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ENGINEERING GEOLOGY & GEOTECHNICAL MODELS

ENGINEERING GEOLOGY

Faulting

Fault Nomenclature

Geologic faults, fault lines or simply faults are planar rock fractures, which show evidence of relative movement.

Large faults within the Earth's crust are the result of shear motion and active fault zones are the causal locations of most earthquakes.

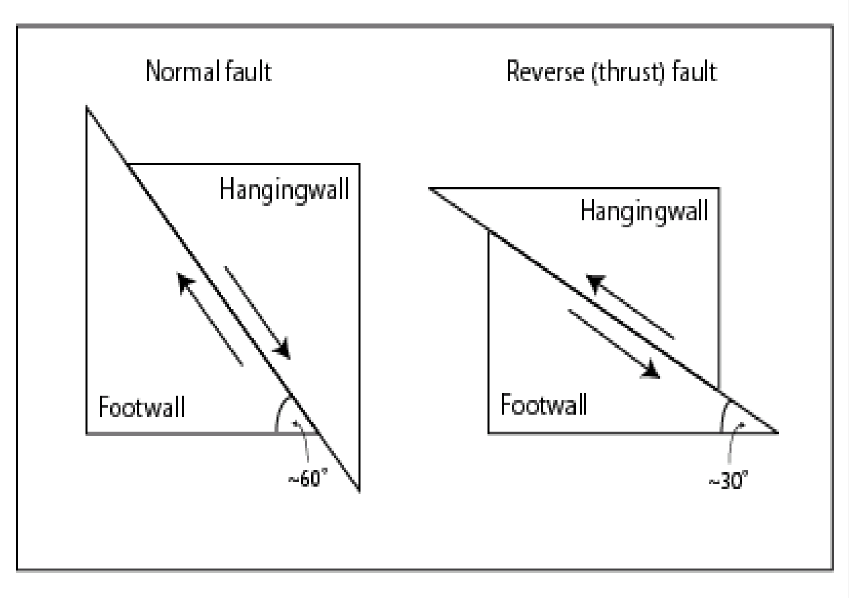
Earthquakes are caused by energy release during rapid slippage along faults.

The largest examples are at tectonic plate boundaries but many faults occur far from active plate boundaries.

Fault zone refers to the zone of complex deformation that is associated with the fault plane.

Dip-slip faults

- A reverse fault is the opposite of a normal fault — the hanging wall moves up relative to the footwall. Reverse faults are indicative of shortening of the crust. The dip of a reverse fault is relatively steep, greater than 45° .



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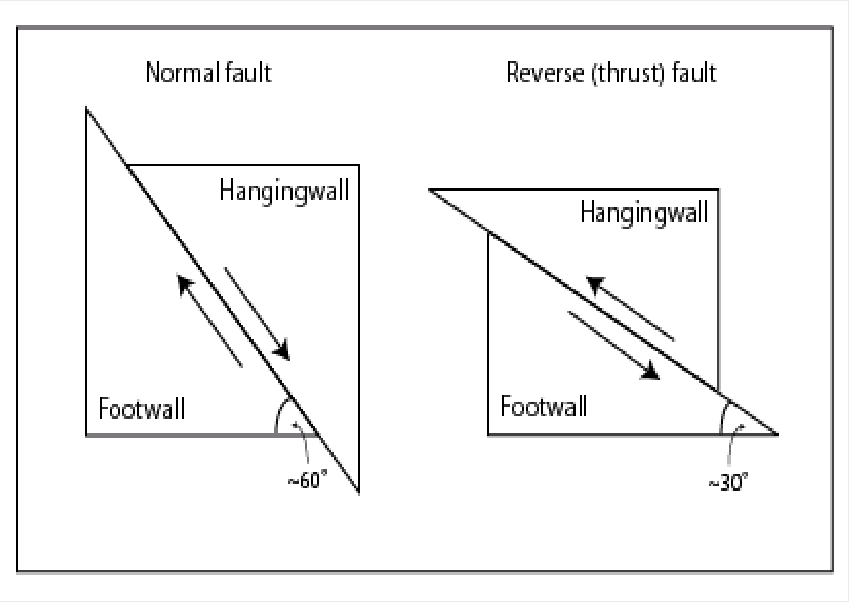

