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DISTORTED OOLITES AND PSEUDOOLITES

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ABSTRACT

Distorted oolites and pseudoolites are relatively rare occurrences in the geological column. They have been described in oolitic iron ores, phosphorites, limestones, argillaceous, and sideritic deposits. The shapes created by the distortion processes are very characteristic and independent from the mineralogical composition. They illustrate a complete gradation from plastic deformation to the rupture of rigid bodies. The distortion, which is localized in pockets or affects only isolated individuals, has always preceded the deposition of the cement and compaction wherever the latter has been active. The conclusion is reached that the distortion was generated during sedimentation in agitated conditions and resulted from the reciprocal impacts among oolites or pseudoolites at different stages of diagenetic induration.

INTRODUCTION

In this paper an oolite is defined as a spherical or subspherical body, 0.25 to 2 mm in diameter, of any composition usually displaying a nucleus around which at least one concentric layer has been deposited by an accretion process (Carozzi, 1960). The term pseudoolite is applied to a spherical body devoid of internal texture, which, however, may very often form the nucleus of associated oolites.

Distorted oolites and pseudoolites are apparently rare occurrences in the geological column. They display very characteristic features, independent of their mineralogical composition, which point to a single and general sedimentary mechanism. We have excluded from our discussion the normal oolites and pseudoolites flattened and deformed by the effects of mutual contacts during early compaction and those which have penetrated each other as a result of intergranular solution during late compaction.

REVIEW OF THE LITERATURE

Brief mentions and illustrations of distorted oolites and pseudoolites appear scattered in the geological literature, particularly in papers dealing with oolitic iron ores, but rarely are they accompanied by discussions or interpretations. Hence, to avoid repetition the review is limited to the most significant contributions.

The first mention of distorted oolites can be attributed to Günbel (1885, p. 80, 173-174). He mentions that in the lower oolitic beds of the Wellenkalk many oolites are quite different from their typical spherical shape. They appear distorted into cylindrical or sausage-like bodies, irregularly bent, penetrated laterally by embayments, and often influenced by the shape of the neighboring individuals. Günbel also describes similar features in pseudoolites frequently found in Jurassic limestones and proposes for them the name of half-oolite (Haloolithe). In spite of the lack of illustration, there is no doubt that Günbel's description deals with the problem we are discussing here as pointed out by Frantzen in 1887.

The first complete description of distorted pseudoolites was given by Bornemann (1886, p. 277-278, plate VII, fig. 1) for a bed of pseudoolitic limestone called Bank 7 of the Lower Muschelkalk at Kirchthal, near Eichrodt in Thuringia. The pseudoolites (fig. 1 of this paper) appear as more or less well rounded bodies of dark cryptocrystalline calcite set in a cement of well crystallized calcite together with grains of granular calcite, fragments of crinoids, and pelecypod shells. In his picture, one can see very clearly zones, generally parallel to the bedding, in which the dark pseudoolites are strongly deformed, displaying notches and narrow apophyses joining adjacent individuals. The distorted bodies appear hooked together into zig-zag patterns and in groups recalling the typographical symbol of $\&$, both trend-
Bornemann calls the distorted pseudoolites "corroded limestone grains" because he interprets them as the result of a corrosion in place before deposition of the cement and caused by the alteration of pyrite. He describes his figure as follows: "the thin section shows a superposition of zones of perfect preservation and of others in which alteration has been active. In the former (lower portion of the picture), the limestone grains display an appreciable encrustation of pyrite which appears also as a fine powder along the crystal boundaries. In the zones of alteration, the pyrite was decomposed into iron sulfate which corroded the dark cryptocrystalline grains and stained them in brown. In the presence of abundant pyrite, the sulfuric acid developed was sufficient to change an appreciable portion of the limestone into gypsum. The latter has left after dissolution cavities filled with iron hydroxide." A year later Frantzen (1887, p. 90-92, plate III, fig. 2 to 4) described the first distorted oolites in the bed of oolitic limestone called Bank 6 of the Lower Muschelkalk of Heldrastein in Thuringia. He discusses his observations in the following terms: "In figure 2 of plate III, (fig. 2 of this paper) there are normal oolites on the left side whereas on the right they have been modified by the movement of the water. The oolites have been distorted, squashed and sometimes broken into two parts along a sharp rupture line. Some individuals display their broken fragments still side by side. The same types of deformations are shown by oolites made of dark cryptocrystalline calcite or of clear calcite. Figure 3 (fig. 3 of this paper) of the same slide shows another portion of the same slide with oolites squashed by the pressure of the water. Figure 4 (fig. 4 of this paper) shows a case in which distortion has been carried so far that the elongated bodies could not be identified as..."
Frantzen's figure 4 (fig. 4 of this paper) displays a situation in which the distorted oolites are not oriented at random but have been further flattened and appreciably oriented parallel to the bedding. The cement is well-crystallized calcite as in the other cases, but is less abundant. As a result, the distorted oolites come in contact with each other much more frequently and have reciprocally affected their shapes. This indicates a localized compaction of the distorted individuals before the introduction of the cement.

