EXPERIMENTS ON THE FORMATION OF WIND-WORN PEBBLES

BY

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(Pl. 3—7).

ABSTRACT.

The influence of the wind laden with sand in modelling pebbles is believed by some authors to be only that of polishing the surface, by others of rounding off bits of stone that already possessed edges and corners, or again by others of wearing any fragment either rounded or angular into definite forms with ridges and facets, dependent on the shape of the basis (Alb. Heim). Experiments, fully confirming the last opinion, are described in this paper: no rounding off took place, while the models were slowly revolved in the sandblast, and vertical planes took on a backward slanting position, cutting eachother along sharp edges. Where sand corrosion is great, as in the desert, the windworn pebbles owe their shape to the laws formulated by Heim; many of the fossil windworn pebbles of Northern Europe have undergone but slight alteration from their original shape and size by the natural sandblast, others seem to have been entirely remodelled by the wind along the lines indicated above.

INTRODUCTION.

Windworn pebbles are characterized by the occurrence of one or more ridges, generally straight or slightly curved; a smaller or larger number of flat or domed facets, generally smooth, sometimes pitted; and a dull polish. The most characteristic shapes are: ovals with one ridge along the central line, three sided pyramids (German ''Dreikanter'') and roof shapes. Frequently the upper and under sides are almost identical in shape. They are a common feature of many deserts and are also found along the margin of the diluvial ice-sheets of Northern Europe and North America as fossil witnesses of a former barren period, when the wind played over large areas of loose sand and boulders. They are found to consist of almost all pebble and boulder forming rocks, but are mostly formed of hard insoluble, homogeneous material, especially sandstones and quartzites. They have been looked upon as stone implements, products of human industry, and their formation has been attributed to the friction in thick deposits of pebbles through which water flowed, but nowadays all are agreed that wind-borne sand is the agent, which changes a pebble or rock-fragment into a typical windworn pebble. Opinion is divided, nevertheless, as to the degree to which the wind is able to alter the shape and reduce the size of a stone, and as to whether new planes can be generated, or original angularity reduced.

The present paper is an attempt to establish by experiments some laws of the corrosion of loose lying bodies over which sand is blown in varying directions, and to analyse the shape of windworn pebbles according to the laws thus found.

OPINIONS AS TO THE INFLUENCE OF THE NATURAL SANDBLAST ON LOOSE LYING ROCK-FRAGMENTS.

It is not my intention to offer a full historical treatment of the development of the various opinions concerning the influence the sandblast has in forming windworn pebbles and what lines of attack it thereby follows. What concerns us principally is to know what opinions are held at the present day and what arguments may be offered in support or against these, thereby showing what problems still remain unsolved.

The first to attribute to the natural sandblast the formation of these pebbles, the New-Zealand geologist TRAVERS, has not expressed a definite opinion on this subject.

A number of geologists, among whom investigators of the desert take a prominent place, are of opinion that rock-fragments may be shaped into the various characteristic forms, where there is a predominating wind from one or more directions. WALTHER, VERWORN, KAISER CLOOS and others have studied regions in the desert where the sandstorm came from one single direction, or two opposite directions, to the exclusion of alle others. In such localities it was found that almost all pebbles had one single ridge at right angles to the direction of the wind. These were formed by the intersection of the one corroded and polished plane turned to the wind and the untouched rough surface on the leeside in the case of a single predominating wind; and of two planes in the case of opposing winds. In a few instances the pebbles had been shifted, which has given rise to the formation of dreikanter or other shapes. On the evidence brought forward by the writers mentioned, it can hardly be doubted that in the cases described their explanation must be accepted. But even in the desert it must be a rare phenomenon for the wind to be restricted to one direction only and in the northern countries this was certainly not the case. It is therefore an unjustifiable assumption that the wind can only wear ridges on a stone when it blows from one single direction.

Neither can the opinion held by HAUG and others and expounded in many textbooks of geology, be maintained that each plane of a wind worn pebble corresponds to one of the directions to which the wind is almost entirely confined. As has been pointed out by HEIM and others, such a limitation of the possible directions of wind is merely hypothetical and the fact that pebbles with two, three, four and more planes are almost always associated together is incompatible with this view. Even if a shifting of the position to account for this fact is assumed, it is hardly sufficient to explain that the opposite sides of pebbles, when both show the effect of the sandblast, should almost invariably be alike. That dreikanters and other forms can be generated where there is no predominating direction in the wind should be the first principle of a theory to account for these shapes.

A second group of investigators holds that the angular, ridged shape must be present before the sandblast commences its work. Some, like FABER are of opinion that no change of shape or weight has been brought about in forming the northern windworn pebbles. The influence of the wind is restricted to the polishing and smoothing of the planes already formed by other agents, whereby the ridges may have been slightly accentuated. Others, among whom ZU LEININGEN and JOHNSEN are to be mentioned, attribute a rounding off influence to the sandblast. After the angular fragments are smoothed an ever increasing rounding off sets in. JOHNSEN even believes that ultimately a windworn rockfragment will only differ from a waterworn pebble by the polish of the surface. LORIÉ and TESCH accept the same view and point out that on the beach, where the influence of the wind-borne sand can be directly studied, a rounding off of angular fragments may be observed. PFANNKUCH is no doubt right, however, where he points to the impossibility of proving that this rounding off must be attributed to the sandblast and not to the rolling of the surf, that now and then sweeps the whole breadth of the beach.

LORIÉ and TESCH have also ascertained that the shape of many windworn pebbles must be attributed to older influences than the wind, the ultimate shape being undoubtedly in close connection with pre-existing planes of fracture. Although they are certainly right that the shape of a great number of windworn pebbles has been almost entirely given by diaclases and other directions of weakness in the rock, this is no proof that the sandblast has in no cases changed the shape beyond the recognition of the original form.

Though the opinions here expounded may be right, we see that a definite proof is missing.

In a short paper HEIM proposed a different theory. The wind forms planes on the rock-fragments according to definite laws, dependent on the shape of the basis of the stone. Where it meets a side of the polygonal basis it is forced to pass over the top of the stone and thereby wears off a facet, forming a ridge at the boundary with the lee side. When the direction changes and it blows on a corner of the basis it is divided in two, each current passing along and obliquely up the planes corresponding to the sides of the basis. The ridge between these two is rounded off somewhat, but only so slightly that when it is again the border between the corroded side and the lee side, after a new change in direction of wind, it is again sharpened to its former degree of keenness. According to this theory the ultimate shape is therefore dependent on the original shape of the basis. The facets will be almost flat and the sides of the basis will be rounded off to cylindrical shapes. When the basis is an oval only one ridge is developed parallel to the longest axis of the oval. When it is rectangular the two longest sides correspond to two large planes that intersect along a horizontal ridge parallel to the long sides of the basis. When once the rock-fragment is so far corroded that a dreikanter or other characteristic shape is formed, it will only diminish in size, but not change shape to any marked degree.

It is obvious, that where a rock-fragment is originally almost the same shape as the form that must be developed according to the laws just described, it will take only a short time to arrive at its ultimate shape. This would explain the fact that so large a number of windworn pebbles appear to be but slightly altered from the shape of the polygonal cleavage fragments. It is because cleavage fragments often resemble the windworn shapes so closely that they have been little altered in form, not on account of the impotence of the wind to corrode them.

PFANNKUCH later came to the same conclusions as HEIM. He examined a great number of pebbles from the island Sylt and gave a systematic subdivision into groups. He also pointed out the importance of the exceptional position of the plane on which the pebble lies. Frequently the stone has not been turned over and this plane then presents the original rough fracture or waterworn surface of the material. The ridge by which it is marked off from the remainder of the pebble's surface is more or less circular or oval in shape. It is also a common phenomenon that the pebble has been repeatedly turned over and then one of the facets on both sides is developed into a supporting plane with a ridge running in a curved line right round it, or along a large part of its circumference. In contrast with the former case, however, the surface has been polished and smoothed, during the periods that the stone lay on its opposite side.

The advantages offered by the theory of HEIM are that we need not assume one or more directions to which the wind is restricted, that it explains all shapes of windworn pebbles met with and that there is a wider range of possibilities for the original shapes than with the theory of JOHNSEN, ZU LEININGEN and others. If on the other hand these latter are right in supposing that the sandblast rounds off, the theory of HEIM must be discarded. There is still another point in which the theory of HEIM needs confirmation and development. It is not clear, namely, how the new facets are formed on a rock-fragment. Are all planes corroded inwards parallel to their original position, that is to say, does a vertical plane remain vertical, a slanting plane slanting, while moving backwards; or do all planes heal over backwards more and more while the sandblast corrodes them; or is a new plane developed directly under a certain angle with the horizontal plane and then moved backwards in this position? It is obvious that without an answer to these questions HEIM's theory cannot be looked upon as complete.

