A METHOD OF MEASURING AND PLOTTING THE SHAPES OF PEBBLES.

By CHESTER K. WENTWORTH.

INTRODUCTION.

The studies of which this paper is a report of progress were begun by the writer at the University of Chicago in 1917 and have since been carried on under the auspices of the United States Geological Survey, both in the field and in the office. Since October, 1920, the work has been done in the department of geology of the State University of Iowa, with the continued cooperation of the Federal Survey. The writer is indebted for suggestions and assistance to numerous friends at all these places. He would be grateful for comment and criticism and particularly for suggestions of localities for studying special conditions and products of pebble-shaping processes.

In a brief but suggestive paper H. E. Gregory[1] says, "Attempts to establish criteria for distinguishing beach pebbles from those formed by rivers, glaciers, or wind or resulting from weathering in place have led to unsatisfactory results." He goes on to show that most of the specific characteristics ascribed to pebbles of different origin are produced only by special sets of conditions and that most of the generalizations which have been made are either untrue or so vague as to be unreliable for the discrimination of deposits in the field. It is true that in a broad way it is possible to distinguish on sight between river pebbles, glacial pebbles, and sand-blasted pebbles. On the other hand, the general separation of beach pebbles from river pebbles can not be made with certainty on the basis of any criteria yet set forth.

THE PROBLEM.

In describing the method of measurement which is outlined below the writer makes no pretense of offering a complete solution of this problem. He desires rather to present the procedure which has been found useful in denoting numerically some of the most significant features of the shapes of pebbles, with the confidence that final success in distinguishing the genetic groups of pebbles by their shapes lies in the use of quantitative methods. The shapes of pebbles might be classified in numerous ways, but the classification most

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[1] Gregory, H. E., Note on the shape of pebbles: Am. Jour. Sci., 4th ser., vol. 39, pp. 300–304, 1915.

likely to be of use to the geologist is genetic. The first factor to be considered is the structure of the parent rock; the second is the agent by which the shape of the pebble is modified; the third is the time factor or stage of the process of modification.

The structure of the original rock finds expression in two principal ways—in its effect on the shapes of fragments produced by the agents of weathering and in its effect on shapes developed from these detrital fragments by the agent or agents of transportation. Although much is known in a broad way concerning the results of weathering and some general qualitative observations have been made on the shapes of the fragments produced, no careful study of the shapes of the products of the different processes of mechanical weathering has yet been made.

Without an attempt to outline here the manifold processes and products of weathering that result in clastic fragments the following may be mentioned:

Exfoliation.
Splitting.
Crumbling.
Sun flaking.
Jointing.
Wedge work of plant roots.
Plucking.
Wedge work of ice.
Nivation.
Moisture changes.
Hydrostatic wedge work of waves.
Wedge work of pebbles in cracks.

Others will occur to one who attempts to make even an "armchair" analysis of the whole process of weathering. Each of these agents has its peculiar effect in the shapes of the pieces produced. Fragments produced by exfoliation differ in shape from those produced by crumbling as a result of differential thermal expansion in different minerals, and both differ in shape from fragments produced by jointing. It is highly probable also that the shapes of fragments due to the single process of exfoliation differ with each of numerous factors, such as amount and rapidity of diurnal change in temperature and the conductivity, specific heat, thermal-expansion coefficient, and elasticity of the rock.

The shapes of disrupted fragments from a given rock in a given region are due in general to a combination of several of the agents suggested above rather than to any one alone. Each agent finds a different expression in rocks of different types, as, for example, coarse or fine grained igneous rock, schist, gneiss, and bedded sedimentary rocks of divers kinds. Evidently the problem of the shapes of the fragments that result from rock disruption is complicated. It is worthy of study, however, for the original shapes of fragments that are carried and abraded by the various transporting agents are relatively persistent for great distances and have considerable influence on the forms assumed by these fragments in stages of their history. Quantitative work in great detail on this question of original shapes is needed to furnish an adequate basis for studies of the generic shape characteristics of pebbles.

It is evident from the foregoing statements that there are an infinite number of shapes of fragments available for transportation. These shapes are believed to belong to a large number of types, which present knowledge does not suffice to describe in detail. They include flat slabs and tabloid forms of quadrangular or irregular profile, joint-bounded blocks, shell-like "exfoliates," fantastic nodular pieces of limestone, and many other types. In his attempt to evaluate the modifications of shape which result in the formation of pebbles, the writer has been obliged to seek as a starting point some one characteristic that is common to all or nearly all the types. That characteristic is angularity, and it is valuable also in the fact that it is the characteristic most quickly and most persistently modified in transportation. There are probably original shapes which are not angular, but it seems unlikely that any other simple characteristic is so generally present as that of angularity, which is, therefore, the basis of the writer's study.

METHOD AND RESULTS.

Theoretically, it is possible to measure any number of specific features of shape, but a practical limit is set by the need of reasonable dispatch and of the use of simple instruments. Because of the desirability of using a coordinate system of plotting in two dimensions only two characteristics have been used in the present scheme. One, which may be called the roundness ratio, is $\frac{r_1}{R}$, in which r_1 is the radius of curvature of the sharpest developed[2] edge and R is the mean radius of the pebble. The other, the flatness ratio, is $\frac{r_2}{R}$, in which r_2 is the radius of curvature in the most convex direction on the flattest developed face or portion of the surface, and R is the same as before.

MEASUREMENTS OF CURVATURE.

An inspection of figure 26 will make clear the relation of the values of r_1 and r_2 to the shape of the pebble as shown in profile. These radii are measured by a simple contact method, with an instrument similar to the gage used by opticians to measure the curvature of lenses. A brief description of the gage is here presented in the hope that it may be helpful to others who may need to make the same or similar measurements or to whom it may suggest other instrumental adaptations.

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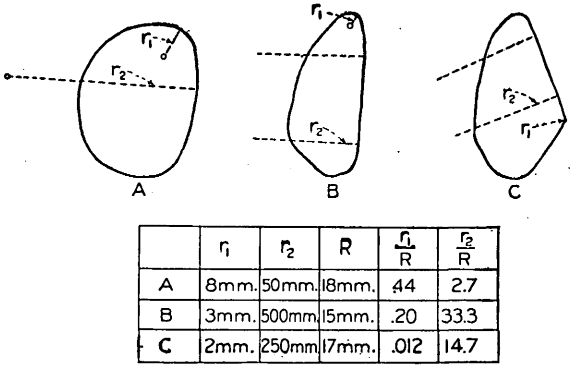
[2] By the use of the term "developed" an attempt is made to discriminate between edges and facets due mainly to abrasive modification, which may be called developed, and those present on the original fractured piece and not due to the work of the transporting agent. The writer is well aware that this line must be drawn arbitrarily according to the judgment of each observer, but he has not yet been able to devise a method of eliminating this undesirable personal factor.

The gage shown in Plate XIV, *A*, and figure 27 was adapted from a test indicator manufactured by the L. S. Starrett Co. The instrument, as constructed originally, was designed to indicate motion of its test point by gradations of 0.001 inch, each turn of the pointer corresponding to 0.1 inch, and the total motion possible was slightly over 0.2 inch. This gage was first adapted to the measurement of convexity by the attachment of two fixed points e, e, as shown in figure 27.



	r_1	r_2	R	$\frac{r_1}{R}$	$\frac{r_2}{R}$
A	8mm.	50mm.	18mm.	.44	2.7
B	3mm.	500mm	15mm.	.20	33.3
C	2mm.	250mm	17mm.	.012	14.7

FIGURE 26.—Profiles and table showing shapes of pebbles and corresponding values of r_1 and r_2 and the ratios derived from these values.

If A equals the distance between the fixed points in inches and B equals the amount of motion of the movable point above the plane of the fixed points expressed in inches, then r, the radius of curvature in millimeters of the surface brought into contact with the instrument, may be computed by the following formula:

$$r = 25.4\ \frac{A^2 + 4B^2}{8B}$$

or

$$r = 3.175\left(\frac{A^2}{B} + 4B\right)$$

This arrangement results in very high relative accuracy of reading for the value of r when r is small, but very low relative accuracy of reading when r is large, as is shown by the following table, giving equivalent values of r and B for A at a constant value of 0.1 inch.

