6. Carbonate Sedimentary Rocks

Carbonate rocks make up 20-25% sedimentary rocks and can be divided into:
Limestone: composed mainly of calcite mineral - $CaCO_3$
Dolomite: composed mainly of dolomite mineral -$CaMg(CO_3)_2$

6.1 Introduction

Mesozoic and Cenozoic carbonates are mainly limestone. Precambrian and Paleozoic carbonate include abundant dolomite.

Limestone yields important information about ancient marine environments and the evolution of life.
Limestone consists of 1/3 of world's petroleum reserves.

6.2 Chemistry and Mineralogy

Calcite, dolomite and aragonite are three main minerals in carbonate rocks.

Calcite: (a) low-magnesian calcite (or simply called calcite): contain < 4% $MgCO_3$. For examples, tests (shells) of planktonic forams, coccoliths, and brachipods etc.
(b) high-magnesian calcite (still in calcite crystal structure): contain > 4% $MgCO_3$. For examples, Echinoids (海膽類), crinoids (海百合), benthonic forams, red algae.

Dolomite (or stoichiometric (化學計量的) dolomite): occurs in a few restricted modern environments, particularly in certain supratidal environments and freshwater lakes, but it is much less abundant in modern carbonate environments than aragonite and calcite.

Aragonite: Aragonite is the metastable polymorph (having the same chemical composition but different crystal structure) of $CaCO_3$ and is converted fairly rapidly under aqueous conditions to calcite. Carbonate older than about the Cretaceous contain little aragonite. Modern ocean is likely to yield aragonite and, to a lesser extent, high-magnesian calcite. For examples, molluscs, calcareous green algae, corals etc.

Stable isotope (e.g., $^{18}O/^{16}O$) composition of carbonate rocks is also of considerable interest in paleoenvironmental studies and time-stratigraphic correlations.

Principal carbonate minerals

Table 6.1 Principal carbonate minerals

	Mineral	Crystal system	Formula	Remarks
	Calcite group			
方解石	*Calcite	Rhombohedral	$CaCO_3$	Dominant mineral of limestones, especially in rocks older than the Tertiary
菱鎂礦	Magnesite	Rhombohedral	$MgCO_3$	Uncommon in sedimentary rocks but occurs in some evaporite deposits
菱錳礦	Rhodochrosite	Rhombohedral	$MnCO_3$	Uncommon in sedimentary rocks; may occur in Mn-rich sediments associated with siderite and Fe-silicates
菱鐵礦	Siderite	Rhombohedral	$FeCO_3$	Occurs as cements and concretions in shales and sandstones; common in ironstone deposits; also in carbonate rocks altered by Fe-bearing solutions
菱鋅礦	Smithsonite	Rhombohedral	$ZnCO_3$	Uncommon in sedimentary rocks; occurs in association with Zn ores in limestones
	Dolomite group			
白雲石	*Dolomite	Rhombohedral	$CaMg(CO_3)_2$	Dominant mineral in dolomites; commonly associated with calcite or evaporite minerals
鎂鐵白雲石	Ankerite	Rhombohedral	$Ca(Mg,Fe,Mn)(CO_3)_2$	Much less common than dolomite; occurs in Fe-rich sediments as disseminated grains or concretions
	Aragonite group			
霰石	*Aragonite	Orthorhombic	$CaCO_3$	Common mineral in recent carbonate sediments; alters readily to calcite
白鉛礦	Cerussite	Orthorhombic	$PbCO_3$	Occurs in supergene lead ores
	Strontionite	Orthorhombic	$SrCO_3$	Occurs in veins in some limestones
碳酸鋇礦	Witherite	Orthorhombic	$BaCO_3$	Occurs in veins associated with galena ore

*Important minerals in limestones and dolomites.

Boggs (2006), p.160

6.3 Limestone Textures

Calcite are present in at least three forms:
1. Carbonate grains
2. Microcrystalline calcite (微晶質方解石, or micrite:微晶質灰泥,微晶石灰岩)
3. Sparry calcite (粗粒方解石)

1. Carbonate Grains (allochems): carbonate grains typically range in size from coarse silt (0.02 mm) to sand (up to 2 mm), but larger particles such as fossil shells also occur. They can be divided into five basic types, each characterized by distinct differences in shape, internal structure, and mode of origin:

A. Carbonate Clasts (lithoclasts): Rock fragments that were derived either by erosion of ancient limestones exposed on land (this type of grain is called **extraclasts**外積岩屑) or by erosion of partially or completely lithified carbonate sediments within a depositional basin (**intraclasts**內積岩屑). The term lithoclast is used in non-distinguishable extraclasts and intraclasts. Lithoclasts range in size from very-fine sand to gravel.

B. Skeletal Particles (bioclast, 化石): Occur as whole microfossils, whole larger fossils, or broken fragments of larger fossils. They are the most common kind of grain in carbonate rocks.

C. Ooids (鮞石): Coated carbonate grains that contain a nucleus of some kind – a shell fragment, pellet, or quartz grain – surrounded by one or more thin layers or coating (the cortex) consisting of fine calcite or aragonite crystals. Oolites (鮞狀石灰岩): Rocks that contain mainly of ooids. Grains with similar internal structures to that of ooids but larger in grain size, > 2mm, are called pisoids (for rock it is called pisolite豆石). Oncoids (藻粒體): spherical stromatolites (疊層石) that reach a size exceeding 1 to 2 cm. Oncolite: 核形石

D. Peloids (球粒): grains that are composed of microcrystalline or cryptocrystalline calcite or aragonite and that do not display distinctive internal structures. Peloids are generally of silt to fine-sand size (0.03-0.1 mm).

The most common kind of peloids are **fecal pellets** (糞球) , produced by organisms that ingest calcium carbonate muds and extrude undigested mud as pellets.

E. Aggregate Grains (rare): Irregular carbonate grains that consist of two or more carbonate fragments (pellets, ooids, fossil fragments) joined together by a carbonate-mud matrix that is generally dark colored and rich in organic matter.

Types of carbonate grains

A. Rounded carbonate clasts cemented by sparry calcite.
B. Angular to subangular carbonate clasts in a micrite matrix.
C. Skeletal grains (B:苔蘚蟲類, Br:腕足動物, C: 海百合, F:有孔蟲) cemented with sparry calcite.
D. Normal ooids cemented with sparry calcite.
E. Radial ooids cemented with sparry calcite (white) and micrite (dark).
F. Pellets cemented with sparry calcite.

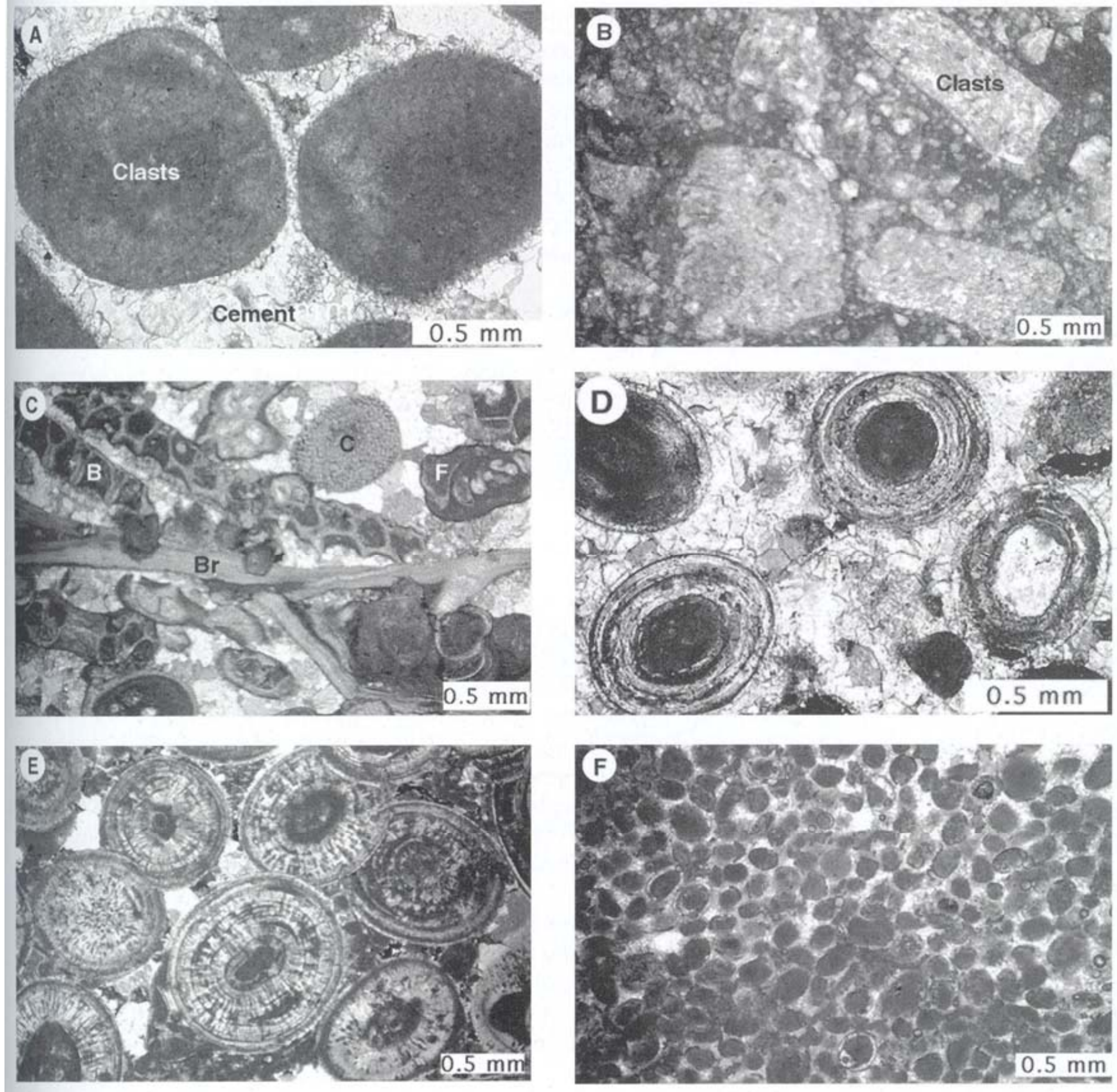

Figure 6.1
Fundamental kinds of carbonate grains (allochems) in limestones: A. Rounded clasts cemented with sparry calcite cement, Devonian limestone, Canada. B. Angular to subangular clasts in a micrite (dark) matrix, Calville Limestone (Permian), Nevada. C. Mixed skeletal grains (B = bryozoan, Br = brachiopod, C = crinoid, F = foraminifer) cemented with sparry calcite, Salem Formation (Mississippian), Missouri. D. Normal ooids cemented with sparry calcite (white), Miami Oolite (Pleistocene), Florida. E. Radial ooids cemented with sparry calcite (white) and micrite (dark); note relict concentric layering, Devonian limestone, Canada. F. Pellets cemented with sparry calcite, Quaternary-Pleistocene limestone, Grand Bahama Banks. Crossed nicols.

Boggs (2006) p.163

2. Microcrystalline Calcite (or micrite): Carbonate mud (or lime mud) composed of very fine size (1~5 microns, 0.001~0.005 mm) calcite crystals. Modern lime mud consists mainly of aragonite, while ancient carbonate mud consists mainly of calcite. Lime mud may contain small amounts of fine-grained detrital minerals such as clay minerals, quartz, feldspar, and organic matters. Micrite may be present as matrix among carbonate grains, or it may make up most or all of a limestone. Micrite may be formed by inorganic precipitation of aragonite, later converted to calcite, from surface water supersaturated with $CaCO_3$. Much modern carbonate mud appears to originated through organic processes. The presence of micrite indicates deposition under quiet-water conditions (analogous to siliciclastic mudrock).

Boggs (2006) p.166

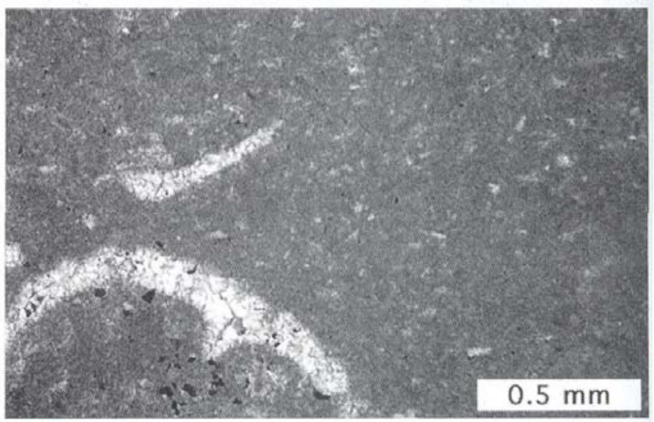

Figure 6.3
Micrite-rich limestone containing a few skeletal grains. Plattin Limestone (Ordovician), Missouri. Crossed nicols.

