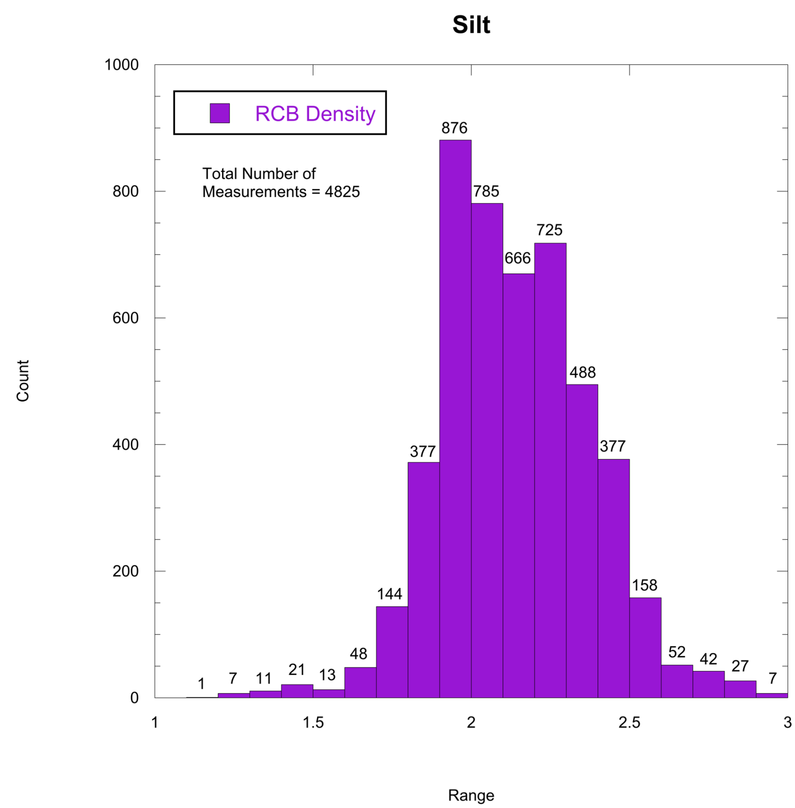
Nannofossil

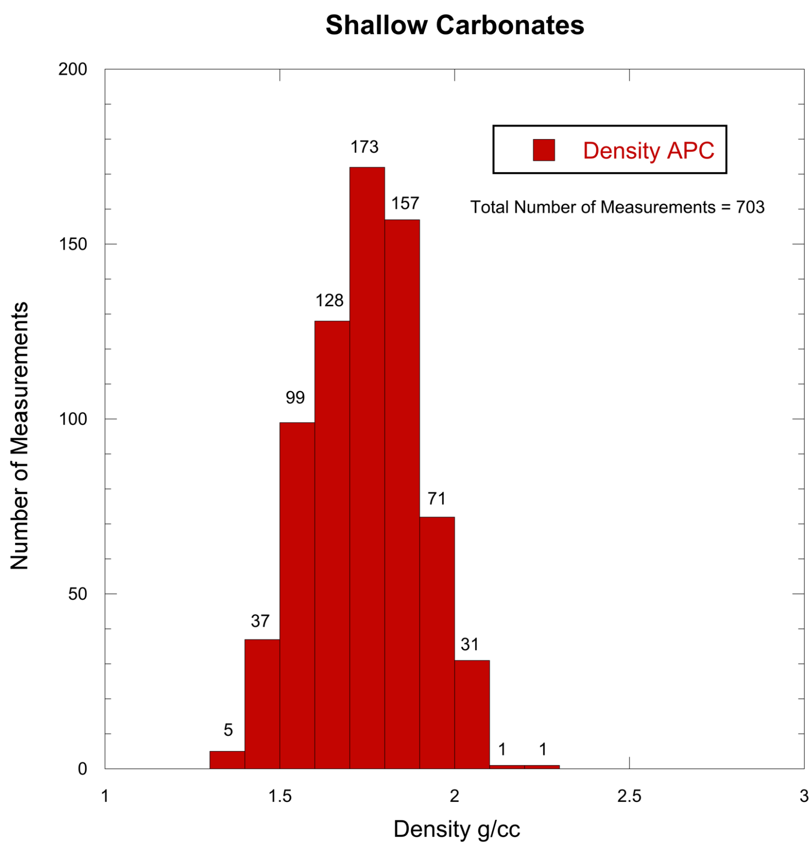



Silts
APC Density
Total Number of Measurements = 4386
Number of Measurements
Bulk Density g/cc
800
700
600
500
400
300
200
100
0
1
1.5
2
2.5
3
3
33
227
414
464
452
534
713
632
602
266
33
7
2
2
1
1

