Laboratory Handbook of Carbonate Petrology

(Volume I)

D.J. Shearman

B.R.C. Granier, editor

PREFACE

(a Word from the Editor)

Although I never had the opportunity to meet Professor Douglas James SHEARMAN in person, his numerous publications on the sedimentology of carbonates and evaporites profoundly influenced my understanding of the subject.

During a summer internship at TOTAL-Compagnie Française des Pétroles, I was fortunate to obtain a xerox copy of his *Laboratory Handbook of Carbonate Petrology* from an engineer who had previously attended one of Professor SHEARMAN's seminars. Since 1983, this collection of documents – enriched with pedagogical sketches of exceptional clarity – has accompanied me throughout my professional trajectory: initially as a doctoral candidate (until 1987), subsequently as an oil and gas exploration geologist (until 2004), and, more recently, as a university professor (until 2025).

This first volume constitutes a lightly revised and digitized version of the original Laboratory Handbook of Carbonate Petrology. Given that the source material dates from the early 1970s, a limited number of concepts and terminological expressions have been updated to reflect contemporary understanding and usage. All such modifications are explicitly indicated in blue to ensure transparency.

A second volume, conceived as an atlas of photomicrographs, is currently in preparation and will complement this edition.

I extend my sincere gratitude to Mary Ann CANNING, Anthony C. SHEARMAN, and Nicholas J. SHEARMAN, the daughter and sons of Professor SHEARMAN, for graciously granting permission to reproduce and publish this material. I am also indebted to Professors Christopher G.St.C. KENDALL (1938-2024) and Richard C. SELLEY, former students of Professor SHEARMAN, whose encouragement and support were instrumental in bringing this editorial project to fruition.

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FOREWORD

This *Laboratory Handbook of Carbonate Petrology* by Doug SHEARMAN is a brief historical summary of his understanding of carbonates and evaporites. It is one of the few documents SHEARMAN created on petrographic problems that interested him. Parts of the booklet are still applicable to present day carbonate petrology, though there are some dated and incorrect concepts. The reader should think through what they read. This preamble is my token of thanks to Doug as one of his graduate students for the education gave me in carbonate and evaporite petrology and facies distribution. He justifiably regarded me as an of out-of-control public schoolboy but even so took the time to teach me to be a better geologist.

Many of the ideas express in the booklet were developed when Doug SHEARMAN was one of the leaders of the Sedimentology Geology Research Group at the Royal School of Mines at Imperial College. Here he directed studies involving sedimentary petrology and its application to the study the shallow-water barrier – island coastline and its adjacent coastal plain – the sabkha of Abu Dhabi. Paradigms he developed in these studies served as catalysts for major advances world wide in carbonate and evaporite geology. They enabled the determination of the depositional settings for the accumulations of modern and ancient carbonate and evaporite facies and what drove their diagenesis. His ideas greatly aided and influenced the search for, discovery, and extension of hydrocarbon reservoirs by oil companies, and will do into the future. It is now recognized that intertidal and supratidal cycles, so called sabkha cycles of Doug SHEARMAN, exist world wide in both Holocene and ancient sedimentary sections. Doug SHEARMAN recognized for the first time the existence of Holocene accumulations of supratidal anhydrite and then its hydration to gypsum. He also recognized analogs of this association in the hydrocarbon fields trapped in these cycles in the Jurassic strata of the Middle East, the Permian strata of West Texas and New Mexico, the Middle East, and Western Canada. These facies included nodular anhydrite, and layered playa gypsum, vertical burrows of insects in anhydrite, and collapsed breccias associated with sabkha cycles. Further Doug recognized the role of mucilaginous organic coatings surrounding and investing almost all Holocene carbonate grains, and involvement with the micritization of the carbonates. He established remnants of the mucilaglnous material acted as a template which preserved the grains' outline and structure during solution and precipitation. He noted that during diagenesis the detailed structure of the grains was lost when the mucilaglnous coatings were destroyed but that the detailed structure was preserved when mucilaginous coatings remained.

Doug SHEARMAN developed most of his ideas when he informally supervised an eclectic loosely organized band of graduate students working towards graduate research degrees at Imperial College. He advised on studies involving sedimentary petrology and in the field. One form of exchange of knowledge came at Imperial College when Doug came to the everyday tea break at 11 am. Ideas flowed easily among us and it helped us all advance our research. It was in settings like this that Doug was at his most eloquent and we all benefited from his mind dumps.

Carbonate and evaporite petrology were topics Doug lectured in but his lectures were often hopeless, taking off on tangents unrelated to what he was supposed to teach but on topics that interested him. However separate from these lectures, Doug's reputation as a great teacher came, when he was one on one with his students, and they were both focused on a problem they both had a common need to solve. Doug was then awash with innovative ideas, presenting challenging conceptual models to solve geologic problems he recognized. He had the great ability to immediately come to a potential interpretation of geologic problem he saw and verbalize his solution. He believed that the laws of nature are consistent and predictable. Under Doug's initial confrontational tutelage I learned not to be intimidated by what one saw but to offer instant interpretations. I learnt how Doug applied oversimple axiomatic fundamental principles to Identify the critical information need to solve a problem and ignore the superficial noise. Doug's extensive knowledge of the carbonate and evaporite literature led me, shortly after my arrival at Imperial College, to spend hours in the library familiarising myself with both current and historical literature on these topics. This way I could compete with him and feel I had the edge. He used an iterative approach with his ideas, accepting but never admitting, he might be incorrect but correcting his models in light of new observations he accepted. He demonstrated an educated well prepared mind can apply the classic scientific method at lightening speed and offer an instant solution. We both had photographic memories, and he showed me how to use mine. The secret involved observation, memorizing the facts and an ability to visualize potential explanatory models and choose the model that best fit the data observed and not be intimidated. This gave Doug the power to be skeptic of the hypotheses of others and show how their misplaced assumptions might distort their conclusions. Doug's skill was based on his combined experience and knowledge of the literature provided him with a huge data base, together with an understanding of the setting in which the rocks he was looking at occurred. At the time I did not realize our dialogues were teaching me both petrology and sedimentology. I have since realized how much I learnt from him.

When Doug helped students interpret their data face to face he was inspirational but his managerial skills with his graduate students were close to non existent. When he wasn't enthusing over some geologic enigma he advised us how to cope with our future. Doug often warned me to be more socially careful, as did my mother. He was speaking from his own experiences in dealing with conservative academic society. This kind man was a razor sharp geologic magician and not the preoccupied fuddy duddy he saw himself as. He was Doug and I learned from him and so have the society of carbonate and evaporite geologists as his ideas have spread. This book is a memorial to him.

Christopher G.St.C. KENDALL
Distinguished Professor Emeritus

University of South Carolina,
Columbia – SC (USA)

Appended are several Professor Douglas SHEARMAN's obituaries:

BUSH P. (2003).- Professor Douglas SHEARMAN: Unorthodox and inspiring geologist.- *Independent* (Friday 23 May). URL: https://www.independent.co.uk/news/obituaries/professor-douglas-shearman-36554.html

EVANS G. (2005).- Douglas James SHEARMAN, 1918-2003. *In*: EVANS G. (ed.), Commemorating the life and work of Douglas SHEARMAN, 1918-2003.- *Proceedings of the Geologists' Association*, vol. 116, nos. 3-4, p. 191-205

SELLEY R.C. (2003).- Professor Douglas SHEARMAN: Eccentric geologist who discovered the origin of salt but did not publish.- *The Times* (Wednesday 21 May). URL: https://www.thetimes.com/uk/science/article/professor-douglas-shearman-fhmj06sv337

SELLEY R.C. (2003).- Douglas James SHEARMAN, 1918–2003.- URL: https://www.geolsoc.org.uk/about-us/history/index-of-obituaries-1828-date/obituaries-s/

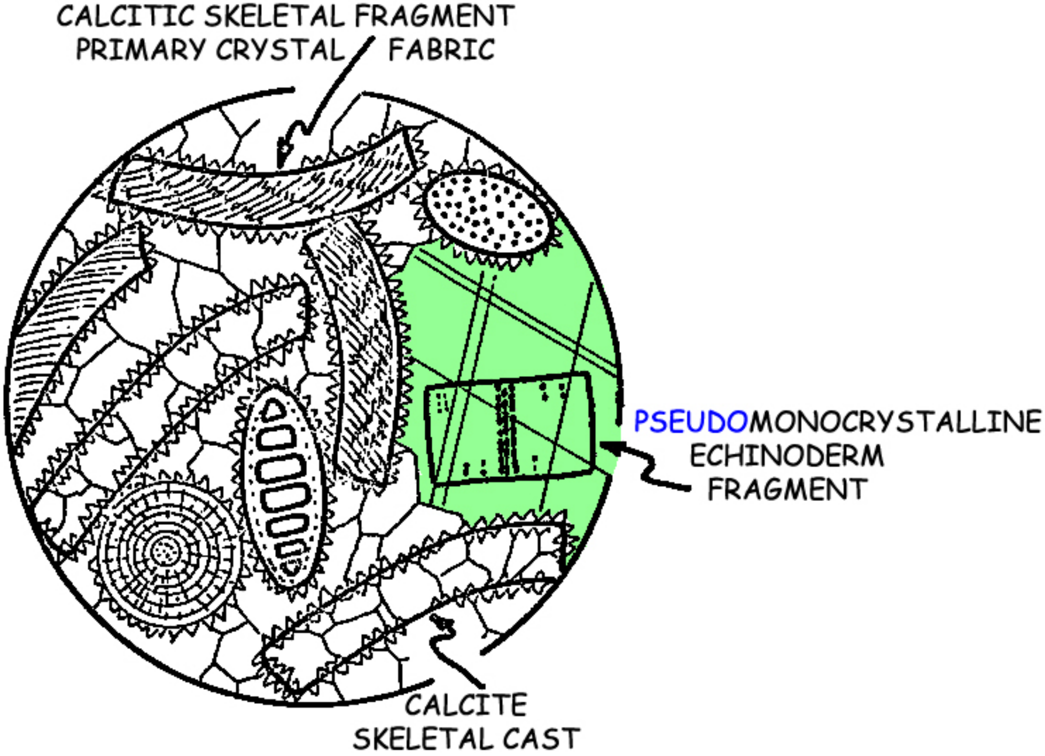
CARBONATE ROCKS

The term 'carbonate rocks' is used to include both limestones and dolomites. Pure limestones are virtually monomineralic, comprising calcite only. Calcite, $CaCO_3$, decomposes at 898°C to form calcium oxide, CaO: hence the name 'limestone', i.e., a rock that can be burnt to produce lime.

The mineral dolomite, $CaCO_3MgCO_3$, is present in some limestones and gradations can be found from pure limestones on the one hand to pure dolomite rocks on the other. The mineral 'dolomite' takes its name from a Frenchman, Count Déodat de Dolomieu (1750 - 1801). In the course of travels through the Tyrol, Dolomieu found that the limestones there were different from the limestones that he was familiar with elsewhere. Analysis of samples showed that they consisted not of calcite, but of what at that time was a new mineral: the double carbonate of calcium and magnesium. The mineral was named 'dolomite' as a tribute to Count Dolomieu, and the mountains of the Tyrol where the mineral was first found subsequently took the name 'the Dolomites'.

Because the word dolomite is used to describe both a mineral and a rock, it has been suggested that the word dolomitic should be applied to the mineral only and the term 'dolostone' introduced to designate the rock. Etymologically, 'dolostone' has no validity and there is little to be gained by using it. There are indeed few if any occasions when the dual meaning of the word dolomite is likely to cause ambiguity.

Despite their mineralogical simplicity the carbonate rocks are a highly complex group of rocks. The complexities are those of textures, crystal fabrics and sedimentary structures that result from the many ways in which the components of the original sediments were generated and deposited, and the diversity of diagenetic processes that subsequently operated on them. Although much can be learnt in the field and by examination of hand specimens, the critical details of components, texture and crystal fabrics can usually only be resolved in thin section under the microscope. This handbook of notes and sketches is therefore designed as an aid to the study of carbonate rocks at the level of the microscope.


CALCITIC SKELETAL FRAGMENT
PRIMARY CRYSTAL FABRIC
PSEUDOMONOCRYSTALLINE
ECHINODERM
FRAGMENT
CALCITE
SKELETAL CAST

Introduction to concepts of components, texture, and crystal fabrics

In the example illustrated, the limestone consists of an assortment of carbonate grains of sand-grade size, cemented by calcite. The rock has the texture of a sandstone.

The components are of two types: depositional components, i.e., the carbonate sand grains; and a post-depositional cement, e.g., the calcite cement. The depositional components comprise skeletal grains and non-skeletal grains (ooids and peloids).

As with any sandstone, the textural elements of the sand grains include such features as: grain size frequency distribution, grain shape, roundness, and packing density.

The term 'crystal fabrics' relates to the arrangement of the constituent crystals of the various components. It will be seen that the crystal fabrics vary from place to place within the rock. Two contrasting types of crystal fabrics are seen in the skeletal grains. Some have retained their original detail intact, whereas others have crystal fabrics that are clearly not primary but are reminiscent of cavity-filling cementations and are designated as skeletal casts in the diagram. The non-skeletal grains, i.e., ooids and peloids, each have distinct fabrics: the ooids have a combined concentric and radial arrangement of crystals, while the peloids are microcrystalline and roughly equicrystalline. The crystal fabrics of the calcite cement are not everywhere the same. Around most of the grains the cement comprises a narrow selvedge of tiny crystals that passes out abruptly into coarser crystals. However, the cement around the pseudomonocrystalline echinoderm fragments behaves like a single crystal of calcite, maintaining optical continuity with the calcite of the host grain.

Approximately half the world's oil reservoirs are in carbonate rocks, and knowledge of processes that influence the porosity and permeability of limestones is therefore of considerable importance. In the example under discussion the original carbonate sand had substantial primary porosity, but this has been completely obliterated by the calcite cement. Attention has been drawn to the fact that, around most of the grains the cement shows two fabric types: selvedges of tiny calcite crystals that pass out abruptly into coarser calcite crystals. The possibility arises that these represent two distinct episodes of cementation that may have been widely separated in time. This suggests that the original skeletal material went into solution to leave voids, i.e., porosity was generated, but these were later filled by calcite that shows a dual fabric similar to that of the calcite cement: i.e., a lining of small crystals that passes abruptly into coarser crystals. The rock illustrated was collected at outcrop, and the possibility arises that the calcite of the second phase of cement may have been introduced by meteoric waters. If this was so then the same formation, where encountered in the subsurface, may have undergone only the first phases of diagenesis, and in consequence be porous. This example, although hypothetical, is introduced to illustrate the importance of the study of crystal fabrics.

Editor's note: In the revised version, the term "mosaic" has been removed (as it should not be used when referring to cement); "equigranular" has been replaced by "equicrystalline" (because crystals are not grains, and vice versa); "monocrystalline" has been replaced by "pseudomonocrystalline"; "oolites and pellets" have been replaced by "ooids and peloids".

CLASSIFICATIONS OF LIMESTONES

Two systems of nomenclature for limestones or modifications of them are presently in common use. These are the classifications of Folk (1959 & 1962) and Dunham (1962) respectively. Each has its own particular advantages, but because of the great diversity of limestones the classifications provide only a series of very broad subdivisions within each of which there is wide and even contrasting variety.

FOLK'S CLASSIFICATION (see table separate sheet)

Apart from in situ organic growth structures, termed biolithites, Folk's classification is based on the relative proportions of three main constituents: allochems, micrite and spar.

Allochems comprise all aggregates of carbonate materials that were formed by chemical end biochemical processes within the environment of deposition. Folk recognized four principal allochems: intraclasts (it should have been lithoclasts, including both intraclasts and extraclasts), ooids, bioclasts, and peloids (Intraclasts are grains that were derived by reworking of weakly consolidated penecontemporaneous carbonate sediments from elsewhere within the general environment of deposition).

Micrite: an abbreviation for 'microcrystalline calcite ooze', i.e., very finely crystalline, often cryptocrystalline calcite.

Sparite: the term applied to relatively coarsely crystalline calcite that was either, introduced as cement, or formed by recrystallization of earlier finer-grained carbonate.

DUNHAM'S CLASSIFICATION (see table separate sheet)

Dunham's classification is based on depositional textures. Where the original sediment was bound together during deposition, the limestone is termed 'boundstone'. Other limestones are classified as mudstones, wackestones, packstones and grainstones, on the basis of the presence or absence of carbonate mud, and the extent to which the grains are mud supported.

