THE SHAPES OF BEACH PEBBLES.

By Chester K. Wentworth.

PURPOSE OF THE STUDY.

There is much confusion in geologic literature as to the shapes of fluvial and beach pebbles and the differences between them, if differences exist. Though the contrary has been asserted, most geologists who have written on the subject appear to hold the view that beach pebbles are generally flatter than river pebbles, having discoid, lozenge-shaped, ellipsoid, or oval forms.[1] It is asserted by some that these forms are produced by pushing of the rock fragments to and fro by the waves.[2] Others have considered that the shapes of the original fragments and the inherent structure of the rock are dominant in determining the shapes of beach pebbles,[3] and with this view the writer is in accord. That beach pebbles, even those composed of massive igneous rocks, are commonly of a flattened oval form seems certain, as has been stated elsewhere,[4] but this fact is probably to be attributed to the development of such forms from original flat fragments or from rocks of schistose structure or to the segregation of such forms under the peculiar action of the waves, rather than to their production by a specialized wave abrasion.

Though many opinions on the subject have been expressed, no one, so far as known to the writer, has made any quantitative test of the development of such shapes on a beach. It was the writer's good fortune during the summer of 1921 to visit two localities on the Atlantic coast of New England where pebbles are being produced by wave abrasion of igneous rock in place. At these localities he measured more than 300 pebbles with the hope of obtaining evidence that would be conclusive, at least so far as these localities are concerned. The results obtained are presented on the following pages. It is the writer's hope that geologists acquainted with localities where similar measurements might be made or where conditions of wave abrasion are especially effective or peculiar will refer him to such places.

BEACH CONDITIONS.

The first locality visited was at the south extremity of Nantasket Beach, at the point shown on the topographic map of the Boston Bay quadrangle under the capital A of "Atlantic." Here, on the east side of the point, is a beach about 200 feet in length which is composed of material ranging from sand to blocks and boulders a foot or more in diameter. At each end the beach is terminated by low promontories of the local light-green to gray igneous rock, which is included in the Mattapan volcanic complex as mapped by Emerson.[5] The greater part of the gravel of the beach is derived from the adjacent outcrops, which show, however, great variations in type within short distances, including some pyroclastic and sedimentary derivatives of the igneous rock. In addition to the local rock there is a considerable admixture of pebbles of granite, porphyry, breccia, felsite, and many other kinds of igneous rock from other parts of eastern Massachusetts which have been transported by glacial ice, by streams, and by shore currents. The general character of the beach gravel is shown in Plate XXVI. The conditions of abrasion at this point are those of a pocket beach. The tides rise and fall, shifting the zone of abrasion by several feet in height and about 75 to 100 feet horizontally. Storm waves break high over the north-south beach ridge and both adjacent rock promontories. Gravel is not transported to any extent from the beach, either

[1] Suess, E., Der Boden der Stadt Wien, pp. 64, 65, 1882 (quoted from Grabau, A. W., Principles of stratigraphy, p. 595, 1913).
Hoernes, R., Gerölle und Geschiebe: K.-k. geol. Reichsanstalt Verh. No. 12, pp. 42 et seq., 1911 (quoted from Grabau, A. W., op. cit., p. 595).
Cole, G. A. J., Rocks and their origins, p. 71, Cambridge Univ. Press, 1912.
Trowbridge, A. C., Classification of common sediments: Jour. Geology, vol. 22, p. 435, 1914.
Stephenson, L. W., The Coastal Plain of North Carolina: North Carolina Geol. and Econ. Survey, vol. 3, pp. 274-275, 1912.
Geikie, A., Textbook of geology, vol. 1, p. 569, 1903.

[2] Suess, E., op. cit. Hoernes, R., op. cit. Cole, G. A. J., op. cit.

[3] Grabau, A. W., Principles of stratigraphy, pp. 715-716, 1913.
Dunn, E. J., Pebbles, p. 7, Sydney, G. Robertson & Co., 1911.

[4] Wentworth, C. K., Quantitative studies of the shapes of pebbles (unpublished thesis, Iowa State Univ.).

[5] Emerson, B. K., U. S. Geol. Survey Bull. 597, p. 200, 1917.

alongshore or out to deep water, and remains indefinitely in the zone of effective abrasion. The coast at this place trends northwest, and the beach is exposed to the full force of waves from the northeast, but not so much to those from south of east.

The site of the second series of measurements was the rocky shore at the entrance to New Haven Harbor, near Fort Hale, Conn. Here, for a distance of several hundred feet, is a wave-cut cliff and abrasion platform cut in the end of a north-south ridge of Triassic trap that reaches the shore. Along the cliff and strewn in both directions on the beach is considerable gravel composed of trap from the local exposure. This gravel extends only a few hundred feet in each direction, giving way to sand and finer materials. Mingled with the trap pebbles of the gravel are a few pebbles and larger pieces from the glacial till that overlies the bedrock at the top of the cliff and is exposed lower down along the adjacent parts of the shore. These are readily identified by inspection. The general character of the shore and gravel at this point is shown in Plate XXVII.