In the first volume of his monograph on the oolitic iron ores of France, L. Cayeux (1909, p. 18-34) mentions but does not illustrate distortion phenomena. These occur in oolites of red hematite in a cement of siderite in the Silurian ore of May-sur-Orne (Calvados) and are described as follows: "the deformation is preferably concentrated along certain zones of the ore where the oolites are almost molded on each other.

Frantzen adds that Bornemann's picture may be interpreted as showing that the pseudoolites were also soft during their formation and even softer than the oolites of Heldrastein, some of which display fragments with sharp boundaries. He reaches the conclusion that the normal oolites indicate relatively quiet water and the distorted ones a very agitated environment, proposing the name of empodoolites (Empodoolithe) for the latter. Frantzen's pictures 2 and 3 show oolites oriented at random in a cement of well-crystallized calcite in which a segment of the concentric envelope has been rotated along a hinge-line or displaced inside the individuals for a variable distance. These movements have often been accompanied by a wrinkling of the displaced segment and may end in a complete shearing or shattering of the oolites. A more elaborate discussion of these oolites if all transitional terms were not present in the same deposit."

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without any intercalation of cement. In some cases, the oolites may be distorted to such an extent that their original oolitic nature has almost vanished. The deformation also exists, but less pronounced, among isolated individuals.”

In his second volume dealing with the Mesozoic oolitic iron ores, Cayeux describes (1922, p. 169-171, plate XI, fig. 24) a chloritic iron ore of the Upper Liassic of Lorraine in which distorted chloritic oolites appear strongly flattened parallel to the bedding in a very reduced amount of chloritic cement. Here again the distortion, even where realized with its maximum intensity, is strictly limited to a portion of the bed and does not develop through its entire thickness. Cayeux concludes: “It is probable that the causes of the phenomenon must be looked for in the deposit itself. Possibly it could be attributed to changes in the physical state of the oolites. The process might then be compared to the folds created by the change of anhydrite to gypsum.” In the two cases just discussed, we have conditions similar to those already described by Frantzen where distorted oolites have been further flattened by local compaction before introduction of the cement.

A general discussion of distortion among oolitic iron ores was announced by Cayeux for the third volume of his monograph; unfortunately it was never published. However, in 1935, in his monumental monograph on carbonate rocks, Cayeux gives a detailed description and discussion of two unusual examples of distorted oolites in specimens from the Jurassic of an unknown locality from the margins of the Massif Central (fig. 5) and from the Muschelkalk of Azerailles, Meurthe-et-Moselle (fig. 6). The two specimens (p. 233-235, plate XV, fig. 55 and 56) display the same types of distortion which he attributes to contraction and stretching, pointing out the following features: “The specimens show stretched oolites, notched oolites, and oolites stretched and notched at the same time. The starting point of the deformations is a limestone in which the oolites appear more or less largely separated from each other and not contiguous. The following situations may be observed in order of increasing complexity (fig. 5 and 6):