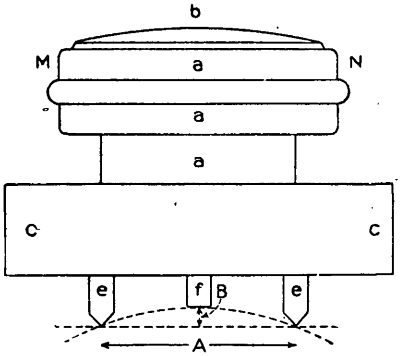
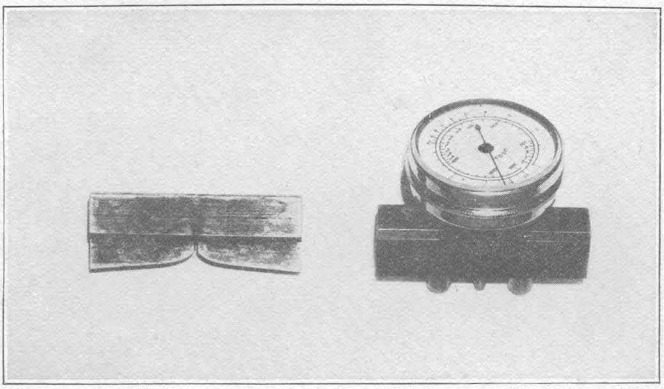


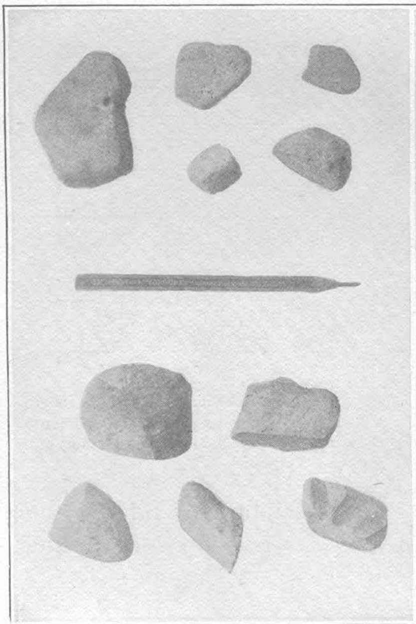
FIGURE 27.—Convexity gage. a, a, a, Original gage; b, edge of the crystal over the dial; f, movable point; c, c, block for the attachment of the points e, e.

r (millimeters).	B (inch).
2	0.018
3	.011
200	.000170
300	.000106

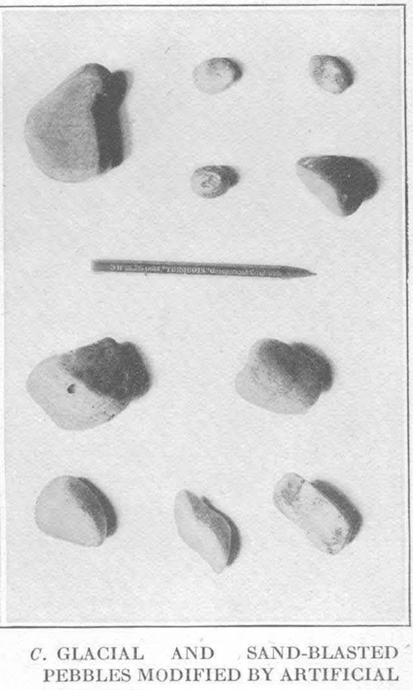
The difference in readings or values of B between 2 and 3 millimeters radius is thus 0.007 inch, an amount readily readable, whereas



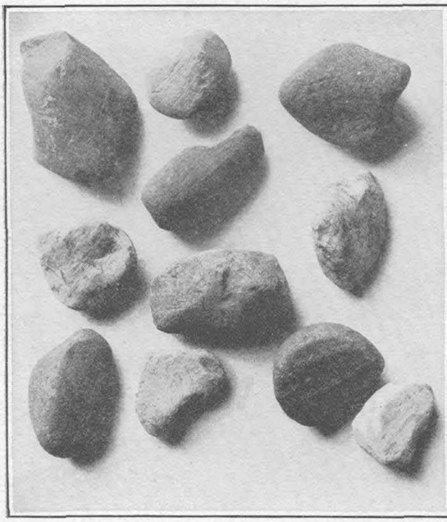
A. CONVEXITY GAGE.



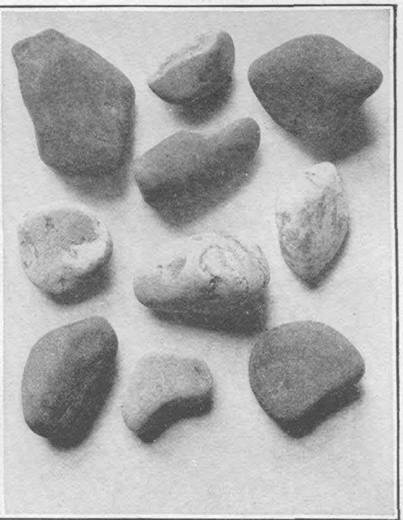
B. GLACIAL AND SAND-BLASTED PEBBLES BEFORE ARTIFICIAL ABRASION.



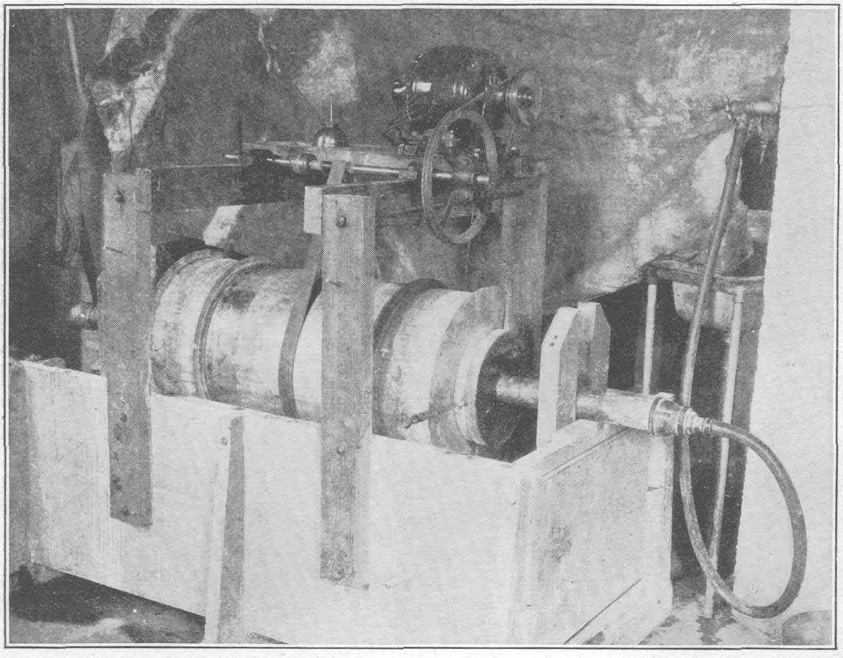
C. GLACIAL AND SAND-BLASTED PEBBLES MODIFIED BY ARTIFICIAL ABRASION.



A. STRIATED GLACIAL PEBBLES FROM AFTON JUNCTION, IOWA.



B. GLACIAL PEBBLES FROM AFTON JUNCTION, IOWA.



C. TUMBLING BARREL IN WHICH EXPERIMENTAL STUDIES OF ABRASION OF PEBBLES ARE MADE.

that between 200 and 300 millimeters radius, which represents an equal relative change in r, is only 0.000064 inch, an amount quite too small to be read on the dial. If the value of A is increased, the range in reading is greatly reduced.

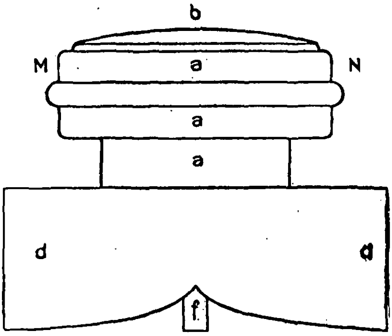


FIGURE 28.—Modified convexity gage. d, d, Profile block.