In fig. 1 a triangular projection is given to illustrate the various opinions on the formation of windworn pebbles. The three influences that are believed to have changed any rock-fragment into a windworn pebble are placed in the corners. The distance to a side of the triangle represents the importance of the influence placed at the opposite corner. As the sum of the three distances to the three sides from any point in the triangle is the same it may be taken as 100 % of the influences exerted. The opinion of various authors as to the relative importance of the influences is given by a dot. The position to represent a pebble when first exposed to the wind must be in the tophand corner. According to each investigator it will arrive ultimately at the stage denoted by the dot to his name.

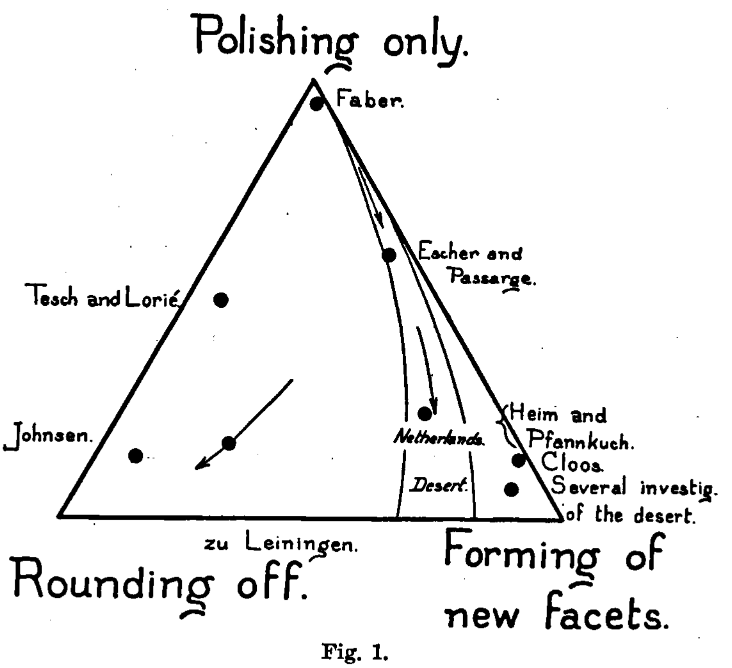


Fig. 1.

Some opinions on the influence of the sandblast in forming windworn pebbles.

Thus the investigators of the desert, JOHNSEN and ZU LEININGEN all attribute little or no influence to the original shape, but according to the former no rounding off occurs, while JOHNSEN is of opinion that the fragment will be entirely rounded off and ZU LEININGEN holds that after forming planes first, the rounding off will then become more and more pronounced. PASSARGE and ESCHER do not believe that large facets and entirely new ridges can be generated, and HEIM und PFANNKUCH believe that the influence of the original shape still remains through the medium of the basis. The point to represent their opinion was placed some distance from the side of the triangle, because of the rounding off of the horizontal ridges they assume. My experiments have led me to suppose that the position for all pebbles of northern Europe will fall within the area between the curved lines and that in the desert the influence of the original form may be so small that the dot should be placed even closer to the basis of our triangle.

FORMER EXPERIMENTS ON THE CORRODING OF THE SANDBLAST.

The first experiments on the corroding of the sandblast were made by DE GEER in 1882. With an artificial sandblast he was able to procure the characteristic dull polish of the natural windworn pebbles on the rough fracture planes of rock-specimens. More extensive experiments followed in 1887 by THOULET. An artificial sandblast played upon the surface of slabs of various materials and 12 laws of corrosion were established. Those of most interest to us are:

1. The corrosion is in proportion to the pressure of the wind.
2. The corrosion is strongest when the wind is at right angles to the corroded surface.
3. The larger the sandgrains the stronger the corrosion.
4. The sharper the sandgrains the stronger the corrosion.
5. The smoother the surface of the slab the weaker the corrosion.

No experiments were made to study the forms generated by the sandblast.

In the same year PREUSSNER tried to obtain windworn pebbles by the aid of an artificial sandblast, but without succes. No particulars about his methods are given.

In 1900 HARLé made some experiments in which he also found that all kinds of rock-material can be corroded by artificial sandblasts.

JOHNSEN as we have seen, was of opinion that angular rock-fragments will be rounded off by the windborne sand and he mentions having made experiments that proved this opinion. Unhappily he does not describe these experiments, so that we are not able to judge in how far the circumstances in his experiments resemble those in nature. Why his results differ so entirely from my own I am, therefore, not able to explain.

HEDSTRÖM made a series of experiments, the results of which he described in a paper in 1903. He employed a glass-etching machine and followed the process of corrosion on pebbles of various rocks. He was able to obtain the polish, the facets and the pitted surface of irregularly grained material also seen in nature. However, the opening of the etching machine was narrower than the pebbles, and these were corroded from one single direction only. Besides, these were hung up in the sandblast on copper gauze, the wind thus playing round them, whereas in nature the pebble lies on the ground so that it is protected from corrosion on one side, while the wind follows quite different streamlines, as we shall see later on. HEDSTRÖM's experiments are therefore not convincing as to what shapes will be generated in nature.

However important these experiments may be in confirming the opinion that the windborn sand is not only able to corrode stones but calls forth the polished and pitted surface we now find on windworn pebbles, they have taught us little that may help to decide between the various opinions illustrated by fig. 1. In the experiments to be described below it was my aim to study the bodily shape that various models would take on under the corroding influence of a sandblast that played upon them from changing directions.

DESCRIPTION OF THE EXPERIMENTS.

The apparatus with which the experiments were carried out was very simple (fig. 2, Pl. 3, fig. 1). The current of air was taken from a

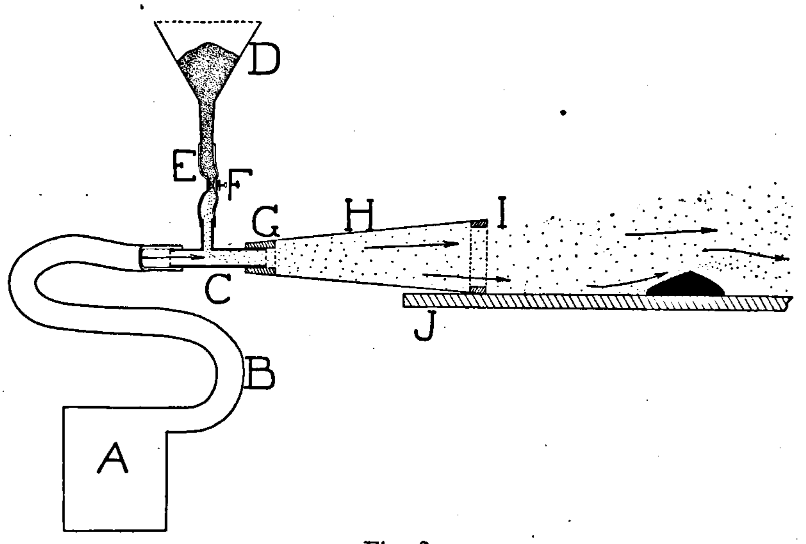


Fig. 2.

The arrangement of the experiments.

vacuum cleaner (A) and conducted by the pipe (B) to a metal tube C). Here the sand was introduced from a funnel (D) over which a packing case was placed, as a large store of sand, with a hole in the bottom, larger than the tube of the funnel. As the hole was on a level with the rim of the funnel, the latter could not overflow, but was all the same always kept full through the large outlet of the packing case. A screw (F) on the rubber tube (E) connecting the funnel with the air conduit enabled me to regulate the supply of sand. In a long cardboard funnel (H) fixed to the end of the metal tube, the sand divided itself equally throughout the current of air. At the opening of the funnel was a wooden frame (I) in which strips of cardboard could be fixed vertically to regulate the current of air so as to be of uniform velocity over the whole breadth of the opening. The sandblast thus formed spread out over a plank (J) on which the models were placed.