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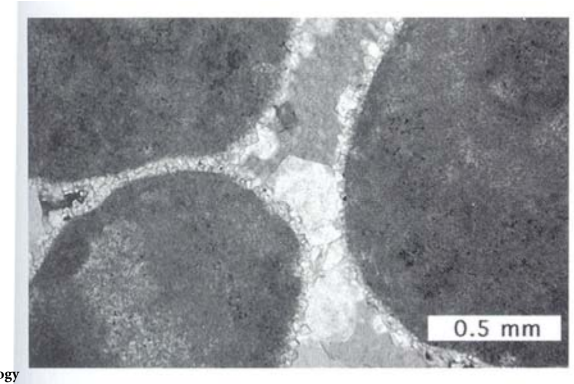
3. Sparry Calcite: Large crystals (on the order of 0.02~0.1 mm) of calcite that appear clear or white viewed with a hand lens or in plane light under a polarizing microscope. It is formed during diagenesis. They are distinguished from micrite by their larger size and clarity and from carbonate grains by their crystal shapes and lack of internal texture. The presence of sparry calcite cement in pore spaces indicates that grain framework voids were empty of lime mud at the time of deposition, suggesting deposition under high-energy flow condition. Sparry calcite can also form by recrystallization of primary depositional grains and micrite during diagenesis.



Boggs (2006) p.167

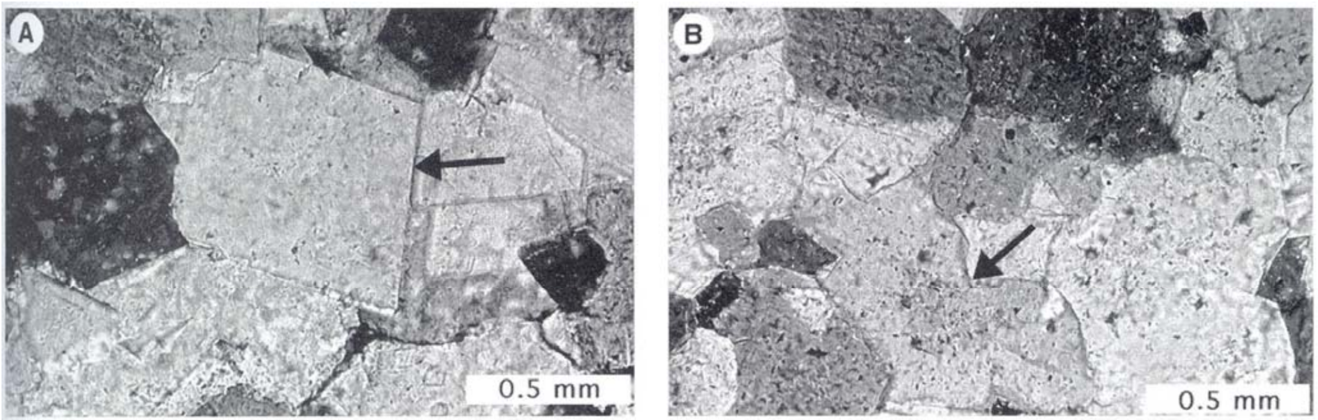
Figure 6.4
Sparry calcite cementing rounded intraclasts. Note that the cement displays drusy texture: small calcite crystals, oriented with their long dimensions perpendicular to the clast surfaces, grade outward from the margins of the clasts into larger, randomly oriented calcite crystals. Devonian limestone, Canada. Crossed nicols.

Boggs (2006) p.1

Note: Micrites form as a matrix; sparry calcites form as a cement.

6.4 Dolomite Textures

Dolomite (dolostone, 白雲岩) is composed mainly of the mineral dolomite (白雲石)[$CaMg(CO_3)_2$]. Dolomite has a largely crystalline (granular texture). Many dolomites form by replacement of a precursor limestone. Original limestone textures may be preserved in such dolomites to various degrees, ranging from virtually unreplaced to totally replaced.



Planar dolomite **Non-planar dolomite**

Figure 6.5
Dolomite crystals: A. Planar dolomite exhibiting euhedral crystals with planar faces (arrow), Bonneterre Formation (Cambrian), Missouri. B. Nonplanar dolomite, with curved or irregular faces, Davis formation (Cambrian), Missouri. Crossed nicols.

Two kinds of dolomites on the basis of crystal shape:

A. **Planar (idiotopic) dolomite**: Rhombic, euhedral (well-formed) to anhedral (poorly-formed) crystals.

B. **Non-planar (xenotopic) dolomite**: Non-planar, commonly anhedral crystals.

Boggs (2006) p.167

6.5 Structures in carbonate rocks

Carbonate rocks contain many of the same kinds of sedimentary structures as those present in siliciclastic rocks except stromatolites.

Stromatolites (疊層石) are formed largely by trapping and binding activities of blue-green algae (cyanobacteria). They consist of flat or hemispherically laminated structures composed of fine calcium carbonate minerals, fine organic matter, and detrital clay and silt. Most ancient stromatolites occur in limestones. They are forming today mainly in the shallow subtidal, intertidal, and supratidal zone of the ocean. Oldest stromatolites: 3450 Ma.

Stromatolites in limestone of the Helena Formation (Precambrian), Montana.


Boggs (2006) p.110

6.6 Classification of carbonate rocks

The principal parameters used in carbonate classification are the types of carbonate grains or allochems and the grain/micrite ratio. Folk (1962)'s classification is the most widely accepted one that bases on the relative abundance of three major types of constituents: (1) carbonate grains (allochems); (2) microcrystalline carbonate mud (micrite); and (3) sparry calcite cement.

Table 6.2 Classification of carbonate rocks

A. Classification based on dominant constituents (Folk)

Boggs (2006) p.170

	Limestones, partly dolomitized limestones					Replacement dolomites	
	>10% Allochems Allochemical rocks		<10% Allochems Microcrystalline rocks				
	Sparry calcite cement > microcrystalline ooze matrix Sparry allochemical rocks	Microcrystalline ooze matrix > sparry calcite cement Microcrystalline allochemical rocks	1%–10% Allochems	<1% Allochems	Undisturbed bioherm rocks	Allochem ghosts	No allochem ghosts
Volumetric allochem composition			Most abundant allochem			Evident allochem	
>25% Intraclasts	Intrasparrudite Intrasparite	Intramicrudite* Intramicrite*	Intraclasts: intraclast-bearing micrite*	Micrite; if disturbed, dismicrite; if primary, dolomite, dolomicrite	Biolithite	Finely crystalline intraclastic dolomite, etc.	Medium crystalline dolomite
<25% Intraclasts; >25% Ooids	Oosparrudite Oosparite	Oomicrudite* Oomicrite*	Ooids: ooid-bearing micrite*			Coarsely crystalline oolitic dolomite, etc.	Finely crystalline dolomite
<25% Intraclasts; <25% Ooids; Volume ratio of fossils to pellets >3:1	Biosparrudite Biosparite	Biomicrudite Biomicrite	Fossils: fossiliferous micrite			Aphanocrystalline biogenic dolomite, etc.	
<25% Intraclasts; <25% Ooids; Volume ratio of fossils to pellets 3:1–1:3	Biopelsparite	Biopelmicrite					
<25% Intraclasts; <25% Ooids; Volume ratio of fossils to pellets <1:3	Pelsparite	Pelmicrite	Pellets: pelletiferous micrite			Very finely crystalline pellet dolomite, etc.	etc.

Source: Folk, R. L., 1962, Spectral subdivision of limestone types, in W. E. Ham (ed.), Classification of carbonate rocks: *Am. Assoc. Petroleum Geologists Mem.* 1. Table 1, p. 70, reprinted by permission of AAPG, Tulsa, Okla.

Note: Names and symbols in the body of the table refer to limestones. If the rock contains more than 10 percent replacement dolomite, prefix the term "dolomitized" to the rock name. The upper name in each box refers to calcirudites (median allochem size larger than 1.0 mm); the lower name refers to all rocks with median allochem size smaller than 1.0 mm. Grain size and quantity of ooze matrix, cements, or terrigenous grains are ignored.

*Designates rare rock types.

Folk’s classification scheme shown in Chinese

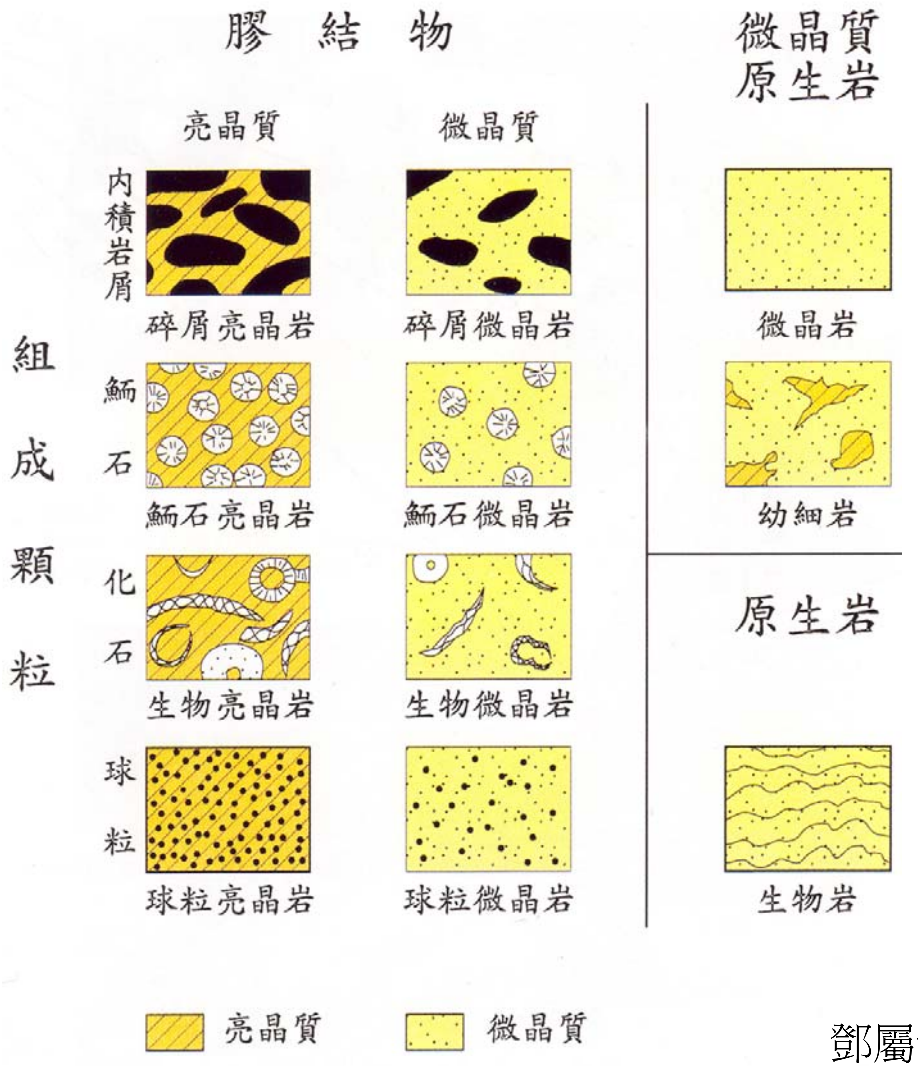


圖3-29 石灰岩分類圖(修改自Folk, 1962)

石灰岩以組成顆粒與膠結物的性質來分類(左半部)，倘若沒有粗粒的碎屑物，或僅有原生的生物體，則以右半部的原生岩命名。

The main allochems are *oöids (鮞石), peloids(球粒), bioclasts* (skeletal grains化石) and *intraclasts(內積岩屑)*.