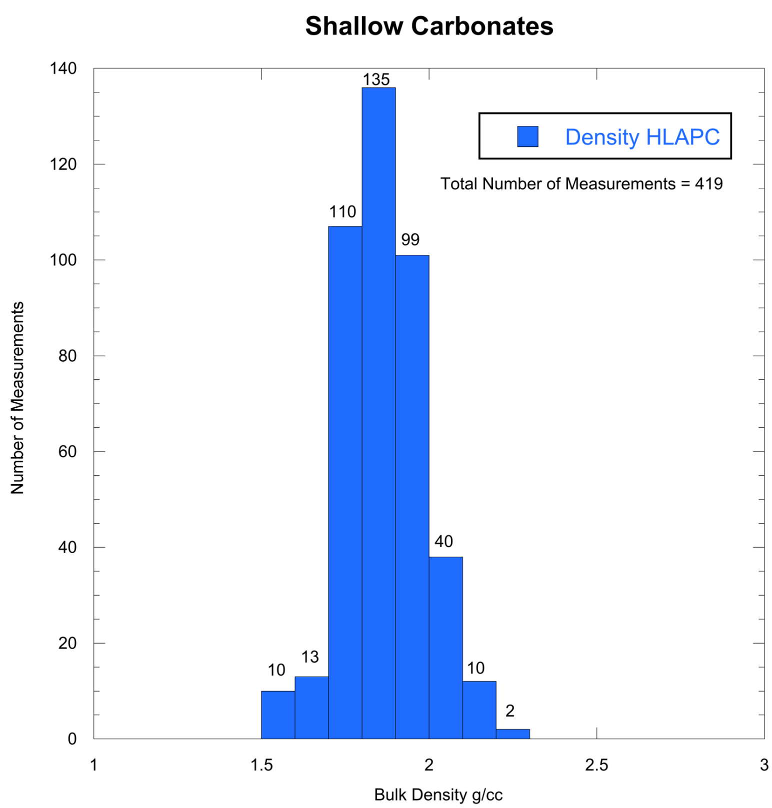

Silts
HLAPC Density
Total Number of Measurements = 982
Number of Measurements
Bulk Density g/cc
250
200
150
100
50
0
1
1.5
2
2.5
3
4
30
27
23
48
112
212
245
243
40
1


Silt
XCB Density
Total Number of Measurements = 2839
Number of Measurements
Bulk Density g/cc
3
16
28
38
103
218
330
638
804
516
112
13
3
5
3
5
3
1

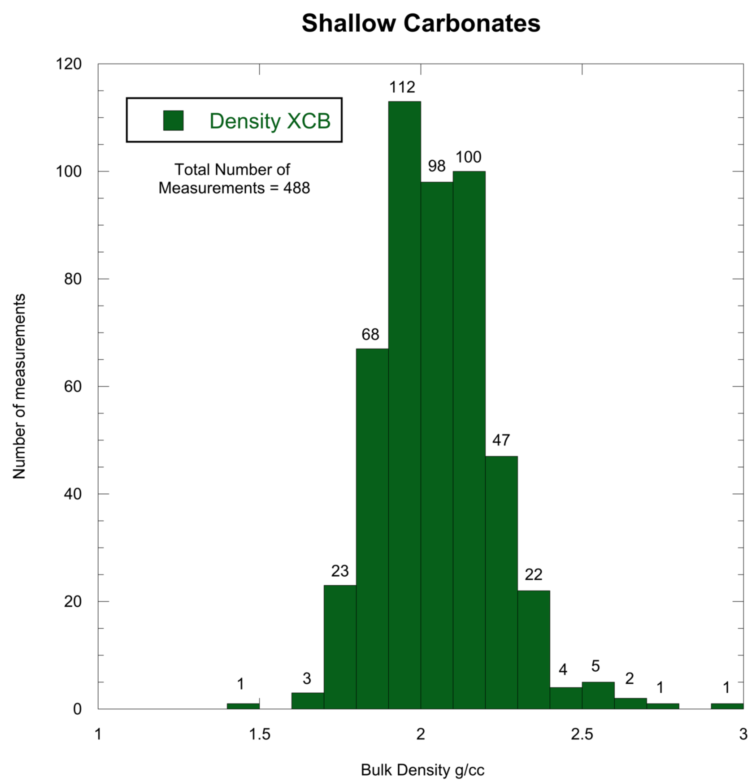

Silt
RCB Density
Total Number of Measurements = 4825
Count
Range
1
7
11
21
13
48
144
377
876
785
666
725
488
377
158
52
42
27
7