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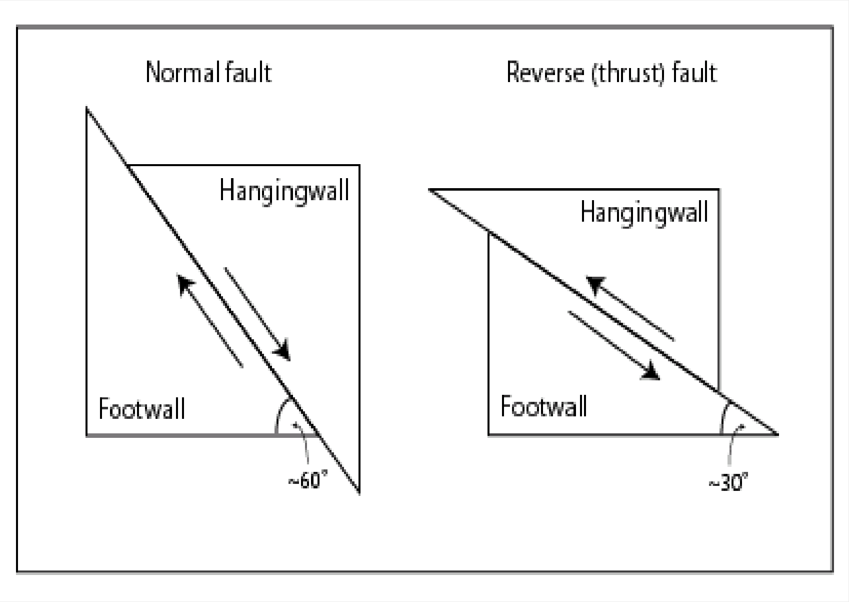
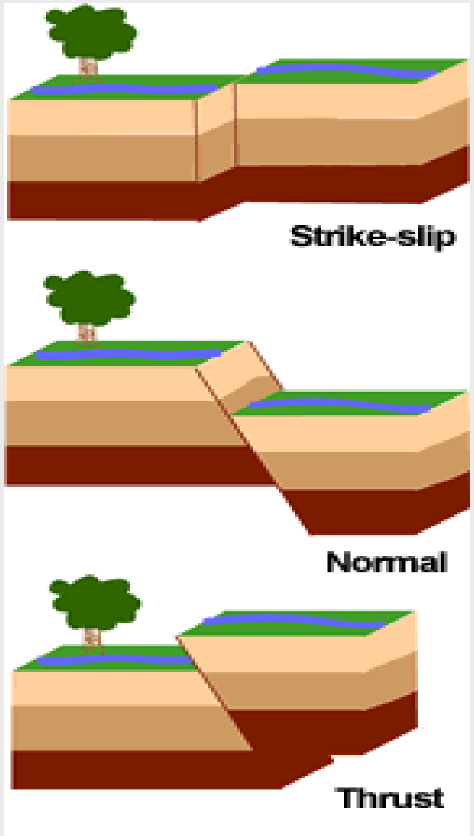