First of all it was necessary to ascertain the breadth over which the sandblast was of maximum strength. The difficulty was to do so without influencing the current by placing an obstruction in its course, that would deviate the streamlines to right and to left. The following method was used. A small dam of dry sand was made at right angles to the current of air some short distance from the opening with the cardboard strips. Pl. 3, fig. 2 shows this dam photographed straight from above. On opening out the current of air nothing happened, but as soon as sand was introduced, it started corroding the dam by the aid of these small projectiles. The dam was slowly worn down, at the same time moving backwards (Pl. 3, fig. 3). In the case illustrated, one side of the current was slightly stronger than the other. By placing a cardboard strip on the corresponding side of the funnel opening this irregularity could be eliminated. Without any strips the corroding force was strongest in the centre, diminishing slowly towards both sides. In fig. 4, Pl. 3 the situation may be seen when the dam had been broken through. The cardboard disc placed in the breach was used as base for the models, which were always of smaller circumference. It will be seen that they were well within the limits of the breadth of maximum and equal corroding power.

No special test was made to see how the corroding power was distributed vertically. In the first place this could of course not be done in the same simple manner as for the horizontal direction. In the second place it might even be wrong to attempt to make it equal over a distance larger than the height of the models. In nature the number and size of the winddriven particles is greater towards the surface of the ground, while on the other hand the velocity of the wind is smaller. Which of these opposing influences is the more important will depend upon a number of things, velocity of wind, average size and number of the sandgrains, and amount of difference in their size. All these factors vary in nature and yet the result is always approximately the same. It cannot be of material importance, therefore, how the circumstances are in the experiments. As the opening of the funnel was 2—4 times as high as the models, and these were sometimes placed on the plank, sometimes on a thick wooden disc, sometimes close to the opening, sometimes further away, always with identical results, we may assume that the circumstances were well within the limits occurring in nature.

The dune-sand, that was used at first, was soon discarded in favour of coarse river-sand ("Maas-sand", used in concrete). The grains of the latter are larger and sharper and therefore have a far greater corroding power (see the laws discovered by THOULET).

The next step was the choice of material for the models. This should be homogeneous and unplastic to resemble the material of rocks, but soft enough to be worn away by the fairly weak sandblast. Dried clay and gypsum ware found to be too hard and ultimately I decided upon using chalk powder (putty powder) with sufficient water to make it into a plastic mass, which was subsequently slowly dried. It then became a fine grained mass, softer than writing chalk, but firm enough to hold together if handled carefully. With a knife it could easily be shaped into the forms required.

To imitate the constantly varying direction of the wind, that must have obtained in the northern alluvium, the models placed on the cardboard disc were either slowly revolved in the sandblast or placed with the notch pointing first north, then south, then west, then east, after that N.E., S.W. ...... etc., and so on in sixteen different positions. Each position was retained for an equal number of minutes, generally five. The first method was hardly ever employed as it required great care to regulate the revolving accurately.

Most experiments took from one to two hours.

1. Does the sandblast round off angular shapes?

A low, three-sided pyramid (Pl. 4, fig. 1), dreikanter, exposed to the sandblast diminishes in size, and the ridges of the basis become slightly curved and cylindrical (Pl. 4, fig. 1). On continuing the corrosion the curvature of the ridges is not accentuated and the model is slowly reduced while still retaining the typical dreikanter shape. To illustrate the influence of a prevailing direction of wind and to show the way in which the corrosion takes place, the same model was corroded from one direction for a longer time (Pl. 4, fig. 1). We see that what HEIM supposed, actually takes place. The ridge on which the wind plays is slowly rounded off and a sharp ridge is formed on the border of the corroded side and the lee side of the model. An example of this in nature is seen in Pl. 7, fig. 2, a large dreikanter from the Veluwe in Holland, one ridge of which is rounded, the other two sharp and bent slightly away from the direction of the prevailing wind.

The result of a second experiment is seen on Pl. 4, fig. 2, a dreikanter shape of which two corners have been cut off. Again the size is greatly reduced, without any marked rounding off or change of shape.

These two experiments prove conclusively that the sandblast does not round off the characteristic shapes of windworn pebbles. Opinions represented by the dots in Fig. 1 far towards the lefthand corner of the triangle can, therefore, no longer be retained.

2. The formation of three sided pyramids (dreikanter).

Two models were made: a roundish block with a rounded three-sided triangular basis, and a disc with the same horizontal section. The former quickly took on the shape of a three-sided pyramid (Plate 4, fig 4). As the outer layer was somewhat harder than the interior, a small wart was left standing on one of the ridges. In later experiments the outer surface of the dried mass was therefore cut away before shaping the actual model. The disc-shaped model took much longer to shape into a dreikanter. Pl. 4, fig. 4 shows the first stage of the process, where it may be seen that the originally vertical sides have taken on an inward slanting position. After continuing the corrosion the result figured in Pl. 4, fig. 4 was obtained. This is the first confirmation of HEIM's theory: the three sided pyramid is obtained from two different models, that have only the shape of the basis in common, a rounded off three-sided triangle.

3. The formation of the roofshaped pebbles ("Firstkanter").

Again two models were made with the same basis, namely a trapezium, one a disc, the other a rounded off mass (Pl. 4, fig. 3). Both resulted in approximately the same shape, the disc by the vertical sides sloping backwards. While the horizontal ridge is clearly marked, the ridges running to the four corners of the basis are not sharp but more or less cylindrical. Why these ridges are so much sharper in nature, than in this and other experiments will be examined later on, the general shape is the same, however. Another experiment is illustrated by fig. 5 and 6, Pl. 4. In comparison to the size of the basis the height was taken about double that of the former example. The sides were sloped inwards slightly and the ridges were not rounded off but blunted by a small facet. Again a roofshape was obtained and on account of the greater steepness, the slanting ridges were more pronounced.

4. The formation of pebbles with an oval basis and one horizontal ridge.

For the production of these shapes two different models could again be used, one the shape of half an egg, the other a disc with identical basis. The formation of ridges followed the same lines as in the former cases. By the time the disc had taken on the definite shape with one ridge it was much lower than the half-egg (Pl. 5, fig. 1). By corroding the latter still further a form resulted absolutely congruent with that resulting from the disc (Pl. 5, fig. 2). An analogous form found on the Veluwe in Holland may be seen on Pl. 6, fig. 5.

5. The formation of a horizontal, winding ridge.

A fine example of this type of windworn pebble is given on Pl. 7, fig. 3. To obtain an artificial imitation the model was made figured on Pl. 5, fig. 3. The result of the sandblast having played upon it from 16 different directions is to be seen on the same figure.

In all these examples therefore, HEIM's theory of the paramount influence of the shape of the basis before corrosion begins, is confirmed.

6. The formation of a supporting plane ("Liegefläche").

As has been noted above, the plane on which the pebble has lain is frequently still rough. In many cases it is at the same time the largest horizontal section, all side-facets slanting inwards and upwards, either to meet along slanting and horizontal ridges, or to be cut off by another horizontal plane, that is parallel to the supporting plane, and that has been smoothed or pitted by the polishing sandblast (Pl. 6, fig. 1). All the experiments described, resulted in shapes comparable to these forms of windworn pebble. There are, however, other forms to be found, in which the supporting plane is smaller than the largest horizontal section of the pebble. This plane then intersects along a curved ridge with roundish planes slanting upwards and outwards to the largest horizontal section. This section is surrounded by cylindrical ridges and has acted as basis for the formation of the facets above it. Pl. 7, fig. 2 shows an example of this kind.

The reason for such a shape being formed was first sought in an undermining of the rock-fragment by the wind. It was thought that the wind formed whirls along the basis of the stone and blew away the sand until the pebble was left on a short pillar of sand. The weight of the stone prevented the whole pillar from being carried away. In this manner the sandblast would be able to corrode the stone from underneath, inwards to a certain limit at which the supporting sand became too much compressed to be driven away.

Various experiments were made to try and imitate this process. The models were placed on a little heap of sand or on a small support or in a shallow box filled with sand, over the top of which the sandblast was driven. The results were not satisfactory, however, for either the sand was blown away from under the model, or the model was built in all round by sand. If a *little* sand was introduced into the sandblast, when placed on the little heap of sand, it slid off on account of the corroding of this support; and when placed on the small cardboard support its shape was etched onto the underside of the model. When a great amount of sand was let into the current the models were half covered.

