S.S. Augustithis

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Atlas of the Sphaeroidal Textures and Structures and their Genetic Significance

DEDICATED TO MY FRIEND, STAVROS D. CATRAKIS,
PROFESSOR EMERITUS OF THE NATIONAL TECHNICAL UNIVERSITY
OF ATHENS.

Preface

The present Atlas on the sphaeroidal forms is a part of the effort to present the textural patterns of the most significant rocks of the earth's lithosphere.
Other Atlases published by the author are:

1) Atlas of the Textural Patterns of Granites, Gneisses and Associated Rock Types. Elsevier Publishing Company, 1973.
2) Atlas of the Textural Patterns of Basalts and their Genetic Significance. Elsevier Publishing Company, 1978.
3) Atlas of the Textural Patterns of Basic and Ultrabasic Rocks and their Genetic Significance. Walter de Gruyter, Berlin, 1979.

The petrofabric analysis has often led to conclusions contrary to the orthodox views. In particular the application of detailed microscopic studies in controversial subjects, such as those of granites, basalts and ultrabasic rocks, have revealed and emphasised aspects which have been either overlooked or ignored in the past.

Admittedly the author's petrofabric analysis has often rather enhanced the controversy instead of solving it. Many positive and negative critiques have been published concerning the author's studies on these controversial subjects.

In contrast the present Atlas aims to present, and petrofabrically analyse, sphaeroidal forms in rocks of diverse origin. The list of contents of the Atlas indicates the wide diversity of textural patterns and rocks studied.

Nevertheless, the textures presented represent only a small fraction of the sphaeroidal forms present in the outer part of the earth's sphere. Therefore, the Atlas is only an introduction to the subject, and often only a restricted number of examples are presented of types that could have been treated with extensive monographs.

In contrast certain sphaeroidal forms, e.g. ooids in bauxites, have been extensively treated, where many small variations of forms and types have been recorded. Such detailed presentations were necessary to serve mainly as a model of detailed petrofabric analysis of some selected textural patterns.

Certain chapters of the present Atlas are based on and developed from research work published by the author in a preliminary form in the early Sixties, e.g. oolites and pisolites in laterites and their diagenetic changes, Augustithis (1962). Other sections of the Atlas have been preliminarily mentioned in earlier publications, e.g. rapakivi textures and orbicular structures in granites (see Augustithis 1973). Those studies on sphaeroidal weathering forms were started in the middle Sixties and have been continued since then.

The author feels obliged to mention that he gained valuable experience of the ore-microscopic study of gel-structures as research worker under Prof. P. Ramdohr at Heidelberg in the middle Fifties. Initial studies on the gel-structures of pitchblende were published in 1964.

However, it is mainly due to the election of the author to the council of ICSOBA (International Committee for the Study of Bauxites, Alumina and Aluminum) in 1977 and a year later, due to his election as president of ICSOBA, that the author has been exposed to vast information and had the access and the possibility to acquire material and to visit many occurrences. It is during this period that an intensified and systematic study of the subject has started. Therefore, the author is most indebted to ICSOBA and its members for their help and cooperation, and to the Yugoslav Academy of Sciences and Arts which sponsors ICSOBA.

Furthermore, material and help was given to the author by many other colleagues who are acknowledged and mentioned in the specific sections of the Atlas.

In conclusion, the author feels that sphaeroidal forms are not only fascinating and impressive* but delicate forms and shapes which would easily record changes or are products of changes themselves. On the other hand one should not disregard the great economic significance of such materials, e.g. bauxites, phosphorites, iron-oolites, manganese nodules, etc. in man's efforts to secure mineral resources.

S.S. Augustithis
Athens
August the 27th, 1981

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Fig. 213, by P. Ramdohr in "Handbuch der Mikroskopie in der Tecknik, Band II, Teil 2 (1954)', published by Umschau Verlag.
Fig. 253, 254, 255, 256 by J. Elliston in "Syntaphral Tectonics and Diagenesis, (1963)", published by the University of Tasmania.
Figs. 310 and 312 by A. Papadakis and G.C. Amstutz in "Rogenpyrite in recent beach sands of Loutra, Eleftheron, Greece, (1980)", published by E. Schweizerbart'sche, Verlagsbuchhandlung, Stuttgart.
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Furthermore, the author is indebted to Mr. N.A. Avgustides for accompaning him to the Karroo trip, South Africa.
The cover-picture showing a "Cannon ball" bauxite sphaeroid is courtesy of Dr. G. D. Coumoulos, Bauxite Parnasse Mining Co, Greece.