Figure 28 shows the device which was used to obviate the difficulty. The profile of the block dd was designed as shown in figure 29. a, b, c, d, e, and f are circles whose centers lie on the line AB, produced if necessary. Their nearest points to A are equally spaced, so that ab = bc = cd, etc. Their radii are in geometric series, so that $\frac{r_a}{r_b}=\frac{r_b}{r_c}=\frac{r_c}{r_d}$, etc. By drawing a series of such circles on a greatly enlarged scale and then drawing the enveloping curves CD and EF, a profile was obtained which was then reduced photographically to true scale and used in forming the profile block shown in figure 28. The valuable property of this profile is that equal relative changes or equal ratios between the radii of successive circular curves applied to the profile produce equal changes in the angular displacements of the recording pointer. Thus the instrument may be read everywhere within its range with the same relative accuracy. As constructed with a motion of about 0.170 inch of the pointer, radii of curvature from 1 to 3,000 millimeters are indicated,

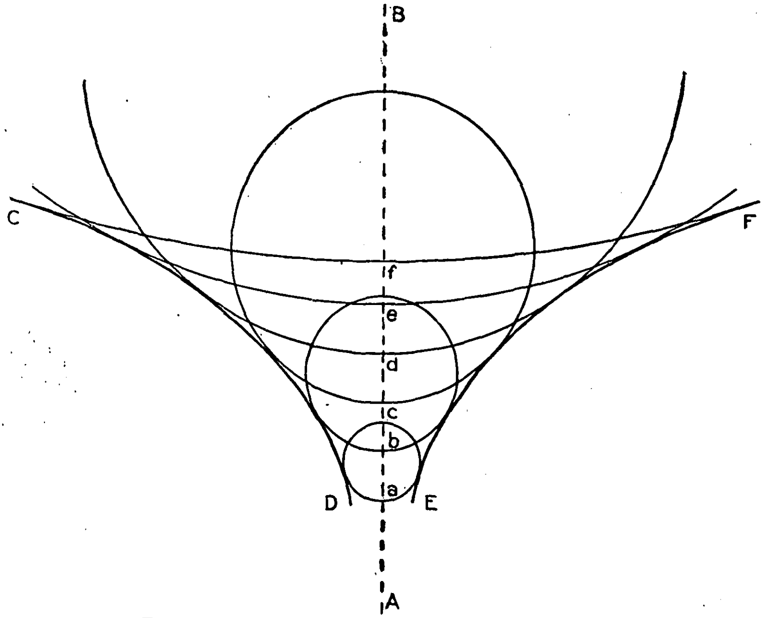


FIGURE 29.—Profile from which block d, d in figure 28 was constructed.

and 1 per cent variation of radius is equivalent to a motion of about 0.2 millimeter on the circular scale. The circular scale reading in 0.001 inch was replaced by a circular scale which was devised to read direct to millimeters of radius and which, because of the form of the profile, is a circular logarithmic scale. It is shown in figure 30. This new scale was then placed in position in the plane MN (fig. 28.)

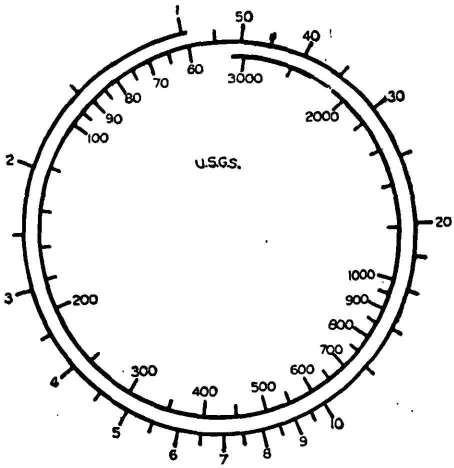


FIGURE 30.—Circular logarithmic scale.

The instrument thus equipped has been found admirable as a compact and portable device for the measurement of nearly circular curves, with a moderate accuracy through a 3,000-fold range of radii of curvature. R is most conveniently computed[3] as the half mean of length, breadth, and thickness as measured in the field, or, more quickly and better still, computed from the weight and density as measured in the laboratory.

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[3] Strictly the mean radius R for a triaxial ellipsoid is one-half the geometric mean of the length, breadth, and thickness—that is,

$$R=\frac{1}{2}\sqrt[3]{D'D''D'''}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

but for the purposes of this paper the arithmetic mean, or

$$R=\frac{D'+D''+D'''}{6}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

is quite accurate enough. However, if the computing is done graphically by the use of alinement or nomographic charts, the first and more correct computation (equation 1) may be made with equal facility and speed by the use of logarithmic instead of arithmetic scales. Problems of the form of equation 1 have been solved by the writer to an accuracy of two significant figures, at the rate of more than four a minute by the use of such charts.

In the use of nomographic or alinement charts for rapid computation where only moderate accuracy is required, the writer has found a black thread more satisfactory than a straight edge or a celluloid sheet with black line on the under side. The thread, though slightly thicker and therefore of slightly less ultimate accuracy, may be handled much more rapidly and conveniently. If, however, the thread is held in the fingers at both ends, there is the difficulty that each end setting is disturbed while the other end is being set and it is necessary to glance to and fro several times before a final reading is made.

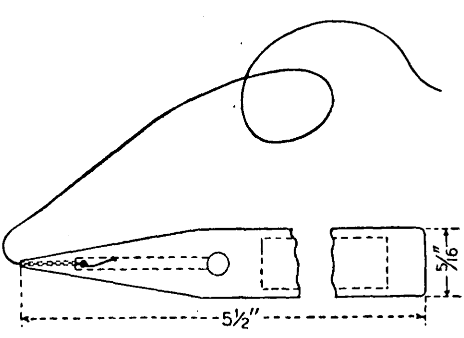

FIGURE 31.—Stylus for use with nomographic chart.

This difficulty was eliminated by the construction of a stylus having one end tapered nearly to a point and having a small hole at the end of the taper (fig. 31). A thread may be inserted in the hole and, by means of the cross hole, secured by tying a knot. By holding the stylus in one hand, one end of the thread may be placed exactly on the scale as desired and with the other hand the other end of the thread may be set without disturbing the initial setting, as the straightened thread pivots about the exact initial point on the scale. The stylus is made hollow for lightness, being constructed of brass tube with the two end pieces soldered into it. The writer has found that much higher speed and greater accuracy can be attained by the use of this device. Similar instruments have doubtless been constructed by others but have not, so far as known, been previously described

RESULTS.

Figure 26 gives in tabular form the measured and computed results on three pebbles of different shapes as seen in profile. When the values of $\frac{r_1}{R}$ and $\frac{r_2}{R}$ for each pebble have been obtained, the position of the pebble is plotted on a double logarithmic chart, the former ratio being used as ordinate and the latter as abscissa. The reasons for the choice of r_1 and R as defined are apparent when it is considered that the largest value which the radius of curvature of the sharpest edge of any piece can have is the radius of the piece, and the limiting condition is that where $r_1 = R$—that is, the piece is a sphere, and the value of $\frac{r_1}{R} = 1$. The values of $\frac{r_1}{R}$ always lie between 0 and 1.

Figure 32 shows the approximate boundaries of three principal shapes of pebbles plotted in this fashion. It follows from the ratios used that a sphere will fall at the top of the chart one-third of the distance from the left corner. Angular pieces with no facets whatever fall outside the chart at the left and bottom. Pebbles with nearly plane facets will fall at or beyond the right edge. The boundary lines for river pebbles are determined from 642 river pebbles measured in the upper course of Russell Fork of Big Sandy River, Va., as reported in the following paper (pp. 103–114). Those for glacial pebbles and sand-blasted pebbles[4] were determined from positions of 40 specimens of each and are probably subject to slight revision when more specimens have been measured. The large dots in each of the latter groups indicate the positions of the 10 pebbles with which the preliminary studies were made to choose the best mode of plotting the measured values. It is significant to note that of 642 pebbles chosen at random from a stream in Virginia, only 3 come within the boundary line for glacial pebbles. More measurements of glacial pebbles may produce a slight confusion along this zone of contact, but there is nevertheless a rather distinctive separation of the two groups. Even more satisfactory is the dispersal on the chart of the glacial and sand-blasted pebbles, where there seems to be little likelihood of confusion.

It should be borne in mind that great reliance can not be placed on the shape of a single pebble. Only the study of 50 or 100 pebbles will give the true shape norm of a deposit with reasonable accuracy, though a study of 10 or 15, where no more were available, might be suggestive. However, as is shown by figure 32, it seems that a wide departure of even a single pebble from the mean shape for its particular mode of origin is very rare. Figure 33 shows the axial line of migration of a river pebble from angularity to sphericity as accurately as it has been determined so far.

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[4] The writer is indebted to Dr. J. B. Woodworth for an excellent collection of sand-blasted pebbles from Marthas Vineyard, Mass., which was used in this study.

