EXPERIMENTS ON THE FORMATION OF WIND-FACETED PEBBLES.*

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ABSTRACT.

Experiments conducted by Kuenen, a Dutch geologist, in 1928 tend to prove that wind-faceted pebbles are produced by variable winds and that the original shape of the base of the sand-blasted pebble is the chief factor controlling its final shape. Since the conclusions reached by Kuenen are in direct opposition to those held by most English and American geologists, the writer undertook to carry on experimental work on the artificial formation of wind-faceted pebbles.

The experiments conducted by the writer demonstrate that: (1) ridge-shaped ventifacts or wind-faceted pebbles of the einkanter and roof-shaped varieties and pyramidal types or dreikanter can be formed by variable winds from models having bases of definite shape, (2) ridge-shaped types of the einkanter variety and triquetous or Brazil-nut types can be formed by constant winds, that is, winds coming chiefly from one or from two opposite directions irrespective of the shape of the base of the model, (3) models supported on a smooth, hard floor become undermined, whereas those surrounded by sand develop inclined facets, (4) faces parallel to the sand blast suffer practically no abrasion, (5) the rate of abrasion on faces sloping 30° is about one-third as great as on faces inclined at angles of 60° and 90°, (6) selenite cleavage fragments or crystals are good negative criteria of wind action, and (7) in the incipient stages of faceting, two facets instead of one are developed.

The final conclusions reached by the writer in regard to the formation of wind-faceted pebbles or ventifacts are as follows: (1) the shape of the base of a pebble and variable winds are controlling factors determining the final wind-faceted form under the conditions postulated by Kuenen, (2) Kuenen's assumptions are improbable and therefore natural wind-faceted pebbles are not formed as believed by him, (3) the shape of the base is not a controlling factor in the development of forms made by constant winds, (4) the triquetous or Brazil-nut type represents the final end-stage in the development of wind-faceted pebbles, and (5) most wind-faceted pebbles are made under conditions of constant winds.

INTRODUCTION.

A wind-faceted pebble or ventifact is one whose present surface is composed of one or more faces or facets cut by the wind. The formation of such pebbles, also known as "dreikanter," and their use as criteria of climatic conditions has engaged the attention and interest of geologists ever since 1870 when the first pebbles of this type were found. The effectiveness of the wind in polishing, carving, grooving, striating and wearing rock surfaces had been noted by Blake[1]

* Contribution aided by a grant from the Shaler Memorial Fund of Harvard University.

[1] Blake, W. P., On the Grooving and Polishing of Hard Rocks and Minerals by Dry Sand; this Journal, **20**, 178-181, 1855; Am. Assoc. Adv. Sc. Proc. 216-220, 1855.

as early as 1855. Travers[2] in 1870 proposed sand-blasting as a cause for faceted pebbles but this explanation did not reach ascendency in Europe until after the publication of Mickwitz's[3] paper in 1885. Woodworth[4] in 1894 set forth a complete and logical explanation of the cutting of these stones. Basing his analysis on the results of Tilghman's experiments, he held that: (1) A face is cut at right angles to the wind, (2) the angle of maximum wear is between 60° and 30 ° from the horizontal and few faces are cut below 30°, (3) overturning or rotation of pebbles with the cutting of inclined facets will produce all the known types of faceted rocks, (4) too frequent rotation or overturn will prevent the formation of facets.

Bryan[5] has recently grouped all wind-worn pebbles or boulders, whether polished, grooved, carved, striated or truly faceted, under the one term "ventifact" although, as introduced by Evans,[6] the term was restricted to pebbles possessing faces cut by wind and sand action. The wind-faceted type of ventifact is found in most desert regions of the world. Such pebbles are also more or less common in the humid temperate regions where they are associated with sea or lake beaches and with glacial outwash gravels. Wind-faceted pebbles have been reported also from formations of the following ages[7]: pre-Cambrian, Cambrian, Devonian, Permian, Jurassic, Triassic, Cretaceous, Tertiary, Pleistocene and Recent.

Various hypotheses have been advanced to account for the origin of wind-faceted pebbles. Among these may be mentioned the following: (1) human agency, (2) waving of grass, (3) rubbing of one pebble against another—*"Packungstheorie,"* (4) grinding by floating ice, (5) grinding by sand and water, (6) frost action along joint planes, (7) solution, and (8) natural sand-blast or wind action. These various hypotheses are reviewed by Bather[8] in his excellent paper on

[2] Travers, W. T. L., On the Sandworn Stones of Evans' Bay, New Zealand Inst. Trans., 2, 247-248, 1870.

[3] Mickwitz, A. von., Über Dreikanter im Diluvium bei Reval mit Einleitung von T. Schmidt, Neues Jahrbuch f. Min., 2, 177-179, 1885.

[4] Woodworth, J. B., Post-Glacial Eolian Action in Southern New England, this Journal, **47**, 63-71, 1894.

[5] Bryan, K., Wind-Worn Stones or Ventifacts—A Discussion and Bibliography, Report of the Committee on Sedimentation, 1929-1930, Reprint and Circular Series, National Research Council, **98**, 29-50, 1931.

[6] Evans, J. W., Dreikanter, Geol. Mag., n. s., **8**, 334-335, 1911; The Wearing Down of Rocks, Part II. Proc. Geologists' Assocn. London, **25**, 260, 1914.

[7] Bryan, K., Op. cit. 37-38.

[8] Bather, F. A., Wind-worn Pebbles in the British Isles, Proc. Geol. Assocn. **16**, 396-420, 1900.

"Wind-worn Pebbles in the British Isles" which was published in 1900 and contains a bibliography of 87 titles. Additional references are given by E. E. Free in a bulletin on "The Movement of Soil Material by the Wind" published by the United States Department of Agriculture as Bureau of Soils, Bulletin 68, and a nearly complete bibliography of 258 titles has been listed by Bryan in his recent paper, "Wind-Worn Stones or Ventifacts—A Discussion and Bibliography." Geologists are now agreed that "dreikanter" are wind-faceted pebbles. Differences of opinion, however, exist in regard to the exact method of their formation. As shown by Wade,[9] Travers[10] and others "dreikanter" may be formed by a sand-carrying wind that blows from one single direction, or from two opposite directions. To this school most English and American geologists belong. The other school, represented largely by German geologists, holds that wind-faceted pebbles are shaped by variable winds. In addition to this disagreement regarding the wind direction, geologists are also divided as to what factors control the final shape of the sand-blasted pebble. According to some geologists the final shape is conditioned by the original shape, others contend that the shape of the original base is the controlling factor, whereas still others hold that only in transitional and incomplete stages is the original shape dominant, and the end form is dependent wholly on the details of the process.

