PITTED PEBBLES

BY

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Pitted pebbles when well developed form a striking phenomenon. They are, however, not merely an interesting freek of nature but they may teach us something on compaction and cementation, two of the major problems in diagenesis of sediments. They therefore form a problem in sedimentary petrology worthy of closer examination.

At first sight of a pitted pebble one is inclined to imagine that the explanation of the indentures must be quite simple. It looks as if in a conglomerate the pebbles have been so firmly pressed together as to have indented eachother mutually. It is surprising to find on examination of the literature that a number of geologists have mentioned and discussed the phenomenon, without a satisfactory conclusion having been arrived at.

A detailed review of the subject and of the attempts at an explanation has been given by KUMM, while an extensive bibliography may also be found in the paper by KEGEL.

The pits vary in size from minute dents caused by grains of sand to cups a few centimeters across and a centimeter in depth. Although limestone pebbles, especially of the Alpine Nagelfluh, have delivered the most striking examples, many pebbles of veinquartz, sandstone, etc. are also clearly pitted. Sometimes the pitted pebbles are crushed but generally they are intact and present a quite smooth surface. Normally the pits are also smooth and sharply cut as if scooped out with a small spoon.

The most obvious explanation, that of mutual indenture by pressure, is easily withlain. Two pebbles squeezed in a vice will always fracture before denting eachother and pebbles of equal hardness should flatten, not indent eachother. The material squeezed from an indenture should form a ridge around the pit, but normally the pebbles are smooth. The absence of deformation in stratified specimens with deep pits, is perhaps the most striking argument against the simple mechanical explanation.

The persistency of this explanation in the literature in spite of its obvious failure is partly due to the occurrence of pebbles with both pits and fractures. And several text books illustrate the phenomenon, only by exemples of this combination, thus encouraging the misconception that enormous pressure accompanied and caused the pitting process. This combination, however, is quite exceptional and according to KUMM it is found especially in the neighbourhood of faults and other tectonic disturbances. The phenomena need have no connection and the fracturing may well have taken place long after the pitting had been brought about. KEGEL mentions a case in which crushing evidently played the major part and in which the resultant finely crumbled material partly filled the larger cracks and formed ridges around the irregular pits. In other words: when crushing is the main agent, the result is not a normal pitted pebble.

Attempts have been made to bolster up the mechanical hypothesis by assuming that the pebbles were softened by infiltering liquids prior to the pitting. But obviously the objections are in no way met by this ad hoc assumption.

On the other hand irrefutable proof is possible that the rock, originally filling the space now occupied by a pit, has been removed by chemical solution.

It is interesting to find, that SORBY, one of the first writers to deal more thoroughly with the pitted pebbles, already gave this proof, but that his arguments have been disregarded by later writers. Incidentally SORBY, nearly 80 years ago, also gave the explanation that I consider to be the correct one for practically all cases, namely that of solution and deposition, in a saturated solution under local pressure at the points of contact.

SORBY in one of his early attempts at microscopic examination of rocks, made slides through stratified calcareous pebbles with pits and found that the strata were cut off sharply by the walls of the pit. The rock showed no alteration of structure along the pits, but a veneer of the insoluble residue of the pitted pebble lined the hollow. The residue is thickest in the middle, where the indenture has gone deepest. SORBY even found that the nature and quantity of this shaley or gritty residue accurately corresponds to the amount originally present in the part now missing from the pitted pebble. Fig. 1 reproduced from his paper, shows convincingly that the material occupying the depression has been removed, not displaced.

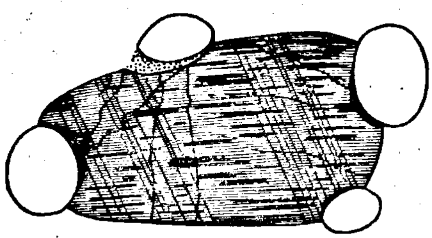

Fig. 1.

Sorby's drawing of pitted Nagelfluh, showing the undisturbed strata in the pebble, the close fit, the unimpaired shape of the indenting pebbles and the solution residue in the pits.

The fact that later authors again invoked pressure, or — as ALB. HEIM — again brought toward the identical arguments, can only be explained by their having overlooked SORBY's paper. For no one acquainted with SORBY's masterly arguments against simple pressure or polishing and in favour of solution, can doubt that removal was by solution. The remaining problem is therefore only to explain the solvent action and its restriction to the points of contact in the conglomerates.

