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Concretion morphologies reflecting diagenetic and epigenetic pathways

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Dedicated to the memory of the sedimentologist Sukomal K. Chanda (1934–1998)

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Abstract

Due to complex physicochemical processes, concretions develop variable, but distinctive morphologies. Reflecting the state of the sediment in subsequent stages of diagenesis and epigenesis, they deserve a study and systematization in their own right. At the same time, concretional morphologies illustrate the effect of hierarchic self-organization, which is a basic element also in biological evolution. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Concretions are homeless objects. Paleontologists reject them as pseudofossils or *lusus naturae*. Geochemists use them as a source of data, but are less interested in their morphologies (for an exception, see Sellés-Martínez, 1996). Yet, it is the variety of odd shapes that fascinates all of us when we take concretions home and deposit them, unlabeled, as conversation pieces on the book shelf.

The present paper tries to analyze and order concretionary shapes in terms of morphodynamics (Seilacher, 1991). This means that, in the tradition of biomorphology, emphasis is laid on morphogenetic processes rather than mineralogical composition. In other words, even if bacterial activity may be involved in some cases (e.g. Coleman and Raiswell, 1995), concretionary morphology can be viewed as *disparity without genomic control.*

2. Dendritic versus 'pneu' morphologies

The distribution and precipitation of dissolved constituents, such as iron and manganese, proceeds in two radically different morphospaces, which are typified by dendrites on the one hand and Liesegang Rings on the other. Both can be observed as epigenetic features on bed surfaces of the lithographic limestones of the Solnhofen area (U. Jurassic, Germany), but while dendrites are restricted to bedding planes, the Liesegang rings continue inside the limestone beds.

The moss-like shapes of *dendrites* (Fig. 1) vex any student before he, or she, is told that these are no fossils and therefore not worth collecting. I disagree. Beyond their aesthetic appeal (for which the two figured specimens decorate our home), dendrites are

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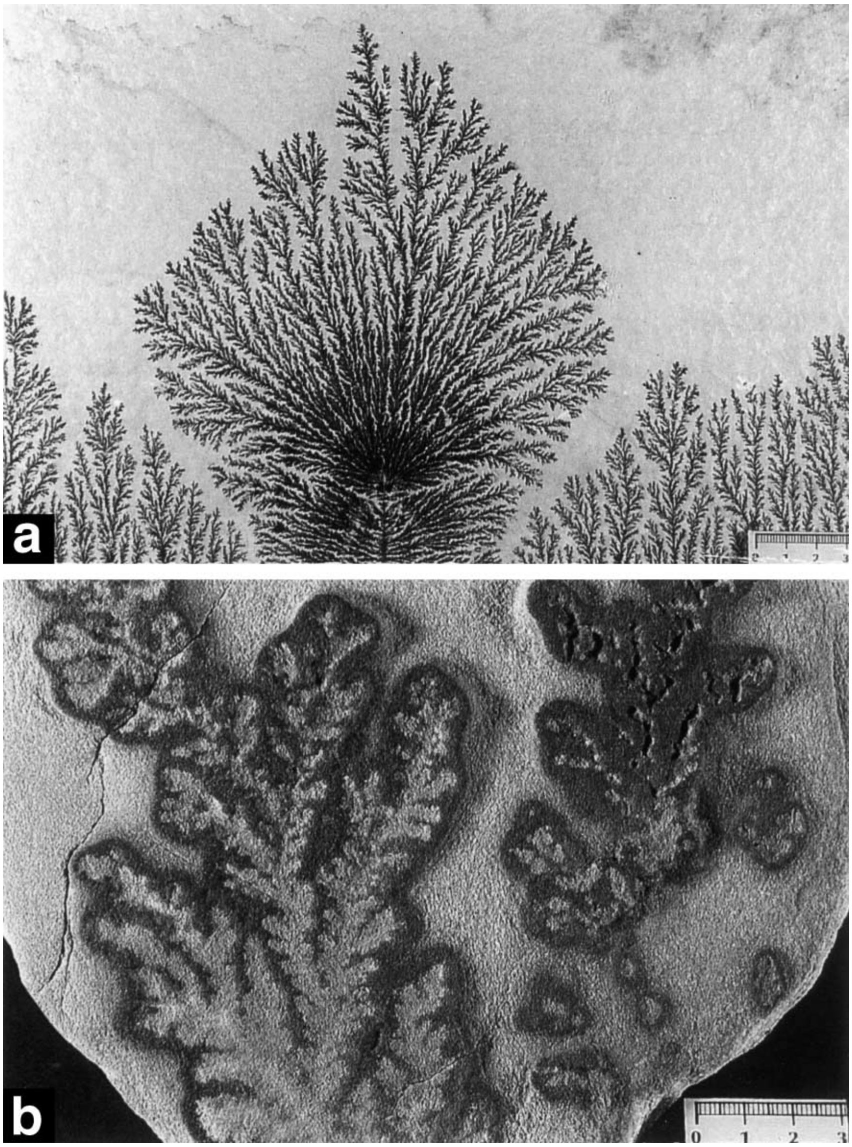


Fig. 1. *Dendrites* are epigenetic in origin. They reflect an advancing front, in which solutions of iron or manganese were fed from the growth center and coalescence of growing tips was impeded by depletion of oxygen. Dendrites on bedding planes of Solnhofen limestones ((a) Upper Jurassic, Germany) show more levels of fractal self-similarity than the ones in Petra sandstones ((b) L. Cambrian, Jordan), which were secondarily contoured by a sideritic halo. Note discordance between branches along the stem and those of the radiating top in the Solnhofen 'tree'.

a perfect example of *fractal self-organization*. Their outstanding property is self-similarity: identical patterns repeat at different scales. Yet, fractality only describes dendrite shapes and says nothing about the underlying morphogenetic process. In the present case, the key phenomenon is distancing; i.e. the protruding tips always stop short before colliding with another element and at larger distances in higher orders. In chondritid burrow systems (Fig. 2), such behavior reflects a sensory reaction (phobotaxis); but what controls it in a purely physicochemical system? One might think about ionic charges that

Fig. 2. The dendritic pattern of the trace fossil *Chondrites* is controlled by behavior (probing and phobotaxis).

prohibit the merging of tips; but in precipitation processes depletion of the surrounding area is the more likely reason. In the Solnhofen dendrites, the dissolved metals (iron or manganese) came from the joints and oxygen from the surroundings (for a model, see Halsey, 2000). In this view, depletion may act like in the backward erosion of river systems: it stops when supply areas between branches get too small.

Liesegang Rings, in contrast (Fig. 3), are evenly vaulted. Only where they cross a joint in the rock do the concentric color bands become offset as in a tectonic fault. Again, there are counterparts in the organic world. Because of the similarity to an inflated rubber balloon we talk about the 'pneu morphospace', in which an elastic membrane with a pressure difference on the two sides is the crucial morphogenetic element. But how can this model be applied to a chemical front advancing through a granular sediment? In some way, the front behaves as a membrane that attracts the metals from the surroundings and may be compared to *Pfeffer Cells* (Pfeffer, 1877), in which a semipermeable membrane forms at the interface between two solutions and grows into succulent plant morphologies by osmosis. The difference in Liesegang Rings is that former positions of the membrane are recorded by rhythmic precipitation.