On this beach wave action is far less effective as an agent of abrasion than at Nantasket. Not only are the waves in this part of Long Island Sound less violent than those of the Atlantic Ocean at Nantasket, but the pebbles here are not confined in a pocket beach.

METHODS OF MEASUREMENT.

Three diameters mutually at right angles were measured for each pebble with a steel tape. The radius of curvature of the sharpest edge of each was measured with the convexity gage described elsewhere.[6] All measurements were in millimeters. The data were recorded in several groups as follows:

	Pebbles.
Nantasket:	
A. Random selection, all materials	61
B. Miscellaneous rock types:	
Quartzite	20
Red porphyry	20
Black porphyry	10
Granite	10
	60
C. Local volcanic rock	80
	201
Fort Hale:	
D. Local trap	101

[6] Wentworth, C. K., Quantitative studies of the shapes of pebbles (unpublished thesis, Iowa State Univ.), p. 61, 1921. See also Wentworth, C. K., The shapes of pebbles: U. S. Geol. Survey Bull. 730, pp. 91-114, 1922.

LABORATORY DETERMINATIONS.

The relative resistance of the local rocks at the two beaches was determined by an abrasion test in the tumbling mill. Four pebbles of each rock were ground at one end on a lap to a sharp 90° edge. They were then subjected to abrasion in the mill for a total distance of about 80 miles. Measurements of the convexity of the prepared edge were made at intervals, and the resulting data were used in comparing the durability of the two types of rock.

COMPUTATIONS.

Computations were made as follows for each pebble:

Mean diameter,[7] computed approximately by the formula $D=\sqrt[3]{D'D''D'''}$ where D', D'', and D''' are the length, breadth, and thickness as measured in the field.

Roundness ratio, $\frac{r_1}{R}=\frac{2r_1}{D}$, where r_1 is the radius of curvature in millimeters of the sharpest edge and R is the mean radius of the pebble.

Flatness ratio, $\frac{D'+D''}{2D'''}$ or the average of the length and breadth divided by the thickness.

All these values were computed to two significant figures by the use of graphic charts. Further description of these ratios and methods of computation has been given elsewhere.[8]

RESULTS.

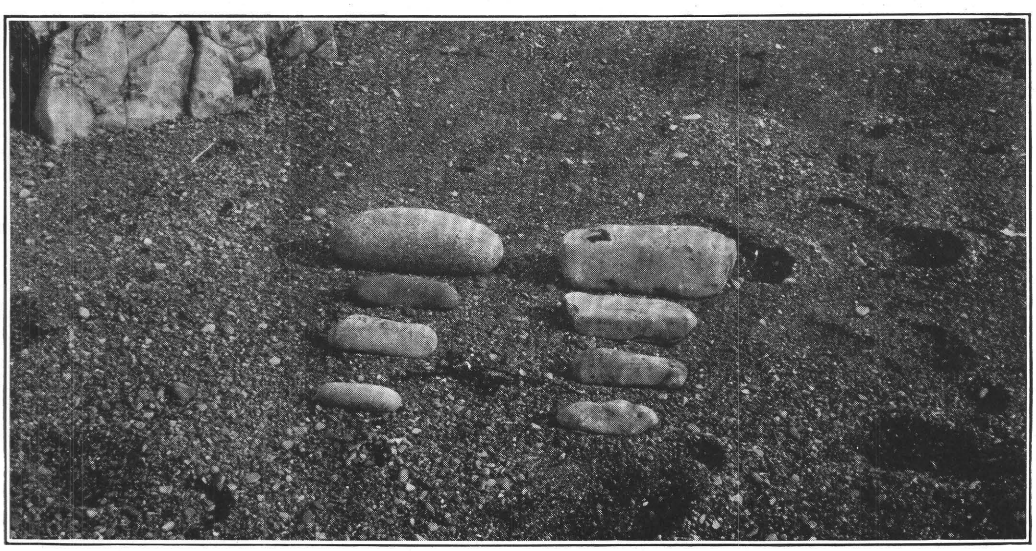
The results of the measurements are plotted on the graphs of figures 5 to 10. The variations of the roundness ratios are so great that for practical considerations it seems better to average these ratios by subgroups. These averages were made as described below, and the subgroups are indicated by the large dots in figure 5 and by all the dots in figures 6 to 10, where the number of pebbles represented by each dot is shown by the small accompanying figures. In the subgroups marked X under

[7] The writer's use of the term "mean diameter" is open to the objection that in the use of the approximate formula given above the true value of the arithmetic mean of all diameters (the ideal concept of the term) is not derived. The writer does not consider the objection to be serious, for it applies in varying degree to all physical constants that are based on empirical data. It is customary to speak of the values derived for these constants as the theoretical constants themselves, and the common practice seems not to be unduly confusing. Therefore, in the following pages where the term "mean diameter" is used, the actual numerical values are understood to be approximations to the true arithmetical mean of all diameters.