The view held by HEIM and several other authors is that microscopic crushing fractures develop at the points of contact and encourage the solvent action of groundwater. Thus a considerable pressure is called for, especially where the pits have already acquired a certain depth and the contacting area is therefore enlarged. The arguments against this explanation are that this disintegration has never been proved, HEIM himself stating that no alteration in the indented pebble is seen under the microscope. The pebble with the sharpest curvature nearly always invades the flatter one, as many authors have remarked. When, however, two pieces of rock of the same composition are pressed together it is the sharper one that disintegrates. If HEIM were right the sharper pebble should therefore generally be flattened against the flat one. Moreover, as soon as a pit has been formed and the two pebbles fit closely together no microscopic disintegration would take place, but the larger pebble would crack right across. This is actually seen to have occurred with conglomerates that are crushed but only slightly pitted. Deeply pitted pebbles that have not cracked must therefore be explained in a different manner.

The first author to claim that the pits are developed above the groundwater table, was DAUBRÉE. He showed that when two limestone balls are pressed together and immersed in acid, they are attacked over the entire surface, except at the point of contact, where a small cone is left standing. KUMM later showed that even without pressure this result ensues. DAUBRÉE also placed two balls in contact and allowed acid to drip on the point of contact, not more at a time than could be held at this point by capillary action. The solution was now restricted to the area where the solvent was caught and thus pits were formed. DAUBRÉE concluded that the denting is brought about when a conglomerate lies above the zone of groundwater saturation and is kept wet by infiltrating water held at the points of contact by capillary action.

Later KUMM adhered to the same view and repeated DAUBRÉE's experiments with like results. He pointed out, that a crust of secondary calcite or silica is often formed before or after the pitting. In the latter case it may also occur in the pits and cement the denting pebble firmly into the hollow, thus proving that there was a narrow space between the two. All irregularities of the surface in the pit are equalized by the layer of cement.

While KESSLER came to very much the same conclusion, KEGEL still believed that pressure was of importance. The conclusion arrived at by KUMM was, that at first there will be contact between the pebbles in a conglomerate and small contact cones will develop in the centre of the solution pitts in accordance with the experiments. Later these cones will generally disappear, being attacked from the sides. As the action takes place above the groundwater table, we must suppose that there is as yet only a thin covering layer of gravel or sand. The weight will be born by a few pebbles forming interrelated vaults. Only at these points will there be pressure sufficient to develop contact cones. When finally the conglomerate becomes more deeply buried the groundwater will swamp it, and the pitting action will come to an end. When elevation and denudation of the region bring the conglomerate above the water table again, the pitting may recommence or take place for the first time.

Valuable support of this view was obtained by KUMM when he discovered a few cases in which contact cones actually occur in nature. As these examples were all from quite young deposits, he considers they prove that in a later stage the cones disappear, thus accounting for their scarcity in most pitted conglomerates.

Against this theory of DAUBRÉE and KUMM several objections must be brought forward.

First. The number of contact points where there is pressure must be considerably larger in a conglomerate than KUMM proclaims. A pebble must rest on at least 3 points (below its largest horizontal section) and after settling on 4 or more. As, however, there are two pebbles at each point of contact, each pebble will support on the average some 4 others. Thus in a heap of pebbles each will have on an average some 8 or more points of contact. In at least three of these the weight of the pebble itself must be carried and these should show a contact cone that must redevelop every time the older ones are dissolved. The number of points at which the pressure is greater because they form part of a vault bearing the weight of overlying material is much larger, than the number with only the weight of the pebble to carry. If there are small vaults around individual pebbles than there are about ten bearing pebbles around each free pebble. If the vaults are larger the relative number of free pebbles in the vaults increases, but then they begin to rest on eachother and those at the bottom of the vaulted chamber have to carry those in the upper parts. I do not know of a method for ascertaining how many pebbles in a conglomerate help to form vault structures to carry the weight of overlaying masses. It appears highly improbable that more than one quarter of the individuals could be removed without the whole mass beginning to settle anew. Even if half could be removed the remaining pebbles would each need at least 4 points with vault pressure, otherwise they would be in labile equilibrium. The conclusion is that the number of points in a conglomerate at which the contact is under pressure of the overlying mass, must be at least twice that of the number of pebbles. On the remaining six or more contacts to the number of pebbles the weight will frequently be more than caused by the weight of the upper pebble only and amount to 2 or 3 times that value.