Afterwards on comparing two dreikanters Pl. 7, fig. 2, one of which had a small supporting plane and the other a large one, I came to the conclusion that it must be owing to the original shape of the pebble, not to the nature of the corrosion that this undermining was produced. To test this idea a model was made with a disc-shape and sharp-cornered triangular basis, in which not only the horizontal ridges of the upper side were blunted by small facets, but also those of the under side. In this manner the sandblast would be able to start corroding the under side from the very beginning. The surmise proved to be correct as will be seen on Pl. 5, fig. 5. While a dreikanter shape was formed on the upper side, the under side was also corroded, leaving the model on a small supporting plane. The largest horizontal section is surrounded by three cylindrical ridges. The only respect in which the artificial form differs from the corresponding natural one is that the supporting plane is not marked off by a sharp ridge. The reason is the same as with the slanting ridges mentioned before, and will be dealt with separately.

7. Influence of the material of he pebbles and models.

On comparing the artificial and natural windworn pebbles there is seen to be one important difference, that has already been mentioned. On the artificial forms namely, the ridges, especially those that have a downward slanting position, are not nearly as clean cut and sharp as on the natural ones. As I observed that this rounding off of the ridges took place almost immediately after the model was exposed to the sand-blast, but did not pass beyond the degree attained during the first few minutes of the corroding, I supposed that it was due to the material employed being so extremely brittle. A grain of sand hitting the ridge not only scraped off a little powder but chipped a flake off the model. With firmer material this chipping would not occur and the ridges therefore remain sharper. After the ridges had broadened out somewhat this chipping would no longer occur, thus explaining why the rounding off was not progressive.

To test this view I made two roofshaped models, one of the chalk used in the other experiments, one of gypsum. These were corroded, while slowly revolved, until about 2 m.m. had been carried away from the surface, thus showing the maximum which the rounding off of the ridges would attain. This process took some 10 minutes with the soft material of chalk, and 1½ hours with the gypsum. To make sure that an equal amount would be worn from both I blunted the horizontal ridge with a small horizontal plane of about 5 m.m. breadth before commencing, and waited until it had disappeared. At the end of the experiment the ridges of the gypsum model were seen to be almost as sharp as those of the natural windworn pebbles, while those of the chalk model were of course as blunt as in the other experiments (Pl. 5, fig. 4).

It is permissable to conclude that, if the experiments lead to angular and facetted forms although the ridges are rounded, in nature, where the ridges are sharper, the same forms will be generated with slightly less loss of material.

Now it might be supposed that the healing over backwards, noted in the former experiments must also be attributed to chipping of the brittle chalk material, and in that case it would not happen under natural circumstances. We shall see that this is not the case, as the reason for the slanting of the sides is not due to the nature of the material used, and moreover, it may be proved to have occurred in nature also (see page 32). An experimental confirmation was obtained by corroding a vertical plane of a gypsum model, partly screened off to show the original position. Pl. 5, fig. 6 shows the result of almost two hours corrosion, and it may be seen that here also the healing over backwards has occurred. Besides the horizontal top surface has been slightly etched and the horizontal ridge somewhat rounded off.

8. The characteristics of the surface of windworn pebbles.

No experiments were made to study the surface of windworn pebbles. In the first place those made by HEDSTRÖM show sufficiently that, in this respect also, the experimental and natural results are the same. In the second place we have seen that the details in shape depend upon the material used. To obtain satisfactory results actual rock material would have to be taken, and the apparatus used was not powerful enough to do so without unreasonable loss of time.

Nevertheless I wish to point out that there are two different kinds of rough surface that may occur, only one of which has been made by HEDSTRÖM. We must distinguish a warted and a pitted form. The first, occasioned by hard particles in a softer base, has been made artificially by HEDSTRÖM. The second is formed when soft particles or hollows occur in the otherwise even material. Many sandstones found in Holland for example (i. e. Revinien quarzite) contain widely spaced negatives of pyrite cubes that have disappeared. Each hollow thus formed is worn by the sand into a small cupshaped depression when once laid bare by the wind. Pl. 6, fig. 1 and Pl. 6, fig. 4 show two examples of this kind. There are, of course, all manner of varieties between these two extremes. One of the pebbles shown on Pl. 6, fig. 2 has a very uneven surface caused partly by hard veins of quartz, partly by the fact that the corroding has evidently not progressed beyond an initial stage.

THEORETICAL EXPLANATION OF THE OBSERVED FACTS.

We must now attempt to explain the mode in which the models are seen to be corroded, the most important phenomenon being that vertical planes heal over backwards when exposed to the sandblast.

There are two subjects to be considered, namely the influence of the projectiles as they hit the pebble, and the shape of the currents of air around it.

A. Influence of the projectile.

If the collision between the sand grain and the pebble were entirely elastic and the first were spherical, the latter smooth, then the grain would be reflected under the same angle as it hit the surface of the pebble, apart from a small deflection due to the wind, or with larger grains due to gravity. The surface of the pebble would remain unchanged.

There are various reasons, however, why this ideal case is not realised. In the first place there is a minute splintering of the surface of the pebble and of the sand grain. The latter will leave a dent in the former that is deeper but shorter, the more at right angles the grain has hit the pebble's surface. In the second place, the surface of the pebble being uneven, the grain will glide along the projections scraping them off, before the actual concussion takes place. Neither is the grain a perfect sphere, so that a projecting angle may hit the rock-fragment first (fig. 3) and it will make a revolving movement round this projection, while slightly gliding up the surface of the plane before the centre of gravity has approached this surface as close as possible. Not until then does the actual collision and reflection take place. Finally the grain may have been given a revolving motion by the current of air itself. While hitting the pebble it will, therefore, grind it slightly too. Which of all these influences will be the largest it is not possible to say and may vary according to the circumstances.

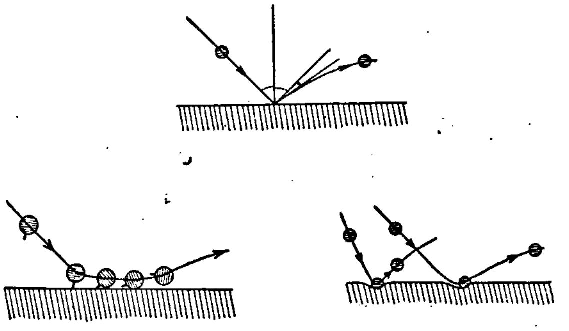


Fig. 3.

The reflection of grains hitting an oblique surface.

B. Shape of the currents of air around the rock-fragment.

When a current of air passing over a horizontal plane meets an obstruction it is forced to pass over the top of it. In front of this obstruction an air cushion is formed in which a revolving movement takes place. As the lowest stream-lines are bent upwards farthest, sand-grains carried along in the current of air will be the more deflected upwards the lower they were when meeting the air cushion. They will not entirely follow the stream-lines, so that they must hit the obstruction all the same. In this manner a greater number of grains will hit the upper than the lower part of the obstruction, with a consequent stronger corrosion of the top than the bottom parts. Moreover, the speed of the wind will be greater further from the ground, another reason for greater corrosion along the upper parts of the obstruction and grains reflected at the base of the plane may hit it again higher up (fig. 4).

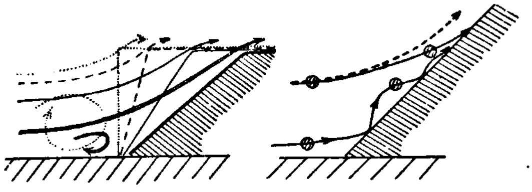


Fig. 4.

The air-cushion in front of vertical and slanting planes; a grain repeatedly hitting a slanting surface and the deflection of a grain in the same sense as the curvature of the streamlines.

The grains rolling along the ground appear to have practically no influence in corroding the models as these were not undercut. This is explained by the fact that the velocity of the rolling grains is too small to allow of an important attack on the basis of the models or rocks, even though these projectiles are larger in size than the grains carried bodily along by the current of air.

The side of an obstructing rock-fragment in the sandblast, that was originally vertical will, therefore, be worn back into a slanting position (fig. 4). The more a plane approaches a horizontal position the smaller the difference in rate of corrosion between its lower and its higher side will be. Another element that has always been present, but too slight to be of noticeable influence, will now become apparent. The size of the particles must be greater closer to the ground and from the laws discovered by THOULET it follows that, apart from other influences, this must occasion a stronger corrosion at the base. For this reason a limit is set to the angle to which the facets can be worn over backwards, a limit that must be different under different circumstances. This might account for the fact, observed by CLOOS in the desert of Nomaland, that for each kind of rock there was a definite angle of the corroded surfaces to the horizontal.