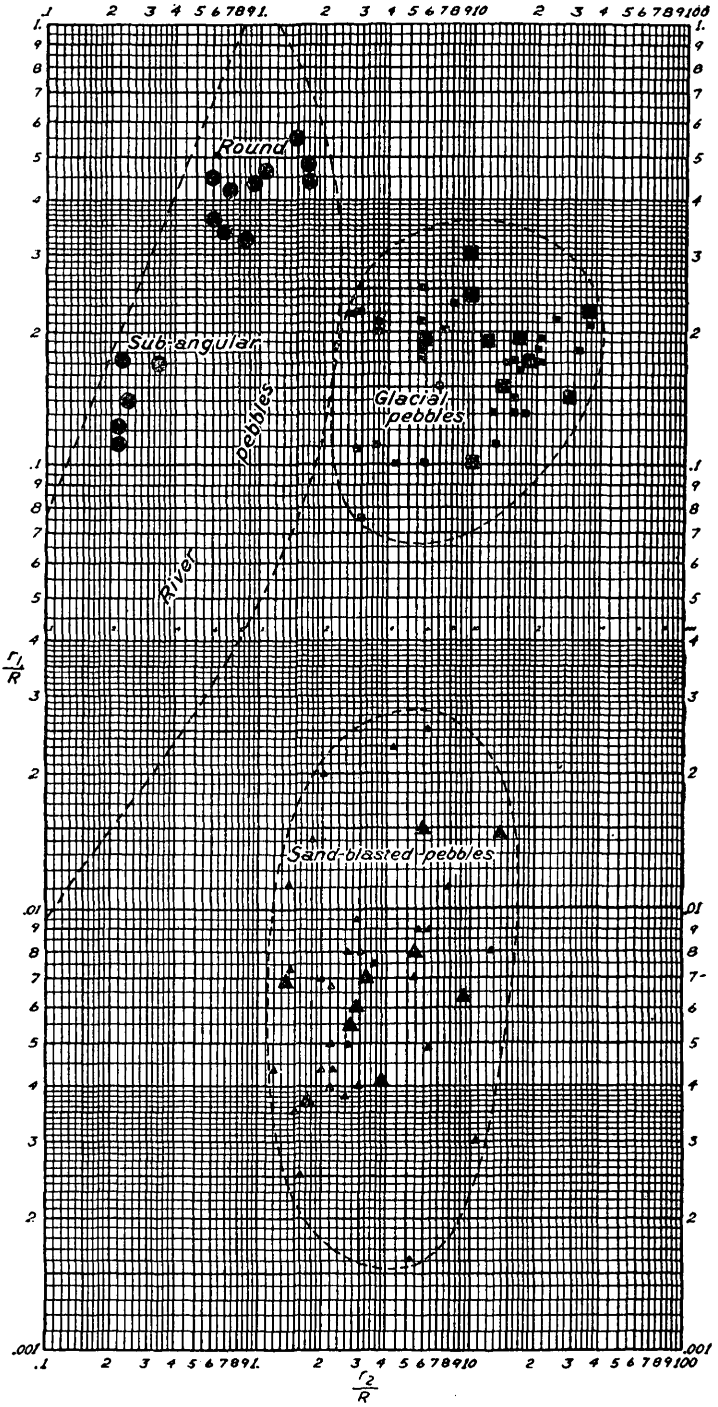

FIGURE 32.—Chart showing characteristic positions of different types of pebbles, according to the scheme of measurement used in this paper.

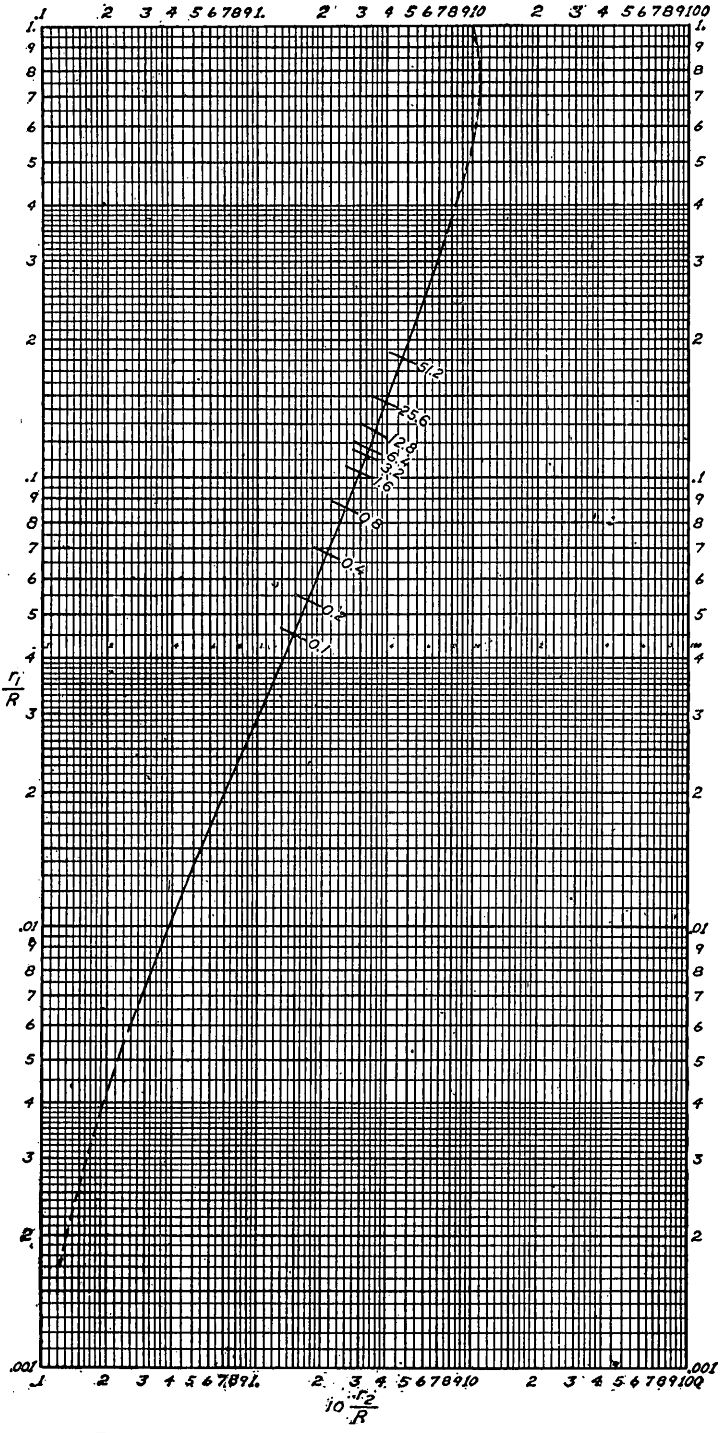

FIGURE 33.—Axial line of migration in shape of a river pebble.

In addition to the allocation of pebbles of nearly pure origin, this method of plotting is especially adapted to the study of transitional shapes. Much of its usefulness in interpretation must wait, of course, until many studies have been made and the graphs plotted of certain "normal" deposits and lines of modification, if there are such lines in matters so complex. To show the possibilities of such studies, the writer has taken five glacial pebbles and five sand-blasted pebbles and subjected them to abrasion in a tumbling mill. This abrasion, as is shown in the accompanying paper, is closely similar in its effect upon shapes to that produced under natural river conditions. The shapes of the pebbles were measured from time to time, and the lines of modification in shape were plotted as shown in figures 34 and 35.

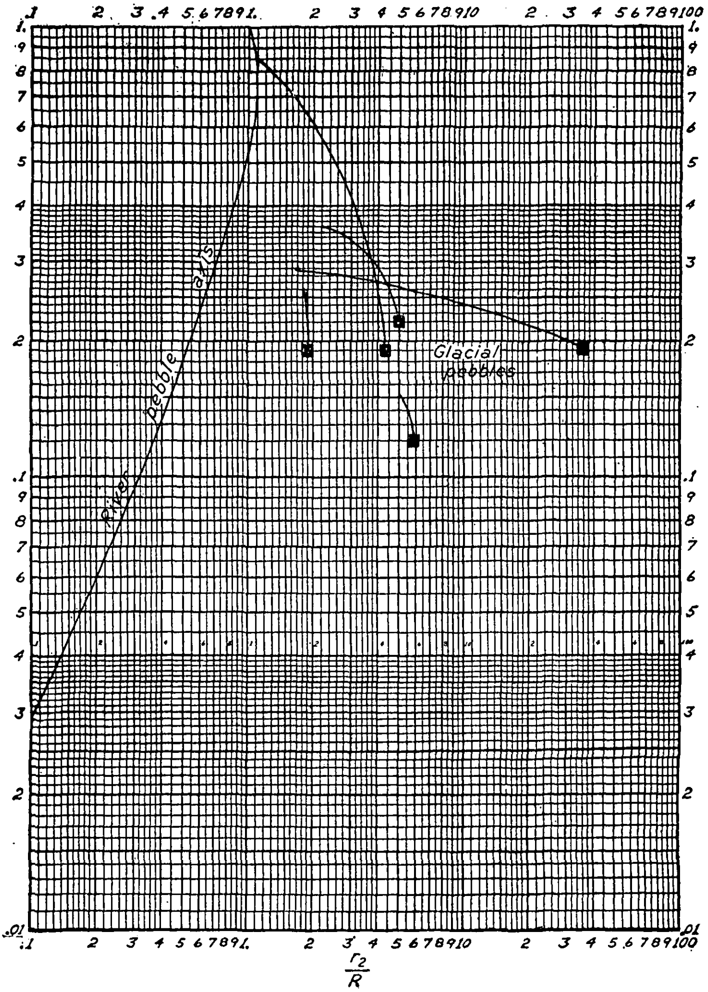

FIGURE 34.—Graph showing modification in shape of five glacial pebbles that were subjected to abrasion in a tumbling mill.