Greatest interest in wind-faceted pebbles or "dreikanter" does not center in their shapes so much as in their value as criteria of past climatic condition. Since such pebbles are commonly associated with desert regions, the presence of wind-worn stones in ancient formations has usually been interpreted as indicating more or less arid conditions at the time during which the beds were formed. Thus the presence of "dreikanter" in a basal sandstone of Cambrian age in southern Sweden[11] and in the pre-Cambrian Torridon sandstone of Scotland[12] is taken as proof that the pebbles were shaped by the wind during a period of relative aridity. Similarly the

[9] Wade, A., On the Formation of Dreikante in Desert Regions, Geol. Mag., **7**, 394-398, 1910.

[10] Travers, W. T. L., On the Sandworn Stones of Evans' Bay, Trans. New Zealand Inst., **2**, 247-248, 1870.

[11] Grabau, A. W., Principles of Stratigraphy, 55, 573, 1913; A Textbook of Geology, Part II, Historical Geology, 184, 225.

[12] Grabau, A. W., Principles of Stratigraphy, 54, 573, 1913; A Textbook of Geology, Part II, Historical Geology, 201.

"dreikanter" associated with the glacial materials of the North German lowlands signify a post-glacial epoch which was at least partially arid. "Dreikanter" or ventifacts are undisputable proof of intensive wind action. They do not, however, necessarily signify aridity and hence should be used with extreme caution as criteria of past arid climates.

Although the bibliography on ventifacts prepared by Dr. Bryan contains a list of 258 titles, references to experimental work on the effects of the artificial sand blast on the corrasion of rock materials and on the formation of wind-faceted pebbles are not numerous. Among the experimenters may be mentioned the following: Egleston,[13] De Geer,[14] Thoulet,[15] Preussner,[16] Harlé,[17] Johnsen,[18] Hedström,[19] Brown[20] and Kuenen.[21] Of these, the work of Thoulet and Kuenen is by far the most important and significant. Thoulet's experiments were not concerned with the formation of "dreikanter," but rather with the general effect of sand in abrading rocks. They give valuable data on the rate of abrasion, on the influence of size, shape and angularity of the abrasive on the abraded substance, on the angular position of the sand-blasted surface in relation to the sand stream, and on the character of the abraded surface, data, all of which is formulated in a series of 12 laws of corrasion. The only paper of any value which is concerned with the actual formation of artificial wind-faceted pebbles is that of Kuenen in 1928. Kuenen's[22] experiments tend to prove that the original shape of the base of the sand-blasted pebble is the chief factor controlling its final shape, a view first

[13] Egleston, T., The Cause and Prevention of the Decay of Building Stone, Trans. Am. Soc. Civ. Engs., **15**, 655, 1886.

[14] De Geer, G. J., Om Vindnötta Stenar, Geol. fören. Stockholm förh., **8**, 501-513, 1886; Abst., Neues Jahrb. Mineral. Geol., 1888, Part II, 302, 1888.

[15] Thoulet, J., Expériences synthétiques sur l'abrasion des roches, Compte rend., **104**, 381-383, 1887; Ann. Mines, ser. 8, **11**, 199-224, 1887.

[16] Preussner, Über die Enstehung der Dreikanter, Zeit. deut. geol. Ges., **39**, 502, 1887.

[17] Harlé, E., Cailloux à facettes des environs de Bordeaux, Bull. Soc. Geol. France, 3^{me} ser., **28**, 70, 1900.

[18] Johnsen, A., Zur Enstehung der Facettengesteine, Neues Jahrb. Mineral. Geol., 593-597, 662, 1903.

[19] Hedström, H., Om konstgjord framställning af vindnötta stenar, Förh. Geol. fören, Stockholm, **25**, 413-420, 1903; Abst. Geol. Centr., **5**, 517, 1904.

[20] Brown, W. O., On Some Erratics of the Boulder Clay in the Neighborhood of Burscough, Proc. Liverpool Geol. Soc., 1905-1906, **10**, 128-131, 1906.

[21] Kuenen, Ph. H., Experiments on the Formation of Wind-worn Pebbles, Leidsche geol. Medellingen, **3**, 17-38, 1928; Reviewed by H. Hedström, Geol. fören, förh., Stockholm, **51**, 129-130, 1929.

[22] Loc. cit.

proposed by Heim.[23] This experimenter assumed that wind-faceted pebbles are produced by variable winds.

The views held by Heim and Kuenen are in direct opposition to those held by most English and American geologists. Because of the conflicting views between the two schools, the writer, under the instigation and direction of Dr. Kirk Bryan of Harvard University, undertook to carry on experimental work on the artificial formation of "dreikanter" or ventifacts. The modest expenses of these experiments were borne by the Shaler Memorial Fund of Harvard University. The experimental work was divided into two parts: (1) a repetition of Kunen's experiments in order to determine whether his results could be duplicated, and (2) experiments involving constant wind direction. Although the immediate purpose of the experiments was to determine what factors controlled the shapes and the faceting of the pebbles, the ulterior motive in mind was to evaluate wind-faceted pebbles as criteria of past wind directions and types of wind systems.

THE EXPERIMENTAL SET-UP.

