

ART. XVI.—*The Rounding of Grains of Sand by Solution;*  
by J. J. GALLOWAY.*Introduction*

The degree of roundness of grains of sand is considered by many geologists as of prime importance in the interpretation of the conditions of deposition of sandstones. A "millet seed," quartz sandstone, that is, one consisting wholly of well rounded grains, is regarded as indicating eolation and the deposition of the sand under desert conditions.

Special importance has been attached to the presence of well rounded grains below one-tenth millimeter in diameter as indicating that such grains were rounded by abrasion in the wind, and could not be rounded in water.<sup>1</sup> This idea evidently originated in Daubrée's statement, "The dimensions of grains which can float in very feebly agitated water appear to be about one-tenth millimeter in average diameter. All finer sand will be without doubt angular."<sup>2</sup>

I have proved by experiment that grains of calcite, dolomite, mica and hornblende, ranging in size all the way down to .01 mm. in diameter can be rounded by mutual abrasion in water in fifty hours at a velocity of four miles an hour; that the lower effective limit of rounding by abrasion in water is about .05 mm.; and that the rate of rounding becomes progressively slower after the grains are reduced to a diameter of about .2 mm., below which size the time taken to round grains is greatly lengthened. I believe these results would apply to quartz grains if the time were sufficiently lengthened, that is to at least 800 hours at four miles an hour. The smallest spherical grain of quartz I was able to produce in 150 hours at four miles an hour measured .2 mm. in diameter.

The fact, however, that fragments of minerals are rounded by solution, and that this process may be of corresponding geological importance, seems to have escaped the attention of most students of sands. Sorby, almost the first and one of the closest observers of the characteristics of sands, recognized the factor of corrosion in the production of rounded grains of quartz. He says,<sup>3</sup>

<sup>1</sup> Grabau, *Principles of Stratigraphy*, pp. 226, 253, 553, 1913.

<sup>2</sup> Literal translation from Daubrée, *Géologie Expérimentale*, p. 256, 1879.

<sup>3</sup> *Quart. Jour. Geol. Soc. London*, vol. 36. Proceedings, p. 47, 1880.

"The quartz in quartzose felsites is often of much more truly crystalline form, the planes being sometimes very perfect; but very often there is a remarkable rounding of the angles, which might easily lead any one to think that they were waterworn. Even the grains of quartz derived from granite sometimes show this character to a less extent, but the rounding is usually accompanied by small surface ridges, which clearly show that their rounded form was not due to mechanical wearing. In the specimens of decomposed granite which I have examined in greatest detail, the larger grains of quartz have a somewhat opaque surface, as if corroded, and the angles are rounded. This rounding is relatively much greater in the case of the smaller grains, which is the reverse of what is met with in worn sand. On the whole the facts seem to indicate that the quartz has been more or less corroded and dissolved by the action of the alkaline silicates set free by the decomposition of the feldspar. The contrast between its corroded surface and the glassy fractures of broken quartz is very great."

A few simple experiments will demonstrate that crystals or mineral fragments of any shape tend to become round in the process of dissolving.

If a pinch of sodium chloride, potassium chloride, sugar or any other finely granular material, which is readily soluble in water is put into a few drops of water on a slide and observed under a microscope, the angular grains will be seen to change to rounded ones by the more rapid dissolving of the corners. The smaller the grains become the more nearly spherical they become. If ground calcite, or any other finely granular, pure, crystalline material is partially dissolved in acid, the grains will be rounded by solution. Fig. 1 shows the forms and character of surface produced when grains of Iceland spar are partially dissolved in warm hydrochloric acid.

As is well known, all the minerals occurring in sands are soluble in natural waters. The process is accelerated when the water contains appreciable quantities of alkalis or acids. The feldspars and ferromagnesian minerals dissolve fairly readily. Quartz, magnetite, rutile, zircon, apatite, garnet, muscovite and monazite are extremely resistant to solution, but even these may be dissolved naturally in water when the amount of water and time are great enough.<sup>4</sup>

The physical process involved in the rounding of small

<sup>4</sup> See Clarke, *Data of Geochemistry*, U. S. G. S., Bull. 616, pp. 478-483, 1916; Merrill, *Rocks, Rock Weathering and Soils*, pp. 189-194, 236-238; Van Hise, *Treatise on Metamorphism*, U. S. G. S., Mon. 47, pp. 516, 848, 1904.

grains by solution is similar to the formation of rounded boulders by exfoliation of granite, by weathering of basalt, the rounding of boulders and mineral fragments by abrasion, and the tendency of chunks of ice to become round in melting, differing mainly in the size of particles

FIG. 1.