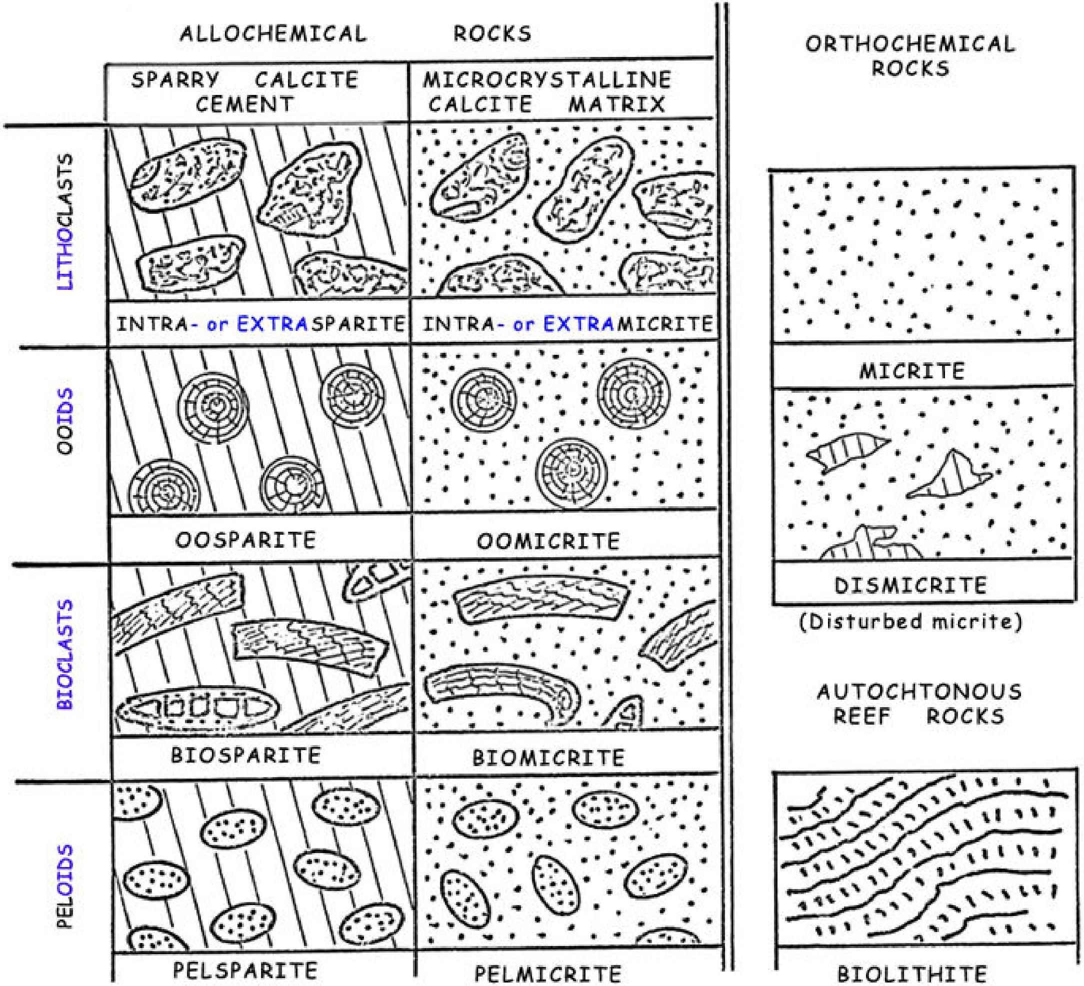
References

Ham W.E. (editor, 1962).- Classification of carbonate rocks. Ass. Am. Petrol. Geol. Memoir, Tulsa - OK, no. 1. A collection of papers including those of Folk and Dunham referred to above.

Embry A.F. & Klovan J.E. (1971).- A late Devonian reef tract on northeastern Banks Island, N.W.T.- Bulletin of Canadian Petroleum Geology, vol. 19, no. 4, p. 730-781.

Editor's note: The only point of Folk's classification is that it serves as a comprehensive introduction to the allochem categories. I prefer to use the Embry's and Klovan's classification (1971), which builds upon the Dunham's classification (1962). In their system, the boundstone category is subdivided into three subcategories: bafflestone, bindstone, and framestone. Additionally, they account for allochems larger than 2 mm, constituting over 10% of the rock, with two categories: floatstone (matrix-supported fabrics) and rudstone (grain-supported fabrics).

FOLK'S CLASSIFICATION



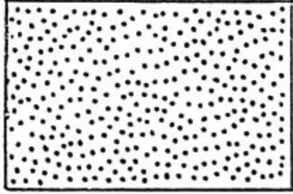
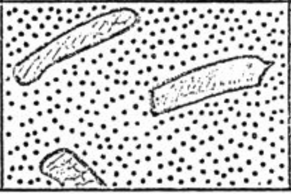
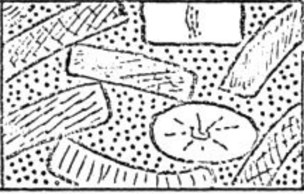
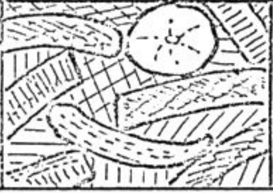
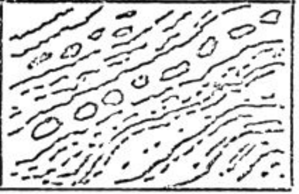
Understanding of carbonate rocks is facilitated by the fact that marine carbonate sediments are accumulating at the present day in many parts of the world, so that primary components and depositional processes can be studied at first hand.

In terms of origin, the depositional components of both Recent carbonate sediments and limestones are essentially similar. They are of two types: skeletal and non-skeletal. Skeletal components may accumulate in situ to form biolithites, or be broken up and transported within the environment to be deposited as carbonate sands and silts. Non-skeletal components include various accretionary grains such as pelleted muds and ooids. The origin of certain very fine grained to cryptocrystalline carbonate muds is uncertain. Their minute constituent crystals may have been direct precipitates from inorganic reactions, or the by-products of biochemical processes. Alternatively it is possible that they may have had a skeletal origin as disseminated carbonate grains in the thalli of certain calcareous algae. In view of the present uncertainty of their origin, these muds are provisionally classed as non-skeletal.

An important fact that has emerged from the study of Recent marine carbonate sediments is that whereas limestones characteristically consist of calcite only, their present day analogues comprise two minerals: aragonite and calcite. Aragonite and calcite are dimorphs of calcium carbonate that crystallize in the orthorhombic and hexagonal (rhombohedral) systems respectively. This dual mineralogy is encountered mainly in skeletal materials. Many groups of organisms construct only calcitic structures, others secrete only aragonite, but some build structures that comprise both aragonite and calcite. In limestones former calcitic skeletal structures generally retain their organic crystal fabrics intact, but what were formerly aragonitic structures are preserved in calcite with entirely different crystal fabrics. In present day marine sediments, most non-skeletal components, e.g., ooids, peloids, accretionary grains, and carbonate muds are dominantly aragonitic in composition. In the limestones these components are calcitic, and their crystal fabrics are commonly, but not always, closely similar to those of their Recent counterparts.

Another important mineralogical difference between modem marine carbonate sediments and limestones is that in many present day calcitic skeletal structures, the calcite is a high magnesium variety. These high magnesium calcite crystals carry between 8 to 30% $MgCO_3$ which is present as an integral part of their atomic lattice. In limestones skeletal structure of the same groups of organisms are present as low magnesium calcite, i.e., less than 5% $MgCO_3$. It is reasonable to suppose that the ancient skeletal structures originally comprised high magnesium calcite, but that the magnesium was lost from the lattice of the calcite during diagenesis. It is interesting to note that despite the loss of magnesium crystal fabrics of the calcite of the skeletal structures do not superficially appear to have been modified.

DUNHAM'S CLASSIFICATION

<table>
<tr><td colspan="4">ORIGINAL COMPONENTS NOT BOUND TOGETHER DURING DEPOSITION</td><td rowspan="4">ORIGINAL COMPONENTS BOUND TOGETHER DURING DEPOSITION</td></tr>
<tr><td colspan="3">CONTAINS MUD</td><td rowspan="3">LACKS MUD AND IS GRAIN-SUPPORTED</td></tr>
<tr><td colspan="2">MUD SUPPORTED</td><td rowspan="2">GRAIN SUPPORTED</td></tr>
<tr><td>LESS THAN %10 GRAINS</td><td>MORE THAN %10 GRAINS</td></tr>
<tr><td>MUDSTONE</td><td>WACKESTONE</td><td>PACKSTONE</td><td>GRAINSTONE</td><td>BOUNDSTONE</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
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Skeletal / Bioclastic
Oolitic
Crinoidal

DEPOSITIONAL COMPONENTS

RECENT

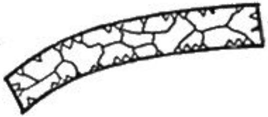
ANCIENT

SKELETAL

Calcitic skeletal structures

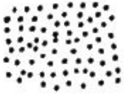
Original calcite crystal fabric of skeletal structure usually preserved intact.

Aragonitic skeletal structures

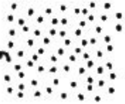


Original crystal fabric lost. Aragonite commonly leached, and cavity filled with drusy calcite crystals: i.e., a calcite cast (*).

NON-SKELETAL

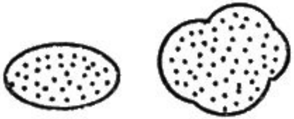


Cryptocrystalline aragonite muds of uncertain origin.

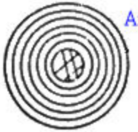


Microcrystalline calcite (micrite).

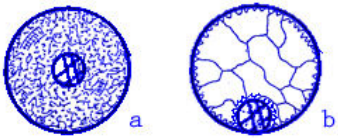
Pelleted aragonite mud and accretionary grains.



Microcrystalline calcite (micritic) pellets and accretionary grains.



Aragonite concentric ooid (of the Bahamian or Persian type)



Original crystal fabric lost: e.g., micritized ooids (a) and half-moon ooids (b).

(*) Editor's note: In the illustrated case, the aragonite skeletal structures were not replaced by calcite crystals exhibiting a mosaic pattern. Instead, the aragonite was leached, leaving behind a cavity which was subsequently filled with calcite cement displaying a drusy pattern. No modern equivalents to fossil calcite ooids with radial-concentric fabrics are currently known.

MINERALOGY AND PETROLOGY OF CALCAREOUS SKELETAL STRUCTURES

MINERALOGY	Aragonite	Aragonite + Calcite	Calcite	
Calcareous algae	++ green	×	++ red	
Foraminifera	+	×	++	
Porifera	+	×	++	
Hydrozoa	+	+	+	
Octocorallia	+	×	++	[Vaterite]
Hexacorallia	++	×	++	
Stromatoporoidea	×	×	++	
Bryozoa	+	+	++	
Brachiopoda	+	×	++	
Bivalvia	++	+	++	[Vaterite]
Gastropods	++	+	×	
Cephalopods	++ (*)	+ (*)	++ (**)	
Annelida	++	++	++	
Arthropoda	+	×	++	
Echinodermata	×	×	++	Pseudomonocrystalline. Each skeletal element behaves as a single crystal of calcite.

(*) e.g., phragmocone

(**) e.g., aptychus, rhyncholite, rostrum

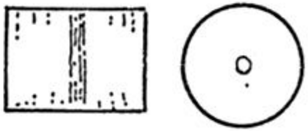
PETROLOGY OF FOSSILS

The crystal fabrics or architecture of calcareous skeletal structures show great diversity and many are objects of extreme intrinsic beauty. Detailed accounts of (bio-)crystal fabrics of skeletal structures are given in

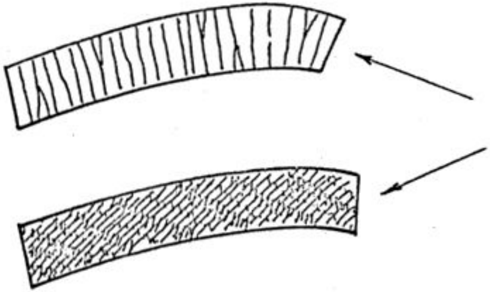
Bathurst R. (1971).- Carbonate sediments and their diagenesis.- Elsevier.
Cayeux L. (1916).- Étude pétrographique des roches sédimentaires. Paris. vol. 1, text; vol. 2, atlas.
Horowitz A.S. & Potter P.E. (1971).- Introductory petrography of fossils.- Springer-Verlag.
Majeske O.P. (1969).- Recognition of invertebrate fossil fragments in rocks and thin sections.- E.J. Brill.

In limestones former calcitic skeletal structures are usually preserved with their crystal fabrics intact, but former aragonitic structures are replaced by calcite with entirely new crystal fabrics that are clearly not organic. Thus for the purposes of basic petrology skeletal structures can be divided into two main groups: calcitic structures and calcite casts. Calcitic structures can be further subdivided into monocrystalline and polycrystalline structures. This subdivision is a natural one, because it splits off the echinoderms from the remainder of the calcitic organisms. Furthermore the subdivision is important because cementation around echinoderm fragments is usually by (mono-)crystalline overgrowth of calcite in lattice continuity with the calcite pseudomonocrystal of the fragment. Certain Mollusca secrete a composite skeletal structure with two layers; one of calcite and the other of aragonite. Where preserved fossil the calcite layer is preserved intact, but the former aragonitic layer is either a more or less empty mold or a calcite cast. It is convenient to designate such structures as composite.

Calcitic skeletal structures



Monocrystalline - i.e., echinoderm fragment

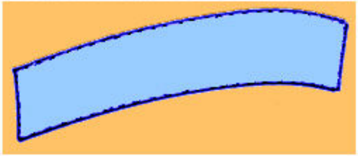


Polycrystalline - primary calcite fabrics preserved intact

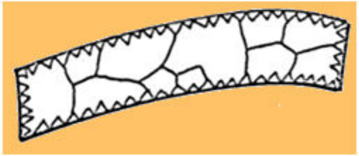
Composite skeletal structures

Former aragonite layer leached away,
resulting cavity (mold) filled with
drusy calcite crystals
Primary calcite layer preserved
intact

Dissolution cavity (mould)



Calcite cast



Former aragonite leached away, and resulting cavity (mold) filled with drusy calcite crystals, forming a calcite cast.

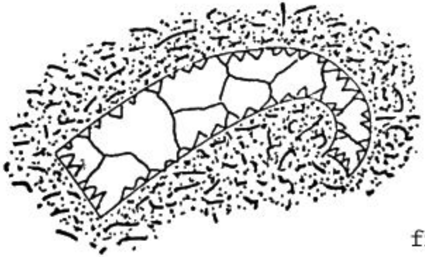


fig. 1

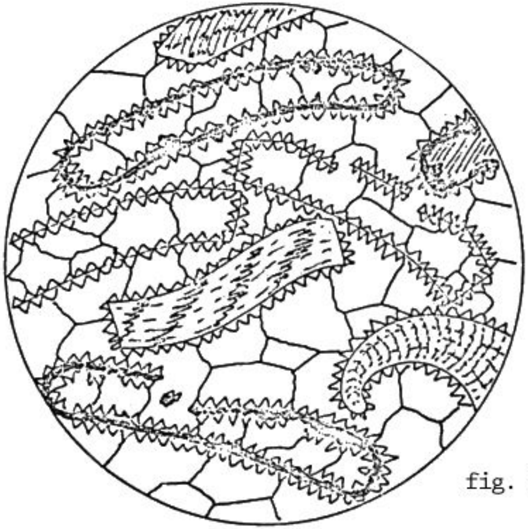


fig. 2

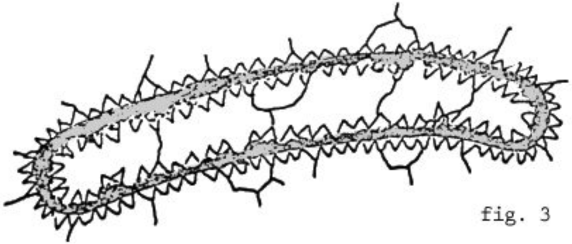


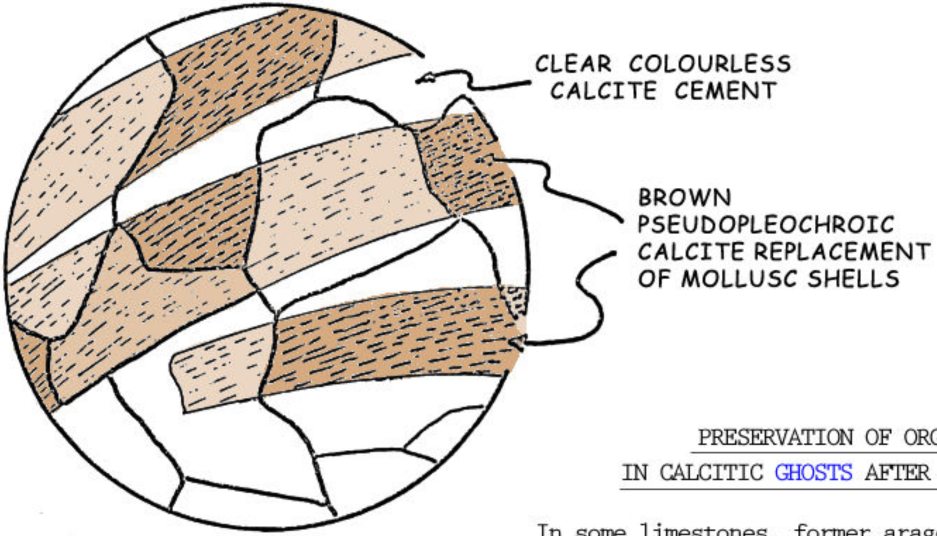
fig. 3

PRESERVATION OF SHAPE OF CALCITIC CASTS AFTER ARAGONITIC SKELETAL STRUCTURES

In many limestones the crystal fabrics of calcite casts after former aragonitic shells commonly correspond to those of cavity-filling drusy cementation. These fabrics imply that the aragonite went into solution to leave voids, i.e., moulds of the shells, that were subsequently filled with calcite cement.