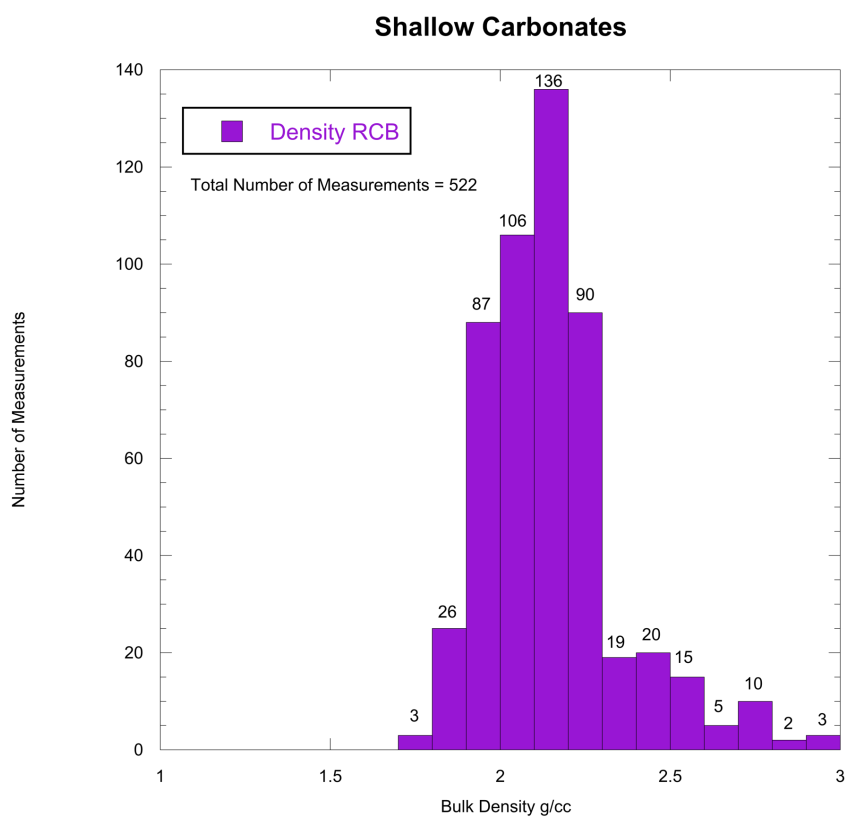


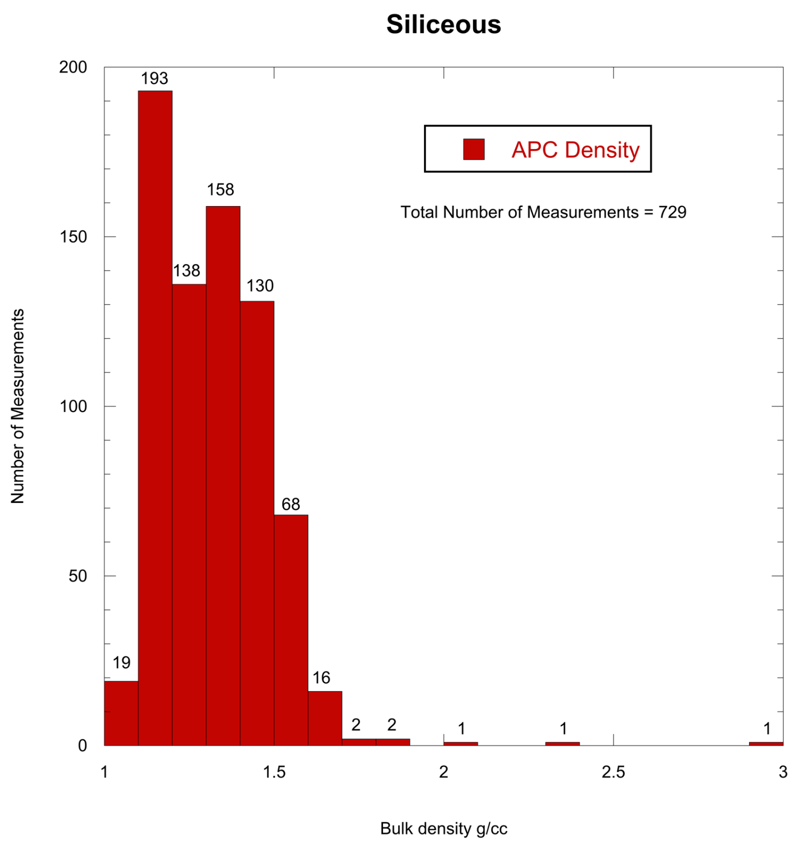
Shallow Carbonates
Density APC
Total Number of Measurements = 703
Number of Measurements
Density g/cc
200
150
100
50
0
1
1.5
2
2.5
3
173
157
128
99
71
37
31
5
1
1



