NEW INSIGHTS IN THE ORIGIN OF CONE-IN-CONE STRUCTURES

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ABSTRACT: Previous theories on cone-in-cone structure origin have failed to explain some of its features, such as the absence of cone-in-cone in veins other than horizontal and the cross-cutting relations of conical surfaces to detritical clay films. They have neither taken in account the importance of pore pressures in the process of growth of veins and concretions nor the effects of its fall in the deformation of these calcite bodies. A new hypothesis for cone-in-cone origin is presented, which states that cones are a secondary feature. They are superimposed on crystalline aggregates that grow in overpressured chambers and formed as a result of brittle fracture induced by a decrease in pore pressure within materials having different mechanical properties (plastic host sediments and brittle calcite bodies). The acceptance of this hypothesis will help in the identification of seals in ancient diagenetic environments and in assessing depth of entrapment for fluids.

INTRODUCTION

Like many other subjects in science, cone-in-cone structures have known several episodes of broad interest and constructive discussion alternating with some others of indifference. In recent times, although interest in the study of concretionary growth has risen again because of its importance in the study of diagenesis; the origin of cone-in-cone structures has remained almost forgotten.

Cone-in-cone structures have been mentioned and described in the geologic literature since the early nineteenth century. They are generally associated with veins and concretions being common in shales but much more scarce in sandstones. Good descriptions and drawings have been published by Gresley (1894) and Gilman and Metzger (1967), while abundant photographs occur in the papers of Woodland (1964a) and Franks (1969), amongst others. Most authors agree that the cone-in-cone structure owes its origin to the crystallization of calcite during early diagenetic stages (e.g. Woodland 1964; Raiswell 1971). Crystallization of calcite forces sediments away from the growing crystals to make room for concretions and veins (displacive growth). However this theory does not explain such features as the absence of cone-in-cone structures in calcite veins present in non-sedimentary rocks or in veins other than horizontal ones. The other unexplained phenomena include telescoping of cones, the systematic downward or upward orientation of cones apices in layers, or inward orientation of apices in concretions, lensoidal arrangements, and equidimensional concretion growth in the non-hydrostatic stress field characteristic of shallow burial. Not account is given for the difficulty in explaining how a crystal should continue growing in a strain field (induced by its own growth) without straining. Although the presence of pore waters is almost universally accepted, the importance of pore pressures has not been fully considered. Pore pressure would keep the clastic framework expanded and allow the crystallization of minerals in veins and concretions before and along with compaction. The purpose of this paper is to present a new interpretation of the origin of cone-in-cone structures, linking them to the growth of veins and rims around concretionary bodies within a zone of excess fluid pressure that subsequently dissipates. If the hypothesis is correct, the presence of these structures should be a guide to the identification of horizons that have acted as seals to allow the preservation of undercompacted units. Accumulation of fluids and the generation of excess pore pressures that permitted the growth of concretionary bodies provides a clue to the identification of depth and temperature for fluid entrapment during diagenesis. This is may be of use in recognizing potential hydrocarbon seals.

A description of general features of cone-in-cone structures will be introduced with a discussion of previous theories on their origin and their pitfalls. Brief discussions on some of the items will be presented, in some cases because they are still controversial, in others, because the subject is probably not familiar to all sedimentologists and it will be helpful to add some background information.

Something must be said here about the use of the term "hydrostatic pressure" in this paper before going on. In its usage in physics "hydrostatic" describes a state of stress in which all three principal stresses are equal, like the situation within water or any fluid. Petroleum geologists have used the term "hydrostatic" to identify the pressure due to the weight of the water column in the overlying strata and "lithostatic" for that corresponding to the weight of the rock strata (some authors use "geopressure" as a synonym). This conflicting usage should be abandoned, keeping the primitive use of the term "hydrostatic" for a situation in which all three principal stresses are equal and no shear stresses are possible. The use of "lithopressure" for the dry overburden, "hydropressure" for the fluid column, "over- or underpressure" for the abnormal fluid pressure and "geopressure" for the actual state of stress in an specific point could help to solve misunderstanding.

GENERAL FEATURES OF CONE-IN-CONE STRUCTURES

Occurrence

According to the published literature cone-in-cone structures appear in horizontal veins or layers and also in calcite rims of concretions in shales or sandy shales. Although involving carbonate material cone-in-cone structures have never been described in calcareous rocks. This suggests the existence of very particular lithological pre-requisites. Al-

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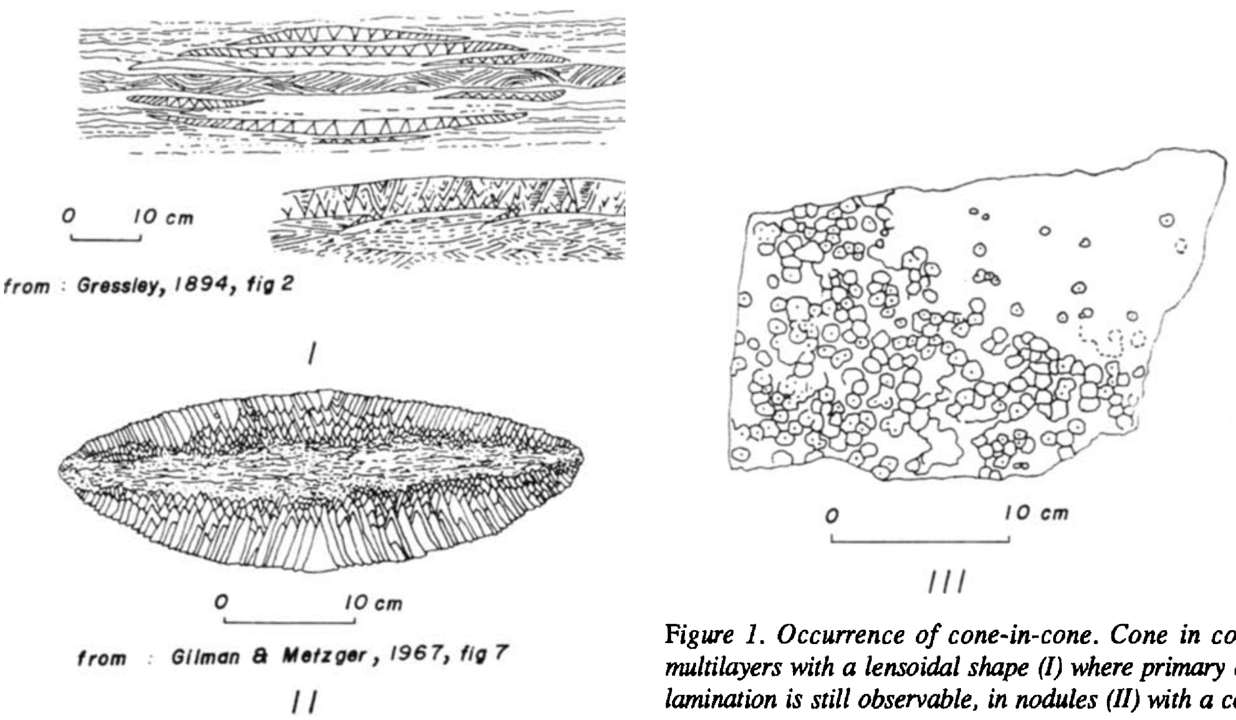

Figure 1. Occurrence of cone-in-cone. Cone in cone in multilayers with a lensoidal shape (I) where primary cross-lamination is still observable, in nodules (II) with a central clayey layer and in veins (III) about 2cm thick.