The shapes of the former shells may be outlined in several ways:

(i) By a surrounding matrix of carbonate mud or silt: Fig. 1.
(ii) By micrite envelopes (micrite envelope the outer parts of a skeletal structure that have been altered to microcrystalline carbonate): Figs. 2 & 3.
(iii) By delicate lines of "dust" particles along which the calcite crystals of the cast and surrounding cement sit back to back: Fig. 2.



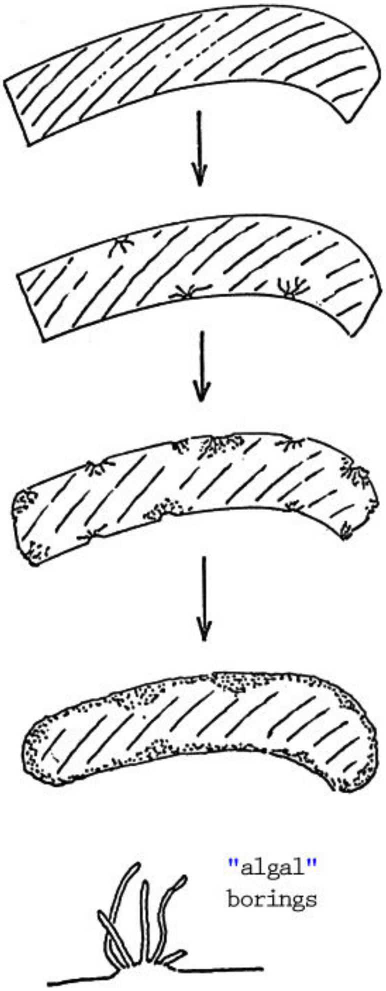
PRESERVATION OF ORGANIC MATTER IN CALCITIC GHOSTS AFTER ARAGONITIC SHELLS

In some limestones, former aragonitic shells have been replaced by coarsely crystalline calcite in which the original organic matter of the shell (conchiolin) is preserved intact.

Preservation of the conchiolin implies that replacement of the aragonite by calcite did not proceed via a void stage. It is likely that the replacement was achieved by a migrating front along which dissolution of aragonite was accompanied by concommitant in situ precipitation of calcite.

The presence of organic matter in the calcite imparts a strong pseudopleochroism to the crystals.

PENECONTEMPORANEOUS 'MICRITIZATION' OF CARBONATE GRAINS

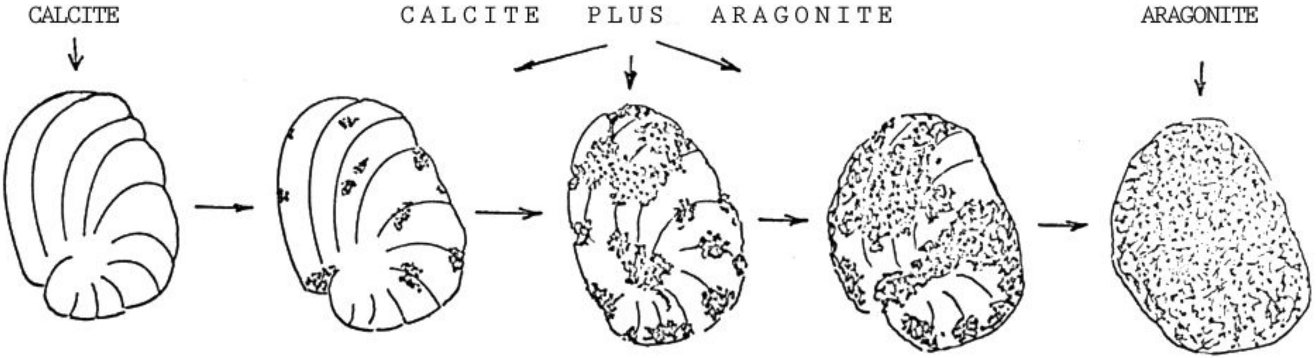


In present day marine carbonate sediments, the outer parts of carbonate grains, both skeletal and non-skeletal, tend to undergo alteration to cryptocrystalline aragonite while the grains are still on the sea floor. The change to cryptocrystalline aragonite takes place irrespective of whether the grain is calcite or aragonite. There are records of grains having been altered to microcrystalline calcite (i.e., micrite) in some recent sediments, but the occurrences do not appear to be common.

The recrystallization is usually associated with infestation of the surface of the grain by blue-green algae and other microbes. The microbes send boring processes into the grains and the alteration takes place in the vicinity of the bores. It is likely that the change is promoted indirectly by the vital activities of the microbes.

Not all grains are equally susceptible to the alteration. Porous and finely crystalline grains appear to be more susceptible than "massive" more coarsely crystalline ones.

PENECONTEMPORANEOUS MICRITIZATION OF PENEROPLID FORAMINIFERA



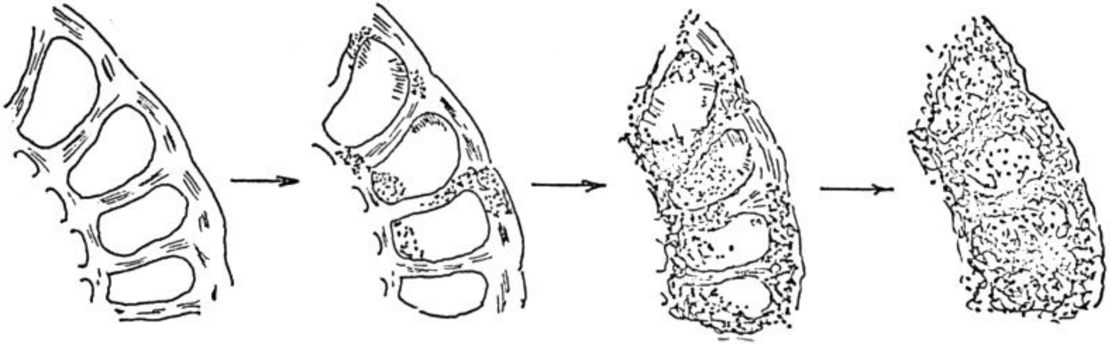
Some forams, e.g., Peneroplids, are highly susceptible to penecontemporaneous micritization. In any one sample of loose sediment, the surface appearance of the foram tests may range from lustrous at one extrerme to dull chalky at the other. The original tests are built of high magnesium calcite, but the chalky altered patches are cryptocrystalline aragonite. Where alteration has gone to completion, the grain loses all resemblance to a foram and can only be classed as a cryptocrystalline peloid.

PENECONTEMPORANEOUS MICRITIZATION OF PENEROPLID FORAMINIFERA

as seen in thin section

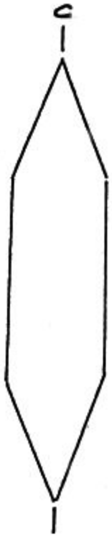
CALCITE

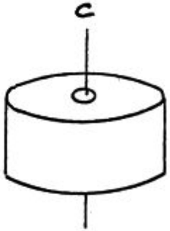
ARAGONITE

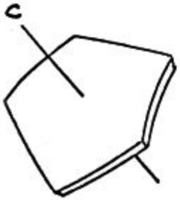


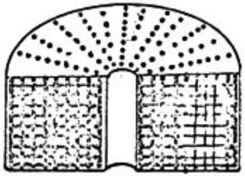
In an unaltered test, bundles of tiny calcite crystals are set in a matrix of organic matter (tectin). As micritization proceeds the calcite is replaced by cryptocrystalline aragonite and the brown organic matter becomes dispersed or oxidized. Aragonite needles grow in the chambers and these, too, are made over into cryptocrystalline aragonite.

ECHINODERMS

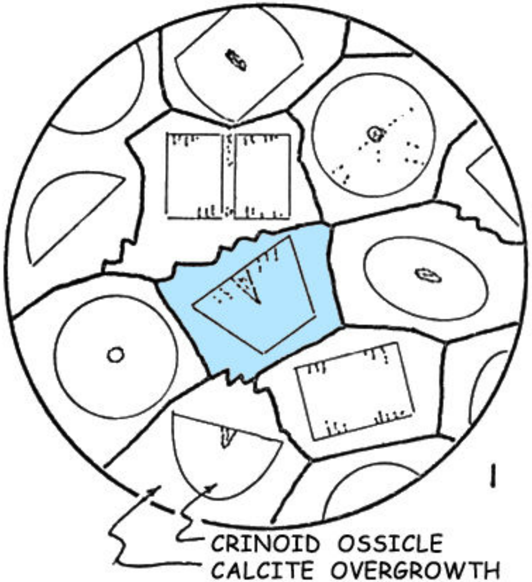




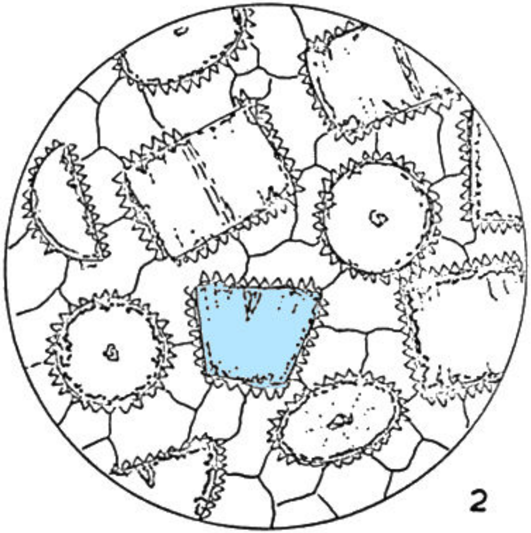




The echinoderms stand apart from all other groups of calcareous organisms in that each skeletal structure commonly behaves as a single crystal of calcite. Each ossicle of a crinoid is a pseudomonocrystal and each plate of the calyx of a crinoid or the test of a sea urchin is also a pseudomonocrystal. In almost every case, the c-crystal axis of the calcite is symmetrically related to the morphology of the particular skeletal element. The skeletal structures (i.e., the stereom) are ramified throughout by delicate networks of minute canals. The calcite of the spines of the modern sea urchin, *Echinus*, has a microporosity of approximately 50%. These canals substantially reduce the effective density of the skeletal structure.



1

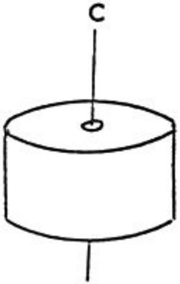


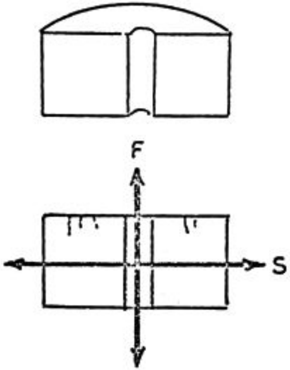
2

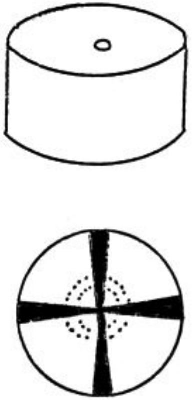
By virtue of the regular shapes of crinoid ossicles and the fact that their crystal and optic axes are symmetrically related, it is possible to infer the orientation of the ossicles relative to the plane of the thin section (see following page).

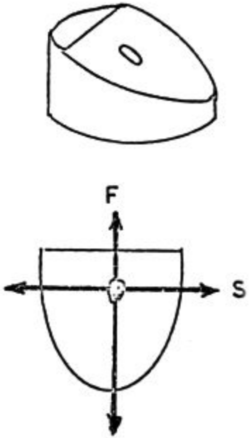
Where the surfaces of the ossicles were clean, cementation around them is usually by growth of calcite in lattice continuity with the ossicles: Fig. 1.

If the surfaces of the ossicles are micritized or coated with carbonate mud, the calcite crystal is effectively sealed off and the surrounding calcite cement usually shows a normal cavity-filling fabric: Fig. 2.

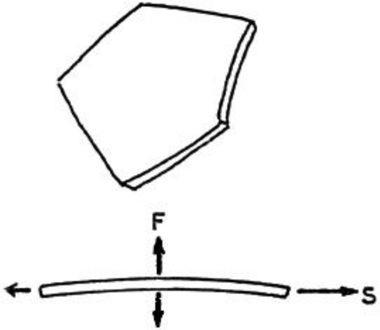


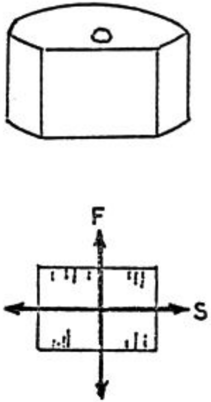


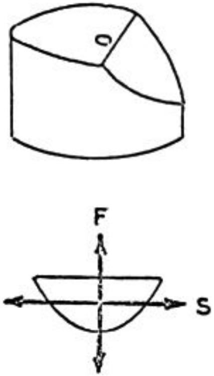


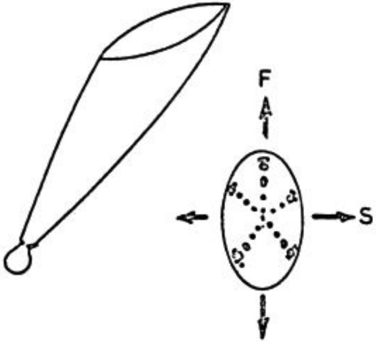


F FAST VIBRATION
S SLOW VIBRATION

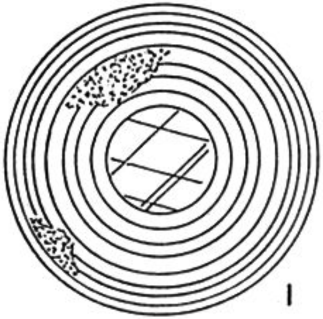








RECENT MARINE ARAGONITE OOIDS: MICRITIZATION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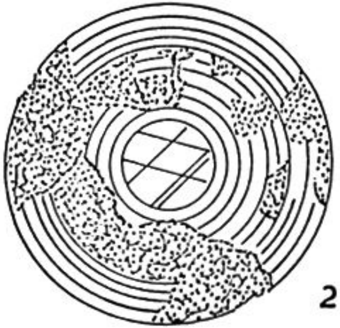
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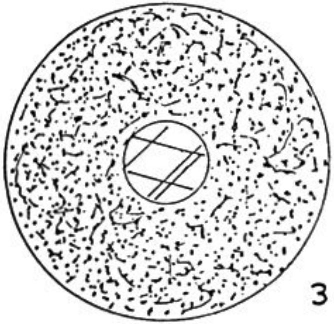
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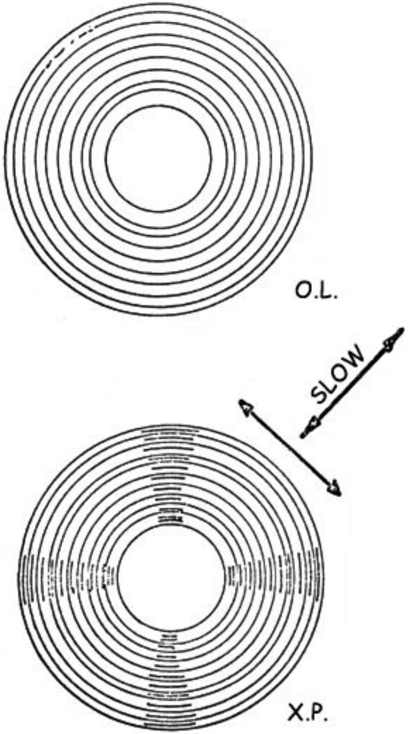
Ooids, like all other carbonate grains, are subjest to penecontemporaneous micritization to unoriented cryptocrystalline aragonite. Where ooids have been partially micritized, the areas of alteration extend irregularly inwards from the present surface, or from one of the inner concentric cortical layers: Fig. 1. The latter arrangement indicates that after the ooid had reached a particular size normal growth ceased and it underwent an episode of micritization. Subsequently normal ooid growth was resumed, and the micritized parts were then sealed in. Some ooids record a complex history of normal growth that alternated with episodes of micritization: Fig. 2. In extreme cases, Fig. 3. the whole of the original concentric structure may be obliterated.