[8] Wentworth, C. K., The shapes of pebbles: U. S. Geol. Survey Bull. 730, pp. 91-114, 1922.

A. GRAVEL IN POCKET BEACH SOUTH OF NANTASKET, MASS.

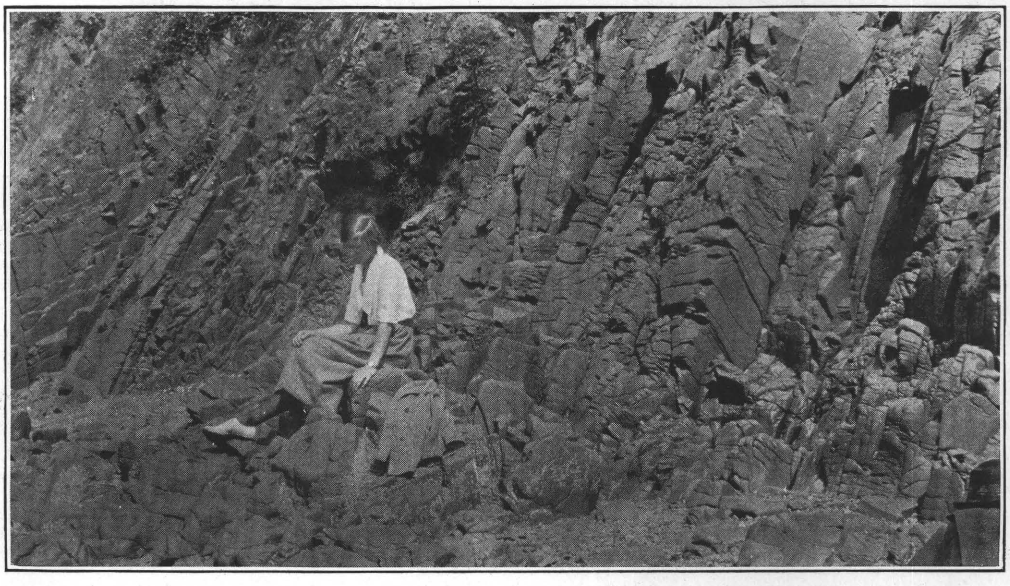
B. GRAVEL AND JOINTED ROCK OF PROMONTORY SOUTH OF NANTASKET, MASS.



C. ROLLER-SHAPED COBBLES IN TWO STAGES OF FORMATION, POCKET BEACH SOUTH OF NANTASKET, MASS.

A. BEACH AT FORT HALE, CONN.

The cliff in the middle distance is the source of pebble material.



B. NEAR VIEW OF CLIFF OF JOINTED TRAP AND LANDWARD EDGE OF ABRASION PLATFORM AT FORT HALE, CONN.

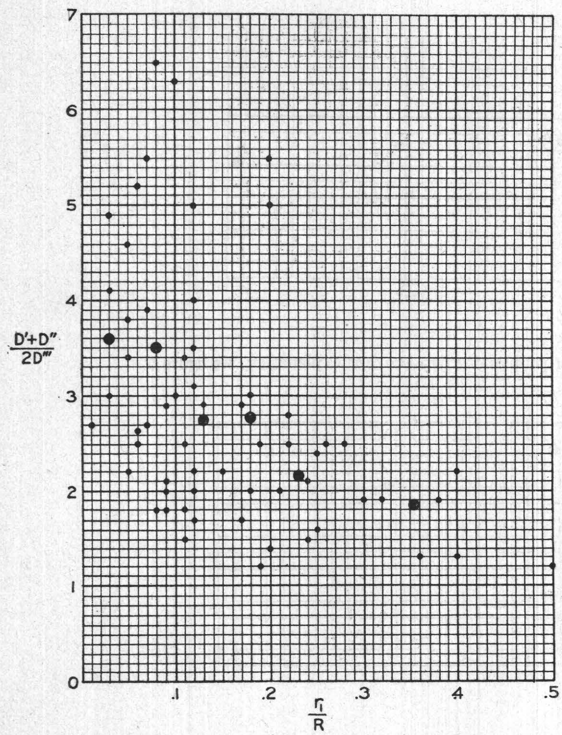


FIGURE 5.—Graph showing flatness ratios $\frac{D'+D''}{2\,D'''}$ (ordinate) and roundness ratios $\frac{r_1}{R}$ (abscissa) of 61 pebbles of group A at Nantasket, Mass. Large dots show average positions for subgroups of pebbles. (See fig. 6.)