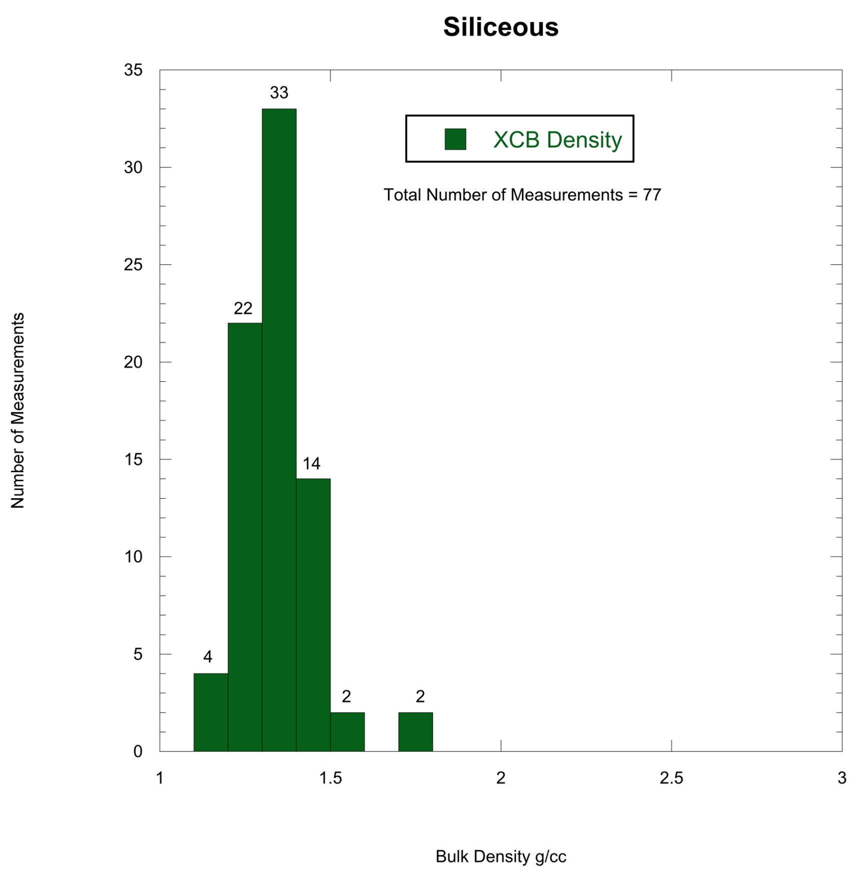
Shallow Carbonates
Density HLAPC
Total Number of Measurements = 419
Number of Measurements
Bulk Density g/cc
140
120
100
80
60
40
20
0
1
1.5
2
2.5
3
135
110
99
40
13
10
10
2


Shallow Carbonates
Density XCB
Total Number of Measurements = 488
112
98
100
68
47
23
22
1
3
4
5
2
1
1
120
100
80
60
40
20
0
1
1.5
2
2.5
3
Number of measurements
Bulk Density g/cc

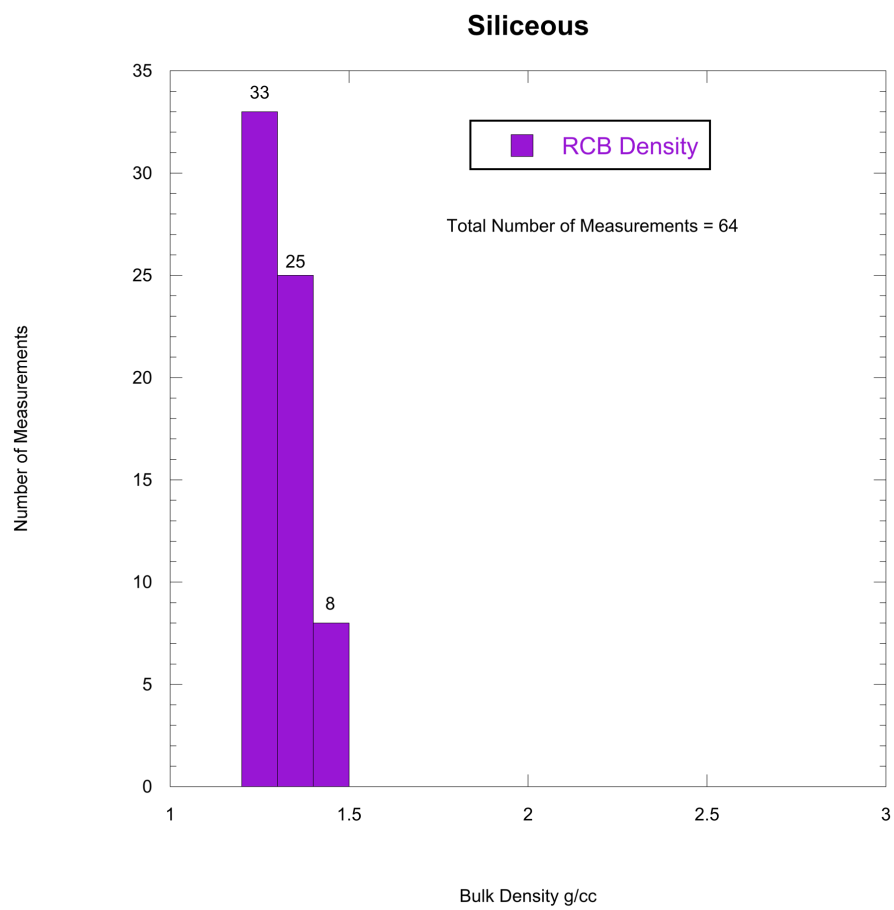

Shallow Carbonates
Density RCB
Total Number of Measurements = 522
136
106
87
90
26
19
20
15
3
5
10
2
3
140
120
100
80
60
40
20
0
1
1.5
2
2.5
3
Number of Measurements
Bulk Density g/cc