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* The author still remembers the "cannon-ball magnesian limestone" in County Durham as a first year Geology student, and the fascinating explanation of its origin by Sir Kingsley Dunham, in the year 1950.

Contents

Chapter 1 Sphaeroidal Structures

Introduction

Macro- and micro-sphaeroidal structures are common in rocks of different genesis, either as products of contemporaneous formation or as products of the multiple changes and influences during the developmental history of a rock. Other sphaeroidal structures are produced by the disintegration of rocks and could represent stages in the processes of their complete breakdown.

As the processes of rock formation are multiple and greatly variable, the sphaeroidal structures, contemporaneous to their formation, are directly interconnected with these rock forming prosesses. During the crystallisation or consolidation of melts micro- and macro-sphaeroids are produced, often reflecting special conditions of component crystallisation or solidification. Other synchronous sphaeroidal textures and structures are syngenetic, particularly in the case of the sedimentogenic rocks, often reflecting special conditions of deposition, solution precipitation, flocculation, rhythmic deposition and precipitation, coagulation, agglutination, etc.

A wide spectrum of syngenetic sedimentary textures and structures of oolites, pisolites, sphaericules, nodules and, in general, sphaeroidal structures may result in the complex processes connected with sedimentation.

In contradistinction to the primary sedimentogenic textures and structures diagenetic and post diagenetic processes may result in the modification or formation of sphaeroids in general. Resorption, partial solution, recrystallisation, replacement, segregation and regeneration textures are common. Processes involving ionic exchange, substitution and, in general, disturbances in the energy equilibrium of the crystal lattice may result in textural changes under diagenetic and post diagenetic conditions.

Despite relatively low temperatures, the role of intergranular solutions, the penetration and solution capacity of intracrystalline solutions is effective and may result in pronounced changes.

Concretions and nodule-forming processes involve solution circulation, increased solubility in the intergranular solutions and, in general, element segregation processes. In the rocks' transformation the boundary between diagenesis and low temperature metamorphism is becoming increasingly uncertain. Within this "boundary field" diagenesis-low grade metamorphism recrystallisation, replacement and low temperature crystalloblastesis may take place affecting the micro- and macro-sphaeroidal structures of initially sedimentary origin.

Furthermore, with increasing influence of the metamorphic metasomatic processes, in the field of ultra-metamorphism due to transformation of pre-existing initially sedimentogenic materials (or due to the blastogenic growth of new ones), metamorphic-metasomatic sphaeroidal structures such as the orbicular and rapakivi structures may be produced.

In the spiral of rock-changes, weathering is an integral part of the unfolding of the spiral (Augustithis 1972/73, 1978). Consequently differential leaching and mobilization of elements, as well as the diffusion-rings and sphaeroids, are processes and structures which belong to chemical weathering and as such are a part of the "geological cycle".

The sphaeroidal weathering-forms are consequently developments in the evolution of rock transformation and should not be treated separately to rock forming processes, Pieruccini (1962). In other words weathering sphaeroids are low temperature rock transformations.

Within the weathering processes, particularly in the case of lateritisation or lateritisation-bauxitisation, pisolitic and nodular structures may be formed involving differential leaching and element mobility.

On the other hand accretions of related elements under lateral segregation may result in nugget and nodule formation. Such processes are particularly effective in lateritic covers or in placers and as a result platinum and gold accretions may be formed.

Despite the fact that sphaeroidal forms (structures) are common and occur in rocks of diverse origin and despite the fact that we have an extensive knowledge of the mechanism involved, the logic of the sphaeroidal forms in rocks seems to me to be problematic.

a. Are the sphaeroidal forms in rocks the result of the mechanism of processes involved in their formation?

b. Is the sphaeroidal form attained because of the inherent properties of the sphere in general, i.e. maximum volume with minimum surface, structural stability of sphaeroidal forms, etc.?

c. Is the logic of a central "initiation" point of growth, out of which growth takes place with equal ease and speed in all directions, a satisfactory explanation?

d. What is the logic of textural patterns in rocks in general and what is the logic of sphaeroidal forms (structures) specifically?

e. What is the significance and participation of organic matter in the formation of ooids and sphaeroids in general?

f. How far can we explain ooids and sphaeroidal structures as a direct function of colloidal precipitations?