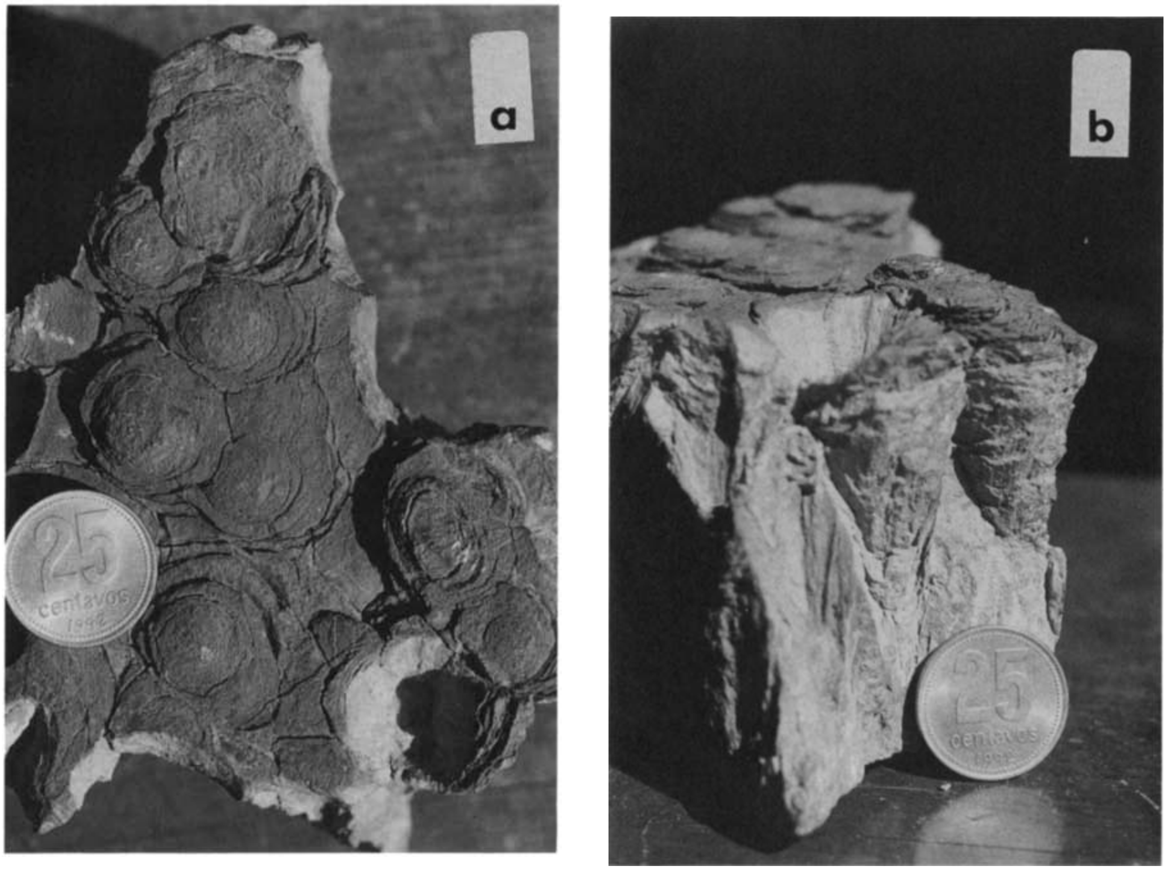

Figure 2. Positively telescoped cones. Sample of unknown origin. a- Upper view, note hollow cone cup in the corner; b- Lateral view. Notice the amount of displacement between nested individuals. The coin is about an inch in diameter.

though cone-in-cone structures are ubiquitous through time and space, the host layers are restricted to specific horizons in a few shale or shaly formations of a given sedimentary sequence. And not all sequences are concretion-bearing ones.

Figure 1 displays some typical examples of cone-in-cone structures. Cones in lenses and layers can form two or more plates separated by non-coned, poorly coned or microconed layers, with an average full width of one to four centimeters. They generally form only an outer shell in cone-in-cone bearing concretions, the shell being of a distinctive composition and texture. They are usually associated with fossils with separated upper and lower parts.

Cones have been reported pointing generally upwards when in isolated layers, but point inward in symmetrical veins, concretions or lensoidal arrangements like those illustrated in Gresley (1894, Plate XXXV). Some strained cones have been reported in the literature (e.g. Gresley, 1894, Plate XXXVI). Due to its circular section and the perpendicularity of cone axis to primary surfaces, cones can provide useful three-dimensional information when preserved in deformed rocks. For example, the relationship between elliptical shapes on the coned surface and the original circle would be related to the amount of pure shear acting normal to the horizontal surface while the angle between the axis of the cones and this surface would represent the amount of simple shear acting in the vertical plane. Cones may be telescoped in a positive or negative way. Figure 2 shows this particular feature.