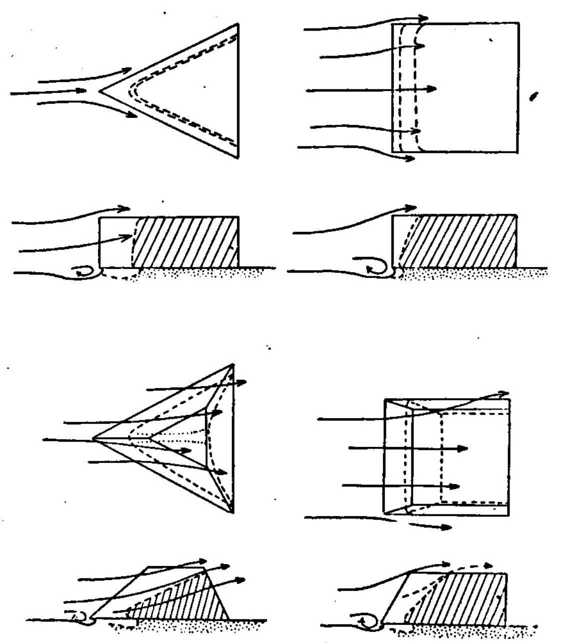


Fig. 5.

The manner in which the currents of air pass round an obstructing body, that is corroded.

I have already described the manner in which the stream-lines pass around the sides of the pebble. Some details and the result of the corroding are illustrated in fig. 5 and I have nothing to add to HEIM's and PFANNKUCH's observations on this side of the problem.

COMPARISON OF THE EXPERIMENTAL RESULTS WITH THE PRODUCTS OF NATURAL CORROSION.

A. Are the planes of rock-fragments worn over backwards under the influence of the natural sandblast?

Although it is to be expected that this is the case, as the causes that gave rise to it in the experiments are also present in nature, it is worth while to seek for confirmation. An example in which this actually seems to have happened is illustrated on Pl. 6 fig. 2 (on the left). A fracture plane in a slanting position has cut off one side of this windworn pebble. Afterwards the sandblast has renewed its work on this rough plane, but has not succeeded in smoothing it, before the pebble was removed from its influence. On careful examination we see that only a narrow rim along the two upper sides of the triangular fracture plane has been smoothed and polished, the remainder retaining its original rough surface. If this were due to the stone having been partly buried and not to a concentration of the corrosion along the upper parts by the air cushion, as is believed to be the case, the smoothed part would have been restricted to the top of the triangle only.

Another observation pointing to the influence of the air cushion is that of practically all flat windworn pebbles that show an uncorroded supporting plane, the sides are either vertical, or slant inwards towards the corroded upper surface. (Pl. 6, fig. 1). This can hardly be accounted for solely by the fact that there must be a tendency for any flat rock-fragment to lie on its largest face, for with very thin slabs this tendency must be exceedingly small.

B. The desert.

The corroding power of the sand-bearing wind of the desert has been sufficiently proved. Although there may be difference of opinion as to the importance of this factor in forming the dry vallies of the desert, nobody doubts that pedestal rocks and other characteristic small features of the desert must be attributed to this agent[1]). This being the case I am of opinion that the formation of windworn pebbles of characteristic shape out of all manner of rock-debris must have followed the lines indicated by Heim in his lucid article cited above: the experiments proved that where corrosion of rock-fragments actually occurs this is the case. The original shape of the basis alone remains and leads the corrosion along definite lines to the formation of one-, three- ,or five-ridged pebbles.

A restriction of this rule has to be made when the wind, as is often the case, is confined to one single, or two opposing directions. Then the resulting shape will have even less connection with the original form. This is the case Walther, Cloos and others took as the general rule,

[1]) It is not meant that pedestal rocks can never be formed by another agent than the sandblast of the desert.

believing it to be necessary for the production of well developed windworn pebbles.

An orientation of the pebble, not of the wind, can also occur when it is, or has become, very small. If it is oblong in shape it will be placed at right angles to the wind each time the direction changes, as follows from the laws of aerodynamics. CLOOS pointed out this fact and showed that it accounts for the small cigar-shaped pebbles frequently met with in the desert. The ends are pointed as they are always at right angles to the sandblast and can never be rounded off, as is the case where the stone is not moved by the varying wind. (Pl. 6, fig. 5).

C. Northern Europe (more especially the Netherlands).

Whether we must believe the windworn pebbles of Northern Europe to have been shaped in the manner supposed by HEIM, depends upon whether a strong corrosion may be assumed or not. If the corrosion has been strong, as in the desert, upon the evidence of the experiments we must believe new facets and ridges have been worn on the stones. It is a fact, however, that in many pebbles there is an evident connection between the present shape and the diaclases and other planes of fracture. This being the case, must not all shapes be attributed to the smoothing and polishing of angular, facetted rock-fragments?

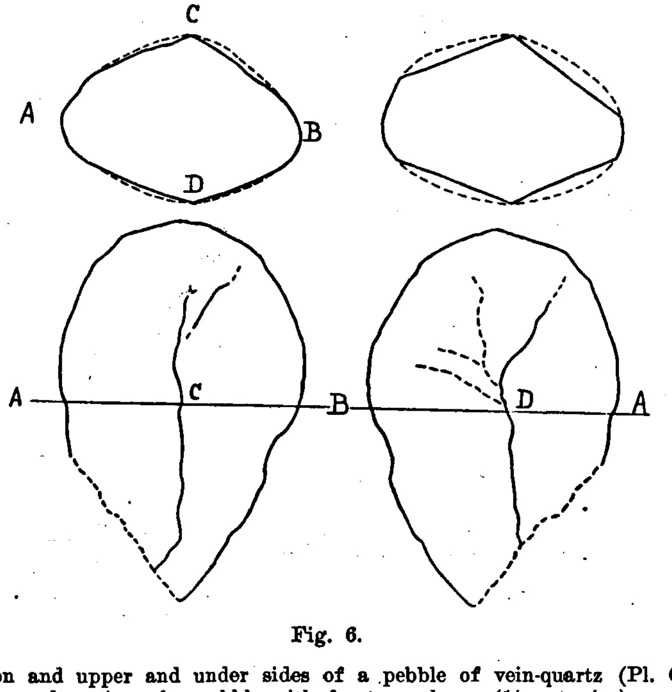


Fig. 6.

Cross-section and upper and under sides of a pebble of vein-quartz (Pl. 6, fig. 3) and section of a pebble with fracture planes (½ nat. size).

In some cases we are able to calculate the minimum thickness of the layer that has been removed from a stone to sharpen the ridges into their present shape.

On Pl. 6, fig. 3 a windworn pebble of veinquartz is shown. Both sides have been sharpened into a ridge. That these cannot be attributed to cleavage planes is evident, not only from the fact that the rock shows no cleavage whatever, but also when we consider the nature of the section at right angles to the ridges. In fig. 6 this section is given (reduced) and beside it a hypothetical section of a similar pebble, that has been cut by cleavage planes. In the latter case 6 ridges would have been formed instead of two. Now, if we attempt to reconstruct the section of the pebble before it was corroded, by rounding off the ribs, we may assume a section as given in the same figure by the dotted line. On measuring the thickness of the layer carried away by corrosion we see that the minimum is 2 m.m. It should be borne in mind, however, that the actual amount that may have been carried away may be considerably larger.

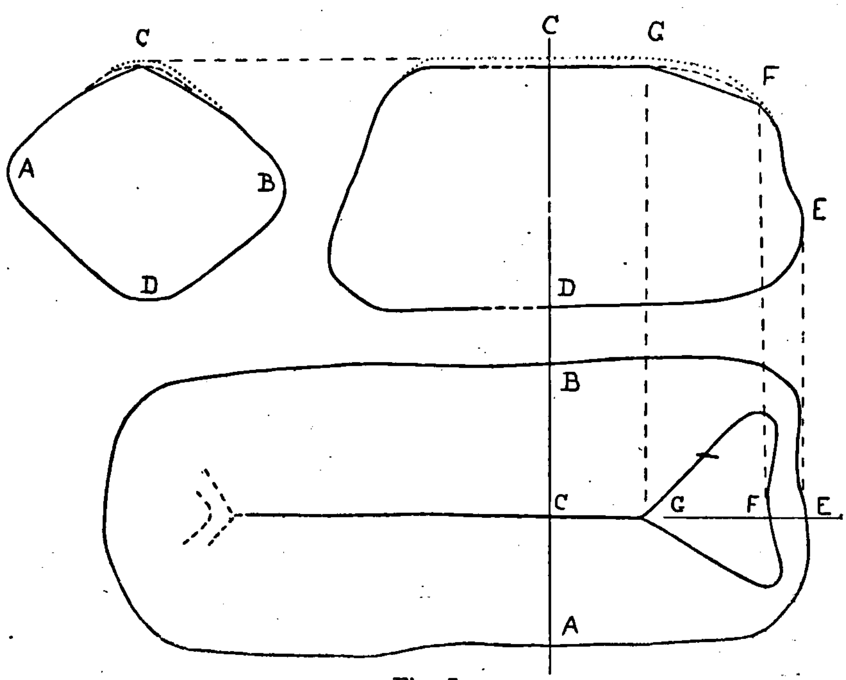


Fig. 7

Cross-section, side view and upper surface of a quartzite pebble of which one ridge has been sharpened by the sandblast (Pl. 6, fig. 6) (½ nat. size).