Chapter 2 Oolitic Structures

General

Oolitic structures occur in rocks of different geological age. The nature of the oolites and their texture depends on the degree of syngenetic-diagenetic reactions, such as the preservation of initial biogenic material and structures and on the transformation of aragonite → calcite. On the other hand the degree of their preservation as such structures depends on the diagenetic processes which have affected them and also on the possible interference of metamorphic changes.

Regarding the formation of oolites Correns (1949) gives a vivid picture in his text book "Einführung in die Mineralogie".

> Auf die Ooidbildung wurde bereits bei den Eisenerzen hingewiesen. Noch häufiger als diese sind Kalkoolithe. Sie bilden sich in lebhaft bewegtem Wasser, das an Kalk übersättigt ist, an kleinen, manchmal nicht mehr feststellbaren Keimen als konzentrisch schalige Kalkkügelchen. Auch hier können Algen mitwirken, die von ihnen erzeugten "Ooide" sind aber nicht regelmäßig konzentrisch gebaut. Makroskopisch den "echten" Ooiden sehr ähnlich und grundsätzlich von gleicher Entstehungsart sind die "Pseudo-Ooide", bei denen noch erkennbare kleine Gesteinsbrocken von meist dünnen Krusten umkleidet sind.

This textbook concept of oolite formation has governed our thinking for decades, however, doubts have been expressed regarding the simplified conditions as outlined by Correns for the formation of all types and structures of the oolites.

In contrast to the mechanism outlined by Correns is the formation of the aragonite oolites-pisolites of the famous Karlsbad springs in Karlovy Vary, Czechoslovakia, where impressive oolites-pisolites are formed as hot springs precipitations, also see Figs. 16-22, Chapter 3 and their explanation. Perhaps one of the most significant contributions on the physico-chemical (inorganic) explanation of oolite formation, is, in addition to the work of Linck (1903), the contribution of Bucher (1918). Bucher quoting H. Schade states the following, "H. Schade, in 1909 and in 1910, in his papers on the origin of urinary calculi and on the formation of concrements, in these he demonstrated experimentally that concretionary bodies form when a substance passes from the state of an emulsion colloid (or "emulsoid") to that of a solid, and that if the change leads to the crystalline state the resulting structures is radial if the substance is pure; if however, other substances, colloid or crystalloid, are precipitated along with it a concentric structure is developed."

It is interesting that Bucher applies the same explanation for the oolitic, concretionary and sphaerolitic sedimentary geological structures: "That these principles underlie the formation of most, if not all, sedimentary oolites, sphaerolites and concretions is rendered probable by the fact that almost all substances which are known in one of these forms are also known in the others and are the same that are known to occur extensively in nature in the colloid state*."

In addition Bucher explains as colloidal coagulations the siliceous concretions, the iron and manganese hydroxides oolites and sphaeroids, and the phosphate and baryte oolites and sphaeroids.

Furthermore, the conclusion of Bucher namely, "This brief survey justifies the assumption that most, if not all †, oolitic and sphaerolitic grains were formed by at least one constituent substance changing from the emulsoid state to that of a solid; that the sphaerical shape of the grains is due to the tendency of the droplets forming during this process to separate to coalesce; and that the difference between radial and concentric structure depends on the amount of other substance thrown out simultaneously with and mechanically enmeshed in the growing structure", is indeed fundamental in interpreting a wide spectrum of ooids and sphaeroids.

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* In the present Atlas, particularly in the Chapters 15 and 16, the significance of the coagulations of colloids in the formation of sphaeroids in rocks of diverse origin is discussed.

† However, the detailed consideration and study of the phenomenology of the oolitic and sphaeroidal structures, each case on its merit, seems necessary and is a fundamental principle followed in the present treatment of the subject.