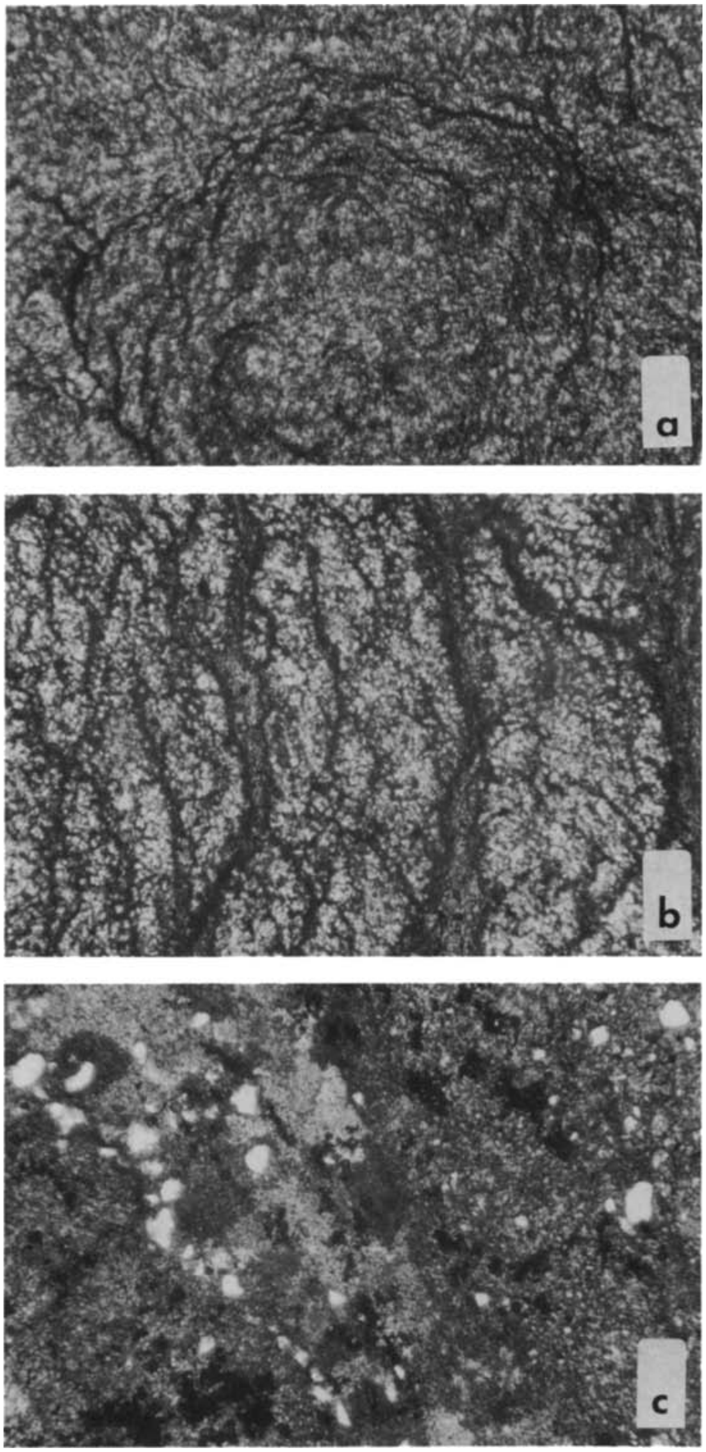

Figure 3. Sections normal to the axis of cone-in-cone. a- Circular shape defined by an arrangement of small arcs. b- Inside the arcs clayey films separate calcite zones. c- Magnification of material in the arcs shows clastic quartz particles squeezed inside conical fractures.

Composition

Cone-in-cone structures are generally composed of fibrous calcite, but primary cones of siderite (Hendricks, 1937) and pyrite (Carstens, 1985) have been described. Gresley (1894) mentions a collection of replaced cones of hematite, limonite, ferrous quartz, quartzite, pyrite, marcasite and iron impregnated silica. The surfaces between nested cones are generally lined by a clay film (Fig. 3). Clay also forms the rings on the conical surface (Fig. 4). Woodland (1964a) reports that bulk carbonate content in cone material is similar to that of calcareous nodules commonly found in shales (residues= 12%). Shales hosting cone-in-cone structures are free of calcium carbonate but some carbonate cement may be present in sandy rocks.

Isotopic features

Numerous isotopic studies on veins or concretions have been carried out (Weber et al 1964, Pepper et al 1965, Criss et al 1968, Raiswell 1971, Oertel and Curtis 1072, Hudson 1978, Marshall 1982, Hudson 1978, Gautier 1982, Boles et al 1985, Dix and Mullins 1987, Hennessy and Knauth, 1985, Hesselbo and Palmer, 1992; Mozley and Burns 1993, Cibin et al 1993; Desrochers and Al-Aasm, 1993, among others) showing that concretionary growth may initiate in the water-sediment interface or at no more than several meters below it and finish in less than ten-thousand years or continue for up to several million years and to depths of several hundreds of meters. This wide span of time-depth requirements shows that environmental conditions for the growth of concretionary bodies and veins although limited are less restricted than those for the development of cone-in-cone structures. Concretionary bodies containing concentric rims do not always bear cones. Although the use of isotopes has yielded interesting results, unexplained uncertainties, arising from the

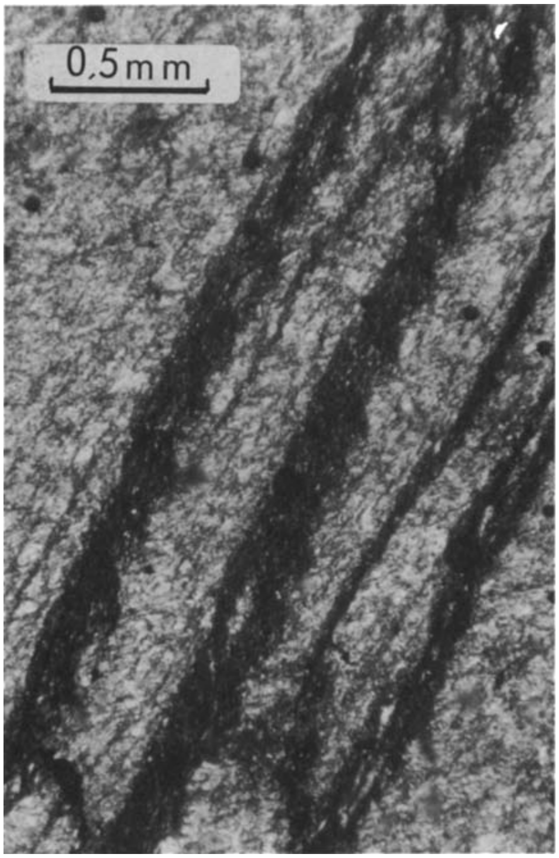

Figure 4. Sections parallel with the axis of cone-in-cone. Calcite shows in light grey while clay shows dark. Note that the "stepped" profile is always in one side of the calcite body, but its counterpart surface is smooth.

incongruence of textural and isotope data lead Marshall (1982) and Criss et al (1988) to advise that conclusions on paleoenvironments achieved on the bases of isotopic studies should be considered with scepticism.

Crystallographic orientation of calcite crystals

The c-axes of calcite crystals in coned material range from being perpendicular to the vein surface to parallelism with conical surfaces. Stereographic diagrams of crystal orientation show circular patterns, but not small circle or annular ones as should be expected for arrangement on a conical surface (see Woodland, 1964a, fig. 86 for plots).

Rate of growth

No information on the time span involved in the growth of coned material has been found by the author. Few absolute dating techniques has been carried out on concretionary bodies; Pantin (1958) obtained a result of about 7,500 years for a calcareous concretion. Boles et al (1965), using diffusion growth models, estimate the time needed for a large concretion to grow is four million years. If a cone-in-cone structure is considered to be a product of soft sediment deformation process or a primary crystallization shape, its development should cover the same time span. However, if it is interpreted as a fracture surface, regardless of the origin of stress, it should be an almost instantaneous feature.

Morphological features

Little information exists about the distribution of the cones on surfaces of veins and concretions. Woodland (1964a) provides some descriptions and illustrations, the case of the coned vein separating dorsal and ventral surfaces of a Trilobite being of outstanding interest. The position of cone axes perfectly lines up with the original segmentation of the fossil. Further studies on this subject will provide important information about the origin of cone-in-cone structures and the state of stress at the time of development. It seems probable that cone axis distribution follows an interference pattern the same way columnar jointing in igneous rocks does, this pattern being related to the overall distribution of stress and the relative orientation of potential fracture planes (Cos and Wright, 1992; DeGraff and Aydin, 1987). Rows and rhombohedral patterns have been identified by the author in samples of the collection at the Departamento de Ciencias Geologicas of the Universidad de Buenos Aires.