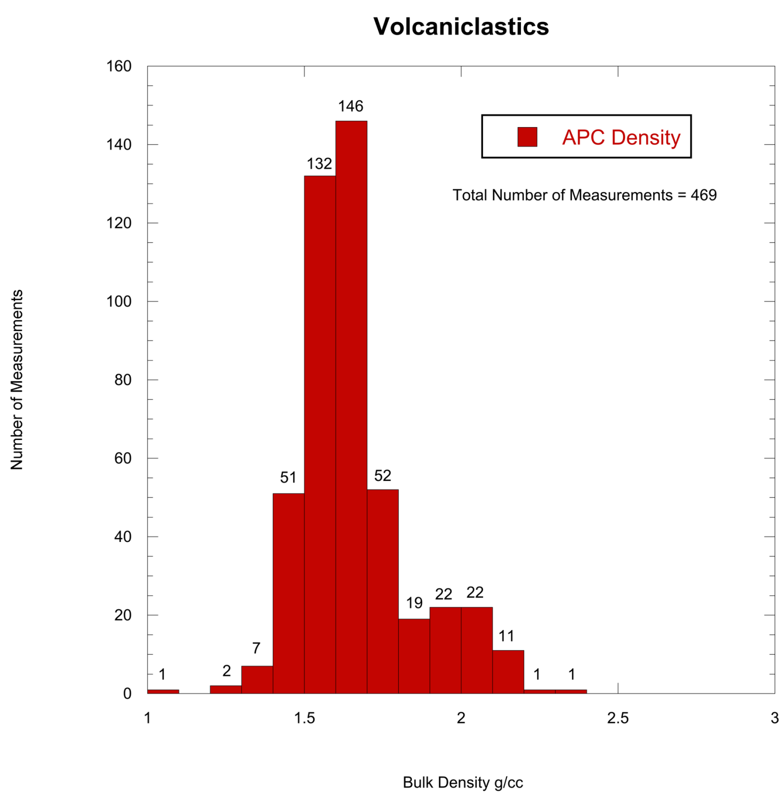


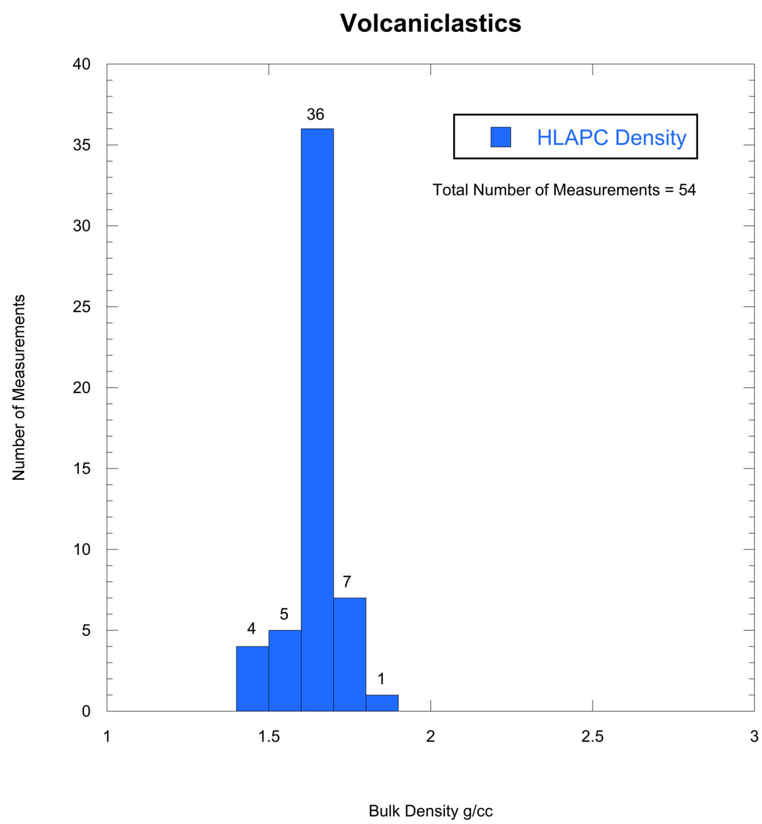
Siliceous
APC Density
Total Number of Measurements = 729
Number of Measurements
Bulk density g/cc
0
50
100
150
200
1
1.5
2
2.5
3
19
193
138
158
130
68
16
2
2
1
1
1