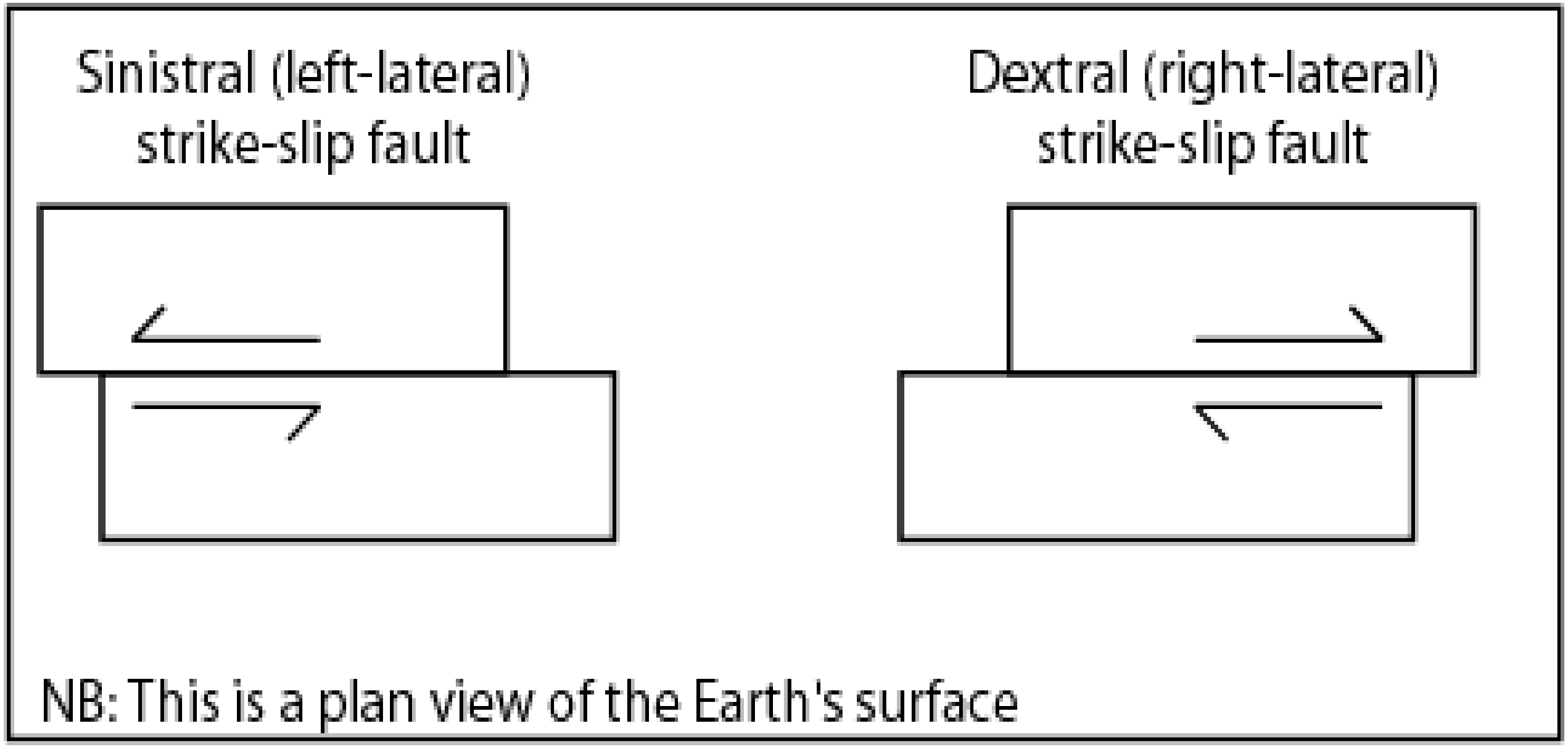
Strike-slip faults

The fault surface is usually near vertical and the footwall moves either left or right or laterally with very small vertical motion. Strike-slip faults with left-lateral motion are also known as sinistral faults. Those with right-lateral motion are also known as dextral faults.

A special class of strike-slip faults is the transform faults which are a plate tectonics feature related to spreading centers such as mid-ocean ridges.



Strike-slip faults



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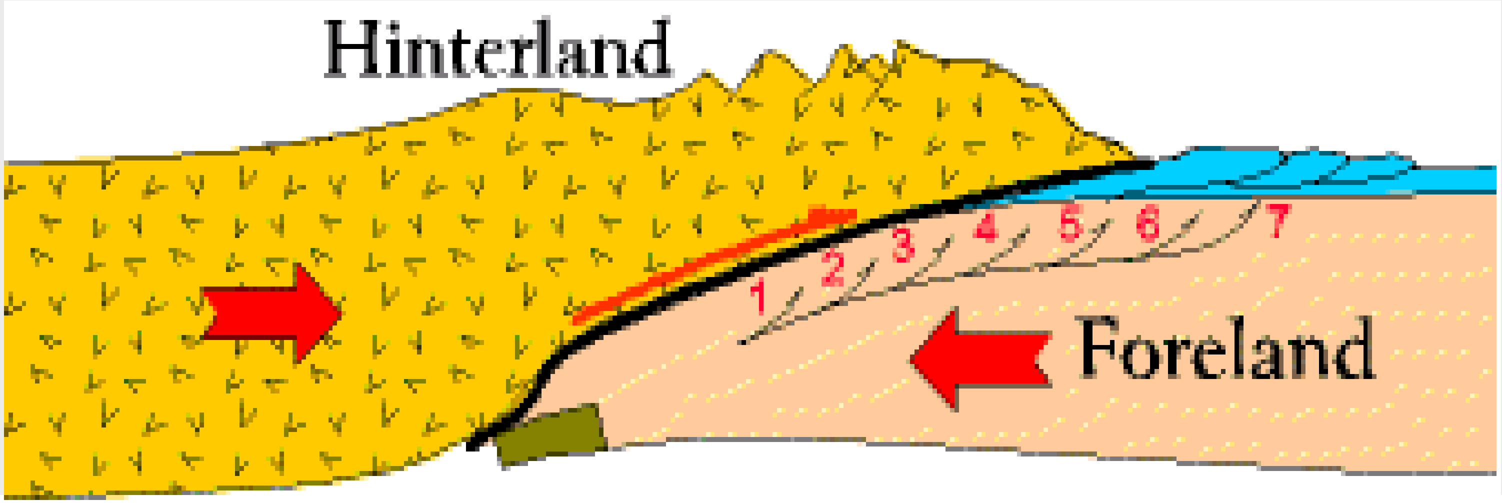
Fault rock