The apparatus and general set-up used in the experiments by Kuenen and the writer were essentially the same. As illustrated in Fig. 1A, the apparatus consisted chiefly of a vacuum cleaner unit, V, a sand box, B, a flat, megaphone-shaped, cardboard funnel, M, and a rotating platform or stage, S. In order to convert the vacuum unit into a blowing apparatus, the usual dirt-receiving bag was replaced by a large hose, H, through which the air was conducted to the sand-receiving tube, T. The latter was made of tin and constructed in the form of a letter "t". This tube was connected to an ordinary tin funnel, F, attached to the bottom of the sand box by means of a rubber hose, R. The sand supply was regulated and controlled by means of a clamp screw, C. On entering the receiving tube, T, the sand was carried forward by the air blast through the megaphone funnel and then distributed over the surface upon which the models had been placed. In order to produce the effect of variable winds a metal rotating platform or stage was constructed. The surface of this disk-like stage was carefully marked off into 16 equal sections by means of engraved lines representing the main directions of

[23] Heim, Albert, Über Kantergeschiebe aus dem norddeütschen Diluvium, Vierteljahrschr. Züricher naturf. Ges., 32, 383-385 (Title falsely dated 1887), 1888.

the compass. A guide line marked on the table top immediately in front of the stage made it possible to orient accurately the mounted model through 16 different positions. The stage was held in place by inserting the thin spindle, which was soddered to the disk, through a narrow hole bored through

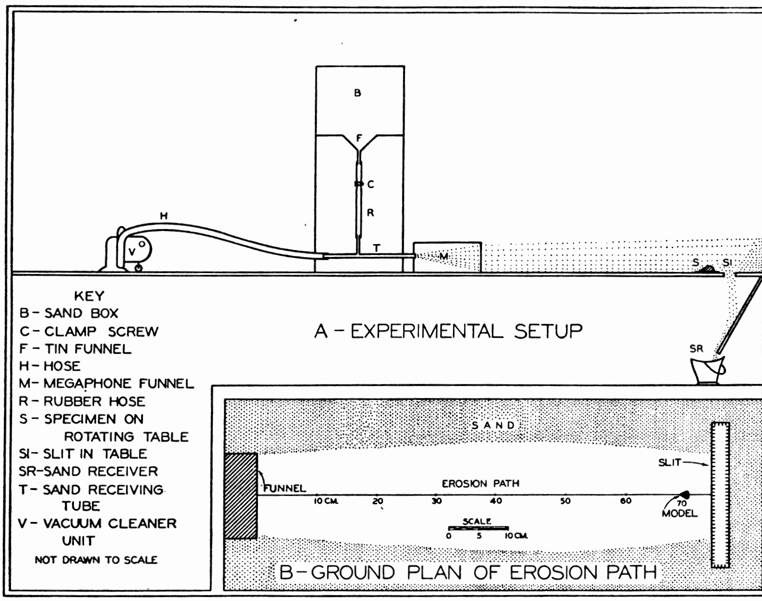


Fig. 1.

the table top. This arrangement made it possible not only to examine the specimen at close range by simply lifting the entire stage from its position but also to replace it in its exact previous orientation without the slightest difficulty and loss of time.

MATERIALS USED IN THE EXPERIMENTS.

At first various kinds of sand* were used in the experiments. It was soon discovered, however, that because of the softness of the material of which the models were composed, the finer sands produced a smoother facet and sharper edges. The

* The sands used were furnished by the Boston Sand and Gravel Co. through the courtesy of Mr. D. D. Reynolds. They were sized by Mr. Reynolds in the testing laboratory of the Company.

sand finally selected was a washed beach sand whose textural range varied between .5 and 1 mm. Kuenen, on the other hand, used fine dune sand at first which he later discarded for a coarse river or concrete-making sand because it cut faster. However, in the writer's experiments, as the models were reduced in size, the coarser sand bombarded the thin edges with such force that large pieces were broken off and no well-defined edges were formed. The writer, therefore, reversed Kuenen's procedure and reduced the size of the sand.

The models used in the experiments were composed of (1) Plaster of Paris, (2) English chalk, (3) magnesium carbonate, and (4) whiting or putty powder ($CaCO_3$). The Plaster of Paris was soon discarded as requiring too long to cut. The English chalk which proved to be not quite as resistant as the Plaster of Paris was used to a limited extent. Most of the models were cut from blocks of magnesium carbonate. These blocks are the commercial type of non-medicinal magnesium carbonate and are of a very uniform and compact texture. Although soft, the material is brittle enough to break with a conchoidal fracture. Models of whiting or putty powder which were used almost exclusively by Kuenen proved to be very satisfactory when well made. These models were made by mixing a quantity of whiting or pulverized calcium carbonate powder with water until a plastic mass was obtained. The mass was then placed in a shallow pan, shaken up and down a number of times to force out all air bubbles and finally allowed to dry slowly.

In the preparation of the models, the magnesium carbonate was more useful than any of the other types of material used. This was due to (1) the ease of obtaining the magnesian carbonate blocks at any drug store, (2) the cheapness of the blocks, (3) the saving of considerable time and effort because of the fact that the blocks could be cut up at once into models of any desired form, (4) the uniformity of the material which resulted in smooth facets and sharp ridges and (5) the softness of the magnesian carbonate which permitted the model to be faceted in a very short time. Models made of whiting or putty powder yielded results equally satisfactory to those cut from blocks of magnesian carbonate. Such models, however, were not used extensively in the experiments as it was necessary first to make blocks of whiting from which the models could later be cut. This process not only demanded extreme care but also required considerable time.

The English chalk was abraded so slowly that only a few of the models were cut from this material. In addition, some of the chalk was not of uniform texture due to the presence of small fragments of shells and hard grains. These impurities were not apparent until after abrasion had taken place. The single advantage of the chalk was that the sand-blasted model did not break as readily as those made of the softer materials.

PRELIMINARY EXPERIMENTS.

Before starting to sand-blast the models, the sand stream was permitted to operate without any interference or obstruction in its path. As a result, an elliptical erosion path was formed along whose borders the sand accumulated (see Fig. 1B). After a short period the sand at the farthest end of the path developed into a dune which on reaching its maximum height for the given wind velocity migrated upstream. It became obvious at once that unless the dune should be prevented from migrating upstream and burying the models, the experiments would not be conducted under stabilized conditions. Consequently, a slit was cut through the table top at the farthest end of the erosion path. This slit not only stopped the formation of the dune but it also served another purpose in that it automatically permitted the sand to drop down into a coal scuttle from which it could easily be poured into the sand box. Proof that the experiments could now be conducted under uniform conditions was indicated by the following facts: (1) artificially made depressions in the sand slopes were quickly filled up with sand and obliterated, (2) sand placed in the erosion path was now removed and carried along by the air current, (3) dunes failed to develop on the lea side of the model and at the farthest border of the erosion path, and (4) the sand slopes ceased to grow in height. Judging from Kuenen's descriptions and especially from his plates, it appears that his experiments were not performed under uniform conditions. No indication is given as to how the accumulating sand was removed at the end of the erosion path. It is conjectured that the sand was removed from time to time by merely shovelling it away. It must be clear that if this procedure was used the sand-blasting could not have been carried on under uniform conditions. However, the lack of uniformity is apparently not very important so far as the form of the cut model is concerned.