However different these two morphospaces may appear, pneu elements in dendrite patterns suggest that they represent end members of an identical

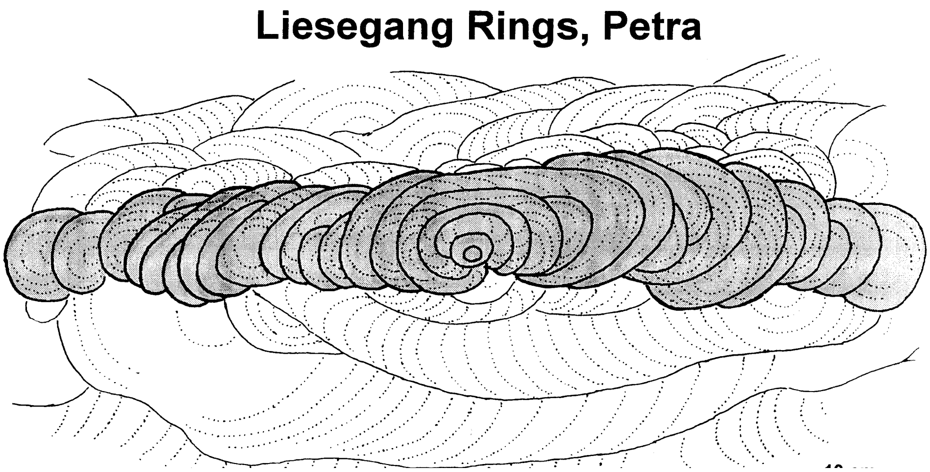


Fig. 3. The *Liesegang Rings* in Petra sandstones (L. Cambrian, Jordan) are epigenetic features. Still, vertical sections show a similar pancake configuration around a nucleation center as in early diagenetic mummy concretions (Fig. 7); but note that the thickness of these pancakes increases away from the center and that there is no top/bottom symmetry.

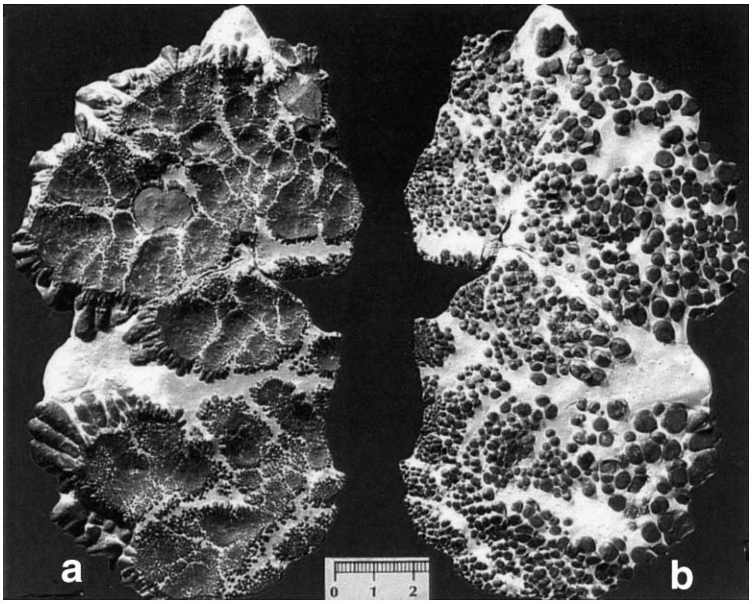


Fig. 4. In a Silurian shale of Libya, the overgrowth of epigenetic siderite concretions an underlying sandstone (molds seen in (a) followed an incipient dendritic pattern (specimen found by H. Luginsland, Geol. Institut Tübingen).

process. In the Solnhofen dendrites (Fig. 1(a)) we must zoom to the smallest elements before shapes become succulent. In contrast, dendrites on the bedding planes of Petra Sandstones (Fig. 1(b)) show iron-stained bulbous tips at a macroscopic scale. A second pneu-like feature is seen in dense thickets of Solnhofen dendrites. Not only do their canopies describe roundish surfaces, but concentric growth zones can also be recognized within them.

3. Ovoid calcareous concretions

Liesegang Rings serve as stepping stones to understanding the 3-dimensional morphologies of real concretions. While dendritic concretions are a rare exception (Fig. 4), globular or ovoidal morphologies are the rule (Coleman and Raiswell, 1995) and occur commonly. They may consist of various minerals, including calcite, siderite and silica and may be syngenetic (ooids), diagenetic (calcareous concretions), or epigenetic in origin (most siderite concretions). Geometries reflect the former permeability of the host sediment. In isotropic sediments, such as sand and fresh mud, the concretions grow spherically. As the mud undergoes compaction, permeability becomes reduced in the vertical direction, so that the concretions grow into vertically depressed ellipsoids. Where sedimentation was slow, the steep compactional gradient in the mud may be reflected by *bread-loaf concretions* with a flattened lower side, or by downward tapering *radish concretions* around vertical burrows (Fig. 5(a)). On the other hand, the interference of concretionary growth and compaction may lead to *lens-shaped* concretions, in which the originally parallel lamination begins to pinch towards the edges already within the calcified part. This is in contrast to the case, in which compaction followed after the concretion had fully formed. Here, the hard nucleus may be surrounded by a *slickensided coating*, which, together with the general symmetry, has caused misdentifications as fossils (*Guilielmites*; *Palaeotrochis*; Häntzschel, 1975).

In all these cases, the concretion grew radially by concentric precipitation, while the carbonate for the new layer was supplied by advection from the sediment around. This is well illustrated by a case in the Lower Jurassic Posidonia Shales of Southern Germany (Fig. 5(b)). Here a previously formed lens-shaped concretion led to a gap in the underlying

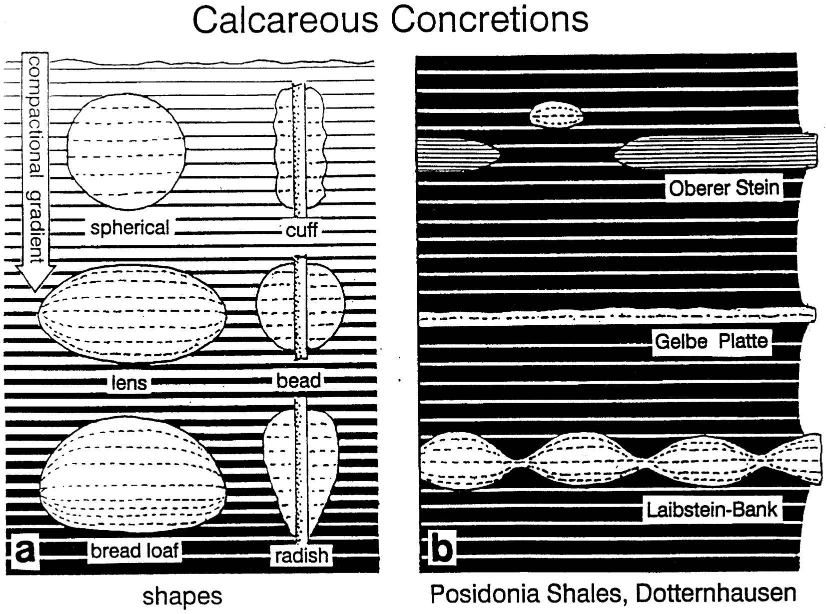


Fig. 5. (a) *Calcareous concretions* are spherical only when formed before compaction, while compactional anisotropy of the host shales causes growth into flattened geometries. *Bread-loaf concretions*, as well as *radish concretions* around vertical burrows, reflect a steep compactional gradient that reduced permeability in the deeper layers. (b) In the Posidonia Shales of Dotternhausen (Lower Jurassic, Germany), three limestone beds have been diagenetically cemented at different stages of compaction. A gap in the uppermost bed ('Oberer Stein') is caused by an earlier lens-shaped concretion on top, which had depleted the shale around it.