1. Two adjacent oolites are joined to each other through the extension of one of them.
2. Two oolites are joined to each other by means of an arcuate apophysis, very thin in its middle portion and sometimes broken by excess of stretching.
3. In most of the preceding cases, the junction of adjacent oolites takes place at the points where they come the closest or almost. There is a quite different situation where the little apophysis joins the opposed ends of two adjacent oolites.
4. Oolites appear notched to a variable extent by wedge-like cracks which, where carried to exaggeration, lead to an almost complete disruption of the bodies.
5. In a general manner, where oolites are notched in such a fashion, the feature is repeated on many neighboring individ-

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**Fig. 4.—Distorted and compacted oolites, oolitic limestone of Lower Muschelkalk of Heldrastein. Camera lucida drawing, X60, parallel nics. This is Frantzen’s (1887) figure 4 of plate III.**
At the same time, the lips of the notches appear to continue into arcuate apophyses, forming elegant curves joining similar features of neighboring oolites. For instance, two individuals, very widely separated by a distance which is sometimes greater than their longest axis, may be joined through the cement by narrow apophyses which always keep a perfect individuality. In the cases of maximum complication, oolites showing the deformations described above may build up corkscrewed series (fig. 5, 6). It is important to point out that such a complex deformation is not present all over the entire specimen but is concentrated in given areas which, however, contain scattered oolites which have kept their original shape.

Cayeux feels that one single explanation should be applied to the distortions in oolitic iron ores and in limestones and presents the following discussion: "the junctions between the oolites, their size, shape and the fragility of the arcuate apophyses require a formation in place without any mechanical actions foreign to the deposit itself. It looks as if oolites, originally in mutual contact and in very plastic condition, had been submitted to an important reduction of volume in a cement which would oppose only a very weak resistance to the movement of materials. The oolites pulled in different directions by the effect of the numerous original points of mutual contact would remain attached by the development of apophyses. The size and shape of the latter are a function of the magnitude of the contraction; their number and position a function of the contact points. Consequently, the apophyses result from the different tractions to which the oolites have been submitted. In this interpretation, the oolites themselves are at the origin of their distortion but nevertheless, the mechanism remains highly enigmatic. If the proposed explanation were true, the cementation processes of such rocks would be extraordinarily complex and
Fig. 6.—Distorted oolites from an oolitic limestone of the Muschelkalk of Azerailles (Meurthe-et-Moselle), France, X25, parallel nicols. White areas are holes in the thin section.
would imply changes of volume of a magnitude unsuspected up to now in calcareous environment."

Cayeux rejects the interpretations proposed for similar deposits by Bornemann and Frantzen as inadequate to explain the observed facts.

Lucas (1942, p. 308, fig. 127) in his description of the mountains of Ghar Rouban and of Sid El Abed, Algeria, mentions oolithes distorted by notching and stretching similar to those discussed by Cayeux. These oolithes occur at the base of the Kimeridgian-Portlandian (J 5) of the Bled Tirheza. No additional information is given concerning their characters or genesis.

Van Tassel describing siderite beds with argillaceous oolithes and pseudoolites in the Westphalian of Belgium, illustrated and briefly mentioned some cases of distortion (1955, p. 366-367, plate A, fig. 3 to 5):

Figure 3 of plate A (fig. 7 of this paper) shows oolithes of kaolinite with well-developed concentric texture built by layers of different color around a relatively small core of carbonaceous matter. The oolite on the extreme right side of the picture reveals that a segment of its rather thin concentric envelope has been sharply bent at its upper end like a hair-pin and terminates at the lower end by a sharp rupture line. The flap thus created shows, in comparison with the remaining portion of the concentric envelope, a decreased curvature, appearing almost flat. The flap has evidently been rotated inside the oolite at the expense of the relatively large core of carbonaceous matter, an appreciable portion of which has been eliminated. This process of distortion will be analyzed with more details in the next section.

Figure 5 of plate A (fig. 8 of this paper) shows well-developed pseudoolites of fine-grained kaolinite devoid of internal texture and of core. In the middle of the picture extends a row of three distorted individuals hooked together by their apophyses.