Comparable concepts about oolite formation also are advanced by Ottemann and Kirchmayer (1967): Dieser verfestigt sich im Verlaufe der Überlagerung durch neues Material u. a. unter Auspressung des Porenwassers und der Ausscheidung der im Porenwasser gelösten Stoffe zu einem festen Gestein, dem Sedimentgestein. Dieser Verfestigungsprozeß heißt Diagenese; er läßt sich auch auf Sinterbildungen anwenden, zu denen ebenfalls die Ooide gehören. In unserem Falle werden diagenetische Veränderungen eines einzelnen Ooides im Zeitraum von ca. 100 Jahren behandelt. Die in der Folge mitgeteilten Beobachtungen beziehen sich auf das Frühstadium der sog. Diagenese. Ooide sind eiähnliche Körperchen, zusammengesetzt aus einem älteren Kern und einer jüngeren Schale. Der Kern, bzw. das Ooid wird kinematisch im Wasser bewegt, bzw. aufgewirbelt, dient dabei als Kristallisationskern von gelöstem Material im umspülenden Wasser, welches sich schalenförmig ablagert. Konkretionen, die nicht Kern und Schale verschiedenen Alters besitzen, gehören nicht zu den Ooiden. Im Verlaufe einer gewissen Zeit können Umlagerungen oder Rekristallisationen der Minerale mit oder ohne Zufuhr neuer Elemente stattfinden. Dieser Prozeß ist ein Teil der Diagenese (genesis [gr] = Entstehung, Erzeugung). Ihr Ablauf kann in Einzelakte aufgelöst werden. Diese diagenetischen Einzeleffekte weisen auf Ursachen hin und können nach SANDER zeitlich dreigeteilt werden: früh-, mittel- und spät-diagenetisch. An die Diagenese anschließende Vorgänge heißen post-diagenetisch (post [lat.] = nach). Die meist nach geraumer geologischer Zeit an die Diagenese anschließenden Veränderungen eines festen Sedimentgesteins unter erhöhten Druck- und Temperaturbedingungen, mit oder ohne Einbau von neuen Elementen, werden als Metamorphose bezeichnet.

However, Ottemann and Kirchmayer relate the oolite formation to diagenetic processes and sinter formation. The formation of oolitic structures could involve more complex processes such as biogenic influences, coagulation, flocculation, etc. Particularly, microprobe studies by Ottemann and Kirchmayer (1966) on ooids from the great Salt Lake showed that early diagenetic processes are a contributing factor in the formation of ooids.

Of particular genetical importance is the formation of "Höhlenperlen" in caves and mine galleries as is vividly described by Ottemann and Kirchmayer (1967): In Bergwerken und Höhlen ist an vielen Stellen eine allgemeine Sinter- oder Tropfsteinbildung zu beobachten, die sich von der Höhlenperlenbildung nur mechanisch, nicht aber chemisch unterscheidet. Bei der gewöhnlichen Sinterbildung lagert sich die $CaCO_3$- Ausscheidung schalenförmig auf die zufällige Unterlage. Bei der Höhlenperlenbildung schwemmen die herabfallenden Tropfen an der Auffallstelle beim Aushöhlen die feinen Sedimentteile des Bodens weg, so daß in den Eindellungen kleine Gesteinsbruchstücke zurückbleiben, die durch die Wasserbewegung nicht flächenhaft versintern können, sondern kugelförmig von Sinter umgeben werden und somit zur Höhlenperlenbildung führen.

Comparing the proposed mechanism of oolite formation by Correns with the mechanism proposed by Ottemann and Kirchmayer for the "Höhlenperlen" it can be seen that convergence of phenomenology can be produced in nature by the operation of diverse processes.

Most significant changes of the oolites can be followed by studying oolites at different phases of their evolutionary history.

Studies of recent aragonitic oolites by Shearman et al. (1970) from the Trucial Coast, Persian Gulf, show a concentric structure in which layers of organic mucilage with shells composed of aragonite are set in a mucilaginous base.

The contribution of organic material* in the composition of oolites is also supported by the studies of Trichet (1968), which showed that the organic fraction of oolites, from the oolitic limestone north of Cruzille, near Tournus, is qualitatively and quantitively similar to that composing the membrane of blue alga (anacystis nidulans).