"Method of computing averages" in the following table the values of $\frac{D'+D''}{2D'''}$ for all the pebbles of the subgroup were averaged arithmetically for the ordinate, and the mean of the limits of $\frac{r_1}{R}$ for the subgroup was used for abscissa. In the subgroups marked Y the values of $\frac{D'+D''}{2\,D'''}$ were averaged similarly for the ordinate and the values of $\frac{r_1}{R}$ for all the pebbles of the subgroup were averaged arithmetically for the abscissa. Method X was used for the subgroups in which values of $\frac{r_1}{R}$ were fairly uniformly and thickly distributed; method Y was used for subgroups in which a few erratic points needed to be averaged. The subgroup limits were chosen to avoid as far as possible very small subgroups or very great differences in the number of pebbles in adjacent subgroups. No data were rejected, and every measurement taken in the field is represented in the averages here presented.

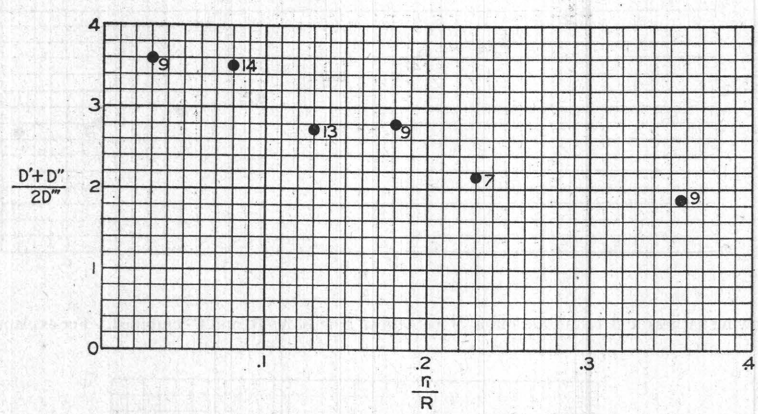


FIGURE 6.—Graph showing flatness and roundness of 61 pebbles of group A. The flatness ratio $\frac{D'+D''}{2\,D'''}$ is plotted as the ordinate and the roundness ratio $\frac{r_1}{R}$ as the abscissa. For simplicity, the pebbles are arranged in subgroups, and each large dot shows the mean position of the number of pebbles indicated by the small figures. It is apparent that as the roundness increases the flatness decreases.

91048°—23——6

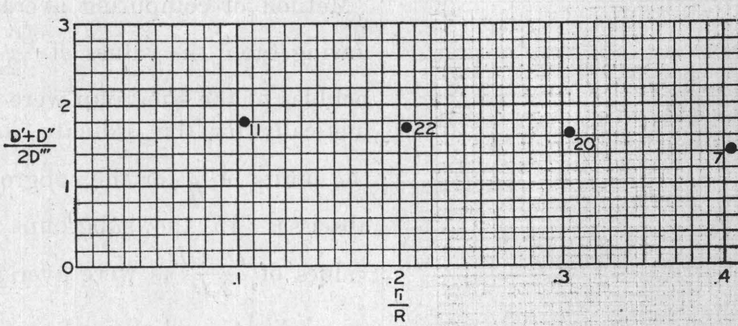


FIGURE 7.—Graph showing flatness and roundness ratios of pebbles of group B. For explanation, see figure 6.

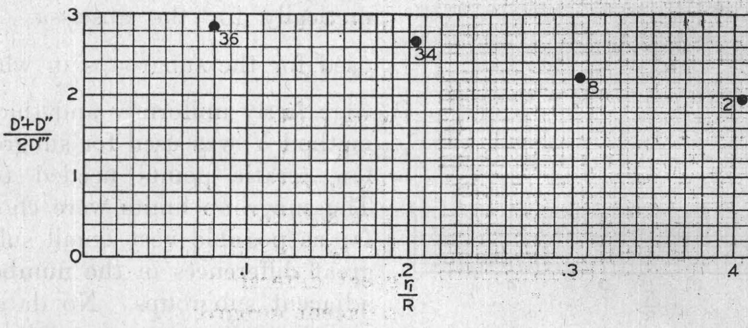


FIGURE 8.—Graph showing flatness and roundness ratios of pebbles of group C. For explanation, see figure 6.