limestone bed, which otherwise maintains exactly the same thickness over tens of miles. In contrast, the lowermost of the three characteristic limestone beds ('Laibstein-Bank') consists throughout of large lens-shaped concretions. Thus, these limestone 'beds' are in fact stratiform concretions that became cemented at different stages of compaction. Lithification of the lower bed took place when the surrounding mud was as yet fairly isotropic and the contained ammonite shells were not yet compressed. In contrast, ammonites had already been reduced to flat periostracal films, and the mud had become highly anisotropic, when cementation occurred in the upper layer. By this time, however, the lens-shaped concretion on top had already drained all carbonate from its surroundings, so that nothing was left for the cementation of the bed below.

In some cases, a cortex layer of chert or cone-in-cone calcite formed around the whole concretion after the host shales had become too impermeable for replacive growth.

4. Glomerulus concretions

Epigenetic concretions formed by meteoric ground water (such as the calcareous concretions in loess, or the sideritic ones in desert sandstones), commonly show agglomerations of spherical bodies (Fig. 6(a)) that may, depending on the phantasy of the viewer, be compared to dolls or Neolithic mother goddesses. Intuitively one tends to explain such complexes by secondary fusion of originally separated spherical concretions. This, however, would be in conflict with the 'phobotactic' behavior of advancing precipitation fronts (see above). Therefore, we more likely deal with a kind of budding; i.e. a leakage in the terminal membrane of the original concretionary pneu led to the formation of a new spherical concretion attached to an earlier one. If this interpretation is correct, the internal structure should be concentric in the nucleus concretion and eccentric in the satellite ones. Unfortunately, cross-sections failed to show internal lamination.

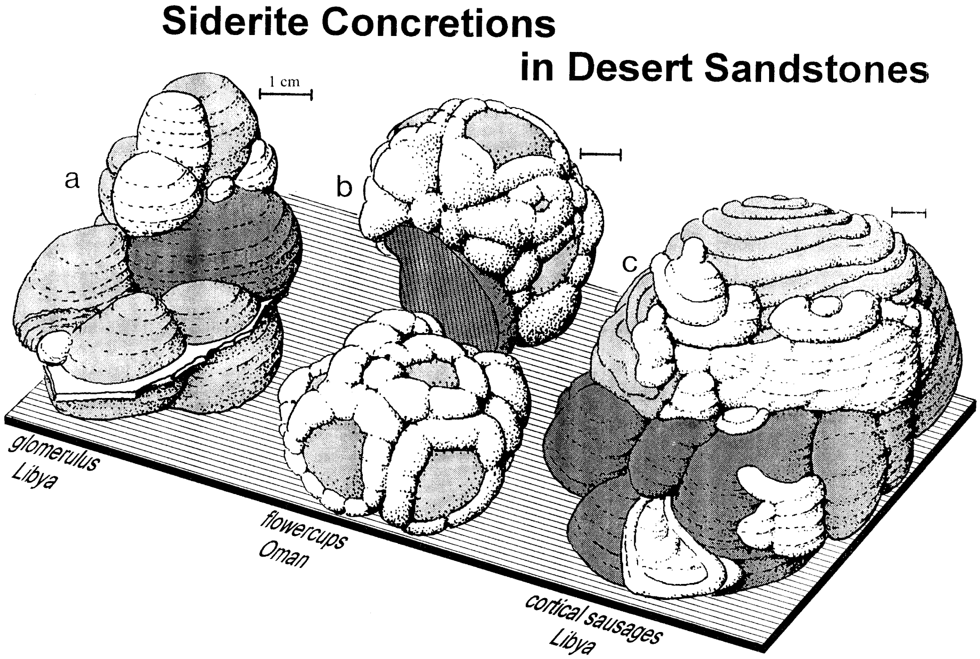


Fig. 6. In desert sandstones, siderite concretions grew epigenetically under the influence of meteoric ground water. In *glomerulus concretions*, a second generation of globular bodies budded from the original sphere. In *flowercup concretions*, a third generation grew in the interspaces between second order globes. In the larger concretion from Libya, later overgrowth developed *dissipative* patterns.

The budding model is further supported by an ironstone concretion from a Cambrian sandstone in Oman (Fig. 6(b)), in which the secondary globes are surrounded by a third generation in the form of radial cups. This example also illustrates the rule that increasing constraints in subsequent generations of structures introduce hierarchical complexity reminiscent of biological morphogenesis.

5. Mummy concretions

In the silty muds that were deposited in shallow seas around the Quaternary glaciers of Norway, calcareous concretions commonly formed around carcasses of small fish. Accordingly, these concretions are elongate within the bedding planes and may have irregular outlines in plan view (*Marleik* = Norwegian for 'sea doll'; Fig. 7); but surprisingly, new layers did not form as concentric laminae coating the whole concretion. Rather they are wrapped-around pancakes of constant thickness, whose steep pneu margins and faint growth rings suggest that growth proceeded tangentially, rather than radially out from the concretion center. Even more surprising is the *symmetry* of these envelopes with regard to the horizontal plane of the concretion: to every pancake on the upper surface corresponds one of similar size and position on the lower surface. Even the latest, and therefore smallest, pancakes repeat like epaulets on the two sides.