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* The early explanation of oolite growth emphasized the association of algae and oolites. Rothfletz (1892), on the basis of the association of oolites and algae, concluded that oolites are "indubitably the product of lime secreting-fission algae." In accordance to the organogenic origin of oolites Wethered (1890) regarded the "wermiform" branching calcareous algal threads as the essential building material of ooids. In addition Dangeard (1936), using special techniques, revealed a residue of organic matter that is associated with oolites, and emphatically excluded physico-chemical theories as a possible explanation of oolitic growth.

Furthermore, Bathurst (1976) pointed out that "as a rule ooids recent and ancient when dissected with weak hydrochloric or other suitable acid do show an organic residue which mimics closely the concentric fabric of the ooid." As a corollary to the significance of organic matter in the formation of oolites Bathurst quotes Mitterer's discovery "that the proteins in ooids are closely akin to those in carbonate secreting organisms". Also quoted is the growth of denitrifying bacteria by Drew (1914), which produced a precipitate of aragonite needles and a laminated concretion with nucleus.

In contradistinction to these oolites with biogenic material, studies of ooids by Halley (1977), from the Great Salt Lake, Utah, show that the ooids consist of a nucleus grain coated by a cortex of concentric layers of aragonite with minor impurities*. Most of the aragonite grains in the cortex are elongated parallel to their c-axis and they may be radially, tangentially and randomly orientated with respect to the ooid surface.

Scanning electron microscopic and electron diffraction studies by Loreau (1970) on the concentric layer building up an ooid showed that the cryptocrystalline layers have an ultrastructure of subsphaerical nanograins which are usually polycrystalline and without preferred orientation. In contrast clear layers which alternate with the cryptocrystalline are formed of monocrystalline aragonite in which the c-axis is parallel to the length of the crystals, which have a tangential orientation.

In contrast to the hypothesis that the inital composition of the layers building up the ooids are always aragonitic in composition, scanning electron microscopic studies by Loreau (1969) on the cortical envelope surrounding the minerals or organic core in old ooliths showed that it is composed of calcareous particles. The calcareous particles are of the order of 1μ and sometimes show geometrical form, sometimes are grains with or without orientation, but are never fibres, so that it seems there is no correspondence with former needles of aragonite.

The transformation of aragonite to calcite is a process of fundamental importance for the understanding of the genesis, derivation and transformations in the calcareous oolites.

The transformation aragonite → calcite is of petrogenetic significance since, as studies of recently formed ooids show, aragonite might represent the initial phase of the layer formation of calcareous ooids.

As a corollary to the initial aragonitic composition of the oolitic layers, are the investigations of Oppenheimer (1961) which showed that "the addition of washings from an oolitic sample from Bahana Bank to filtered sea water from the Gulf of Mexico together with small amounts of $NaNO_3$ and $Na\ H(CO_3)_2$ giving a pH of 8.3 gave after 1-12 months a small precipitation of crystalline aragonite."

Furthermore, experimental studies by Dandurand (1970) showed that on pulverising pure calcite, aragonite appears and respectively calcite if aragonite is pulverised. In addition McLester et al. (1970) showed the effects of alkaline earth metal ions on the transformation of aragonite to calcite in aqueous solution.

Despite the fact that both the above mentioned experimental conditions do not correspond exactly to natural conditions in nature it is believed that the transformation aragonite → calcite takes place diagenetically at relatively low temperatures.

The transformation of aragonite to calcite is experimentally achieved, Dusgupta (1964) "if aragonite is heated to 400°C for 3 hours, X-ray single crystal investigations of the transformation of aragonite to calcite show that the (100), (110) and (001) directions in aragonite become respectively $(10\bar{1}0)$, $(01\bar{1}0)$ and $(000\bar{1})$ in the calcite. The transformation also involves the re-orientation of the CO_3 group about aragonite (001) through 30°, different rows of CO_2 being turned in opposite directions. The layers of Ca ions are shifted along the basal plane so that the arrangement perpendicular to (0001) in calcite becomes ABCABCA – instead of ABABABA – as in the aragonite."

As the crystallographical studies of Dusgupta show the transformation involves pronounced rearrangements in the crystal lattice which take place at the relatively high temperature of 400°C. The question is whether and how such transformations take place at lower temperatures under diagenesis.