Most of the descriptive work carried on cone-in-cone structure studies has been centered on individual cones. The following terms are of almost universal acceptance and are illustrated in figure 5. *Cone*: one of a group of nested cones; *Cone cup*: conical surface left by a cone when it is removed; *Clay rings*: developing parallel with the bases of cones, triangular in section, covering cone cups. Rings in different cups show different dimension in section, and even in the same cup variations can be found, with rings showing larger sections in the vicinity of the base of the cone. Sometimes they do not appear exactly as rings but show bifurcations and anastomose into each other. According to Gilman and Metzger, 1967, *major fractures* are those defining the surface of the cones and *minor fractures* those shaping clay rings. *A conical scale* is a fragment of a minor cone attached to a main one, this would be equivalent or associated to what Durrance, 1965, called an "individual conical leaf".

Although a great variation in cone-in-cone structure dimension is possible amongst cones from different localities the following types can be considered representative: *Coned body height*: up to several decimeters, but usually several centimeters; *Cone height*: from less than a millimeter to several centimeters; *Apical angle*: from 14° to 100° generally between 20° and 60°.

Similar structures

Shatter cones (like such as are produced by meteorite impact, Ramsay and Huber, 1987; Hargraves et al, 1990; Roach et al, 1993) and shear cones (like those developed in coals (Bartrum, 1941; Woodland, 1964)) differ from cone-in-cone structures in that they are the product of very high in-

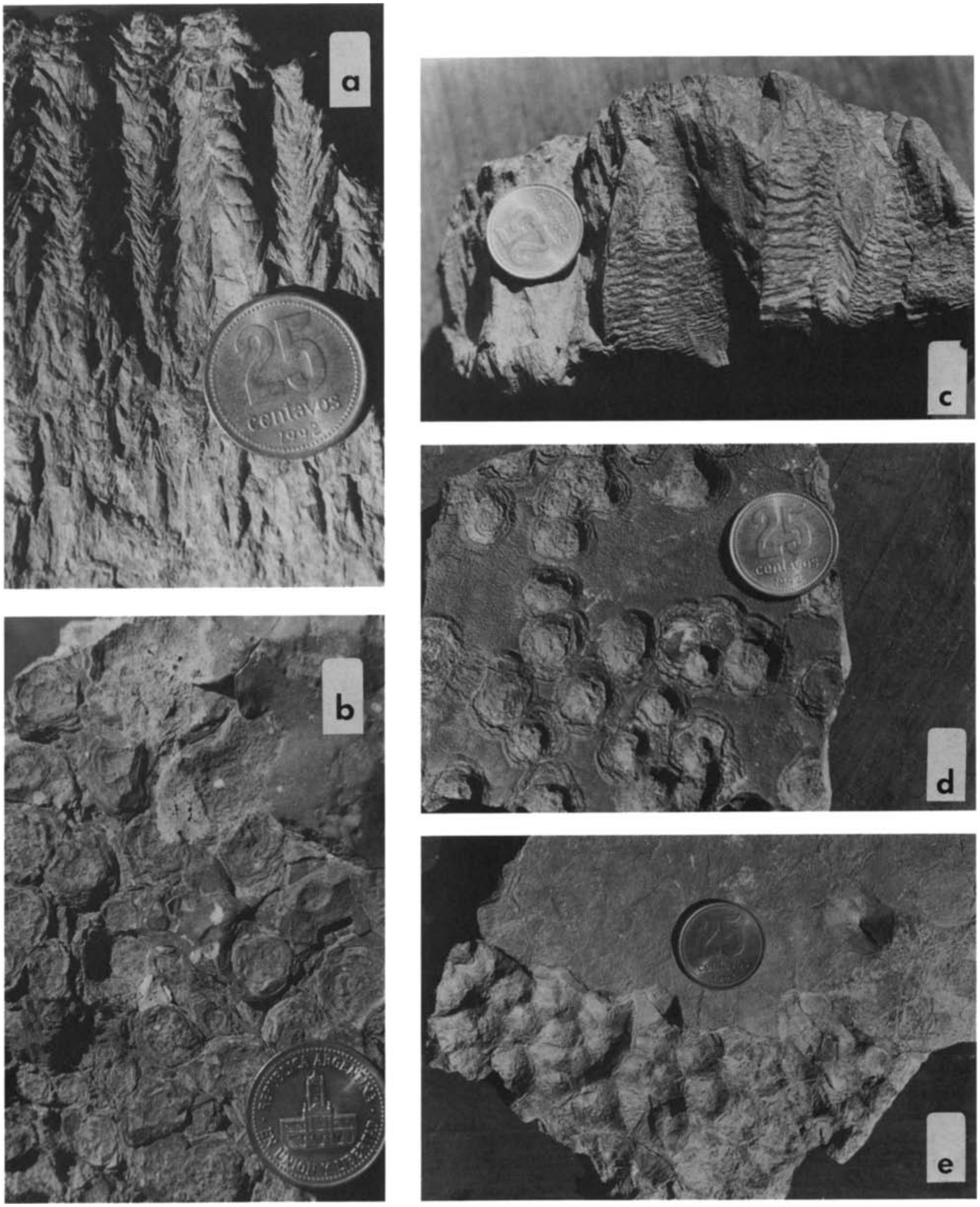

Figure 5. Other morphological features of cone-in-cone. a- Nested cones in lateral view. b- Upper view of the same, notice that each four adjacent cones define a rhomb, not a square. c- to e- Different morphologies of cone cups (see also figure 2), c displays typical anastomosing and size changing corrugations or clay rings, d shows imperfectly rimed cups with flat apices in a thin slab and e illustrates cups with no corrugations.

stantaneous stresses. These structures develop in a situation in which maximum principal stress is by far greater than medium and lesser principal ones so shear fractures develop because of the sudden increase in the radius of the Mohr Circle and it's intersection with the Mohr envelope corresponding to the material being crushed. These structures are not confined to rocks or minerals of specific composition or a particular layer. They have a spatial dependence on impact areas and fault zones, in the case of shatter cones and shear cones, respectively. Conical arrangements of magmatic dikes, usually named cone-sheets (Best, 1982, Barker, 1983) may be envisaged as an overscaled cone-in-cone-like structure, where magmatic chambers modify regional stress field and magma emissions play the role of the clay film present in true cone-in-cone structures. Woodland (1964b), describes conical features of millimetrical scale in a soft shale he considers shear fractures associated to "compaction pressures around carbonized plant material". Giraud and Seguret (1987) describe conical fractures of decimetrical scale affecting siltstones and clays, reaching the conclusion that "this microfaulting resulted from vertical shortening without horizontal extension, but with volumetric loss". The association of this latter example to fluid escape structures should be pointed out. Aassoumi et al (1992) and Aso et al (1992) describe cone-in-cone structures associated with pedological and septarian nodules, respectively. However, it has been difficult for the author, based on their descriptions, to identify the type of structure they are dealing with, cone-in-cone structure or just conical arrangements of calcite needles.