A second example of this kind is given in fig. 6, Pl. 6 and textfig. 7. An oblong prism of hard quartzite, evidently a cleavage fragment, has had its edges rolled off. Afterwards one of the four principal ridges has been sharpened again by the natural sandblast. As it is extremely likely that the ridge opposite the one that has been corroded shows the same degree of roundness, originally presented by the sharpened one, we are again able to reconstruct the cross-section. On the figure the dotted line represents the most likely position, giving a corrosion of 3 m.m., the broken line the minimum with 2 m.m. corrosion.

On Pl. 7 fig. 3 a windworn pebble of quartzite is given that has been strongly corroded on one side, but is only slightly touched on the other. On assuming that both sides were originally approximately of the same shape, we are led to assume a corrosion by the sandwind of about 1 c.m. fig. 8. In this case the reconstruction is not so certain, but as the planes cutting each other along the central ridge are not flat but form a waved surface following the bends of basis and ridge, a shape that could not have been formed otherwise than by the sandblast, it is not unlikely that at some points the corrosion has been even more.

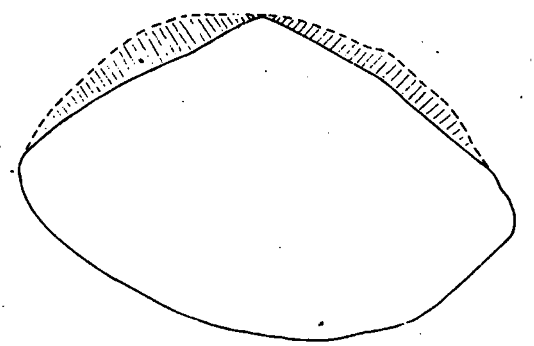


Fig. 8.

Cross-section of a quartzite pebble (Pl. 7,fig. 3) ($^1/_1$ nat. size) showing approximate, original section.

Most windworn pebbles do not allow of an evaluation of the amount of corrosion, and, moreover, those that have been corroded most must show the least clear signs of the shapes from which they have been obtained. For this reason we can hardly doubt that from some pebbles of the Northern diluvial deposits, perhaps even from many, the windborne sand has removed a layer of several c.m. thickness. The experiments lead us to suppose that in that case the present shape is very different from the original form, only the basis having retained its shape, larger new facets having been formed in the manner Heim explained.

The probability of this supposition is strengthened by the fact that the number of pebbles showing large facets and ridges as they should be generated according to Heim's laws, sometimes equals or even exceeds the number of pebbles in the same locality that have not been corroded, or insufficiently to show an even and regular facetted shape. Among the material that is found in localities where the sandwind has evidently not played a part, the number of pebbles that could be changed into the characteristic windworn shapes by the removal of but a few m.m. from the surface is very small indeed. The simplest explanation is that in the former case the corrosion has been considerable. As we know neither the rate at which the corrosion takes place, nor the length of time that conditions favouring the formation of the windworn pebbles lasted, I do not think there is sufficient reason to doubt this explanation.

Naturally there must be many pebbles that, although corroded, have not attained the shape that HEIM's theory supposes must eventually ensue. An example is given on Pl. 6, fig. 4, of a pebble of quartzite, that shows a different shape on the two opposite sides. Such unfinished shapes occur frequently.

As has been noted above, many windworn pebbles have evidently been little changed from the original cleavage shapes, which has led some investigators to suppose that the changes never have been great. The smallness of this change is not in contradiction with the view given in this paper, for cleavage fragments will more easily be shaped into the characteristic forms and with smaller loss of material, as others already pointed out. It only proves that a large number of windworn pebbles from Northern Europe have not been exposed to the sandblast for very long, but cannot be taken as evidence that this was never the case.

BIBLIOGRAPHY.

1869 W. T. L. TRAVERS, On the sand-worn stones of Evan's Bay. Trans. and Proc. o. t. New Zealand Inst. Vol. 2, p. 246.

1878 J. D. ENYS, On sand-worn stones from New Zealand. Quart. Journ. Geol. Soc. London. Vol. 34, p. 686.

1882 G. DE GEER, Om vindnötta stenar. Geol. Fören i Stockholm. Förhandl. Bd. VIII, p. 501. (Ref. N. J. f. M. etc. 1882, Bd. 2).

1884 G. BERENDT, Geschiebe-Dreikanter oder Pyramidal-Geschiebe. Jahrb. d. kgl. preuss. geol. Landesanstalt für 1884 (1885). (Ref. N. J. f. M. etc. 1885 II, p. 177).

1886 A. G. NATHORST, Ueber Pyramidal-Gesteine. N. J. f. M. etc. 1886 I, p. 179.

1886 A. MICKWITZ, Die Dreikanter ein Product des Flugsandes. Mém. d. l. Soc. imp. de mineralogie St. Petersburg. (Ref. N. J. f. M. etc. 1888 II, p. 301).

1887 O. JÄCKEL, Ueber diluviale Bildungen im nördlichen Schlesien. Zeitschr. d. d. geol. Gesell. p. 287.

1887 THOULET, Comptes rendus CIV, p. 381.

1887 A. HEIM, Ueber Kantengeschiebe aus dem norddeutschen Diluvium. Viertj. d. Züricher Naturf. Gesell.

1887 WHANSCHAFFE, Zeitschr. d. d. geol. Gesell. p. 226.

1887 PREUSSNER, Zeitschr. d. d. geol. Gesell. p. 502.

1890 A. SAUER und C. CHELIUS, Die ersten Kantengeschiebe im Gebiete der Rheinebene. N. J. f. M. etc. 1890 II, p. 89.

1896 M. VERWORN, Sandschliffe am Djebel Nakûs. N. J. f. M. etc. 1896 I, p. 200.

1900 E. HARLÉ, Cailloux à facettes des environs de Bordeaux. Bull. d. l. Soc. géol. de France 28, p. 70.

1901 MÜGGE, Ueber Facettengerölle von Hiltrup b. Münster i. Westfalen. 14 Jahresber. d. naturw. Verein zu Osnabrück, p. 1.

1903 H. HEDSTRÖM, Om konstgjord framställning af vindnötter stenar. Geol. Fören i Stockholm. Förhandl. Bd. 25, p. 413. (Ref. Geol. Centralblatt V, 1904, p. 157).

1903 A. JOHNSEN, Zur Entstehung der Facettengesteine. Centralblatt p. 593.

1903 KOKEN, Facettengeschiebe. Centralblatt, p. 625.

1907 E. HAUG, Traité de Géologie, p. 395.

1908 W. GRAF ZU LEININGEN, Ueber Kantengerölle aus der Umgegend von Nürnberg. Mitt. d. Geogr. Gesell. in München III.

1910 L. J. WILLS, On the occurence of wind-worn pebbles in High-level gravels in Worcestershire. Geol. Mag., p. 299.

1911 J. WALTHER, Ueber die Bildung von Windkantern in der Libyschen Wüste. Zeitschr. d. d. geol. Gesell., p. 410.

1911 J. LORIé, Die Bildung der Dreikanter. Ber. niederrhein. geol. Ver., p. 19.

1911 CLOOS, Geologische Beobachtungen in Südafrika; I: Wind und Wüste im Deutschen Namalande. N. J. f. M. etc. Beil. Bd., p. 49.