The main types of fault rock are:

- Mylonite - A fault rock which is cohesive and characterized by a well developed planar fabric resulting from tectonic reduction of grain size, and commonly containing rounded porphyroclasts and rock fragments of similar composition to minerals in the matrix
- Tectonic or Fault Breccia - A medium- to coarse-grained cataclasite containing >30% visible fragments.
- Fault Gouge - An incohesive, clay-rich fine- to ultrafine-grained cataclasite, which may possess a planar fabric and containing <30% visible fragments. Rock clasts may be present

Thrust Faults

Thrust faults develop when one block of earth, the hinterland, collides with and compresses another block, the foreland. The force of the hinterland and its movement creates horizontal stresses in the foreland rocks causing them to thrust fault and move. Similarly, stresses in the hinterland also lead to thrust faulting.



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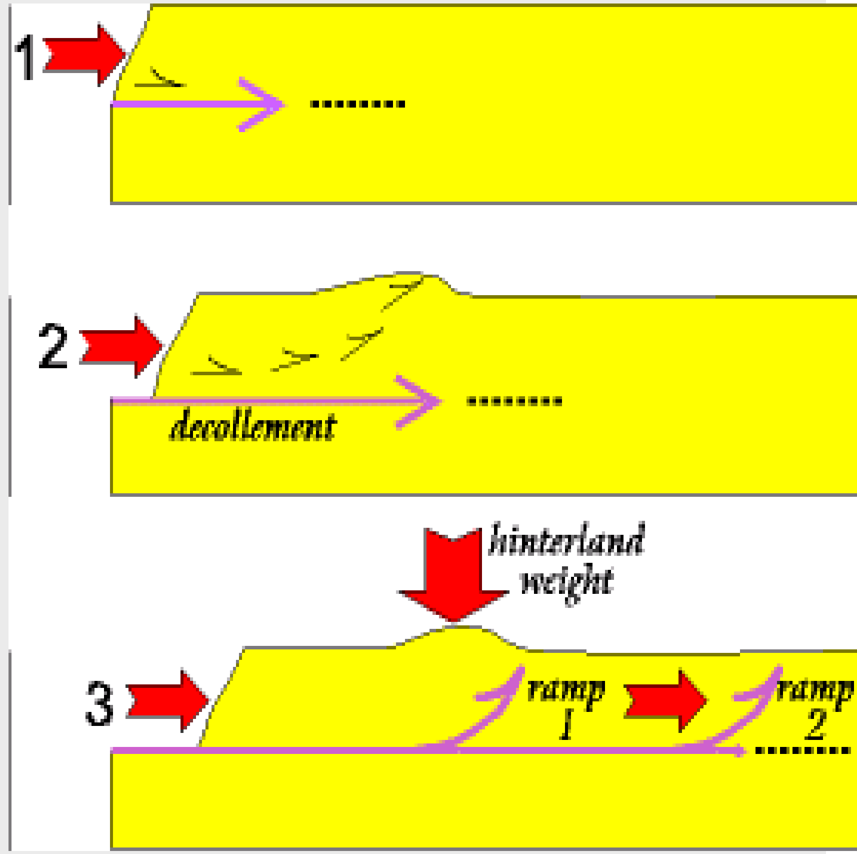
Thrust Faults

- **Block 1** - a block of the earth undergoing horizontal stresses and deforming.
- **Block 2:** As the rock strength fails, the overlying layer begins to slide over the underlying layer
- **Block 3**: The ramp, however, is only a short term solution because it can become locked. There is just too much downward directed weight and the upward directed stress cannot overcome it. So, now the easiest way for the stress to be released is forward again toward the foreland. The decollement reactivates and a horizontal fault begins to extend itself forward again . . . until it becomes locked again for the same reasons as above, leading to the formation of Ramp 2.