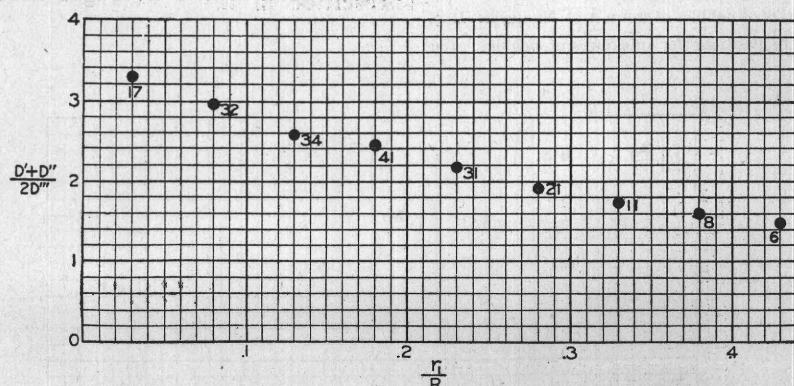


FIGURE 9.—Graph showing flatness and roundness ratios of pebbles of groups A, B, and C combined. For explanation, see figure 6.

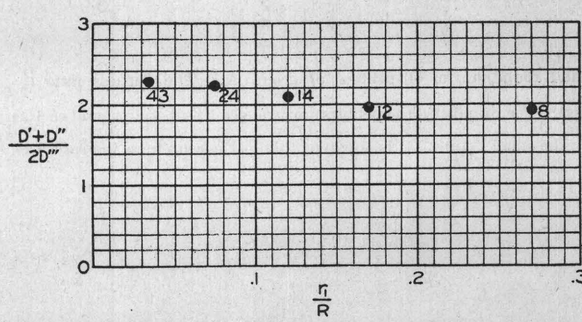


FIGURE 10.—Graph showing flatness and roundness ratios of pebbles of group D. For explanation, see figure 6.

Method of computing averages for subgroups.

Graph.	Group.	Subgroup.	$\frac{r_1}{R}$	Method of computing averages.
Figures 5 and 6, five large dots at left...	A	1	0. 01–0. 05	X
		2	. 06– . 10	
		3	. 11– . 15	
		4	. 16– . 20	
		5	. 21– . 25	
Figures 5 and 6, large dot at right..	A	6	. 26 and over	Y
Figure 7, all dots....	B	7	. 06– . 15	X
		8	. 16– . 25	
		9	. 26– . 35	
		10	. 36– . 45	
Figure 8, all dots....	C	11	. 01– . 15	X
		12	. 16– . 25	
		13	. 26– . 35	
		14	. 36– . 45	
Figure 9, all dots....	A,B,C	15	. 01– . 05	X
		16	. 06– . 10	
		17	. 11– . 15	
		18	. 16– . 20	
		19	. 21– . 25	
		20	. 26– . 30	
		21	. 31– . 35	
		22	. 36– . 40	
		23	. 41– . 45	
Figure 10, four dots at left............	D	24	. 02– . 05	X
		25	. 06– . 09	
		26	. 10– . 14	
		27	. 15– . 19	
Figure 10, dot at right..............	D	28	. 20– . 45	Y

Roundness and flatness ratios of pebbles.

Group A, figures 5 and 6.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
1..........	0. 01	2. 7	Method X, abscissa 0.03; ordinate (32.3÷9) 3.59.
	. 05	2. 2	
	. 03	3. 6	
	. 03	3. 0	
	. 03	4. 1	
	. 05	3. 8	
	. 05	4. 6	
	. 05	3. 4	
	. 03	4. 9	
		32. 3	
2..........	. 07	3. 9	Method X, abscissa 0. 08; ordinate (49.0÷14) 3.50.
	. 07	2. 7	
	. 09	2. 9	
	. 08	6. 5	
	. 08	1. 8	
	. 10	6. 3	
	. 06	5. 2	
	. 06	2. 5	
	. 10	3. 0	
	. 09	2. 1	
	. 07	5. 5	
	. 09	2. 0	
	. 09	2. 0	
	. 06	2. 6	
		49. 0	

Roundness and flatness ratios of pebbles—Continued.

Group A, figures 5 and 6—Continued.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
3..........	0. 12	3. 1	Method X, abscissa 0.13; ordinate (35.5÷13) 2.73.
	. 12	1. 7	
	. 11	3. 4	
	. 12	5. 0	
	. 11	1. 5	
	. 12	4. 0	
	. 12	3. 5	
	. 12	2. 2	
	. 11	2. 5	
	. 15	2. 2	
	. 12	2. 0	
	. 13	2. 9	
	. 11	1. 5	
		35. 5	
4..........	. 17	2. 9	Method X, abscissa 0.18; ordinate (25.2÷9) 2.80
	. 19	5. 5	
	. 18	3. 0	
	. 19	5. 0	
	. 18	2. 0	
	. 19	2. 5	
	. 20	1. 4	
	. 19	1. 2	
	. 17	1. 7	
		25. 2	
5..........	. 22	2. 5	Method X, abscissa 0.23; ordinate (14.9÷7) 2.13.
	. 22	2. 8	
	. 21	2. 0	
	. 24	2. 1	
	. 25	1. 6	
	. 25	2. 4	
	. 24	1. 5	
		14. 9	
6..........	. 28	2. 5	Method Y, abscissa (3.20 ÷9) 0.355; ordinate (16.7÷9) 1.86.
	. 26	2. 5	
	. 32	1. 9	
	. 40	1. 3	
	. 40	2. 2	
	. 50	1. 2	
	. 30	1. 9	
	. 36	1. 3	
	. 38	1. 9	
	3. 20	16. 7	