1913 PFANNKUCH, Die Bildung der Dreikanter. Geol. Rundschau IV, p. 311.

1914 PFANNKUCH, Die Formen der Kantenkiesel. Geol. Rundschau V, p. 247.

1915 W. DELHAES, Eine Sammlung zur Erläuterung des Windschliffs. Geol. Rundschau VI, p. 202.

1915 J. LORIé, Over het ontstaan van driekanters. Versl. der geol. sec. Geol. Mijnb. Gen. Deel 2, p. 68.

1916 B. G. ESCHER, De gedaanteveranderingen onzer aarde, p. 119.

1918 C. GAGEL, Der Geschiebeinhalt des wolhynischen Diluviums. Zeitschr. d. d. geol. Gesell., p. 84.

1919 W. PFANNKUCH, Zur Entstehung der Kantenkiesel. Geol. Rundschau X, p. 122.

1924 P. TESCH, Over kantige rolsteenen. Gedenkboek R. SCHUILING.

1924 PASSARGE in: Grungzüge der Geologie, W. SALOMON, Part. I, p. 689.

1924 J. WALTHER, Das Gesetz der Wüstenbildung, p. 204.

1926 J. W. JACKSON and O. T. JONES, Facetted pebbles in the south Manchester district. Mem. and Proc. Manch. Lit. and Phil. Soc. Vol. 70, p. 125.

1926 E. KAISER, Die Diamantenwüste Südwest-Afrikas. Bd. II, p. 224.

1926 F. J. FABER, Geologie van Nederland, p. 83.

DESCRIPTION OF PLATES.

Pl. 3. Fig. 1. Apparatus used by the author.

„ 2. Dam of sand to test the breadth of equal, maximum corrosion seen straight from above.

„ 3. The same after a few seconds of corrosion; on one side slightly stronger action.

„ 4. The same after the dam has been worn away, with disc on which the models were placed during the experiments.

Pl. 4. Fig. 1. Above: threesided pyramid with the model after equal corrosion from 16 directions; Below: after further corrosion, ending with prolonged treatment from one direction, rounding off of the exposed ridge, sharpening of the other two.

„ 2. Stunted threesided pyramid beside the model that has been corroded from 16 direction. No rounding off has taken place.

„ 3. Uncorroded model with two models with symmetrical basis, that in the centre originally identical in shape with the uncorroded model on the left, that on the right a disc with the same basis. The resulting forms are about the same.

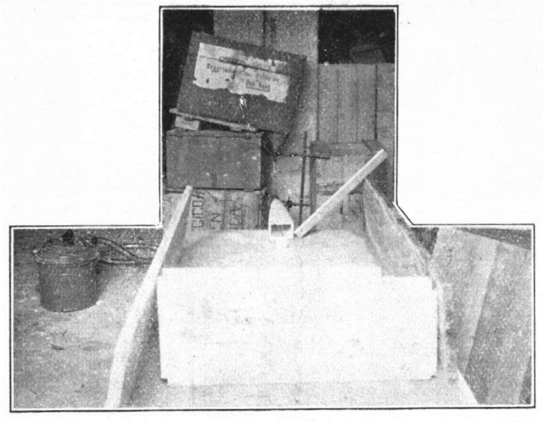
„ 4. Below: rounded threesided mass with behind it the same shape after corrosion, on the left the shape that the disc (above) took on before changing to the threesided pyramid (above on the right).

„ 5. Vertical and slanting view of two identical models, one of which has been corroded to a roof-shape.

Pl. 5. Fig. 1.	Above: Half eggshape with corroded form and corroded disc with the same basis. Below: slanting view of the first two.
„ 2.	Same models after further corrosion (disc on left side).
„ 3.	Models to illustrate production of horizontal winding ridge, on the left corroded form.
„ 4.	Two models, on the left of gypsum, on the right of chalk, after an equal amount has been removed from the surface. The gypsum shows much sharper ridges.
„ 5.	A model that has given rise to the formation of a small supporting plane.
„ 6.	Gypsum model of which the further side has been shielded off from the sandblast to show that the vertical plane has been worn into a backward slanting position.
Pl. 6. Fig. 1.	Upper- and uncorroded underside of a quartzite. The side faces are vertical or heal inwards towards the corroded upper side.
„ 2.	Broken dreikanter, with smoothing of the fracture surface along the upper edge and irregular shaped, "unfinished" pebble.
„ 3.	Pebble of vein quartz, with line showing position of cross-section of text figure 6 (same scale as fig. 4).
„ 4.	Quartzite pebble of which the upper side and under side are different.
„ 5.	On the left eggshaped pebble with one ridge, centre roofshaped pebble with curved ridge denoting a supporting plane, on right a pebble of which the planes do not correspond to the shape of the basis.
„ 6.	Upper and under side of quartzite pebble with but one sharpened ridge, discussed and illustrated in text (text-figure 7).
Pl. 7. Fig. 1.	Roof-shaped pebble with supporting plane, denoted by round ridge.
„ 2.	Above: small and large dreikanter, the latter with supporting plane much smaller than the largest horizontal section. Middel and Below: same pebble, showing supporting plane with rounded ridge and on the other side the bending away of the sharpest ridge from the prevailing wind direction (compare Pl. 4, fig. 1 left bottom corner).
„ 3.	Quartzite pebble that shows a strongly corroded side with winding ridge (compare Pl. 5, fig. 5) and almost untouched under side. The quartz veins stand out in relief.

PLATE 3.

Fig. 1.



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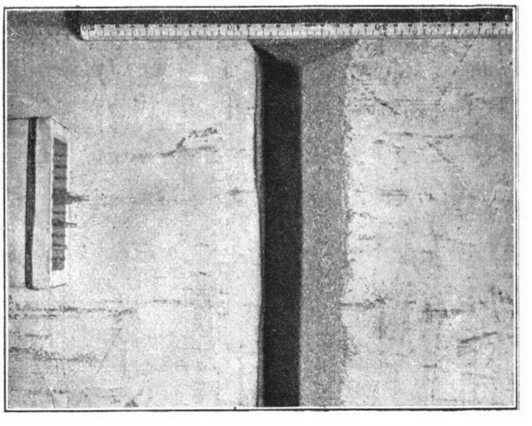

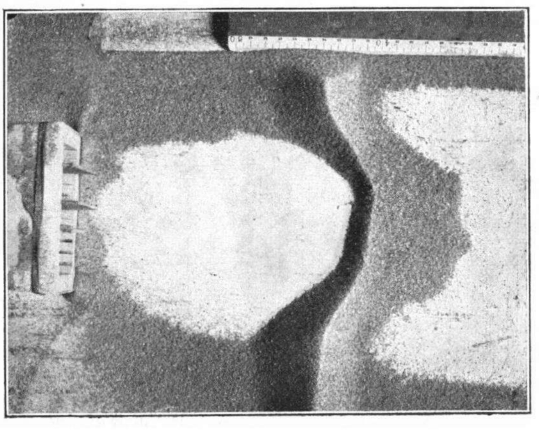

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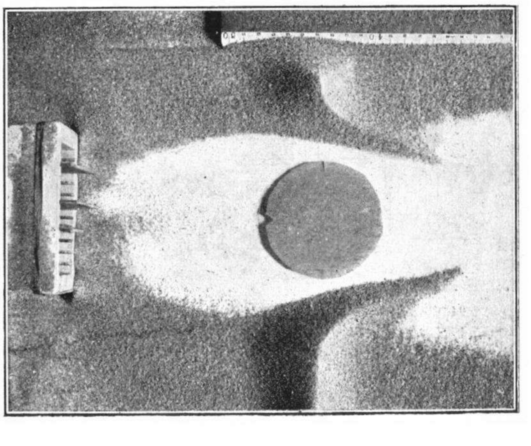

Fig. 4.