Kumm treats this problem as if the pebbles in a conglomerate remain floating in mid air when the original points of contact have been indented by solution. But the number of points of contact and the percentage of these bearing the vaulting pressure is hardly reduced by pitting; there will merely be a shifting of the load from one point to another and a gradual increase in the number of pits as the pebbles become more and more closely packed. Yet Kumm himself says: „Stehen die Gerölle jedoch unter dauerndem Druck, so musz sich auch ein Berührungskegel so lange erhalten wie überhaupt Auflösung stattfindet", and also: „Das Fehlen der Berührungskegel in der weitaus gröszten Mehrzahl der Eindrücke..." (p. 210). In other words, if Kumm's explanation were correct there would have been no „dauerndem Druck", „in der weitaus gröszten Mehrzahl" of contacts and consequently the pebbles were floating as it were.

Conclusion: In a conglomerate the weight of overlying strata is born on an average by some 25 percent of the contact points. If, as Kumm claimes, cones are developed at these points they should be evident in any conglomerate, even if only a few pitted pebbles were examined. Actually they are entirely absent in all but a few conglomerates, and even in these they are quite rare. These conglomerates are the highly exceptional cases in which the Daubrée-Kumm system of solution in capillary contact wetting may possibly be active. In all other cases the hypothesis certainly fails.

Second. In order to posses solvent power the water held by capillarity at the contact must be continually renewed. This must take place by trickling from contact to contact over the surface of the pebbles. Why are these not frequently groved by this trickle of solvent liquid? Only one single case has been noted by Kumm.

Conclusion. The absence of groving and of all corrosion of the surface proves the pebbles to have been embedded in a saturated solution (an entirely dry state being out of the question).

Third. In order that the water held at the contacts can dissolve pits in the pebbles, these may not be in contact, for then a cone is left standing. Apart from the physical impossibility of this floating condition mentioned above, a statistical study disproves it. Except a few slides made by SORBY und HEIM, all investigators appear to have examined pebbles picked out of the rock. Thus the relations between indenting and indented pebble are not brought out. I followed a different method, that of cutting and polishing a piece of conglomerate [1]). In a light brown, sandy base a large number of well rounded pebbles are firmly embedded. They consist of quarzites, sandstones, veinquartz, lydites, jaspis, gneises and volcanics, the first two types greatly predominating, in very variable types. Almost all pebbles are in contact with one or more of their neighbours on the polished surfaces. On the exposed surfaces of the block hardly any clear indentures were visible, but on the polished cuts they are very frequent. In all some 900 cuts of pebbles are visible. Between these there are a great number of contacts, where denting is possible or probable but nevertheless doubtfull, while in 170 contacts the shapes display unmistakable signs of indenture. In only 4 of these, that is 2—3 percent, do the pebbles fail to make perfectly close contact [2]). If the cementing sand were to be removed and water were allowed to wet the points of contact it could only enter into a few of the pits. The solvent action would therefore take place along the seam at the edge of the pits. These pits would be changed to curiously formed hollows as shown in fig. 3. Not only could the pits never have been generated by water held by capillarity, but if the pitted conglomerate were to be exposed to such action, a most striking shape would be produced. Such „nested pits" never having been observed, they do not appear to have been developed in nature.

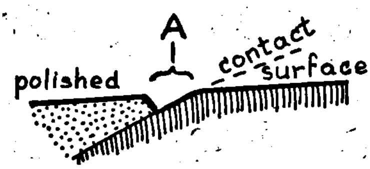

Fig. 2.

Much enlarged profile through two contacting pebbles to show that on a polished cut there will wrongly appear to be some distance between them. A = false breadth of contact.

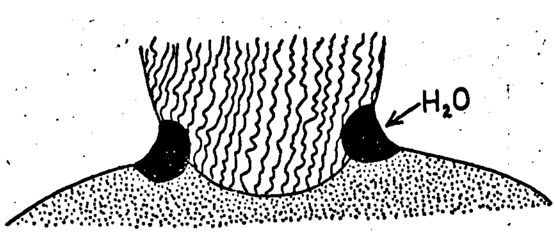

Fig. 3.