RECENT ARAGONITE OOIDS - OPTICS (1)

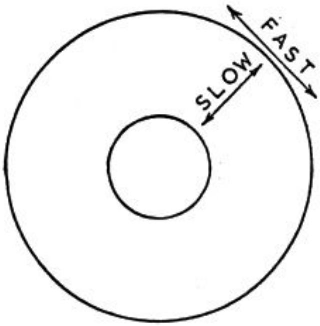


Most present day marine ooids are aragonitic. Many have perfectly developed concentric structure and a strong yellow-brown body colour in thin section. Individual crystals are too minute to be resolved under the optical microscope, however under crossed polars individual ooids show a symmetric extinction cross thus indicating that the constituent crystals are symmetrically arranged. Optically the ooids are radially slow. From this it is inferred that statistically the c-crystal. axes of the aragonite crystals are tangentially orientated.

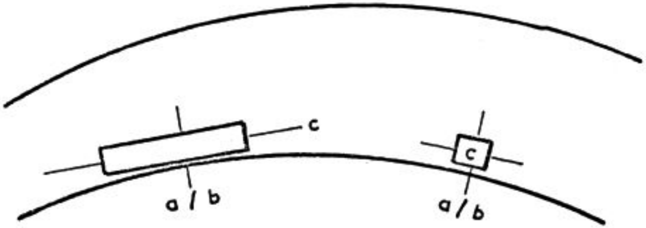
The ooids carry a volumetrically high proportion of organic matter, and it may be this that imparts the brown body colour. The organic matter is concentrated into concentric zones, and it is probably these that emphasize the concentric structure.

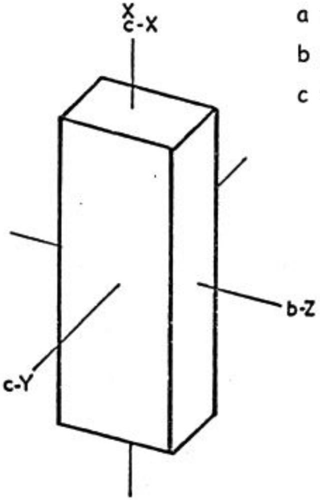
N.B. Not all recent ooids are wholly concentrically arranged aragonite. Some have radial structure, others are in part calcite. However, they are not abundant, but where they are found they may be diagnostic of particular sub-environments.

RECENT ARAGONITE OOIDS - OPTICS (2)



INTERFERENCE COLOURS OF ARAGONITE OOIDS SUGGEST AN AGGREGATE B.R. OF APPROXIMATIVELY 0.04
MEASURED R.Is. (L.V. ILLING): RADIAL 1.64, TANGENTIAL 1.605,
i.e., B.R. 0.035





$a = Y = n_\beta = 1.682$

$b = Z = n_\gamma = 1.686$

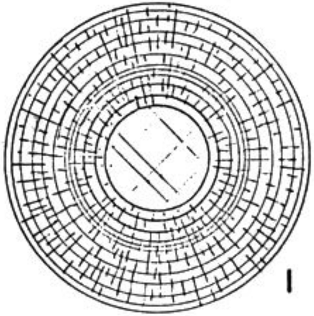
$c = X = n_\alpha = 1.530$

THEORICAL R.I. RADIAL = 1.684
THEORICAL R.I. TANGENTIAL = (1.530 + 1.682) / 2 = 1.606

THEORICAL B.R. = 0.078

DISCREPANCY PROBABLY DUE IN PART TO A MEASURE OF RANDOMNESS IN ORIENTATION OF THE CONSTITUENT CRYSTALS, AND IN PART TO THE MATRIX OF ORGANIC MATTER.

CALCITE OOIDS: CRYSTAL FABRICS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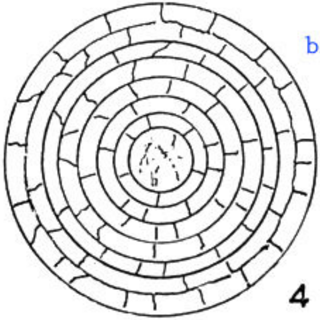
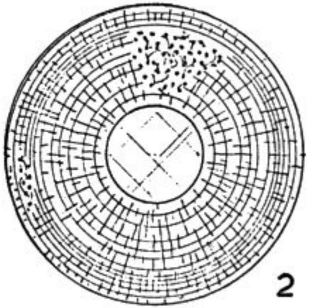

4

brick-like texture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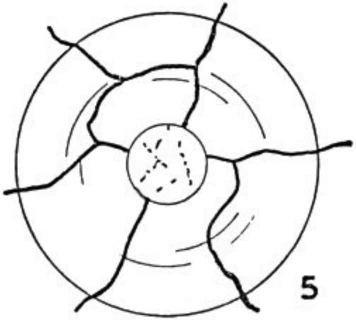
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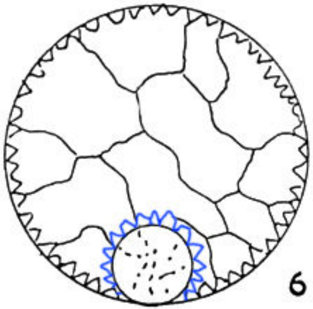
3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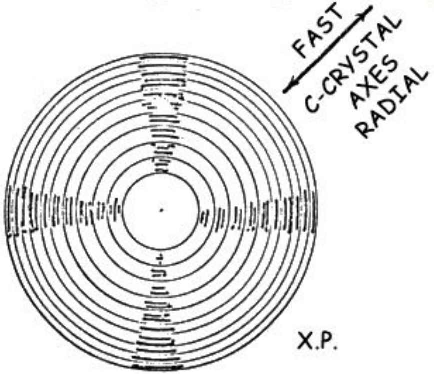
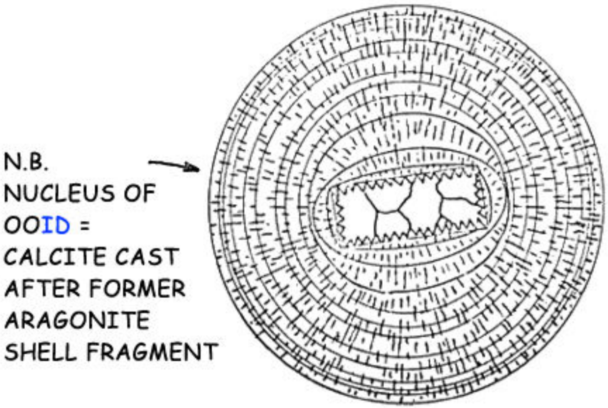
CALCITE OOIDS: CRYSTAL FABRICS





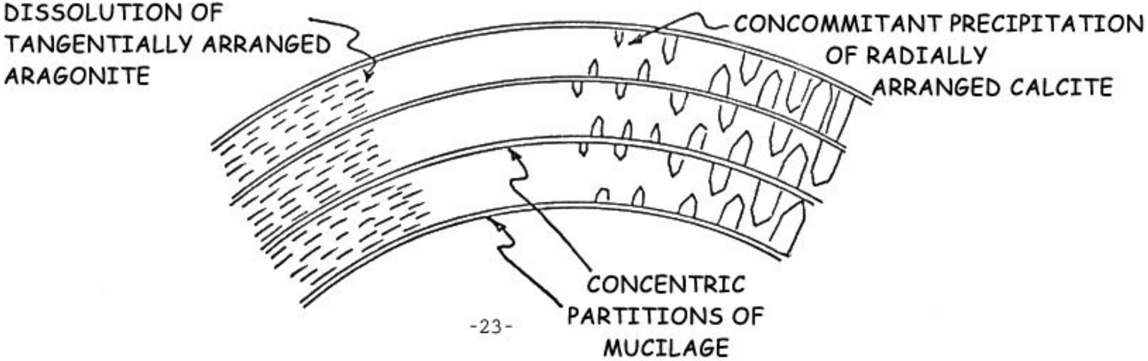
The original author (Shearman *et al.*, 1970) presented a model of "alteration from tangentially arranged aragonite crystals to radially arranged calcite crystals within the concentric mucilagineous layers" of an ooid.

Later, this model was proven wrong (Kahle, 1974; Sandberg, 1975).

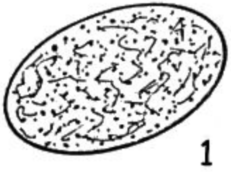
Kahle C.F. (1974).- Ooids from Great Salt Lake, Utah, as an analogue for the genesis and diagenesis of ooids in marine limestones.- Journal of Sedimentary Petrology, Tulsa, vol. 44, no. 1, p. 30-39.

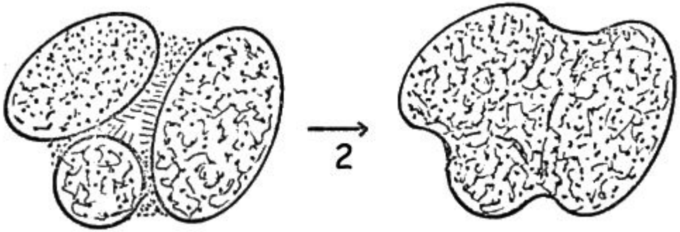
Sandberg P.A. (1975).- New interpretations of Great Salt Lake ooids and of ancient non-skeletal carbonate mineralogy.- Sedimentology, vol. 22, p. 497-537.

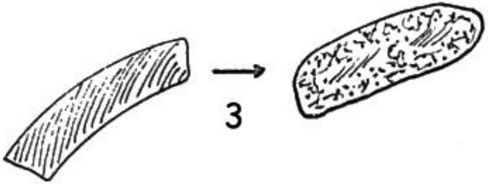
Shearman D.J., Twyman J. & Zand Karimi M. (1970).- The genesis and diagenesis of oolites.- Proceedings of the Geologists' Association, vol. 81, no. 3, p. 561-564 (Pls. 16-18).

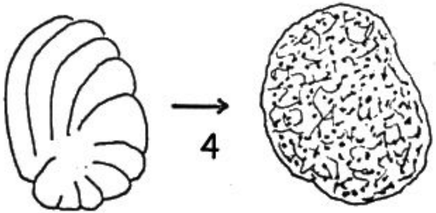


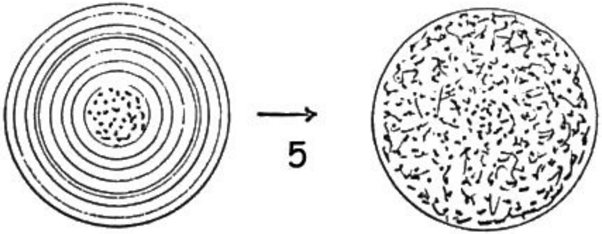
PELOIDS & ACCRETIONARY LUMPS

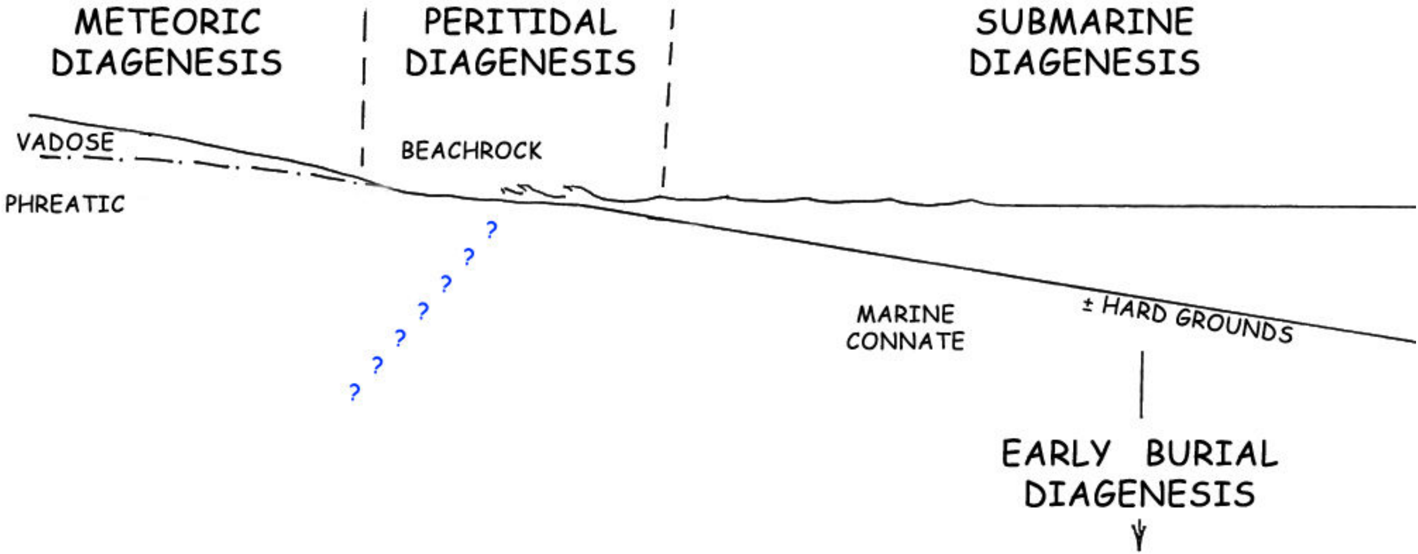






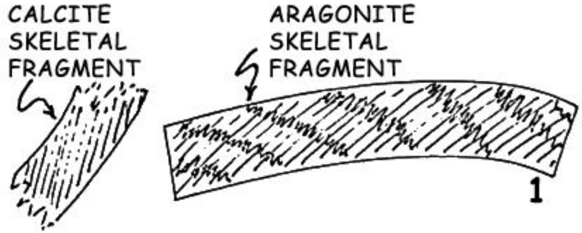




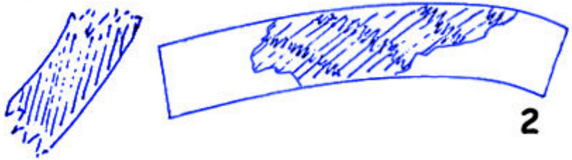


EARLY DIAGENETIC ENVIRONMENTS

SIMPLE TWO-PHASE CEMENTATION



1



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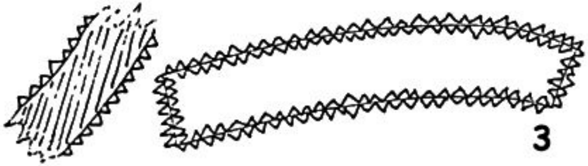

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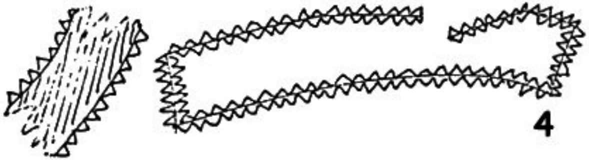

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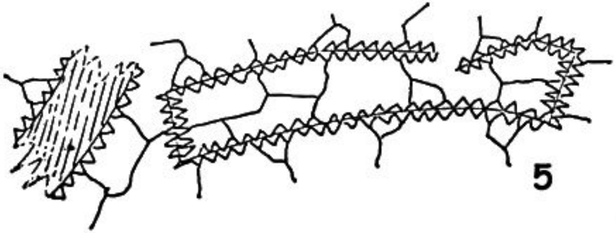


5

The crystal fabrics of the cement of many limestones, fig. 5, indicate that the rock was cemented in two distinct and separate episodes. The calcite of the cement and the skeletal casts comprises selvedges of tiny crystals that pass out abruptly into coarser crystals, and the outlines of some of the casts are locally ruptured. It is evident from figures 3-5 that cementation was achieved in two separate stages. The first phase, fig. 3, involved the emplacement of the narrow selvedges of calcite crystals uniformly over all surfaces, thus cementing the grains at their points of contact. The delicate moulds after former aragonitic skeletal fragments were then ruptured by compaction, fig. 4, before the introduction of the final phase of void-filling cement. Thus porosity was retained in the interval between the two phases of cement. The overall fabric evidence suggests that the calcite of the first phase of cement was supplied by the redistribution of the calcium carbonate formerly present as aragonite: figures 1 and 2. However, it must first be demonstrated that we were dealing with a closed system. Additionally, aragonite leaching requires acidic waters, whereas calcite cementation requires alkaline brines.

REPLACEMENT OF ARAGONITE BY CALCITE: VOLUME CHANGES

In those limestones where the calcite of the first phase of cement was supplied by redistribution of calcium carbonate formerly present as aragonite, the change from the high density to the low density dimorph must necessarily involve an increase in volume. This require that the system was essentially a closed one.