In the experiments conducted by the writer the models were placed in the erosion path at a distance of 70 cm. from the mouth of the megaphone funnel. Kuenen, on the other hand, sand-blasted his models at a position approximately 17 cm. distant from the funnel mouth. The 70 cm. position, which was determined by experiments as described below, marked the place where the sand was distributed more nearly equally in a vertical direction and where abrasion was more uniform and slower than at nearer positions.

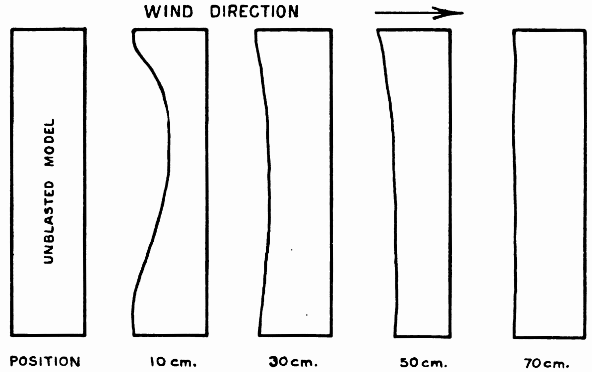


Fig. 2. Diagrams of test blocks showing the effect of the sand blast on models at distances of 10, 30, 50 and 70 cm. from the megaphone funnel.

Five test blocks of magnesian carbonate, each 8.3 by 2 by 2 cm. in size, were made. One of these blocks was then exposed to the sand stream for two minutes at a distance of 10 cm. from the funnel mouth. A second block was then abraded for a similar period at the 30 cm. position after which the third and fourth blocks were successively sand-blasted for two minutes each at the 50 and 70 cm. positions respectively. The fifth block was not subjected to the sand blast and served as the control model. The effect of the sand blast was then noted on each test block and compared with the control model. As may be seen from Fig. 2, the greatest and most unequal effect was on the test block placed nearest to the funnel mouth and the least and most uniform wear was on the model located at the 70 cm. position.

KUENEN'S EXPERIMENTS REVIEWED.

Kuenen's experiments were based upon the supposition that "dreikanter" are produced by variable winds and that the formation of facets on a pebble is dependent upon the shape of its base. Accordingly, Kuenen started experimenting with models having bases of definite shapes. In order to simulate variable winds, he placed the models on the rotating stage turning it first so as to orient the specimen to face north, then south, followed by west, east, northeast, southwest, etc., through 16 different positions. The sand stream was permitted to corrade the model in each of the 16 different positions for an equal length of time, usually five minutes. Kuenen's results may be summarized by means of the following table.

TABLE I. Summarizing Kuenen's results with models having bases of definite shapes and with variable winds.

Model	Shape of base	General shape of model	Form produced
1	Rounded off three-sided triangle	Roundish block	Pyramidal or dreikanter type
1a	Rounded off three-sided triangle	Tabular	Pyramidal or dreikanter type
2	Trapezium	Roundish block	Ridge-shaped type, roof-shaped variety*
2a	Trapezium	Tabular	Ridge-shaped type, roof-shaped variety
2b	Trapezium	Truncated rectangular pyramid	Ridge-shaped type, roof-shaped variety
2c	Trapezium	Like 2b but height twice as great	Ridge-shaped type, roof-shaped variety
3	Oval	Half-egg	Ridge-shaped type, einkanter variety
3a	Oval	Tabular	Ridge-shaped type, einkanter variety

As may be seen from Kuenen's results, models having a triangular-shaped base produced pyramidal or typical dreikanter forms, whereas roof-shaped and einkanter varieties of the ridge-shaped type were derived respectively from models

* The writer has adopted Bryan's terminology of ventifacts, but distinguishes at least two varieties under his ridge-shaped type: namely, einkanter and roof-shaped forms. Einkanter are those forms which have either one or two wind-cut facets and one horizontal edge or ridge. The roof-shaped forms possess more than two wind-cut facets of which the two dominant ones are inclined toward each other to form an edge or ridge. These varieties of the ridge-shaped type are illustrated by figs. 4c and 3d of Plate I respectively.

having trapezium and oval-shaped bases. Forms similar to those obtained by Kuenen are illustrated on Plate I.

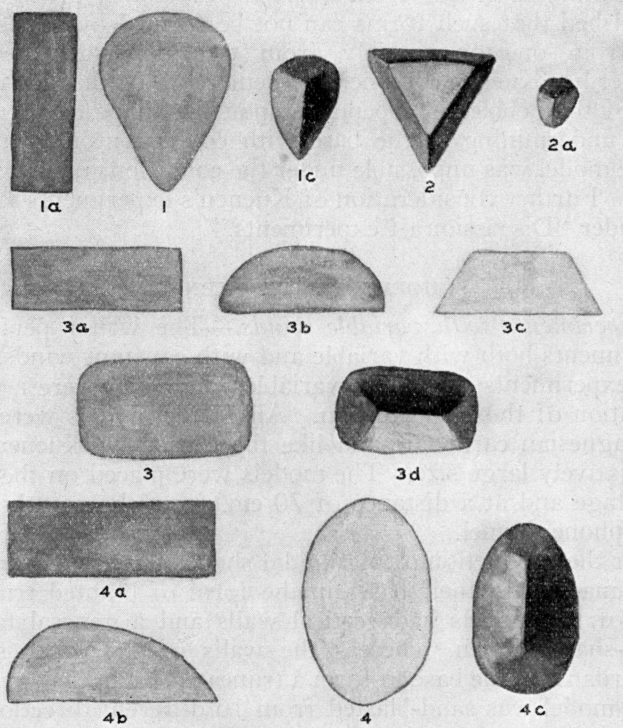
Although the above forms were produced by sand-blasting that simulated winds from variable directions, proof is not established that such forms can not be formed by winds coming from one or possibly from two opposite directions. Neither has Kuenen convincingly demonstrated that the modelling of the pebbles is dependent upon the shape of their base since undermining at the base with consequent reorientation of the model was impossible under the conditions of the experiment. Further consideration of Kuenen's experiments is taken up under "Discussion of experiments."