Undersaturated, capillary water attacking a pitted pebble would cause a curious shape.

Conclusion. Close contact of the two pebbles being the rule, a solvent held by capillarity would not develop, but destroy the cupshape.

Fourth. In spite of the rough surface of some pits in quarzites and sandstones, the two walls fit perfectly, like stylolites. Had there

[1]) The derivation of this block is not known, as it was found amid a heap of discarded material in the garden of the institude at Groningen.

[2]) On photographs of a cut through a conglomerate pebbles are apt to appear less closely pressed together than they actually are. Owing to the generally oblique position of the contacting surface with respect to the polished saw-cut, the upper of the two pebbles is generally slightly chipped off (see fig. 2). The contact surface is seen as a narrow dark zone (A) instead of as a sharp line.

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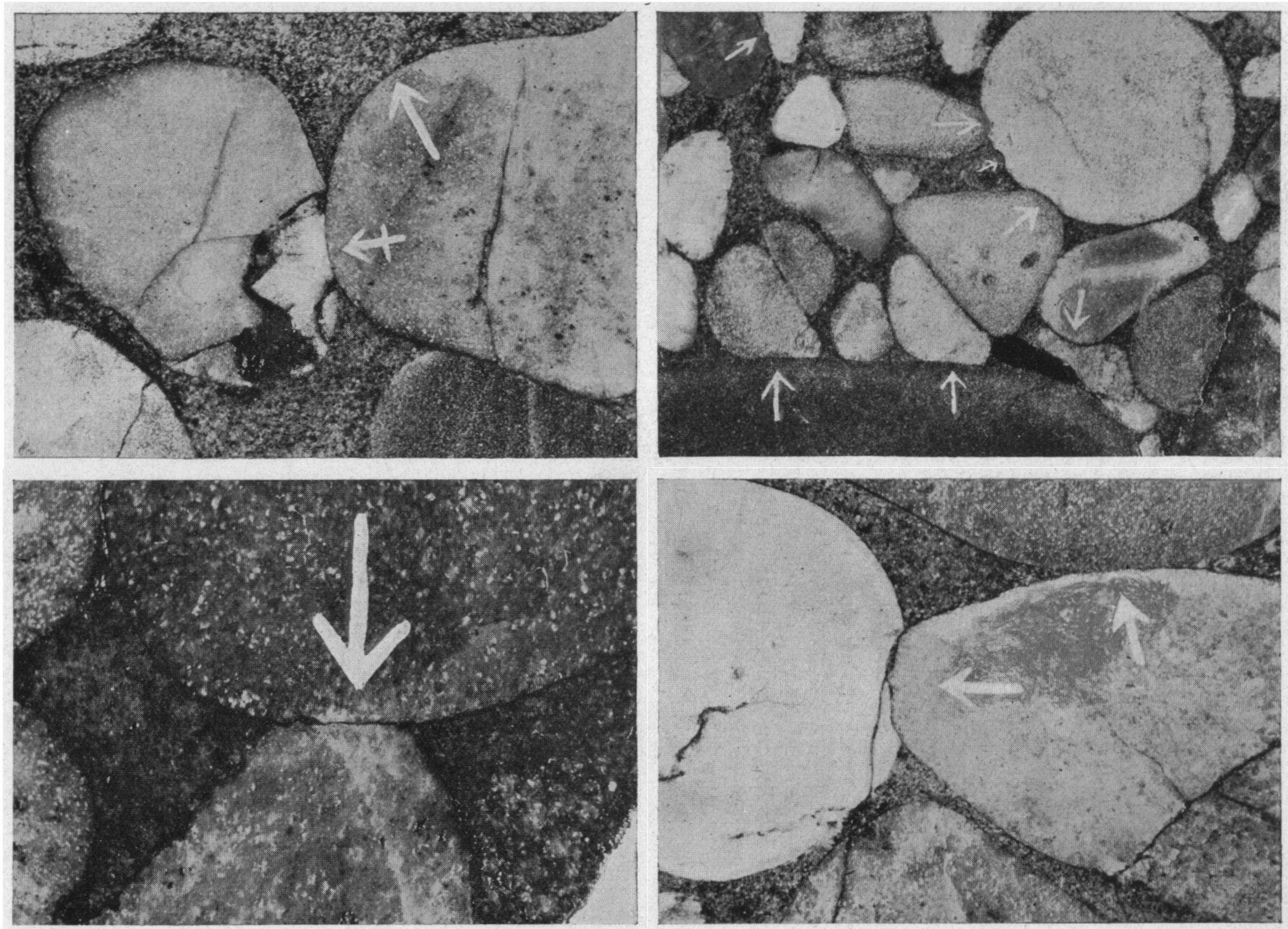

