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Concretion morphology, classification and genesis

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Abstract

A discussion of the most relevant morphological features of concretionary bodies and the different classifications, and the criteria involved in these classifications is presented, together with suggestions for improvements to the various classification schemes. The meaning of syngenetic, diagenetic and epigenetic related to the relative timing and environment of growth of concretionary bodies is also reviewed and discussed. The replacement of mixed morphogenetic classifications, which lead to conflicting results, by classification categories based on textural features is proposed. Because the identification of the genetic environment of a concretionary body tells little about its history, I recommend defining growth patterns in which the successive steps associated with changes in composition and/or texture and the development of new structures are recorded. A new path is presented that accounts for the contradiction between textural and isotope features, which suggests respectively syngenetic and diagenetic (or even epigenetic) signatures. This new path is characterized by the preservation of large porosities over very long time spans and down to depths that are somewhat greater than expected, due to the inhibition of normal compaction caused by early overpressuring. This overpressuring is the result of the development of hydraulic seals since approximately the syngenetic phase times. The concepts of "force of crystallization" and "displacive growth" are also reviewed. It is being suggested to discard some controversial interpretations of their actual importance for true concretionary displacive growth under epigenetic conditions. In accordance with other authors, the conclusion is reached that displacive growth is only possible if the shear strength of the host is very low and the stress field within the host is almost hydrostatic. A new model (the Symcompactional Concretionary Growth Model) is proposed which explains how a concretionary body, generally a nodule, can grow while its host thins down by compaction.

This overpressured-undercompacted model will be useful for the interpretation of an assemblage of features such as injection dikes, hydraulic breccias, cone-in-cone sructures, among others that are thought to be representative of the former presence of overpressured horizons. These overpressured horizons could serve as detachment planes in paleotectonically active basins. Seals that could have controlled the movement of brines and hydrocarbons during the diagenetic evolution of the basin can also be assessed; this is relevant for the identification of maturation conditions. The potential development of secondary fracture permeability due to hydraulic fracturing in buried areas of the basin can also be evaluated based on the identification of formerly overpressured horizons in outcrops.

"The origin of concretions is generally a geological puzzle" Clifton (1957).

Keywords: concretions; cements; diagenesis; abnormal pressure; force of crystallization; displacive growth; cone-in-cone

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1. Introduction

Authigenic precipitates in the form of veins, concretions or cements (concretionary bodies — CB's — as they shall be called throughout this paper) have been extensively described and studied morphologically and genetically, since the earliest times of sedimentology. Nevertheless, the above statement of Clifton (1957) still holds, and features not adequately explained and subject to debate, still remain. The reasons why veins form under some circumstances and concretions in others and how and why extensive cementation can predate, follow or replace both are a few of such questions. Another is why the chemistry and isotope composition of some concretions are more complex than expected from their textures. An additional problem arises when it is proposed that a concretion, 2 m in diameter, is formed by cementation of soft muds in the uppermost centimeters of the sea bottom.

Further problems arise when a classification is attempted. As in many other fields of geology (and sciences in general) there is an unavoidable tendency to mix descriptive features and genetic interpretations. Because genetic interpretations are modified through time (which seems to be an inexorable rule) classifications become more and more confusing and even misleading. This has also happened in the case of the classification of CB's. Genetic implications of textural features have ruled out some classifications. Therefore several discussions on these problems are presented attempting to unify descriptive and classification criteria.

A review of current terminology relating to morphological types of CB's and their classification schemes, along with a brief discussion on growth stages (a subject historically intertwined with their classification) is also presented. One of the goals of this paper is to establish a new growth pattern for CB's, one that considers that the growth of such bodies can contiue over very long periods of time, from the syngenetic to the metamorphic stages, which could not be clearly differentiated by former classifications. This "overpressured-undercompacted cell (OUC) model", stresses the preservation of high initial porosities over longer time spans and up to depths higher than generally assumed. In this model, textures trapped in the growing CB would reflect sea bottom ones regardless of the fact that precipitation starts long after deposition. Identification of such a pattern would lead to the recognition of early seals, the assessment of the stratigraphic position of overpressured horizons in the sedimentary record and the relative timing of fluid expulsion and/or injection. The recognition of overpressured-undercompacted horizons would also introduce second order corrections in burial depth curves and decompaction calculations, as compaction of a certain layer could actually be highly asynchronous with those under- and overlying it as long as certain environmental conditions (the OUC path) are met. The proposed OUC model can also assist with the identification of possible detachment horizons in paleotectonically active basins. Moreover, it can also relate concretion-bearing horizons in outcrops to overpressured, potentially highly porous or intensely hydrofractured levels present as lateral continuations of the former in the buried sections of the basin. From the point of view of fluid circulation at depth, the new model stresses the possibility of large amounts of fluids, formerly trapped in pore spaces, to be released after the seals break. The identification of potential units for the development of abnormally high secondary porosities by cement dissolution at advanced diagenetic stages (resurrected porosity) could be another application of the OUC model. Former interpretations of the origin and evolution of ooidal and stratabound deposits in economic geology may also be modified with this model.

This paper is subdivided into four main parts in order to follow a relatively organized sequence that starts with the description of the broad aspects of the general features of host layers, presents a description of morphological CB's types and associated features relevant to environmental interpretations, continues with a discussion on different classification systems, their applications and limitations and ends with a discussion on growth scenarios and their weak points. A redefinition of traditional stages is proposed and the importance of describing growth patterns rather than simply defining a syn-, dia- or epigenetic origin is stressed. Additionally, the so-called "syncompactional growth mechanism'' replacing what was loosely defined before as ''displacive growth'' in the diagenetic stage, is also proposed.

2. General remarks

Modes of occurrence and growth mechanisms of CB's will be briefly described and discussed in this chapter. Most questions relate to the growth mechanisms. Paraphrasing Dewers and Ortoleva (1990), the effects of the sophisticated studies of solution chemistry, lithology, multiphase rock rheology and growth kinetics on the interpretation of growth models still remain to be investigated.

2.1. Occurrence and general features

Although widespread in time and space, CB's in a basin are generally restricted to a single or several distinct beds representing the sedimentary record. They can be found in marine and continental environments. Non-marine conditions give rise to CB's such as oolites and pisolites, pedologic nodules and espeleothemes (see Carozzi, 1972; Curtis and Coleman, 1986; Aassoumi et al., 1992; Aso et al., 1992; Gonzalez et al., 1992 and Jones and Kahle, 1993, among others). Although CB's can grow directly inside organisms (pearls, kidney-stones) or indirectly from biologically controlled reactions (framboidal pyrite), most CB's have an inorganic origin in the sense that they precipitate from saturated brines. This does not mean that most of the reactions controlling the evolution of brines during diagenesis are not influenced by the decay of organic matter and hydrocarbon chemistry. The fact that CB's are usually local concentrations (''segregations'') of mineral species which were formerly dispersed as secondary components in the host (quartz in limestones, carbonate in shales and sandstones, pyrite in black shales, etc.) initially encouraged the study of concretionary growth to identify the mechanisms responsible for dissolution and reprecipitation. The first attempts concerned the ''free energy budget'' in dispersed and concentrated stocks. Later on, it was discovered that dissolution–reprecipitation reactions were not that simple and many environmental conditions (like circulation of fluids) are of the utmost importance.

The areal extent of concretion-bearing layers has made them useful tools for correlation and stresses that when conditions for concretionary growth are met, they occur at a regional scale. They can synchronously develop in coastal plains and the innermost parts of the basin. Most concretions are found close to (but not lying on) the base of their host. The reasons why they concentrate at a specific level cannot be easily explained. Presence of fossils (or organic matter) has been invoked as a positive factor inducing precipitation but the presence of concretions cannot always be linked to the presence of organic matter or fossils. In several cases concretions seem to be associated not to a definite lithology or facies arrangement but to physico-chemical conditions that are reached synchronously in a broad area of the basin. Some of them start to grow in the water–sediment interface (or even precipitate directly from the body of water), whilst others are formed under several kilometers of overburden. Most concretions consist of carbonate and are associated with clayey horizons, but not exclusively as they may have different mineralogies and can also be hosted by sandy, limy and volcaniclastic horizons.

Evidence for preservation of hydrocarbons inside concretions has been reported by Weeks (1953, 1957) and Clifton (1957) and Glover (1957) among others. Sondheimer et al. (1966) analyze fossil fish carcasses that ''burn when ignited''. Isotope relationships in CB-forming minerals have proved to be rather complex. Although isotopic studies must be considered an important tool to decipher the growth environment of CB's, they usually produce results that challenge simple relationships (Weber et al., 1964; Sondheimer et al., 1966; Berner, 1968; Oertel and Curtis, 1972; Hudson, 1978; Gautier, 1982; Marshall, 1982; Hennessy and Knauth, 1985; Siegel et al., 1987; Criss et al., 1988; Dix and Mullins, 1993; Mozley and Burns, 1993a,b; Prosser et al., 1993, 1994; Morad and De Ros, 1994). Most authors ascribe their conflicting isotopic results to complex fluid circulation patterns and/or mixing of waters coming up or going down respectively, from deep seated brines or younger meteoric sources. The isotopic composition of many CB's which were assigned a syngenetic origin, proves the influence of parent waters having an isotopic composition which is rather different from the present-day oceanic ones. In several cases this would reflect reactions taking place under at least several hundred meters of burial and complex fluid circulation patterns. Although Macaulay et al. (1992) found strong evidence for the persistence of stratified waters in the diagenetic environment for at least 35 million years, this does not appear to be the usual situation. Sometimes irregular, otherwise spherical or flattened parallel to the layering, their shape is associated with mechanical and physico-chemical parameters during the growth stage. The fact that a preferred orientation of the long axis of concretions can be observed in some outcrops, has led researchers to assign this anisotropy of shape to depositional conditions (primary fabric of enclosing sediments) or hydraulic parameters (anisotropic flow in the host), two features that are generally linked. Relative timing of authigenic precipitation episodes can usually be established on the basis of textural relationships, chemical variations and isotopic paths (e.g. Hudson, 1978; Dix and Mullins, 1987; Craig, 1985 in Collinson, 1994), but absolute rates of formation of CB's seem to be quite unpredictable, taking into account the many variables involved. A few attempts have been made to this end. Pantin (1958), performed some isotope analyses on carbon in calcite which yielded a value of somewhere between 7500 yr and 20,000 yr. Boles et al. (1985) obtained greater figures for the giant Moeraki Boulders, 140,000 yr for a 18-cm radius concretion and 4,000,000 yr for one with a 95-cm radius, but the authors themselves severely criticized the methodologies used to determine the ages. Sondheimer et al. (1966) describe some very recent calcite concretions containing carcasses of fishes fossilized over a time span of approximately 1350 years, although some uncertainties about the original isotopic composition of Carbon in the fossilizing environment jeopardized their results. Prosser et al. (1993) have restricted the time span required for the formation of either continuous cement layers or discontinuous large stratabound concretions studied to about 65 m.y. Jansa and Noguera-Urrea (1990) estimate that precipitation of different cementation pulses in their study lasted about 75 m.y. Meanwhile the concretions-bearing unit was buried from 200 m to 1600 m. On the other hand, the crusts covering objects in submerged archaeological sites just a few centuries old, clearly show how fast chemical precipitation can take place under favorable conditions.

2.2. Features in host and neighboring layers

Some additional features of host layers and those in their vicinity like the presence of hydraulic seals and associated fluid scape structures, such as injection dikes and hydraulic breccias, are related to the occurrence of precipitated bodies. They will be described and analyzed in the following paragraphs. As the mechanisms for the development of hydraulic fractures which are the conduits for fluids and fluidized materials that were squeezed from the overpressured layer have not been definitively established, a short paragraph is also devoted to this question. Fluid pressures exceeding the hydrostatic pressure, have long been recognized in sedimentary basins and many reasons for their development have been found. A discussion of these subjects is beyond the scope of this review and the reader is referred to the papers of Thomeer and Bottema (1961), Bishop (1979), Carstens and Dypvyk (1981), Barker (1987), Cosgrove (1991), Cassidy and Ranganathan (1992), Luo and Vasseur (1992, 1993), Miller and Luk (1993) and Cartwright (1994) for further information.

Hydraulic seals: Actual fluid pressure in a formation, different from the normal "hydrostatic" one for that depth (assuming normal compaction trends during burial), is currently referred to as "abnormal pressure". Abnormal pressures can be either higher or lower than normal and the terms "overpressure" and "underpressure" are respectively applied to these cases. Overpressuring is not an unusual feature. During the burial history of a sedimentary unit, there is a need to keep the velocity at which excess fluids are generated (by normal compaction, hydrocarbon generation, etc.) and that at which they are expelled from their source rocks, in balance. If generation cannot be counterbalanced by outward migration of fluids, overpressure results. The presence of relatively more impermeable strata (aquitards, aquicludes) may be an impediment to the normal escape of fluids and generates what is known as an hydraulic seal. The following would appear to be a suitable definition of "seal" for the present purpose:

A sedimentary layer, facies configuration or tectonic structure producing a low permeability barrier relative to the surrounding beds and allowing accumulation and preservation of fluid pressures. However a discussion about the degree of efficiency and duration can modify this definition (see Bredenhoeft and Hanshaw, 1968; Hanshaw and Bredenhoeft, 1968; Bradley, 1975 and Deming, 1994 for further details on the interpretation). Effective porosity, pressure gradients, mineralogy, clast size and morphology among others, define the efficiency of a seal, which can also display anisotropic behavior.

Hydraulic fractures: The recognition of hydraulic fractures and associated structures in ancient and modern environments, is a key to the identification of formerly overpressured horizons and associated seals. These fractures result from the influence of fluid pressures on the stress field, modifying effective stresses, which are being lowered, but leaving the shear stress unchanged. Although the weakening effect of pore fluids can induce shear fractures under compressional stress, most perpendicular-to-layer, tensile fractures in sedimentary rocks are thought to be the result of a tensile (least effective) stress (Price, 1975; Carter et al., 1990; Sibson, 1990). However, Lorenz et al. (1991) discuss the existence of tensile fractures due to pore pressure which does not actually exceed the least compressive stress in real systems and propose an alternative mechanism for fracture development based on the anisotropy of the stress field. The highly localized layer-parallel shear stresses arising from the viscosity contrast between adjacent compacted and undercompacted horizons should not be neglected in the study of the process leading to fracture, in the same way that they lead to the more easily recognized boudinage process. Hydraulic fractures can grow either normal to (McA. Powell, 1969; Behrmann, 1991) or parallel with layering (Srivastava and Engelder, 1990; Cosgrove, 1991; Vernik, 1994) and in many cases they follow pre-existing discontinuities.

Injection dikes and other fluid escape structures. Clastic infilling of fractures in sedimentary horizons that closely resemble igneous features but are actually filled with clastic material have been recognized and interpreted early in the history of sedimentology (see Maltman, 1994). They are generally referred to as "clastic dikes" without distinction as to the origin of the infillings, which can either come from the surface or from buried layers. The terms "injection dike" or "Neptunian dike" are preferable to those cases in which it is clear that the infilling material comes from a neighboring layer and has been mobilized by fluidization and injection mechanisms; the term "debris dikes" is suggested when the infilling of exposed fractures and joints are products of erosion.

Injection dikes result from the infilling of tensional fractures with material that comes from the destruction of primary structures in under- or overlying units. Destructive mechanisms are fluidization by overpressure and destabilization of under- and overconsolidated materials by changes in the stress field (see Jones, 1994). Pressure gradients between the fluidized layer and the fractured layer allow mobilization of the plastic material which is injected into the fractures. Injection sills are the horizontal equivalent of the structure. An interesting discussion on the origin and mechanism of emplacement of injection dikes can be found in McA. Powell (1969, 1970) and also in Criss et al. (1988) (see fig. 4 in his paper) and in Martel and Gibling (1993). McA. Powell (1970) ataches great importance to fluid pressures in the mechanism of fracturing of host rocks and infilling of dikes, giving evidence for the pushing apart of dike walls and of minor but actual deformation of bed lamination due to the forced intrusion of fluidized material. The proportion of carbonate content found in the dikes (up to 60%) is relatively greater than that found in the host (about 10%) and reflects the higher porosity of the dike material (with greater fluid content) than that of the host layers. These were already lithified at the time of injection, and therefore precluded late compaction of the dike material. Hydraulic dikes of microscopic dimensions have been described associated with cone-in-cone structures (Woodland, 1964; Becq-Giraudon, 1990). Dikes and diapirs at the microscale, as those illustrated in Carstens (1985), are given here a different interpretation, linking them not to dendritic growth of pyrite — as the author does — but to pore pressure induced deformation.