SCHOEWE'S EXPERIMENTS.

Experiments with variable winds.—The writer performed experiments both with variable and with constant winds. The first experiments were with variable winds and were a partial repetition of those of Kuenen. All of the models were made of magnesian carbonate and like those used by Kuenen were of relatively large size. The models were placed on the rotating stage and at a distance of 70 cm. from the mouth of the megaphone funnel.

For the production of pyramidal shapes the first two models were made with their bases in the form of blunted triangles. One of the models had vertical walls and a general tabular, heart-shaped form, whereas the walls of the other slanted upwards from the base to form a truncated triangular pyramid. Each model was sand-blasted from 16 different directions for five minutes each or for a total period of 80 minutes. The final form produced in both cases was the same, namely a three-sided pyramid or dreikanter. (Figs. 1c and 2a, Plate I.) Facsimiles of the original models together with the end-form resulting from the corrasion of the heart-shaped model are illustrated in Figs. 1 to 2a, Plate I. The next group of models to be sand-blasted was made with a rectangular base and several types of profiles, rectangular, elliptical, and pyramidal. As may be seen from Fig. 3d, Plate I, these models after having been oriented through 16 positions and corraded for 80 minutes each developed into a form characterized by one dominant horizontal edge and with more or less rounded ends, the roof-shaped variety of the ridge-shaped type of ventifact. The original shape of the base of the next two models was oval. One of the models had straight, vertical walls or a

PLATE I



ORIGINAL MODELS
SIDE VIEWS----1a,3a,3b,3c,4a,4b.
BASES----1, 2, 3, 4.
WIND-FACETTED MODELS
PYRAMIDAL TYPE OR DREIKANTER -- 1c, 2a.
RIDGE-SHAPED TYPE, ROOF-SHAPED VARIETY--3d
RIDGE-SHAPED TYPE EINKANTER VARIETY----4c

0 1 2cm.

DRAWINGS OF MODELS SHOWING SHAPES BEFORE AND AFTER SANDBLASTING UNDER CONDITIONS OF VARIABLE WINDS rectangular profile, whereas the other model had a profile like that of half an egg. After 60 minutes of sand-blasting each of the models had been converted into a typical ridge-shaped type of the einkanter variety or into a form with one well-developed horizontal edge and two distinct facets. See Fig. 4c, Plate I.

The next experiment was similar to the first and second. The model, however, was composed of English chalk and was about half the size of the previous model. Instead of developing into a three-sided pyramidal form after having been corraded for 80 minutes as did the models in experiments 1 and 2, the model simply became smaller in size and remained unchanged in form. Why the English chalk did not assume a pyramidal form as expected is in part explained by subsequent experiments. (See Miscellaneous experiments.)

With the exception of the model made of English chalk, the forms produced in these experiments are similar to those obtained by Kuenen and thereby confirm his experiments. The writer is in perfect agreement with Kuenen that under the conditions postulated by him the shape of the base and variable winds are the controlling factors in the development of wind-faceted pebbles. On the other hand, the writer is not convinced that variable winds such as those postulated by this experimenter really occur in nature and that, therefore, wind-faceted pebbles are actually formed in the manner thus described.

Experiments with constant winds.—In the following experiments the models were corraded by winds coming only from one or from two opposite directions instead of 16 as in the experiments just described. The models, except for size, were in all respects similar to those used before. After placing the longer axis of the model at right angles to the wind direction the exposed face was corraded by the sand blast from eight to fifteen minutes depending upon the original size of the model. In most cases the model was then reversed and sand-blasted for a second and equally long period of time. The data of these experiments are summarized in the following table:

TABLE II. Summarizing data of experiments with constant winds.

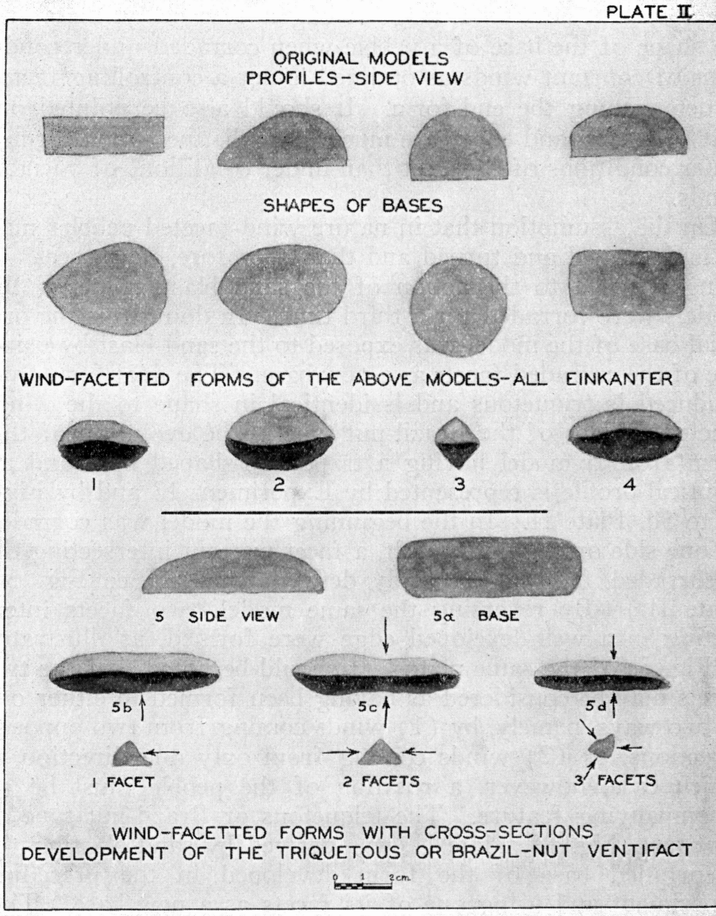
Experiment No.	Model: Size—mm. L.	W.	Ht.	Shape: Base	Profile	Corrasion: Faces	Time'	End-form	Illustrations Plate II
9	40	31	10	Heart	Tabular	2	15	Ridge-shaped type, einkanter variety	Fig. 1
10	42	26	16	Oval	Half-egg	2	10	Ridge-shaped type, einkanter variety	Fig. 2
11	33	33	21	Circle	Hemi-sphere	2	10	Ridge-shaped type, einkanter variety	Fig. 3
12	39	21	16	Trapezium	Elliptical	2	10	Ridge-shaped type, einkanter variety	Fig. 4
13	42	20	15	Trapezium	Elliptical	1	10	Ridge-shaped type, einkanter variety	Fig. 5, 5a, 5b
14	42	20	15	Trapezium	Elliptical	2	10	Ridge-shaped type, einkanter variety	Fig. 5, 5a, 5c
15	42	20	15	Trapezium	Elliptical	3	10	Triquetous or Brazil-nut type	Fig. 5, 5a, 5d