Group B, figure 7.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
7..........	0. 13	1. 3	Method X, abscissa 0.105; ordinate (19.7÷11) 1.79.
	. 08	1. 9	
	. 09	1. 7	
	. 14	1. 4	
	. 09	1. 8	
	. 13	1. 5	
	. 09	3. 2	
	. 13	2. 2	
	. 11	1. 8	
	. 14	1. 6	
	. 15	1. 3	
		19. 7	

Roundness and flatness ratios of pebbles—Continued.

Group B, figure 7—Continued.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
8	0.19	1.7	Method A, abscissa 0.205; ordinate (37.4÷22) 1.70.
	.25	2.0	
	.23	2.1	
	.21	2.6	
	.22	2.2	
	.23	1.2	
	.24	1.4	
	.18	1.6	
	.19	1.9	
	.25	1.2	
	.18	1.5	
	.16	1.6	
	.20	1.6	
	.19	1.2	
	.16	1.2	
	.19	1.8	
	.25	1.4	
	.23	2.2	
	.22	1.2	
	.16	1.9	
	.21	2.0	
	.22	1.9	
		37.4	
9	.32	2.0	Method X, abscissa 0.305; ordinate (32.5÷20) 1.63.
	.26	1.4	
	.34	1.5	
	.30	1.5	
	.26	1.6	
	.26	1.8	
	.26	1.8	
	.34	1.8	
	.28	1.7	
	.32	1.8	
	.30	1.6	
	.26	2.0	
	.26	1.9	
	.32	1.8	
	.28	1.4	
	.26	1.7	
	.30	1.1	
	.32	1.1	
	.32	1.5	
	.28	1.5	
		32.5	
10	.45	1.3	Method X, abscissa 0.405; ordinate (9.9÷7) 1.41.
	.40	1.5	
	.38	1.4	
	.42	1.3	
	.40	1.2	
	.45	1.6	
	.45	1.6	
		9.9	

Group C, figure 8.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
11	0.05	2.5	
	.03	2.0	
	.02	2.3	
	.04	3.2	
	.05	3.3	
	.02	3.8	
	.04	3.4	

Roundness and flatness ratios of pebbles—Continued.

Group C, figure 8—Continued.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
11.—Contd.	0.05	3.2	Method X, abscissa 0.08; ordinate (102.7÷36) 2.85.
	.13	2.2	
	.08	1.8	
	.13	2.2	
	.14	3.1	
	.07	4.7	
	.10	1.2	
	.12	2.2	
	.10	2.4	
	.15	2.1	
	.10	1.5	
	.15	1.7	
	.08	3.9	
	.12	2.6	
	.08	2.3	
	.14	3.1	
	.12	2.2	
	.14	7.1	
	.15	3.3	
	.14	3.0	
	.10	2.7	
	.14	3.7	
	.07	3.4	
	.09	2.4	
	.08	2.3	
	.09	3.9	
	.11	3.7	
	.08	2.0	
	.13	2.2	
		102.7	
12	.16	2.2	Method X, abscissa 0.205; ordinate (90.5÷34) 2.66.
	.16	1.2	
	.25	4.3	
	.22	2.5	
	.16	1.7	
	.20	4.0	
	.16	1.8	
	.18	2.8	
	.20	1.8	
	.22	3.5	
	.17	1.9	
	.21	4.5	
	.24	2.5	
	.18	5.3	
	.18	2.1	
	.23	1.8	
	.17	1.7	
	.22	1.7	
	.22	1.7	
	.16	1.9	
	.18	2.3	
	.23	1.3	
	.17	3.1	
	.19	2.0	
	.16	2.7	
	.19	5.5	
	.25	3.2	
	.18	2.5	
	.20	2.8	
	.18	3.2	
	.25	2.0	
	.16	2.3	
	.17	3.5	
	.17	3.2	
		90.5	

Roundness and flatness ratios of pebbles—Continued.