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Conglomerate with dented pebbles. Fig. 1. A dented quartzite cracked by the indenting quartzite (1½ ×). Fig. 2. Showing many dents, partly in the form of flattening at the bottom (1 ×). Fig. 3. Quartzite (with arrow) flattening the nose of another quartzite (3 ×). Fig. 4. A coarse quartzite indenting a fine grained quartzite and flattening a quartzite at the top (1½ ×).

formerly existed a distance between them, they could only show a rough parallelism. In limestones the pits are frequently perfectly smooth and the indenting pebble fits in right up to the edge of the dent. Had they stood apart formerly they could never fit on being brought into contact.

Moreover in a deep pit the water is more quickly renewed at the edges. The indenting pebble should fit into the pit as a smaller ball into a larger saucer (fig. 4). HEIM noted, however, that frequently the upper rims of

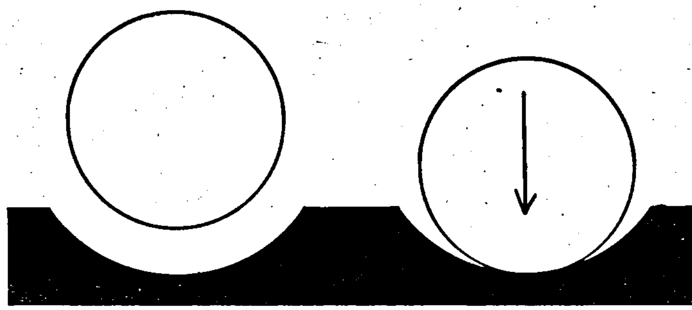

Fig. 4.

To show that a pit formed by capillary water, as supposed by DAUBRÉE and KUMM, could not fit the pebble forming it.

the pits fit so closely, that the gradually penetrating pebble has formed slickensides.

Conclusion. The perfect fit of the pits proves that the walls were always in direct contact and never stood apart to allow capillary water to flow in between them.

Fifth. The fact that with pebbles of the same type of rock the more sharply curved one indents the flatter one, is not explained. If it were merely, that — as KUMM supposes —, they are dissolved in equal amount, but that the smaller one sinks into the pit formed in the larger one, most pits should be flat bottomed. There must be a reason why the flatter surface is attacked more succesfully by solution as the sharper pebble retains its original shape almost unimpaired.

Conclusion. The immunity of the sharper pebble to solvent action is unexplained.

Sixth. The matrix presents some difficulties. HEIM says, that in the Alpine Nagelfluh the pitting is restricted to parts that originally contained no matrix between the pebbles. Afterwards it was formed by precipitation, during or after the process of pitting. When, however, the matrix consists of sand, as is generally the case in siliceous conglomerates with pits, the grains must either have been sedimented together with the pebbles, or they must have been washed in by rain from overlaying sand after the gravel had been deposited.

The conception of the subsequent introduction of the sandy matrix is hardly satisfactory for most conglomerates. There should be voids below larger pebbles and in many angles were the pebbles happen to fit more closely together. But the chief difficulty is that in order to retain the slow, regulated flow of water necessary to the mechanism of DAUBRÉE the conglomerate must be covered by a stratum of soil (see KUMM p. 219). Either this material is washed in at the outset, before the pitting has well started, or it is not able to enter between the pebbles and no sandy matrix could be introduced at all. DAUBRÉE needs first a covering regulating the influx of water from above for many hundreds or thousands of years, without its being carried down between the pebbles. Afterwards when the denting is completed, this covering is washed in between the gravel, where we find it now. Why are finer silt and clay, formed in the overlying soil, not introduced before the less mobile sand?