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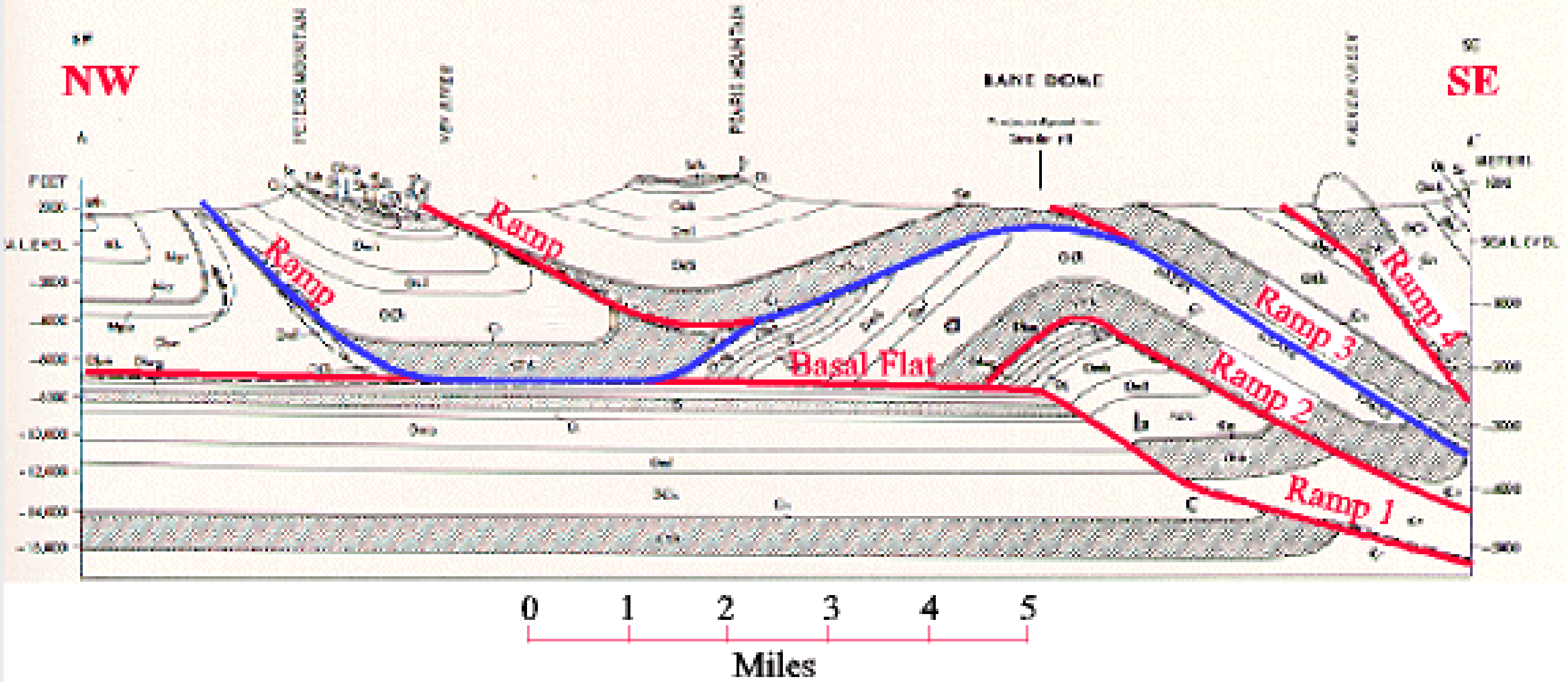
Imbricated Ramp



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Complex Appalachian Structure in Virginia