Criss et al. (1988) have shown the association of CB's with fluid escape structures at the outcrop scale and how some of these bodies have been driven by the fluidized sediment and injected into clastic dikes and sills. This is relevant and confirms the fact that concretion-bearing layers are still uncemented and fluid saturated while these bodies continue to grow. Some of the mobilized concretions show evidence of plastic deformation during transport which is also an important feature to consider for the analysis of the mechanical behavior of CB's during compaction and changes in the stress field induced by fluid pressure or depth variations.

The explosive crushing of a rock due to hydraulic fracturing produces a hydraulic breccia often characterized by the exclusive presence of angular fragments of walk rocks. They are different from fault breccias that may not have a hydraulic origin and involve other complementary mechanisms, like milling due to the relative motion of the hanging and foot walls. However, they can be associated with them under certain circumstances. It is not uncommon to find the combined effect of brecciation and injection resulting in a mixed material with angular particles of consolidated sediment (derivated from the hydraulic crushing of the dike-hosting layer) with clastic material (squeezed from the neighboring fluidized bed). If clastic infilling is not possible but fractures are kept open by pore fluids, veins will grow following the crack-seal mechanism and will remain as evidence of the process. Some other interesting structures can arise if the hydrofractures reach the sea bed (e.g. Holzer and Clark, 1993; Kelley et al., 1994). Extrusion of fluidized material may form mounds on the sea bed (or even be dispersed by marine currents) and result in the collapse of the depleted chambers. Nichols et al. (1994) describe physical models of features related to fluidization and fluid escape structures, making interesting statements about the instability of overpressured-undercompacted layered systems. The reader is referred to this work for further information.

In summary, when high fluid pressures are associated with the co-existence of competent and soft layers (the competent layer being generally the hydraulic seal) different mechanical properties result in the development of different structures in each layer. Those materials that (depending on the degree of compaction or cementation) behave in a brittle way will develop hydraulic fractures while those preserving or acquiring plastic rheologies will flow because

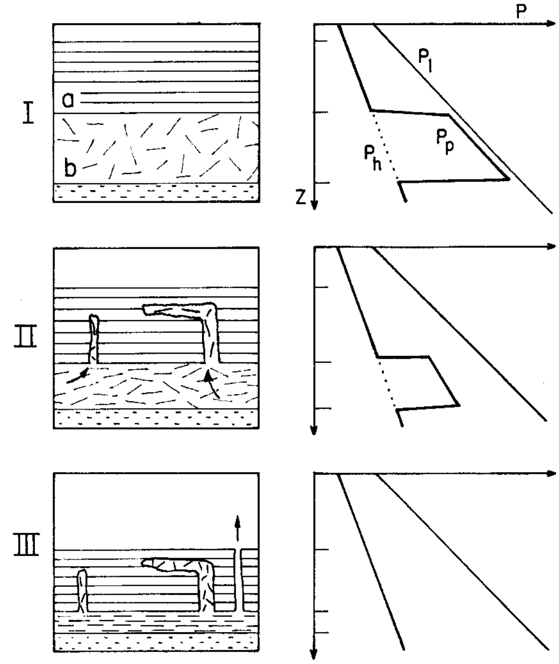


Fig. 1. Development of hydraulic fractures and injection of fluidized sediment to form a neptunian dike. I depicts initial conditions: a competent layer (a) overlies a soft one (b). Although both can be overpressured, only b can behave as a particulate medium when fluid pressure equals the least stress. In the transition from I to II hydraulic fracture of the competent unit (probably under extensional conditions) allows injection of fluidized b into the opening spaces producing clastic dikes. The process would stop when excess fluid pressure dissipates and b loses its fluid behaviour. After that fluid (but not clasts) can move from b to a to infill veins. As a consequence of this continuous loss of fluid and the decay of pore pressure to normal hydrostatic values, normal compaction of b is achieved through time.

of pressure gradients. The infill (sometimes forced) of the hydraulic fractures generates injection dikes. If the overpressured horizon is not fluidized and there is no available sediment source to fill the hydraulic fractures, brines will precipitate their solubles resulting in normal-to-bedding veins of diagenetic age. Fig. 1 depicts the process.

2.3. Force of crystallization and displacive growth

Force of crystallization was first discussed by Weyl (1959) as a concept contrary to that of pressure solution. He tried to estimate the energy balance, describing the tendency of a certain mineral to crystallize or dissolve within specified environmental conditions. External stresses, namely an applied load and fluid pressure, were fundamental to his reasoning. Different authors subsequently extended the application of the term to cases of replacement of one mineral by another, that is to say to compare the forces of crystallization and solution of different mineral phases, the one a solid state, the other a supersaturated brine. Some authors have overemphasized the force of crystallization (see definitions of the epigenetic stage below) assuming that it is possible for the growing crystal to push aside indurated host rocks. The fact that concretions were thought to be "foreign" to host rock, ignoring that they actually cemented and incorporated it, made it necessary to find a mechanism to explain how this growth was possible. The candidate was displacive growth and the means were the forces of crystallization. Entering a circular argument, the textural and structural features that previously led to postulate that concretions grow late in the diagenetic history of the sediment, were used afterwards as proof of their growth against the confining host. In such a case it is necessary for the forces of crystallization to overcome the shear strength of indurated rocks. The only mechanism to deform a solid under normal burial conditions, is to overcome its yield resistance. When shear stress overcomes shear strength the material deforms. If it is brittle, fracturing and local inverse fault-like structures, which are not actually observed, are expected. On the other hand, plastic deformation (flow of the host after its shear strength has been overcome) will only be possible if large amounts of fluid are retained and bonds between particles are extremely weak, a condition not usually associated with the epigenetic scenario, unless early and continuous overpressured conditions had been met previously. If the involved materials are consolidated (and unless bonds between clasts are broken by mechanical forces or chemical processes), they would only acquire a plastic rheology under metamorphic conditions, thus removing the subject from the present area of interest. To conclude this analysis, it is clear that the forces of crystallization and concretionary growth should be given their true meaning, restricting their application to those events for which they have been defined.

"Force of crystallization is of renewed interest as a diagenetic replacement mechanism" state Dewers and Ortoleva (1990). It is worth emphasizing the importance of the term "replacement" in this sentence, which by no means is interchangeable with "growth", as many researchers seem to understand it and thus requires a careful look at the meaning and possibilities of actual displacive growth. Dewers and Ortoleva point out that crystallization forces can result in displacive growth only if the host is not very viscous. Further on in their paper they exemplify that this would be the case of a concretion (they are actually dealing with a siliceous nodule) growing in relatively unconsolidated sediments. If it is viscous enough and, moreover if it is rigid, growth is restrained to regions of dissolution of a pre-existing mineral, but there is no possibility at all of actual displacive growth. It has been ruled out by the rheology of the host. Displacive growth forces, although real, are very weak if compared with the shear strength of materials under most common geological situations. Taking it to extremes, a crystal growing from a seed in the bottom of a crystallization vase has to displace the surrounding water! Anisotropies in the stress field probably have a strong influence on the dissolution–precipitation equilibrium, as isotropic (that is to say hydrostatic) conditions probably favor precipitation whilst anisotropic conditions inhibit crystallization. It is important to take into account the fact that the force of crystallization is highly sensitive to average effective stress (which in turn is itself related to the normal stress and the fluid pressure). Experiments carried out by Becker and Day (1916) (quoted in Weyl, 1959) show a dramatic fall in growth with only a 0.7 mg weight placed on the seed crystal. They found that its rate of growth was 1:25 compared to an unloaded specimen. Discussions favoring the hypothesis of displacive growth of single crystals and nodules can be found in Criss et al. (1988), Bain (1990), Dewers and Ortoleva (1990). Strong arguments against are given in Shearman et al. (1972), based on the statement that concretionary growth forces could never lift the sedimentary column overlying the veins he was studying. It will be very difficult to accept that crystallization forces can actually do any important work against the overload. It must be underlined also that as suggested above, most elements given in the past as evidence for displacive growth can be reversed and used as evidence that compaction actually post-dates authigenic concretionary growth, no matter if it was displacive or replacive. In this sense it can be argued that if orientation of flaky elements (bending of schistosity around the concretions) is assigned to "pushing aside" by crystal growth forces, these forces should have acted from the very beginning (producing a series of concentric spheres of oriented clay and mica platelets or fossil debris) and random fabrics should not be preserved inside the concretion, which contradicts the available descriptions. The structural relationships of layering or schistosity inside and outside a CB and their bearing on the time and growth mechanisms, are going to be dealt with further on.

Displacive growth can be taken as the main growth mechanism for nodular bodies when oversaturation of parent brines is associated with uncemented, highly porous hosts. This is only possible under shallow burial conditions or through early overpressuring of sealed layers. If conditions for precipitation are met, but displacive growth is not possible (due to the fact that bonds between particles exceed crystallization forces) the new mineral will fill the available pore spaces. On the contrary, if there are no fluid filled spaces to crystallize, the brines will remain oversaturated until a point is reached at which they become reactive with solid phases. Replacive growth would then be possible either by replacement of early cements or by corrosion and replacement of the clastic framework of the host. Any displacive growth (veins or nodules) will be possible against the overload in a sedimentary basin if overpressuring does not act as a jack and pushes the sedimentary framework aside. The author is doubtful at this point, if this process can actually be called "displacive" as long as the mechanical work is not done by the crystallization forces themselves. The term "expansive" seems to better define CB/host relationships. No other growth mechanisms different from inclusive, replacive, displacive and expansive ones can be envisioned, but this simple scheme appears to account for real situations and overcomes previous misuses and conflicting observations.

3. Classification of concretionary bodies

The first steps in acquisition of knowledge are generally description and classification of the objects of study. But as stated before, classification of natural objects has always brought about complex problems, because it is seldom easy to separate the fields of description and interpretation clearly. The organization of CB's into categories has not escaped this stigma and will be discussed further on when referring to growth environments.

Some of the terms describing CB's are apparently applied, without strict definitions, which makes their meaning very loose (i.e. "concretion"). Moreover, sometimes they have even lost their original meaning through time (i.e. "epigenetic"). In several cases, their use is almost subconscious and qualifications are given without explicit reference to a classification scheme. As done in previous sections of this paper, CB's are given shapes, compositions, textures, etc., but without a prior attempt to organize them into categories bases on these. Pettijohn (1976) differentiates four groups of mineral segregations, namely nodules, regular crystalline growths (spherulites, dovetail crystals), concretions in a restricted sense and finally veins, geodes, septarians and all those forms associated with open cavities. Several objections can be made to this scheme, e.g. septarian features are more related to nodules or concretions than to veins, nodules are only replacive, etc.

Many different criteria for the classification of CB's are available such as their shape, morphological features, chemical composition and textural relationships (see Table 1). On the basis of these primary "descriptive" classifications, chronological relationships, modes of emplacement and genesis have been proposed. These are the most controversial of all, as they involve unavoidable subjective interpretations.

3.1. Descriptive classifications

Descriptive classifications are a first approach to the study of any subject. Their importance is that they are based on objective observations and are not yet influenced by subjective criteria. This clearly shows that until clear and efficient descriptive classifications are available, any interpretation will be short-lived.

Differentiation according to shape: From the point of view of their shape CB's can be grouped into: irregular, botroidal, spherical, elliptical, lensoidal, tabular and unshaped. The difference between ellipti-

Table 1
Classification systems for concretionary bodies. See text for discussion

Descriptions	Shape	Irregular Botroidal Spherical Ellipsoidal Lensoidal Tabular Unshaped
	Crystallinity	Euhedral Transitional Anhedral Pseudomorphic Polycrystalline
	Mineralogy	Carbonate Sulfur Sulfate Phosphate Siliceous etc.
	Relationship with host	Parasedimentary Synsedimentary Precompactional Syncompactional Postcompactional
	Morphology	Cement Vein Nodule Concretion
Interpretations	Mode of emplacement	Coplacive Displacive Replacive
	Environment of growth	Syngenetic Diagenetic Epigenetic OUC path

cal and lensoidal rests on the fact that elliptical bodies are not controlled by structures in the host whilst most lensoidal are (see plate XXXV in Gresley, 1894). Tabular refers to veins and concretions in which two dimensions are considerably greater than the third. Unshaped refers to all those cementations with diffuse borders or bounded by sedimentary contacts, not having a definite border of themselves (which makes them different from irregular ones).

Another attempt to classify CB's according to their shape is associated with their crystallinity and applies mainly to nodules. Euhedral, transitional, anhedral, polycrystalline and pseudomorphic types of CB's may be identified, bearing the following characteristics. Euhedral individuals may be found alone or in more or less interfering arrays. Transitional forms result from the incorporation of impurities (usually clastics from the host) in the crystalline framework, giving them a poikilotopic texture, though crystalline forms are still identifiable. This structure can be considered a mixed, a "nodule" because it is made not only of a pure mineral but of a single crystalline individual, and as a "concretion" since it cements the clastic framework. Anhedral shapes are the result of anhedral growth and when they are the product of replacement of pre-existing euhedral minerals they give origin to pseudomorphic shapes. Pseudomorphism may also occur after biologic remains (silicified wood, pyritized ammonites, etc.). The application of this classification can be illustrated by gypsum, which can be found as translucent, sometimes twinned euhedral crystals enclosed in clayey sediments, but also as anhedral gypsum nodules or veins. In between these "end forms" are "sand crystals" displaying crystalline shapes but incorporating large amounts of their host.

Morphological types: Based on their morphology (anatomy for several authors) CB's are grouped in: cements, veins, nodules and concretions. The last one displays several subtypes. Table 2 summarizes the most outstanding features of these bodies, to be described and discussed in forthcoming section due to their importance in establishing genetic relationships.

Structural relationships: The relationship between the structure of CB's and that of the host makes it possible to divide them into: parasedimentary (the CB has grown out of its host), synsedimentary (the CB has grown during deposition of the host layer), precompactional (the CB has grown after deposition of the host but has finished growing before it attained any perceptible degree of compaction, syncompactional (at least an important part of the growth pattern is contemporaneous with compaction), postcompactional (the growth of the CB postdates the complete compaction of the host). This classification will obviously help to establish the relative timing between different generations of CB's coexisting in a single layer (see e.g. Raiswell, 1971).

Mineral composition: Based on their chemistry CB's can be divided into two initial fields, one

Table 2
Different concretionary bodies and their morphologies and growth features

Type	Subtype	Morphological classification of concretionary bodies						
		Other classificationsCategories	Principal features				Comments
			Clast %	Texture	Size	Composition	
Cement		UnshapedSyn-, pre- or postcompactional Co- or replaciveDia- or epigenetic	0	Varied	Local to regional	Varied	Sometimes in patches, others stratabound Several pulses of different composition Replacement textures not unusual
Vein	Normal to- Parallel with- Oblique to- layering En-echelon arrays	Tabular Syn-, pre- or postcompactional "Displacive" (actually expansive) Dia- or epigenetic	0	Equant Fibrous	Micro- to mesoscale	Varied, mainly carbonate, gypsum or silica	Sometimes with anastomosing arrays Crosscutting arrays can give time relationships "Beef" is the name given to fibrous veins
Nodule		Irregular, botroidal, etc. Euhedral to pseudomorphic Parasedimentary to postcompactional Co- to displacive Syn- to epigenetic	0	Varied	Micro- to mesoscale	Highly varied	Sometimes with seed clasts or fossil fragments Can furnish ore deposits Polymineral nodules can display concentric zonation
Concre-tion	Concretion (s.s.) Geodes Druses Septarians	Botroidal, spherical, etc. Synsedimentary to postcompactional Syn- to epigenetic	90–10	Varied	Micro- to mesoscale	Highly varied	Sometimes preserving random fabrics and fossil volume. Sometimes with brines or hydrocarbons in hollow centres Geodes grow inwards after formation of external crust Septarian and pseudoseptarian cracks may display euhedral crystalline linings.

corresponding to monomineralic individuals, the other to polymineralic ones. Most nodules fall into the first category, whilst concretions and subtypes fall into the other, but polymineralic nodules and monomineralic concretions are not exceptional. The degree of development of crystal lattices can be used for further subdivisions (amorphous, cryptocrystalline, radial spherulitic, fibrous, etc., can be some of these subcategories).

3.2. Interpretative classifications

Interpretative classifications are based on different features, that change according to their purpose. In this respect genetic classifications that aim at reconstructing the environment and the mechanism of growth in relationship to morphology and composition, are the most common ones.

Emplacement mechanism: The most simple genetic classification divides CB's according to their mechanism of emplacement. The term coplacive (proposal of this paper) describes the fact that both, clasts and CB's enter the sedimentary system at the same time. The CB's may fall from the overlying water body, or grow at the sediment–water contact. Displacive relationships correspond to those CB's that make room for themselves pushing away their host (parent brines or sediments). The replacive category includes all those CB's that originated in the chemical reaction of parent solutions with their host. Pseudomorphosis can be a common result of this mechanism.