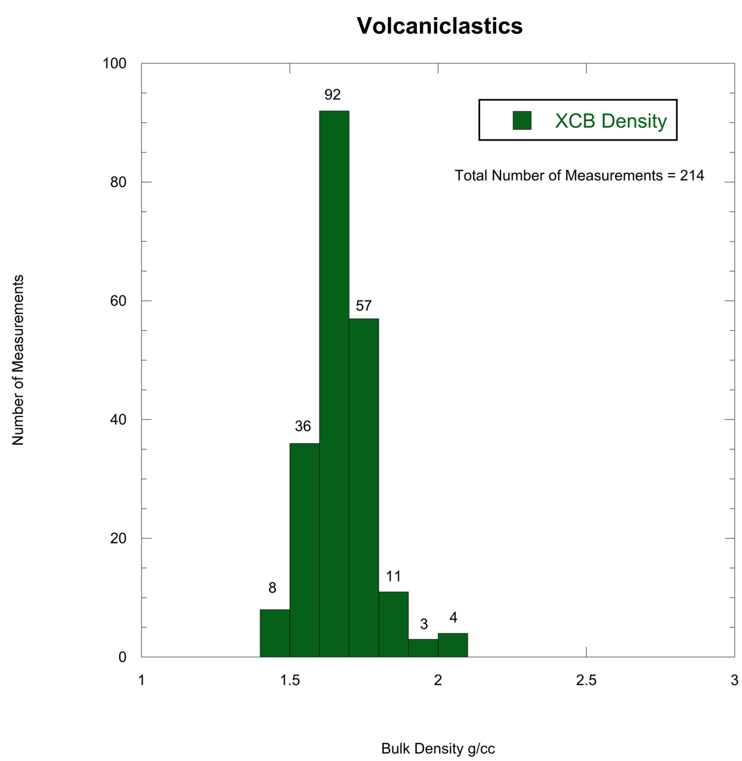


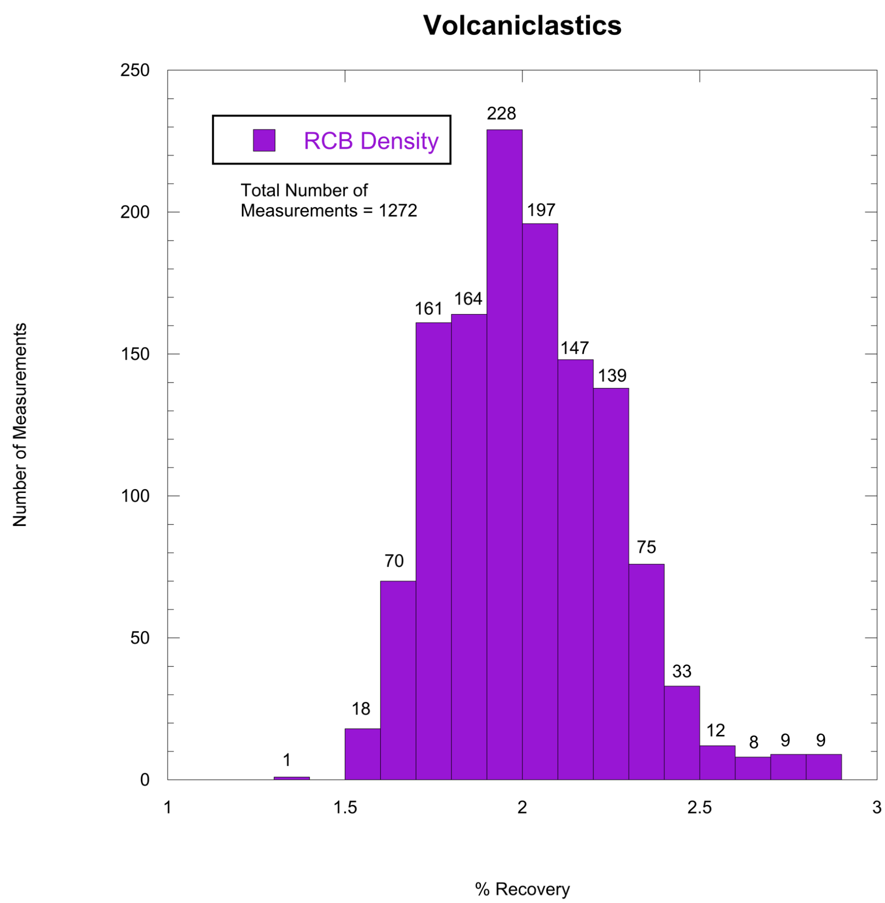
Siliceous
XCB Density
Total Number of Measurements = 77
Number of Measurements
Bulk Density g/cc
0
5
10
15
20
25
30
35
1
1.5
2
2.5
3
4
22
33
14
2
2