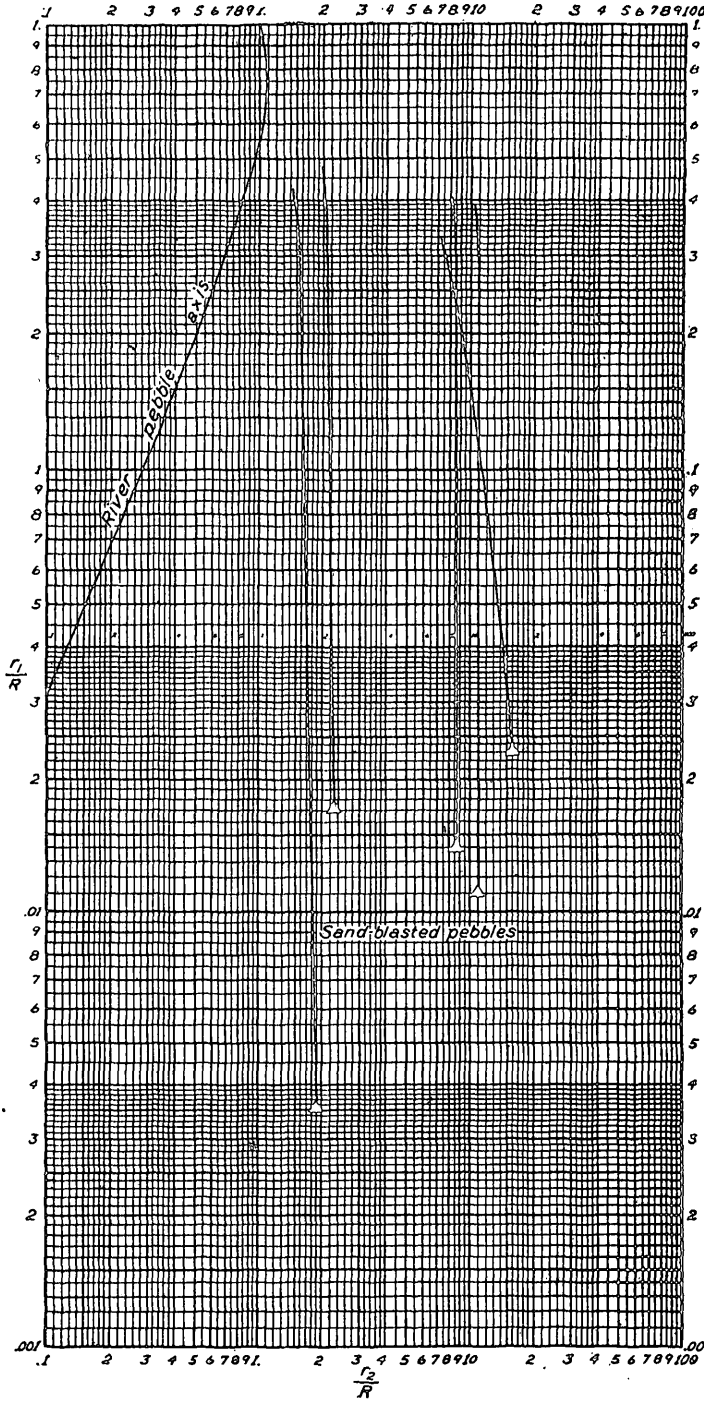

FIGURE 35.—Graph showing modification in shape of five sand-blasted pebbles that were subjected to abrasion in a tumbling mill.

The dominant vertical trend of these lines with only slight trend to the left indicates that the facets are relatively persistent, whereas the more rapid modification is the rounding of the edges. Only when the edges become greatly rounded and the areas of facets much reduced are the facets modified to greater convexities of form. Plate XIV, *B* and *C*, shows these pebbles before and after the abrasion. Three of the glacial pebbles that were of softer rock became very much rounded, and their glacial form was nearly obliterated, as will be seen in both figure 35 and Plate XIV, *C*.

The foregoing examples will indicate some of the practical uses of the method described in this paper. Its greatest usefulness will be reached only when considerable quantitative data have been placed on record and are available for comparison. It will then be useful for studying the effect of rock structure and of different agents of transportation at different stages on shapes of pebbles, and inversely in the interpretation of the history of ancient deposits from a study of the shapes of their constituent pieces. Neither the measurements nor the computations are difficult, and the whole procedure resulting in the shape chart is not laborious. The measurements, computations, and working plots may be made for about 20 to 30 pebbles an hour when the process becomes familiar.

The writer is now studying the problem of the flat, discoid, and ellipsoidal forms sometimes found on beaches. When measured by the foregoing method, they show the characteristics of only moderately rounded pebbles, yet it is apparent from their symmetry that they have suffered long-continued abrasion. Considerable modifications or additions to the method will be needed to assign these pebbles to their proper place in interpretations of genesis.

A FIELD STUDY OF THE SHAPES OF RIVER PEBBLES.

By CHESTER K. WENTWORTH

INTRODUCTION.

The study here reported was undertaken in order to determine the relation between the roundness of pebbles and the distance they have been transported by running water. That pebbles become less and less angular and approach rounded, spheroidal forms as they travel farther and farther downstream has long been an axiom in geology. Qualitatively, this fact is amply proved by casual field observations. To the writer's knowledge, no quantitative field study has heretofore been made of this relation between roundness and distance.

The writer has been engaged for several years in experimental measurements of pebble rounding.[1] The results of these studies, though of value for comparisons, have obviously been open to the criticism of being obtained under highly artificial conditions and hence not being applicable to field problems. The study here reported has rendered available data from a large number of measurements of river pebbles and also, through comparison of these data with the experimental data, has proved conclusively that the two sets of results are in close agreement. Much valuable work may therefore be done by the experimental method, which affords better facilities for control.

The field work on which this paper is based was done in connection with the investigation of the coal resources of southwestern Virginia under the direction of M. R. Campbell. The work was carried on under cooperative agreement between the United States Geological Survey and the Virginia Geological Survey. While studying the course of Russell Fork of Big Sandy River from another standpoint,[2] the writer discovered a peculiarly favorable situation for the study of the shapes of pebbles. Accordingly, in September, 1920, he spent four days in making measurements in the field, taking readings of

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[1] Wentworth, C. K., A laboratory and field study of cobble abrasion: Jour. Geology, vol. 27, pp. 507-521, 1919.

[2] Wentworth, C. K., Russell Fork fault of southwest Virginia: Jour. Geology, vol. 29, pp. 351-369, 1921.

three diameters and an average of four convexities on each of 642 pebbles. The subsequent computations and plotting and the experimental work with the tumbling barrel were done in the geologic laboratory at the State University of Iowa. A considerable part of the apparatus there used was furnished by the United States Geological Survey. The writer wishes to acknowledge his indebtedness to many friends for suggestions in the course of the work. Special thanks are due to Messrs. M. I. Goldman and A. C. Trowbridge for their valuable assistance and criticism.

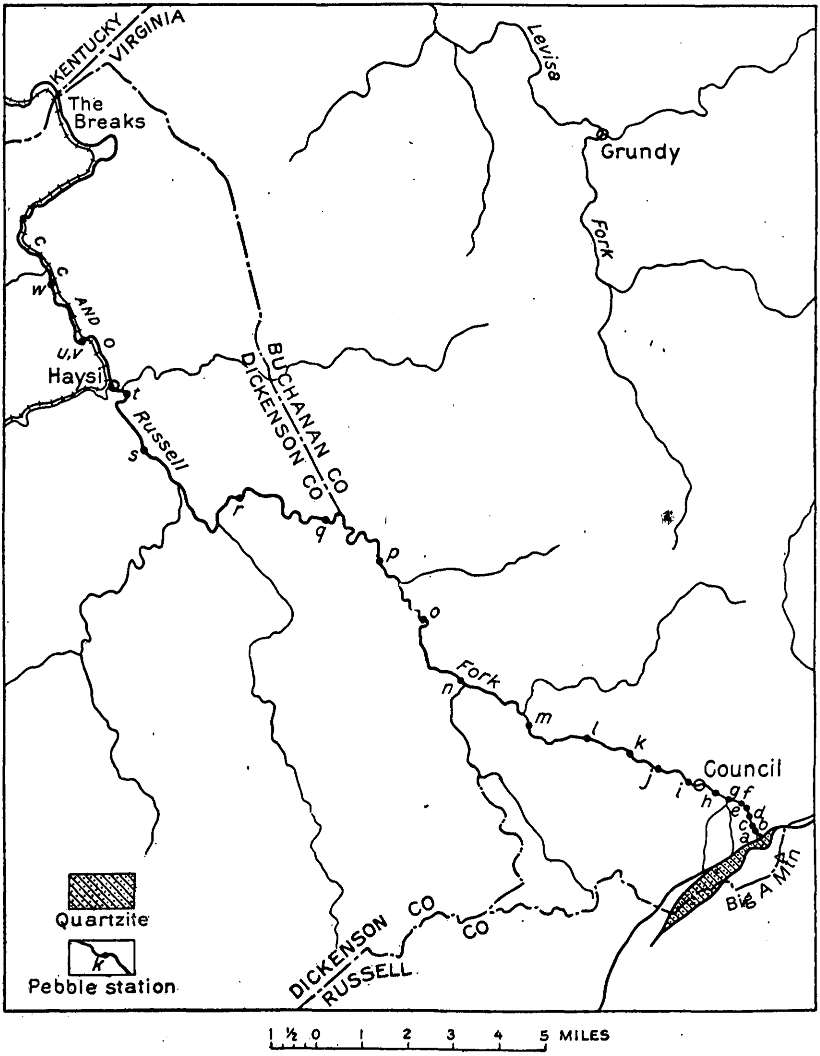

FIGURE 36.—Sketch map of vicinity of Russell Fork of Big Sandy River, Va.