ARAGONITE $CaCO_3$		CALCITE $CaCO_3$	
mol wt -	100	mol wt -	100
density -	2.93	density -	2.71

$$\text{VOLUME}_A \approx \frac{100}{2.93}$$

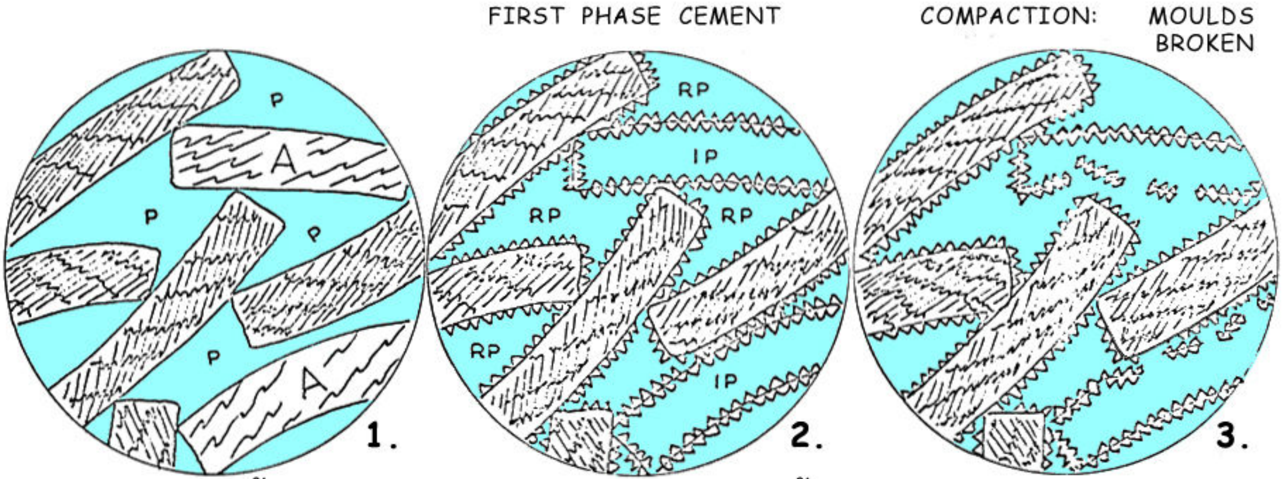
34.13 VOLUMES ARAGONITE
100 '' ''

$$\text{VOLUME}_C \approx \frac{100}{2.71}$$

36.9 VOLUMES CALCITE
108 '' ''

REPLACEMENT OF ARAGONITE BY CALCITE IN A CLOSED SYSTEM SHOULD RESULT IN AN INCREASE IN THE VOLUME OF THE SOLID PHASE OF APPROXIMATIVELY 8%.

POROSITY CHANGES



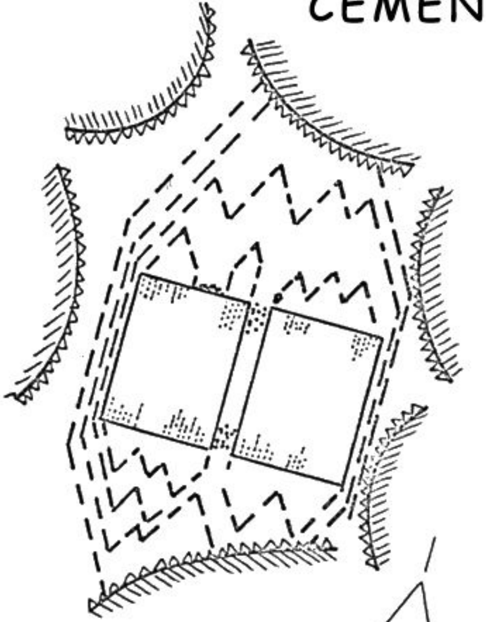
	%
CALCITE	45
ARAGONITE	20
POROSITY	35
	100

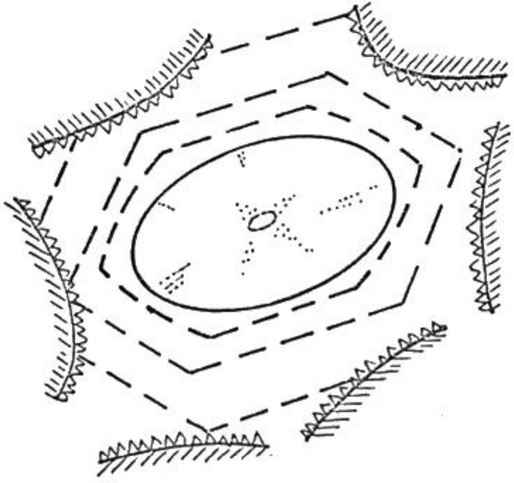
	%
CALCITE	45
CALCITE CEMENT	21.5
POROSITY	33.5
	100

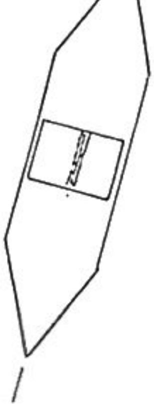
RP: RESIDUAL PRIMARY POROSITY	SAY 18.5
IP: INDUCED POROSITY	SAY 15
	33.5

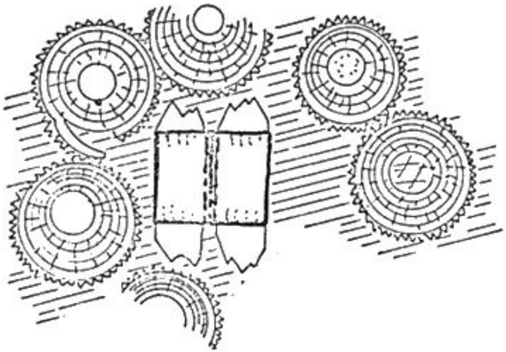
Where the calcite of the first phase of cement was produced by redistribution of calcium carbonate formerly present as aragonite, the diagenetic changes resulted in a rearrangement of the pattern of pore spaces. If the moulds after former aragonite shells were perfect, fig. 2, the porosity induced in the moulds would have been closed, and the effective porosity would only have been that of the residual primary porosity. However, compaction breaks the moulds, fig. 3, and opens up the induced porosity. Thus we have the apparent paradox that compaction can increase porosity.

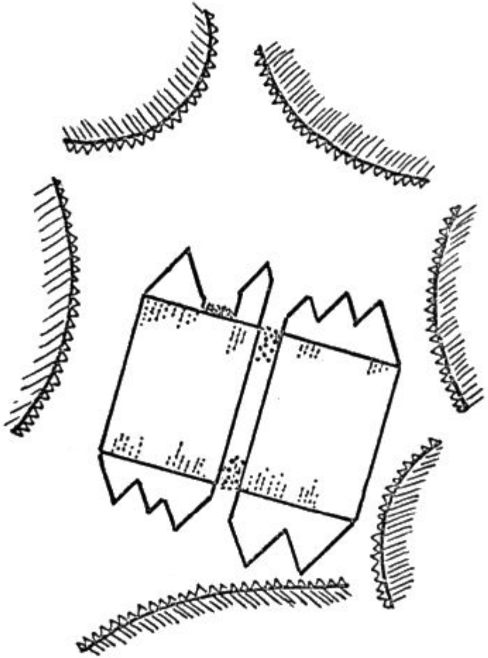
CEMENT STRATIGRAPHY

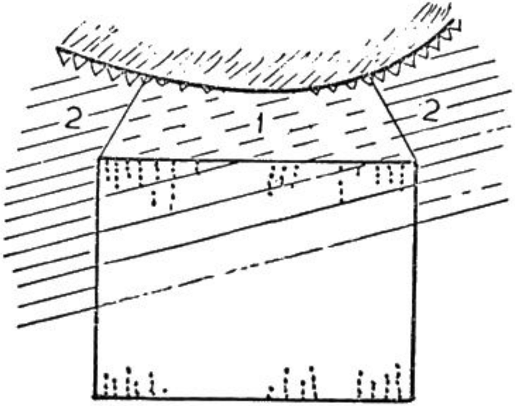


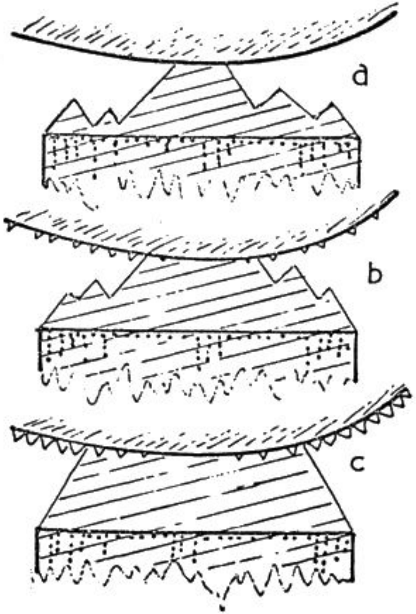


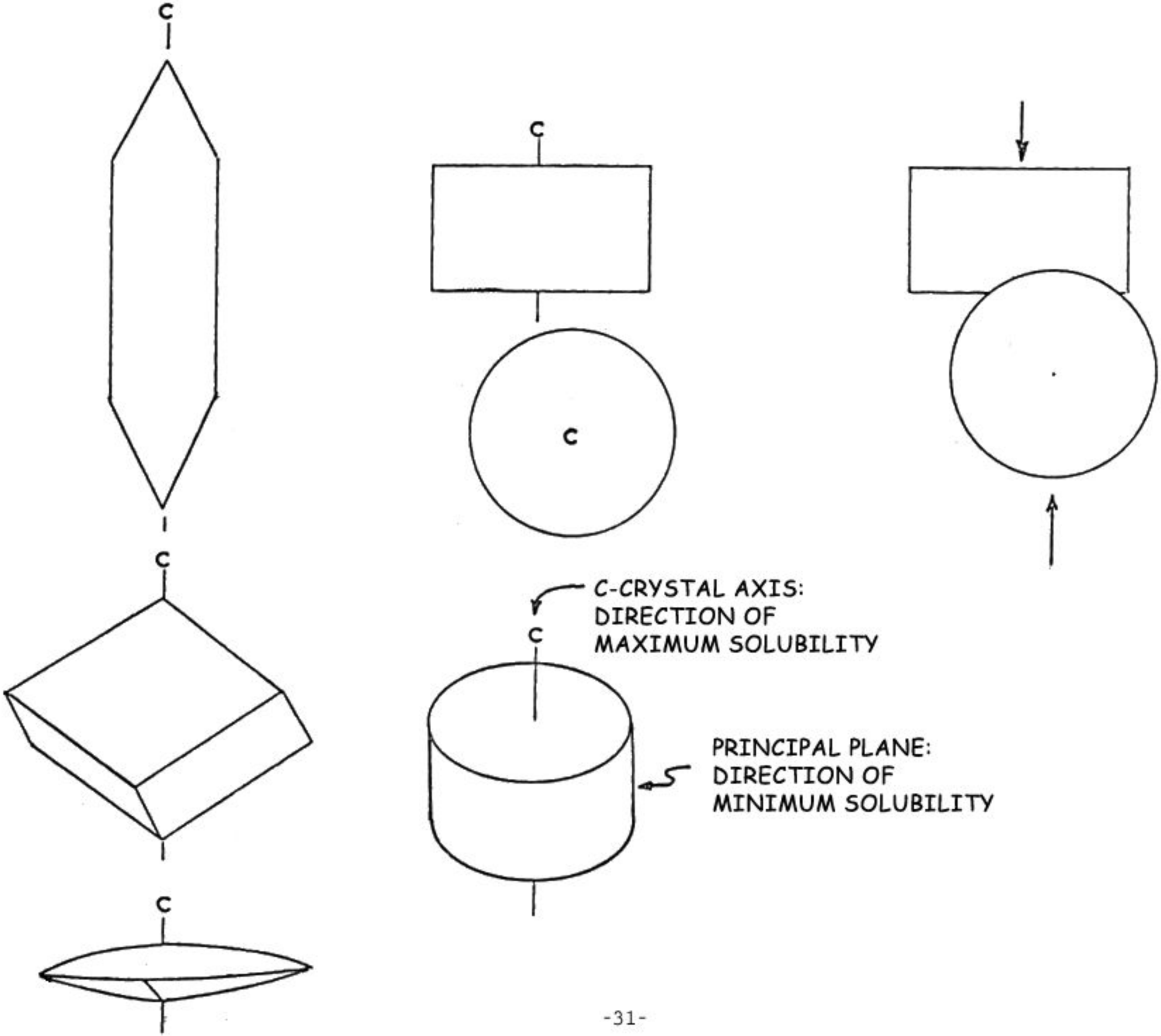


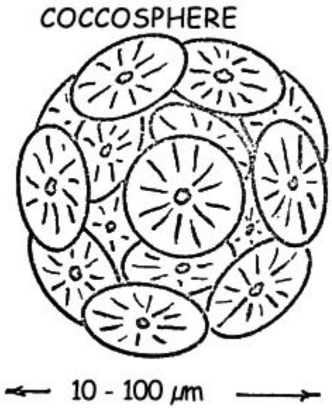


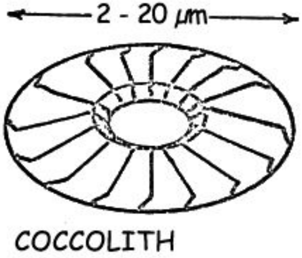



2
1
2


a
b
c

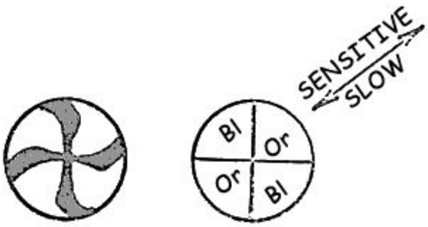

C
C
C
C
C
C
C-CRYSTAL AXIS:
DIRECTION OF
MAXIMUM SOLUBILITY
PRINCIPAL PLANE:
DIRECTION OF
MINIMUM SOLUBILITY





CHALKS

Chalks are very fine grained limestones, that are generally relatively lightly cemented and friable; but some chalk rocks may be well ccmented. Petrographically chalks comprise very fine grained aggregates of coccoliths, and minute fragments of 'comminuted' foram tests.

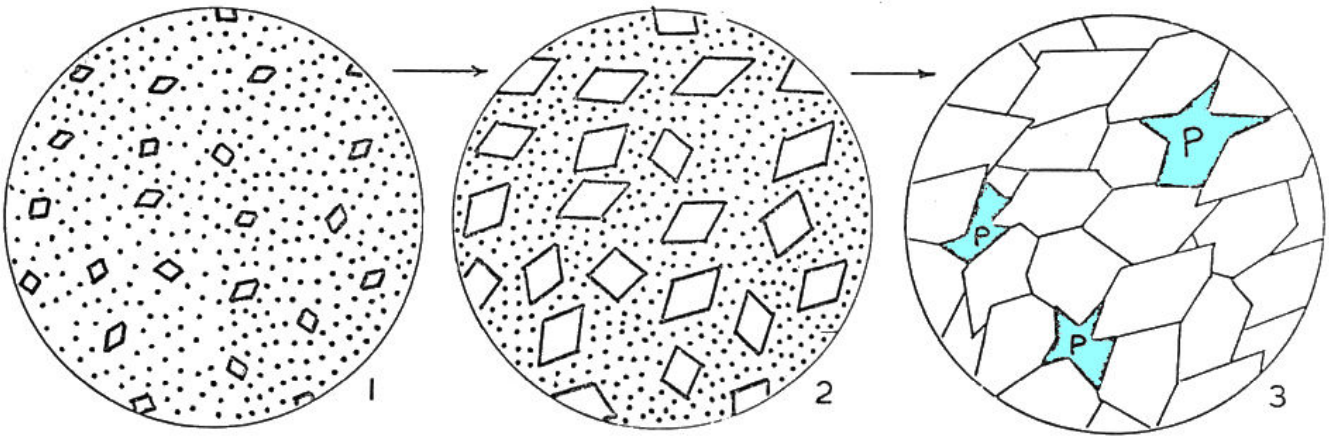


Bl - BLUE
Or - ORANGE

This very fine grained material cannot be resolved in this section uder the optical microscope, but is well seen with the SEM. Unbroken tests of planktonic foraminifera are abundant in some samples. Porosities of chalks may range from 0 to 40%, but perneabilities are generally low, being in the range 0.01 to 1.0 Md. In general permeabilities tend to increase with increase in porosity in a roughly linear fashion.

The paucity of calcite cement in chalks probably results from the fact that the majority of the depositional components were calcitic. In the absence of sighificant anounts of aragonite there was little calcium carbonate to redistribute as first phase cement. There is evidence from SEM studies that lithification, such as it is, was achieved in part by pressure solution.