Allochems > 10%

碎屑亮晶岩(Intrasparite)
鮞石亮晶岩(Oösparite)
生物亮晶岩(Biosparite)
球粒亮晶岩(Pelsparite)

碎屑微晶岩(Intramicrite)
鮞石微晶岩(Oömicrite)
生物微晶岩(Biomicrite)
球粒微晶岩(Pelmicrite)

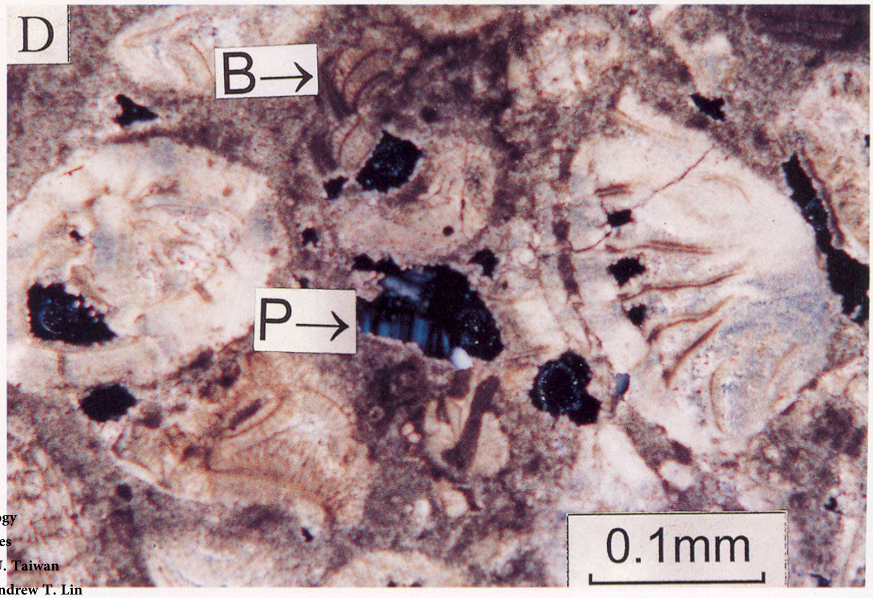
Allochems < 10%

微晶岩(micritic limestone)
幼細岩(dismicrite, micrite with cavities (usually spar-filled)

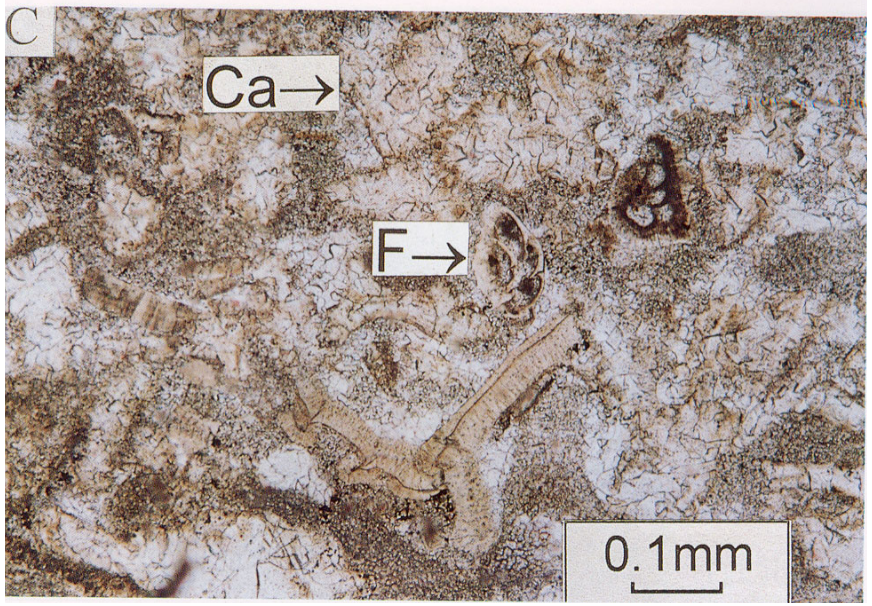
生物岩(biolithite, e.g, reef-rock or stromatolite)

鄧屬予 (1997)

圖版四十一 【東河石灰岩二】
採自臺東縣東河鄉都巒山層頂部的上新統石灰岩，爲白色生物微晶岩(圖版A、B)，組成以有孔蟲(F)爲主，並有藻類(B)與少量的斜長石(P)。質地緻密，但孔隙仍多，生物組織明顯。顆粒間由微晶質方解石膠結，具有輕微的再結晶現象(圖版C、D)。

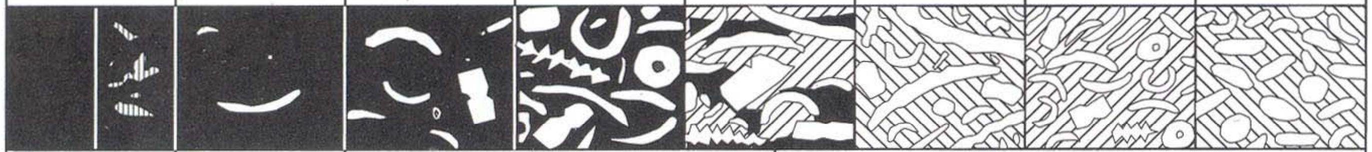


圖版十四 【半屏山石灰岩】
採自高雄市半屏山的更新統礁灰岩體，爲白色略帶粉紅色的生物亮晶岩(圖版A、B)，質地堅硬，有許多孔隙。組成以珊瑚(Co)爲主，另有貝類、藻類、有孔蟲(F)和少量的石英，顆粒間由亮晶質方解石(Ca)膠結(圖版C、D)。



Additional textural information can be added by use of the textural maturity terms shown here:

	OVER 2/3 LIME MUD MATRIX				SUBEQUAL SPAR & LIME MUD	OVER 2/3 SPAR CEMENT		
Percent Allochems	0 – 1%	1 – 10%	10 – 50%	OVER 50%		SORTING POOR	SORTING GOOD	ROUNDED & ABRADED
Representative Rock Terms	MICRITE & DISMICRITE	FOSSILI- FEROUS MICRITE	SPARSE BIOMICRITE	PACKED BIOMICRITE	POORLY WASHED BIOSPARITE	UNSORTED BIOSPARITE	SORTED BIOSPARITE	ROUNDED BIOSPARITE
Terminology	Micrite & Dismicrite	Fossiliferous Micrite	Biomicrite			Biosparite		
Terrigenous Analogues	Claystone		Sandy Claystone	Clayey or Immature Sandstone		Submature Sandstone	Mature Sandstone	Supermature Sandstone



LIME MUD MATRIX   SPARRY CALCITE CEMENT

Figure 6.8

Boggs (2006) p.171

Textural classification of carbonate sediments on the basis of relative abundance of lime mud matrix and sparry calcite cement and on the abundance and sorting of carbonate grains (allochems). [After Folk, R. L., 1962, Spectral subdivision of limestone types, *in*

Informal names for carbonate rocks:

• **Coquina** (殼灰岩屑) a mechanically sorted and abraded, poorly consolidated carbonate sediment consisting predominantly of fossil debris; Coquinite (殼灰岩) is the consolidated equivalent.

• **Chalk** (白堊) is soft, earthy, fine-textured limestone composed mainly of the calcite tests of floating micro-organisms, such as foraminifers.

• **Marl** (泥灰岩) is an old, rather imprecise, term for an earthy, loosely consolidated mixture of siliciclastic clay and calcium carbonate.

B. Classification based on depositional texture (Dunham)

Boggs (2006) p.173

Table 6.3 Classification of limestones according to depositional textures

<table>
<tr><td colspan="5">A DEPOSITIONAL TEXTURE RECOGNIZABLE</td><td>DEPOSITIONAL TEXTURE NOT RECOGNIZABLE</td></tr>
<tr><td colspan="4">Original components not bound together during deposition</td><td rowspan="4">Original components were bound together during deposition . . . as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.</td><td rowspan="5">CRYSTALLINE CARBONATE
(Subdivide according to classifications designed to bear on physical texture or diagenesis.)</td></tr>
<tr><td colspan="3">Contains mud
(particles of clay and fine silt size)</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>
</table>

<table>
<tr><td colspan="6">B ALLOCHTHONOUS LIMESTONE
Original components not organically bound during deposition</td><td colspan="3">AUTOCHTHONOUS LIMESTONE
Original components organically bound during deposition</td></tr>
<tr><td colspan="4">Less than 10% >2 mm components</td><td colspan="2">Greater than 10% >2 mm components</td><td rowspan="3">By organisms that build a rigid framework</td><td rowspan="3">By organisms that encrust and bind</td><td rowspan="3">By organisms that act as baffles</td></tr>
<tr><td colspan="3">Contains lime mud (<0.03 mm)</td><td>No lime mud</td><td rowspan="3">Matrix-supported</td><td rowspan="3">>2 mm component-supported</td></tr>
<tr><td colspan="2">Mud-supported</td><td colspan="2" rowspan="2">Grain-supported</td></tr>
<tr><td>Less than 10% grains >0.03 mm <2 mm</td><td>Greater than 10% grains</td><td colspan="3">BOUNDSTONE</td></tr>
<tr><td>MUD-STONE</td><td>WACKE-STONE</td><td>PACK-STONE</td><td>GRAIN-STONE</td><td>FLOAT-STONE</td><td>RUD-STONE</td><td>FRAME-STONE</td><td>BIND-STONE</td><td>BAFFLE-STONE</td></tr>
</table>

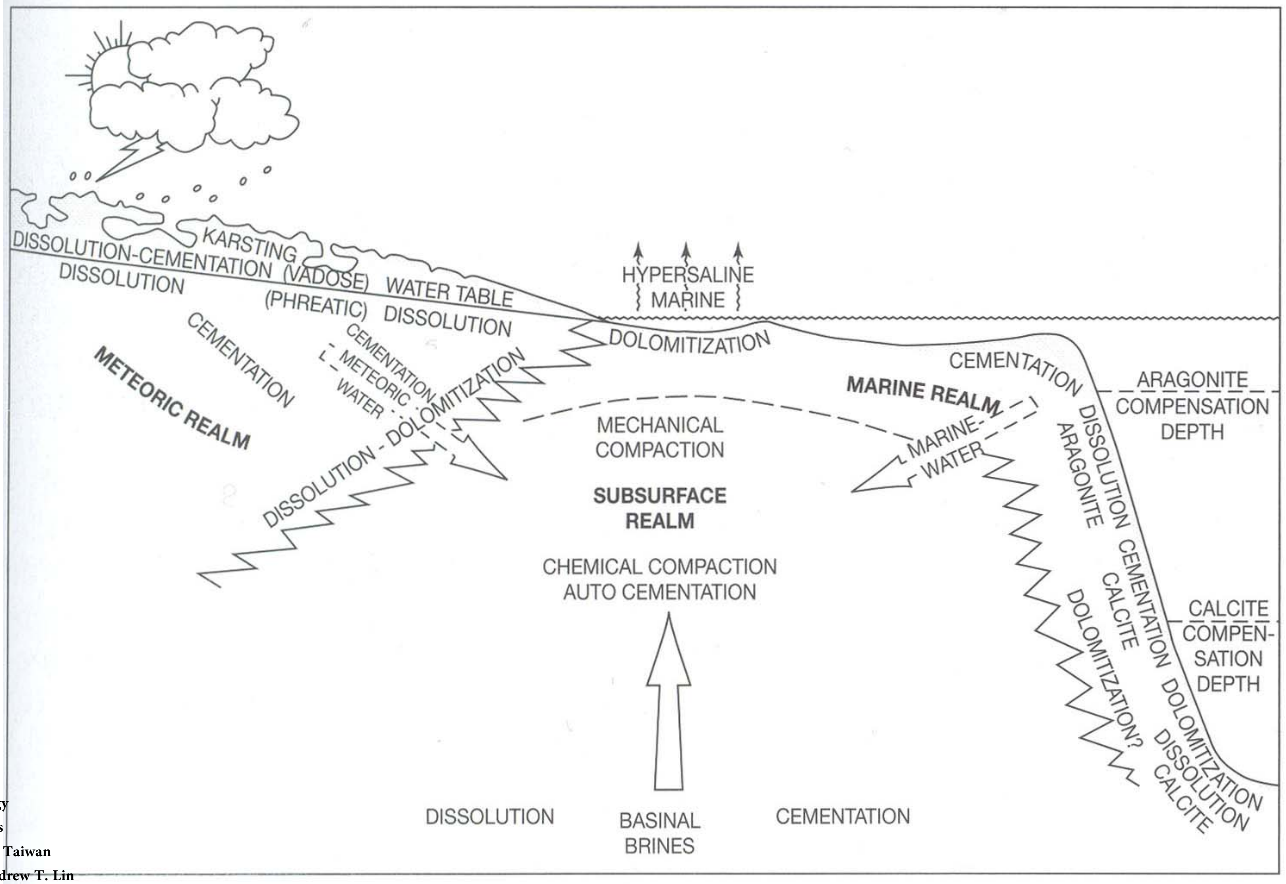
Source: A, After Dunham, R. J., 1962, Classification of carbonate rocks according to depositional textures, in Ham, W. E., ed., Classification of carbonate rocks: *Am. Assoc. Petroleum Geologists Mem.* 1. Table 1, p. 117, reprinted by permission of AAPG, Tulsa, Okla. B, after Dunham, R. J., 1962, as modified by Embry, E. F., III and J. E. Klovan, 1972, Absolute water depth limits of late Devonian paleoecological zones: Geol. Rundschau, v. 61. Fig. 5, p. 676, reprinted by permission.