THE FIELD.

Russell Fork of Big Sandy River, in southwestern Virginia (fig. 36), rises on the north flank of Big A Mountain, a high point on Sandy Ridge, which lies between the Clinch River drainage basin on the south and the Big Sandy River drainage basin on the north. Russell Fork flows in a general northerly direction across nearly horizontal Pennsylvanian rocks from Big A Mountain to The Breaks, where it has cut a magnificent gorge through the harder rocks of the core of the Pine Mountain anticline. Beyond Pine Mountain it joins other streams to form Big Sandy River, which is tributary to the Ohio. The head of the permanent stream of Russell Fork is at an elevation of about 2,600 feet. It falls about 1,200 feet in the first 10 miles and has a considerably lower gradient for the next 18 or 20 miles (fig. 37). There is a slight break in the profile and a progressive increase of gradient starting at about 14 miles from station A. This increase of gradient continues well through The Breaks, and the gradient again becomes lower beyond the Pine Mountain barrier. Only the upper portion of the course of Russell Fork, down to station W (fig. 37), which is about 2 miles above The Breaks, is discussed in this paper.

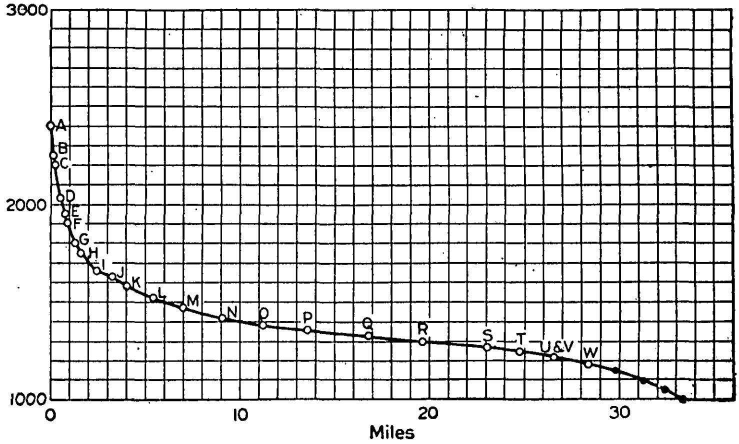

FIGURE 37.—Profile of the upper course of Russell Fork of Big Sandy River, Va.

At station A, at an elevation of 2,400 feet, there is exposed a quartzite of pre-Carboniferous age. It is not more than 100 feet thick and is exposed in this situation as a result of an overthrust from the south, the entire upper part of Big A Mountain consisting of overthrust material. The quartzite is a yellow vitreous to white sugary rock which is the source of many yellow and brown "casehardened" cobbles and pebbles that can be distinguished in the gravel bars for many miles downstream from cobbles and pebbles composed of the local Carboniferous sandstone. No rock likely to be confused with the quartzite is exposed at any other place in the basin of Russell Fork above The Breaks. It is thus apparent that all pebbles of quartzite in the valley or channel of the stream have come from the exposure at or very near station A, and the distance which each pebble has traveled is therefore readily determinable.

METHOD OF WORK.

The method of field study consisted in measuring the length, breadth, and thickness of the pebbles, the radius of curvature of the sharpest edge, and the radius of curvature of the flattest developed face. (See preceding paper, pp. 91–102.) The linear measurements were made with a steel tape and the measurements of convexity with the gage described on page 94. The pebbles, cobbles, and boulders were collected in groups of 10 to 70 at stations designated by letters on the map and profile (figs. 36, 37). In the upper part of the valley many more pebbles of the quartzite are available than were measured, but from station Q downstream they are less numerous, and the study stopped of necessity with station W, 28.4 miles from station A, where a half-hour search on an extensive gravel bar revealed only two small quartzite pebbles. In all, 642 boulders, cobbles, and pebbles were measured. A few of the pebbles were collected for comparison with other rocks in the laboratory.

After the writer returned to the office, the necessary computations of the ratios $\frac{r_1}{R}$ and $\frac{r_2}{R}$ (p. 93) were made and the positions of the pebbles plotted on the double logarithmic charts described in the preceding paper (pp. 97–102). The result is shown in figure 38. The values of $\frac{r_1}{R}$ were then averaged for each station, and the curve shown in figure 39, A, was plotted. It will be noted that, although the points show a general trend, they do not lie very close to a smooth curve. The value of $\frac{r_1}{R}$ for the pebbles at a given station seemed to correspond not only to the hardness of different pieces of the quartzite but also to the size of the pebble. Instead of $\frac{r_1}{R} = \text{f (hardness)}$—that is, some function of hardness alone—the following is more nearly true:

$$\frac{r_1}{R} = \text{f (hardness)} \times f'(R)$$

Because the hardness or durability of the pebbles was for the most part unknown, the value of this factor had to be ignored in the hope that in the averaging of large numbers its effect would be smoothed out. The effect of size could still be studied, however. Preliminary to this study the value of $\frac{r_1}{R}$ for each of the 642 pebbles was corrected,

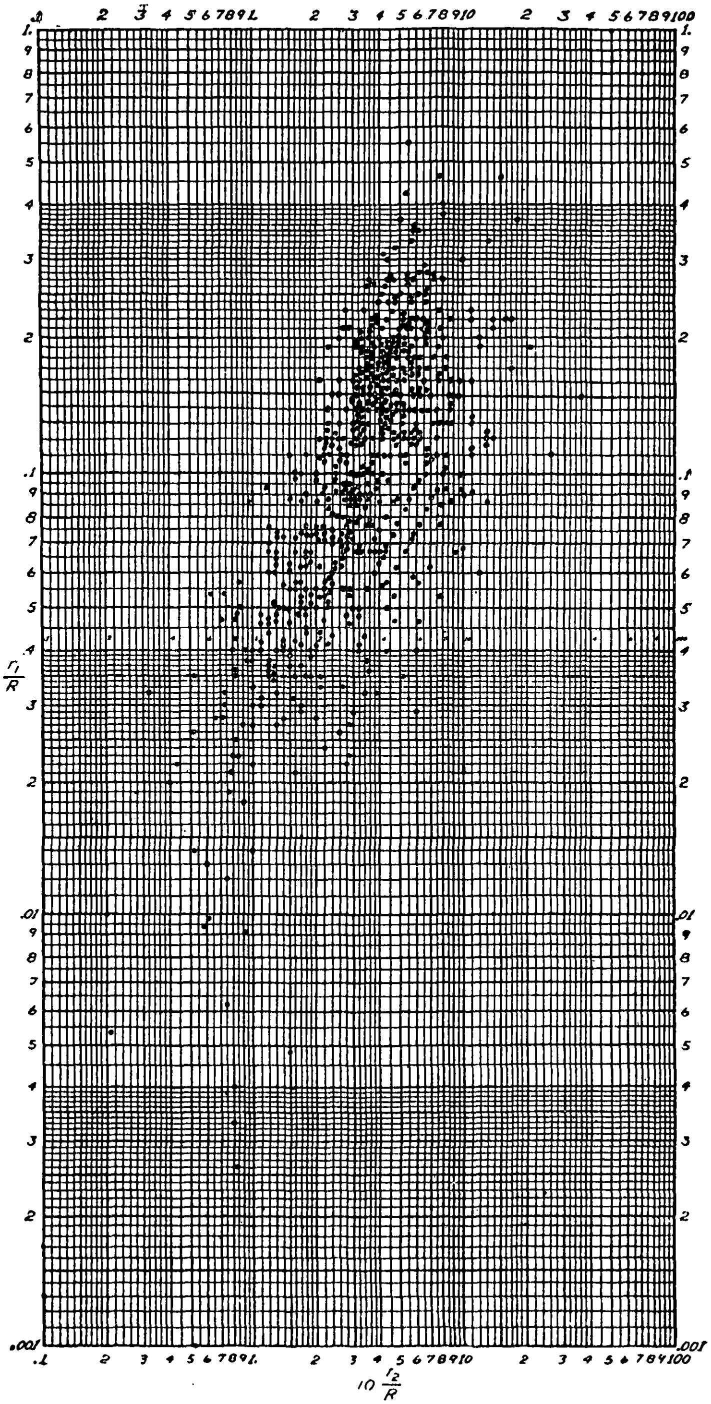

FIGURE 38.—Chart showing distribution according to shape of 642 river pebbles, cobbles, and boulders from Russell Fork of Big Sandy River, Va.

by the use of the curve of figure 39, A, to its corresponding value for a standard distance of 25 miles. This was done by multiplying each value of $\frac{r_1}{R}$ by a station factor, which consisted of the ratio of the ordinates at 25 and at x miles, respectively.