PREVIOUS THEORIES ON THE ORIGIN OF CONE-IN-CONE STRUCTURES

Theories on the origin of cone-in-cone structures have been exhaustively discussed in Woodland (1964b) and Franks (1962) so only a brief description will be presented here, with the inclusion of some papers published after their reviews. Theories can be classified in four main groups on the bases of whether or not they consider the structure to be of primary or secondary origin and the product of brittle behavior or not. The meaning of these terms in this paper is the following: Primary: developed during vein or concretion growth. *Secondary*: produced after the vein or concretion formed. *Non-brittle*: implying bending of clay layers to the shape of chevron folds with an interfering pattern. *Brittle*: development of true conical fracture surfaces.

Regardless of their origin conical fractures require for their formation a fixed pattern of stress distribution (Ramsay 1967), namely $\sigma 1 > \sigma 2 = \sigma 3$, but this pattern is different from the one required for the growth of equidimentional concretions, where hydrostatic conditions must be prevalent ($\sigma 1 = \sigma 2 = \sigma 3$) so a change in the overall or the local stress fields must predate (or trigger) the generation of cone-in-cone. Aso 1991 has produced a Ph.D Thesis on the origin of septaria and cone-in-cone structures but the author has not had access to the manuscript, anyway the main ideas on the subject are supposed to be present in Aso et al 1992.

Table 1 is a compendium of published theories (available to the author through the papers itself or cited in other ones) grouped on the basis of the above mentioned criteria.

Pitfalls in previous theories

Previous theories fail to explain some of the observed features of cone-in-cone structures and its environment of occurrence. Woodland (1964a), Franks (1969) and Marshall (1982) analyze theories on cone-in-cone structure development, giving good reasons to abandon most of previous theories, but arriving to different conclusions. Woodland (1964a, page 189) states that "Cone-in-cone owes its origin to the concretionary growth of carbonate (calcite) during the very early diagenesis of the containing sediments (...). The fibrous nature of the calcite, its orientation and its differential growth, which produced the corrugated, partially conical clay layers, so typical of cone-in-cone, are the result of the stress field in which the crystallization took place. The stress field was produced by the pressure of superincumbent -which must have been slight because of the early diagenetic time of development- and by the expansive force of the concretionary action itself". He also states (page 299) that "The microcones arise directly from the mode of growth of individual fibre groups, which develop as tuft-like aggregates from a nucleation point, the microcone apex (...). Macrocones are stablished by layers or lenses of clay that remain coherent and are forcibly deformed by the crystallizing calcite.". The model of growth of concretions depicted by this author (Woodland 1964a, figures 87 to 89) seems no longer compatible with present day interpretations. Franks (page 1452) agrees with him that "the cone structures are the products of the growth of cone-shaped plumose aggregates of fibrous calcite in argillaceous sediments (...). The clay films that outline the cones and conic scales stem from the disturbance and displacement of the original sediment by the growing fibers of calcite". He points out that "the so-called cone fractures (...) are not the product of fracturing but rather are the growth boundaries between sets of plumose aggregates of fibrous calcite" but gives no reason why those plumose aggregates have so regular shapes, are so regularly spaced and have so sharp borders. Both authors fail to explain how the deformation of clay films is so regular when it should be expected a constant loss of amplitude radiating away from growing centers. The paper from Marshall (1982) updates with geological knowledge and states that "fibre curvature and the patterns of internal zones of symmetrical veins demonstrates growth by a process of antitaxial (outward) addition of carbonate at the vein margins". It is important to point out that he finds that "The fibrous calcites are displacive and presumably therefore grew into relative plastic sediments. The isotopic evidence, however, suggests a later diagenetic origin (...). To explain this apparent contradiction it is necessary to invoke a mechanism whereby effective overburden pressure (and decreased shale plasticity) could be temporarily and periodically reduced under tens or more prob-

Table 1. Princepal theories on cone in cone development

PRIMARY, NON-BRITTLE	PRIMARY, BRITTLE
Sorby, 1860. Fan shaped crystallization	**Gressley, 1894.** Lateral radial contractional stresses
Young, 1892. Ebullition of gases passing through plastic sediments	**Keyes, 1898.** Crystallization forces of calcite
Cole, 1893. Conical growth of crystalline aggregates	**Reis, 1903-1914.** Contraction tensions produce polygonal pyramidal splitting
Richardson, 1923. Conical shear surfaces control calcite growth	**Shaub, 1937.** Volume shrinkage during dewatering
Bonte, 1942, 1952. Concretionary growth with lateral compression	**Durrance, 1965.** Crystallization forces in a confined space
Morawietz, 1961. Rapid crystallization of tuft and cone like aggregates	**Denaeyer, 1939.** Tractionary stresses in a "plastic between brittle" sandwiched system
Woodland, 1964. Concretionary growth, overburden load	
Franks, 1969. Growth of cone shaped plumose aggregates	
Carstens, 1985. Dendritic growth	
Aassoumi et al, 1992. Calcification of bacterial communities	
SECONDARY, NON-BRITTLE	SECONDARY, BRITTLE
Link, 1930. Crystallization of a preexisting colloidal gel	**Tarr, 1922.** Stresses arising from overburden load and aragonite inversion
Aso et al, 1992. Fibrous growth in organic gel	**Weller, 1960.** Overburden load caused shear fractures
	Muller, 1962. Recrystallization of a colloidal concretion under confining pressure
	Gilman and Metzeger, 1967. Stresses due to aragonite inversion
	Shearman et al. 1972. Pore fluid fall and fracturation of calcite due to the effect of overburden load transmission

ably hundreds of meters of burial" and, after quoting Shearman et al (1972) points out that the key to solving this problem must be found in "overpressured horizons".

Some features have not been taken in account in most of the published literature so they are going to be discussed herein.

a)As far as the author knows no vertical veins with cone-in-cone have been described. This is an important argument against many of the previous theories on cone-in-cone origin, because the mechanism invoked should have acted independently of spatial orientation of the vein.

b)It is not clearly stated how sedimentary clasts are "pushed away" vertically and laterally while calcite fibers keep growing. Displacive growth in a plastic host sediment is easy to sketch but difficult to explain. In the presence of a clastic framework carbonate material precipitates as a cement, and this happens mostly before fibrous rims of concretions are formed, so cementation occurred in more plastic sediments and under lighter overburdens than those present when displacive growth took place. Which environmental conditions lead to fibrous growth and not to pore space filling? No clear answer is offered by previous theories and the subject is still under debate. Dickson, 1993, has worked on the interpretation of crystal fabrics and the environmental conditions leading to them concluding that the work is in its beginnings. Crystallization forces, often invoked as "clast-pushers", are generally calculated supposing volume-to-volume replacement (Dewers and Ortoleva, 1990) and are extrapolated to the syn-sedimentary environment. Shearman et al (1972) give many strong arguments against displacive growth and its capability to carry on mechanical work.

c) If the model of displacive growth is accepted, and conical surfaces are considered fractures originated in the relief of stress stored as the consequence of such growth, it is not easy to explain why the fibrous body should store energy up to the value required to fracture itself in place of dissipating it deforming host sediments, which, for the general model, are wet, plastic and (for several authors) only several centimeters thick. Although in the presence of pore pressures it can not be assumed that it will be easier to fracture brittle calcite needles than to deform soft host clays.

d) Woodland's (1964a) plots of calcite orientation shows that c axes in a single cone can be oriented with a greater angle to the perpendicular to bedding than the conical surface itself.