Environmental (or "stage") classification: Classification of CB's according to their time of growth relative to that of host sediment deposition results from textural relationships, as stated above, in search of a useful tool to describe growth scenarios. Unfortunately, this classification has been mixed from the very beginning with depth of burial and other environmental parameters like the degree of compaction of host layers. Most often used by researchers has been the subdivision into "syn-", "dia-" and "epi-

Table 3
Relevant features associated with main types in genetic classification. See text for discussion

Stage	Features	Problems
Syngenetic	Sea bottom to a few centimetres	Concretionary growth rates greater than sedimentation ones
	Fluid saturated particulate host	Concretionary weight too high to be supported by soft muds
	Low temperatureHigh void–clasts ratios	Concretions too large for the stage thickness
	Almost isotropic stress field	
Diagenetic	From a few centimetres up to several kilometres	
	Anisotropic stress fields	Conflicting isotope signatures
	Variable fluid pressures	Preservation of random fabrics and hollow cores to great depths
	Variable void–clasts ratios	Expansive growth during host compaction
	Gradually consolidating host	
	Variable temperatures	
Epigenetic	High temperature	Difficult to differentiate from low-grade metamorphism
	High confining pressures	Displacive growth against consolidated host
	Low fluid content	
	Consolidated and stiff host	
OUC Model	Independent of depth	
	High fluid pressures	
	High void–clasts ratios	

Notes: The terms low and high are of relative significance in terms of a few tenths of degrees Celsius. The terms pressure and stress are also of relative magnitude to normal overburden load. Stress fields in the diagenetic stage can show inversion of relative values of vertical and horizontal stress as a function of fluid pressure fluctuation.

genetic bodies'', associated with the homologous scenarios (see Table 3). As an undesired outcome of subjectivity in the use of primary classifications to assess growth timing and environment the need for constant redefinitions by different authors has rendered most of them useless. The importance and extent of a discussion on this subject justifies its special consideration further on after a detailed review of morphological classification (and the environmental implication of morphological features) is presented.

4. Morphological classification of concretionary bodies

A review of terms associated with the morphology of CB's and their growth environment is presented here. Most definitions follow current usage in papers and textbooks but some new proposals have been introduced with the purpose of distinguishing between similar structures (like septarian and compactional cracks) with different origins.

''Why the calcium carbonate should take the concretionary form instead of being uniformly distributed must be determined by future studies'' Tarr stated in a paper ''read before the Society'' (the GSA) in 1920 (Tarr, 1921). Much has been done in this respect, but many aspects still need further investigation. Pervasive cementation is probably associated with normally (hydrostatic) pressured host units, while overpressured conditions would be associated with concretionary growth and vein formation. In the following pages some of the environmental characteristics leading to one or another concretionary type will be discussed as well as their relationship with morphological features.

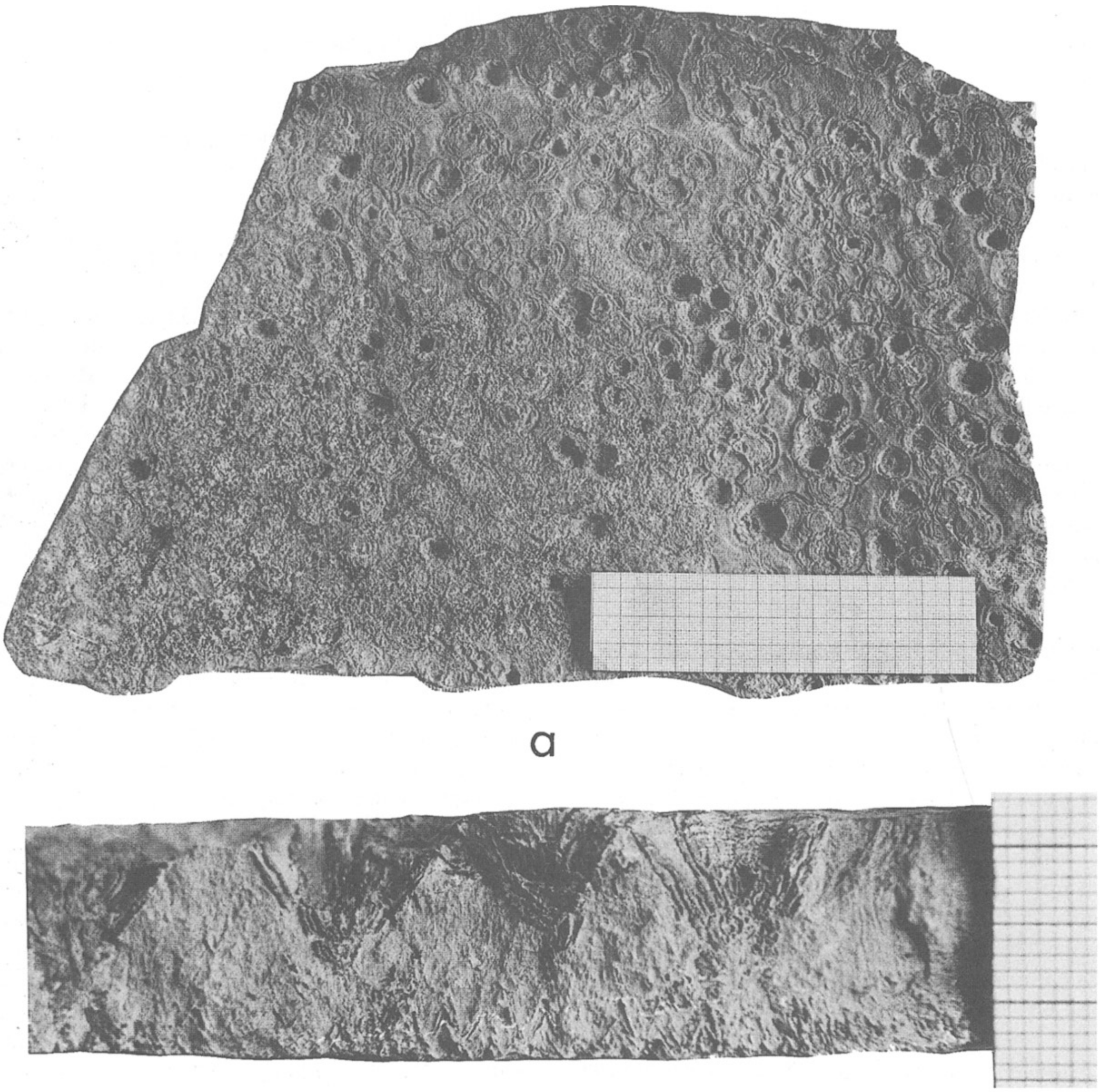
The most comprehensive terms for the description of chemically differentiated bodies in sedimentary sequences, referring to any particular morphology or physical environment are: ''concretionary body'', ''precipitated body'' and ''authigenic mineral segregate''. Oolites, flintstones, fossiliferous concretions, planar veins, etc., all fall in these categories, and their use is recommended in all those cases where references or conclusions apply to concretionary bodies as a whole and not to one or several of the morphological types.

4.1. Concretionary body types

The four main categories of classification currently used divide CB's in ''cements'', ''veins'', ''nodules'' and ''concretions''. Much of this section is devoted to nodules and concretions. Only the most relevant features of the first two will be outlined just to keep the subject within the scope of this review.

Cement: This term describes a massive precipitate that fills pore spaces in between clasts. Corrosion and replacement of clasts (or even previous cements) is not an uncommon feature in most diagenetic histories. The chemical composition of cements is highly variable and pulses of different cementing minerals can form rims and patches at any scale in the sedimentary sequence. The main factors affecting precipitation of cements are changes in temperature and fluid pressure associated with changes in depth (both burial or uplift), seepage of volatiles, input or output of fluid phases, oxidation or reduction of organic and inorganic materials. Some of these processes, but not all of them and not always, would be identified through textural relationships and isotope analyses. Dix and Mullins (1987) mention that more than 200 references were available at that time on subjects related to the physico-chemistry of authigenic precipitation. The papers of Jansa and Noguera-Urrea (1990) and Prosser et al. (1993) present interesting case histories in the analysis and interpretation of cements and their incidence in the evolution of the sedimentary basin. The reader is referred to them and current text books for further information on cement textures, composition, etc. For our purpose it will be sufficient to point out that cementation may occur at any moment after deposition. Early cements may fossilize open textures with only very few point contacts between grains, while late cements may be accompanied by large scale of replacement of the clastic framework. The infilling of large pore spaces in uncompacted (or even expanded?) sediments results in cement to clast ratios that are sometimes exceeding 90%, while very late cements, bonding a sediment that has formerly attained total compaction, the ratio can be less than 10%. In most cases, the volume of parent solutions required for the precipitation of the total amount of cementing material clearly surpasses that of the initial local pore filling brines, implying that large volumes of fluids passed through the cemented layer before its pore spaces were completely occluded. Cementation is thought to occur under almost normal hydrostatic pressures.

Veins: Veins are tabular in shape, with variable sizes ranging from millimetres to metres. They do not display such great mineral variations as other CB's do. Most diagenetic veins are composed of calcite, quartz or gypsum and are usually free of clasts. Their growth results from infilling of a space that is created by the pushing aside effect of fluid pressure, in a way that, as discussed before, cannot accurately be called displacive. Fig. 2 shows a tabular, layer-parallel fibrous calcite vein displaying



a

b

Fig. 2. Calcite vein displaying cone-in-cone structure. (a) Top view, the holes left by missing cone cups are clearly seen on the surface. (b) Section view, missing cones clearly noticeable.

cone-in-cone structure. Veins may appear as isolated individuals or shape parallel or anastomosing arrays. Material in the veins can have different crystalline shapes, from equant to fibrous individuals and variable in size. Fibers are generally normal-to-vein-walls (''beef'' structure for some authors, see Bonte, 1952; Durand-Delga, 1952 and Marshall, 1982). Tabular vein-sets may display a layer-parallel, layer-perpendicular or layer-oblique attitude depending on the stress configuration to which they have been subjected. ''En echelon'' vein arrays are special cases resulting from ductile or transitional shear deformation (see e.g. Ramsay and Huber, 1987). Layer-normal and layer-parallel fractures are thought to have a tensile origin because they display single parallel arrays (which is not be the case with shear fractures that develop intersecting systems of two joint or vein sets). However, the exact stress configurations during their development, is still subject to debate. Layer-parallel veins are thought to result from inversion of the stress field (the vertical stress becomes the least) as a mechanical consequence of increasing fluid pressure in previously normally compacted sequences while normal-to-layer veins should require not only fluid pressure increase but also some additional tectonic stress. The reader is referred to Shearman et al. (1972), Narr and Currie (1982), Stoneley (1983), Watts (1983), Henderson et al. (1990), Lorenz et al. (1991), Karig and Morgan (1994) and Vernik (1994) among others for details and references on the subject. Nichols et al. (1994) present a physical model that shows how a strong planar discontinuity separating fluidized and non-fluidized sediments can develop in an overpressured layer, providing a suitable place for authigenic precipitation. Stratification or lamination surfaces and other primary structures like cross-bedding can furnish an appropriate location for stress concentration and void opening leading to the formation of veins (e.g. plate XXXV in Gresley (1894) and Woodland, 1964). Anastomosing veins, displaying irregular patterns and enclosing sharp edged host fragments, may be related to hydraulic brecciation as will be discussed further on.

Formation of cracks and growth of veins is thought to occur according to what Ramsay (1980) called the ''Crack-Seal Mechanism''. He used the term ''crack-seal'' to describe a tectonic vein-forming process that ''mutatis mutandis'' also applies to the diagenetic realm. In this model, fractures are induced by hydraulic fracturing and filled with material precipitating from the fluids. Successive steps of growth are characterized by the influx of pore fluids into the opening fissure and subsequent crystallization due to oversaturation because of strain relief inside the crack. The repeated process of fracture opening, fluid influx, crystallization and sealing, gives way to the formation of polycyclic veins, and explains some features like inclusion lines and inclusion trails. Fig. 3 is a simplified model of the crack-seal mechanism and depicts how a vein originates in this way. Due to the fact that water is almost incompressible, only a small decrease in water volume (just equal to that entering the fissure) may lead to dissipation of excess pressure in the whole system. Vein width will remain stable until physical or chemical factors raise the fluid pressure again pushing aside the contact surface between vein and wall to reopen and refill it once more.

Nodules: The term ''nodule'' is used here to describe a CB that differs from cements and concretions in that it does not incorporate clastic material during growth. Nodules must also be differentiated from veins because they do not fill preexisting cracks but rather acquire their shape during growth. They can display great variations in size and shape, from minute and perfectly spherical (like in the case of calcite oolites), to large flat accumulations that tend to coalesce (like stratabound chert masses), or fairly irregular like pedologic ones. The absence of clastic grains in the nodular body and evidence of rolling on the sea bottom explain why most authors usually assigned a syngenetic origin to them, but nodules can also indicate replacive origins. Nodules are sometimes monomineralic and homogeneous but polymineralic nodules displaying concentric zonation, are not exceptional. They can act as a nucleus for further concretionary growth after burial. Different mineralogical compositions have been reported for nodular bodies. Prokopovich (1953) and Harris (1958) describe chert nodules, Pepper et al. (1985) refer to small barite nodules hosted by larger carbonate ones (also described in Criss et al., 1988). Bain (1990) suggests a new interpretation for the origin of gypsum crystals and nodules, assigning them a diagenetic stage due to oxidation of sulfides whilst Machel

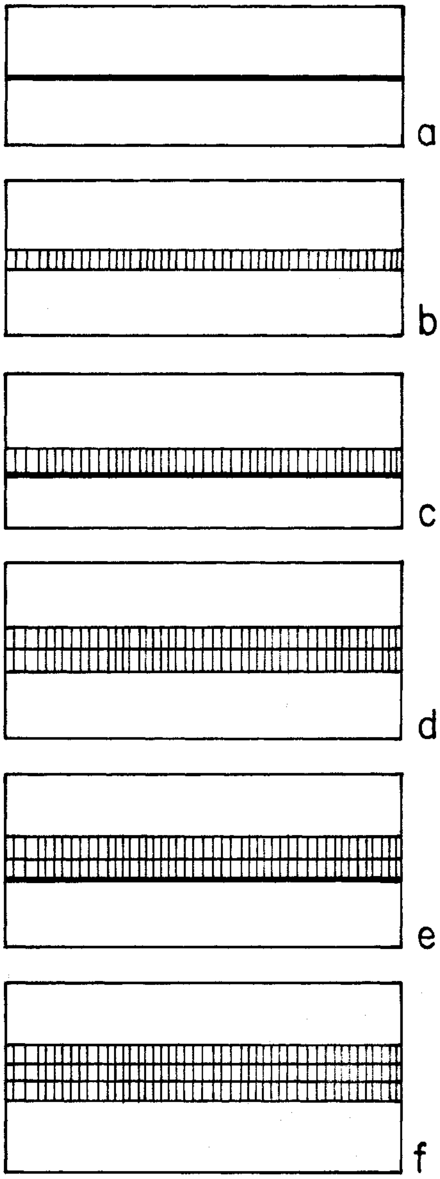


Fig. 3. The crack seal mechanism. (a) Presence of an inhomogeneity leads to stress magnification and first crack opening that balances fluid pressure and finally stops pushing aside the vein walls, (b) Growth of first generation fibers and first sealing. New fluid pressure increment produces a new crack. After reopening of the crack (c) a new generation of fibers grows (d). This process can reinitiate (e–f, etc.) as long as the sources of pressure and fluid are available. See further disccussion in text.

(1993) describes anhydrite nodules from depths of about 3 km, putting their environmental and genetic significance into perspective. In a recent paper, Morad and Al-Aasm (1994) provide a complete study of the characteristics and mode of formation of phosphate nodules. Manganiferous nodules have been reported to be forming in present day sea bottom (Mc Kelvey, 1986) but some discrepancies about the calculated rate of growth of these nodules and that of sedimentation made it impossible to establish if they really grow on the bottom or have been concentrated there by removal of soft sediment by ocean currents.