The introduction of the sandy matrix together with — or immediately following — the deposition of the gravel is the only logical supposition. But in that case the whole stratum is a capillary retainer. The points of contact between pebbles are not moistened in preference to the remaining surface of the pebbles, neither is the water, held at those contacts, refreshed more thoroughly than the practically continuous film held over the remaining surface by the sand grains. These grains would be attacked vigorously and settle, leaving voids below well supported pebbles.

Conclusion. The DAUBRÉE system could only act in a conglomerate without sandy matrix and the subsequent introduction of this sand is most improbable.

Seventh. KUMM shows (p. 218—219) that the principle would only work under a constant and unvarying supply of groundwater and goes on to say that it could not begin till after burial to some depth and must have stopped after sinking below the groundwater table. He forgets, however, that before and after the period showing the requisite conditions, pitting would not take place, but solution would nevertheless be active. Why is the result of corrosion similar to that of DAUBRÉE's first experiment, not evident in most cases? For in the history of a deposit the period spent under the required conditions must be short compared to the periods when the pebbles were entirely immersed in groundwater, that flowed easily and rapidly.

Conclusion. The absence of corrosion outside the pits shows that the pebbles were soon buried far below the groundwater table in stagnant conditions.

Eigth. In sandstones and quartzites one would expect the grains to stand out in pattern in the pits, instead of being cut off by a common smooth surface as is generally the case (fig. 5).

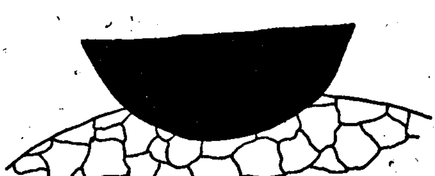

Fig. 5.

Denting of a quartzite; there is often no differential solution of the grains, the surface of the pit cuts smoothly through them.

General conclusion on Daubrée's theory. In a few highly exceptional cases the indenting by solution through undersaturated water at the points of contact is a possible explanation (cases cited by KUMM). In practically all pitted conglomerates, however, this mechanism would fail to bring about the observed shape of the pits.

It was pointed out above that SORBY brought convincing proof of the pits having been formed by solution. If the mechanism proposed by DAUBRÉE has to be discarded and the disintegration hypothesis of HEIM is also invalid, the only remaining explanation is that given by SORBY himself.

SORBY imagined the conglomerate to be drenched by stagnant, saturated groundwater. At the points of contact where the pebbles are squeezed together by the weight of overhanging strata, the material is dissolved under pressure. It crystallizes out in the intervening spaces between the pebbles and sandgrains. p. 805: „...... dass in Folge mechanischen Druckes der Kalkstein ganz umgeben und durchdrungen von mit Kohlen-saurem Kalk gesättigtem Wasser aufgelöst wird, da wo der Druck am grössten, und krystallisieren, da wo solcher am geringsten. Dass derartige Vorgänge sehr langsam von statten gehen, unterliegt keinem Zweifel; ......"

SORBY mentions having made experiments to prove the influence of pressure on solubility.

The principle of solution under stress was again called upon by RIECKE fifty years later to account for diagenesis and schistosity. It then entered geological speculation under the designation RIECKE's principle. NIGGLI, HARKER, ESKOLA to name but a few, proclaim its effectiveness in metamorphism. SENG also emphasized the importance of RIECKE's principle in two recent papers, RUSSELL showed by experiment, that a crystal in its saturated solution is actually dissolved under local strain, growing on the other faces.

Now the conception of the pitting of pebbles by pressure in stagnant groundwater may have been a bold flight of speculation in the days of SORBY, it is, however, but a special application of RIECKE's principle that is now generally accepted by petrologists. Thus HARKER wrote in his „Metamorphism" pp. 144—145: „A stressed crystal and an unstressed, in „contact with a saturated solution, are to be regarded as two distinct solid „phases, and therefore cannot be in equilibrium. Material will be dissolved „from the one and added to the other until the former has disappeared. „So, too, if a single crystal be unequally stressed in its different parts, „differential solubility may cause a transference of material from one part „to another, gradually changing the shape of the crystal."

I will now attempt to show, that the objections raised against this hypothesis are invalid, and that it explains all phenomena observed.