It will be seen at once that with one exception (Experiment 13) all of the end-forms listed in the column next to the last are einkanter of the ridge-shaped type or forms with one dominant horizontal ridge or edge. Obviously, therefore, the shape of the base of a pebble when corraded under conditions of constant winds as outlined is not a controlling factor in determining the end-form. It should also be pointed out that the facets and edges are much more distinct when formed under conditions of constant than under conditions of variable winds.

On the assumption that in nature wind-faceted pebbles may be undermined and turned and that, therefore, new faces are being exposed to the action of the sand blast, some of the models were corraded for a third time. In doing this the original base of the model was exposed to the sand blast by using one of the corraded facets as a new base. The final form thus produced is triquetous and is identical in shape to the wind-faceted pebbles of the Brazil-nut type. The evolution of this form from a model having a trapezium-shaped base and an elliptical profile is represented by Experiment 13 and by Figs. 5a to 5d, Plate II. In the beginning the model was corraded on one side only. As a result, a facet was cut intersecting the uncorraded face in a sharply defined edge. (See Fig. 5b, Plate II.) By reversing the same model, two facets intersecting in a well-developed edge were formed, as illustrated in Fig. 5c of the same plate. It should be noted that the two facets may be considered as having been formed in either one of two ways, namely, by (1) winds coming from two opposite directions, or (2) winds coming from only one direction in which case, however, a rotation of the pebble must be an accompanying feature. The triquetous or Brazil-nut type of ventifact, Fig. 5d, Plate II, was derived by sand-blasting the uncorraded base of the form developed in the preceding experiment and using one of its facets as a new base. This procedure is equivalent to having the wind blow from one direction with two cases of rotation and overturn or to two opposite winds with but a single case of rotation.

Since all of the models, irrespective of the shape of the base, yielded, when corraded by constant winds, similar end-forms, that is, the einkanter variety of the ridge-shaped type, it follows that the triquetous form may be developed from any one of them. Hence, the triquetous or Brazil-nut type represents the final or the most complete end-form, all others being either incipient or partially developed.

PLATE II



DRAWINGS OF MODELS SHOWING SHAPES BEFORE AND AFTER SANDBLASTING UNDER CONDITIONS OF CONSTANT WINDS

Miscellaneous experiments.—During the course of the experimental work a number of interesting facts were discovered or verified relating to the formation of wind-faceted pebbles. In the earlier experiments the models composed of the softer materials of magnesian carbonate and putty powder were always undermined, as illustrated by Fig. 3 below, whereas models of English chalk, whether rotated or not, gradually diminished in size without forming inclined facets. In these experiments the models were either placed on the smooth surface of the table or else mounted on a piece of cardboard or

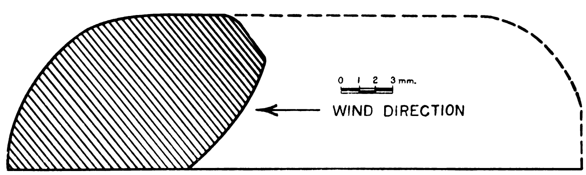


Fig. 3. Diagram of a model showing undermining at its base.

window glass. By building a dam across the erosion path at a distance of about 15 cm. away from the model, sand accumulated on the lea side of the dam and some of the sand grains were carried forward by rolling along the table top. As a result the model was no longer entirely surrounded by a smooth surface and the tendency to undermine had greatly diminished. This suggested the thought of making the entire surface around the model rough or sand covered. This was accomplished by surrounding the model by glass, coating with glue and sand. Models sand-blasted under such surroundings ceased to be undercut and slanting facets were developed even on the chalk models. It is believed that the formation of the facets and the failure to undermine is due to the fact that the sand grains on striking the rough surface are deflected upward and hence more sand grains strike the upper surface of the exposed face than the lower. Apparently sand grains that strike a smooth floor act very much like a pebble which is thrown roughly parallel to a hard surface, such as a concrete road. The pebble skips from point to points on its forward flight without being much projected into the air. Sand grains rebound from the rough surface and do not skip. Consequently they are carried by the sand stream toward the top of the model.

A second factor in undermining is to be found in the resiliency of the models which in all cases were composed of material much softer and less elastic than that of the sand grains. Consequently, the rebound of the sand grains was not as great as it would have been had the models been composed of quartz or normal rock types of which ventifacts are made. It is believed that the sand grains did not rebound sufficiently far away from the corraded face to be carried upward to any extent by the oncoming wind. Hence, corrasion would tend to be approximately uniform over the entire surface and no inclined facet would develop. A cursory examination of natural wind-faceted pebbles shows that in some specimens partial undermining has taken place. Although it is not known what caused the undermining, it is suggested that the surface surrounding the specimen may have been at the time of faceting relatively smooth and free from a sand covering.

The experiments also demonstrated that the surfaces, whether horizontal, vertical or inclined, that extend parallel to the wind direction suffer little or no abrasion and that ridge-shaped types probably do not form in which the edge between the two facets is parallel to the wind direction as held by some observers. This is especially well illustrated in connection with another experiment in which several thin blocks of selenite were introduced into the sand stream. Those specimens whose surfaces lay parallel to the sand-blasting stream, whether oriented in a horizontal or in an inclined position, showed very little effect of abrasion, whereas other specimens with faces inclined or vertical to the wind direction were immediately frosted or matted.