(B) is the modification of the Dunham classification (A) by Embry and Klovan (1972), adding five additional categories for reef rocks (three of these were boundstones in Dunham’s original scheme)

6.8 Diagenesis

Carbonate diagenesis takes place in three major regimes or realms: marine, meteoric and subsurface.

Marine realm: includes the seafloor and the very shallow marine subsurface. Principal diagenetic processes: bioturbation or boring, cementation of grains in warm-water areas.
Meteoric (天水) realm: Vadose zone (滲流帶) versus phreatic zone (井泉水帶). Principal diagenetic processes: dissolution, alteration of aragonite and high-Mg calcite to calcite, calcite cementation.
Subsurface realm: Principal diagenetic processes: physical compaction, chemical compaction (dissolution at grain boundaries), and additional chemical or mineralogical changes that may include dissolution, cementation, aragonite-to-calcite transformation, and replacement of calcite by another mineral such as dolomite.



Boggs (2006) p.189

Figure 6.13
The principal environments in which postdepositional modification of carbonate sediments occurs. The dominant diagenetic processes that occur in each of the major diagenetic realms are also indicated. See text for details. [From Moore, C. H., 1989, Carbonate diagenesis and porosity. Fig. 3.1, p. 44, reprinted by permission of Elsevier Science Publishers, Amsterdam.]

Diagenetic fabrics in limestones

A. Biogenic alteration (micrite rims)
B. Cementation (sparry calcite cements).
C. Neomorphism (recrystallization destroyed part of fossils).
D. Replacement (chert replaces calcite).
E. Physical compaction.
F. Chemical compaction (pressure solution).

Boggs (2006) p.191

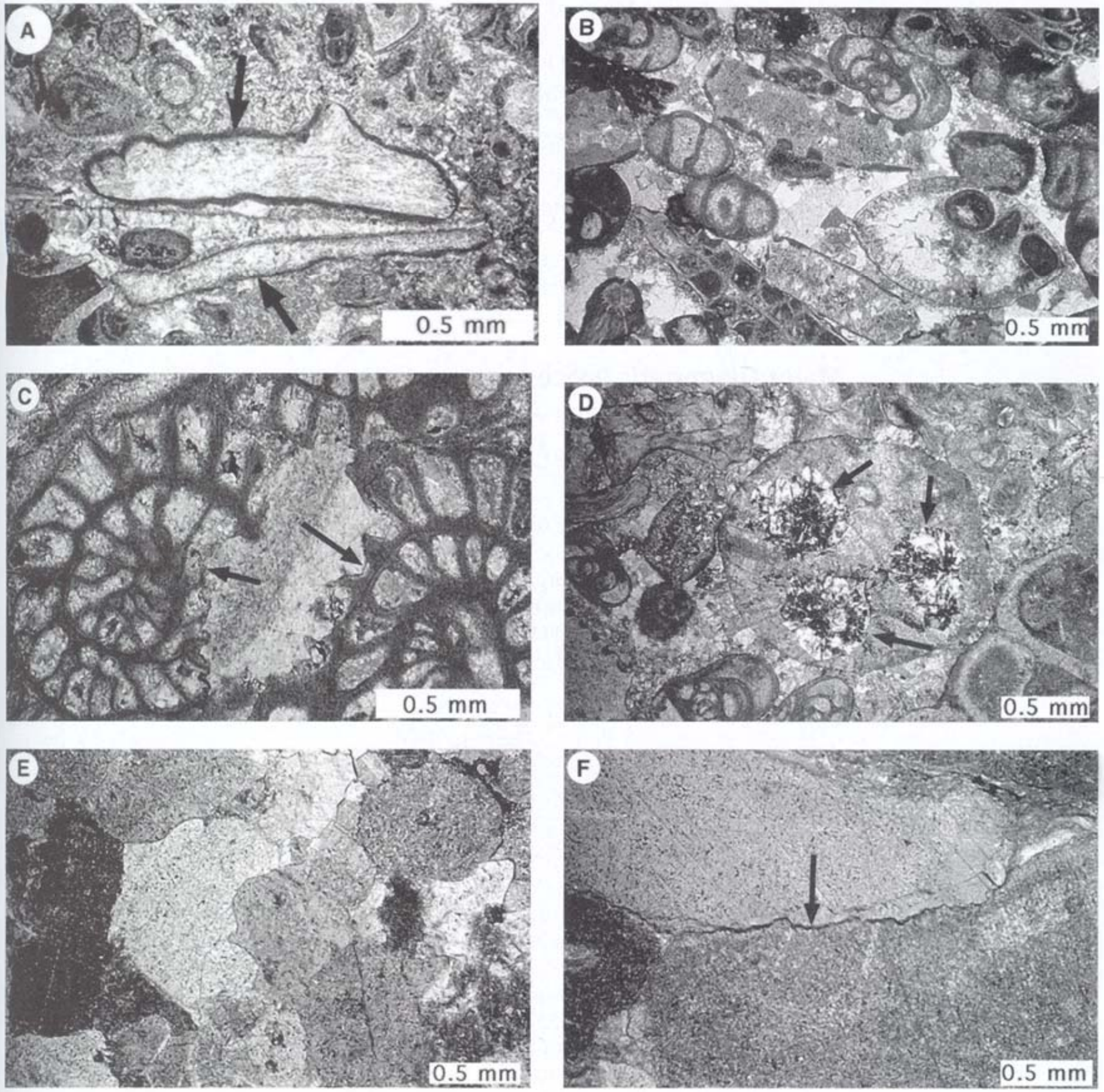


Figure 6.14
Diagenetic fabrics in limestones: A. Dark, micrite rims or envelopes (arrows) around fossil fragments, Renault Formation (Mississippian), Missouri. B. Sparry calcite (white) cementing fossils and fossil fragments, Salem Formation (Mississippian), Missouri. C. Recrystallization fabric that has partially destroyed fossil fusulinid foraminifers (arrows), Morgan Formation (Pennsylvanian), Colorado. D. Patchy replacement of a fossil fragment by chert (arrows), Salem Formation (Mississippian), Missouri. E. Grain fabric that is tightly packed owing to physical compaction of echinoderm (crinoid) fragments, Kimswick Limestone (Ordovician), Missouri. F. Irregular boundary (arrow) between two echinoderm fragments formed as a result of pressure solution (chemical compaction), middle Mississippian limestone, Oklahoma.

Major diagenetic processes and changes

A. Biogenic alteration: Organisms rework sediment by boring, burrowing, and sediment-ingesting activities. Fine-grained (micritic) aragonite or high-Mg calcite may then precipitate into these holes. The boring and micrite-precipitation process may be so intensive in some warm-water environments that carbonate grains are reduced almost completely to micrite, a process called micritization. If boring is less intensive, only a thin micrite rim may be produced around the grain.

B. Cementation:

Types of cements in different diagenetic environments:
Seafloor: mainly aragonite of meniscus (彎月形), pendant (懸垂形), isopachous (等厚形), needle, botryoidal (葡萄狀) cements.

Meteoric: mainly calcite of meniscus and pedant cements in vadose zone; isopachous, blocky, and syntaxial (順向連生的) rim cements in the phreatic zone.

Subsurface: mainly calcite of syntaxial rims, bladed (刃狀的) prismatic, and coarse mosaic types.

Boggs (2006) p.192

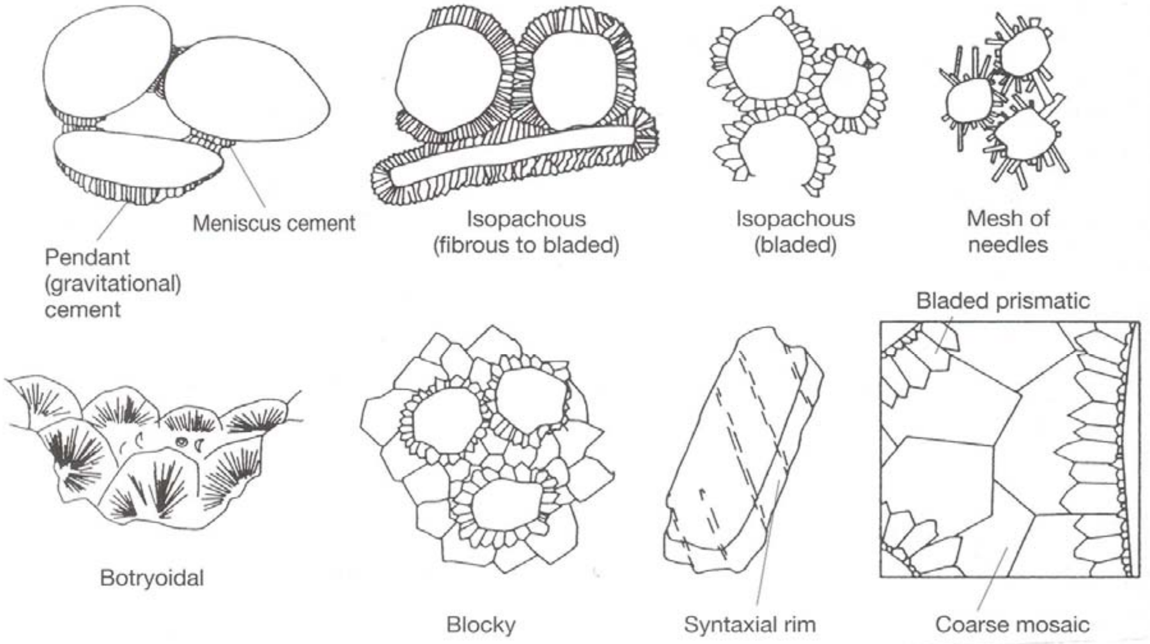


Figure 6.15
Principal kinds of cements that form in carbonate rocks during diagenesis. **Seafloor diagenetic environments** are characterized particularly by aragonitic meniscus and pendant cements (in beachrock), isopachous cement, needle cement, and botryoidal cement. **Meteoric-realm** cements are composed dominantly of calcite and include meniscus and pendant cements in the **vadose zone** and isopachous, blocky, and syntaxial rim cements in the **phreatic zone**. Cements of the **subsurface burial realm** are also mainly calcite and include syntaxial rims, bladed prismatic, and coarse mosaic types. [Modified from James, N. P., and P. W. Choquette, 1983, Geoscience Canada, v. 10, Fig. 3, p. 165; 1984, Geoscience Canada, v. 11, Fig. 24, p. 177; 1987, Geoscience Canada, v. 14, Fig. 21, p. 16.]

C. Dissolution: Dissolution is favored by unstable mineralogy (presence of aragonite or high-Mg calcite), cool temperatures, and low pH (acidic) pore waters that are undersaturated with calcium carbonate. Dissolution is relatively unimportant on the seafloor but is particularly prevalent in the meteoric realm especially along the water table.

D. Neomorphism (新生變形作用): neomorphism is the combined processes of inversion (e.g., transformation of aragonite to calcite) and recrystallization. Neomorphism occurs in all three diagenetic realms but is particularly important in the meteoric and subsurface diagenetic environments. This process destroys original textures and fabrics and, when pervasive, may cause the entire rock to become recrystallized.

E. Replacement: Involving the dissolution of one mineral and the nearly simultaneous precipitation of another mineral of different composition in its place. Dolomitization of $CaCO_3$ sediment is one kind of replacement process.

F. Physical and Chemical compaction: Newly deposited, watery carbonate sediments have initial porosities ranging from 40 to 80%. Chemical compaction initiates at depths ranging from 200 to 1500 m where pressure-solution seams called stylolites develops. Stylolites are marked by the presence of clay minerals and other fine-size noncarbonate minerals (commonly referred to as an insoluble residue) that accumulate as carbonate minerals dissolve.

Boggs (2006) p.194

Figure 6.16
Well-developed sutured stylolites in Cretaceous limestones, Calcare Massicio, Tuscany, Italy. [Photograph courtesy of E. F. McBride.]