Group C, figure 8—Continued.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
13	0.32	1.5	Method X, abscissa 0.305; ordinate (17.7÷8) 2.21.
	.26	2.1	
	.28	3.3	
	.26	2.7	
	.34	1.8	
	.26	2.1	
	.26	1.9	
	.26	2.3	
		17.7	
14	.45	1.9	Method X, abscissa 0.405; ordinate (3.9÷2) 1.95.
	.40	2.0	
		3.9	

Groups A, B, and C combined, figure 9. [a]

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
15	.....	56.0	Abscissa 0.03; ordinate (56.0÷17) 3.29.
16	.....	95.1	Abscissa 0.08; ordinate (95.1÷32) 2.98.
17	.....	88.1	Abscissa 0.13; ordinate (88.1÷34) 2.59.
18	.....	100.4	Abscissa 0.18; ordinate (100.4÷41) 2.45.
19	.....	67.6	Abscissa 0.23; ordinate (67.6÷31) 2.18.
20	.....	40.1	Abscissa 0.28; ordinate (40.1÷21) 1.91.
21	.....	19.0	Abscissa 0.33; ordinate (19.0÷11) 1.73.
22	.....	12.8	Abscissa 0.38; ordinate (12.8÷8) 1.60.
23	.....	8.9	Abscissa 0.43; ordinate (8.9÷6) 1.48.

Group D, figure 10.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
24	0.02	2.1	
	.02	2.5	
	.03	2.3	
	.03	1.8	
	.03	1.8	
	.04	2.7	
	.05	2.9	
	.05	1.9	
	.04	2.7	
	.02	2.3	
	.03	1.6	
	.02	2.4	
	.03	1.9	
	.02	2.7	
	.03	2.5	
	.04	1.8	
	.02	3.1	
	.02	2.8	
	.05	4.0	
	.04	1.7	
	.05	1.5	
	.05	2.0	

[a] The averages for subgroups 15 to 23 were computed by method X. The measurements for the individual pebbles that fall in the subgroups are given above and are therefore not repeated. The figures in the third column represent the totals from which the averages were obtained.

Roundness and flatness ratios of pebbles—Continued.

Group D, figure 10—Continued.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
24.—Contd.	0.03	1.8	Method X, abscissa 0.035; ordinate (97.1÷43) 2.26.
	.03	2.0	
	.04	2.7	
	.04	2.4	
	.02	1.6	
	.04	2.4	
	.05	2.2	
	.04	1.1	
	.04	1.7	
	.05	2.0	
	.04	1.4	
	.04	3.1	
	.04	3.3	
	.05	1.4	
	.02	2.0	
	.04	2.7	
	.03	1.7	
	.03	3.6	
	.05	2.6	
	.03	2.0	
	.03	2.4	
		97.1	
25	.06	1.6	Method X, abscissa 0.075; ordinate (53.6÷24) 2.23.
	.09	1.2	
	.09	2.0	
	.07	1.7	
	.06	2.7	
	.06	2.9	
	.09	1.2	
	.06	3.0	
	.09	1.8	
	.07	1.7	
	.07	1.8	
	.07	3.5	
	.07	1.3	
	.07	1.8	
	.06	2.4	
	.06	2.2	
	.08	1.6	
	.09	2.9	
	.08	2.2	
	.08	1.4	
	.09	3.2	
	.08	1.3	
	.08	4.2	
	.07	4.0	
		53.6	
26	.12	1.7	Method X, abscissa 0.12; ordinate (29.3÷14) 2.09.
	.12	1.8	
	.10	2.5	
	.13	2.0	
	.12	1.2	
	.14	2.1	
	.13	2.2	
	.12	2.1	
	.10	1.4	
	.11	1.7	
	.10	1.7	
	.10	3.0	
	.12	2.7	
	.14	3.2	
		29.3	

Roundness and flatness ratios of pebbles—Continued.

Group D, figure 10—Continued.

Subgroup.	$\frac{r_1}{R}$	$\frac{D'+D''}{2D'''}$	Abscissa and ordinate.
27	0.15	1.4	Method X, abscissa 0.17; ordinate (23.7÷12) 1.97.
	.17	2.9	
	.19	2.2	
	.19	1.2	
	.16	1.8	
	.16	1.7	
	.15	3.2	
	.15	1.2	
	.18	3.1	
	.17	1.1	
	.16	2.5	
	.16	1.4	
		23.7	
28	.23	1.7	Method Y, abscissa (2.17÷8) 0.271; ordinate (15.4÷8) 1.92.
	.30	2.7	
	.20	2.2	
	.45	1.8	
	.34	2.0	
	.20	1.6	
	.24	1.9	
	.21	1.5	
	2.17	15.4	

It is evident that in each one of the five groups of pebbles the flatness and roundness of edges stand in inverse relation—that is, the more rounded the edges the less flat the pebbles. It is valid to assume that the pebbles with rounder edges have been longer affected by wave action than those with sharper edges. The former, which have been on the beach longer, are less flat than the latter, which have been a shorter time on the beach and are nearer to their original shape. It is conclusively proved that at these two beaches the pebbles become less flat as abrasion proceeds and that any predominance of flat, discoid forms is to be attributed to the flatness of the original fragments resulting from the current processes of disruption. Likewise the rather common roller-shaped cobbles and pebbles are the result of the rounding and smoothing of original elongate fragments, as suggested by the series shown in Plate XXVI, *C*, and evidence that these shapes are the result of any special sort of abrasion or motion was not seen by the writer.