Concretions: This term refers to that portion of a sedimentary rock which has been cemented differentially from its host. Concretions are usually spherical

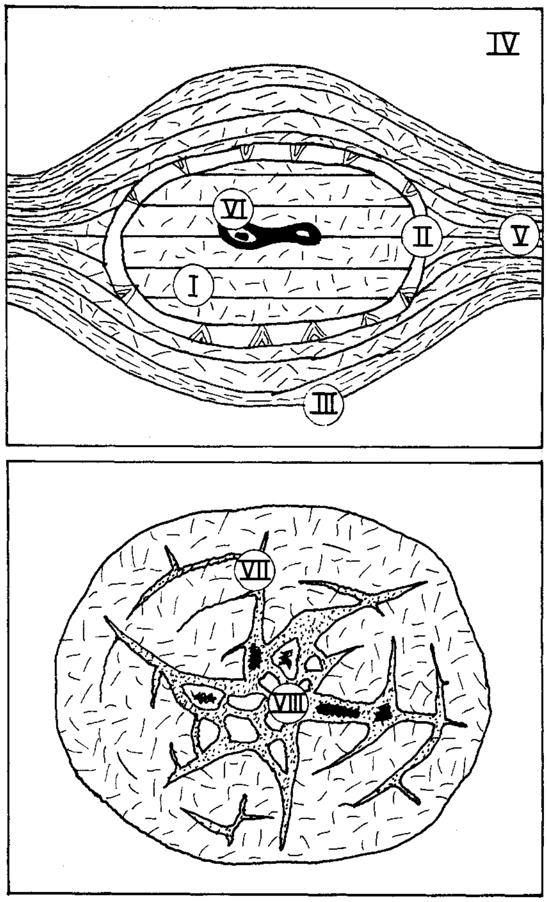


Fig. 4. Typical concretions displaying most of their morphological features. *I*. Main body displaying relict primary lamination, *II*. Crystalline rim with cone-in-cone, *III*. Outer selvage fossilizing graded compactional schistosity, *IV*. Layer-parallel compaction schistosity, *V*. Almond-shaped compactional schistosity, *VI*. Non compacted fossil, *VII*. Septarian cracks with late mineral infillings. *VIII*. Hollow spaces may remain in the core and fracture sets displaying drusoidal linings.

or ellipsoidal in shape. They result from precipitation of authigenic material incorporating the clastic framework, and this makes them different from nodules. Most of the concretions described in literature are calcite (Pantin, 1958; Hudson, 1978; Pepper et al., 1985; Cibin et al., 1993, calcite–siderite Gautier, 1982 or just siderite Weber et al., 1964; Oertel and Curtis, 1972). However, later replacement or alteration of the original composition can occur, resulting in a wide range of compositions. The main features of CB's are sketched in Fig. 4. Large fossil remains (crushed or whole) may or may not occupy the center of the concretion or its median plane. The cemented nucleus (where unstable detrital minerals and near initial porosity and fabric may be preserved) completes the core of the concretion. An external rim of variable size wrapped around the nucleus is usually present. Some concretions also display an outer transitional crust or selvage of relevant interest for relative timing purposes. Warping of internal laminae toward the border of the concretion and gradual change in texture and fabric (becoming more clastic and mechanically oriented outwards) are taken as evidence of syncompactional origin of selvages.

Some secondary features can be found in concretions which give rise to the subtypes described below.

Drusoids: This term refers to CB's with a hollow core partially filled by neocrystalized minerals. Drusoidal surfaces can also result from crystallization on the surface of septarian cracks. Fig. 5 is an example of infilling of chambers in an ammonite by calcite crystals that grow from the ammonite walls to the center, being always perpendicular to the substratum. In this case, it can be assumed that the void space could be preserved by the rigidity of the shell but in other cases there is no evidence for the origin of the void and/or the mechanism that preserved it. Was it filled with a material subsequently dissolved? The answer is not yet definite, but such voids are unlikely to be a long-term feature in the burial history of any sedimentary sequence. Preservation of voids may result from the protection of the rigid carcass of a

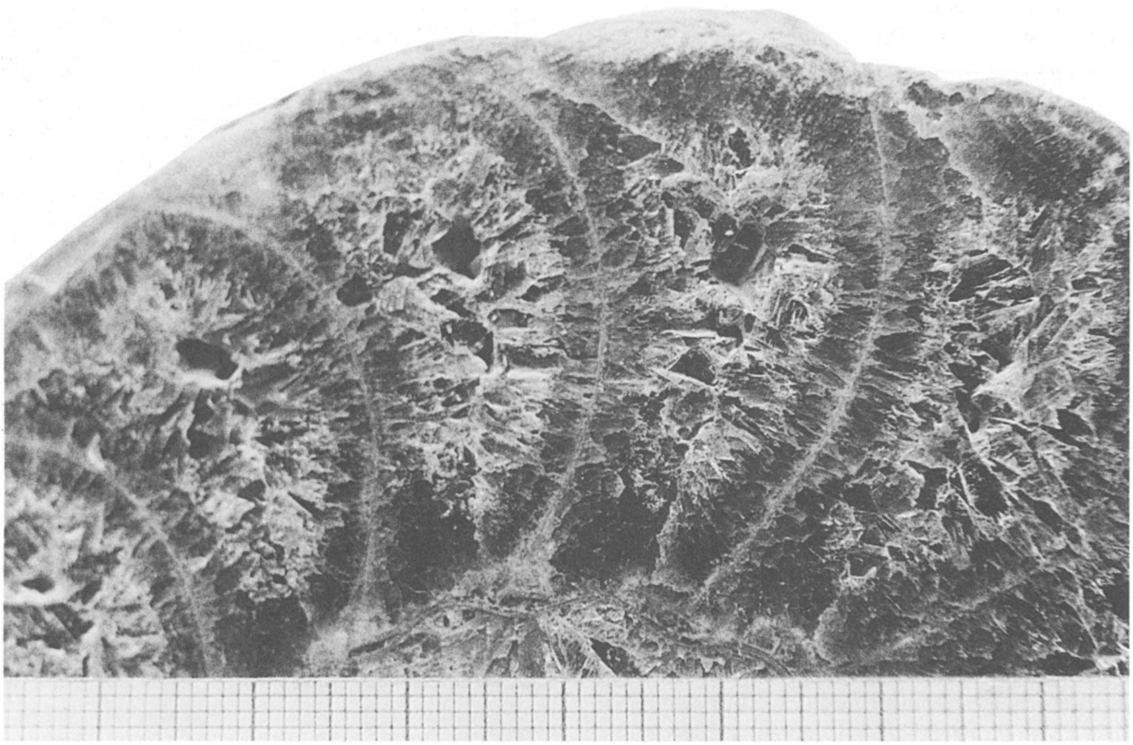


Fig. 5. Drusoidal infilling of the chambers in an ammonite by large calcite crystals growing normal to the walls.

fossil, an earlier concretionary crust or from the fact that the host sediment has been lithified before the voids were formed thus inhibiting further thinning of the layer. However, it must be pointed out that voids in this context should not be identified with empty spaces. Void-filling fluids (and associated fluid pressures) are of paramount importance in the preservation of void spaces because of their incompressibility and in balancing internal and external pressures.

Geodes: Geodes are a particular type of CB's with their core completely filled with crystallized minerals. Growth occurs inwards in geodes, while outwards in concretions, establishing a difference among them that can be of great importance as the outer crust may act as a shield for later throughput of brines. Van Tuytl (1916) and afterwards Hayes (1963) discuss the origin of chalcedony and quartz specimens in illustrative case histories. The latter describes a rather complete sequence of evolution from the primary calcite concretions to the final products of diagenetic metamorphosis, with some intermediate individuals illustrating the pattern followed.

Implosive and explosive features have been described in association with geodes. An inverse pressure gradient (lower in the fluid-filled core of the concretion) can cause its external crust to be crushed. The process is sometimes associated with the injection of fluidized clastic material into the hollow core (e.g. Hayes, 1963). Nevertheless, it has not yet been clarified if these cores remain hollow (and how and why) or if this condition is just the result of selective dissolution of a former cement. What shows up clearly from the existence of ''implosomes'' is that a hollow or relatively depressured chamber can only grow in the diagenetic realm until the increased load or a rise in external pore pressure breaks it down. The already mentioned fact of mud being squeezed in to the interior of the broken crust favors the existence of overpressured and non-cemented host layers at the time of breakdown and injection. It has been said that the most interesting feature of geodes (Pettijohn, 1976) is that they grow out of the expansion of a pre-existing gel bubble. The existence of some explosive textures (Bassler, 1908 as quoted in Pettijohn, 1976) was interpreted as evidence that geodes grow in the cavity of fossils, where colloidal gels started expanding until the fossil itself was broken into pieces expanding with growth. The weak point of this theory is that these fragments have not been identified and are supposed to finally dissolve or get lost during the process. Thererfore, no proof of their former existence remains. As a matter of fact, the author has failed to find any other mention of explosive mechanisms. The hydrostatic component of stress at depth leads to volumetric compaction, and makes it very difficult to accept that considerable dilation of the CB could be attained because of internal pressures during the ''blowing'' stage of geodes as several authors state, unless the external fluid pressure has fallen relative to the internal pressure. This may occur either because of overpressure during the growth of the geode and reaching afterwards hydrostatic values, or because the host layer rose (due to basinal uplift) to shallower depths after concretionary growth, with lower overburden and hydrostatic pressures.

Septarians: It is not absolutely clear if the term ''septarian'' refers to the crack set, to the concretion bearing it or to both. Most authors refer to ''septarian nodules'' or ''septarian concretions'' and to the ''septarian cracks'' as well. Others like Richardson (1919), who gave an accurate description of the structure and stated that it resulted from ''chemical dessication of a colloid'', used the expression ''septarian structure'' to describe both the body and the cracks. In the future it will probably be useful to distinguish between the CB displaying the cracks (nodule or concretion), the crack set (septarian cracks) and their infilling (septarian crystal linings and melikaria).

Although the crack set geometry identifies the stress field that caused it, it is still conjectural whether they result from the expansive force of inner fluids, shrinking of colloidal gels or synaresis of a cored mud bubble inside the CB. Furthermore, not all crack sets display the same geometry, probably reflecting different local stress patterns at the time of origin (see below).

Two complementary aspects of crack sets in septarians will be discussed. One is the geometry of crack set arrays, and the other their mechanical interpretation. The best examples of septarian cracks display a double set of fracture systems. One is radial and characterized by polygonal intersections of fracture planes that can look like joint surfaces (see Fig. 6) The other displays a wedge-like geometry that thins outwards and ends before reaching the exterior. A hollow core may result from the coalescence of wedges towards the interior of the concretion. Hollow cores can host a couple of offspring in unusually large concretions as illustrated in Boles et al. (1985). The radial array is cross-cut by concentric fractures that are usually better developed (their walls are widely separated) closer to the radial cracks. In theory radial cracks should intersect each other displaying a pentagonal pattern due to the fact that the pentagon gives a regular and complete covering of the spherical surface leading to a dodecahedral body. The development of pentagonal crack patterns should be interpreted as the result of the homogeneous distribution of stresses in the spherical body the same way as hexagonal joint columns and layer parallel joints develop in tabular bodies and will result in a sphere composed of pyramids with a pentagonal section all pointing to the center of the concretion. These pyramids are in turn cross-cut by the concentric fracture set accounting for radial contraction (equivalent to the layer parallel ones in tabular bodies). A different crack set array arises when two sets of mutually normal fractures appear, giving rise to a ''chocolate tablet'' structure (see fig. 157 in Comité des Techniciens, 1966). These fractures are preferably linked to deformation by overload (flattening of a precompactional CB) and not to radial contraction. A single or double set of vertical fractures in the core of the concretion can also result from local tensile stresses associated with stress amplification (see fig. 4.34 in Maltman, 1994). In this case no change in concretionary shape is associated directly with the fracture). This stress amplification could be related to contrasting rheological properties of the concretion and the matrix (see Lorenz et al., 1991). Perhaps new names should be given to the last two types of pseudoseptarian structures to distinguish them from the true septarians described first. When not completely infilled, fracture walls are generally lined with crystals in a druse-like way. It is not always clear if these spaces are primary features or the result of dissolution of a former solid core.

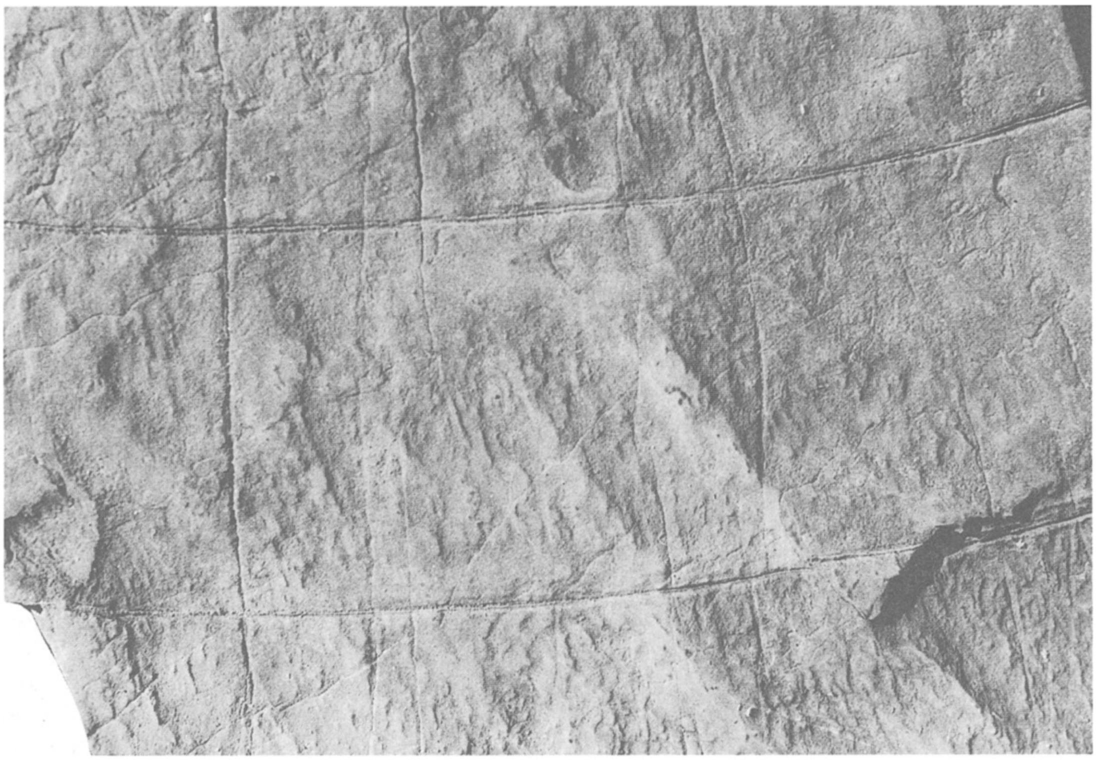


Fig. 6. Septarian cracks. Minute concentric and radial fractures decorating a large CB, about a meter in diameter.

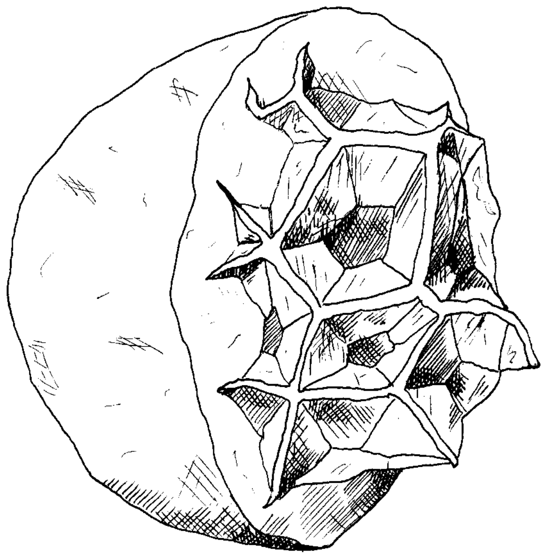


Fig. 7. Melikaria. Notice the almost perfect pentagonal shapes resulting from the intersection of septarian cracks. Sketched by the author after fig. 156 in Comité des Techniciens, 1966.

The infillings of septarian cracks are similar to those veins in their morphology (fibrous or more equant crystals) but are usually very complex in their mineralogy and isotopic signature, reflecting the evolution of parent solutions. In some cases it has been reported that fluids were contained in inner voids derived from the fractures when concretions were broken (e.g. Glover, 1957). Melikaria is the name given to the structure resulting when dissolution of concretionary material allows exhumation of crystalline infillings of the cracks which makes it easy to identify their spatial arrangement (see Fig. 7).

The complex mineralogy of septarian concretions and their infillings has led to intensive mineralogical and isotope studies suggesting that all those many successive stages of crystallization, would provide relevant information about the evolution of environmental conditions during growth. Hyde and Landy (1966), Raiswell (1971), Hudson (1978), Marshall (1982), Gautier (1982), Gautier and Claypool (1986), Dix and Mullins (1987), Boles et al. (1985), Siegel et al. (1987), Hesselbo and Palmer (1992) and Desrochers and Al-Aasm (1993), McKay et al. (1995) are being referred to.