The experiment with the selenite blocks not only demonstrated that abrasion is practically nil on faces parallel to the wind direction but it also confirmed the conclusion reached by Tilghman[24] that the zone of maximum corrasion lies between the angle of 30° and 60° or that wear on a nearly vertical surface of a pebble proceeds slowly, goes forward more rapidly after a time when a surface had been worn down to a place inclined about 30° to the vertical, and again wears very slowly when the plane had been worn down to an angle of 60° with the vertical. In this experiment several bright, glistening cleavage fragments of selenite about two by two inches were introduced into the sand stream and corraded for five minutes

[24] Tilghman, Gen. B. C., See article by G. F. Barker in Johnson's New Universal Cyclopedia, **4**, 62-65.

each. One of the specimens was placed so that its surface lay horizontal and parallel to the wind direction, a second had its face vertical or at right angles to the sand blast, a third and a fourth had faces inclined at angles of 30° and 60° respectively, while a fifth block was so arranged that its upper surface was parallel to the sand blast but inclined at an angle of 60° to the vertical. The blocks whose faces extended parallel to the wind direction were but very little affected by the sand blast and remained bright, glistening and transparent after the run had been completed. All of the other blocks, on the other hand, were very quickly frosted. The block inclined at an angle of 60° to the vertical shows less abrasion than those having angles of 30° and 0°, of which the former shows the greatest effect. In order to obtain more specific data on the rate of abrasion, three models of English chalk were made all of the same size but with their ends sloping at different angles. In one model the face was left vertical, in a second, the face sloped at an angle of 30°, while in the last model the slope was 60°. Each model was then sand-blasted for an hour with the following results: the vertical and the 60° face retreated each 6 mm., whereas the 30° face retreated only a trifle over 2 mm. or about one-third as much as in the other models. This slower retreat is probably to be explained on the basis that surfaces inclined 30° or 60° to the vertical present the optimum plane for sand grains (1) gliding over the surface with minimum corrasion, (2) bouncing off very easily and quickly, and (3) rebounding the least.

The experiment with the selenite blocks was further useful in suggesting a new criterion which may be used to indicate the presence or absence of wind action.[25] Most of the bright, glistening cleavage fragments of selenite were immediately frosted when introduced into the sand blast. The effect took place so rapidly that it is inconceivable that bright selenite fragments could exist in an area having any effective action by wind-blown sand. In arid regions the optimum condition obviously exists for the formation, preservation and accumulation of selenite crystals or cleavage fragments at the surface. Since solution would gradually dull the selenite crystals or fragments in a relatively short time, it is concluded that bright, glistening fragments or crystals have only a short stay on the surface but long enough to signify an absence of effective

[25] Schoewe, W. H., and Bryan, K., Selenite Fragments and Wind Action, Science, n. s. **72,** 169-170, 1930.

wind action. The presence of these fragments or crystals of selenite in the vicinity of niches and pedestal rocks, such as occur at so many localities in the Cretaceous, Jurassic, and Triassic areas of the Western United States, might be used as indicative of the general absence of effective wind scour.

The general impression gained from the literature regarding the cutting of facets is that they are developed by bevelling the top of the exposed face. As time goes on the newly cut facet gradually enlarges until it intersects the base. The experiments, however, show that instead of forming but one single facet, two facets are actually formed, a lower one with

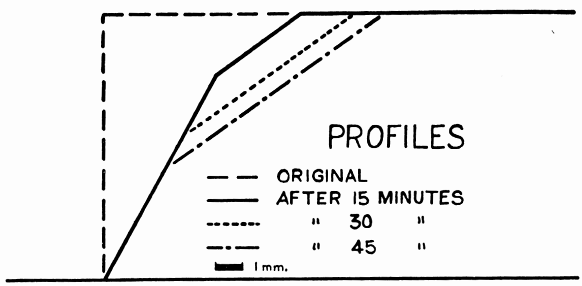


Fig. 4. Diagram showing the profiles of a model sand-blasted for 15, 30 and 45 minutes. Note that the two facets will eventually develop into one face.

a steep angle, and an upper one with a lower angle as is illustrated in Fig. 4. The upper and smaller facet gradually enlarges at the expense of the lower and steeper one until finally but one facet exists.

DISCUSSION OF EXPERIMENTS.

Although the writer was able to duplicate Kuenen's experiments and obtain similar results and thereby apparently confirm Kuenen's conclusion that variable winds and definite-shaped bases are the controlling factors in the development of wind-faceted pebbles, he is not convinced that natural wind-faceted pebbles are thus developed. The writer is in perfect agreement with Kuenen that under the conditions postulated by him definite end-forms result from variable winds and models with bases of definite shapes. Winds of such uniform variability as imitated by Kuenen and the writer are, however, not likely to occur in nature. Winds coming from 16 different directions and each blowing with the same velocity and for an equally long period of time seem to the writer to require an adjustment which is entirely too delicate and one hardly to be realized in nature. Winds blowing from a lesser number of directions and for unequal lengths of time may well produce results entirely different from those obtained in the experiments here described. Furthermore, it is conceived that variable winds would have a tendency to keep the pebbles buried under the sand and thus prevented from becoming wind-faceted. This, to be sure, would not be true if the sand supply were very limited. In such a case, the process of forming facets on the pebbles would proceed at an extremely slow rate. To form wind-faceted pebbles it is necessary that the pebbles remain exposed to the sand-blast action. Such conditions are most likely to be met with where the supply of sand is not too great and where the winds blow in one general direction and carry the sand across the pebbles and out of the area, never to return. Under certain favorable conditions, such as have been described by Travers[26] for Evans' Bay near Wellington, New Zealand, "dreikanter" may be formed by winds which, coming from two opposite directions, shift the same sand to and fro over the wind-faceted pebbles.

It should also be pointed out that the models used in the experiments with variable winds were proportionately too large in relation to the height of the sand stream. Wind-faceted pebbles are seldom more than three inches in height and well-developed, typical ventifacts are usually smaller. As reported by various observers[27] wind scour is more or less confined to the first three feet above the ground. Assuming 24 inches as the height of the sand stream and three inches for the wind-faceted pebble, the ratio is eight to one. Since the opening of the funnel in Kuenen's experiments was only from two to four times as high as the models and since the latter were placed no more than about 17 cm. from the funnel mouth, it is obvious that a ratio of eight to one was not even

[26] Travers, W. T. L., On the Sandworn Stones of Evans' Bay, Trans. New Zealand Inst., **2**, 247-248, 1870.