In addition to the transformation aragonite → calcite, diagenetic changes may result in complex textural modification of the oolites. The diagenetic changes in calcareous oolites involve complex processes. Gurova (1962) describes the development of diekite, kaolinite and podolite in cavities of carbonaceous oolites as a result of migration of solutions after the diagenesis stage. Instances of selective solubility of oolitic layers are described by Carozzi (1963) in which case "ooliths in the Upper Cambrian Allentown Dolomite of New Jersey originally contained concentric layers of sulphate minerals. Selective solution of these prior to dolomitisation caused the residual insoluble layers within the ooliths to develop characteristic collapse structures."

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* The organic content of the Great Salt Lake oolites is 0.54% according to chemical analyses by Eardly (1938).

Chapter 3 On the Phenomenology of Oolitic Textures (Structures)

Growth of oolites – general

Most of the limestone oolites observed could be explained in accordance to Correns' interpretation of calcareous oolites, in which case aragonite layers are deposited around a nucleus of clastic grains or microfossils under "kinematic" movement of sea water supersaturated with $CaCO_3$.

Considering the growth of oolites, experimental studies by Weyl (1964) have shown that if nuclei (above colloidal size) are present precipitation can take place. Nucleation can be heterogeneous, in the sense that calcite nuclei can be surrounded by aragonitic layers and vice versa. In addition Weyl concluded that the growth* of ooids follows a cycle. The growth passes through a stage of rapid precipitation, then follows a stage when the "overgrowth is increasingly soluble" and precipitation becomes slower and finally follows the resting stage when the ooid is buried. Ball (1967) considers as a critical requirement the burial of the oolite. Repetition of the above cycle is common in the evolutionary history of an ooid. In this connection it should be emphasised that Cayeux already in 1935 had stated that growth necessarily occurs while the ooids are suspended in the solution.

Phenomenology of oolites

Fig. 1 shows a microfossil nucleus surrounded by layers of $CaCO_3$ in a fine crystalline calcitic matrix. The shape of oolitic structures can show most complex forms and this can be due to resorption phenomena. Fig. 2 shows a calcareous oolite containing a microfossil as nucleus and exhibiting complex outline, which is conditioned by the effects of resorption. Similarly Fig. 3 shows complex forms of calcareous oolites which are due to resorption and recrystallisation phenomena. Veinlets of "recrystallised" calcite transverse the oolitic structure.

In contradistinction to the microfossiliferous nuclei Figs. 4 and 5 show calcareous nucleus (most probably a limestone fragment*) surrounded by a number of $CaCO_3$ layers. In both cases (see Figs. 1 and 4) the oolitic structures are symmetric in respect to the central nucleus around which layer deposition occurred.

Often asymmetric oolites, in respect to the central nucleus or central layer, are observed which could indicate anomalies (i.e. deviations from the schematic concept of Correns for the oolite formation) in the layer deposition (see Fig. 6).

More problematic cases are observed on diagenetically affected recrystallised oolites. Fig. 7 shows a green chlorite nucleus irregular in shape (actually consisting of fine chlorite aggregates) surrounded by layers of $CaCO_3$, resulting in an irregular and asymmetrical ooidal structure, in a recrystallised calcitic matrix.

The complexity of oolite formation is exhibited in Fig. 8 in which case a fragment of a layered oolite acts as nucleus of a second generation of oolite, which in turn is in a recrystallised diagenetically calcitic matrix. As a corollary to the hypothesis of reworked oolitic structures (i.e. two generations of oolite formation) Figs. 9, 10 and 11 show ooids included in a second generation oolitic structure.

Such twinned ooids have been studied by Carozzi (1960) and are referred to as "compound reworked ooids with two nuclei". A typical example of reworked oolitic material is illustrated in Fig. 11 which shows a fragment of oolite generation I forming the nucleus

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* In this connection it should be mentioned that Carozzi (1960) has pointed out that when an ooid has reached a critical size it cannot be moved by local currents and thus it stops growing. In contradistinction to accepted sizes of ooid growth, Fig. 13 shows ooids about 5 mm. in size. Also of importance as a delimiting factor of the size attainable by ooids is the abrasion that the ooids inflict on one another. Fig. 33 shows abrasion effects on large ooids, which result in the "destruction" of their outer layers.

* The presence of calcite-diffuse mass, which appears as fragment in the central part of the oolites could represent replacement of aragonite by calcite.