REPLACEMENT DOLOMITE



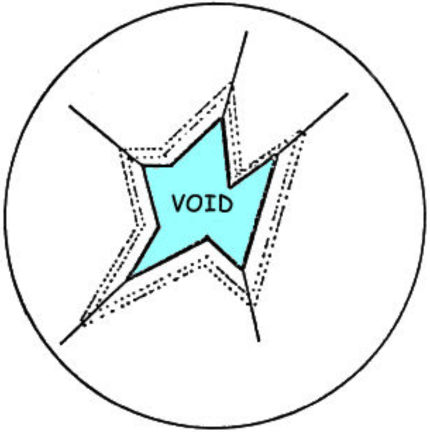
POROSITY ≈ 12.5%

DOLOMITIZATION OF LIMESTONES GENERALLY RESULTS IN DEVELOPMENT OF POROSITY, THAT MAY REACH 12% OR SO IN FULLY DOLOMITIZED ROCKS.

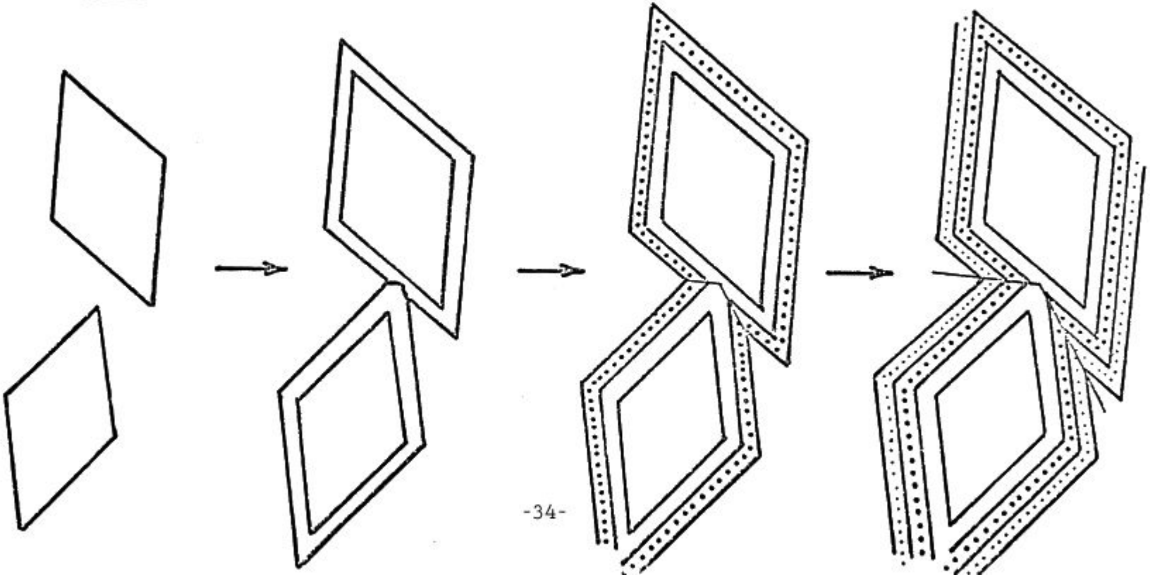
As seen in thin sections, the pore spaces are angular in outline with acute and obtuse re-entrants, thus indicating that pore spaces are moulded on the dolomite rhombohedra.

In partially dolomitized limestones the rhombohedra are generally all of the same order of size, and this suggests that the dolomite crystals were all growing at the same time.

ZONED REPLACEMENT DOLOMITE



In some dolomite rocks the dolomite crystals are stained with rhombohedral zones of ferric oxides. These zones cross the grain boundaries and pass uninterrupted from one crystal to the other. This arrangement demonstrates that the crystals all grew at one and the same time and at essentially the same rate.



REPLACEMENT DOLOMITE

1) $CaCO_3 + Mg^{++} + CO_3^{--}$ $CaCO_3\,MgCO_3$

2) $2\,CaCO_3 + Mg^{++}$ $CaCO_3\,MgCO_3 + Ca^{++}$

VOLUME CHANGES

CALCITE	DOLOMITE
mol wt 100	mol wt 184.4
density 2.71	density 2.86

1) $CaCO_3 + Mg^{++} + CO_3^{--}$ $CaCO_3\,MgCO_3$

$VOLUME_C \approx \frac{100}{2.71}$ $VOLUME_D \approx \frac{184.4}{2.86}$

36.9 VOLUMES CALCITE
100 '' ''

64.48 VOLUMES DOLOMITE
174.7 '' ''

INCREASE IN VOLUME OF APPROX 75%

2) $2\,CaCO_3 + Mg^{++}$ $CaCO_3\,MgCO_3 + Ca^{++}$

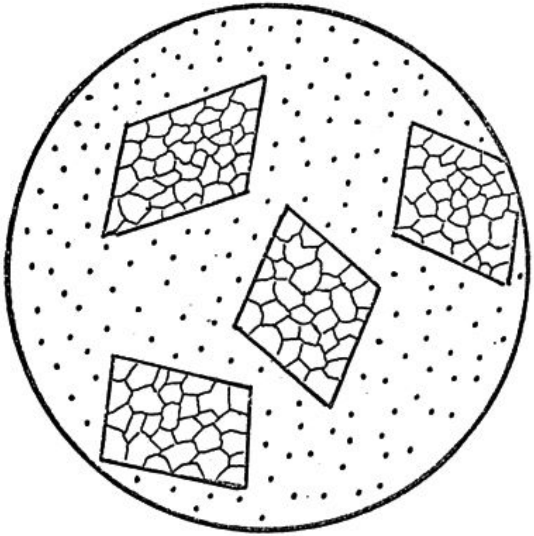
$VOLUME_C \approx 2 \times \frac{100}{2.71}$ $VOLUME_D \approx \frac{184.4}{2.86}$

73.8 VOLUMES CALCITE
100 '' ''

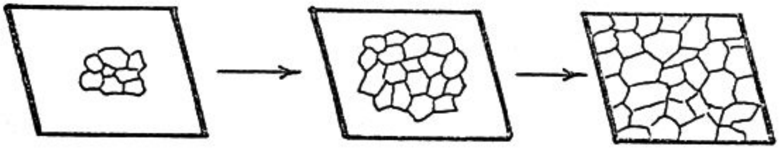
64.48 VOLUMES DOLOMITE
87.4 '' ''

REDUCTION IN VOLUME OF APPROX 12.5%

DEDOLOMITIZATION: COMPOSITE CALCITE RHOMBS



Each dolomite crystal is replaced by a polycrystalline mosaic of smaller calcite crystals. The calcite crystal fabrics of the rhombs are not those of cavity fillings. Where only partial dedolomitization has taken place, the replacement of dolomite by calcite appears to have started at the centres of the rhombohedra and proceeded outwards centrifugally.

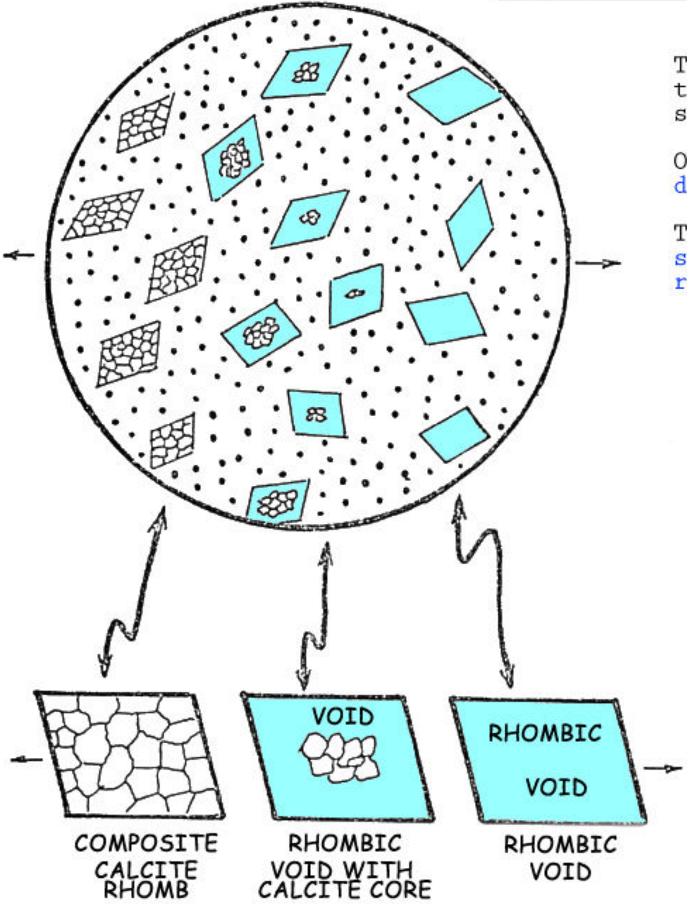


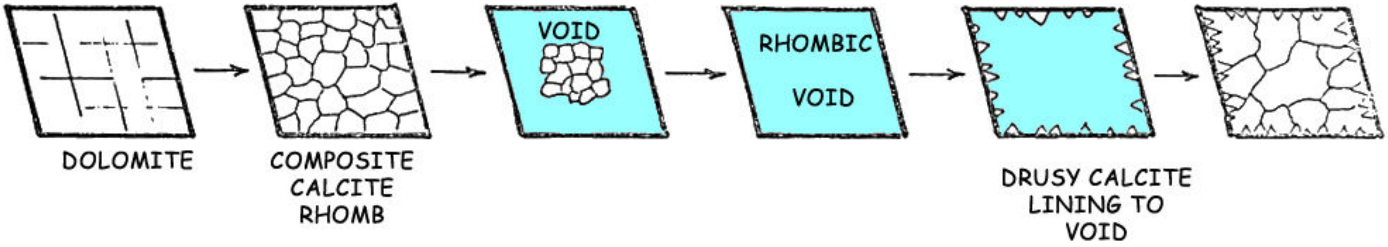
DEDOLOMITIZATION WITH FORMATION OF RHOMBIC VOIDS

There are two possible interpretations of the origin of the rhombic voids. These are shown on the next page.

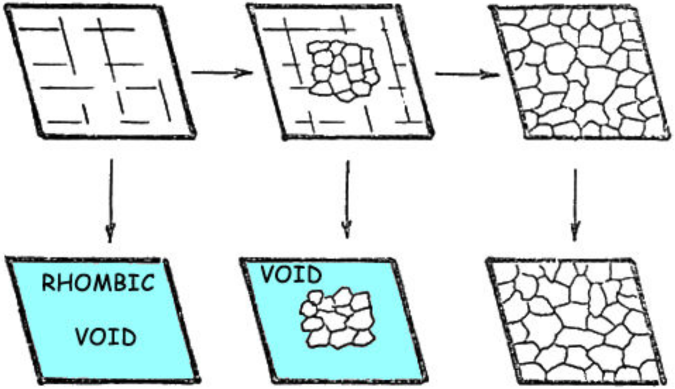
One is that the voids were produced by dissolution of dolomite.

The other is that the voids were formed by selective dissolution of the calcite that replaced dolomite.



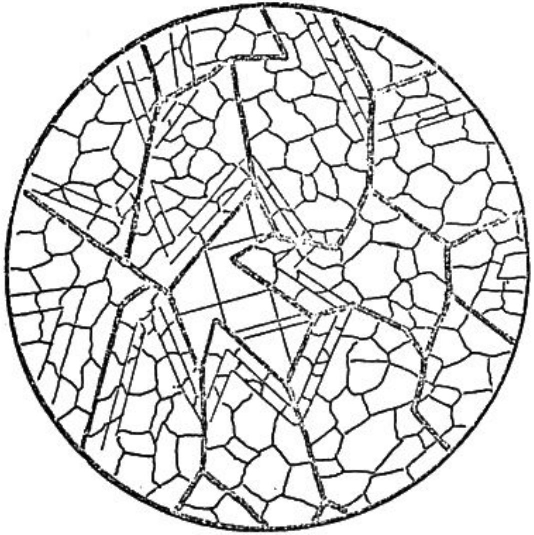


FORMATION OF RHOMBIC VOIDS BY SELECTIVE DISSOLUTION OF THE CALCITE THAT HAD REPLACED DOLOMITE



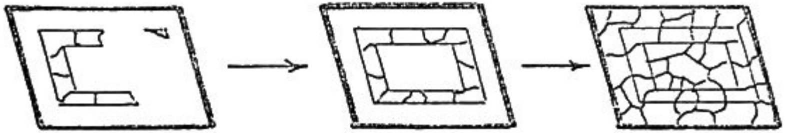
FORMATION OF RHOMBIC VOIDS BY DISSOLUTION OF DOLOMITE

ZONAL DEDOLOMITIZATION

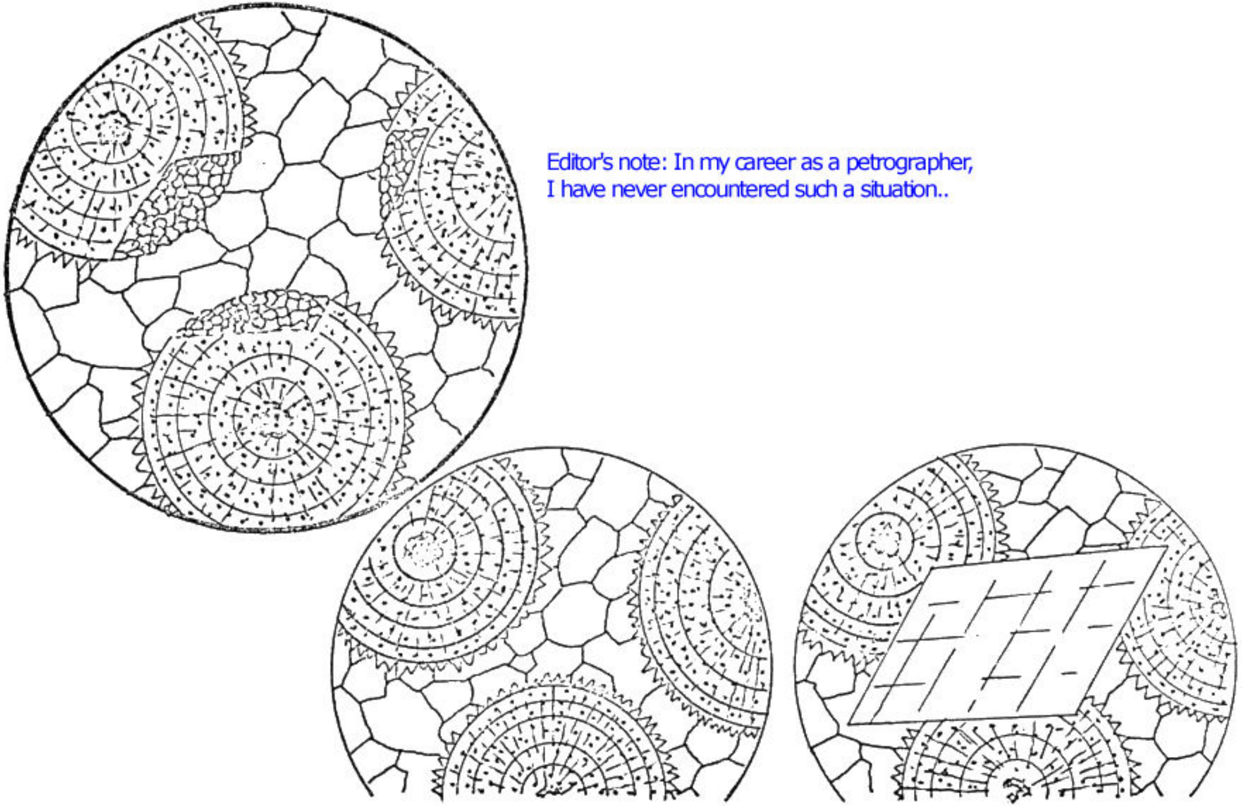


The crystal fabrics of the individual composite calcite rhombs are zoned, and the arrangonent of zones is the same in all of the rhombs.

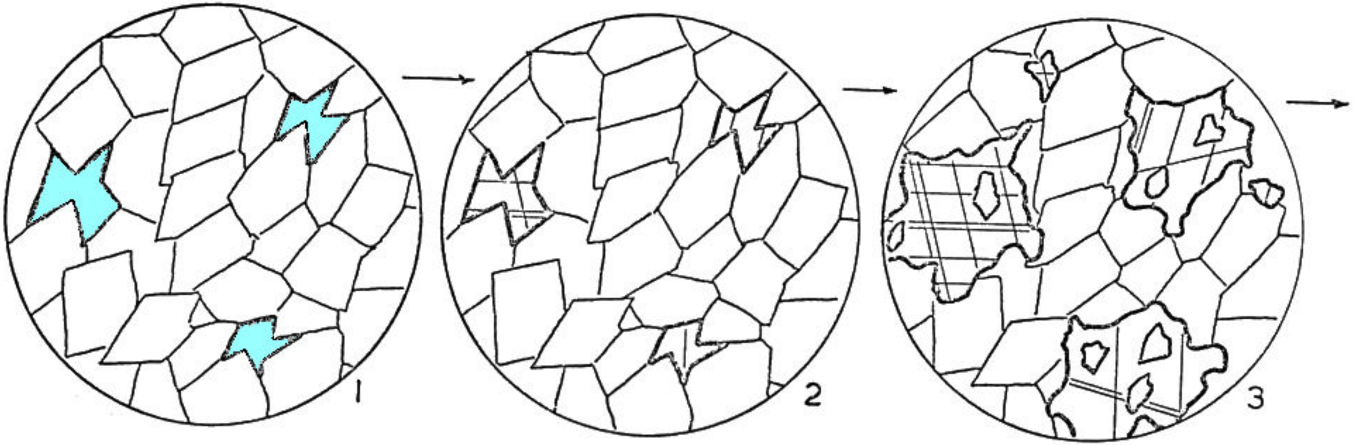
In partially dedolomitized rocks, the replacement proceeds zonally thus indicating that certain zones in the dolomite crystals were more susceptiple to dedolomitization than others: i.e., the former dolomite crystals were inherently zoned.