While the vertical symmetry of overgrowth in the Marleik concretions is as yet unexplained, its pancake shape has a counterpart in the colorful Liesegang Rings (Fig. 3) that decorate the sandstone walls of the tombs in the ancient Nabataean city of Petra (Jordan). In vertical section they are organized into bodies similar to the mummy layers of the Marleik concretions, but arranged as horizontal rings around the nucleus. These bodies are separated by more prominent ironstone seams, commonly with an additional yellow band. Together with the finer internal banding inside each body (dotted lines in Fig. 3), the temporal sequence of the pancakes can be clearly

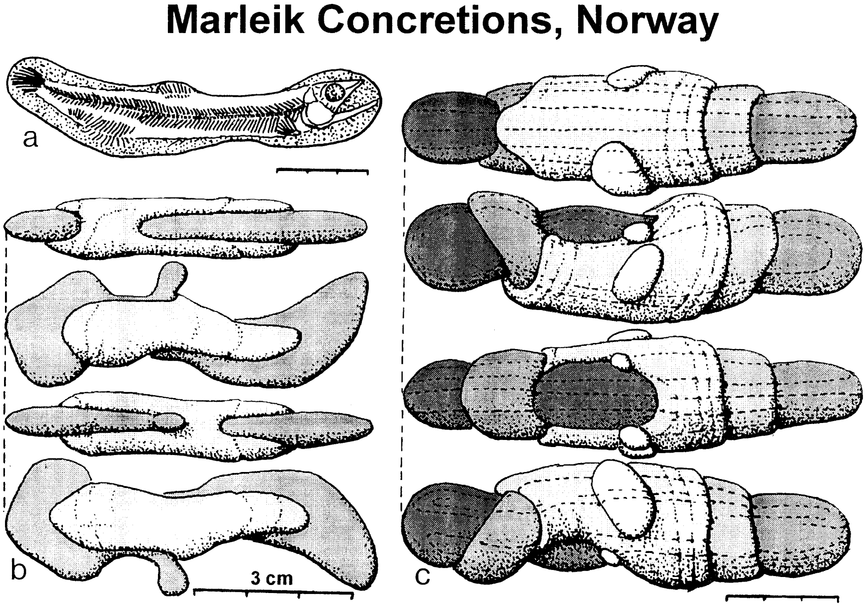


Fig. 7. *Marleik* concretions in Quaternary silts of Norway owe their elongate shapes to enclosed fish carcasses. Further growth proceeded transversally in the form of *mummy envelopes* of uniform thickness. Note the symmetry of these pancakes on upper and lower sides.

reconstructed, because the rings are evenly vaulted on their free sides. At their contact with the previous ring, however, they lack the 'phobotactic' behavior of advancing precipitation fronts. On the contrary, new rings hug the previous ones as tightly as the chambers in a foraminiferan shell.

In Marleik concretions as well as the Petra Liesegang Rings, concretionary growth was rhythmical. Each layer started by radial budding; but after the balloon-shaped initial bud had reached a certain diameter, it expanded tangentially to form a cuff- or ring-shaped envelope of uniform thickness. We use the term *mummy concretions* for shapes involving radial and tangential growth in alternation. Thus the 'phobotactic' interaction was replaced by a nucleation relationship. In all mummy concretions, there must have been a constraint that determined the uniform thickness of the pancake layers. The gradual color change in the Petra mummy pancakes and their increasing thickness away from the nucleation center (Fig. 3) suggest that concentration increased during the growth of individual sausages and that their pneu growth stopped when a threshold concentration had been reached.

6. Dissipative concretionary overgrowth

The rhythmicity of mummy concretions results from two growth processes, the stepwise radial addition of new envelopes and the tangential expansion of the latter with a constant thickness. In a related class of concretionary bodies, the envelopes themselves are regularly subdivided into sausage-like bodies that contour previous ones by growing at both ends.

The resulting pattern resembles other 'dissipative' structures, although the generating process is different in every case. *Bénard Cells* reflect the thickness of the fluid layer, in which cylindric convection becomes spontaneously established. *Belosov-Zhabotinski* figures (Kauffman, 1995) result from a rhythmic chemical reaction, while it is probably a threshold concentration that stops the expansion of a precipitation front in concretionary envelopes.

Dissipative overgrowth has been observed in a siderite concretion from Silurian sandstones of Libya (Fig. 6(c)). A larger and more spectacular calcareous version (Fig. 8) is found in a quarry at *Westerstetten* near Ulm (Germany), where big blocks of the host Jurassic limestone are floating in the red clay of

Fig. 8. The micritic *Westerstetten structures* cover blocks of Jurassic limestones floating in the clay of Tertiary karst fissures. (From Seilacher, 1997).

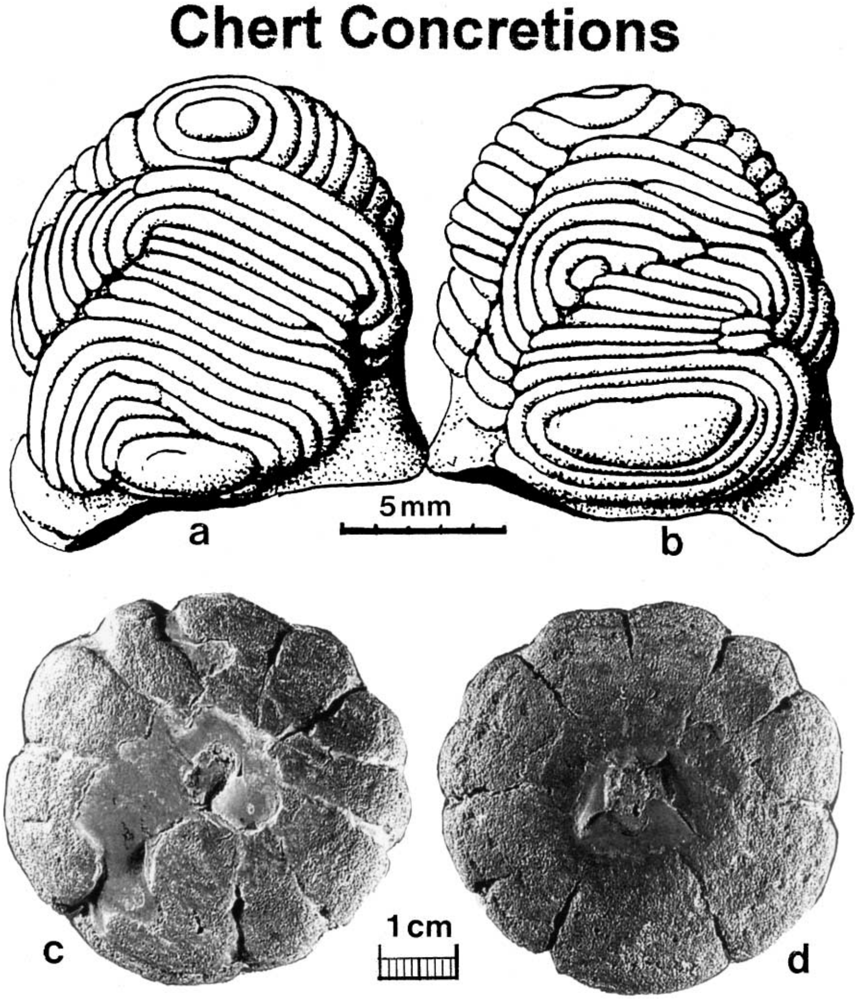


Fig. 9. (a) Dissipative patterns resembling the Westerstetten structures, but much smaller in size, are found as secondary overgrowth on chert nodules in North African chalks. In the figured specimen (drawn from photographs kindly provided by Prof. H. Linde, Humboldt Universität, Berlin) envelopes on the upper and lower side are nearly symmetrical.(b) An unlabeled chert concretion (courtesy of Prof. C. Mendelson, Beloit College) was squashed during compaction like an orange, showing that the cortical layer was tougher than the interior.

karst fissures. Their upper surfaces are coated with several layers of micritic pancakes several centimeters thick that show the same rhythmic pattern in endless variations (Fig. 8; Seilacher, 1997). At a much smaller scale, chert concretions in Cretaceous and Tertiary chalks of North Africa (Fig. 9(a) and (b)) are commonly overgrown by chert layers of similar configurations. There is also a certain symmetry between pancakes on the upper and lower side of the nodule, as in Marleik concretions (Fig. 7). Since such overgrowth has never been observed in the millions of chert nodules washed out from the chalk cliffs of Northern Europe, we probably deal with an epigenetic overgrowth caused by silica mobilization under arid conditions. A climatic control is also likely for the Westerstetten karst system, which formed during warm Cretaceous and Tertiary periods, as well as for the Liesegang Rings in Petra sandstones (Fig. 3). Nevertheless the rhythmicity of these patterns is probably intrinsic, rather than reflecting climatic or seasonal cycles.