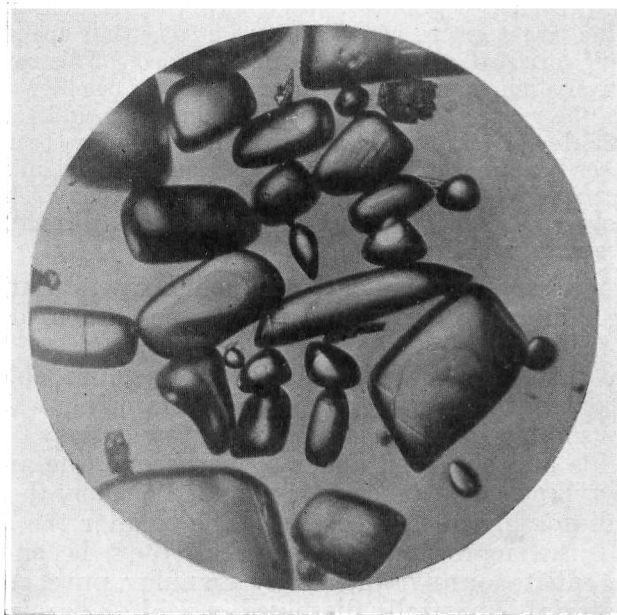


FIG. 1. Grains of crushed Iceland spar rounded by solution in warm hydrochloric acid. Note that the smallest grains are the most nearly round. Transmitted light. Magnified 70 diameters.

removed from the respective surfaces. In all these methods of rounding, the larger amount of material is removed from the corners.

The surfaces of grains rounded by rapid solution, or solution accompanied by motion of the grains, are smooth like glass, though sometimes minutely pitted or corroded, but never "frosted" like ground glass. When solution is very slow, as in the case of weathering of quartzite pebbles in conglomerates, or vein quartz, or the corrosion of quartz grains in decomposed granite and residual soils, glacial till and clays which I have examined, the surfaces are dull, giving an effect easily mistaken for that pro-

duced by strong abrasion. The solution surfaces of minerals containing impurities or other lack of homogeneity are pitted or develop other irregularities, especially if the rate of solution is slow.

*Factors in Rounding by Solution*

Several factors enter into the rounding of grains of sand by solution, the most important of which are:

FIG. 2.

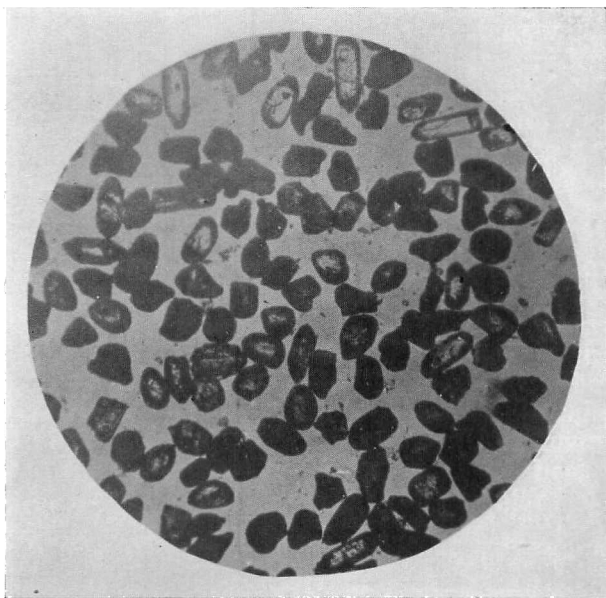


FIG. 2. Grains sifted from beach sand from Rockaway, L. I., about half of which may be considered as well rounded. These grains vary in size from .05 to .1 mm. Transmitted light. X 50.

(1) rate of solution, (2) time, (3) size of grains, (4) original shape of grains, (5) motion of grains and solvent, (6) cleavage, and (7) purity of the mineral.

*Rate of solution.*—The more soluble a mineral is the more rapidly grains of it will approach roundness until the saturation point of the solvent is reached. A balance is then obtained between mineral and solvent, and the grains tend to assume their crystalline outlines. When the solvent becomes supersaturated, as by evaporation, the grains are built up into more or less perfect crystals.

Garnets, feldspars, magnetite, hornblende, tourmaline, zircon and apatite are more soluble in water than pure quartz, as proven by the fact that quartz remains when every other mineral is removed, and should more often occur in rounded forms. I have seen rounded grains of these minerals and of smoky quartz varying from .05 to .1 mm. in diameter in young beach sand from Rockaway, L. I., the smallest grains of which are shown in fig. 2.