4.2. Other relevant features of concretionary bodies and their hosts

A description of as many as possible different morphological, textural, mineralogical and isotopical features of CB's and host layers will obviously help to establish their relationships and to interpret their genesis, allowing to identify growth stages and formulate growth patterns. A discussion on the characteristics and interpretation of the most relevant features is presented as follows.

Concretionary texture: Texture in this context refers to the ratio of cement to clasts which is in turn converted into a pore–clast relationship during cementation. This proportion can be as high as 90%, reflecting almost syndepositional porosities, and decreasing to the lowest values when cementation has occurred, after compaction was completed. On the other hand, high porosity values in the CB can contrast with those in the host (sometimes less than 10%) giving clear evidence that compaction has been diachronous in the CB and its host layer. The particles embedded in the concretionary cement (both clasts and fossils) are usually the same that form the host rock unless differential dissolution of unstable mineral assemblages (intrastratal dissolution, see below) has been active prior to cementation. As a result of differential compaction, flaky particles and fossil remains trapped in the precipitated body, may not show any preferential orientation while a strong schistosity (due to mechanical reorientation, not to recrystallization) may be present in the host layer. This is clearly illustrated in the papers of Clifton (1957), Oertel and Curtis (1972), fig. 3), Dix and Mullins (1987) among others. Preferred orientation of clay minerals seems to develop in the very early stages of compaction and is enhanced by fluid content (e.g. Meade, 1966). As stated above, platy particles within the innermost parts of some precipitated bodies display almost random orientations, giving strong supporting evidence for the fact that compaction was precluded since the very beginning of diagenesis. Two reasons can account for preservation of open textures and random fabrics: Early cementation or inhibition of compaction by overpressuring.

Concretionary cements also serve as insulation shields for later alteration. Hennessy and Knauth

(1985) report radiolarians whose presence is restricted to the interior of concretions, having been leached from host rocks. Mineralogical analysis of clastic material trapped in the concretion can give additional insights into the original composition of the host layer, as most reactive species can be "fossilized" and protected by early cementation, while equivalent grains in the host are corroded and dissolved by intrastratal solution (see Friedman and Sanders, 1978, for fundamentals and Cibin et al., 1993, for a case history). In a similar way, the development of resurrected porosity is related to dissolution of early cements and may be associated with flow and storage of hydrocarbons. Jansa and Noguera-Urrea (1990) refer to high porosities (more than 30% of pore space) that are considered excessive after normal compaction trends at the involved depths (more than 3 km) and illustrate point to point contacts among clasts that are supposed to result from open fabrics (representative of the first hundreds of meters of burial) that have been preserved by early cementation and/or overpressuring and resurrected by dissolution of cement.

Relationships of layering inside the CB and in its host: This feature has long been recognized as an important criterion establishing time relationships of concretionary growth relative to host deposition and compaction. Although very few variations are possible, their interpretation has changed through time. Newberry (1873) (quoted by Criss et al., 1988) based on the pronounced arching of the beds above and below concretions thought that the concretions grew in partially consolidated sediment and that the arching resulted from subsequent compaction that deformed the sediments but not the rigid concretions (a point of view widely accepted at present). However, other authors like Daly (1900) as quoted in Tarr (1922), Tarr himself and more recently Woodland (1964, see his fig. 89), have interpreted this feature as proof of forced growth against a relatively plastic host. The interpretation of internal laminae in CB's also followed a controversial path. Tarr (1921) stated that internal laminae in CB's were primary features of concretionary growth on the sea bottom that developed independently from those in the surrounding sediments. More recently, Gilman and Metzger (1967) state that "The syngenetic character [of concretions] is also suggested by the beds which can be traced through the concretions suggesting that sedimentation of clay was going on at the time the carbonate concretion was developing". Present interpretations favor the hypothesis that internal laminae are trapped during concretionary cementation after (not along with) sedimentation.

The different relationships of laminae inside and outside CB's are illustrated in Fig. 8 and discussed below.

Layers that pass through median planes of concretions: A thin layer, relatively more clayey, occupies the median part of many concretions (e.g. fig. 7 in Gilman and Metzger, 1967, fig. 60 in Woodland, 1964 and plate XXXV 1 and 2 in Gresley, 1894).

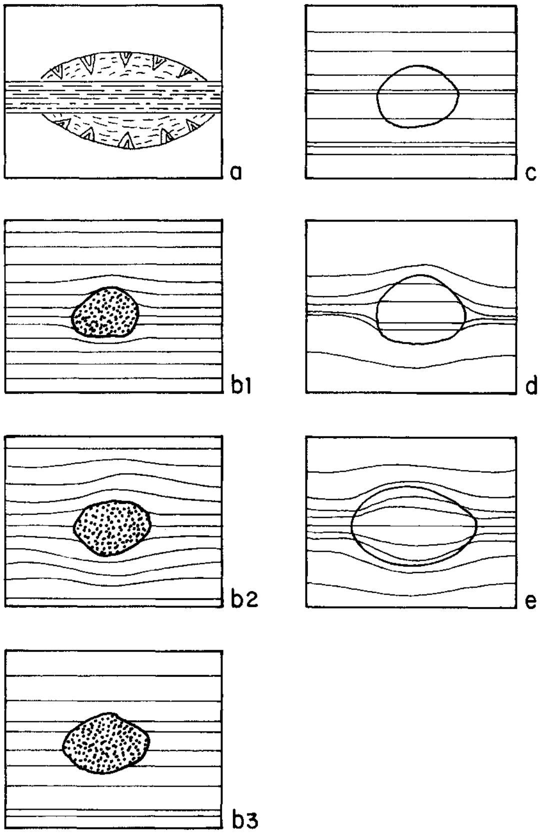


Fig. 8. Layering geometries inside/outside concretionary bodies. (a) Clastic layer passing through the median plane of concretion. (b) Nodule without internal layering (see text for discussion on subtypes). (c) Primary layering passing through the concretion. (d) Parallel layering inside the concretion and warping around it in the host. (e) Almond shaped layering inside concretion. See text for details.

Could the clayey layer have retained pore fluids for a longer period of time relative to the surrounding ones and have served as a fluid and ion source during concretionary growth? There is the possibility for these layers to channel flow in the cell and ''concentrate'' some chemical species in the CB. As long as no change in the thickness of this central layer is observed inside and outside the concretion, it must be concluded that it compacted uniformly and synchronously in both places. Fig. 8a illustrates this case.

Nodular CB's in layered hosts: This situation is depicted in Fig. 8b. The absence of clastic remains inside nodules limits their application to only three possible situations depending on the deformation or not of host layering. One is that of a syngenetic origin (Fig. 8b1). The nodule has grown on the sea bottom or at very shallow burial depths before perceptible compaction. Late compaction would produce warping of the layering around the nodule if early cementation has not consolidated the initial thickness of the host. This case is actually difficult to differentiate from the next one in normal outcrop conditions. The second possibility (Fig. 8b2) is displacive growth of the nodule during diagenesis, which would only occur if the host layer has sufficient plasticity (high fluid content, isotropic stress field) to allow deformation by concretionary growth. Warping of layering will be the result of nodular growth but part of the process may also be related to late compaction of the host, before it acquires complete rigidity. The third case reflects a replacive origin (b3). The nodule takes the place of pre-existing material (clastic and/or authigenic). Warping should not be expected in this case, but abrupt cut-offs in host layering against the nodule should be representative. Corrosive textures and detrital relics inside the nodule can be used as guides for the identification of its replacive origin.

Three additional cases can be envisioned when the clastic framework, and thus the primary sedimentary structures, are preserved inside concretions.

Layers in the host that pass through the concretion without changes: This relationship may generally reflect a late origin of the cementing material, that precipitated after compaction was completed (see Fig. 8c). There is a possibility of nodular replacement of an early cement that fossilized the texture before a large degree of compaction was attained, but evidence of corrosion would provide elements for differentiation. Concretionary Types IIa and IIb of Raiswell (1971, see his fig. 2), fall into this category.

Parallel layering inside concretions associated with warped layering and variations of thickness change in the host: The preservation of parallel layering inside the CB (Fig. 8d) reflects early concretionary growth before compaction of the host layer. Most examples in the literature describe this relationship although it is not always interpreted in the same way (Tarr, 1921; Clifton, 1957, fig. 5b and c; Hayes, 1963, figs. 5, 6 and 7; Weeks, 1957, plates 2 and 4; Franks, 1969 and Dix and Mullins, 1987). Slickensides have frequently been described on the surface of concretions and have been interpreted as proof for compactional friction.

Almond shaped layering inside the concretion associated with warping of layering in the host: This case reflects the synchronous growth of the external selvage of the CB with compaction of the host sediments. Fig. 8e illustrates this relationship. Compaction can result from normal trends or follow an OUC pattern. Distinction between these two alternatives is possible if the relationship of parallel layering in the nucleus of the concretion with bent layering in its selvage is weak. I.e. compaction was not precluded at any time during concretionary growth, as would be the result from overpressuring. This relationship is clearly illustrated in Clifton (1957), fig. 2; Marshall (1982); Hennessy and Knauth (1985); Criss et al. (1988), fig. 2; and also corresponds to Type I of Raiswell (1971), fig. I.

Outer rims: Many CB's have an outer rim of almost pure mineral composition (usually calcite, sometimes with cone-in-cone structures, others pyrite or marcasite). Rims are obviously concentric with the concretionary nucleus they envelop, and crystal fibers in them radiate. Marshall (1982) gives a detailed description of the mineralogy and chemical evolution of fibrous calcite in rims and veins, but it has not yet been succesfully explained why some concretions stop incorporating the clastic framework and develop an outer rim of almost pure material, producing an abrupt change in texture. It undoubtedly reflects important changes in environmental conditions. Under abnormal fluid pressures, the influx of pore fluids into the mechanical discontinuity underlying the contact between the cemented sphere and the surrounding material, will be enhanced by local magnification of stresses (see Lorenz et al., 1991). This influx would push host sediments aside making room for the rim to grow following the crack-seal mechanism described above. The possibility that the cemented nucleus could experience some contraction due to mineralogical changes or loss of fluids, must not be ruled out when searching for mechanisms that can make room for the rim, nor the fact that the hydrostatic component of stress at depth would enhance volume reduction, if the CB retains any porosity and plasticity. Top and bottom vein-like fibrous layers (usually with cone-in-cone structures) are sometimes associated with concretions although they do not feature a complete rim.

Orientation of fibre crystals: Calcite crystals in veins or rims generally show a distinctive shape (bladed crystals, beef structure) and orientation pattern. Their long axis is normal-to-the-walls of tabular veins or almost radial in spherical bodies (see stereoplots in Woodland (1964), fig. 86). Fibres in this context are different from needle crystals and related forms associated with pores in soils, etc. as described in Jones and Kahle (1993), Aassoumi et al. (1992) and in Aso et al. (1992). Gonzalez et al. (1992) assign the fibrous shape of calcite crystals in speleothems to circulation of fluids during crystallization, and suggest that this can also work for syngenetic and diagenetic cements. This may be possible in an unstressed environment but the orientation and morphology of calcite fibers infilling fractures at depth, should be more related to stress patterns than to fluid flow direction. Extensive work on this subject is still required to define where, when and up to what degree each different parameter plays a leading role.

Fossil remains within CB's: These sometimes occupy the centre of the concretion. Others are flattened along its median plane or dispersed within it when relatively small. Fossils are closely associated with CB's. This relationship is not fortuitous. Mechanical and chemical reasons can be invoked to explain it. The fossil–sediment contact may be an active surface controlling fluid circulation (e.g. Brown, 1954). The decomposition of organic matter is generally assumed to play a leading role in the control of chemical reactions during burial, including those leading to the CB's formation (Sondheimer et al., 1966; Berner, 1968). In several cases, uncompressed bodies remain as illustrated, amongst many others, by Weeks (1953, figs. 2, 3 and 5); Weeks (1957, plates 1 and 4); Sondheimer et al. (1966); Pepper et al. (1985); Criss et al. (1988, fig. 8B), giving unequivocal evidence for the preservation of the original volume of the organism and posing the question of how compaction was inhibited until fossilization was completed. The preservation of delicate fossil structures inside the concretions (Woodland, 1964; Hudson, 1978) also implies that no actual compaction affected the fossil before cementation. This author describes a complete succession of different degrees of fossil preservation in concretions growing at different times during burial and diagenesis of the host sediments. The degree of preservation and that of preferred orientation of fossils inside and outside the concretions is undoubtedly one of the strongest arguments for clearly establishing the relative timing of concretionary growth and early dissolution episodes, as has been emphasized in previous paragraphs. Intriguing relationships in taphonomic studies, arising from contradictory evidence of well preserved and crushed specimens occurring together, can easily be related to selective concretionary growth that protected some species or individuals but not others. This protection has to be associated not only with mechanical crushing but also with intrastratal dissolution.

Local expansive structures: Expansive structures lead to an increment in the volume of host material. Only a few mechanisms can produce actual expansion under normal conditions. The most relevant ones, during diagenesis, are pore volume increase due to overpressured fluid injection, displacive growth of CB's and expansive veining. Pore volume increase by fluid injection is restricted to highly overpressured horizons and can result in liquefaction and reprecipitation or even in fluidization and forced injection of the material into neighboring fractures which will be discussed further on. Displacive growth is usually limited to those cases in which host material is soft and plastic (see previous discussion). Expansive veining (pseudodisplacive growth) is also associated with overpressure that keeps fractures open. Brown (1954) and Woodland (1964) describe different cases of a fibrous vein separating upper and lower parts of fossils. This feature points to the fact that both parts, initially in close contact, have been pushed apart during vein growth. Examples in Woodland (1964), figs. 68 and 69, clearly show how matrix and/or calcite are introduced into the sedimentary framework, separating elements that were formerly side by side. Hudson (1978) describes the mould of an ammonite which has evidently broken from the shell and is separated from it by a thin layer of calcite. There are several similar ones in the collection of the Geology Department of the Universidad de Buenos Aires, considerably larger than the one described in Woodland (1964). It displays a central parting where the neat design of a *Thysanopyge* can be found as a positive and a negative impression (see Fig. 9). The external surface of the concretion (top and bottom) shows all the morphological features of the fossil finely outlined by small circles resulting from cone-in-cone structures.

Cone-in-cone: Veins and rims of concretions displaying cone-in-cone structures have been extensively described in the literature. Gresley (1894), Tarr (1922), Brown (1954), Woodland (1964), Franks (1969), Becq-Giraudon (1990) have described their morphology and suggested different mechanisms of origin (see discussion in Selles-Martinez (1994). This author has proposed his own model assuming that cone-in-cone structures result from mechanical fracture of the material forming layer parallel veins and rims of concretions. Conical fractures in this model result from the effect of overburden load (formerly supported by fluid pressure during vein or rim growth) on the detrital skeleton. Shear stresses fracture the rigid crystalline material but not the host layer (still wet and uncemented). This model was proposed to account for some shortcomings in previous models, like the fact that not a single vein bearing cone-in-cone structures has been described with a non layer-parallel structural trend. If crystallization forces fracture the veins and shape the cones in horizontal veins, there is no reason why they cannot do the same in a vertical one. The hypothesis which relates cone-in-cone structures to the growth of conically shaped aggregates of needle crystals, fails to explain the patterns in the stereoplots illustrated in Woodland (1964). In a conical distribution, poles form a girdle with very few data in its center (like those found when plotting striae on shutter cones, see fig. 3 in Hargraves et al., 1990) and not a circle of homogeneous density. These arguments among others (see discussion in Selles-Martinez, 1994) show how most of the proposed mechanisms contradict several observations that are explained by the OUC model.

Depressions in upper and lower surfaces of concretions. The presence of depressions in the center of upper and lower surfaces of concretions (''Funnel shaped depressions'' of Criss et al., 1988) were explained by Clifton (1957, figs. 1, 2 and 4) stating that after most of the concretion was formed ''further crystallization builds up ridges around upper and lower surfaces of large concretions, leaving depressions on top and bottom'' because ''water circulation would build up material in a ring at the top and bottom, giving a depression at the very center, since the waters reaching this point would already have lost their mineral matter and none would be deposited''. Hudson (1978) atributed them to the collapse of the central structure of concretions, but if that were the case bending of the layering inside the concretion should reflect this collapse.