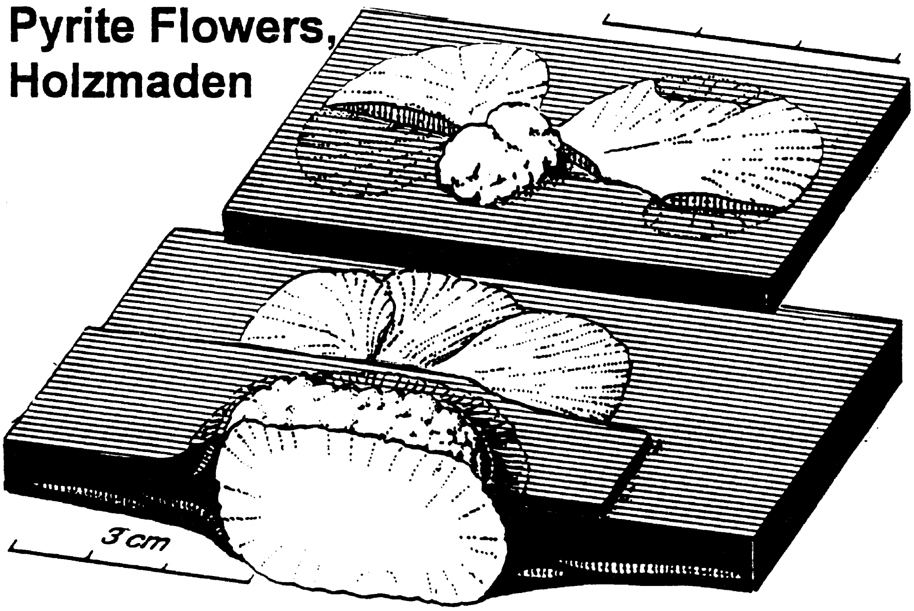


Fig. 10. *Pyrite Flowers* in the bituminous Posidonia Shales (L. Jurassic; S. Germany) combine two generations of pyrite concretions. The central concretion is spherical, because it grew when the mud was still isotropic. Subsequent compaction produced a slickensided halo and made the sediment so stiff and anisotropic that a later generation of pyrite grew in the form of discs along bedding planes.

7. Sandwich concretions

7.1. Pyrite discs

In the concretions discussed so far, minerals precipitated as cement in pore spaces during early stages of diagenesis (Fig. 5) or at a much later time, when roll fronts of meteoric ground water migrated through the permeable rock and re-distributed soluble constituents (Figs. 3, 4 and 6).

In contrast, *pyrite* (or markasite) does not enclose sedimentary particles; it grows displacively in the form of pure crystals or crystal aggregates, that push the sediment aside. More exactly, the pushing agent is probably a pressured fluid cell or film from which the crystals can grow. Pyrite concretions are most common in bituminous shales, where they occur in two distinct morphologies, as illustrated by *pyrite flowers* from the Lower Jurassic Posidonia Shale of Holzmaden, Germany (Fig. 10). When the mud was still soft and isotropic, a *spherical* nodule grew around a burrow structure, presumably by addition of new layers from outside. As compaction went on, a slickensided halo (*Guilielmites*) developed around this initial nodule. The disc-shaped pyrite *petals* surrounding the globular nucleus formed at a later stage, when compaction had made the mud impermeable, cohesive, and anisotropic. Thus, pyrite growth acted as a wedge splitting the stiff mud along the bedding plane.

Larger and less eccentric pyrite discs that can be found in rock shops (mostly from Devonian black-shales of upstate New York; Fig. 11) tell us more about the process involved. Their radial sculpture resembles *frondescent casts* on turbidite soles (Pettijohn, 1949), which formed by fractal crack propagation in cohesive mud. It agrees with the crack origin, that patterns are identical (but with opposite relief) on the two sides of the pyrite discs (Fig. 11(a) and (b)). More surprisingly, the stepped-up growth lines are also identical. This can only mean that new layers were added not on the outside, but from the inside of the concretion — almost as new layers are deposited in a growing bivalve shell. As to be expected in such a *sandwich concretion*, cross fractures (Fig. 11(c)) show a midline with a banded cone-in-cone structure on either side, while the margin is split in another specimen (Fig. 11(d)). The symmetry of the