Edwards, in his description of oolitic iron formations in Northern Australia (1958, published 1959, p. 668-682, fig. 4, 13 and
14), has given some of the best illustrations ever published of distorted oolites but did not elaborate at length on their possible origin. He mentions, however, that the same type of cement encloses distorted and spherical oolites, indicating that cementation occurred after the deformation of the oolites.

His figure 4 (fig. 9 of this paper) shows an oolitic ironstone from Roper Bar, Northern Territory, of late Proterozoic age, in which hematite oolites are set in a micro-crystalline cement of quartz. In the lower half of the picture appear from left to right, three distorted individuals. The first one has been split open into two parts which have rotated outward limiting a sharply defined V-shaped crack. The oolite in the middle shows a deep notch made by a flap which apparently was pushed obliquely inside the body and curled on itself. The third oolite displays a flap flattened in the same manner as illustrated by figure 3 of Van Tassel (1955).

All these distorted individuals are set in the quartz cement and display only very limited contacts with neighboring normal individuals.

Figures 13 and 14 display in a remarkable way distorted oolites of chamosite in a cement of crystalline siderite from Upper Proterozoic deposits in the Constance Range area, Northwestern Queensland. The distorted oolites are associated with normal ones indicating once more that cementation occurred after the processes of distortion. It is appropriate to take advantage of these excellent conditions of preservation to describe here two very characteristic sections of distorted oolites which occur in all previously discussed cases. The first one is shown by the oolites in the middle and right middle of figure 14 (fig. 11 of this paper). In both individuals a segment of the concentric envelope, extending from one of the summits of the elliptical section to approximately ¾ of its longest axis, appears sharply bent at one end like a hair-pin and terminates at the other by a straight or curved rupture line. The flap thus created displays, in comparison with the remaining portion of the envelope, a decreased curvature or even has been completely flattened. It has been rotated around its hinge inside the original outline of the oolite and for a variable distance. The penetration of the flap inside the oolite requires a plastic deformation of the latter for obvious geometrical reasons, the external dimension of the flap being larger than the internal dimension of the opening. When such a plastic deformation was not enough, the penetration of the flap was partially hindered, and the latter may display a wrinkling on itself or a refolding of its end. The displacement of the flap reaches its maximum when it comes in contact with the concave internal margin of the opposite portion of the concentric envelope. Naturally, the penetration of the flap has always been made at the expense of the core which has suffered a great amount of reduction reaching often almost complete disappearance. As shown in the upper middle portion of figure 13 (fig. 10 of this paper), the hinge-line of the flap may appear partially broken in its internal layers which are separated from one another to a variable extent and also individually wrinkled.

The second typical section is shown by the oolite in the upper-central portion of figure 14 (fig. 11 of this paper). Here the concentric envelopes appear sharply ruptured at two

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**Fig. 9.—** Distorted hematite oolites (black) in a cement of microcrystalline quartz. Oolitic ironstone, Upper Proterozoic from Roper Bar, Northern Territory, Australia. X35, crossed nics. This is Edward's 1958 (1959), figure 4.
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Oolitic siderite, Upper Proterozoic of Constance Range, Queensland, Australia showing normal and distorted oolites consisting of outer concentric rings of a chamosite-like substance enclosing darker shells containing black opaque carbon and siderite (white). The cement is crystalline siderite. X30, parallel nicols. This is Edward's 1958 (1959) figure 13.

points, no hinge line is visible, and a flap also showing a decreased curvature appears displaced, but not rotated, inside the original outline of the oolite. Occasionally, concentric layers of the flap appear wrinkled and separated from each other. Here also it should be pointed out that the external size of the flap is larger than the inner dimension of the opening through which it moved. Hence, the displacement requires a plastic deformation of the oolite. The core has been strongly reduced to an elliptical and narrow slit. As will be seen later, these two sections occur in reality at right angle to each other and across one of the basic forms of distortion.