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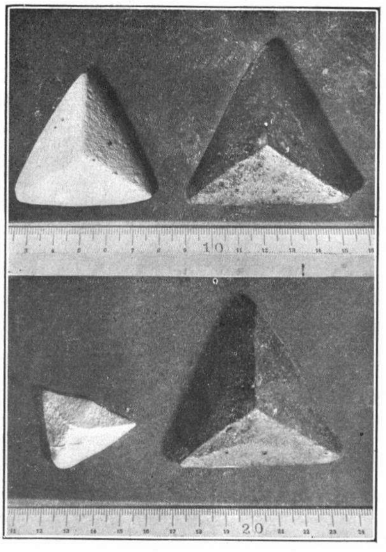

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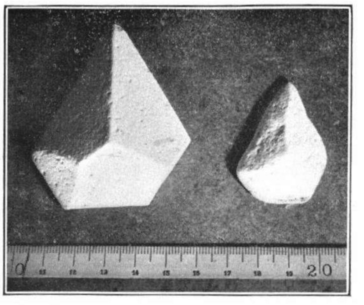

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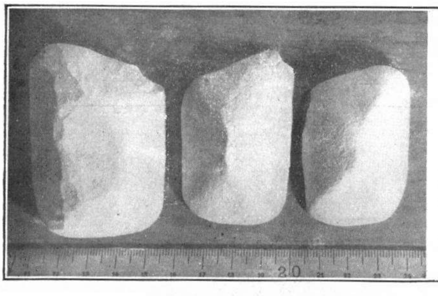

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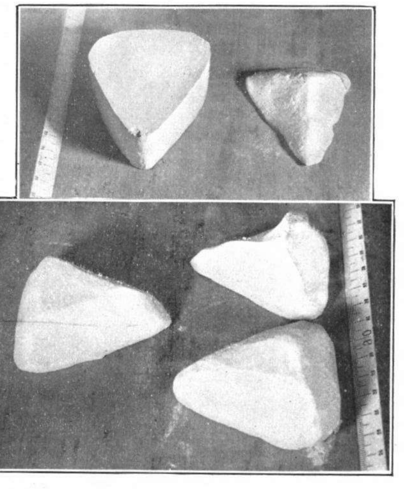

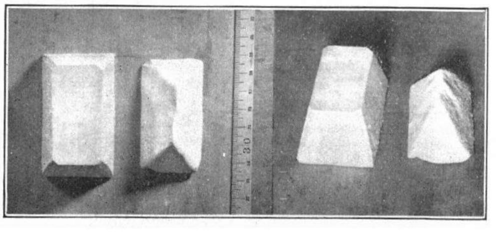

Fig. 5.

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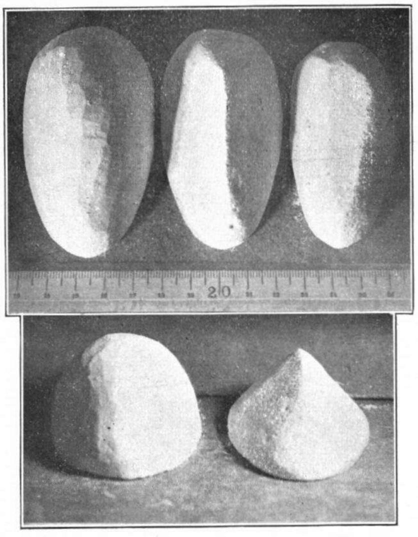

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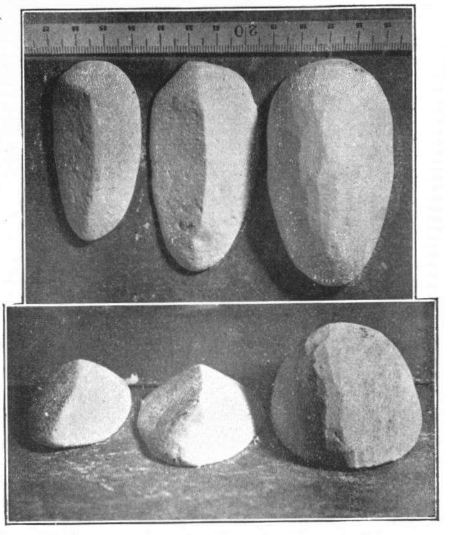

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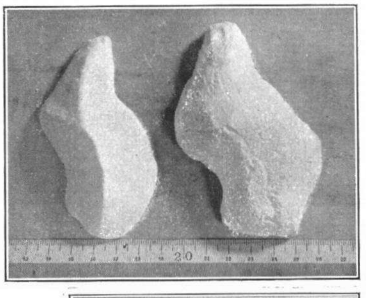

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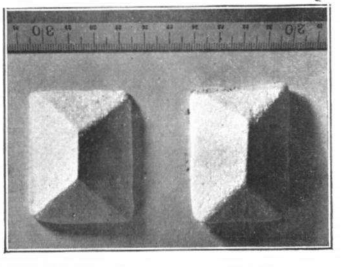

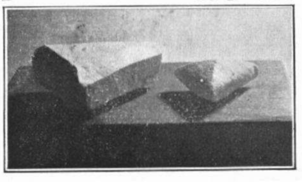

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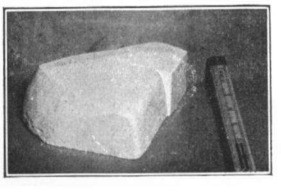

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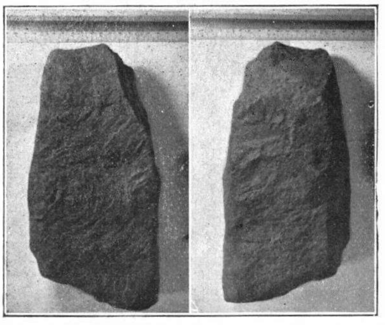

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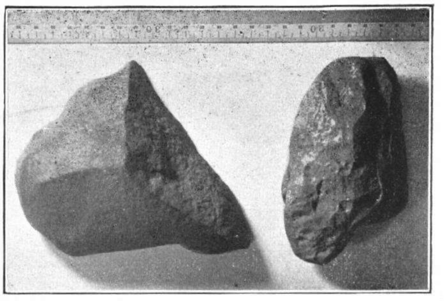

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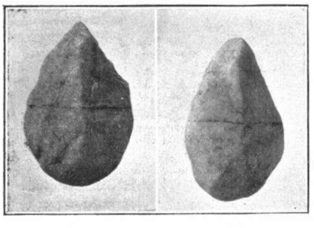

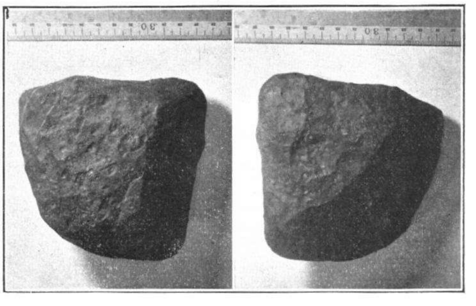

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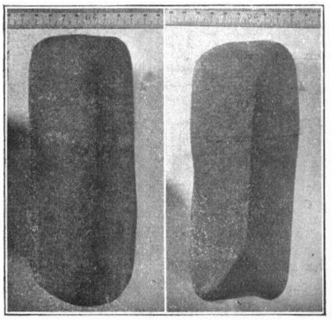

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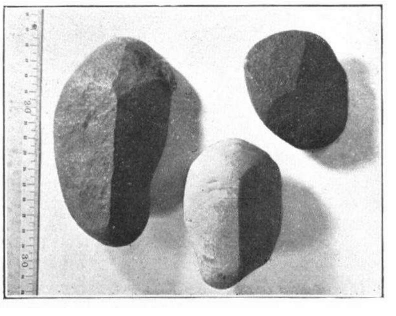

Fig. 5.

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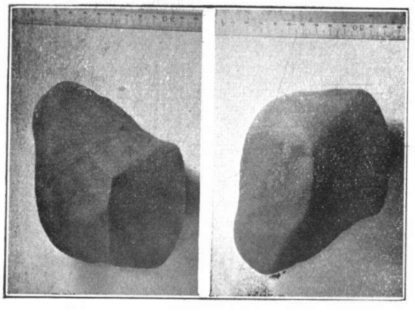

Fig. 2.

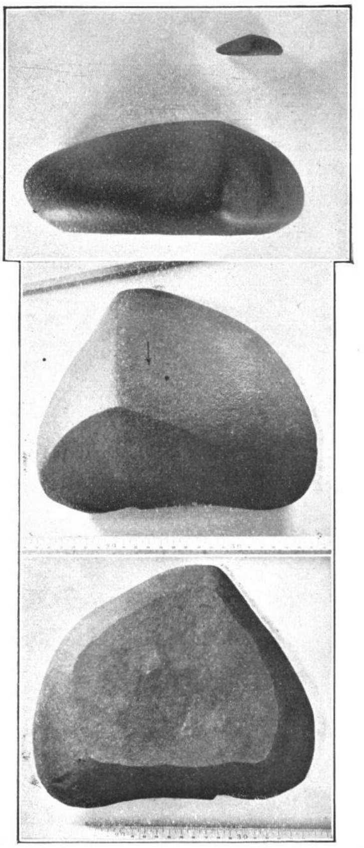

Fig. 3.