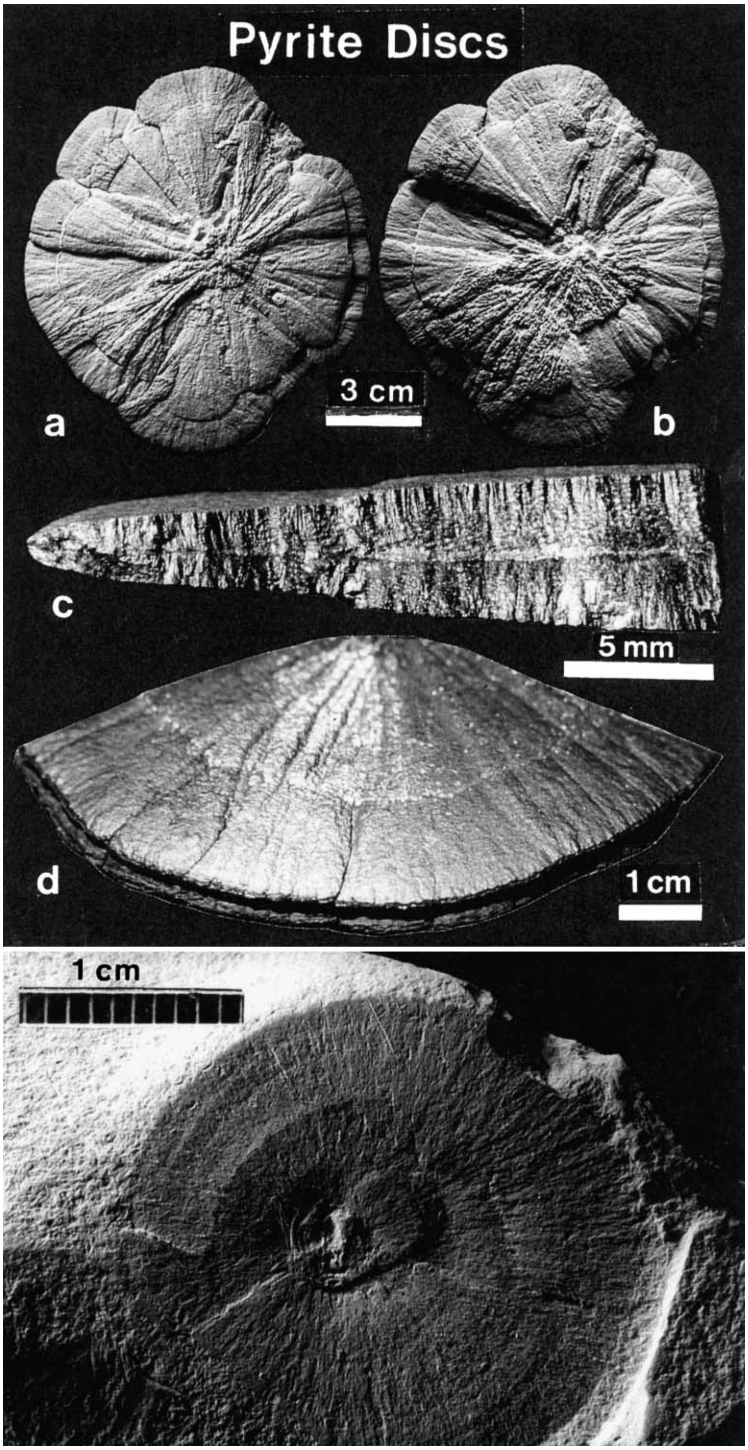


Fig. 11. The *frondescent pattern* of pyrite discs ((a) YPN 201 440) results from radial crack propagation in a stiff mud. Therefore, it is repeated in opposite relief on the other side ((b) mirror image). Cross breakage (c) reveals a median seam, from which new pyrite layers were added and pressed into a fibrous cone-in-cone structure. *Sandwich growth* is also documented by discs with a split margin ((d) sector). In shales leached by arid weathering, *disc shadows* ((e) YPM 201 433) show that these shales were originally bituminous.

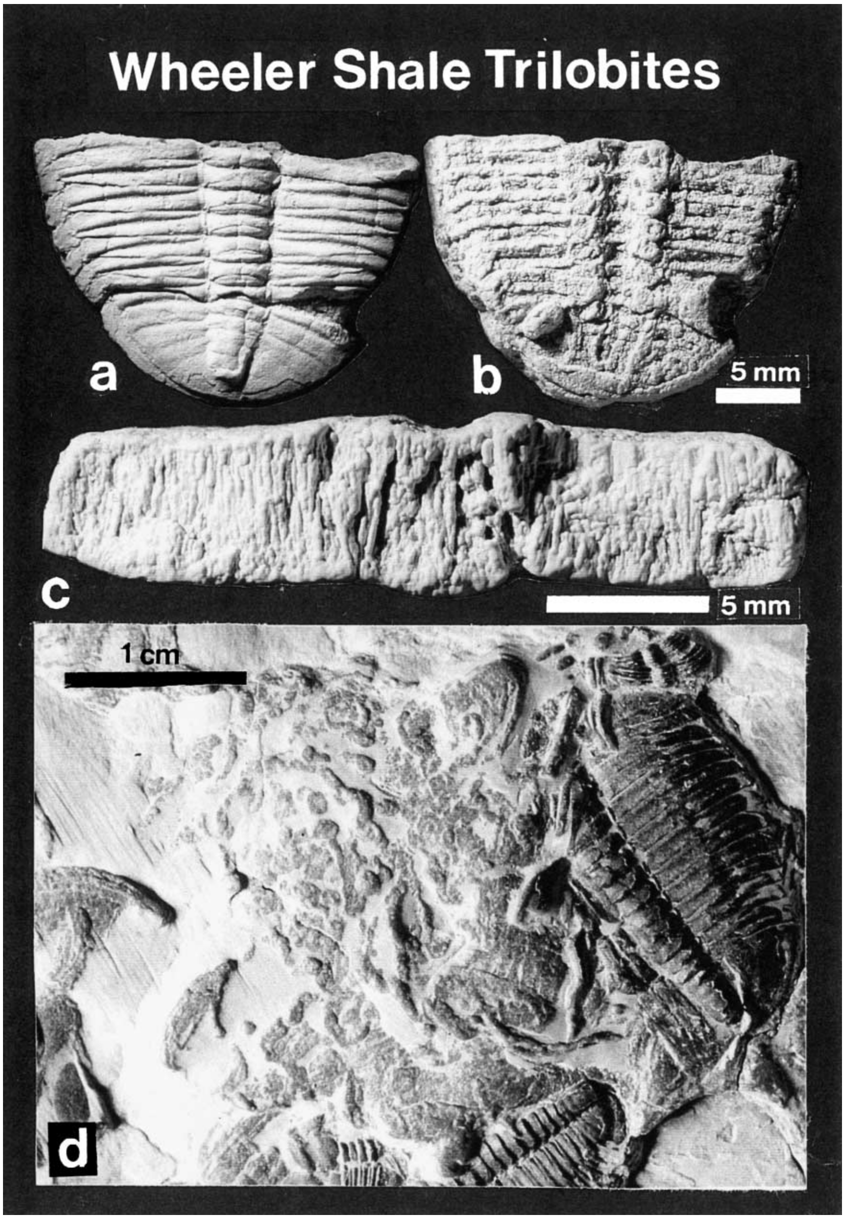


Fig. 12. Padded trilobites ((a) *Elrathia* from bituminous Wheeler Shales of Utah: YPM 200 171), preserve a blurred replica of the fossil on the ventral side ((b) mirror image). In cross breakage (c), the thick calcite layer separating the original from its replica shows a cone-in-cone structure. Elements scattered on a bedding plane ((d) YPM 200 202) are always padded on their ventral sides, irrespective of up or down positions.

two sides is only broken by spots of a more strongly reflecting cortical layer, which independently encrusted upper and lower surfaces of the disc as a terminal overgrowth.

7.2. Pyrite-disc shadows

In desert areas, where black shales have turned white or greenish gray by intensive weathering, splitting

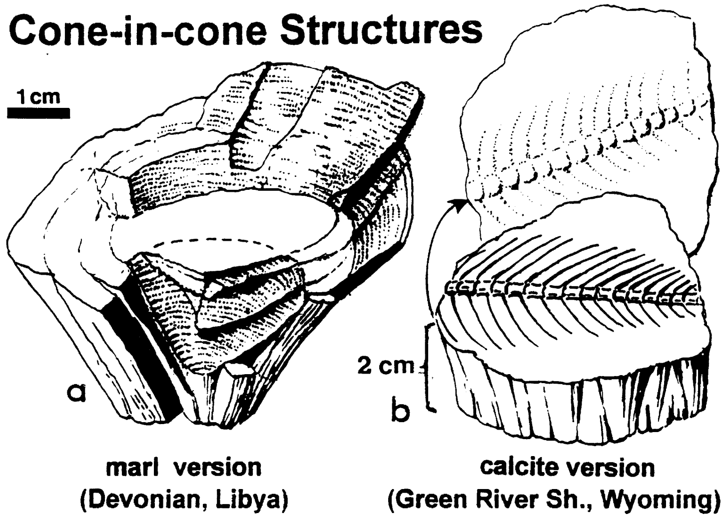


Fig. 13. Layers of *cone-in-cone calcite* in the Green River Shales (Eocene, Wyoming) follow bedding planes and separate the skeleton of a fish from its replica on the other side ((a) drawn after photograph in Brown, 1954).

often reveals round spots with a fine radial structure (Fig.11(e)). Assuming that we deal with leached-out pyrite discs, such 'shadows' can be used as an indication of originally organic-rich shales.