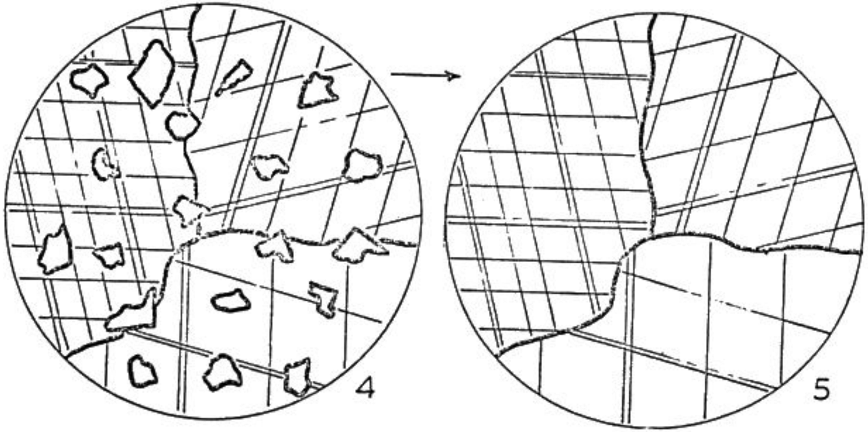


DEDOLOMITIZATION WITH REGENERATION OF FORMER LIMESTONE CRYSTAL FABRICS



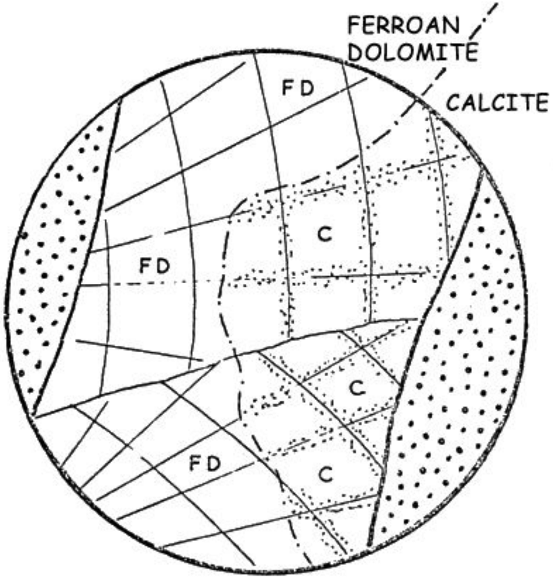
Editor's note: In my career as a petrographer, I have never encountered such a situation..





Dolomite is replaced by a coarsely crystalline mosaic of calcite. This mode of dedolomitization only affects rocks that were formerly 100% dolomite. Replacement starts by growth of calcite crystals in void spaces, and these crystals spread out replacively into the surrounding mosaic of dolomite. Where dedolomitization has gone to completion the resultant limestone has a crystal fabric that resembles that of marble.

DEDOLOMITIZATION IN LATTICE CONTINUITY

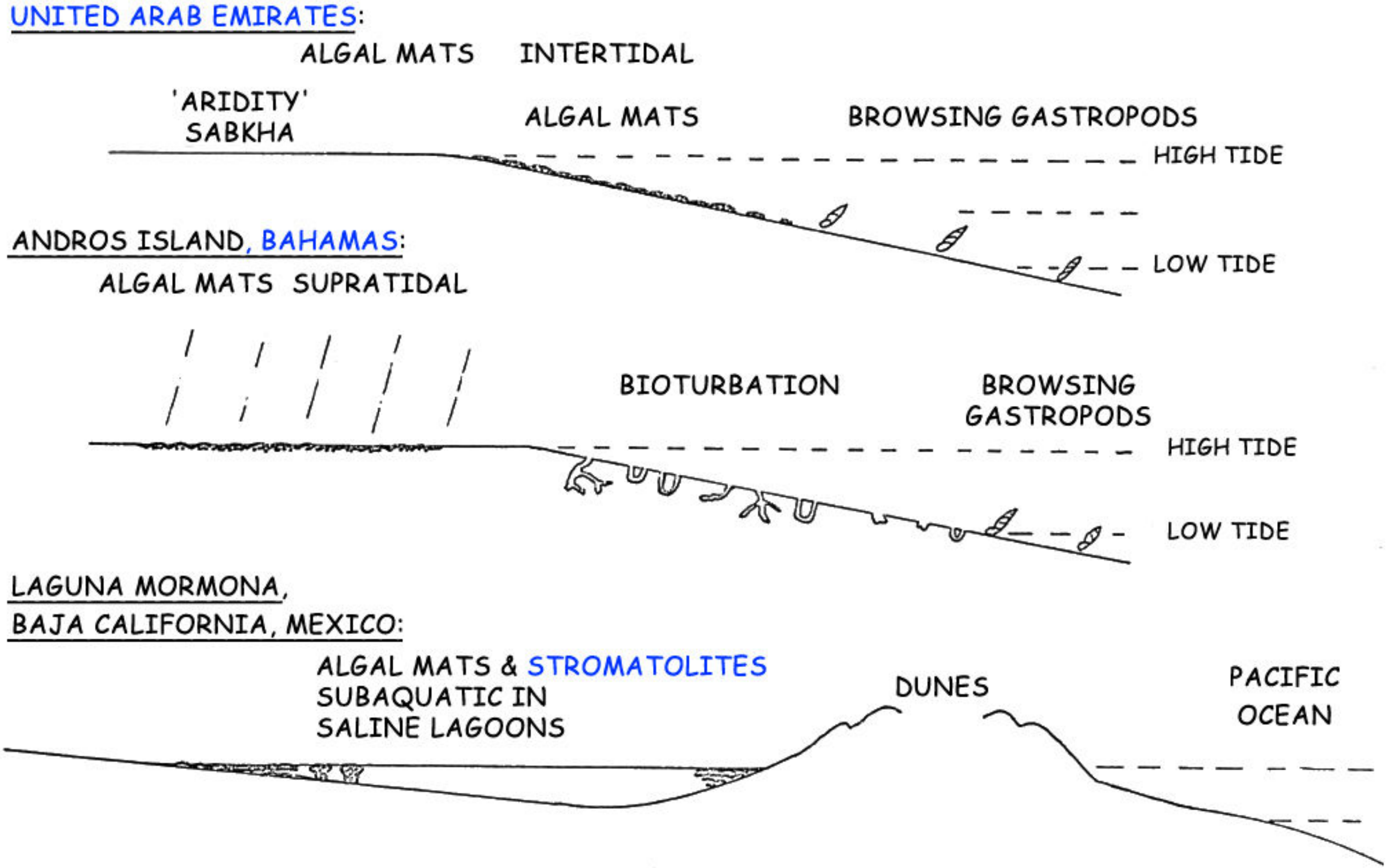


The calcite that replaced dolomite inherited the same lattice (optical) orientation. The birefringences of calcite and dolomite are similar, and in consequence the dolomitic and calcitic parts of the crystals are not readily differentiated by normal optical methods.

However, differential microchemical staining with alizarin red-S solution readily distinguishes between the two.

In the example illustrated, the dolomite is a ferroan dolomite, but the calcite is not ferroan However, the calcite is feintly stained brown by ferric oxides, and it seems that the iron was expelled from the lattice in the course of the replacement.

RECENT ALGAL MATS: ECOLOGICAL CONTROL



UNITED ARAB EMIRATES:

ALGAL MATS INTERTIDAL

ANDROS ISLAND, BAHAMAS:

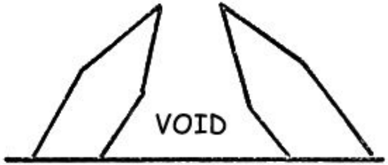
ALGAL MATS SUPRATIDAL

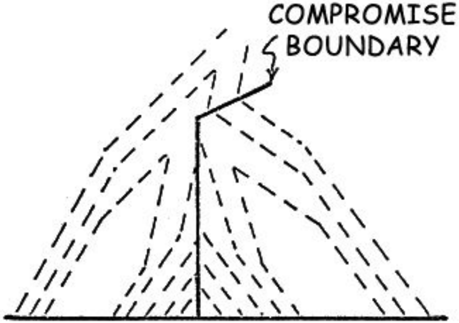
LAGUNA MORMONA,
BAJA CALIFORNIA, MEXICO:

ALGAL MATS & STROMATOLITES
SUBAQUATIC IN
SALINE LAGOONS

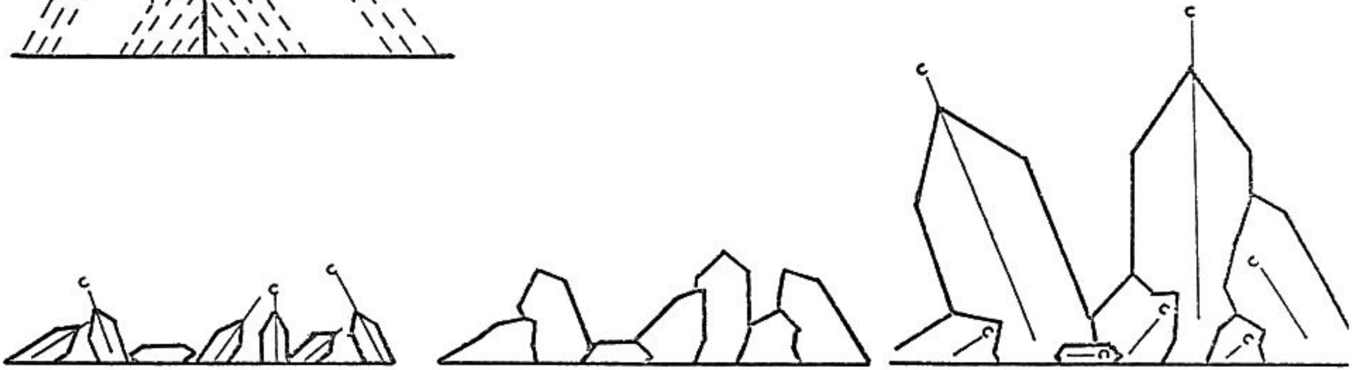
CRYSTAL FACES & COMPROMISE BOUNDARIES

CRYSTAL FACES



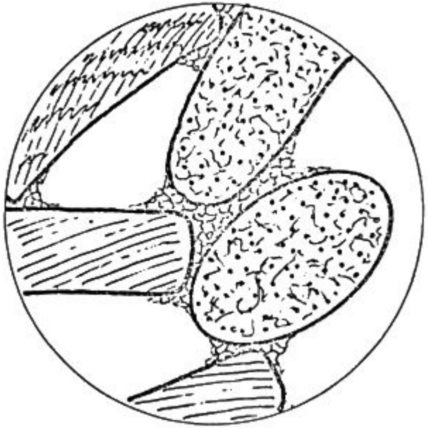


COMPETITIVE GROWTH

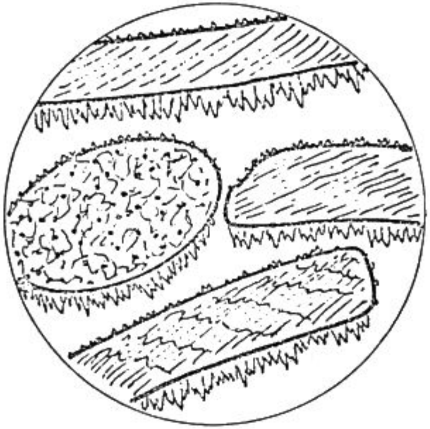


EARLY CEMENT FABRICS

MENISCUS CEMENT

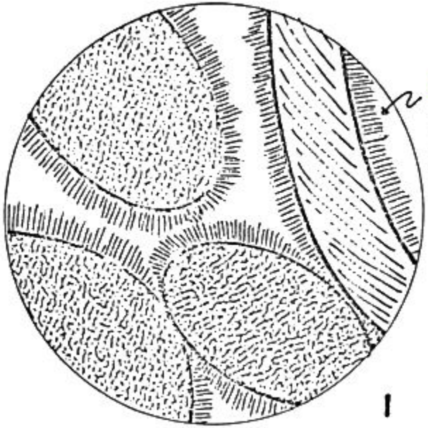


'STALACTITIC' / PENDANT CEMENT



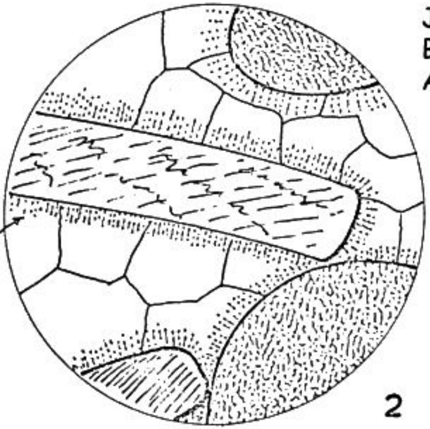
HARDGROUND CEMENT

RECENT HARDGROUND



1

POSSIBLE JURASSIC HARDGROUND



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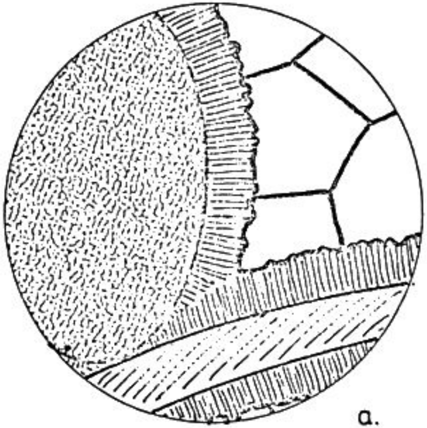
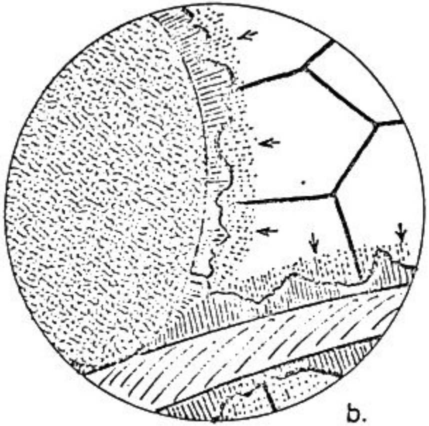
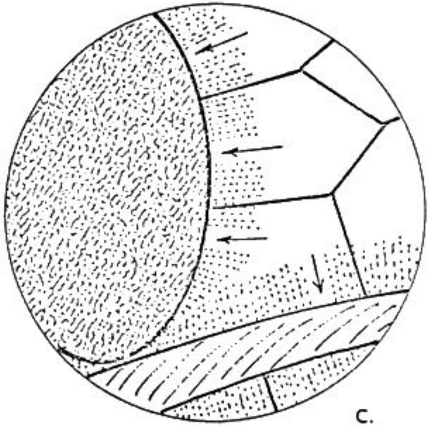


a.

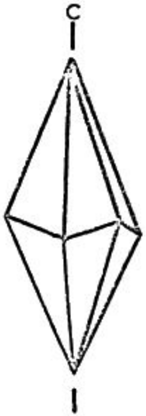


b.



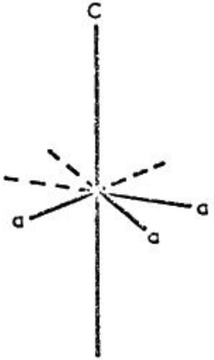
c.