The diagenetic transformation of aragonite → calcite, could be a function of time, in consequence of which the transformation starts from the oldest central part.

for the growth of oolite generation II. Ooids very difficult to explain (with calcareous nuclei) are illustrated in Fig. 12, in which case two different and separate ooids are interconnected and share a common outer layer, which extends across and forms a bridge between the separated ooids. The structure is included in diagenetically recrystallised matrix. Indeed such textural patterns are difficult to interpret with the classic concept of oolite formation (see Correns (1949)). Resorption of complex oolitic pattern could perhaps be suggested.

In contrast to the autochthonous oolitic types described, Usdowski (1962) has proposed a partly allochthonous genesis for the case of oolitic calcareous sandstone (oolitische kalksandsteine), in which case the oolitic sphaeroids are in matrix consisting of quartz-feldspar-calcite with argilaceous materials.

The oolitic calcareous sandstones are genetically explained by Usdowski as "having been formed in situ, i.e. autochthonous, however a part of the oolites is transported and deposited with clastic materials."

> Die Hauptmasse der Ooide wird am Ort ihrer Entstehung abgelagert. Ein Teil von ihnen wird jedoch durch Strömungen transportiert. Mit zunehmender Entfernung vom Entstehungsort findet eine zunehmende Transportbeanspruchung der Ooide statt. Hierdurch erfahren sie eine Kornverkleinerung, werden teilweise oder ganz zerstört und zusammen mit klastischem Material vorwiegend psammitischer Korngröße abgelagert.

Present microscopical observations, in accordance with the excellent studies by Usdowski, show layered oolitic sphaeroids in quartz-feldspar-calcite (also clay minerals are present) matrix, see Fig. 13. The oolitic sphaeroids illustrated are more or less intact and do not contain conspicuous groundmass components. As arrow "a" Fig. 13 shows, radiating fibres "Fasern" of calcite, orientated in accordance to the c-axis of the calcite, cut across the layers of the oolitic sphaeroid. This radiating pattern of fibres is due to diagenetic recrystallisation of $CaCO_3$ and most probably indicates a replacement of calcite after the initial aragonite which built the layers of the sphaeroid.

In contradistinction to the intact oolitic sphaeroids others show attrition phenomena due to their transportation and support an allochthonous derivation, however the same ooids include as nucleus a clastic quartz grain (see Fig. 14). Fig. 14 shows that there is an intergrowth of two ooids, such phenomena are described by Usdowski as "Drucksutur" ("suture-line") caused by the pressing together of two ooids.

Most impressive "compound reworked ooids with two or more nuclei" are common in the case of oolites in calcarous sandstone, and similarly oolitic sphaeroids with a nucleus consisting of an oolitic fragment (i.e. oolites of two generations). These observations are again in accordance with the excellent illustrations by Usdowski.

Additional observations indicating the complexity of oolitic forms are illustrated in Fig. 15. A coalescence of oolites can result in the formation of a sphaerical ooid corresponding to the "Ooidvielling" of Usdowski and resembling the "Walzenooid" of the same author.

Some of the most impressive oolitic-pisolitic sphaeroids are those formed from thermal waters and which consist of radially orientated fibrous aragonite, surrounding nuclei which could be of variable mineralogical composition, e.g. quartz grain, sericitised mass, aragonite, calcite, feldspars or combinations of these.

Such aragonite pisolites are described by Lacroix (1922) from the massif of Itasy (Madagascar) and they have been termed as ktypéite.

Present microscopic observations show aragonite pisolites in a binding aragonitic-calcitic matrix. Due to the radial orientation of the aragonite fine fibres in respect to the aragonite layering, "extinction-crosses" appear when these aragonite pisolites are examined under crossed nicols (cross polarized light), see Fig. 16.

Figs. 17 and 18 show pisolitic sphaeroid including a feldspar/quartz intergrowth greatly sericitised. Fig. 19 shows layered aragonite-pisolite consisting of fine fibrous radially arranged aragonite. The nucleus consists of quartz and feldspar grains, it is dubious whether they are of detrital origin.

Similarly Fig. 20 shows aragonite pisolite with a rounded nucleus of aragonite which in turn consists of radially arranged fibres. As mentioned, the nuclei of the pisolites may consist of calcite. Fig. 21 shows an aragonite pisolite with rounded calcite nucleus surrounded by a "diffuse" aggregate of calcite, and followed by rhythmic layers of aragonite.