7.3. Padded trilobites

A calcitic counterpart to the pyrite discs can be observed in trilobites (*Elrathia*) from the M. Cambrian Wheeler Shales of Utah (Bright, 1959, Fig. 12(a)). They are also favored by rock dealers, because the otherwise thin and fragile carapace is conveniently reinforced by a calcitic crust on the ventral side. Even if this crust is several millimeters thick, its surface shows a blurred replica of the trilobite, or rather of the carapace's inner surface (Fig. 12(b)). In cross breakage (Fig. 12(c)), original and copy are again separated by a fibrous cone-in-cone layer, but in this case of calcite. In contrast to pyrite discs, however, the sandwich has only one deck and a steep outer margin, because the generating crack did not propagate beyond the circumference of the trilobite. As seen in larger rock samples (Fig. 12(d)), the cone-in-cone padding is always on the internal side of the carapace, irrespective of its up or down position. Since it is also developed on disarticulated elements, soft parts were not involved. Rather it was the presence of an organic cuticle, which did not allow such padding to grow on external surfaces.

7.4. Cone-in-cone calcite layers

Also in bituminous shales, single-or double-decked layers of cone-in-cone marl or calcite may extend over several meters. Although there is no particular nucleus, the growth mechanism is the same as in padded trilobites. This is illustrated by a fish skeleton from the Eocene Greenriver Shales of Wyoming that became separated from its replica by two centimeters of cone-in-cone calcite (Fig. 13(b)). The origin of cone-in-cone structures has been variously discussed (Brown, 1954; Usdowski, 1963; Woodland, 1964; Durrance, 1965; Gilman and Metzger, 1967). The mechanism can be most conveniently studied in *cone-in-cone marls* (*Interconulites* Desio, 1940), in which individual cones reach sizes of up to 5 cm (Fig., 13(a)). Their interfaces are ornamented by cross ridges that are not slanted but nevertheless, suggest an upward slip of the inner cones relative to the outer ones. Such motion is also expressed by the upward bulge of the stack's outer surface, which blurs the replicas and has led to the German term of 'nail limestone' (*Nagelkalk*) for cone-in-cone layers. Like in tectonics, such differential movements may contribute, in addition to the internal accretion of new crystal lawns, to the thickening of the layer against sediment pressure.

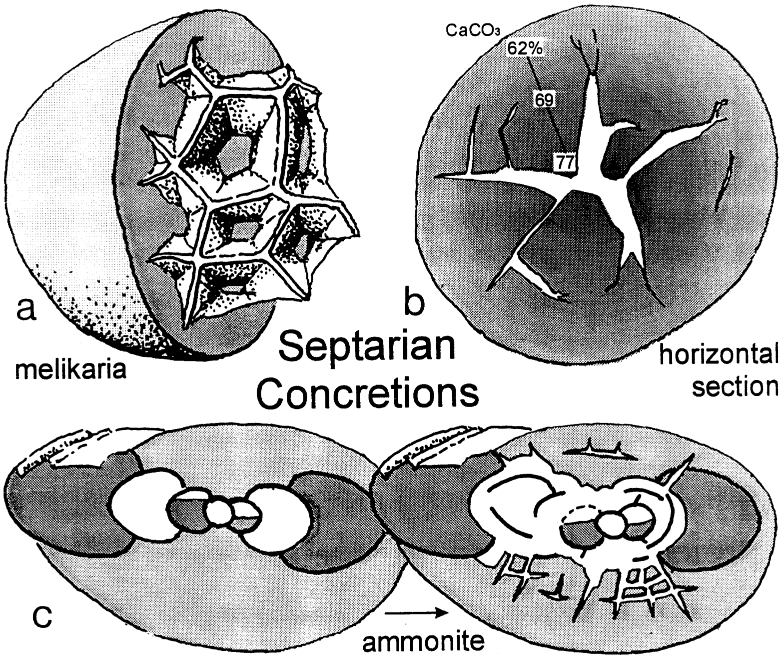


Fig. 14. In the core of *septarian concretions*, secondary shrinkage cracks in the core became filled by clear calcite. (a) Weathered-out crack fillings resemble honeycombs (*melikaria*; after Sellés-Martínez, 1996). (b) Cracks radiate from the center without reaching the surface of the concretion. Carbonate content outside the cracks decreases in the same direction (from Wetzel (1992)). (c) Cracking separated the sedimentary infill, mold and fragments of an enclosed ammonite shell. This and the volume loss suggest that the center of the original concretion was not yet rigid.

Intuitively, one would make crystallization pressure responsible for this displacive growth; but since crystals can only grow from fluid, it is probably more correct to think of a cell or film of *overpressured fluid* (Sellés-Martínez, 1996), in which crystal lawns grew as in a druse, but without the volume of the fluid becoming reduced.