5. Stages of concretionary growth

The terms ''scenario'', ''stage'' and ''setting'' have all been used to represent the complex environmental (physical, biological, mechanical and chemical) conditions associated with a particular location in a sedimentary basin. They are also almost equivalent to ''environment''. Maybe this is a case of oversaturation of terminology. The meaning of the term ''stage'' is indeed twofold. On the one hand, it is synonymous with ''scenario'' (like the one in a theatre) as it describes the environmental features (the scene) where the CB, its morphological features and growth mechanism must be placed. On the other hand, it means ''step'', that is to say a particular point in a succession of events. In this sense we can distinguish different stages (steps) of the evolution of a CB in a single or several different stages (settings). Changes in each type of stage may or may not coincide. The development of septarian fracture-sets in a concretion is undoubtedly an important stage in

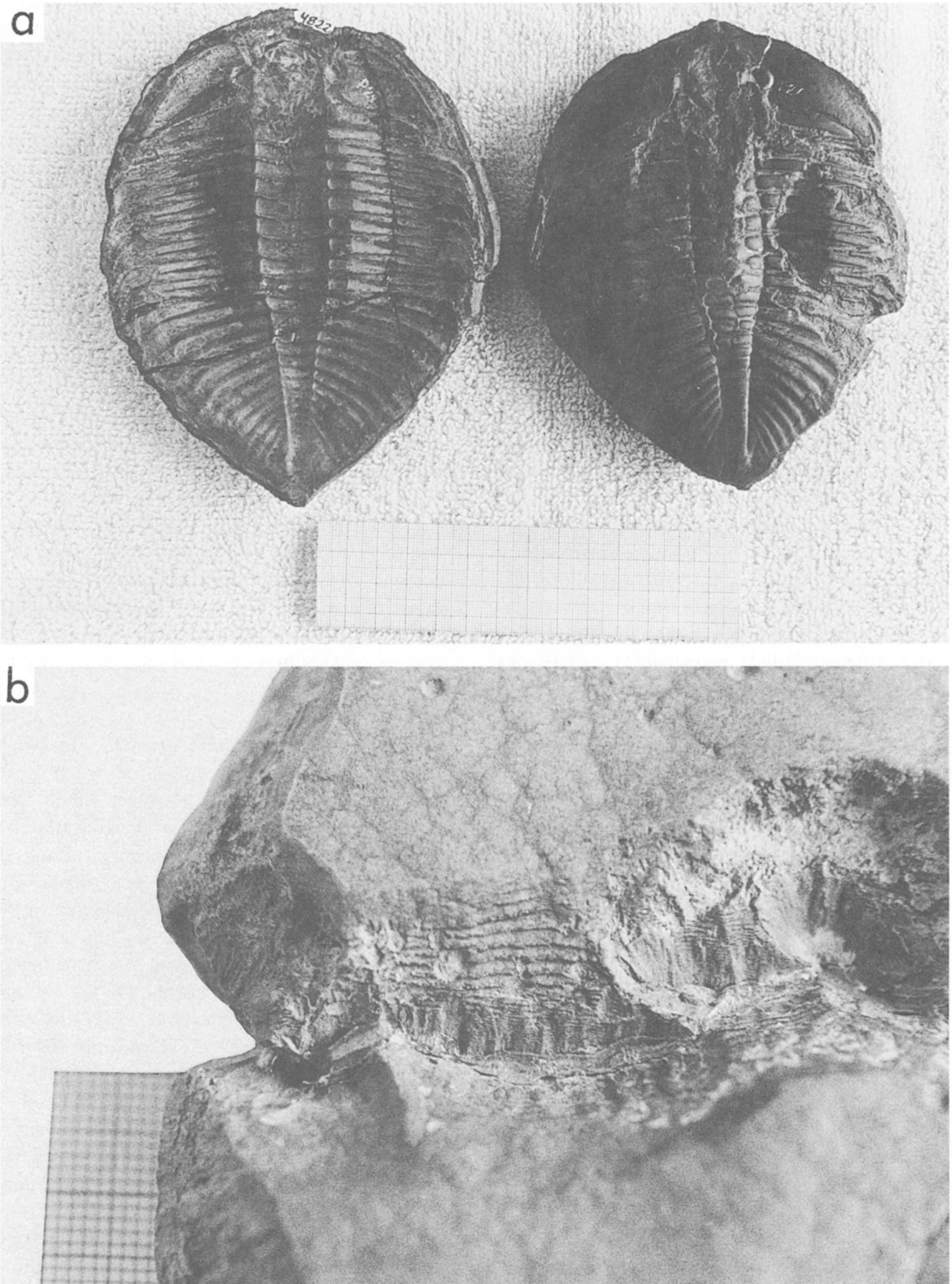

a
b

Table 4
Different concretionary growth stages established by several authors. See discussion in text

Reference feature	Richardson (1921)	Tarr (1921)	Pantin (1958) and others	Hudson (1978)	Dix and Mullins (1987)	This paper
	Contemporaneous	Syngenetic	Syngenetic		Depositional Stage	Syngenetic
Sea bed						
				Early diagenetic	Early diagenetic I --- 10 m	
				--- 100 m		
	Penecontemporaneous	Epigenetic	Diagenetic	Middle diagenetic --- 500 m	Early diagenetic II	Diagenetic
					Intermediate diagenetic	
			--- Few thousand yr		--- 2000 m	
Complete consolidation				Late stage diagenesis	Late stage burial diagenesis	
	Subsequent		Epigenetic			Epigenetic

its evolution, but this feature is, in fact, not related to any dramatic change in the regional stage. An important conclusion of this review would probably be that in most cases concretionary growth histories are so complex that in place of assigning each CB to a particular stage (a rather rigid framework) it would be better to define their growth paths, in the same way P–T–t paths are reconstructed from metamorphic assemblages. Growth paths, in this sense, can make their way through different growth scenarios, different associations of physico-chemical parameters with time and/or depth, and, of course, they can also be characterized by a variable number of successive steps. The latter reflect changes in mineral composition, development of new textural or structural features, etc., as a consequence of synchronous changes in macro- or microenvironmental conditions.

5.1. *The three traditional stages*

Three main different environments have long ago been proposed in relationship with the timing or depth at which the concretionary growth is initiated. As shown in Table 4, these scenarios have been given different names by the authors who described them. Tarr (1921) proposed two categories of origin, calling those concretions forming at the same time as the enclosing beds "syngenetic" and those which have been formed subsequently to the deposition of the surrounding beds "epigenetic". He also discusses classifications used at his time, indicating that many interesting criteria for relative relationships of textural features appeared early in the century. Pantin (1958) suggested replacing the terms "contemporaneous", "penecontemporaneous" and "subsequent" established by Richardson (1921) with the already quoted "syngenetic", "diagenetic" and "epigenetic" equivalents. Weeks, in his twin papers of 1953 and 1957, distinguished only between "syngenetic" and "diagenetic" origins; "diagenetic" being a subordinate category restricted to those bodies growing shortly after deposition of host sediments. He classified the CB's in his studies as "syngenetic" or "early diagenetic" on the basis of preservation of the volume of fishes in the centre of the concretions (which he used as evidence of very early concretionary growth, before any compaction could have deformed the fossil carcass) and because host layering was bent around the concretion (evidence that compaction postdated concretionary growth). Clifton (1957, p. 120) noted that several authors used the term "epigenetic" to refer to the fact that growth of the concretion postdated compaction and consolidation of the host shale. Although he assigned an epigenetic origin to the particular bodies he was studying, he stressed that compaction did not fully

Fig. 9. A *Thysanopyge*-bearing concretion. (a) Positive and negative impressions of the fossil in the central parting of the concretion, (b) Layer-cake structure shown in a broken zone of the concretion.

preceed concretionary growth but was instead synchronous with it during a certain time span (a relationship that would be interpreted as diagenetic by other authors). Pantin (1958) also related concretionary growth to the degree of compaction of the host. In his classification all those CB's growing at the water–sediment interface, are considered of "syngenetic" origin; all those being formed under slight overburden and along with sediment compaction are assigned a "diagenetic" one and, finally, of "epigenetic" origin are considered all those late CB's which grow after the compaction and consolidation of the host. Although he did not give relative depths in his classification, he assumed a time span of less than a few thousand years as being characteristic of the "diagenetic" stage between the end of the "syngenetic" and the beginning of the "epigenetic" ones. His definition of "epigenetic" is more restrictive than previous ones, which made no clear distinction between "consolidating" and "consolidated" materials. This had an important influence on the application of the force of crystallization and the concretionary growth force hypothesis to explain concretionary growth at this stage. Later on, Raiswell (1971) pointed out that current classification criteria were ambiguous and that the use of inadequate terminology had introduced much confusion in the literature (Raiswell (1971), p. 148). This author analysed some previous definitions and criticized the misuse of textural criteria. Several years later, Hudson (1978) proposed four stages of evolution, namely "depositional", "early diagenetic", "middle stage digenetic" and "late stage digenetic". Although these terms seem to be easily correlated with the former, the author himself prevented any attempt to relate his stages to other definitions. He argued that these were relative terms that did not have the same meaning in terms of pressure, temperature or pore brine composition or even time after deposition in different sedimentary basins. He did had a point. Although a discussion on the exact definition of the term "diagenesis" and the physicochemical parameters that define it, is beyond the scope of this paper, it is worth paying attention to the fact that it is far from being a simple stage in itself and its limits are rather difficult to establish under certain circumstances. The fig. 9.1 and table 9.1 in Boggs (1992) are clearly illustrative of this.

Much confusion about the use and assignment of any concretionary growth scenario has arisen from the overgeneralization of conclusions (this attitude being more noticeable in the pioneers, who believed that all concretions should have grown in the same way). Concretionary growth mechanisms, as demonstrated by morphological and chemical features, are representative of a certain layer or even a certain basin, but can not easily be correlated with those occurring in other layers or basins. Moreover each CB type has its own history, which can be rather different from other CB's in its neighborhood, displaying different morphological and/or mineralogical features, no matter how slight these differences are.

In the following paragraphs a brief description of each of the three categories is presented, followed by some remarks on the characteristics and usefulness of concretionary growth patterns. The section is completed with the presentation of the Overpressured-Undercompacted Cell Model, an alternative growth patterns for CB's, developed to overcome several incongruities in previous models, along with several comments on the possibility of displacive growth and compaction of the host to proceed synchronously.

The Syngenetic Stage: This stage was originally representative of concretionary growth on the sea bottom. Three main features have been used to characterize the syngenetic stage: the first is bending of the layering over the concretion; the second, the fact that in most cases concretions are related to a single layer or even to a more or less regular surface and, the third, the relatively high cement to clast ratios in the cores of concretions. Since the beginning of the century, many CB's in the sedimentary record have been interpreted as having a syngenetic origin based on the first of these three features. This bending was supposed to be the result of sediment deposition on the preexisting CB, see Tarr (1921, fig. 1), and also of the uplifting of this layer by the growing body itself. This geometry is different from the usually symmetrical to median plane wrapping of the host layer around concretions. The layer on which the concretions are supposed to rest is mostly undeformed and those other layers overlying them are the ones that are deformed. Wedge-shaped edges around concretions resulted from sliding of sediment grains from the top of the concretion during sedimentation. These and other statements, like the one about calcite layers precipitating directly from sea water, no longer hold. Assessing a syngenetic origin on the basis of concretionary alignment on a continuous surface, that was supposed to be representative of the sea bottom at the time of growth of CB's, is not a tenable statement any longer. Most concretions with a diagenetic origin, also display such a spatial arrangement.

Open textures with only few point-contacts among clasts are no doubt representative of the sea bottom and the first centimetres of burial where sediment weight is still neglegible, but not exclusive. Upwelling waters, released from underlying compacting strata, may form subaqueous springs and transfer their kinetic energy to the unbonded clasts in the uppermost sediments, allowing them to enhance their porosity and to maintain a fairly open fabric under moderate overburden. During diagenesis, late liquefaction of loose sediments in overpressured horizons can also reset textural parameters to depositional conditions at considerable depths and long after initiation of burial.

Several authors extended the realm of the syngenetic stage to the uppermost centimeters of sediment on the sea bottom. Along this line Prokopovich (1953), Harris (1958), Sondheimer et al. (1966), Oertel and Curtis (1972) among others, classified the CB's they were analyzing as syngenetic. Gilman and Metzger (1967) and Gilman (1968) classify as of syngenetic origin concretions that are almost identical to the ones that Franks (1969) classifies as diagenetic. Problems with isotopic compositions have challenged the syngenetic origin in several cases, a subject already discussed at the beginning of this paper.

Present-day examples of syngenetic precipitates have been quoted in the literature (e.g. nodules growing at the water–sediment interface have been described from present-day environments by Mc Kelvey, 1986). Oolites and pisolites are also assigned a syngenetic origin.

The Diagenetic Stage: This stage is the broadest. According to Boggs (1992) the realm of diagenesis extends from the depositional interface to perhaps 10 km or more, covering a wide range of environmental situations and processes from weathering to metamorphism, from which diagenesis cannot easily be differentiated under certain circumstances. Pressure and temperature variations may usually cover a range respectively, from almost atmospheric to about 2 Kb and from a few centigrades to 300 centigrades. Many subdivisions of the diagenetic realm have been proposed, see e.g. Boggs (1992, table 9.7), a subject that will be omitted in this review. Anyway, the most relevant processes during diagenesis are: (a) loss of primary structures and compositional mixing if bioturbation is active, (b) gradual compaction with progressive burial unless (and whilst) fluid pressures arrest the process, (c) biochemical reactions that modify the chemistry of brines and (d) chemical reactions leading to dissolution and precipitation of new minerals resulting in concretionary growth.

Concretionary bodies grown during this stage show a great variety of mineralogies. Differences may be found not only between CB's coming from different basins or formations but even between those belonging to a single outcrop, although concretionary types tend to be uniform in each host layer. This does not imply that CB's with different morphologies and mineralogies may not coexist in the same layer. This type of association of different CB types is not uncommon and results from complex evolutionary paths of host layers. Assessing relative timing of growth is not an easy task in these cases but several successful attempts have been made (see Raiswell, 1971 and Jansa and Noguera-Urrea, 1990 for case histories of concretions and cements respectively). Most chemical changes in the sediments and pore fluids take place in the diagenetic realm. Reduction of sulfides, oxidation of organic matter, gas and hydrocarbon release, corrosion and replacement of clasts or early cements by new minerals, are among many other processes that characterize this stage. The CB's analyzed in Pantin (1958), Hayes (1963), Oertel and Curtis (1972), Hudson (1978), Gautier (1982), Pepper et al. (1985), Boles et al. (1985), Criss et al. (1988), Bain (1990), Desrochers and Al-Aasm (1993) and Cibin et al. (1993) were assigned to the diagenetic stage under little overburden (from a few centimeters to about 100 meters). McKay et al. (1995) offer an interesting analysis of the different diagenetic evolution of a set of CB's of varied compositions, relating them to the original depositional environment in the basin. Direct observation of present day diagenetic environments has been provided by the oil industry, which gathered mechanical, physical and chemical data from the subsurface. Its findings, related mainly to actual relationships between host lithology, CB features, state of consolidation, fluid content, fluid pressure and chemistry, temperature, etc. have been of invaluable importance.

The Epigenetic Stage: This stage, at the frontier of diagenesis, where it is not always easily differentiated from the lower stages of metamorphism, has been stated on the assumption that concretionary growth occurred by displacive mechanisms. Evidence of an epigenetic origin was the bending of schistosity around CB's (the same evidence used for the syngenetic scenario). Lateral deformation (folding or fracturing) of the host layer at the edges of the concretion is to be expected in this situation, but such features have not been described in the literature. Finding examples of epigenetic CB's is not so easy, probably because, as has already been mentioned, very diffuse boundaries separate them from metamorphic conditions. Colombian emeralds associated with carbonate–pyrite veins hosted by black shales are "undoubtedly epigenetic" (Cheilletz et al. (1993)), but they are associated with hot basinal brines whose temperature (not composition) cannot be explained without an external heat source. It is important to point out that these emeralds are clearly associated with overpressuring and brecciation. The most important challenge to the growth of authigenic mineral bodies (both veins or concretions) in the epigenetic scenario is the need to push apart the host rocks in order to make room for the newly crystallized minerals (which would not be the case if growth occurs by replacement). This paper proposes that the epigenetic scenario is unrealistic in that it does not take into account that indurated sediments require large shear strains to be deformed, values that are quite beyond the capabilities of crystallization forces (see previous discussion on the subject). Concretions can grow late in the diagenetic evolution both by replacement or displacement mechanisms, but in the latter case deformation of the host material is not possible if it has a shear strength greater than that of the challenger, so it will probably be restricted to those layers that have remained unconsolidated or have lost their resistance due to the breakage of their bonds by mechanical collapse (overconsolidation or underconsolidation under increasing fluid pressures). Most of the cases assigned to this stage must be applied to the OUC model which better accounts for the observed features.