Summary results of carbonate diagenesis

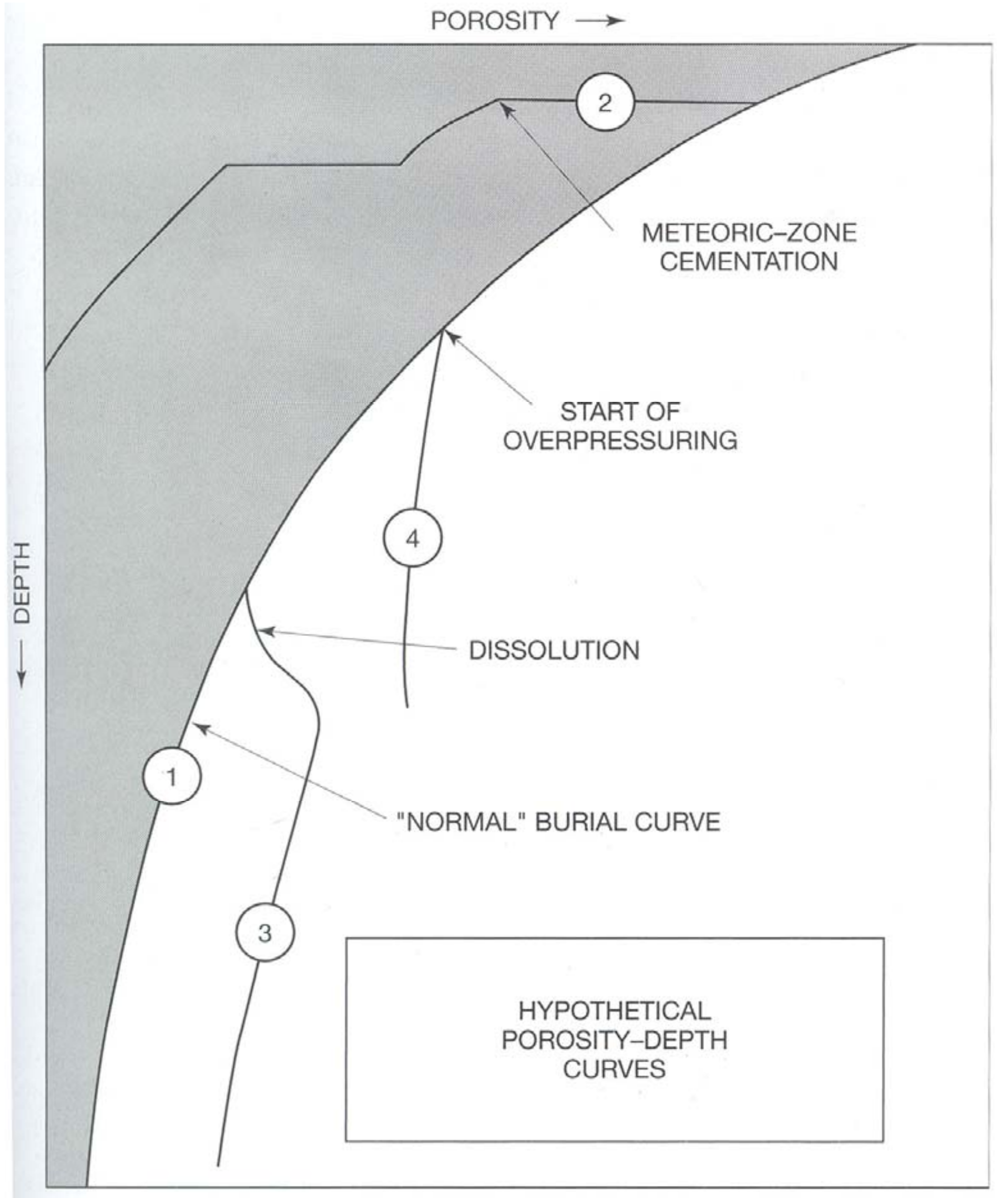


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Figure 6.17
Hypothetical curves illustrating (1) a "normal" porosity-depth relationship for fine-grained sediments with marine pore waters; (2) cementation in the meteoric zone (horizontal segments) alternating with burial in marine pore waters; (3) reversal of normal-porosity depth trend owing to dissolution in the deep subsurface, followed by resumption of normal burial; and (4) arrested porosity reduction owing to abnormally high pore pressure. [From Choquette, P. W., and N. P. James, 1987, Diagenesis 12. Diagenesis in limestones—3. The deep-burial environment: Geoscience Canada, v. 14, Fig. 33, p. 23, reprinted by permission of Geological Association of Canada.]

A limestone block on the Tsengwenchi river bed

Rock name:

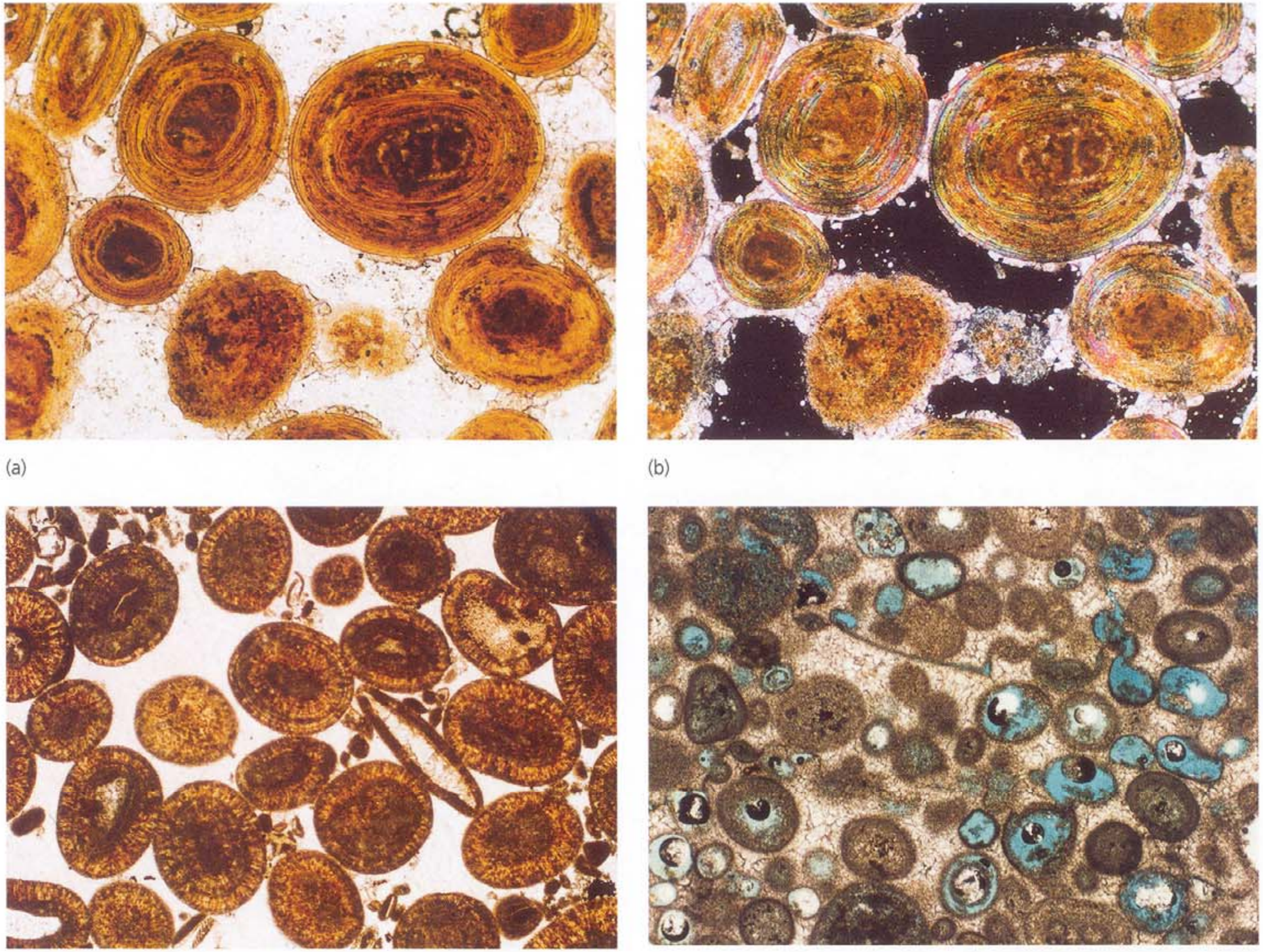
(a) Folk's classification:______________

(b) Dunham's classification:___________

a, b: Ooids composed of aragonite showing concentric structure and a nucleus. Meniscus cement (b) precipitated in vadose zone; c: calcite ooids, Oolitic grainstone; d: formerly aragonitic ooids, now composed of calcite with poor preservation of original concentric structure and oomoulds.

Plate 6

(a, b) Holocene ooids composed of aragonite showing concentric structure and a nucleus, several of which are peloids, and one in the centre of the biggest ooid is a bioclast. Structureless oval grain at lower left is a peloid. Also present is a meniscus cement of calcite precipitated in the meteoric vadose zone. The white areas between grains in (a) and the black areas in (b) are pore space: **(a)** plane-polarized light; **(b)** crossed polars. Joulters Cay, Bahamas. Field of view 1.2 × 0.8 mm.
(c) Primary, calcitic ooids with strong radial-concentric structure and nuclei mostly of peloids. Bivalve fragment, now composed of clear calcite spar crystals, is also coated. Notice contact between grains; a little interpenetration indicating some burial compaction before cementation. The ooids are contained in a very large poikilotopic calcite cement (here appearing white). Oolitic grainstone, Jurassic. Lincolnshire, England. Field of view 3 × 2 mm.
(d) Formerly aragonitic ooids, now composed of calcite with poor preservation of original concentric structure and oomoulds (filled with blue resin). Some compaction of oomoulds indicating that the drusy calcite spar cement is a burial precipitate. Oolitic grainstone, Smackover Formation, Jurassic. Subsurface Arkansas, USA. Field of view 3 × 2 mm.



(a) (b) (c) (d)

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a: Peloids; b,c: bivalve fragments with micrite envelope; d: peloids and bivalve with micrite envelope; e: sponge boring filled with micrite.

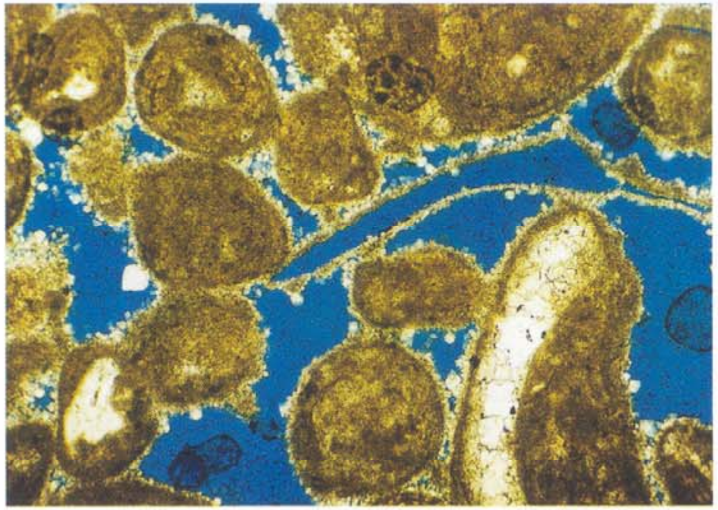
Plate 7

(a) Peloids; many are micritized bioclasts and ooids, some are faecal pellets. Micrite envelope defines a bivalve shell that has dissolved away; bivalve shell within coated grain is replaced by coarse calcite crystals. The sparse cement consists of small, stubby calcite crystals of probable meteoric phreatic origin. Small dolomite rhombs also present. Blue resin shows porosity. Jurassic. Dorset, England. Field of view 0.8×0.8 mm.

(b,c) Modern bivalve fragment with micrite envelope. Shell, composed of aragonite, consists of minute crystallites giving a sweeping extinction under crossed polars **(c)**. Abu Dhabi, UAE. Field of view 0.8×1.0 mm.

(d) Bivalve fragment (the elongate grain) in centre with a prominent micrite envelope and shell now composed of drusy calcite spar, a cement. The micrite envelope has fractured (in the centre) as a result of compaction. Also present are numerous peloids, most of which are micritized bioclasts, and some crinoid fragments, in a sparite cement.Urgonian, Cretaceous. Vercors, France. Field of view 3×2 mm.

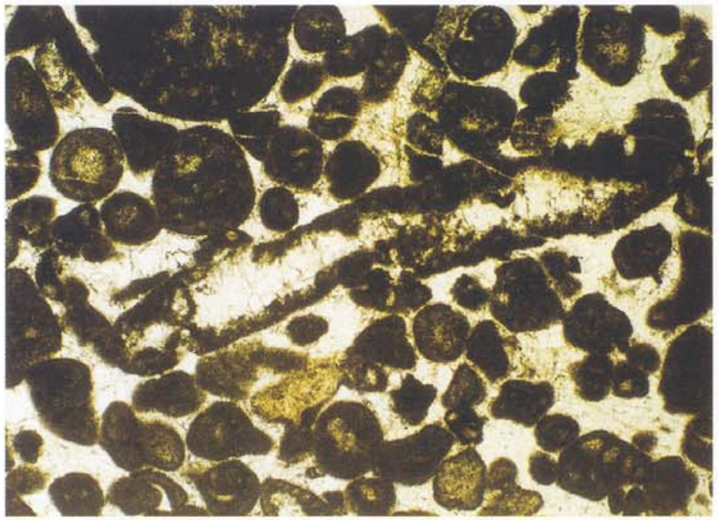
(e) Hippuritid rudist bivalve (the conical, attached valve) showing brown, well-preserved fibrous calcite outer wall, and thinner inner wall with tabulae, which originally were aragonite, but are now composed of calcite spar. Round areas of sediment (micrite) are the fills of sponge borings. Cretaceous. Provence, France. Field of view 6×4 mm.