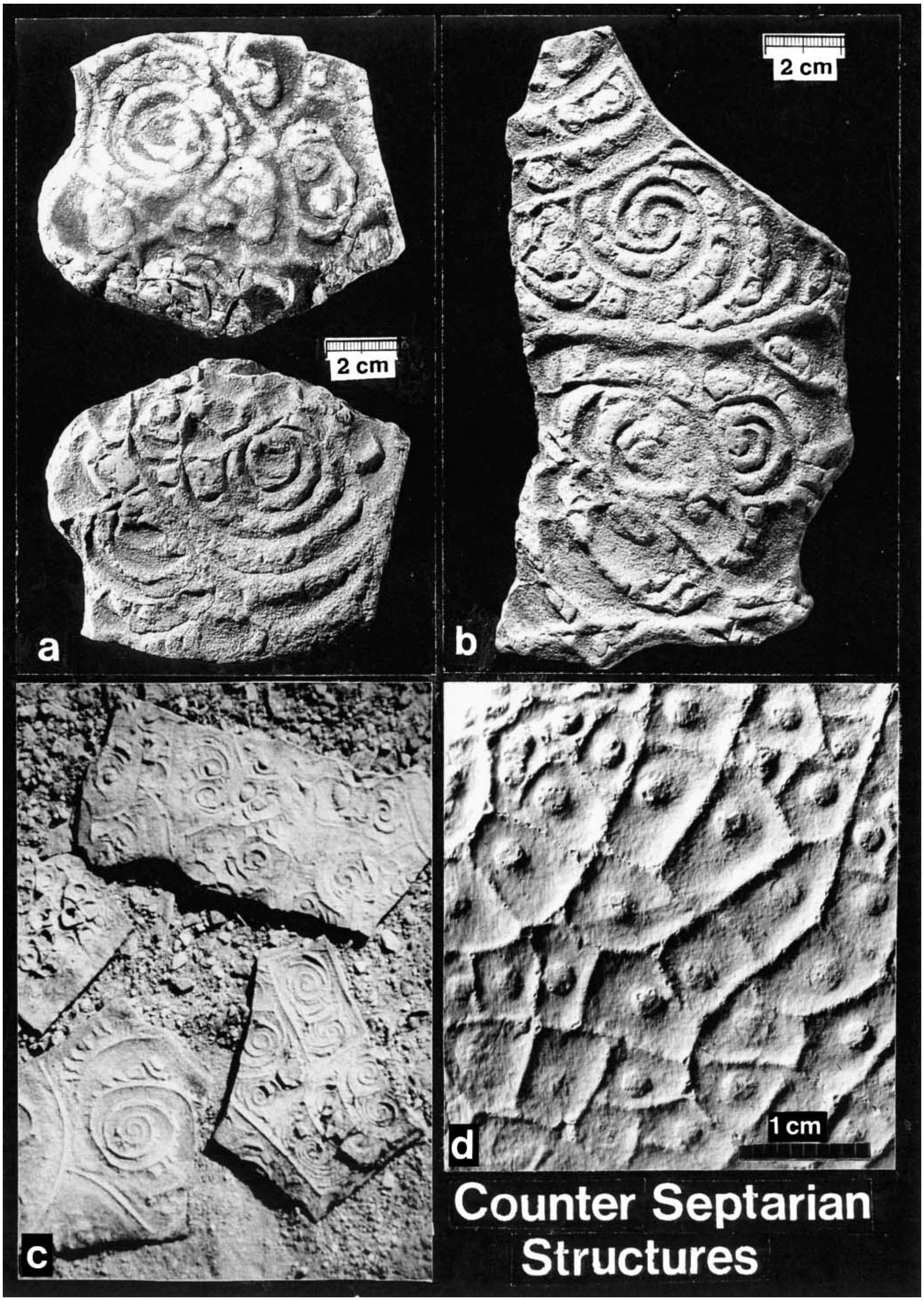
8. Cracked concretions

In this category we group concretions, or concretionary layers, in which the original morphology has secondarily become modified by shrinkage cracks—no matter whether shrinking was induced by desiccation or fluid pressure.

8.1. Septaria

In certain shales, ovoid calcareous concretions of early diagenetic origin commonly show honeycomb cracks in the center (Fig. 14). Since the cracks are healed with clear calcite, they must originally have been filled with fluid rather than air. This paradox is

Fig. 15. Complex *counter-septarian crack patterns* form during desiccation at the gradational contact between rigid stratiform concretions and the host shale. (a,b) While cracks of the first generation were vertical and developed an unconstrained polygonal pattern, tangential second-order cracks started at the boundary of each shard and propagated spirally towards its center. Eventually, the spiral fields became segmented by third-order cracks that are vaulted like the septa in a *Nautilus* shell (Pliocene Shales near Tucson, Arizona; courtesy of Prof. Susan Kidwell, University of Chicago). (c) Similar patterns on the lower side of a hard crust that developed on the residue ponds of a Surinam bauxite mine (field photograph by W. Casadevall, courtesy of Prof. C. Mendelson, Beloit College). (d) In this example from the Triassic Werfen Beds of Northern Italy, the first order polygons were too small for spiral patterns to develop during second order cracking. Instead, a single tangential crack propagated towards the center of each polygon, leaving a round knob in the center. (Plaster cast of specimen described by Fuchs, 1895, YPM 15354.)


2 cm
2 cm
a
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1 cm
Counter Septarian
Structures

usually explained by *syneresis*, in which the sediment behaved as a colloidal gel (Pettijohn, 1949), although it cannot be excluded that fluid overpressure was also an essential factor. In any case the crack pattern reflects a consistency gradient away from the center of the primary concretion, where cracking always starts (Fig. 14(a)). Wetzel (1992) also demonstrated that the carbonate content of the cracked sediment increases towards the center of the concretion, in spite of its secondary volume reduction by cracking (Fig. 14(b)). If the septarian concretion contains a fossil shell (Fig. 14(c)), cracks follow the shell surface and may isolate shell fragments that now float in the calcitic crack fill.

All these observations indicate that the original concretionary body was not rigid (as suggested by Astin, 1986), but remained compactable — at least in the inner parts that had formed earlier in the compactional history of the sediment.

8.2. Orange concretion

In septaria, the softness and inhomogeneity of the early concretion is expressed by internal cracking. It is also reflected in an ellipsoidal chert concretion (Fig. 9(c) and (d)) that I owe to C. Mendelson (Beloit College, Wisconsin). Although we do not know where it came from, this specimen is of interest here because of its radial cracks. Evidently, the outer layer was tougher than the ones inside, so that the concretionary ball cracked like an orange peel under sediment pressure.

8.3. Counter septaria structures

As a last and most perplexing example of diagenetic self-organization, the patterns shown in Fig. 15 are so regular and complex that one might mistake them for fossils or for artifacts of an ancient culture: polygonal fields are filled with regular spirals, whose segmentation resembles the vaulted septa of a *Nautilus* shell. Yet there is no doubt about a purely physical origin. I was made aware of this phenomenon by a photograph (Fig. 15(a); courtesy of Prof. C. Mendelson, Beloit). It shows the lower side of a hard crust that developed on the drying mud in residue ponds of a Surinam bauxite mine. Fossil counterparts (Fig. 15(a) and (b); courtesy of Prof. S. Kidwell, University of Chicago) come from a concretionary layer in the Pliocene near Tucson, Arizona. Here the patterns developed on both surfaces, with some of the polygonal cracks penetrating the core layer. In all cases the boundary of the hardened layer was gradational, so that the adhering mud could not simply detach when it dried out. In addition, crack propagation was constrained at every step by the pattern of the previous crack generation.

In a less spectacular version of such *counter septarian structures*, the tangential cracks did not propagate spirally. Instead they formed a round knob in the center of each first-order polygon, thus mimicking the nuclei in a cellular tissue (Fig. 15(d)). This suggests that the defoliating cracks started from the polygonal cracks of the previous order and propagated towards the center of the enclosed area. It would be interesting to simulate this hierarchical process in the computer.

9. Conclusions

1. Even though their morphogenetic pathways are controlled only by physical processes, the shapes and patterns of concretionary bodies fall into distinct morphospaces.
2. Complex structures emerge from the hierarchical constraints of previous structures on subsequent processes.
3. Since concretionary morphologies reflect the original state and the diagenetic and epigenetic histories of the host sediments, they are an useful tool in facies analysis.
4. Their indicator value may be increased in the future by additional geochemical data.
5. In general, concretions illustrate the effect of self-organizational processes. Such processes are also involved in the shaping of biological forms (Seilacher, 1991), where they become 'tamed' by genomic control in Darwinian evolution.

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