[27] Bosworth, T. O., Wind Erosion on the Coast of Mull, Geol. Mag. n. s. Dec. IV, **7**, 353-355, 1910; Buckley, E. R., On the Building and Ornamental Stones of Wisconsin, Wis. Geol. and Nat. Hist. Survey, Bull. **4**, 26, 1898; Free, E. E., Movement of Soil Material by the Wind, U. S. Dept. Agric., Bur. Soils, Bull. **68**, 27, foot-note m, 1911; Mendenhall, W. C., Ground Waters of the Indigo Region, California, U. S. Geol. Survey, Water-Supply Paper **225**, 26, Plate 7A, 1909; Smock, J. C., Building Stones in New York, N. Y. State Mus. Bull., **2**, 386, 1890.

realized approximately. It is believed that the models used are more nearly comparable to large boulders in the path of a sand-blasting wind than to the normal type of wind-faceted pebbles. Large boulders are known to split the sand-blasting stream, and are cut on the sides, whereas the smaller pebbles are engulfed in the sand stream.

SUPPLEMENTARY DATA.

In order to supplement the laboratory experiments and to arrive at first-hand information regarding the occurrence of wind-faceted pebbles, the writer in company with Dr. Kirk Bryan and several graduate students of Harvard University made a field trip to Cape Cod, especially to the localities known as Highland Light and North Truro. At these two localities glacial outwash sands and gravels occur which according to Woodworth[28] are of pre-Wisconsin age. Practically all of the pebbles which at Highland Light are overlain by several feet of modern wind-blown sand show the effects of some wind action. According to Davis[29] the pebbles at Highland Light are now in the process of formation, whereas those found at North Truro have been formed in the past. The writer is of the opinion that most of the wind-faceted pebbles on Cape Cod are ancient and probably were formed during the period of deposition of the outwash or immediately afterwards. The surfaces of many of the pebbles are more or less weathered, thus pointing to their antiquity.

All stages of wind-faceting from pebbles showing incipient facets to typical ridge-shaped, pyramidal and triquetous types are represented. Of these, the einkanter variety of the ridge-shaped type occurs in greatest number. That overturning of pebbles with consequent formation of new facets takes place is well illustrated by specimens which show facets on all sides. This overturning or rotation of the pebble may be attributed to (1) undermining of the base upon which the pebble rests due to wind or rain-wash action, (2) sudden and very strong gusts of wind, (3) frost action, (4) animals, (5) creep or slump, (6) settling, (7) solution of underlying pebbles, etc.

The presence of all types from incipient forms to well-developed pyramidal and triquetous forms, all associated in one

[28] Woodworth, J. B., and Wigglesworth, E., Geology of Cape Cod and the Adjacent Islands, Mus. Comp. Zool. Mem., **52**, In press.

[29] Davis, Wm. M., Facetted Pebbles on Cape Cod, Massachusetts, Boston, Soc. Nat. Hist. Proc., **26**, 166-175, 1894.

place, seems to the writer to refute the hypothesis of variable winds. According to the latter hypothesis one would hardly expect to find typical triquetous forms and pebbles corraded only on one side associated with pyramidal and ridge-shaped types. The triquetous or Brazil-nut forms require overturning and the pebbles corraded only on one side winds from a single direction. The writer is willing to grant that einkanter or single-ridged forms with single facets may possibly be formed by variable winds under special conditions of interference by neighboring pebbles or obstacles. It is equally possible, however, to conceive of other special cases in which a pebble may be oriented just right in relation to a wind coming from one or two opposite directions in connection with neighboring pebbles to develop into a good pyramidal form. Thus any exception may be accounted for whether related to variable or to constant winds. Another argument favoring the formation of wind-faceted pebbles by constant rather than by variable wind action, is suggested by the fact that most of the ventifacts seen on Cape Cod are einkanter or single-ridged forms. According to Kuenen's experiments these forms are only produced from pebbles whose original bases are oval. Hence, it follows that if wind-faceted pebbles are made by variable winds by far the greater number of the Cape Cod pebbles must originally have had oval-shaped bases. Such an assumption seems to the writer to be unwarranted and untenable. It is very much easier and simpler for the writer to explain the wind-faceted pebbles of Cape Cod on the basis of constant winds coming either from one or from two opposite directions and accompanied to a certain extent by overturning and interference by other pebbles than to variable winds.

SUMMARY AND CONCLUSIONS.

The experiments demonstrated that (1) pyramidal and ridge-shaped forms can be formed by variable winds from models having bases of definite shape, (2) einkanter and triquetous forms can be formed by constant winds, *i.e.*, winds coming chiefly from one or from two opposite directions irrespective of the shape of the base of the model, (3) models supported on a smooth hard floor become undermined, whereas those surrounded by sand develop inclined facets, (4) faces parallel to the sand blast suffer practically no abrasion, (5) einkanter, or single-ridged forms whose edges between the two facets are parallel to the wind direction are not likely of being formed, (6) the rate of abrasion on faces sloping 30° or at an angle of 60° to the vertical is about one-third as great as on faces inclined at angles of 60° and 90°, (7) selenite cleavage fragments or crystals are good negative criteria of wind action, and (8) in the incipient stages of faceting, two facets instead of one are developed.

The final conclusions reached by the writer in regard to the formation of wind-faceted pebbles are as follows: (1) the shape of the base of a pebble and variable winds are the controlling factors determining the final wind-faceted form under the conditions postulated by Kuenen, (2) Kuenen's assumptions are improbable and therefore natural wind-faceted pebbles are not formed as believed by him, (3) the shape of the base is not a controlling factor in the development of forms made by constant winds, (4) the triquetous or Brazil-nut type represents the final end stage in the development of wind-faceted pebbles, and (5) most wind-faceted pebbles are made under conditions of constant winds.

The writer wishes to acknowledge his sincere appreciation to Dr. Kirk Bryan of the Department of Geology and Geography of Harvard University for helpful criticism and for suggesting the experimental problem.

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