(a)

(b)

(c)



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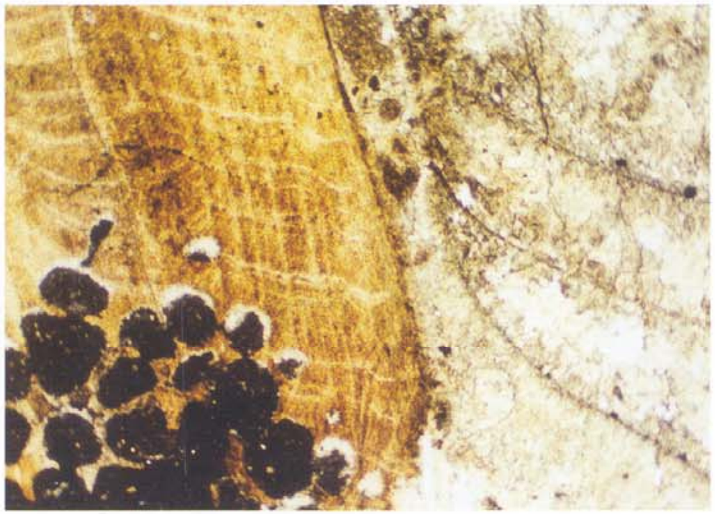

(e)

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a, b: calcitized bivalve shells with sparry calcite cement; c: gastropods (腹足類); d,e: Brachiopod(腕足類)

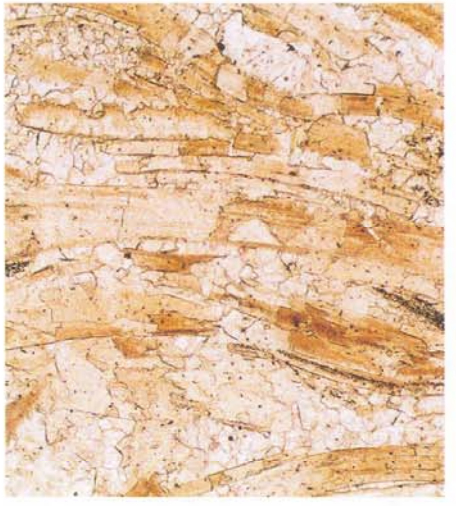
Plate 8

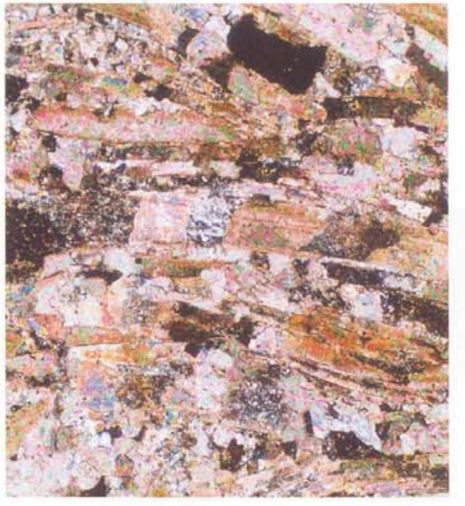
(a, b) Calcitized bivalve shells. Shells originally composed of aragonite but replaced by calcite with some retention of original shell structure. Calcite crystals cross-cut the shell structure and are pseudopleochroic (different shades of brown on slide rotation): **(a)** plane-polarized light and **(b)** crossed polars. Jurassic. Dorset, England. Field of view 0.8 ×0.8 mm.

(c) Gastropods, in long- and cross-section, defined by thin micrite envelopes (black). The shells, originally aragonite, dissolved out and voids were filled by marine fibrous calcite cement (pale brown). A later clear calcite cement filled remaining pores (white). Jurassic. Sicily, Italy. Field of view 4 ×4 mm.

(d) Brachiopod shell with puncti, some filled with lime mud sediment, showing preservation of internal structure consisting of obliquely arranged fibres. Other grains are micritized bioclasts (peloids). Bioclastic grainstone. Cretaceous. Vercors, France. Field of view 3×2 mm.

(e) Brachiopod shells and spines with well-preserved shell structure, but limestone has suffered compaction and many shells are broken. Thin-section is stained with Alizarin Red S and potassium ferricyanide; bioclasts are pink (calcite) and cement is blue (ferroan calcite). Cement occurs within cracks showing that it is a burial precipitate. Crinoids and clay (brown) also present. Bioclastic packstone. Carboniferous. Northumberland, England. Field of view 6×4 mm.


(a)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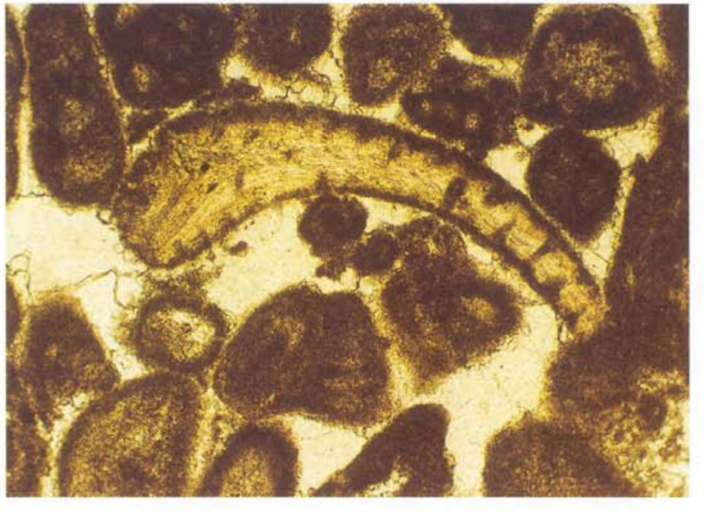
(c)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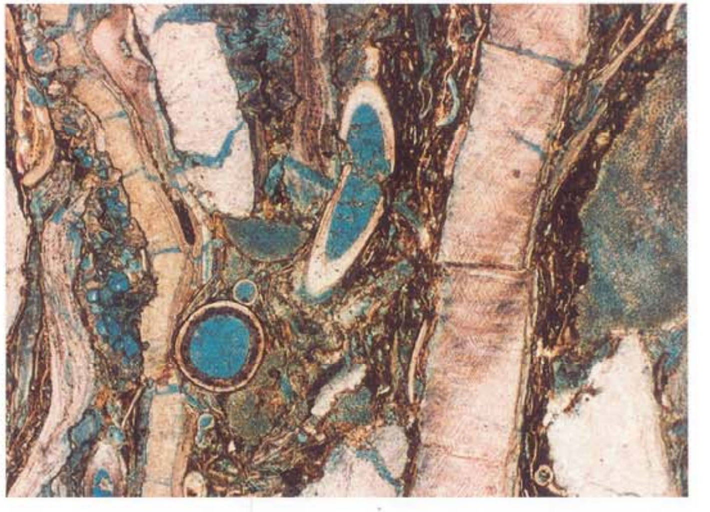
(e)

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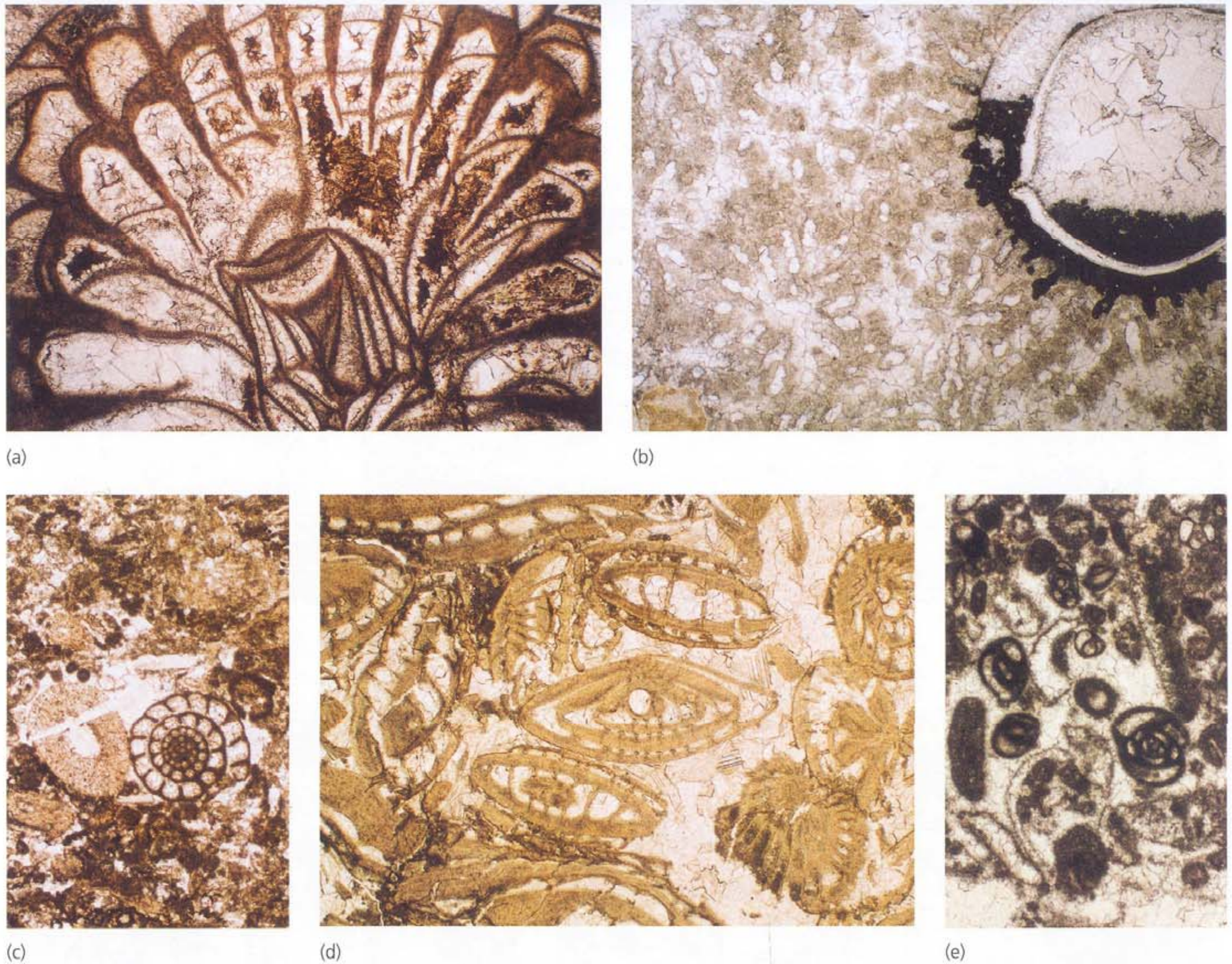
a: Rugose coral (四射珊瑚); b: Scleractinian coral (石珊瑚) and a boring with geopetal structure; c; Forams; d Nummulites (貨幣石) ; e: Miliolids.

Plate 9
(a) Rugose coral (*Lithostrotion* sp.) showing internal plates (septa, tabulae and dissepiments). The pores within the coral are partly filled with an initial isopachous fibrous marine cement and then by internal sediment. Carboniferous. Durham, England. Field of view 6×4 mm.
(b) Scleractinian coral from a Jurassic patch reef showing variable preservation of structure as a result of replacement of the original aragonite by calcite. Also present, on the right, is a boring made by a lithophagid bivalve (shells present); the boring shows a geopetal structure, with sediment below (dark) and drusy calcite spar above (white). Yorkshire, England. Field of view 6×4 mm.
(c, d, e) Foraminifera. **(c)** Endothyracid foram, crinoid to left, cut by a calcite vein. Carboniferous. Clwyd, Wales. Field of view 4×2 mm. **(d)** *Nummulites*. Bioclastic grainstone, Eocene. Tunisia. Field of view 6×4 mm. **(e)** Miliolids, also bivalve fragments. Cretaceous. Vercors, France. Field of view 4×2 mm.