The new values of $\frac{r_1}{R}$ were then divided into 11 groups on the basis of size of the pebble, and the averages for each of these groups were computed. These averages were plotted as shown in figure 40, curve a, where

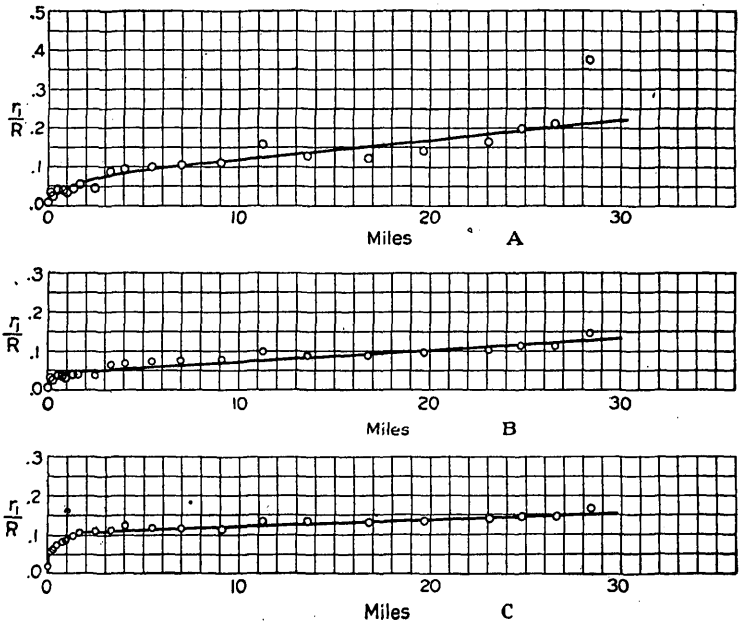

FIGURE 39.—Curves showing relation of roundness of pebbles to distance of transportation.

$$\frac{r_1}{R} = 5.26\ (2\ R)^{-1.15} + 0.133$$

was found to fit these points well. Curve b represents the values of $\frac{r_1}{R}$ on the assumption that r_1, the radius of curvature of edges, is a constant regardless of the size of the pebbles, when the distance is the same. Curve c follows the alternative assumption that r_1 is proportional to the linear size of the pebbles and hence $\frac{r_1}{R}$ = some constant as shown. The form of the actual curve (a) shows that the latter assumption is more nearly true for a wide range of the large sizes.

As the diameter of the pebbles measured at most of the stations where the effect of size was critical ranged from 25 to 150 millimeters, and as the average size at the different stations varied somewhat, it seemed desirable to correct the original values of $\frac{r_1}{R}$ for size, and this was done on the basis of curve a of figure 40. From the corrected values curve B of figure 39 was plotted. It is seen to be much smoother than curve A. Finally, by plotting a curve of the relation of roundness to size for each station similar to that of figure 40, and correcting the values of $\frac{r_1}{R}$ by these curves instead of using curve a of figure 40 for all, a third set of roundness ratios was derived. These ratios were averaged, and curve C of figure 39 was plotted. This is believed to be the best curve derivable from these data. It is shown plotted on a greater vertical scale in figure 41. When account is taken of the number of unknown variables that enter into the problem, aside from distance traveled and from the size, which have been approximately eliminated, this curve will be regarded as fairly satisfactory, in spite of two or three erratic points.

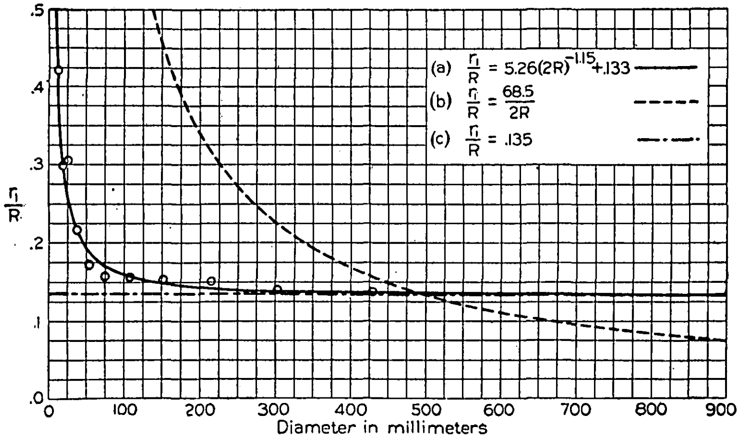

FIGURE 40.—Curves showing relation of roundness ratios to size of pebbles.

SIGNIFICANCE OF RESULTS.

The form of the curve of figure 41 is about what might be expected, except that the transition from the rapid rounding represented by the steep part to the more gradual change represented by the flatter part is more abrupt than would be anticipated. It seems probable that the steeper part of the curve represents the rounding of edges by spalling of corners and that the flatter part represents the slower rounding by a grinding process, spalling being very rare after a certain degree of rounding has been reached.

Interpretation of the form of this curve is vitiated to some extent by the changing of gradient and consequently of violence of transportation, which the writer has called "rigor," from one part of the stream to another. The form of curve showing the relation of rounding to distance with a constant rigor was investigated experimentally by subjecting angular pieces to abrasion in a tumbling barrel. The general arrangement of the apparatus is shown in Plate XV, *C.* The barrel is driven at a rate of about 33 revolutions a minute. The inside is lined with wood, and the abrasion is due entirely to the action of a certain definite number of grinding pebbles on the pebbles that are being studied. A continuous stream of water is fed into the barrel, and the abrasion takes place partly under water and partly above. The grinding pebbles are renewed frequently so as to maintain a nearly constant size. The results of the study of rounding under conditions of constant rigor are shown in figure 42, in which the field curve from figure 41 has been redrawn, the values of $\frac{r_1}{R}$ as determined experimentally plotted, and the dotted experimental curve drawn. The rate of abrasion in the barrel is not the same as that in the stream, so that it was necessary to change the horizontal scale of the experimental curve by a constant factor to match the two curves at $x=29$ miles. As it is the form rather than the scale of the curve that is significant in this connection, this change is quite permissible.

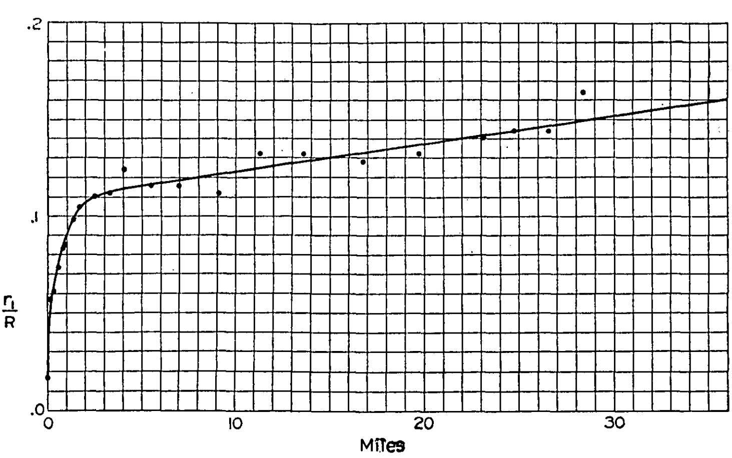

FIGURE 41.—Final curve of rounding of pebbles with respect to distance traveled.

The similarity of the curves is striking, amounting practically to identity for a considerable part of their length. The differences may easily be accounted for by lack of uniformity of rigor in the stream. In the steeper head portion of the stream the curves are practically the same; from $x=2$ miles the stream is less effective in rounding than the curve of constant rigor calls for, and the effectiveness diminishes to the end of the course. It is very suggestive that there is an inflexion in the stream profile at about 14 miles, and the gradient increases as The Breaks are approached. Beyond pointing out the apparent significance of this relation, it is not possible at present to correlate stream rigor and stream gradient, for the rigor probably varies with sizes of pebbles transported and with many other factors not yet determined.