Laugier, describing salt-bearing beds in the Middle Liassic of Lorraine (1959), gives petrographic details on peculiar oolites consisting essentially of magnesite with some halite in the concentric rings and set in a cement of anhydrite. He illustrates a distorted oolite (plate III, fig. 6) and a corroded oolite (plate III, fig. 7) whose shape he attributes to replacements resulting from the growth of the anhydrite crystals of the cement. The aspect of this particular oolite is identical to that of many others described in this paper: it shows clean-cut boundaries, an undulated flap displaced toward its center, and no appreciable change in texture of the surrounding cement. These features seem in favor of a mechanical distortion rather than replacements, the latter being shown beautifully elsewhere in the same paper (plate IV, fig. 7, 10 to 12).

Zadnik has kindly communicated to the writer several thin sections of oolitic dolomites from the Upper Cambrian of the Middle Delaware Valley, near Easton, Pennsylvania, which display scattered zones of distorted oolites in all details similar to the cases discussed above.

ANALYSIS OF THE SHAPES OF DISTORTED OOLITES AND PSEUDOOLITES

From the review of published pictures and from thin section studies of samples from

Fig. 10.—Oolitic siderite, Upper Proterozoic of Constance Range, Queensland, Australia showing normal and distorted oolites consisting of outer concentric rings of a chamosite-like substance enclosing darker shells containing black opaque carbon and siderite (white). The cement is crystalline siderite. X30, parallel nicols. This is Edward's 1958 (1959) figure 13.

Fig. 11.—Distorted chamositic oolites adjacent to the band of rock shown in figure 10. X30, parallel nicols. This is Edward's 1958 (1959) figure 14.
the Muschelkalk of Azerailles (Meurthe-et-Moselle), France, the Westphalian of the Charbonnage du Poirier, Charleroi, Belgium, and the Upper Cambrian of the Delaware Valley, it has been possible to assemble a great number of differently oriented sections of distorted oolites and pseudoolites. At a first glance, the variety of the shapes appeared quite large but soon the repetition of similar forms indicated three main groups of basic types to which all the observed shapes could be derived by increased stretching and distortion. Such a derivation was confirmed by constructing plastic models and cutting them along oriented sections.

Group 1
It includes the most common shapes resulting from the rupture of the outer shell of oolites and pseudoolites accompanied by an elimination of a variable proportion of the core. The reconstruction by models of such ruptured oolites shows that the two sections described in the deposits of the Constance Range area are located at right angles to each other. They cut across a spheroidal or ellipsoidal body in which a flattened flap corresponding to a small circle has been pushed inside by rotation along a short hinge-line (fig. 12 a, b).

According to the size of the flap and the thickness of the external skin which has been ruptured, apophyses are created which vary in shape from sharply acute types (increased by further stretching) to rather massive beak-like forms (fig. 13, 1 to 7). The flap may display a curling of its end (fig. 13, 3) or several wrinkles (fig. 13, 2). It may have its hinge-line broken (fig. 13, 4), and such a condition may lead to a complete shattering of the body (fig. 13, 6).

In the section at right angles to the preceding one (fig. 13, 8 to 13), the flap may also appear wrinkled (fig. 13, 11) and the two apophyses strongly stretched in many instances (fig. 13, 12 and 13). Oblique and tangential sections across distorted individuals belonging to the first group may give quite unusual shapes (fig. 13, 16 to 21). In some cases (fig. 13, 22 to 24), the flap no longer appears flattened but is curled on itself displaying an increased curvature in comparison with the rest of the oolite (fig. 12, c). In such a case, a rather thick beak-

![Fig. 12. Schematic models of the major types of distorted oolites. a, b: shapes resulting from the penetration of a flattened flap (group 1), c: shape resulting from a curled flap (group 1), d: shape resulting from squashing and rupture along a great circle (group 2). See text for additional explanations.](image-url)
Fig. 13.—Schematic representation of the major types of distorted oolites as they appear in thin section. Shell of concentric rings: black; core: oblique ruling. 1-24: shapes of group 1; 25-30: shapes of group 2; 31: shapes of group 3. See text for additional explanations.

like apophysis is generated, particularly when the curling has taken place without the flap being rotated too much inside the oolite.