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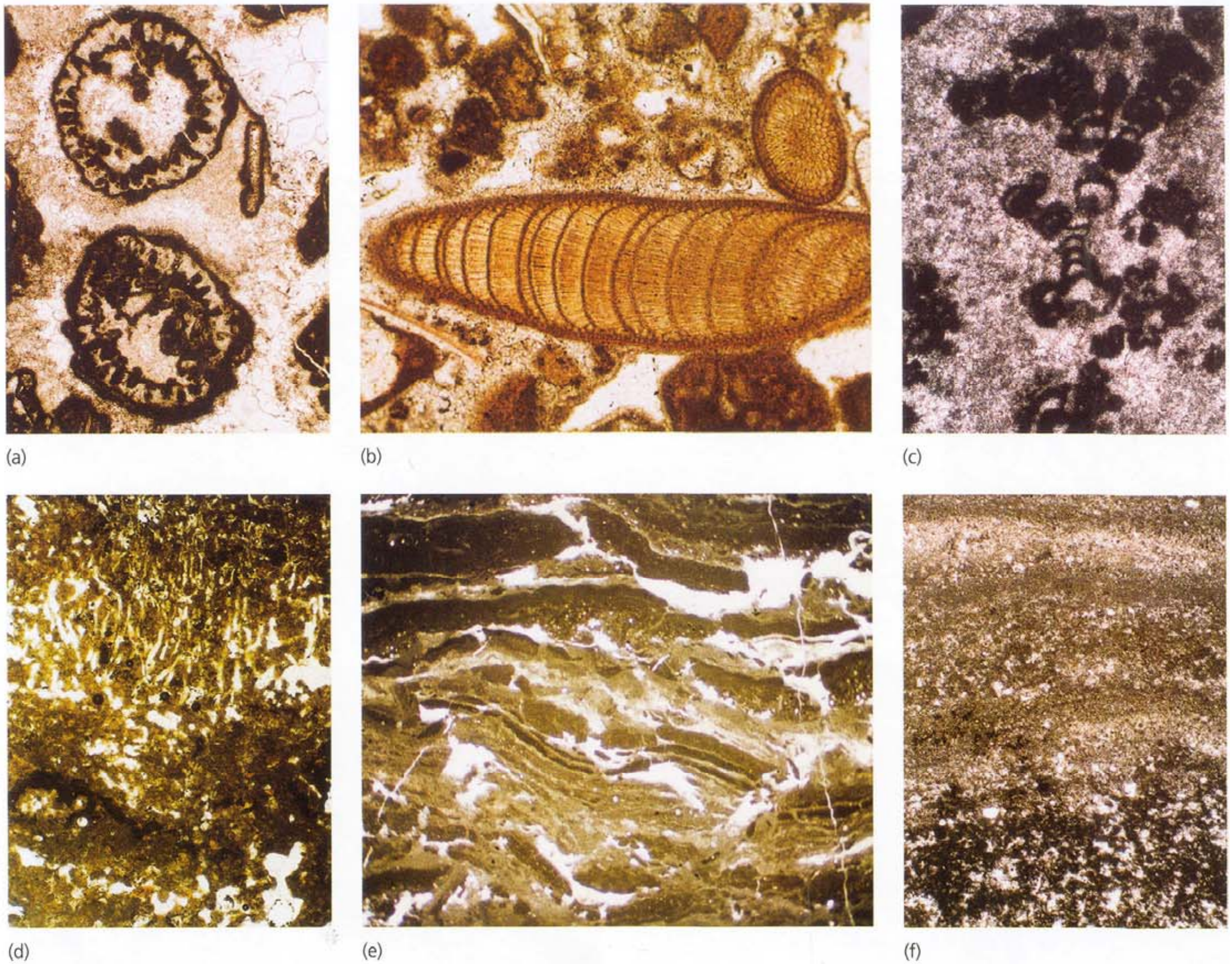
a: Dasyclad algae; b: calcareous red algae, isopachous marine cement; c: calcified microbes; d: microbial mat of dolomite; e, f: stromatolite

Plate 10

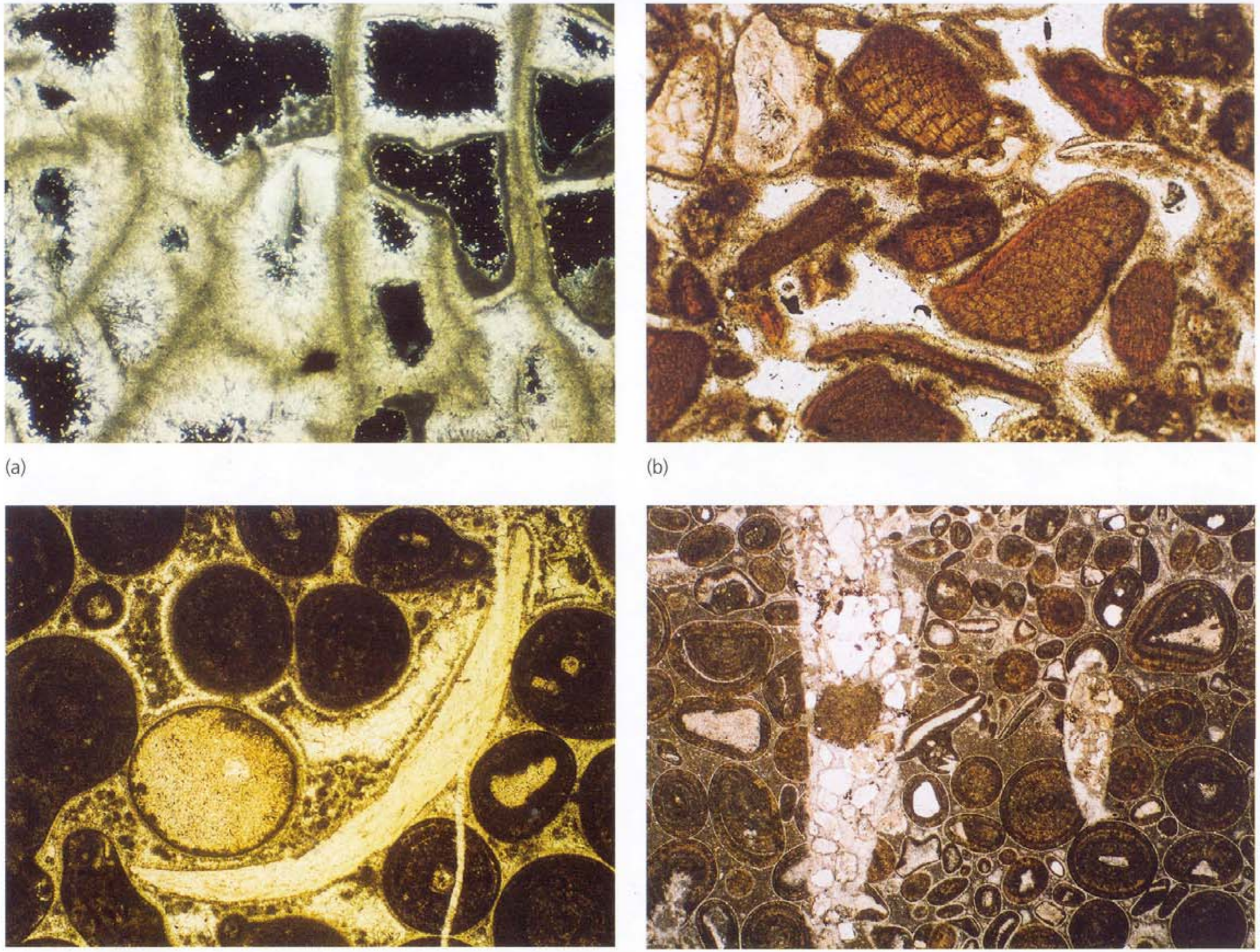
(a) Dasyclad algae. Capitan, Permian. Texas, USA. Field of view 4×2 mm.
(b) Calcareous red algae, *Lithothamnion* in longitudinal section (showing seasonal growth zones) and cross-section. The grains here are cemented by isopachous high-Mg calcite marine cement. Recent. Belize. Field of view 1.0×0.8 mm.
(c) Calcified microbes, *Renalcis*. Devonian. Guilin, China. Field of view 4×2 mm.
(d) Modern microbial mat composed of dolomite. The filaments of the cyanobacteria are clearly visible, but the dolomite crystals are submicroscopic. Recent. Bahamas. Field of view 4×2 mm.
(e) Stromatolite (microbial mat) composed of micrite laminae and laminoid fenestrae, with some intraclasts from desiccation. Carboniferous. Glamorgan, Wales. Field of view 5×4 mm.
(f) Stromatolite composed of micritic and grainy laminae, and small spar-filled fenestrae. Precambrian. Flinders, Australia. Field of view 4×2 mm.



Tucker (2001)

a: coral with agragonite cement; b: isopachous calcite cement; c: isopachous marine cement, then internal sediment of peloids, followed by drusy calcite cement; d: hardground.

Plate 11
(a) Coral with aragonite cement—needles and a botryoid within the corallites, and lime mud internal sediment (black) and peloids in other pores. Crossed polars. Recent. Belize. Field of view 6×4 mm.
(b) Isopachous high-Mg calcite cement around skeletal grains (including calcareous red algae). Recent fore-reef debris. Belize. Field of view 1.2×0.8 mm.
(c) Oolitic grainstone with brachiopod and crinoid fragments (with thin micrite envelope—black) cemented by early isopachous fibrous marine cement (calcite), then some internal sediment of peloids, followed by drusy calcite spar cement. Carboniferous. Glamorgan, Wales. Field of view 6×4 mm.
(d) Hardground with ooids surrounded by thin isopachous marine cement fringe and then pore space filled by lime mud, now micrite. Cemented rock then cut by annelid borings, which later filled with quartz grains. Jurassic. Gloucestershire, England. Field of view 6×4 mm.

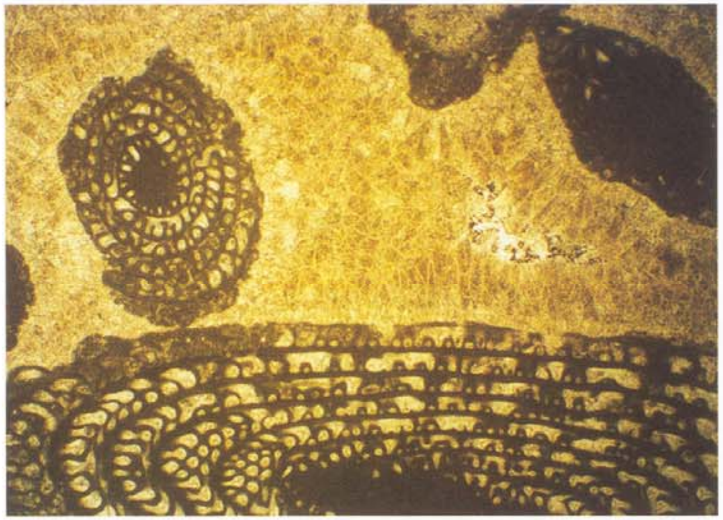


(a) (b) (c) (d)

Tucker (2001)

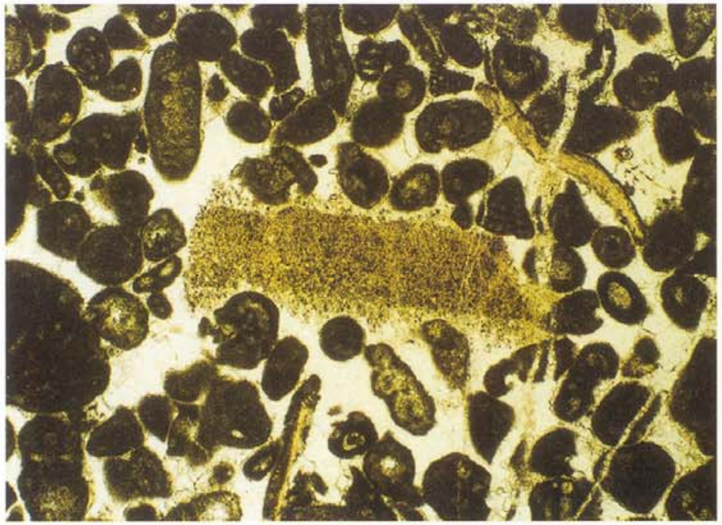
a, b: Fusulinid foraminifer cemented by radiaxial fibrous calcite; c, d: syntaxial calcite overgrowth cement.