The data are insufficient to warrant drawing ideal curves correlating the diminution of flatness with the increase of roundness, but the definite trend described above is established for the two localities visited. In figures 11 and 12 are shown diagrammatically the average shapes of the extreme pebble subgroups at the two localities with regard to both the flatness and the roundness. In each of these figures the flatness and roundness shown in the upper and lower diagrams are those of the subgroups

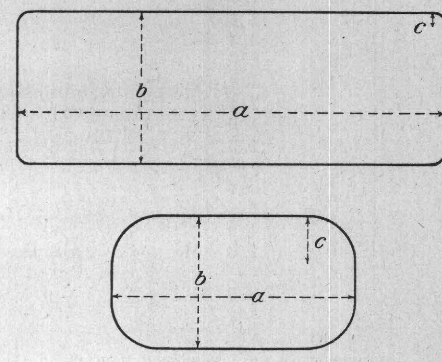


FIGURE 11.—Diagrams showing average flatness and roundness of most angular and most rounded subgroups of pebbles of group C at Nantasket, Mass. Top diagram represents these values for the average of the 36 pebbles of the left-hand subgroup of figure 8. Bottom diagram represents these values for the two pebbles of the right-hand subgroup of figure 8.

$$\frac{a}{b}=\frac{D'+D''}{2D'''} \qquad \frac{C}{\frac{1}{2}\sqrt[3]{a^2b}}=\frac{r_1}{R}$$

Sizes are arbitrary, but dimensions show true flatness and roundness ratios as indicated in the equation above.

represented by the dots at the extreme left and extreme right of figures 8 and 10, respectively. It will be noted that the Nantasket material yields flatter original fragments than that at Fort Hale. This is a result of factors related to the structure of the rocks and the processes

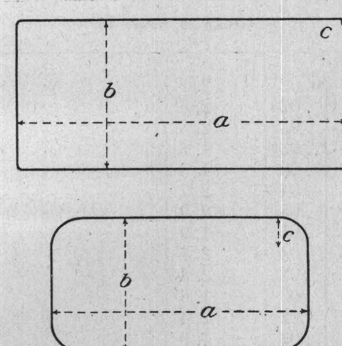


FIGURE 12.—Diagrams showing average flatness and roundness of most angular and most rounded subgroups of pebbles of group D at Fort Hale, Conn. Top diagram represents these values for the average of the 43 pebbles of the left-hand subgroup of figure 10. Bottom diagram represents these values for the 8 pebbles of the right-hand subgroup of figure 10. Notation same as in figure 11.

and conditions of disruption. The writer has not yet made a study of this important aspect of the problem.

Comparisons of the average roundness of the several groups follow. All the pebbles of group B and some of those of group A are at an unknown distance from their source, and little can be said about them except that they are rounder as a whole than those of groups C and D shown in figures 8 and 10. Between those of groups C and D an interesting comparison can be made. The pebbles of group C are much rounder and indicate more travel or abrasion than those of group D. On comparing the average roundness of the two groups on the basis of his previous studies of the relation between abrasion and the roundness ratio[9] the writer finds that the pebbles of group C (Nantasket) indicate greater wear by abrasion than those of group D (Fort Hale) in the approximate ratio of 3.4 to 1. It was found by abrasion tests, however, that the Nantasket rock requires much more abrasion to produce a given degree of rounding than the Fort Hale rock. The ratio is approximately 5. On multiplying this ratio by the ratio given above, we find that the average pebble at Nantasket represents about 17 times the amount of abrasion that those at Fort Hale have received. The ratio is a result of two factors—the violence of wave action and the effectiveness of retention of the same pebbles in the zone of wave action.

[9] Wentworth, C. K., The shapes of pebbles: U. S. Geol. Survey Bull. 730, pp. 91-114, 1922.

Although the writer has ventured to express the ratios in numerical form, he does not wish to convey any false impression as to their accuracy. He is aware, probably more clearly than the reader, of the extreme complexity of the problem, which involves a large number of unknown factors. The figures given are believed to be within 25 per cent of the truth, and it is hoped they may provoke more accurate and extensive investigation.

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