Group 2

In this group are included the shapes resulting from the plastic squashing of oolites and pseudoolites into two parts usually along a great circle (fig. 12, d). The individuals appear split open to a variable extent (fig. 13, 25 to 27). In advanced cases, the fragments are deformed and remain attached to each other only by their outer skin; wavy distortion and stretching are frequently noticed (fig. 13, 28 to 30). This type of distortion displays all gradations between cases in which a small loss of volume has occurred to cases in which the core has been largely eliminated, leaving only distorted and empty outer skins. These may either remain in loose connection or be completely detached or hooked together.

Group 3

This group generally includes oolites which have been broken along well-defined lines but not distorted. The rupture appears in most of the cases as a V-shaped crack cutting across concentric envelopes and the core, the two parts have commonly been rotated away from the crack (fig. 13, 31). In other cases, the oolites appear decorticated, showing indentations caused by fragments of their concentric rings torn off or in the process of being detached. The isolated portions of concentric rings resulting from this process may be found isolated in the cement (fig. 13, 31).

RELATIONS BETWEEN DISTORTED AND NORMAL OOLITES AND THEIR INTERPRETATION

A certain number of characteristic relations are present in all the deposits containing distorted oolites and pseudoolites no matter what their mineralogical composition may be. They are following:

1.—The distorted individuals are not uniformly distributed in the deposits but concentrated in irregular pockets and in zones parallel to the bedding.
The distorted individuals may either be isolated and oriented at random or appear hooked together by their apophyses, in which case they are oriented parallel to the bedding, forming irregular chains. The individuals hooked together frequently display a stretching of their apophyses and advanced distortion of their general shape.

In some instances, distorted individuals have been locally flattened by later compaction and molded on to one another.

Normal oolites and pseudoolites are associated in the same beds with distorted ones, but both kinds appear rarely in contact with each other. It should be pointed out, however, that according to their orientation some sections across distorted individuals may simulate normal ones.

There are no geometrical relations in the deposits indicating that the distorted individuals have been affected in their shape by the associated normal oolites and pseudoolites except in the cases of local compaction following distortion.

The shapes described in the first group of distorted individuals imply a phase of rupture of the outer skin preceded and followed by a plastic deformation. The shapes of the second group result from an entirely plastic deformation and those of the third display an entirely rigid behavior of the bodies. The implication of these facts is the coexistence of individuals at different stages of a process of induration which develops from the periphery toward the inside of oolites and pseudoolites.

The cement displays no effects of the deformation and no traces of the material building the cores of some oolites and which must have been eliminated by some of the types of distortion. The cement does not show any modification of texture or composition wherever it includes normal or distorted individuals as well as where distorted oolites have been further flattened by local compaction.

In order to explain satisfactorily all the relations just described, the mechanism of distortion must have been active only during the time interval corresponding to the deposition of certain zones of the beds displaying variable thickness and sometimes only in very localized spots. This is also shown by the fact that the agent which has broken, squashed, and strongly distorted certain oolites and pseudoolites has also hooked them together and stretched their apophyses, building complex chains or local concentrations.

The process of distortion was completed before the introduction of the cement. Hence, it is concluded that the agent of distortion can only be of subaqueous nature, corresponding to strong waves or currents sweeping the bottom, generating local eddies and creating reciprocal impacts among oolites and pseudoolites freshly deposited and at different stages of induration. These conditions stress once more the rapidity of diagenetic processes.

**DISCUSSION OF EARLIER INTERPRETATIONS**

Our conclusions are identical, in essence, with those expressed in 1887 by Frantzen who considered the agitation of the water as the agent responsible for the distortion.

The idea of corrosion in place after deposition presented by Bornemann (1885) cannot be sustained, mainly because of the identical shapes generated in oolites and pseudoolites of different mineralogical composition. Cayeux (1935) made basic contributions to the question by stressing the fact that the distortions were present in isolated individuals and in localized portions of the beds. He considered that the oolites themselves were at the origin of their distortion and that a single explanation should be applied to all cases, whichever their mineralogical composition happened to be. However, by assuming that the distortion took place after the deposition of the cement, Cayeux was forced to assume very complex and unusual properties for both the oolites and the cement. As a result, his tentative explanation contains contradictions and does not agree with the observed facts.

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