The chief argument brought forward by DAUBRÉE and KUMM is the result of their experiments. They found, that when pressed firmly together, or even when only just touching, the points of contact protect eachother against the solvent and tend to form elevations instead of depressions. This result is so inevitable as hardly to need an experiment for proving it. But the experiment has nothing to do with the problem at issue. SORBY clearly stated, that the action is *due to solution under pressure in a saturated solution*. DAUBRÉE should not have immersed his marble spheres in dilute acid but in a bath of water saturated with lime. Increasing the speed in the experiment by adding acid, introduces a new element, absent in SORBY's conception, namely *solution by undersaturation*, not by pressure. Consequently there then is solution also beyond the points under pressure. This new element has so swift and powerfull a result as to entirely obscure the action of pressure, that must be exceedingly slow. Removal of the lime dissolved at the point of contact and its expulsion from between the contacting surfaces of the two pebbles is by diffusion. The only permissible manner in which the experiment could be accelerated would be by raising the temperature so as to increase the rate of diffusion. Even so we should probably need thousands of years to obtain pits as deep as those found in Nagelfluh-pebbles. With siliceous rocks the action must be very much slower still. In fact we cannot do much to speed up the natural process because we must work on about the natural scale. Thus the objection most stressed by SORBY's opponents is found to be easily refuted.

Some other arguments, due principally to KUMM, are the following:

1. The material deposited beside the pit may be older or younger than the pitting. KUMM draws the conclusion that the intersticial liquid was oversaturated before or after but not during the period of pitting. But although according to SORBY an oversaturated solution is formed at the points of contact, precipitation is not a necessary consequence because the concentration will only be raised very slightly and the oversaturated liquid may be drained off by slow movements of the groundwater. SORBY's explanation does not require intersticial deposition during the pitting any more than does KUMM's own view, but the simultaneousness is possible.

2. There may be a thin veneer of lime or silica in the pits, cementing the pebbles firmly together and KUMM concludes that pebble and pit did not touch, otherwise there would have been no room left for the cement. It should be realised, however, that during the pitting process the conglomerate is in a continual state of movement by settling. Pressure is now exerted in this pit, now in that and after having been forced into a pit a pebble will afterwards be pressed a short distance out again, or at least be relieved of pressure. Pebbles are rotated, pressed aside and gradually pitted in an increasing number of points as the conglomerate sinks together. As soon as a pit is releaved of pressure or opened, the deposition of cement is possible.

3. As all particles of which the crystal lattice is distorted by the pressure are open to attack by solution, the solvent action is not restricted to the actual points of contact, so that the fit need not be absolute. But on the other hand it should be almost perfect to the naked eye.

The slight movements just mentioned, especially the rotations, easily explain the missfit in many pits as observed by KUMM. My own sample shows that the missfit is generally only of microscopic dimensions.

4. When two pebbles in contact are of different solubility, the more soluable one will be attacked most. Thus in my own sample there are many instances of sharp pebbles flattening their noses against entirely unaltered neighbours. It may be that the statement is correct, that in the Nagelfluh the pebble with the sharpest form invariably causes a pit in the flatter one. But it should be born in mind, that whereas a sharp dent in a flat pebble is a striking feature, the flattening of a pebble against another may easily escape notice. But HEIM was so careful an observer, that his confirmation of this law for pebbles of equal solubility, carries great weight. The explanation offered by DAUBRÉE and KUMM (that both pebbles suffer solution, but the smaller one sinks into the hole made in the larger) would hold as well for SORBY's view, but I have offered reasons for doubting its validity. Possibly the stresses set up at the contact in a round and a flat pebble are such, that given identical solubility the latter is dissolved, while the former is spared. This point needs confirmation by theory or experiment.

5. The presence of a sandy matrix offers no difficulty to SORBY's conception. Solution takes place wherever pressure is concentrated. When the pebbles are pressed into eachother the grains of the matrix must also be compacted. This compaction will continue either until the pressure becomes too low per unit of area, or until the interstices are entirely closed.