Plate 12
(a,b) Fusulinid foraminifer cemented by radiaxial fibrous calcite. The crystals are columnar and cloudy with inclusions, and have undulose extinction under crossed polars. Small area of clear calcite spar: **(a)** plane-polarized light, field of view 6×4 mm; **(b)** crossed polars, field of view 3×2 mm. Capitan, Permian. Texas, USA. **(c,d)** Syntaxial calcite overgrowth cement on crinoid grain. Early part of overgrowth calcite cloudy with inclusions is probably a marine precipitate; clear later overgrowth a burial precipitate. Grains mainly peloids, micritized bioclasts and faecal pellets, showing concavo-convex/interpenetrative contacts, indicating some compaction. Very thin isopachous calcite cement fringes around grains seen in **(d)** are probably marine precipitates. Rock also cut by thin calcite veins. **(c)** Plane-polarized light; **(d)** Crossed polars. Cretaceous. Alps, France. Field of view 3×2 mm.

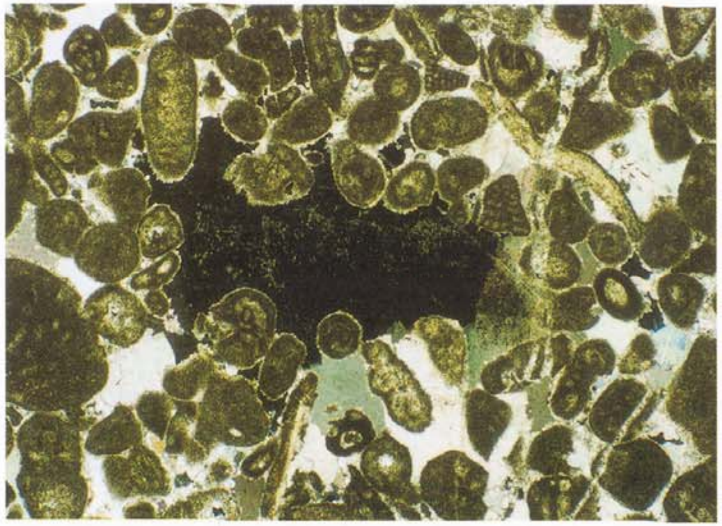


(a)

(b)



(c)

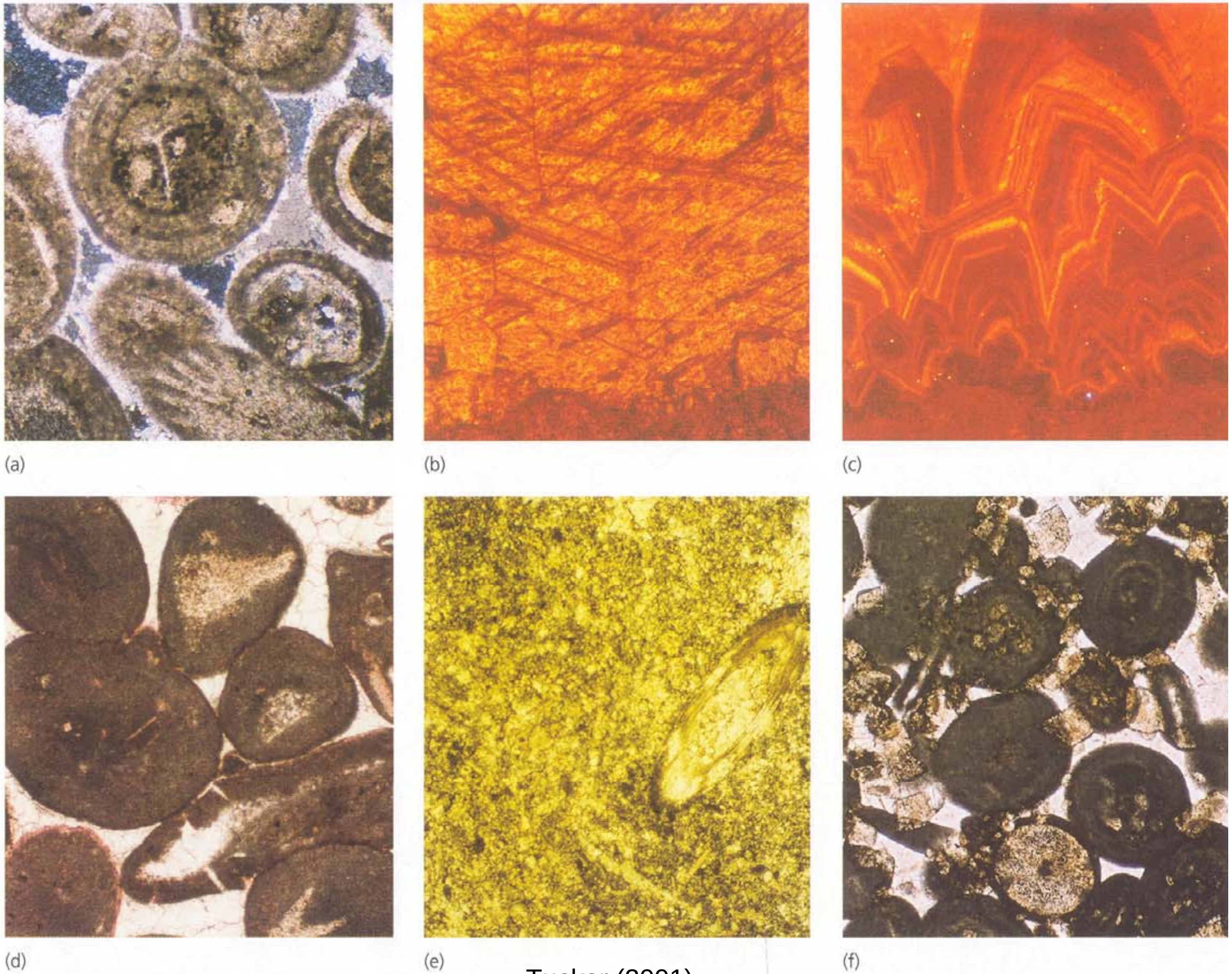


(d)

Tucker (2001)

a: cementing in meteoric vadose zone; b, c: calcite spar; d: sutured contacts because of compaction; e: microspar-pseudospar formed during neomorphism; f: Ooids with scattered dolomite rhombs.

Plate 13
(a) Calcite cement at grain contacts and irregularly around grains, indicating near-surface, meteoric vadose environment. Later precipitation of large poikilotopic calcite (black, in extinction) took place during burial after some compaction. Crossed polars. Carboniferous. Glamorgan, Wales. Field of view 0.8×0.8 mm.
(b, c) Calcite spar.
(b) Calcite spar under plane-polarized light showing drusy fabric (crystal-size increase away from the substrate) and prominent twin planes. **(c)** Same field of view under cathodoluminescence showing delicate growth zones resulting from subtle variation in manganese and iron contents. Triassic. Glamorgan, Wales. Field of view 2×2 mm.
(d) Sutured (microstylolitic) contacts and concavo-convex contacts between grains (micritized ooids and bioclasts) and mechanical fracture of lower grain. Calcite spar between grains is a post-compaction burial cement. Jurassic. Burgundy, France. Field of view 2×2 mm.
(e) Microspar–pseudospar formed through aggrading neomorphism with fossil relics (brachiopod spine on right). Carboniferous. Yorkshire, England. Field of view 2×2 mm.
(f) Oolitic grainstone with scattered dolomite rhombs precipitated after early compaction (see grain contacts), before calcite spar cement. Carboniferous. Glamorgan, Wales. Field of view 2×2 mm.



Tucker (2001)

a: Dolomitized oolite with stylolite. Xenotopic dolomite below stylolite and idiotopic dolomite above; b: dolomitized grainstone; c: Baroque dolomite; d: delolomite; e: dolomite moulds

Plate 14

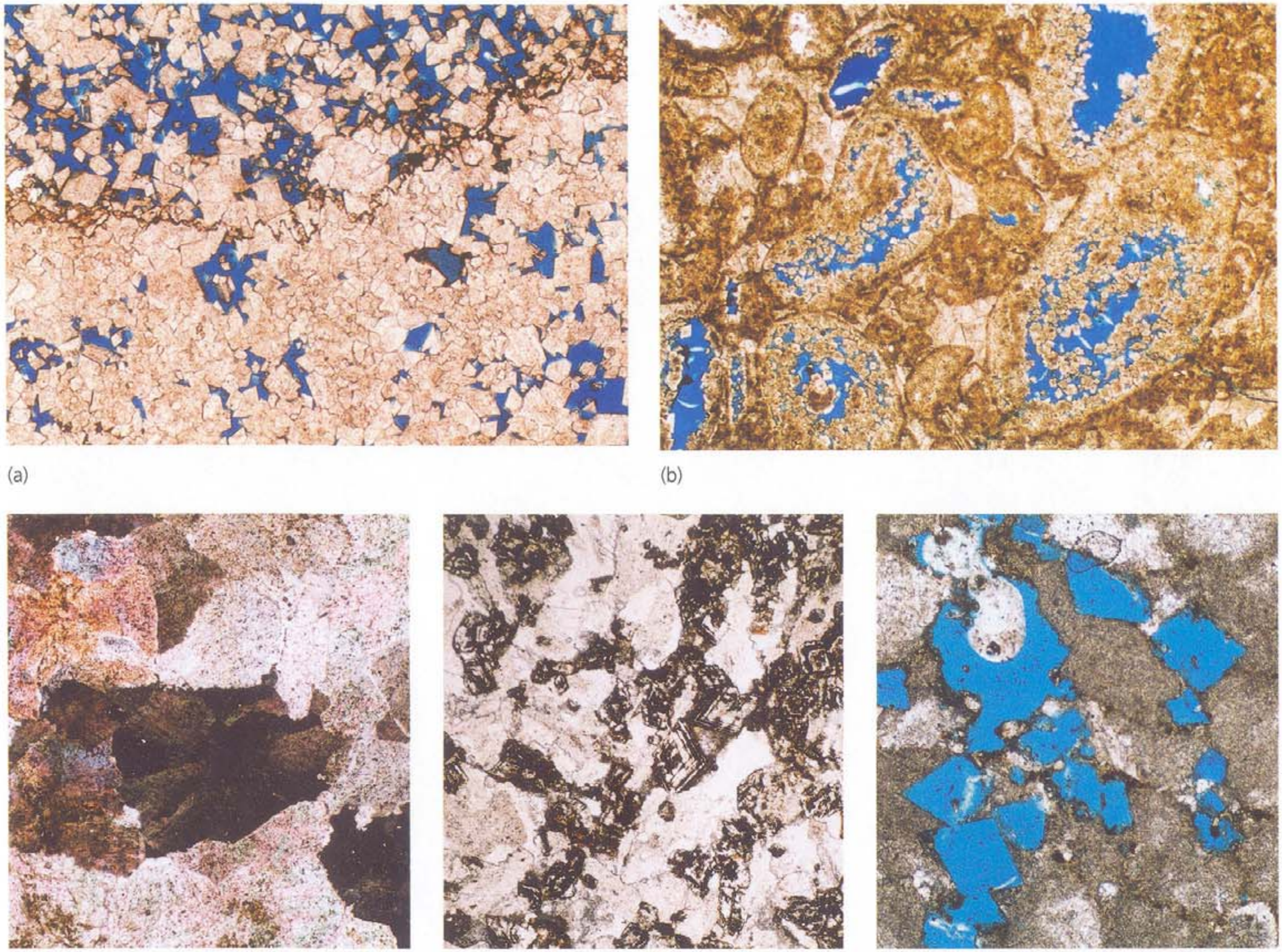
(a) Dolomitized oolite (no relics of original grains) with stylolite, highlighted by iron-rich clay. Xenotopic dolomite (anhedral crystals) below stylolite and idiotopic dolomite (euhedral crystals) above. Intercrystalline porosity shown through impregnation with blue resin. Arab Formation. Offshore UAE. Field of view 3 × 2 mm.

(b) Dolomitized grainstone with moderate preservation of original ooids. Intercrystalline porosity is present, shown up by impregnation with blue resin. Cretaceous. Offshore Angola. Field of view 6 × 4 mm.

(c) Baroque dolomite: coarse crystals with undulose extinction. Rock is an oolite but there are no relics. Crossed polars. Carboniferous. Glamorgan, Wales. Field of view 2 × 2 mm.

(d) Dedolomite: crinoidal grainstone with overgrowths containing scattered dolomite rhombs that have been replaced by calcite. The dark material is iron oxide/hydroxide, suggesting the dolomite was originally ferroan. Carboniferous. Northumberland, England. Field of view 2 × 2 mm.

(e) Dolomite moulds: grainstone with scattered dolomite rhombs that have been dissolved out to give a good porosity, as shown by blue resin. Stylolitic contacts between grains. Jurassic. Burgundy, France. Field of view 0.8 × 0.8 mm.



(a) (b) (c) (d) (e)

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