FIG. 3.

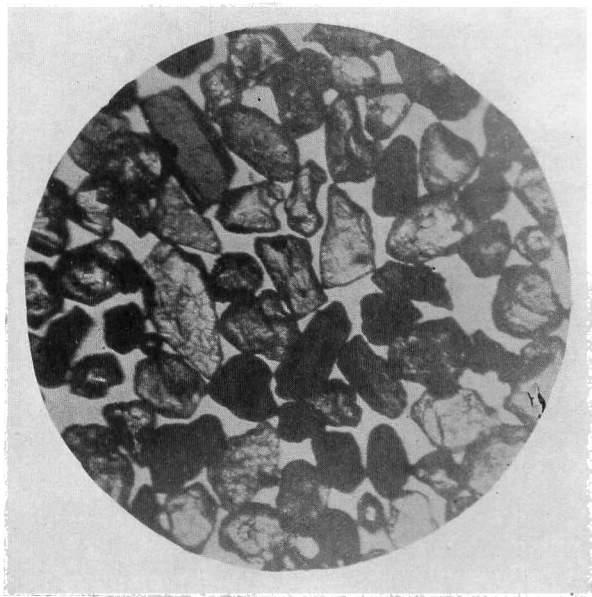


FIG. 3. Grains from the same sand as that shown in Fig. 2, varying from .1 to .2 mm. in diameter. Note that fewer of the grains are rounded than in the finer sand. Transmitted light. X 50.

Grains of the same minerals from .1 to .2 mm. in diameter are much less rounded in the same sand, as illustrated in fig. 3. The smallest grains were probably mostly rounded by solution, for the larger the grain the more the abrasion both in water and in wind, although abrasion and the original roundish form partly account for the present outlines. The surfaces of the rounded grains have a dull, corroded appearance when seen by reflected light, probably indicating their production both by solu-

tion and abrasion. The smallest perfectly round grain of quartz in this sand was .06 mm. in diameter.

When grains of calcite have been rounded by solution in warm acid and which have brilliant, smooth surfaces, are subjected to solution in a very weak, cold acid, the surfaces are etched and become dull in appearance, showing that the rate of solution has more effect on the character of the surfaces produced than on the shape of grain produced by solution.

*Time.*—All minerals are soluble in water if sufficient time is given, and especially if alkalis or acids are present in the water. Quartz can be dissolved in a few hours in hot water under pressure. The temperature and pressure of water in which sands are accumulated, however, are not high enough to be important factors in solution. Just how rapidly solution takes place in nature is not known, but it probably requires hundreds, perhaps thousands, of years to produce any noticeable effect on the roundness of a grain of sand.

When the surface exposed remains constant, and the solute far from the saturation point, the rate of solution varies directly with the time. When other factors remain constant, the longer solution acts the more nearly round the grains become.

The brilliant, glistening surface of the grains of most beach sands is no doubt partly due to solution. The surfaces of quartz grains which I mechanically rounded in water were pearly, not glassy like freshly broken quartz, nor "frosted" as in old, wind-worn sands, nor like old beach sands like that noted by Merrill from Santa Rosa Island, Florida,<sup>5</sup> whose history seems to be complex.

*Size of grains.*—The smaller the grains the more rapidly and the more completely they are rounded by solution. Grains of sodium chloride and of calcite .2 or .3 mm. in diameter partially dissolved experimentally are subround and retain some of their original form, while grains of the same materials under otherwise identical conditions but less than .1 mm. in diameter were mostly subspherical. Fig. 4 shows the forms assumed by common table salt undergoing solution in water.

The rate of solution varies with the area of surface acted upon, hence finely divided substances dissolve more rapidly than the same quantity in larger pieces. The

<sup>5</sup> Merrill, Rocks, Rock Weathering and Soils, p. 243, 1904.

same law accounts for the dissolving off of corners, for the more irregular the shape the greater the surface in proportion to volume.

A sample of very fine sand from a bubbling spring at Dayton, Maine, consists of quartz, fresh feldspar, hornblende and biotite grains, all between .04 and .15 mm. in diameter, many of which are round or subround. The

FIG. 4.