To enable the reader to visualize the data presented in graphic form, the general shapes and degrees of rounding noted will be described. At the head of the stream the fragments are sharp-edged. As the stream was followed the gradual rounding of the edges was clearly noticeable, even without making measurements. The surfaces of the pebbles are smooth and show some polish. At the lower stations the pebbles are moderately well rounded, though the original form still persists in its essential outlines and only the corners and edges are greatly changed. None of the pieces have nearly the roundness or symmetry of an egg, or even that of an average potato. The total loss of weight, as deduced from the change in shape and experimental studies, averages about 6 per cent. A few of the pebbles or cobbles show evidence of fresh breaks and of shapes resultant from fracture subsequent to their removal from the head of the stream. This phenomenon was sufficiently rare to be noticeable in comparison with the shapes of most of the pebbles derived by abrasive work only from the original angular form.

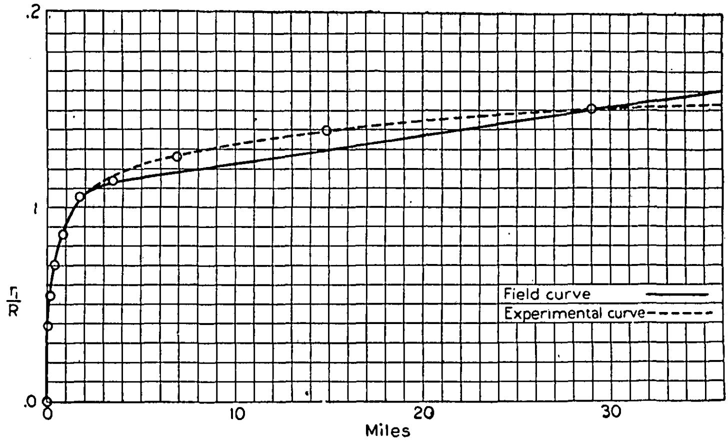

FIGURE 42.—Comparison of curves of rounding of pebbles with respect to distance traveled obtained by field and experimental measurements.

As has been pointed out above, the abrasion in the tumbling barrel varies widely with the number and size of pebbles used in it, and it can not be employed by itself as a measure of the distance necessary to form rounded pebbles under natural conditions. Bonney[3] has called attention to this fact and to the inadequacy of such methods to

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[3] Bonney, T. G., Observations on the rounding of pebbles by Alpine rivers: Geol. Mag., dec. 3, vol. 5, pp. 54-61, 1888.

determine the rate of rounding. He went further, however, and concluded that the abrasion of angular blocks in a revolving cylinder is not of general application because the only sort of river work similar to it is the abrasion of pebbles in potholes. This conclusion the writer can not accept, because the comparison here made of the forms of the field and experimental curves proves conclusively the essential similarity of the field and experimental processes for streams of the general type of Russell Fork. It is true that in the tumbling barrel the work done is almost pure abrasion and impact, whereas in the stream there are in addition the effects of weathering, such as cracking, crumbling, and spalling off of flakes, during the delays in transit. The importance of these factors can not be stated until further studies have been made. It is apparent, however, from a comparison of the two curves in figure 42 that the results, so far as shaping is concerned, are closely similar to those of the experimental studies. The method of the tumbling barrel therefore seems to be of far wider application than has heretofore been thought, and it needs only to have its rate determined by comparative measurements in streams of different sorts to become of considerable value.

One of the most valuable applications of the roundness-distance curve is in determining the distance certain pebbles have traveled by a measurement of their roundness. A gage of the reliability of such a method may be obtained by assuming that the distance is unknown for each of the station groups in the Russell Fork study and determining the distance by use of the mean roundness on the curve of figure 41. Comparison of distance thus determined with the actual distance will give the error of such a determination. The average error for all the stations, 21 in number, was found to be 24 per cent. The determinations for four of the stations were very erratic, owing, in part at least, to the use of a small number of pebbles—only two at one station. With these four stations omitted, the average error was only 11 per cent.

It must be understood that this figure represents only the error due to variation of hardness and of individual history at each of the stations, the perfection of the curve as drawn being assumed. Other factors that would affect such a determination for material from other streams are as follows:

1. The comparative rigor of the type stream and the unknown stream will affect the ratio of roundness to distance very considerably. The larger features of relation between gradient and load, on the one hand, and rigor, on the other, can be investigated by combined field and laboratory study.

2. The comparative durability of the pebbles of the stream used for the type curve and of those whose distance of travel is to be determined can easily be ascertained experimentally.
3. The effect of original shape can be largely investigated experimentally.
4. The effect of nonhomogeneous structure, schistosity, etc., can also be evaluated to a large extent experimentally.

Grabau[4] gives tables showing the distance pebbles of a certain size and material are carried before being obliterated, but he does not state what method was used in obtaining these results. On the basis of the amount of abrasion the Russell Fork quartzite has undergone in 28.4 miles and the relative rates of loss by abrasion for different sizes,[5] the writer has computed the distance necessary to reduce a 50-gram angular piece of quartzite to a pebble of one one-hundredth the initial weight—that is, 0.5 gram. The result is approximately 400 miles. This computation was made on the assumption of constant rigor, the same in amount as the average of the upper 28.4 miles of Russell Fork. For smaller pebbles, carried farther downstream, it is reasonable to suppose that the rigor becomes very much less and that the estimate of 400 miles is much too low.

Though some of the above-mentioned factors are still unknown, the writer has deemed it worth while for the sake of discussion to deduce by this method the distance of travel for pebbles of vein quartz taken from the Lee conglomerate, of Pennsylvanian age. These were collected at Big Stone Gap, Va., and measured in the manner described. They were found to be as round as the Russell Fork pebbles of the same size which had traveled 16.5 miles. The durability of the Lee pebbles, however, with respect to abrasion was found experimentally to be approximately three times as great as that of the quartzite pebbles of Russell Fork. The distance of travel for the Lee pebbles, if conditions of similar kind and rigor are assumed, is 3×16.5, or about 50 miles. This estimate is of course subject to wide revision when further studies throw light on other conditions of transportation in streams or otherwise and the interpretation of such conditions by a study of shapes becomes possible.

A determination of the roundness of limestone pebbles from a supposed intraformational limestone conglomerate in the Black Hills of South Dakota has been made by Miss Fillman.[6] The average of measurements on 90 of these pebbles indicates a roundness equal to that shown by quartzite pebbles on Russell Fork at 0.45 mile. The limestone pebbles were found by abrasive tests to be only one-thirteenth as durable as the quartzite, and from this ratio the equiva-

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[4] Grabau, A. W., Principles of stratigraphy, p. 247, 1913.

[5] Wentworth, C. K., A laboratory and field study of cobble abrasion: Jour. Geology, vol. 27, fig. 2, 1919.

[6] Fillman, L., On the so-called limestone conglomerate of the northern Black Hills of South Dakota (unpublished thesis, State University of Iowa, 1921).

lent travel under the same conditions was derived as approximately 0.035 mile, or slightly less than 200 feet. These limestone pebbles are for the most part flat and lozenge-shaped, though not very symmetrical. It is impossible, in the light of present knowledge, to make any definite statements as to what were the stream or beach conditions under which these pebbles were rounded, and the figures given above furnish a statement only of the amount of abrasion they have sustained. More definite utilization of the measurements of these pebbles must wait until adequate data on the significance of the flat and elliptical shapes of pebbles found on some beaches are available.

An estimate was made by a similar method of the transportation and consequent abrasion necessary to remove striae from glacial pebbles. Plate XV, *A*, shows 11 striated pebbles from the vicinity of Afton Junction, Iowa. These pebbles were subjected to abrasion in the tumbling barrel until the striae were practically removed. Faint traces of the striae may still be seen on one or two of the pebbles, which were photographed after the abrasion (Pl. XV, *B*). The distance of travel, after taking account of the difference of rigor between the experimental conditions and those of the natural stream, was 0.35 mile. Though differing conditions in rigor would modify this figure, the results show how short is the travel necessary to obliterate the striae. The pebbles are still recognizable as glacial in origin by their facets, though not so conclusively as before. Some of these pebbles were hard limestone and others a fairly compact greenstone.

The above estimates indicate very imperfectly some of the interpretations which may be made very much more accurately later, when the evaluation of more of the unknown factors has been accomplished. The writer hopes to be able by further field and laboratory work to make additional studies of this subject. Localities where rocks of easily identifiable types crop out in clearly defined areas and furnish to streams pebble material which can be distinguished from local rocks are necessary for further field studies. Suggestions in regard to such localities will be especially helpful.