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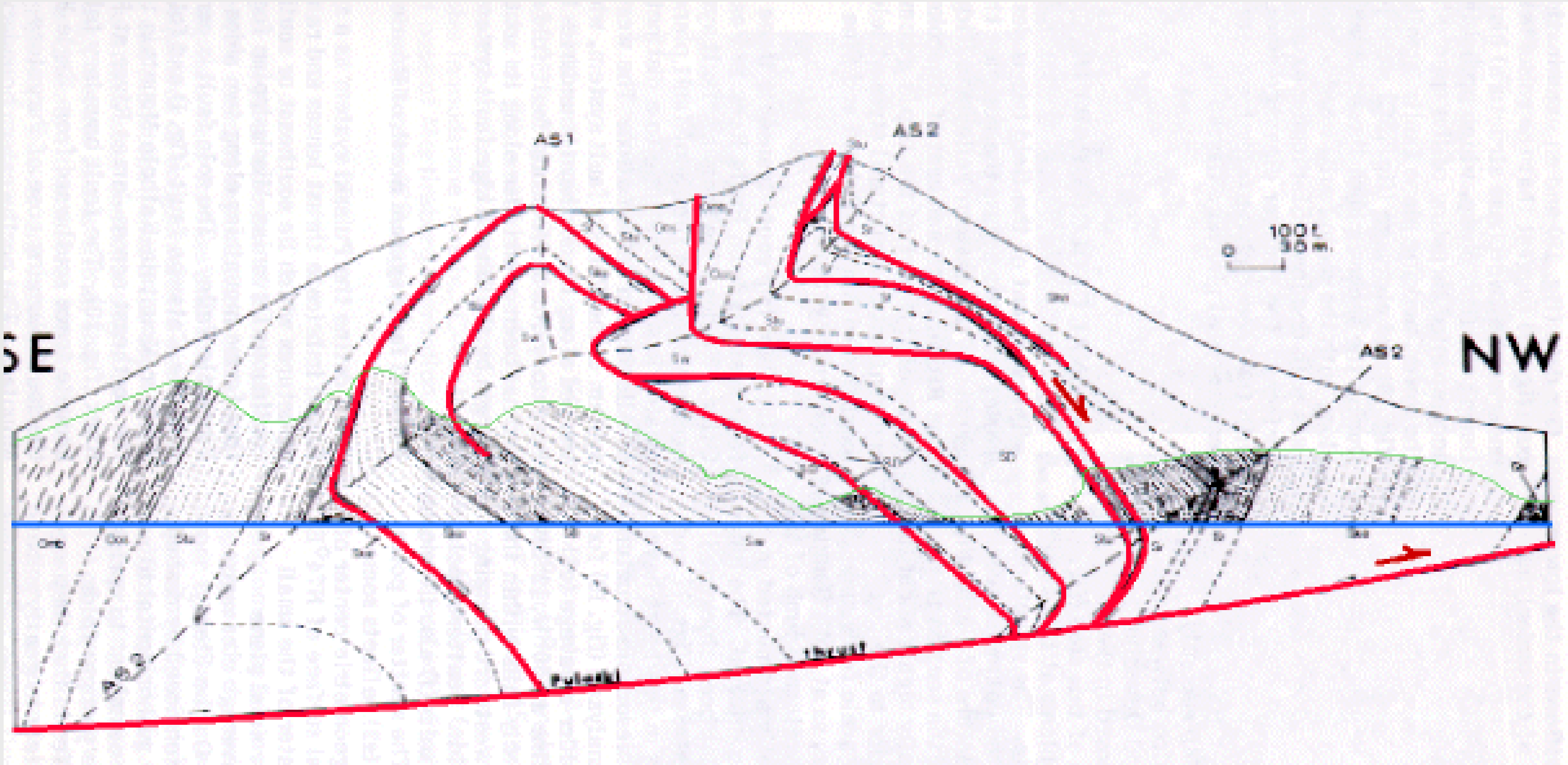
Complex Appalachian Structure in Virginia



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Geologic Modelling

Fault in shales near Adelaide.

The two sides of a non-vertical fault are called the hanging wall and footwall. By definition, the hanging wall occurs above the fault and the footwall occurs below the fault.