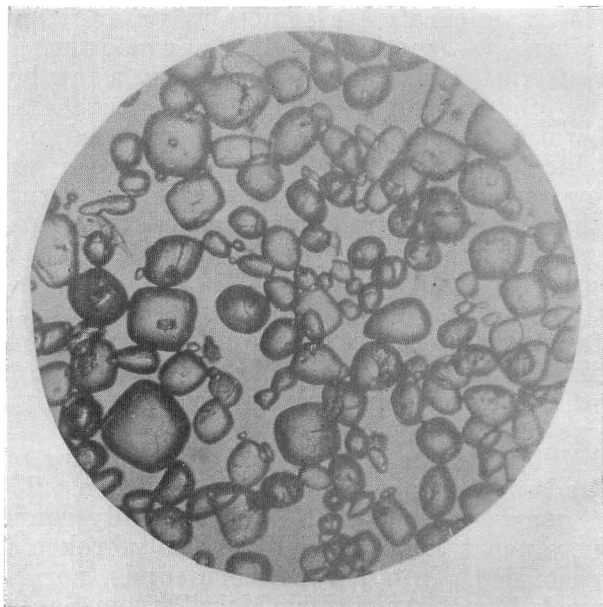


FIG. 4. Grains of common table salt rounded by solution in water. The smaller grains are the most nearly round. Grains seen in water by transmitted light. X 50.

smallest grains are the most nearly round, which shows that solution was the main factor in the process of rounding them. The smallest perfectly round grain measured was of quartz which was .04 mm. in diameter. If the rounding has been due entirely to mechanical action, either by wind or water, the largest grains would have been rounded most. Flakes of biotite .1 mm. and over were also round and were undoubtedly so formed by abrasion in the feeble spring. The surfaces of the rounded grains of quartz and feldspar were perfectly smooth, with an oily luster, the most brilliant surfaces I have ever seen

on rounded sand grains. Such surfaces can be produced either by polishing in a liquid, as glass is polished, or by solution, but solution seems clearly to be the main factor in this case.

The sand seems to be of glacial origin, which shows that it is geologically young. The time it was acted upon by

FIG. 5.

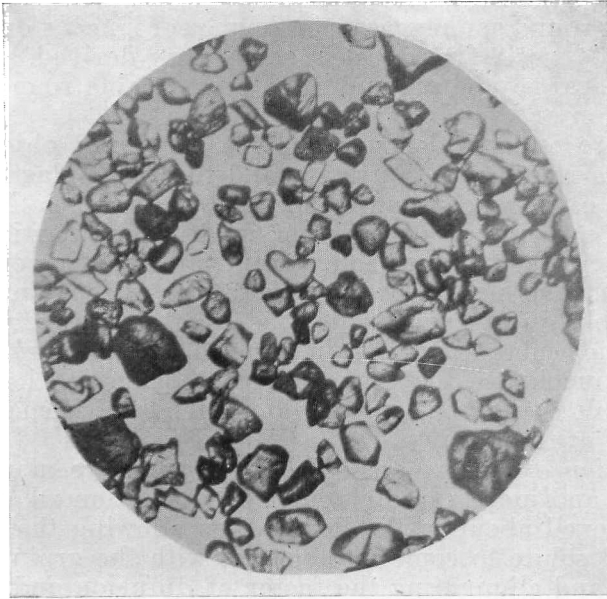


FIG. 5. Sand from a bubbling spring, Dayton, Me. All the grains are somewhat rounded, the largest ones the least. The surfaces of the quartz and feldspar grains are perfectly polished. Transmitted light. X 50.

the waters of the spring are to be measured in a few thousands of years at most, probably a much shorter time, which would indicate that noticeable effects of the solvent action of water upon quartz can be accomplished in a short time geologically, especially where the water is changed continually and the grains are in motion.

*Original shape of grains.*—The more angular and irregular the shape of grains the more rapid the solution, but the more regular the shape the more nearly spherical the grains become. Thus cubical and rectangular grains of common salt rapidly assume rounded forms, while grains of ammonium chloride, consisting of aggregates



of acicular crystals, dissolve into bizarre forms bounded by curved surfaces. Long crystals or rhombohedral fragments as of calcite, produce oval, roller shaped or very prolate spheroids. Grains of garnet, magnetite, zircon, apatite, monazite and others which have a comparatively equidimensional crystalline form to start with, more rapidly assume or reach a better rounded form than more angular crystals, as those of hornblende and feldspars. Mineral grains, including quartz, are often more or less round as they occur in the parent igneous or metamorphic rock from which sands are derived. These could scarcely be distinguished from grains rounded by abrasion or by solution.

There is a tendency in nature for large objects to become round due to gravity and for small plastic particles to take such form by surface tension, the effects of which are universally present in drops or particles of liquids. Snow flakes change from flat, radiating crystals to subround pellets or "snow sand" without melting, probably due to sublimation, as suggested by Cornish.<sup>6</sup> The molecular attraction in minerals of ordinary sands is so much greater than surface tension in the same minerals that grains of sand do not tend to become round in any of these ways.