The complexity in the formation of the layered aragonite pisolites is illustrated in Fig. 22. Two generation sphaeroids exist, the first has as a nucleus a rounded quartz grain. Sphaeroid generation I and additional quartz grains act as nucleus for the formation of sphaeroid II.

As the above observations show the aragonite-pisolites formed under thermal water deposition exhibit complex textural patterns which involve multiple phases of formation and variation in the supply of material.

Chapter 4 Diagenesis of Oolites

The relation of diagenesis and oolite formation is emphasised by Ottemann and Kirchmayer (1967) as can be seen by the following quotation:

"The consolidation of the sediments through accumulation of additional sediments and by pressing out the water of the pore spaces and the precipitation of the solved substances from the pore water, results in the consolidation of the sediments into a hard rock. The consolidation process is referred to as diagenesis and is applied to the sinterformation which the ooids formation also belongs to."

Sander (1930) recognises "Früh, mittel" and "spätdiagenesis". In contrast to these rather general concepts regarding diagenesis and in reference to the case of oolite calcareous sandstone and to "Rogensteine", Usdowski (1962) recognises as diagenetic changes, crack formation, pressure-sutures, "Sammelkristallisation" and allochemical changes in sediments. Despite the fact that these diagenetic changes occur as late as post diagenetic changes, nevertheless they are an integral part of diagenesis and conspicuous changes can take place.

Fig. 23 illustrates ooids affected by a microfault system which transverses several ooids. Often recrystallisation of the limestone takes place also. The maintainance of ooids in calcareous limestones is also a function of the genesis of the oolites. Halley (1977), in discussing the ooid fabric and fracture in the Great Salt Lake, states the following: "Ooids with radial fabric are characteristic of hypersaline and of fresh water environments, and are weaker than ooids having tangential or random fabrics. Consequently broken ooids are more than 100 times as abundant in Great Salt Lake ooilite sands as in normal marine oolites. It follows than more than 1% broken ooids in the oolite should be considered an indication of unusual salinity."

In contradistinction to the fractured ooids, in which case the fracturing is due to microfaulting or microcracks, Fig. 24 shows ooidal fracturing not interconnected with microfractures. In addition to the fracturing of the oolites, collapse structures are described by Carozzi (1963):

"Ooliths within the upper Cambrian Allentown Dolomite of New Jersey originally contained concentric layers of sulphate minerals. Selective solution of these prior to dolomitization causes the residual insoluble layers within the ooliths to develop characteristic collapse structures."

In addition to the fracturing of the ooids due to microfissures, calcite recrystallisation resulting in a veinform calcite following a fracture system of an ooid often takes place, see Fig. 25. Despite the fact that the recrystallised calcite is transversing the ooid in a veinform manner, some selective replacement of the "oolite layers" is indicated.

Some of the most conspicuous diagenetic changes are phenomena interconnected with calcite recrystallisation. Fig. 26 shows recrystallisation of the calcitic matrix in which the oolites are embedded. The recrystallised calcite has also affected the outer layer of the ooid. In contradistinction recrystallised calcite has been formed by changes of the matrix and of the central part of an ooidal structure, in cases some selective replacement of the layers of the ooid has taken place, see Fig. 27.

In contrast most impressive "Sammelkristallisation" cases are described by Usdowski (1962). According to him "Sie vollzieht sich derart, dass auf Grund der Porositätsunterschiede die Matrix einer Probe quantitativ umkristallisiert, während die Anzahl der umkristallisierten Ooide, deren Fasertextur hierbei völlig zerstört wird stets gering ist."

In contrast to the described case of "Sammelkristallisation" by Usdowski, present observations show the recrystallisation of the outer layer of an ooid, whereas the central part remains unaffected, see Fig. 28. Similarly recrystallisation of the outer calcitic layers of an ooid has taken place (Fig. 29) – only the central nucleus is unaffected. The recrystallisation of the ooidal structure is comparable to and commensurable with the "Sammelkristallisation" of the ooid described by Usdowski and in this case a granular calcite recrystallisation of the greatest part of an ooid has taken place with the loss of layering and fibrous structure.

An additional case of diagenetic changes is exhibited in Fig. 30 where a zone of an oolite is recrystal-