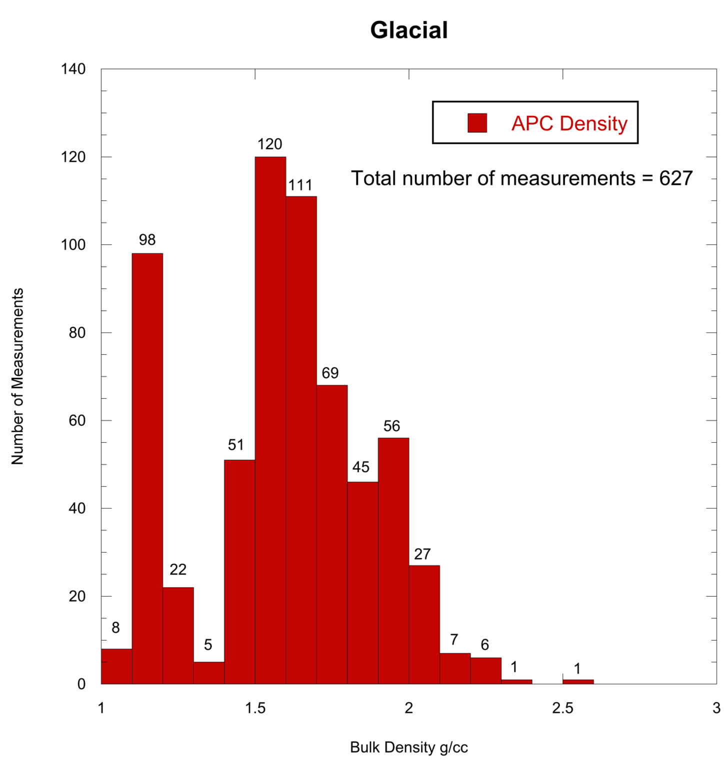

Siliceous
RCB Density
Total Number of Measurements = 64
Number of Measurements
Bulk Density g/cc
33
25
8
0
5
10
15
20
25
30
35
1
1.5
2
2.5
3

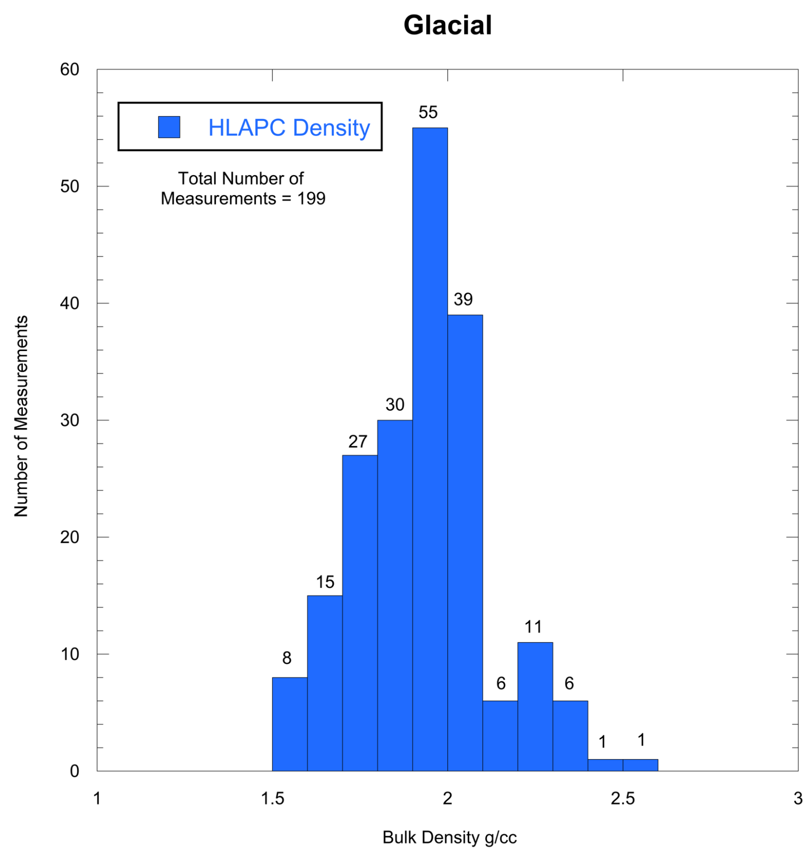

Volcaniclastics
APC Density
Total Number of Measurements = 469
Number of Measurements
Bulk Density g/cc
1
2
7
51
132
146
52
19
22
22
11
1
1
0
20
40
60
80
100
120
140
160
1
1.5
2
2.5
3