The sandy matrix of the conglomerate I described above is exceedingly interesting in this connection. Under the microscope it is seen to consist for the greater parts of quartz grains, some with strain shadows. Now these grains touch eachother along irregular, deeply interlocking surfaces, leaving no or only small spaces unoccupied. The picture resembles that offered by many quartzites. This structure must have been generated after the sedimentation of the conglomerate. Although the interlocking structure of the matrix implies shrinkage, there are no voids in the conglomerate. In other words, the rock as a whole and also the inclosed pebbles were pressed considerably closer together, after the matrix was in situ. Obviously this compaction of the rock is identical with the process of pitting. In this manner the pitting is proved to have taken place after the sandy matrix was introduced between the pebbles. But when there is a matrix of sand, the water is no longer held by capillarity exclusively at the contacts between the pebbles, but everywhere in between the grains of sand also. In consideration of the small size of these grains, the resultant interlocking shapes and the absence of solution channels to bring along fresh solvent water, it is evident that the DAUBRÉE-KUMM principle cannot be applied.

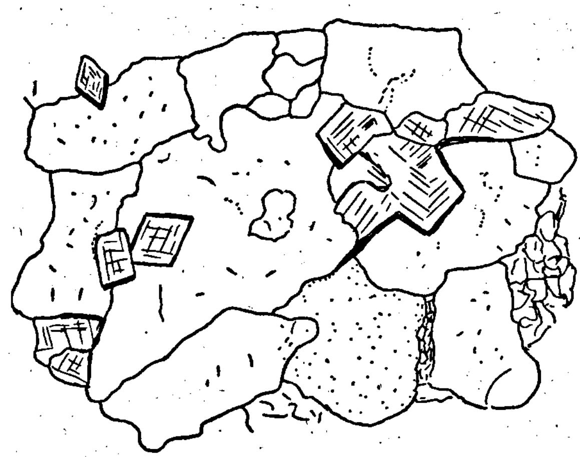

Fig. 6.

Microscopic structure of the matrix of the investigated conglomerate. Note the interlocking, closely fitting quartz grains and the idiomorphic carbonate rhombohedrons.

The matrix shows yet another significant characteristic. The kind of grains coming second in abundance are idiomorphic carbonate rhombohedrons. They frequently indent the quartz with sharply cut, well developed crystal faces. In a circulating, undersaturated liquid the carbonate would be dissolved much faster than the quartz. Only REICKE's principle can explain the occurrence of carbonate crystals with almost perfect idiomorphism growing into quartz.

6. The occurrence of pebbles that are pitted on one side only, can be explained by assuming, that the neighbouring pebbles on the smooth side happened to be more soluable[1]).

7. Cases in which one in every few pebbles is cracked are the consequence of sufficient overburden to cause rupture when concentrated at a few points in the shape of vaulting pressure.

[1]) KESSLER noted a case of recent gravels near Strasburg where the pits in all pebbles were practically restricted to the lower surface. There were voids below the pebbles also with incrustations of lime. A detailed investigation in situ would be necessary to ascertain what was the cause of this one-sided attack.

8. While the DAUBRÉE-KUMM principle is inapplicable to by far the greatest majority of cases, SORBY's explanation only meets with some difficulty for the pebbles showing contact cones. Part of these may, however, be stylolites, that are not opposed to the explanation, others may be percussion cones and finally there may be cases in which DAUBRÉE's explanation is correct.

9. KUMM described pitted pebbles from a recent gravel in the neighbourhood of Heidelberg, some of which were collected only 2½ m below the surface. He argues that in this case the pressure was evidently absent. Assuming, however, that the specific gravity of the gravel is 2 and that the surface of the contacts forms 10 percent of the horizontal section, the average pressure on the contacts is already 5 atmospheres, and will vary up to considerably higher values for each point by vaulting pressure during the settling. Moreover, this special case is possibly one of the exceptional examples of the DAUBRÉE-KUMM effect, as the small depth of burial is combined with the occurrence of contact cones and an example of a flow-off channel.

SUMMARY.

As early as 1863 SORBY proved that pitted pebbles are the result of solution at the points of mutual contact in a conglomerate. As cause he suggested solution under pressure in saturated, stagnant groundwater by what has afterwards been designated RIECKE's principle. By the examination of polished cuts through a pitted conglomerate I found confirmation of this hypothesis. The alternate explanation by DAUBRÉE, KUMM and others of solution in water held by capillarity at the points of contact could not cause the observed shapes of the pits. The experiments they used to disprove SORBY's view are fundamentally incorrect. They attempted to form pits by a solvent liquid, instead of using pressure and saturated water.

Groningen, November 1942.

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