This clearly reflects that the crystalline needles are cross-cut by the conical surface. This can not be explained if it is assumed that cones owe their shape to conical aggregates of needles, because, in this case the maximum possible crystallographical deviation from the direction of cone axes should parallel the conical surface.

e) The development of "clay shadows" associated with fossil fragments and clast included in coned material (e.g. Woodland, 1964a, figures 43 and 83) are not explained by displacive growth theories.

f) Clay films on the conical surfaces are not primary layers bent to conical shapes. This is clearly demonstrated by the coexistence in the same sample of cone-shaped clay films with thin sedimentary laminations which are not warped to the conical shape (Woodland 1964a provides many good illustrations on the subject).

THE SPACE QUESTION

This point has to be considered not only in connection with cone-in-cone growth but also in the general case of concretionary growth and independently of the origin of the forces eventually needed to make the room necessary to veins and concretions. Deformation of layering has been interpreted as the result of stresses arising from concretionary growth by several authors. The need to lift the overlying strata to make room to concretions has also been taken in account (Brown 1954, Shearman et al 1972, Marshall 1982, Stoneley, 1983.

The author (Selles-Martinez, 1994) has proposed elsewhere that there is no need for an actual displacive growth of mineral fibers to account for the creation of room. It has already been demonstrated from preservation of undeformed fossils and the random particle orientation in concretions that crystallization of calcite fibers pre-dates compaction of host sediments. This late bearing stress crushed fossils and created a strong mechanical orientation of particles (e.g. Criss et al 1988). Therefore, the room required for the growth of fibers is not actually made by lifting overburden or pushing aside the clastic framework, but is taken from compactional volume loss in the surrounding sediment. Figure 6 illustrates the process.

THE OVERPRESSURED MODEL

The mechanism proposed in this paper puts in a single picture several preexisting ideas developed by the authors quoted in previous items through the observation of concretionary growth and mode of occurrence of cone-in-cone. It is strongly coherent with Shearman's (1972) hypothesis on the origin of cone-in-cone, of which, although being independently developed, can be seen as a detailed extension of that work. It is based on the rise and fall of pore pressure during diagenetic stage, given that this environment is characterized by the lack of pervasive cementation and a rate of compaction variable with depth.

Abnormal pressures in sedimentary basins

Abnormal fluid pressures (and associated undercompacted sedimentary beds) have been reported from recent and past environments (see Lohman 1961, Poland 1961, Davis et al. 1965, Thomeer and Bottema 1961, Bredenhoeft and Hanshaw 1968, Hanshaw and Bedenhoeft 1968, Bradley 1975, Bishop 1979, Barker 1987, Carstens and Dypvyk 1981, Luo and Vasseur, 1992). The rheological and chemical effects of these overpressured fluids on sediments and concretions are of primary importance in the evaluation of environmental conditions for the growth of concretions and the origin of cone-in-cone. However, as stated before, they have not been taken in account in previous interpretations. Structures associated with fluid escape in concretion-bearing sequences have been described in the literature. Criss et al (1988, page 7 and figures 4 and 5) describe clastic dikes with removed and deformed concretions, Hayes (1963, page 126 and figure 4) re-

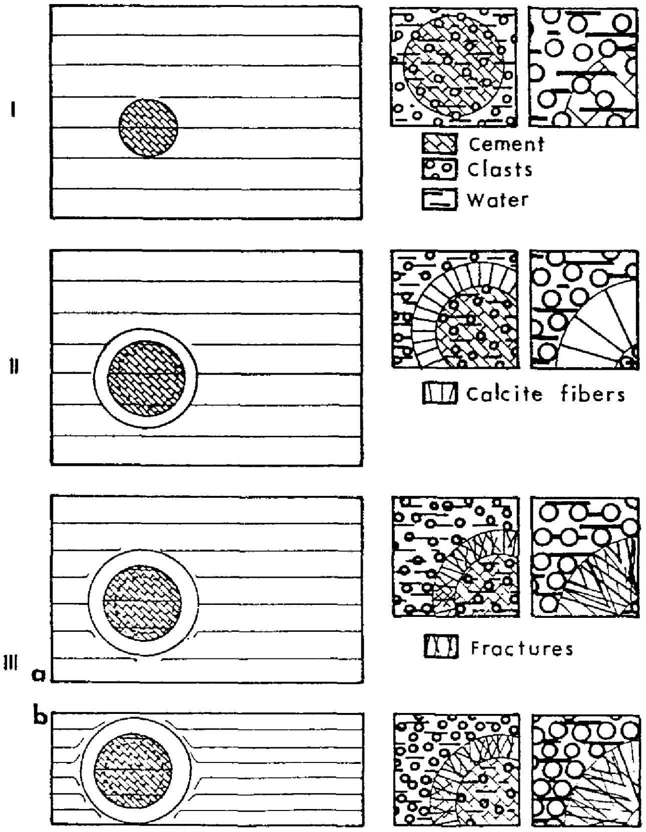

Figure 6. The undercompacted-overpressured-chamber model for the growth of concretionary material. Although the growth of a nodule or concretion may start at the water-sediment interface (I) it does so as a cement, displacive growth or "non inclusive" growth can only occur when the presence of an overlaying seal prevents fluid expulsion and compaction of sediments (III). The room for the growth of this individual layer or rim is taken from the undercompacted sediment and does not require lifting of overburden or the displacing of host sediment. When fluid pressure is lost compaction reduces bed thickness to normal values and warps layering around concretion (IIIa & b). Sketches are out to scale.

ports crushed concretions that clearly show evidences of implosion and Carstens (1985, figure 2) describes microscopical cones affecting pyrite aggregates that are clearly associated to a fluid injection. All these elements can be interpreted as evidences of the existence of abnormal fluid pressures during concretionary growth.

An earlier version of the proposed theory (Selles-Martinez, 1992) proposed that pressures in excess of overburden were needed to rise the sedimentary cover and make room for crystallization of veins and concretions. This was objected to (McBride, 1993 pers. com.) because such pressures were to be found at depths exceeding that of formation of veins and concretions. Consideration of a sealed chamber of regional extension filled with undercompacted sediments with abnormal pore pressure as the appropriate environment overcomes that serious objection and allows further consideration of the proposed scheme of evolution. Cassidy and Ranganathan (1992) and Grauls and Cassignol (1992) describe overpressured chambers that can be taken as environments with physical conditions like the ones proposed in this paper.

The mechanical effects of pore pressures on geological materials

The effect of pore pressure on the rheology of geological materials and the structures associated with it have been extensively analyzed in the last decades (Handin et al, 1963, Secor, 1965; Price, 1975; Narr and Currie, 1982; Carter et al, 1990; Sibson 1981, 1990; Lorenz et al, 1991; Behrmann, 1991.

Summarizing the conclusions of Ragan(1985), and Ramsay and Huber (1983) it must be said that the presence of pore fluids weakens materials, makes stresses needed to induce shear fractures lesser, and if pore pressure rises to equal minor principal stress tension fractures can develop (hydraulic fracturing).