*Motion of grains and solvent.*—Grains are more perfectly and more rapidly rounded by solution when they are moved about in the liquid, thus allowing the unsaturated solute to come into contact with the grain on all sides, and eliminating the factor of diffusion and corrosion. When the grains are not moved, as in the decomposed granites, residual soils, clays and loess which I have examined, or in experiments on solution rounding, corrosion produces a peculiar texture of the surface not like that of abrasion but easily mistaken for it.

Quartz grains washed from Cretaceous clay from New Jersey, varying in size from .06 mm. down to .001 mm., are not transparent like ordinary quartz but are translucent, due to the corroded surfaces. The grains are not sharply angular but somewhat roundish in form, and the surfaces are not smooth like glass, nor have an even curve and "frosted" surface like abraded grains, but have a minutely rough surface like rusted iron or weathered feldspars. I believe these features were due to slow

<sup>6</sup> Cornish, *Waves of Sand and Snow*, pp. 117-121, 1914.

solution unaccompanied by movement of the grains. The same features were noted in quartz grains .1 to .04 mm. in diameter from residual clay from Brick Haven, Va., and in decomposed granite from the District of Columbia. In so-called loess from Muscatine, Ia., most of the quartz grains are round or subround, especially those between .05 and .01 mm. in diameter, and the surfaces are all corroded. I do not believe that such small grains could be rounded by abrasion in either air or water, but solution would account for the form. In glacial silt from Ithaca, N. Y., the quartz grains .1 mm. and less in diameter are only slightly corroded and all are noticeably rounded, differing strikingly from the perfect angularity of crushed quartz grains of the same sizes with which I compared them. In fuller's earth from Whigham, Ga., there are quartz grains .05 mm. and less in diameter, and most of them are smoothly round, the surfaces are brilliant and show no corrosion, and they certainly were not produced by abrasion.

Streams, beaches and springs are favorable places for the rounding of minute grains by solution, on account of the more or less continual motion of the water and sand. Moreover, since the smaller grains are more often and longer in motion than the larger grains, the smaller ones would have the best chance of becoming rounded both by abrasion and by solution. It is possible also that water softens the surfaces of grains and makes abrasion more rapid and polishing more complete than when the grains are dry.

*Cleavage.*—Cleavage has little effect on the shape of grain produced by rapid solution, even when so pronounced as in calcite or halite, except as it influences the shape of the grain before solution begins. The patterns produced on crystals by etching with acid is due to molecular arrangement rather than to cleavage. When the cleavage planes have separated, solution and disintegration are favored, and flat or irregular forms are produced as well as round grains of silt or clay size. Under continued solution grains become almost perfectly round just before they disappear. When solution is slow, cleavage and twinning planes are attacked more rapidly than other parts of the crystal, causing disintegration and favoring decomposition rather than solution.

*Purity of the mineral.*—Grains consisting of more than one chemical substance, such as impure salts, calcite,

dolomite and feldspars, which are not usually simple crystals but are twinned and vary in composition in the same crystal, dissolve according to the solubility of each constituent, producing somewhat rounded forms with numerous irregularities. Included gas bubbles and crystals of other minerals, and distorted crystals also interfere with regularity of surface produced by solution. In the case of complex grains, such as those composed of interlocking crystals or other lack of homogeneity, the attempt to form rounded grains experimentally by solution is not usually successful.

#### *Conclusions*

Grains of sand of any mineral makeup can be rounded by solution, and the process is especially competent on those of very small size, i. e., grains below one-tenth millimeter in diameter.

Four types of sand grains are produced by solution, depending upon the factors discussed above. They are: (1) sharply angular grains with brilliant surfaces, as in rock flour from glaciers with practically no solution; (2) angular grains with corroded surfaces, as in Pleistocene glacial silt and Cretaceous clays; (3) round grains with corroded surfaces, as in the Rockaway Beach sand and the loess from Iowa; and (4) round grains with brilliant surfaces, as in the spring sand described above and in fuller's earth from Georgia. These four types usually occur together, one or the other predominating.

While it is probably always true that a sandstone consisting wholly of well-rounded grains, many of which are less than .1 mm. in diameter, was deposited by and owes its roundness of grain to the wind, the presence of a small percentage of minute, round grains is of itself not a safe criterion for assigning the origin of a sandstone to wind action. It rather points to water action.

Any reliable set of criteria for the genesis of a sedimentary rock are more complex than is usually assumed. All available data, the physical form and mineralogical character of grains, the structure of the rock, the stratigraphy and field relations, the fossil evidence and paleogeography, must be weighed before the origin of doubtful rocks can be correctly determined.