5.2. Growth patterns

The incorporation of growth patterns description into classification systems (while being careful to avoid establishing fixed links among them) is probably a reasonable solution to the problem of assigning CB's a growth stage. Descriptions and interpretations of concretionary growth patterns are still mainly restricted to specialized papers and most text books usually ignore them. Hudson (1978), Dix and Mullins (1987), McKay et al. (1995) and also Craig (1985) (in Collinson, 1994) produced illustrative diagrams relating concretionary morphology and chemistry to environmental conditions, as Jansa and Noguera-Urrea (1990) and Prosser et al. (1993) do in the case of cements. This type of infographies needs probably to be complemented with others that will provide valuable additional information displaying a variation of physical parameters (pore pressure, degree of compaction) in the basin as a function of depth and/or time. The variations in the relationship of compaction with depth (and time) should highlight under which circumstances overpressures can result in fluidization or fracturing, or even reflect episodes of uplifting in the basin that would not be noticed by any other means.

The overpressured–undercompacted growth pattern: The review of features, successes and pitfalls of existing growth scenarios for CB's lead the author (Selles-Martinez, in prep.) to propose an alternative growth pattern. This model provides results that look contradictory compared with previous ones and is characterized by the early development of hydraulic seals resulting in the isolation of a portion of the basin (here called a "cell"). This isolation inhibits normal compaction trends and allows accumulation of abnormally high pressures in the cell. The uncompressible quality of overpressuring fluids preserves initial porosities during a considerably longer stretch of the diagenetic path than suspected before. Different stages can be identified during this process of rise and fall in fluid pressure. These stages are associated with the precipitation of neominerals, changes in packing and migration of fluids summarized in Fig. 10. Authigenic precipitation can proceed at any stage in the evolutionary path from the sea bottom to the onset of metamorphism (see Table 5). The new model, requiring only the persistence of a sealed cell where abnormal pore pressures last for a long time, does not imply that brines should be immobilized, but just requires the persistence of unbalanced rates of fluid input–output to and from the cell. Depending on the size of the sealed cell and the magnitude of fluid exchange, important variations in fluid composition can take place due to "in situ" reactions. The application of this model to the analysis of strained oolites (Selles-Martinez in prep.) also simplifies previous interpretations (Chanda et al. (1977)) relating them not to complex local stress patterns and strain histories in the diagenetic scenario but to a simple concretionary growth path under OUC conditions. Oertel and Curtis (1972), p. 2604, pointed out that much of the stress exerted by the overburden is supported by fluid pressure in the pores and stressed how relevant this is for preservation of open textures during the syngenetic stage. Restricting the possibilities to the highly porous clays

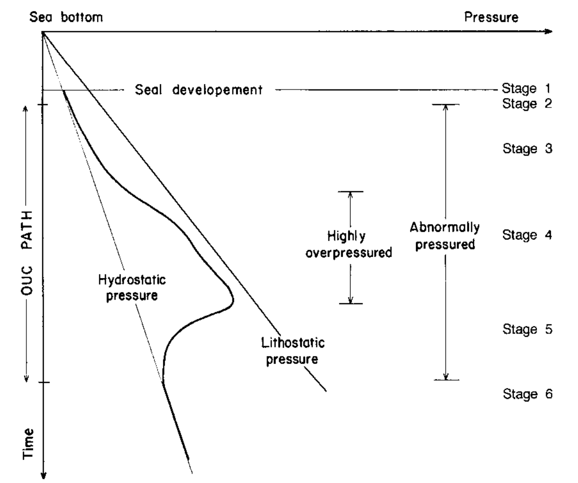


Fig. 10. The overpressured–undercompacted cell (OUC) model for growth of concretionary bodies. See Table 5 for relationships with concretionary body types.

Table 5
Concretionary body types and its characteristic environment of growth in the overpressured–undercompacted model. Numbers refer to stages in Fig. 10

Concretionary type	Environment					
	1	2	3	4	5	6
Cement		–				–
Veins			–			
Nodules	–	–				–
Concretions	–	–	–			–
Geodes		–				
Drusoids		–				
Implosomes			–	–		
Septarians						–
Other features						
Hydraulic dikes				–		
Cone-in-cone					–	
Schistosity in host						-

in the top several meters or so of fluid rich sediments and disregarding the possibility of preservation of those open textures in overpressured systems, are the main differences between their proposal and the OUC model. Fig. 11, based on a real stage (see Grauls and Cassignol (1992)) depicts a probable OUC setting.

The syncompactional growth mechanism: When the growth of CB's in the form of veins and nodules is analyzed from a mechanical point of view the need of fluid pressures high enough to actually lift the overburden in order to make the necessary room is acute, becoming a serious challenge to current interpretations of concretionary growth. Fluid pressures exceeding those of overloading can provide the means, but even though fluid pressures higher than hydrostatic ones (and close to the overload pressure) have been reported from all over the world, mention of pressures exeeding lithostatic ones seems to be rare, if any. The possibility of transient fluid pressures exceeding the lithostatic value during short periods of time due to meteorological or tectonic causes is discussed in many contributions (e.g. Maltman, 1994; Hickman et al., 1995) and can provide an alternative explanation in several cases but not in all. Anyway, fluid pressures in the sedimentary basin may remain below lithostatic values without any requirement of actually uplifting the overlying sedi-

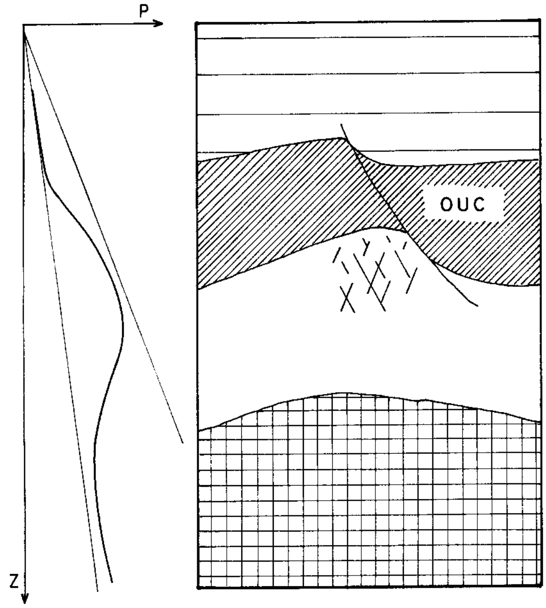


Fig. 11. Sketch of a large scale overpressured–undercompacted cell (based on Grauls and Cassignol, 1992). This case history is similar to the OUC model of concretionary growth. Total depth in the section is about 4 km.

mentary column to make room for expansive growth if it occurs in loose sediments. The OUC model suggests that the CB grows not "against" compacted host material (as traditionally established for the epigenetic stage) but "whilst" it is being compacted. The room is taken from the porosity itself in the way depicted in Fig. 12 through the reorganization of the sedimentary fabric (changes in packing and/or reorientation of platy particles). Almost paradoxically, the CB acquires greater and greater volumes whilst the host layer compacts and thins with time.

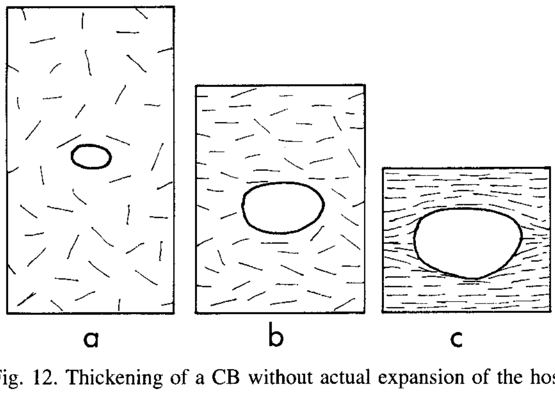


Fig. 12. Thickening of a CB without actual expansion of the host layer. Due to the fact that the host layer is water saturated and fluidized (isotropic stress field) the CB can grow almost freely. (a) Random fabrics and open textures with very few clast to clast point contacts are preserved. (b) Onset of host compaction due to the continuous fall in pore pressure. The CB can continue growing with decreasing cement to clast ratio. (c) Development of compactional schistosity in the host with lose of fluids.

6. Discussion and conclusions

Authigenic mineral segregates show a great variety of types that were described in previous chapters. This makes it possible to attempt several different classifications. Most of their morphological and textural features have been used as a guide to interpret their growth scenarios but some of them have proved controversial. For example, warping of the layering around the concretionary body has served as proof of a syngenetic origin if related to synchronous deposition of sediment over the concretion while it grew, as evidence of a diagenetic one if it was supposed to be the result of late compaction of the host around the already formed concretion or even of epigenetic origin if it was thought to be the product of displacive growth. The exact meaning of the terms "syngenetic", "diagenetic" and "epigenetic" is now a puzzle, probably because, from the beginning, they had been assigned ambiguous time and depth connotations. As shown by most case histories, the growth pattern of a concretion from early nucleation to late replacement may start under syngenetic conditions and end (or even continue) when almost metamorphic conditions are reached. In such complex cases, assessing a genetic category seems meaningless and the definition of a "growth path" seems more appropriate. Relative timing is generally assessed through textural relationships of CB's and their hosts and, if this relationship is established on the basis of classification (without assuming any environmental stage) the probability of ambiguities and misuses would be less. Terms like "precompactional" and "postcompactional" are clear in themselves if no absolute depth implications are provided. On the other hand concretionary growth can be displacive and replacive in any of the proposed stages and therefore cannot be used as a criterion to differentiate between them. Mineralogical and isotope relationships, in the new context of the OUC cell model, will probably provide accurate timing for the main authigenic precipitation and dissolution events without being puzzled by textural relationships as before.

The OUC model overcomes these and other conflicting features and also offers a likely solution to the problem of space for concretionary growth, assuming that growth takes place accompanied by the flow of fluid-saturated uncemented host around the CB, in a process that can simultaneously lead to the enlargement of the CB and compaction and thinning of the host layer. Extremely high porosities (similar to those found on or just below the present sea bottom) when preserved in CB's would reflect not only their growth in the uppermost centimetres of the sea bottom (which is difficult to accept for a spherical concretion 2 m in diameter) but also the preservation of high porosities in overpressured cells, resulting from the development of an early hydraulic seal.

The OUC model will help to identify formerly overpressured cells where chemical reactions and their products could be different from usually expected ones for similar lithologies and diagenetic patterns and would be enhanced by the great amount of fluid available. It could also help to identify the former presence of seals in oil producing sequences, which are relevant in order to establish time and depth of maturation.

Identification of areas of potential fracture porosity related to hydrofracturing would be another application of the model, if it is taken into account that hydrofracturing is not unusual in modern and ancient producing fields and UOC path-related CB's may be indicative of fracturing in the neighboring strata. These fractures and dikes may act as horizontal barriers or conduits to flow depending upon their infillings.

Assessment of the least initial thickness of concretionary bearing horizons may be achieved assuming porosity in the CB to be representative of the depositional one. The recognition of OUC patterns will also help paleontologists in their taphonomic studies as it illustrates that variations in the degree of preservation of some species or individuals are associated with post-burial processes and are not primary features. In the field of economic geology, the OUC model will be useful in the interpretation of the genesis of some oolitic and stratabound deposits.

Many redefinitions have been proposed in order to simplify current terminology, and new suggestions have been made with the purpose of finding better explanations for the origin and mechanisms of growth of concretionary bodies. These proposals appear to explain some of the previous troublesome features better, but... "An irrefutable answer may never be found" states Clifton (1957).

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References

Aassoumi, H., Broutin, J., El-Wartiti, M., Freytet, P., Koeniger, J.C., Quesada, C., Simancas, F. and Toutin-Morin, N., 1992. Pedological nodules with cone-in-cone structure in the Permian of Sierra Morena (Spain) and Central Morocco. Carbonates Evaporites, 7(2): 140–149.

Aso, E., Gisbert, T.J. and Valero-Garces, B., 1992. Type septaria-cone-in-cone nodules in the Stephano-permian of the Catalan Pyrenees. Carbonates Evaporites, 7(2): 2132–2139.

Bain, R.J., 1990. Diagenetic, nonevaporative origin for gypsum. Geology, 18: 447–450.

Barker, C., 1987. Development of abnormal and subnormal pressures in reservoirs containing bacterially generated gas. Am. Assoc. Petrol. Geol. Bull., 71(11): 1404–1413.

Bassler, R.S., 1908. The formation of geodes with remarks on the silicification of fossils. U.S. Nat. Mus. Proc., T 35: 133–154. (See reference for Pettijohn, 1976).

Becker, G.F. and Day, L., 1916. Note on the linear force of growing crystals. J. Geol., 24: 313–333. (See reference for Weyl, 1959).

Becq-Giraudon, J.F., 1990. La structure cone in cone en milieu de depot siliclastique. Observations nouvelles sur les cones. Geol. France, 2: 11–20.

Behrmann, J.H., 1991. Conditions for hydrofracture and the fluid permeability of accretionary wedges. Earth Planet. Sci. Lett., 107: 550–558.

Berner, R.A., 1968. Calcium carbonate concretions formed by the decomposition of organic matter. Science, 159: 195–197.

Bishop, R.S., 1979. Calculated compaction states of thick abnormally pressured shales. Am. Assoc. Petrol. Geol. Bull., 63(6): 918–933.

Boggs, S., 1992. Petrology of Sedimentary Rocks. Macmillan, New York, 707 pp.

Boles, J.R., Landis, C. and Dales, P., 1985. The Moeraky boulders. Anatomy of some septarian concretions. J. Sediment. Petrol., 55(3): 398–406.

Bonte, A., 1952. Reflexions sur le "beef", à propos d'une note de M.L. David. Soc. Geol. Fr. C.R., 7: 110–112.

Bradley, J.S., 1975. Abnormal formation pressure. Am. Assoc. Petrol. Geol. Bull., 59(6): 957–973.

Bredenhoeft, J.D. and Hanshaw, B.B., 1968. On the maintenance of anomalous fluid pressures. Geol. Soc. Am. Bull., 79(9): 1097–1106.

Brown, R.W., 1954. How does cone-in-cone material become emplaced ? Am. J. Sci., 252: 372–376.

Carozzi, A.V., 1972. Microscopic Sedimentary Petrography. Robert Krieger, New York, 485 pp.

Carstens, H., 1985. Early diagenetic cone in cone structures in pyrite concretions. J. Sediment. Petrol., 55(1): 105–108.

Carstens, H. and Dypvyk, H., 1981. Abnormal formation pressure and shale porosity. Am. Assoc. Petrol. Geol. Bull., 65(2): 344–350.

Carter, M.L., Kronenberg, A.K., Ross, J.V. and Wiltschko, D.V., 1990. Control of fluids on deformation of rocks. Geol. Surv. London, Spec. Publ., 54: 1–13.

Cartwright, J.A., 1994. Episodic basin-wide fluid expulsion from geopressured shale sequences in the North Sea Basin. Geology, 22: 447–450.

Cassidy, D.P. and Ranganathan, V., 1992. Groundwater upwelling near bay St. Elaine Salt Dome in southeastern Louisiana, as inferred from fluid property variations. Am. Assoc. Petrol. Geol. Bull., 76(10): 1560–1568.

Chanda, S.K., Bhattacharyya, A. and Sarkar, S., 1977. Deformation of ooids by compaction in the Precambrian Bhandir Limestone. India. Implications for lithification. Geol. Soc. Am. Bull., 88: 1577–1585.

Cheilletz, A., Giuliani, G. and Arhan, T., 1993. Late Eocene–Oligocene shortening episode in the Eastern Cordillera of Colombia viewed by emerald dating. Second ISAG, Oxford (UK), Extended Abstracts, pp. 473–476.

Cibin, U., Cavazza, W., Fontana, D., Milliken, K.L. and Mcbride, E.F., 1993. Comparison of composition and texture of calcite-cemented concretions and host sandstones, Northern Apennines, Italy. J. Sediment. Petrol., 63(5): 945–954.

Clifton, H.E., 1957. The carbonate concretions of the Ohio shale. Ohio J. Sci., 57(2): 114–124.

Collinson, J., 1994. Sedimentary deformational structures. In: A. Maltman (Editor), The Geological Deformation of Sediments. Chapman and Hall, London, 362 pp.

Comité des Techniciens, 1966. Essai de Nomenclature et Caracterisation des Principales Structures Sedimentaires. Technip, Paris, 233 pp.

Cosgrove, J.W., 1991. Fluid migration and concentration during the deformation of a sedimentary sequence. The Geometry of naturally deformed rocks (Zurich). Abstracts, p. 11.