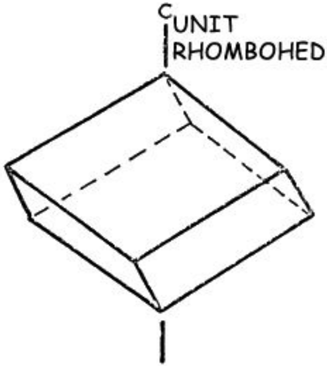
CALCITE HEXAGONAL (RHOMBOHEDRAL)



SCALENOHEDRON

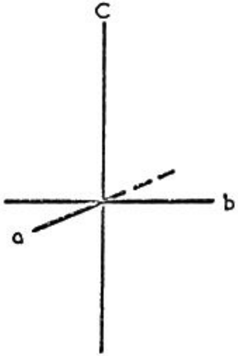
PRISMS + RHOMBOHEDRON (OBTUSE)

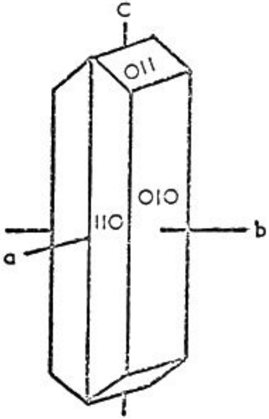




UNIT RHOMBOHEDRON

ARAGONITE ORTHORHOMBIC

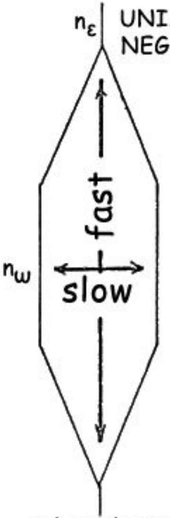




CALCITE

ARAGONITE

OPTICS



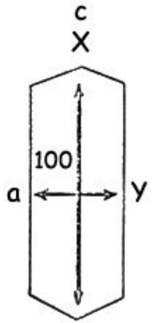
UNIAXIAL
NEGATIVE

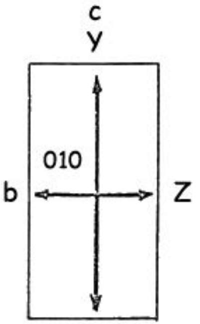
$n_\varepsilon = 1.486$; $n_\omega = 1.658$

BR = 0.172
very high

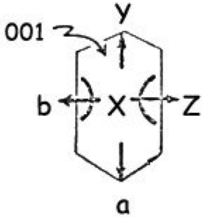
prismatic crystal
length fast

basal sections
uniaxial negative





BIAXIAL
NEGATIVE

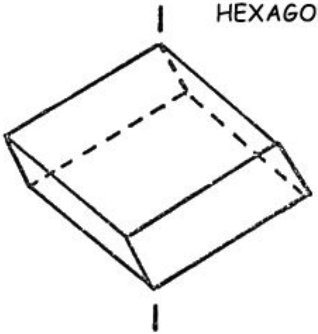


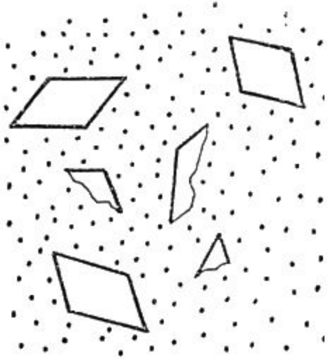
BP 0.156 very high
2V = 18°

$n_\alpha = 1.530 = c = X =$ fast
$n_\beta = 1.682 = a = Y$
$n_\gamma = 1.686 = b = Z =$ slow

DOLOMITE $CaCO_3\ MgCO_3$

HEXAGONAL (RHOMBOHEDRAL)





dolomite rhombs in thin section of fine grain limestone

OPTICS

$n_\varepsilon = 1.500 - 1.526$

$n_\omega = 1.680 - 1.716$

BP 0.180 - 0.190 very high

UNIAXIAL NEGATIVE

curved 'saddle-shaped' dolomite
(= baroque dolomite)

MICROCHEMICAL STAINING TECHNIQUES

Although it is difficult to distinquish the various carbonate minerals optically, they can be readily differentiated by microchemical staining techniques. Most of these techniques are applicable to hand specimens, cuttings and thin sections. When thin sections of carbonate rocks are prepared it is an advantage to leave them uncovered, in order that staining tests may be carried out.

Aragonite v. Calcite

Method 1. Boil in solution of cobalt nitrate $Co(NO_3)_2$ for approximately I5 to 20 minutes. Aragonite turns lilac-purple calcite remains unstained. With continual boiling calcite may also stain. This method is not suitable for use with thin sections, as boiling water softens the mounting medium and the thin section may disintegrate. Useful on loose materials.

Method 2. Treat the sample with Feigel's solution. After a few minutes a black precipitate settles out on aregonite but calcite remains unaffected. Suitable for use on thin sections. Lay the thin section in a small Petri dish and cover it with Feigel's solution. Watch the black precipitate develop on the aragonitic components and remove the thin section as soon as sufficient precipitate has developed to establish the identity of the aragonite. If too much precipitate is allowed to accumulate it will obsure the underlying crystal fabric.

Feigel's solution: Dissolve 11-12 g of manganese sulphate, $MnSO_4\ 7H_2O$, in 100 ml of distilled water. Add solid silver sulphate, Ag_2SO_4, and boil. Cool and then add two drops of sodium hydroxide, NaOH. Filter and store the solution in a dark bottle.

Calcite and Aragonite v. Dolomite

Method 1. Boil in a solution of Titan Yellow with approximately 30% sodium hydroxide, NaOH. Dolomite stains orange; calcite and aragonite remain unstained. Not suitable for thin sections. Useful on slabs where the rock carries only a small proportion of dolomite.

Method 2. Treat the thin section with a slightly acidified solution of Alizarin Red S. Calcite and aragonite stain red; dolomite does not stain. An excellent method for staining thin sections. The method is not always suitable for hand specimens that are microporous, as microdolomite may take on a pink colour as the solution dries out.

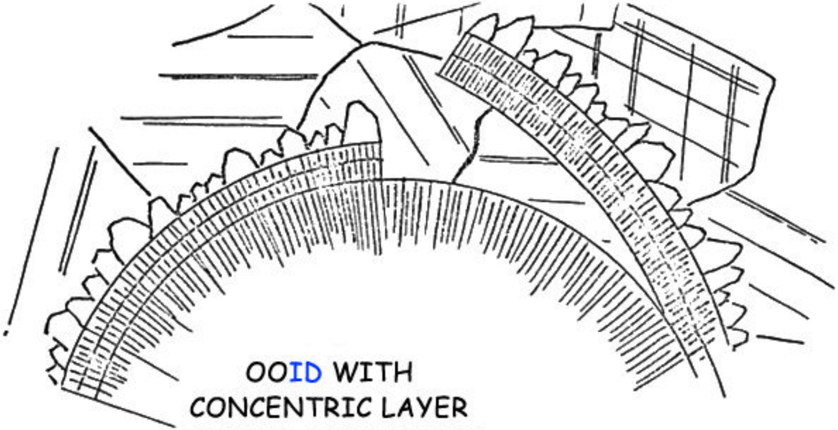
Preparation: Dissolve 0.1 g of Alizarin Red S in 100 cm^3 of distilled water. Acidify the solution slightly by adding 2 or 3 drops of dilute hydrochloric acid (Alizarin Red S throws down a red precipitate in the presence of calcium ions. The acidified solution dissolves calcite, releasing calcium ions, but does not attack dolomite).

Detection of ferroan carbonates

Some calcite and dolomite crystals carry ferrous iron as a trace element. Ferrous ions react with potassium ferricyanide to precipitate Turnbull's blue, and this reaction provides a means of detecting the presence of ferrous iron in carbonate minerals. Immerse the thin section in a strong cold solution, 100 ml,,of potassium ferricyanide to which a few drops of dilute hydrochloric acid has been added. Ferroan carbonates or ferroan zones within carbonate minerals stain blue within a minute or so. NB. Potassium ferricyanide is deadly poisonous if drunk. Further, potassium ferricyanide gives a deadly cyanide gas when mixed with acid. However, the addition of the few drops of dilute hydrochloric acid necessary for the test should.not produce any harmful amounts of cyanide.

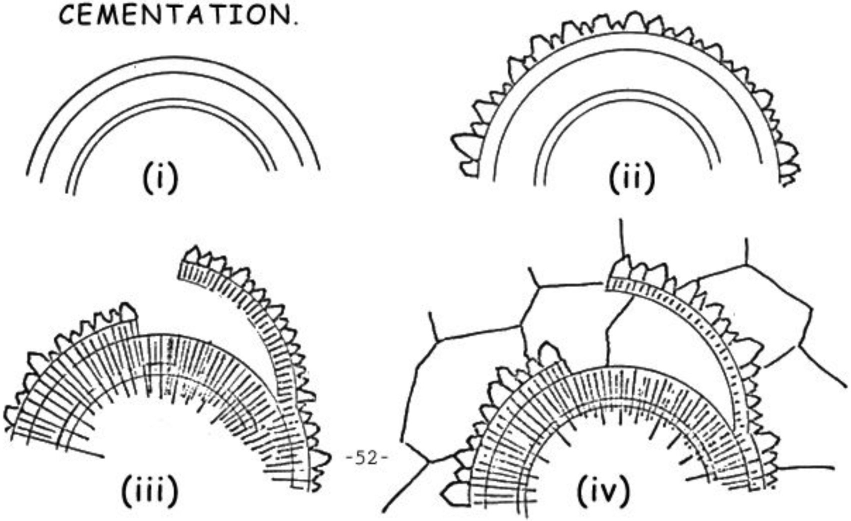
Combined stains for detection of calcite ferroan calcite, dolomite and ferroan dolomite.

If the thin section is treated with a slightly acidified solution of Alizarin Red S and potassium ferricyanide:
Iron-free calcite stains red;
Ferroan calcite stains purple;
Iron-free dolomite remains unstained;
Ferroan dolomite stains blue.

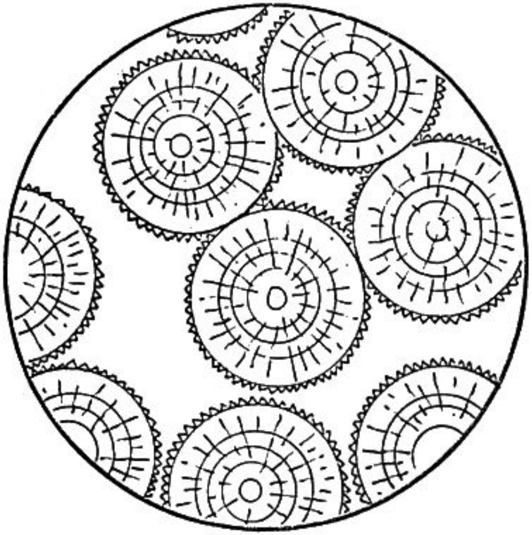


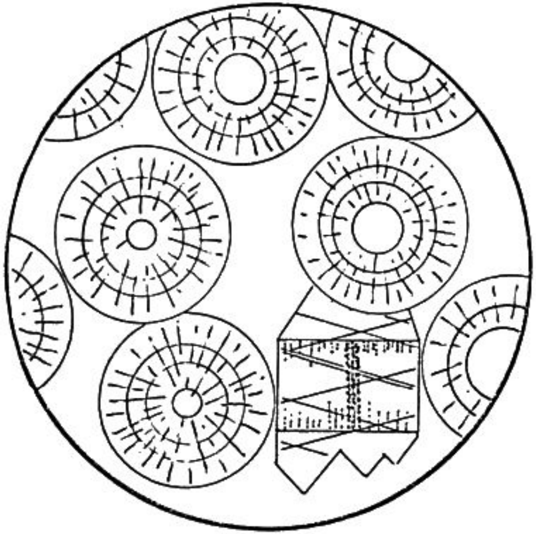
OOID WITH CONCENTRIC LAYER SPALLED OFF DURING COMPACTION.

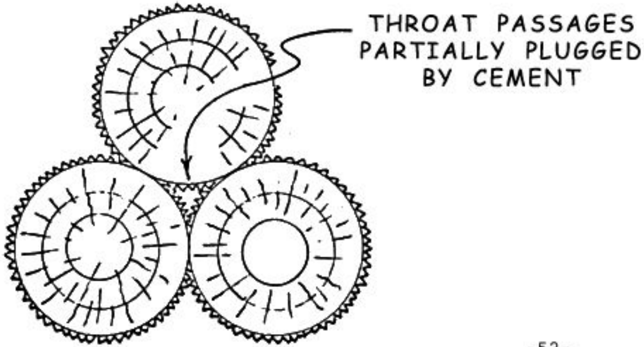
N.B. DEFORMATION OCCURRED AFTER 1ST PHASE OF CEMENTATION, BEFORE LATER PHASES OF CEMENTATION.

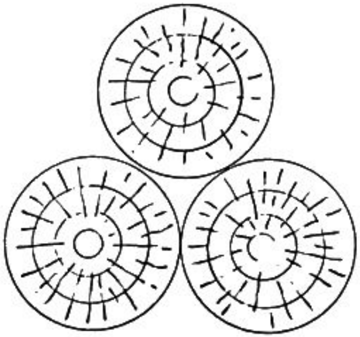


INFLUENCE OF FIRST CEMENT FABRICS ON PERMEABILITY CHARACTERISTICS









PRESSURE SOLUTION

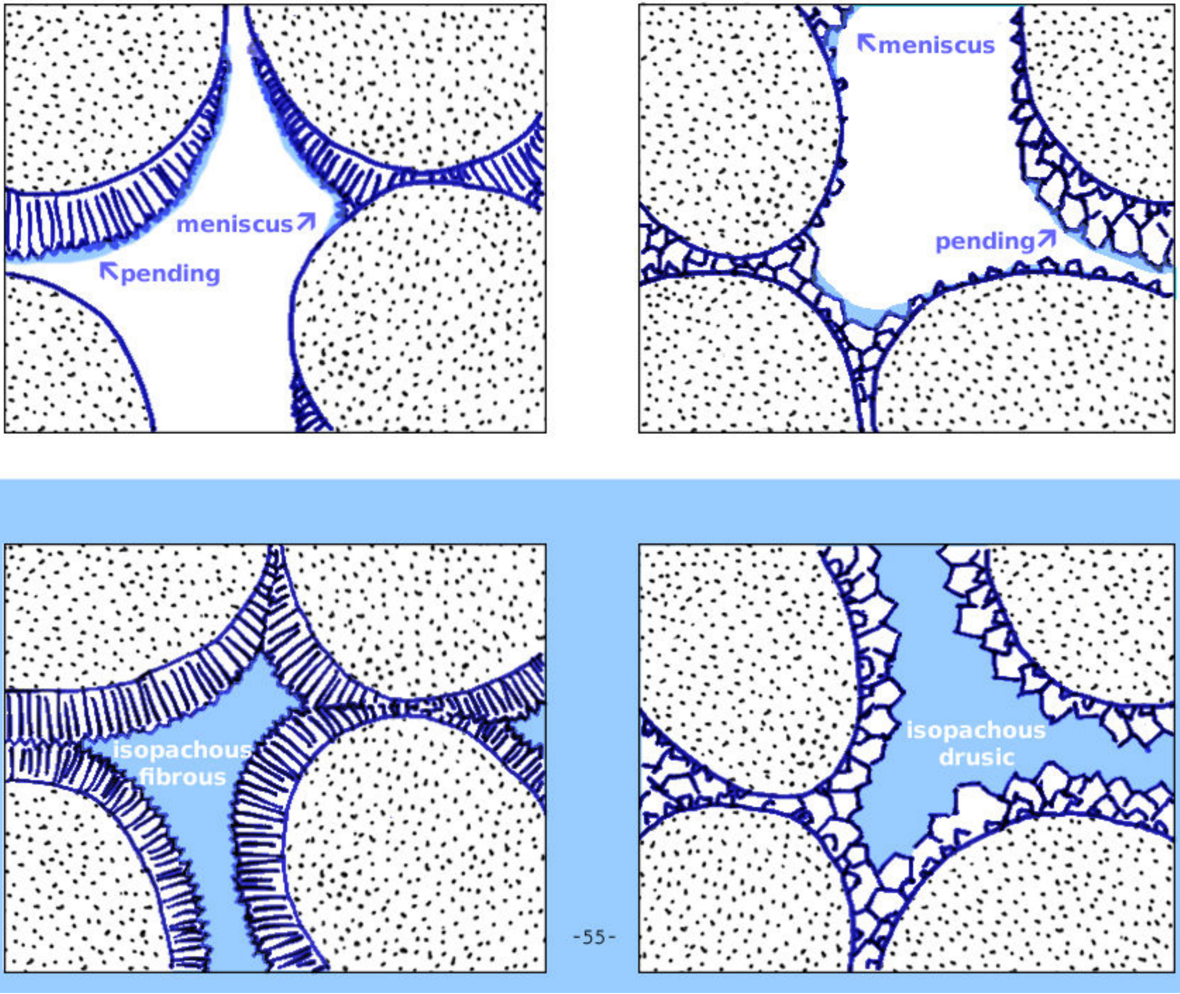
FIRST CEMENT FABRICS

MARINE WATER

METEORITIC GROUNDWATER

VADOSE ZONE

PHREATIC ZONE



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