The crack-seal mechanism of vein growth

Ramsay (1980) used the term "crack-seal" for a particular type of vein filling process and although it was used to explain tectonically induced deformation, there is no objection to invoke it in a non-tectonic stress regime. He described how layer parallel tensile fractures, induced by hydraulic fracturing, are filled with recrystallized material in successive steps, due to the influx of pore fluids to the opening fissure and subsequent crystallization due to oversaturation in the microenvironment. The repeated process of fracture opening, fluid influx, crystallization, sealing (as a consequence of the former), fluid pressure rise and reopening of the fracture is considered to have worked in the formation of fibrous veins and rims of concretions. The rheological discontinuity between plastic host sediment and rigid concretion surface will be easily fissured by a rise in pore pressure due to pulsation in regional values. Additional local pressures can also arise from the beginning of compaction, that should "squeeze" pore fluids to jacket potential fissures. Fissurization can also be initiated because of shrinking of concretion leading to the development of septarian fractures.

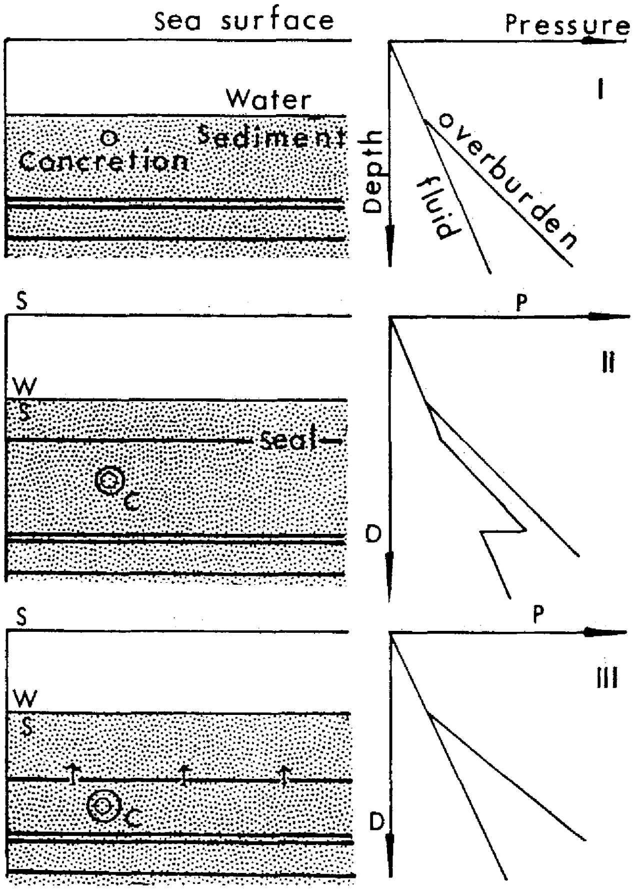

Figure 7. Successive steps in the development of cone in cone. I: First stage. the growth of a concretionary body starts at shallow depths. Hydrostatic conditions, high porosities, and cementation of clastic particles. II: Second stage. A seal has developed allowing preservation of initial porosities and development of an overpressured chamber. Fluid jackets the opening of fissures and the growth of crystalline fibers by the crack-seal mechanism. III: Third stage. Seals open and pore pressure starts to fall. Overburden load is transferred from fluid to clasts and concretions. Crystalline calcite is fractured but uncemented and still highly porous and wet host sediment compacts plastically.

Description of the proposed mechanism

The sequence depicted in figure 7 starts within a sediment in which the clastic components are still uncemented at the water-sediment interface or at shallow (less than a few meters) depths.

First stage: A nodule or a concretion starts growing cementing highly porous sediments (non-inclusive veins are supposed to grow in the second stage). Syngenetic or diagenetic conditions are prevalent. An hydraulic seal starts to form above concretion-bearing sediments (Figure 7.I).

Second stage: As illustrated in Figure 7.II this stage shows the presence of an undercompacted-overpressured chamber, not deeply buried (overpressures can be a shallow feature) and growth of concretionary bodies is still active. The porosity of host sediments is close to that in the first stage. Non-inclusive veins and rims start to grow in this stage. A mechanical discontinuity in the sedimentary body, jacketed by hydrofracturing under appropriate stress conditions allows continuous opening of spaces between layers and also between already formed concretions and host sediments. These spaces are filled by the crystallization of calcite. Calcite is generally fibrous, with fibers statistically oriented parallel with the minimum differential stress. This stress is generally vertical in veins or almost radial in concretions. The porosity of the carbonate material is lower than the host sediment one, but some pore spaces between calcite needles retain pressured fluid.

As previously mentioned, the differences in physical and chemical properties of the environment that lead to the development of veins versus concretions is not well established, but the presence of compositional and/or mechanical lamination and the amount of pore pressure must play the first role in the process. The existence of true hydrostatic conditions should probably favor the development of spherical bodies. It is important to remember that under hydrostatic conditions deformation can only be achieved through volumetric changes with no shape distortion, as long as no shear stresses are possible.

Third stage. A time is reached when fluid pressure falls. It is unknown how long it should take to dissipate abnormal pressure, but it should certainly be a function of pressure gradients and permeabilities. Clastic particles make increasing contact with one another (Figure 7.III). The host sediment begins to compact, fluids are expelled from pores, but, taken in account that clay is generally involved in the process, this process can last for thousands of years.

Evolution of stress conditions during the process

First stage: Due to the very thin sedimentary cover vertical stress is related to the water column above the sea bottom. Both horizontal stresses will be equal and be close to the value of the vertical stress (almost hydrostatic conditions).

Second (overpressuring) stage: Vertical stress is increased by the increase in sediment thickness. In the absence of tectonic (or slope-induced stresses), both horizontal stresses will be equal. Again, and because of fluid pressures, near hydrostatic conditions are prevalent and shear fractures are inhibited in the brittle calcite. Sediment particles are not resting on each other but are "swimming" in the overpressured fluid which supports most of the overburden load. Calcite bodies are **crystalline** and **submerged in a saturated uncemented soft sediment**.

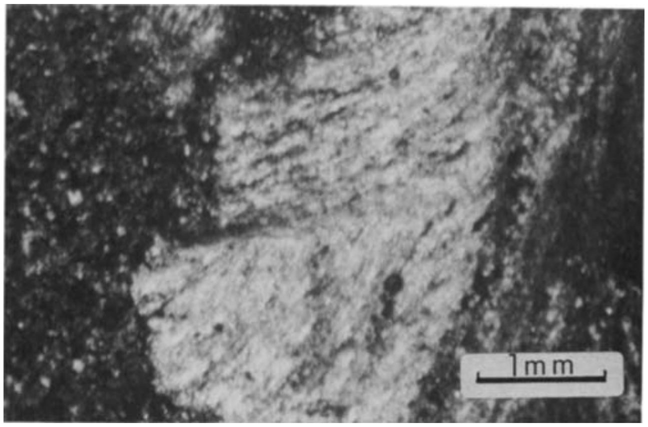

Figure 8: Feather like aggregates of curved calcite needles associated with the joint between a cone and the cone cup. They display sharp contacts with clay rings defined by major and minor fractures.