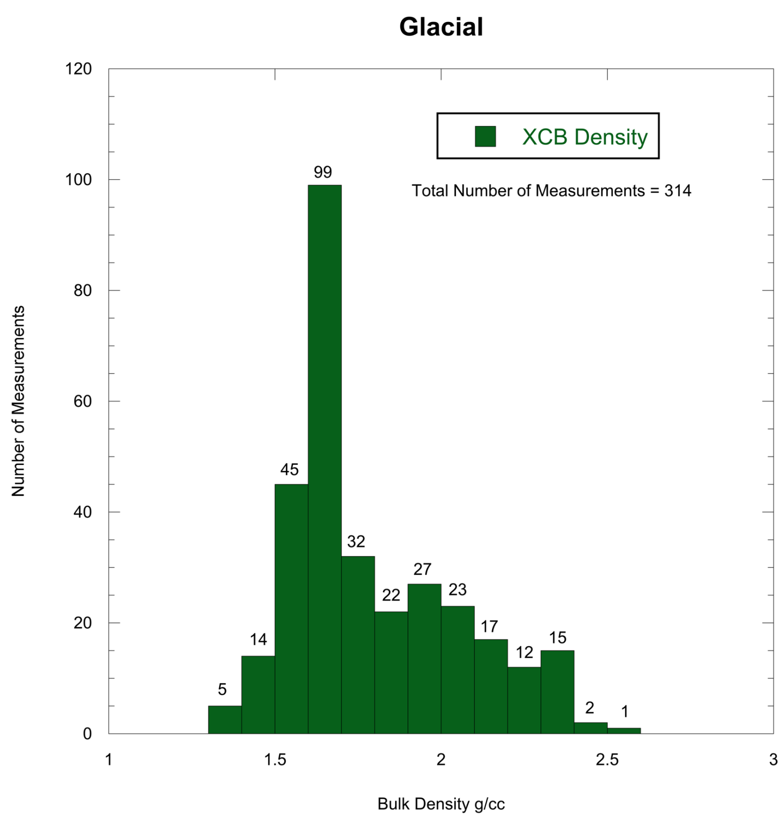

Volcaniclastics
HLAPC Density
Total Number of Measurements = 54
Number of Measurements
Bulk Density g/cc
0
5
10
15
20
25
30
35
40
1
1.5
2
2.5
3
4
5
36
7
1

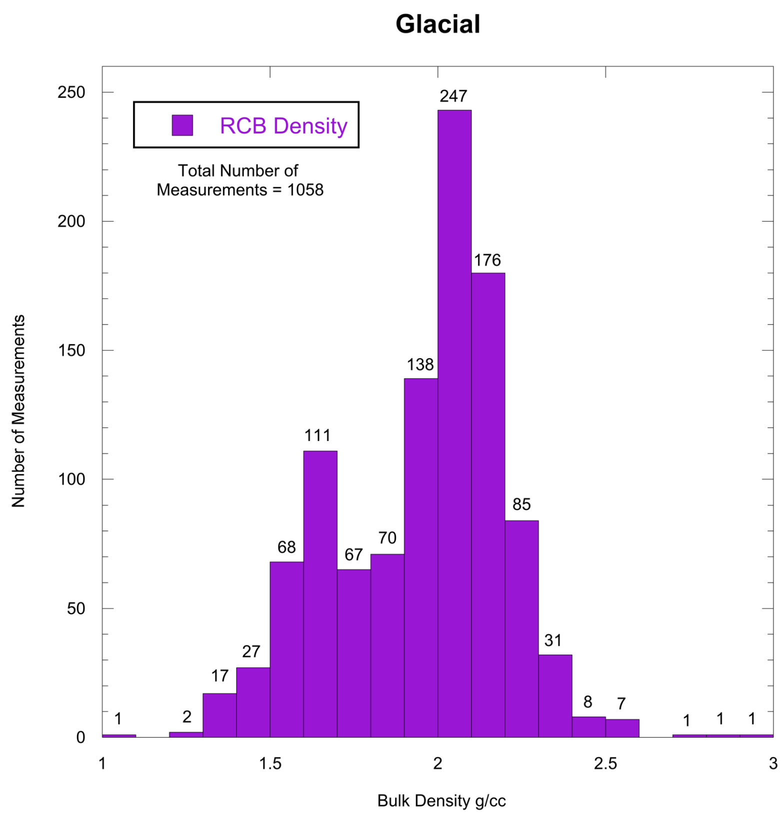

Volcaniclastics
XCB Density
Total Number of Measurements = 214
Number of Measurements
Bulk Density g/cc
0
20
40
60
80
100
1
1.5
2
2.5
3
8
36
92
57
11
3
4


Volcaniclastics
RCB Density
Total Number of Measurements = 1272
Number of Measurements
% Recovery
250
200
150
100
50
0
1
1.5
2
2.5
3
1
18
70
161
164
228
197
147
139
75
33
12
8
9
9


Glacial
APC Density
Total number of measurements = 627
Number of Measurements
Bulk Density g/cc
140
120
100
80
60
40
20
0
1
1.5
2
2.5
3
8
98
22
5
51
120
111
69
45
56
27
7
6
1
1


Glacial
HLAPC Density
Total Number of
Measurements = 199
Number of Measurements
Bulk Density g/cc
60
50
40
30
20
10
0
1
1.5
2
2.5
3
55
39
30
27
15
8
11
6
6
1
1


Glacial
XCB Density
Total Number of Measurements = 314
Number of Measurements
Bulk Density g/cc
120
100
80
60
40
20
0
1
1.5
2
2.5
3
99
45
32
27
23
22
17
15
14
12
5
2
1


Glacial
RCB Density
Total Number of Measurements = 1058
Number of Measurements
Bulk Density g/cc
0
50
100
150
200
250
1
1.5
2
2.5
3
1
2
17
27
68
111
67
70
138
247
176
85
31
8
7
1
1
1