Craig, J., 1985. Tectonic Evolution of the Arc between Brth and Cardigan. Dyfed. west Gales. PhD. Thesis, Univ. College of Wales, Aberystwyth, 3 vols. (See reference for Collinson, 1994). (unpubl.)

Criss, R.E., Cooke, G.A. and Day, S.D., 1988. An Organic Origin for the Concretions of the Ohio Shale. U.S. Geol. Surv. Bull., 1836, 21 pp.

Curtis, C.D. and Coleman, M.L., 1986. Controls on the precipitation of early diagenetic calcite, dolomite and siderite concretions in complex depositional sequences. In: D.L. Gautier (Editor), Roles of Organic Matter in Sedimentary Diagenesis. Soc. Econ. Paleontol. Mineral. Spec. Publ., 38: 23–33.

Daly, R.A., 1900. The clacareous concretions of Kettle Point, Lambton count, Ontario. J. Geol., 8: 135. (See reference for Tarr, 1921).

Deming, D., 1994. Factors necessary to define a pressure seal. Am. Assoc. Petrol. Geol. Bull., 78(6): 1005–1009.

Desrochers, A. and Al-Aasm, I., 1993. The formation of septarian concretions in Queen Charlotte Is. B.C., Evidence for microbially and hydrothermally mediated reactions at shallow burial depth. J. Sediment. Petrol., 63(2): 282–294.

Dewers, T. and Ortoleva, P., 1990. Force of crystallization during the growth of siliceous concretions. Geology, 18: 204–207.

Dix, G.R. and Mullins, H.T., 1987. Shallow subsurface growth and burial alteration of Middle Devonian Calcite Concretions. J. Sediment. Petrol., 57(1): 140–152.

Dix, G.R. and Mullins, H.T., 1993. Oxygen and carbon isotopic composition of marine carbonate concretions: An overview. Discussion. J. Sediment. Petrol., 63(5): 1007.

Durand-Delga, M., 1952. Reflexions sur le "beef", a propos d'une note de M.L. David. Soc. Geol. France C.R., 7: 110–112.

Franks, P.C., 1969. Nature, origin and significance of cone-in-cone structures in the Kiowa Formation. J. Sediment. Petrol., 39(4): 1438–1454.

Friedman, G.M. and Sanders, J.E., 1978. Principles of Sedimentology. Wiley, New York, 792 pp.

Gautier, D.L., 1982. Siderite concretions, indicators of early diagenesis in the Gammon shale. J. Sediment. Petrol., 52(3): 859–871.

Gautier, D.L. and Claypool, G.E., 1986. Interpretation of methanic diagenesis in ancient sediments by analogy with processes in modern diagenetic environments. Studies in Diagenesis, U.S. Geol. Surv. Bull., 1578: 111–123.

Gilman, R.A., 1968. Kink bands of non tectonic origin. J. Geol., 76: 702–709.

Gilman, R.A. and Metzger, .., 1967. Cone-in-cone concretions from western New York. J. Sediment. Petrol., 37(1): 87–95.

Glover, L., 1957. Occurrence of free oil in limestone concretions in Puerto Rico. Bull. Am. Assoc. Petrol. Geol., 41(3): 565–566.

Gonzalez, L.A., Carpenter, C.J. and Lohmann, K.C., 1992. Inorganic calcite morphology, roles of fluid chemistry and fluid flow. J. Sediment. Petrol., 62(3): 382–399.

Grauls, D. and Cassignol, C., 1992. Fluid pressure-induced open anomaly — Characterization from well data and seismic velocities; mechanisms and major implications. Bull. Elf-Aquitaine, 16: 275–284.

Gresley, W.S., 1894. Cone in cone. How it occurs in the Devonian Series in Pennsylvania. USA. Geol. Soc. London Quart. J., 50: 731–739.

Hanshaw, B.B. and Bredenhoeft, J.D., 1968. On the maintenance of anomalous fluid pressures. Geol. Soc. Am. Bull., 79(9): 1107–1122.

Hargraves, R.B, Cullicot, C.E., Deffeyes, K.S., Hougen, S., Christiansen, P.P. and Fiske, P.S., 1990. Shatter cones and shocked roks in southwestern Montana: The Beaverhead impact structure. Geology, 18: 832–834.

Harris, L.D., 1958. Syngenetic chert in the middle ordovician Hardy Creek Limestone of Southern virginia. J. Sediment. Petrol., 28(2): 205–208.

Hayes, J.B., 1963. Geodes and concretions from the Mississippian Warsaw Formation. J. Sediment. Petrol., 34(1): 123–132.

Henderson, J.R., Henderson, M.N. and Wright, T.O., 1990. Water-sell hypothesis for the origin of certain veins in the Meguma Group, Nova Scotia, Canada. Geology, 18: 654–657.

Hennessy, J. and Knauth, L.P., 1985. Isotopic variations in dolomite concretions from the Monterey Formation, California. J. Sediment. Petrol., 55(1): 120–130.

Hesselbo, S.P. and Palmer, T.J., 1992. Reworked early diagenetic concretions and the bioerosional origin of a regional discontinuity within British Jurassic marine mudstones. Sedimentology, 39(6): 1045–1065.

Hickman, S., Sibson, R. and Bruhn, R., 1995. Mechanical involvment of fluids in faulting. J. Geophys. Res., 100(B7): 12,831–13,132.

Holzer, T.L. and Clark, M.M., 1993. Sand boils without earthquakes. Geology, 21: 873–876.

Hudson, J.D., 1978. Concretions, Isotopes and the Diagenetic history of the Oxford Clay. Sedimentology, 25: 339–370.

Hyde, C. and Landy, R.A., 1966. Whewellite from septarian concretions near Milan, Ohio. Am. Mineral., 51: 228–229.

Jansa, L.F. and Noguera-Urrea, V.H., 1990. Geology and diagenetic history of overpressured sandstone reservoirs, Venture Gas Field, offshore Nova Scotia, Canada. Am. Assoc. Petrol. Geol. Bull., 74(10): 1640–1658.

Jones, B. and Kahle, C.F., 1993. Morphology, relationship, and origin of fibre and dendrite calcite crystals. J. Sediment. Petrol., 63(6): 1018–1031.

Jones, M., 1994. Mechanical principles of sediment deformation. In: A. Maltman (Editor), The Geological Deformation of Sediments. Chapman and Hall, London, 362 pp.

Karig, D. and Morgan, J., 1994. Tectonic deformation, stress paths and strain histories. In: A. Maltman (Editor), The Geological Deformation of Sediments. Chapman and Hall, London, pp. 167–204.

Kelley, J.T., Dickson, S.M., Belknap, D.F., Barnhardt, W.A. and Henderson, M., 1994. Giant sea-bed pockmarks: Evidence for gas scape from Belfast Bay, Maine. Geology, 22: 59–62.

Lorenz, J.C., Teufel, L.W. and Warpinsky, N.R., 1991. Regional fractures I: A mechanism for the formation of regional fractures at depth in flat-lying reservoirs. Am. Assoc. Petrol. Geol. Bull., 75(11): 1714–1737.

Luo, X. and Vasseur, G., 1992. Contributions of compaction and aquathermal pressuring to geopressures and the influence of environmental conditions. Am. Assoc. Petrol. Geol. Bull., 76(10): 1551–1559.

Luo, X. and Vasseur, G., 1993. Contributions of compaction and aquathermal pressuring to Geopressures and the influence of Environmental Conditions. Reply. Am. Assoc. Petrol. Geol. Bull., 77(11): 2011–2014.

Macaulay, C.I., Haszeldine, R.S. and Fallick, A.E., 1992. Diagenetic pore waters stratified for at least 35 Million years. Am. Assoc. Petrol. Geol. Bull., 76(10): 1625–1634.

Machel, H.G., 1993. Anydrite nodules formed during deep burial. J. Sediment. Petrol., 63(4): 659–662.

Maltman, A. (Editor), 1994. The Geological Deformation of Sediments. Chapman and Hall, London, 362 pp.

Marshall, J.D., 1982. Isotopic composition of displacive calcite fibrous veins. J. Sediment. Petrol., 52(2): 615–630.

Martel, A.T. and Gibling, M.R., 1993. Clastic dikes of the Devono-Carboniferous Horton Bluff Formation, Nova Scotia: Storm-related structures in shallow lakes. Sediment. Geol., 87: 103–119.

McA. Powell, C., 1969. Intrusive sandstone dykes in the Siamo Slate near Negaunee, Michigan. Geol. Soc. Am. Bull., 80: 2585–2594.

McA. Powell, C., 1970. Intrusive sandstone dykes in the Siamo Slate near Negaunee, Michigan. Replay. Geol. Soc. Am. Bull., 81: 3181–3184.

McKay, J.L., Longstaffe, F.J. and Flint, A.G., 1995. Early diagenesis and its relationship to depositional environments and relative sea-level fluctuations. Sedimentology, 42: 161–190.

Mc Kelvey, V.E., 1986. Subsea Mineral Resources. U.S. Geol. Surv. Bull., 1689-A, 106 pp.

Meade, R.H., 1966. Factor influencing the early stages of the compaction of sands and clays—Review. J. Sediment. Petrol., 36(4): 1085–1001.

Miller, T.W. and Luk, C.H., 1993. Contributions of compaction and aquathermal pressuring to geopressures and the influence of environmental conditions. Discussion. Am. Assoc. Petrol. Geol. Bull., 77(11): 2006–2010.

Morad, S. and De Ros, L.F., 1994. Geochemistry and diagenesis of strata-bound calcite cement layers within the Rannock Formation of the Brent Group. Comment. Sediment. Geol., 93: 135–141.

Morad, S. and Al-Aasm, J.S., 1994. Conditions of formation and diagenetic evolution of upper Proterozoic phosphate nodules from Southern Sweden. Sediment. Geol., 88: 267–282.

Mozley, P.S. and Burns, S.J., 1993a. Oxygen and carbon isotopic composition of marine carbonate concretions: An overview. J. Sediment. Petrol., 63(1): 73–83.

Mozley, P.S. and Burns, S.J., 1993b. Oxygen and carbon isotopic composition of marine carbonate concretions: An overview. Reply. J. Sediment. Petrol., 63(5): 1008.

Narr, W. and Currie, J.B., 1982. Origin of fracture porosity. Example from altamont Field, Utah. Bull. Am. Assoc. Petrol. Geol., 66(9): 1231–1242.

Newberry, J.S., 1873. Geological structure of Ohio Devonian System. Ohio Geol. Surv. Rep., 1: 140–167. (See reference for Criss et al., 1988.)

Nichols, R.J., Sparks, R.S.J. and Wilson, C.J.N., 1994. Experimental studies of the fluidization of layered sediments and the formation of fluid scape structures. Sedimentology, 41: 233–253.

Oertel, G. and Curtis, C.D., 1972. Clay ironstone concretions preserving fabrics due to progressive compaction. Geol. Soc. Am. Bull., 83: 2597–2606.

Pantin, H.M., 1958. Rate of formation of a diagenetic calcareous concretion. J. Sediment. Petrol., 28: 366–371.

Pepper, J.F., Clark, S.H.B. and De Witt, W., 1985. Nodules of Diagenetic Barite in Upper Devonian Shales of Western New York. U.S. Geol. Surv. Bull., 1653, 11 pp.

Pettijohn, F.J., 1976. Rocas Sedimentarias. 2nd Ed. Editorial Universitaria de Buenos Aires, 731 pp.

Price, N.J., 1975. Fluids in the crust of the Earth. Sci. Prog. Oxford, 62: 59–87.

Prokopovich, N., 1953. Silicification in the Oneota Dolomite. J. Sediment. Petrol., 23(3): 174–179.

Prosser, D.J., Fallick, A.E., Daws, J.A. and Williams, B.P.J., 1993. Geochemistry and diagenesis of stratabound calcite cement layers within the Rannock Formation of the Brent Group. Sediment. Geol., 87: 139–164.

Prosser, D.J., Fallick, A.E., Daws, J.A. and Williams, B.P.J., 1994. Geochemistry and diagenesis of stratabound calcite cement layers within the Rannock Formation of the Brent Group. Reply. Sediment. Geol., 93: 135–141.

Raiswell, R., 1971. The growth of Cambrian and Liassic concretions. Sedimentology, 17(3/4): 147–171.

Ramsay, J.G., 1980. The crack-seal mechanism of rock deformation. Nature, 284: 135–139.

Ramsay, J.G. and Huber, M., 1987. The Techniques of Modern Structural Geology. Vol. 2. Academic Press, London.

Richardson, W.A., 1919. On the origin of septarian structure. Mineral. Mag., 56: 327–337.

Richardson, W.A., 1921. The relative age of concretions. Geol. Mag., 63: 114–124.

Selles-Martinez, J., 1994. New insights in the origin of cone-in-cone. Carbonates Evaporites, 9(2): 172–186.

Shearman, D.J., Mossop, G., Dunsmore, H. and Martin, M., 1972. Origin of gypsum veins by Hydraulic fracture. Trans. Inst. Min. Metall., Sec. B181: 148–155.

Sibson, R.H., 1990. Faulting and fluid flow. In: B.E. Nesbitt (Editor), Mac Short Course on Crustal fluids Handbook, V18, pp. 93–132.

Siegel, D.I., Chamberlain, S.C. and Dossert, W.P., 1987. The isotopic and chemical evolution of mineralization in septarian concretions. Evidence for episodic paleohydrogeologic methanogenesis. Geol. Soc. Am. Bull., 99: 385–394.

Sondheimer, W.A., Dense, W.A., Mattick, L.R. and Silverman, S.R., 1966. Composition of combustible concretion of the Alewife. Science, 152: 221–223.

Srivastava, D.C. and Engelder, T., 1990. Crack-propagation sequence and pore fluid condition during fault-bend folding in the Appalachian Valley. Geol. Soc. Am. Bull., 102: 116–128.

Stoneley, R., 1983. Fibrous calcite veins, Overpressures and Primary oil migration. Am. Assoc. Petrol. Geol. Bull., : 1427–1428.

Tarr, W.A., 1921. Syngenetic origin of concretions in shale. Bull. Geol. Soc. Am., 32: 373–384.

Tarr, W.A., 1922. Cone-in-cone. Am. J. Sci., 4: 199–213.

Thomeer, J.H.M.A. and Bottema, J.A., 1961. Increasing occurrence of abnormally high reservoirs pressure in boreholes. Am. Assoc. Petrol. Geol. Bull., 45(10): 1721–1730.

Van Tuytl, M., 1916. The Geodes of the Keokuc Beds. Am. J. Sci., 42: 34–42.

Vernik, L., 1994. Hydrocarbon generation induced microcracking of source rocks. Geophysics, 59(4): 555–563.

Watts, N.L., 1983. Microfractures in chalks of Albuskjell Field, Norwegian sector, North Sea: Possible origin and distribution. Am. Assoc. Petrol. Geol. Bull., 67(2): 201–234.

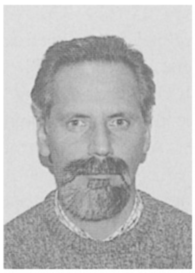
Weeks, L.G., 1953. Environment and mode of origin and facies relationships of carbonate concretions in shales. J. Sediment. Petrol., 23(3): 162–173.

Weeks, L.G., 1957. Origin of carbonate concretions in Shales, Magdalena Valley, Colombia. Geol. Soc. Am. Bull., 68: 95–102.

Weber, J.N., Williams, E.G. and Keith, M.L., 1964. Paleoenvironmental significance of Carbon isotopic composition of siderite nodules. J. Sediment. Petrol., 34(4): 814–818.

Weyl, P.K., 1959. Pressure solution and the force of crystallization— A phenomenological theory. J. Geophys. Res., 64(11): 2001–2025.

Woodland, B.G., 1964. The nature and origin of cone in cone structure. Fieldiana Geol., 13: 185–305.



Jose Selles-Martinez finished his studies in 1979 in the Department of Geology of the Universidad de Buenos Aires, where he also obtained his Doctorate in 1992. He has been involved in teaching since he was a student there and presently he is professor in graduate (geologial mapping) and postgraduate (mechanical properties of geologic materials) courses. He has been, and still is actively participating in different research projects, some of them international, mainly in the fields of structural geology and tectonics. His involvement with sedimentology and diagenesis has only been a coincidental result of testing the different hypotheses about the origin of cone-in-cone structures for structural analsyis and rock mechanics. This led to the publication of a new hypothesis about their genesis and environmental significance. Several problems with the genesis of concretionary bodies developed while doing this research. A broad investigation of the different hypotheses on concretionary growth, mainly concentrating on several concepts concerning the mechanical properties of geologic materials, has led JSM to conclusions that are different from previous ones and are considered to be of interest for presentation in this paper.