Third (depressuring) stage: The sedimentary load formerly supported by the fluid, is now transferred gradually to detrital grains and normal litho- plus hydro-pressure exists. Rheological conditions for the vein or concretion have changed. The crystalline body now "feels" the overload and stress conditions are not the same as in second stage. **The sedimentary layer which remains wet and plastic is now compressed against the vein or concretion which is crystalline and brittle.** Pore pressures inside the vein weaken it now and shear fractures can develop in response to the lithostatic stress field thus achieved. Shear fractures have a conical pattern because both intermediate and minor stresses are equal.

Late evolution of cone-in-cone structures

Circulation of fluids through the conical fracture surfaces to equilibrate pressures in both sides of the coned body would provide the means for the introduction of clay particles in favorably oriented fracture sets and produce clay rings and (if pressure gradients are strong enough) would telescope cones in a positive or negative way. Some other features, like the presence of later feather-like aggregates in the surface of conical steps (see figure 8 and also Plate XXXVI 11 and 12 in Gresley 1894) and the presence of sheared cones with their apex curved, can be interpreted as post-fracturing phenomena, best explained by fluid migration, compaction and sliding of surfaces.

CONE-IN-CONE FEATURES AS EXPLAINED BY THIS NEW HYPOTHESIS

A revision of morphological and environmental features of cone-in-cone along with its interpretation under the above developed model follows.

Conical surfaces: They are shear-fracture surfaces that display a conical shape because of stress distribution as already explained. The variation in conical angle is due to the variation in rheological conditions in different environments.

Major and minor fractures: At a first glance major fractures can be regarded as defined by the principal conical surfaces like those with their apex pointing inward the cone-in-cone bearing concretion while minor fractures should correspond to cones pointing in the opposite direction (Gilman and Metzeger, 1967, figures 7 and 8). In the interpretation of these authors slipping directions in the fracture system are representative of a stress distribution opposite to the one postulated here for the origin cone-in-cone, but it must be taken into account that the specimen in discussion belongs to a telescoped sample, and the original structure could have been reversed and enhanced by the process of telescoping. A closer examination shows that major fractures are not actually parallel to conical surfaces, they are restricted, as it happens also with minor fractures, to the conical cup. Further investigations in the line of Durrance, 1965, should certainly help in the interpretation of these features.

Striae: The so called "striae" on the conical surfaces can be the result of sliding of cones on conical cups due to compaction or telescoping, but they can also be the intersection of different non exactly coaxial conical surfaces. Further SEM imaging will help in solving this question. It should require additional studies to identify plumose marks on conical surfaces and test the results with those on planar joints. Roach et al 1993 have carried out some comparative studies between planar joints and shatter-cone surfaces, future broadening of these studies to include cone-in-cone surfaces will be welcomed for the fractal description and comparison amongst different types of conical fractures. Textures on conical surfaces could be also studied as equivalent to main surface and steps in plumose fractures (Roberts, 1961; Hodgson, 1961). Opening-of-the-feather direction in plumose joints is indicative of progression-of-the-fracture direction.

Clay films: Clay films underlying contact between cones and cone cups are the result of injection of sedimentary clays by fluids being squeezed at the time of compaction, and are not the result of sedimentary layers being deformed by growing crystals.

Clay rings: Slight deformation of cones, due merely to compaction, "opens" the intersections of major and minor fractures allowing flow of clay to form pressure-release rings. In a sample of unknown origin in the author's collection (but probably from the same area as those depicted by Gresley, 1894 and Gilman and Metzeger, 1967) these rings show a feather-like growth, with curved extinction in plane-polarized light and clearly post-date formation of cone-in-cone.

Displacive growth: Associated to the jacketing of fissures by pore pressure and pressure of fluids being squeezed from host sediments. The process should be more exactly described as "non cementative" or "non inclusive", except for minor films included during crack-seal growth.

Orientation of calcite crystallographic axes: In the crack-seal growth model adopted in this hypothesis, the orientation of crystallographic axes is the result of the local state of stress. Dispersion in calcite axis orientation is the consequence of several causes, such as natural deviation and partial recrystallization in different stress regimes after compaction. The radius of the circle in the point diagram should be a function of primary dispersion but by no means related to the conical fracture geometry.

Orientation of cone apex: Pressure gradients between the core of the concretion and the host sediment (or the upper and lower parts of a vein) would cause the preferential development of one of the two conjugate shear systems. In the case of concretions, where cones axis are radially distributed and which always point inward, it could be the expression of differences between pressures inside and outside the concretionary body. This pressure gradient would also lead to the expulsion of inner fluid-saturated clays, occasionally leading to the telescoping of the cones already mentioned and illustrated in Figure 1. In the case of symmetrical veins, expulsion of fluids in both upward and downward directions during compaction should be expected in the central layer. This would develop opposite shear systems in each case and create the final pattern of opposite cones in each layer.

Woodland's 1964a paper on cone-in-cone is possibly the most complete atlas on the subject. Despite this, there are many ambiguous statements in this work such as, "this feature is not already explained" or "it is difficult to explain how this feature developed". It is not possible in this paper to discuss each of this features, but most of them have a simple explanation if the crack-seal mechanism is taken into account, the overpressured model for the growth of both veins and concretions is adopted, and a secondary and brittle origin for cone-in-cone is preferred.

CONCLUSIONS

On the basis of the observed features and documented occurrence of undercompacted-overpressured sediments in present and past basins, a new mechanism for the origin of cone-in-cone is proposed. The mechanism, which considers cone-in-cone to be of secondary origin and the result of true conical fracturing, can be summarized as follows:

Weak points or planes present in a highly porous sediment are forced to open by pore pressure. Calcium carbonate crystallizes. Abnormally high fluid pressures produces a nearly hydrostatic stress distribution and precludes both compaction and shear fractures. Seals are opened. When this critical stage is reached, pressures tend to reach normal hydrostatic values. Fluids begin to be expelled. In this environment the vein behaves in a brittle way while the host sediment is still saturated and plastic. The model implies transference of the overload from the fluid to the clastic framework and from it to the vein. Fractures cross-cutting vein or rim adopt a conical pattern because both of the lesser stresses are equal. Residual pressure gradients develop those previously formed conical fractures which are favorably oriented and infilled them with clay. Compaction squeezes pore fluids out of nodules and lenses. Later, high fluid pressure gradients can telescope cones, overburden load and geothermal gradient can modify the structures of both clayey and carbonate bodies, and the replacement of original materials can take place with different degrees of macro- and microscopic modifications.

Not only classical cone-in-cone morphological features, but also some environmental uncertainties arising from comparison of textural and isotopic data, are better explained by this theory. The author, who is neither a sedimentologist nor a geochemist has only outlined the possibility of a reinterpretation of how cone-in-cone formation affects concretions and veins using some criteria of rock and soil mechanics. Further evaluation of this hypothesis should be carried out by applying it to existing cone-in cone published data and by careful analysis of new examples of this phenomenon.

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