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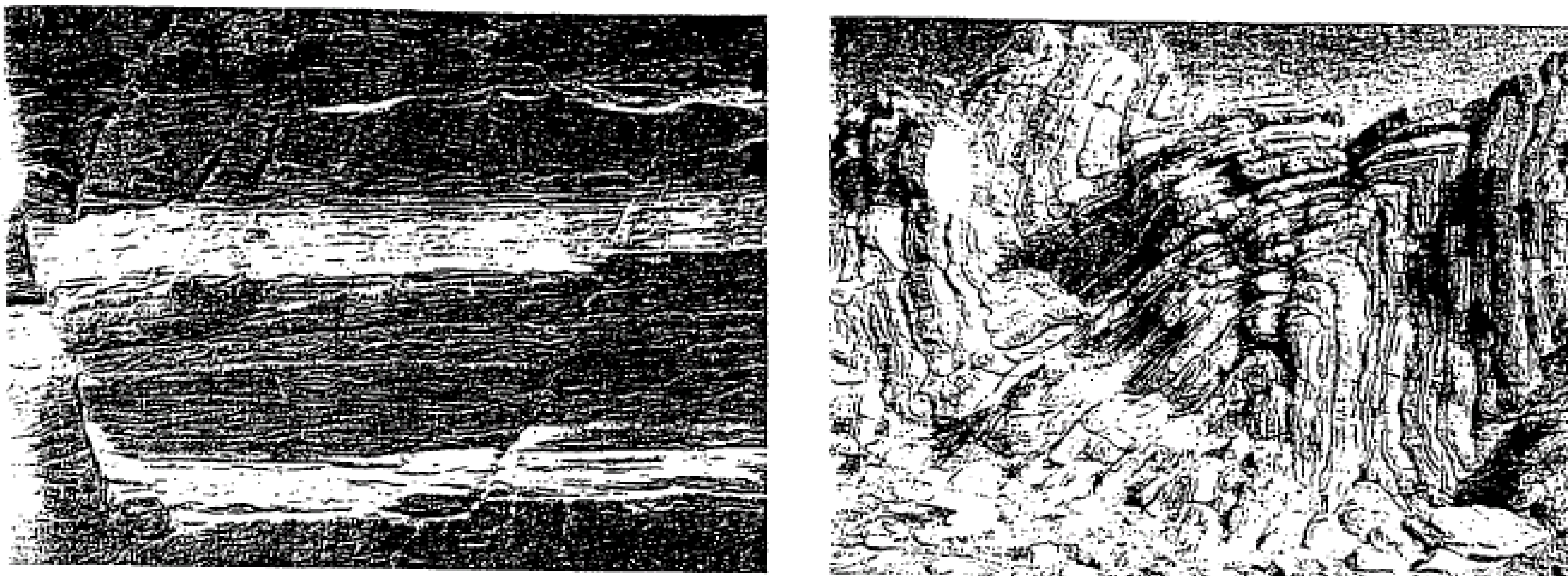
Brittle vs `Ductile



A

B

Figure 15.5 Brittle Versus Ductile Examples of rock deformation. A. Fracture of strata by brittle deformation; Triassic-aged Bunter-Sandstone, Merseyside, U.K. B. Bending of strata by ductile deformation; limestones in Crete.

Terminology - Curvature

Curvature is a fundamental property of a folded surface. Curvature varies from maximum (positive) values, through zero to minimum (negative) values. For a single surface, lines joining points of maximum curvature or joining points of minimum curvature are known as *hinge lines* and lines joining points of zero curvature are known as *inflexion lines* (Ramsay & Huber, 1987).

Anticline - Syncline

Anticline and *syncline* are terms that relate to the "younging" direction of the stratigraphy with respect to the fold. An *anticline* refers to a fold where the oldest strata are in the core of the fold; a *syncline* refers to a fold where the youngest strata are in the core of the fold. Thus antiformal anticlines (known simply as anticlines), synformal synclines (known simply as synclines), antiformal synclines and synformal anticlines are all possible (Hobbs *et al* 1976).

Fold Tightness

The degree of tightness of a fold is defined as the *interlimb angle*, which is the angle between tangents to the fold limbs drawn through the inflexion lines. *Interlimb angle* may be classified as follows:

- gentle: 180°-120°,
- open: 120°-70°,
- close: 70°-30°,
- tight: 30°-0°,
- isoclinal: 0°,
- elastica: negative interlimb angle.

Folds with narrow, angular hinge zones are known as *kink folds*, where the fold limbs are approximately the same length these may be referred to as *chevron folds*.

Fold Classification

TABLE 1

CLASSIFICATION OF APPROXIMATELY PLANE CYLINDRICAL FOLDS BY ORIENTATION

Orientation of Axial Surface		Orientation of Hinge Line		
		Horizontal	*Plunging*	*Vertical*
	Vertical	Horizontal Normal	Plunging normal	Vertical
	Dipping	Horizontal Inclined	Plunging Inclined Reclined	
	Horizontal	Recumbant		

Table after Hobbs et al (1976).

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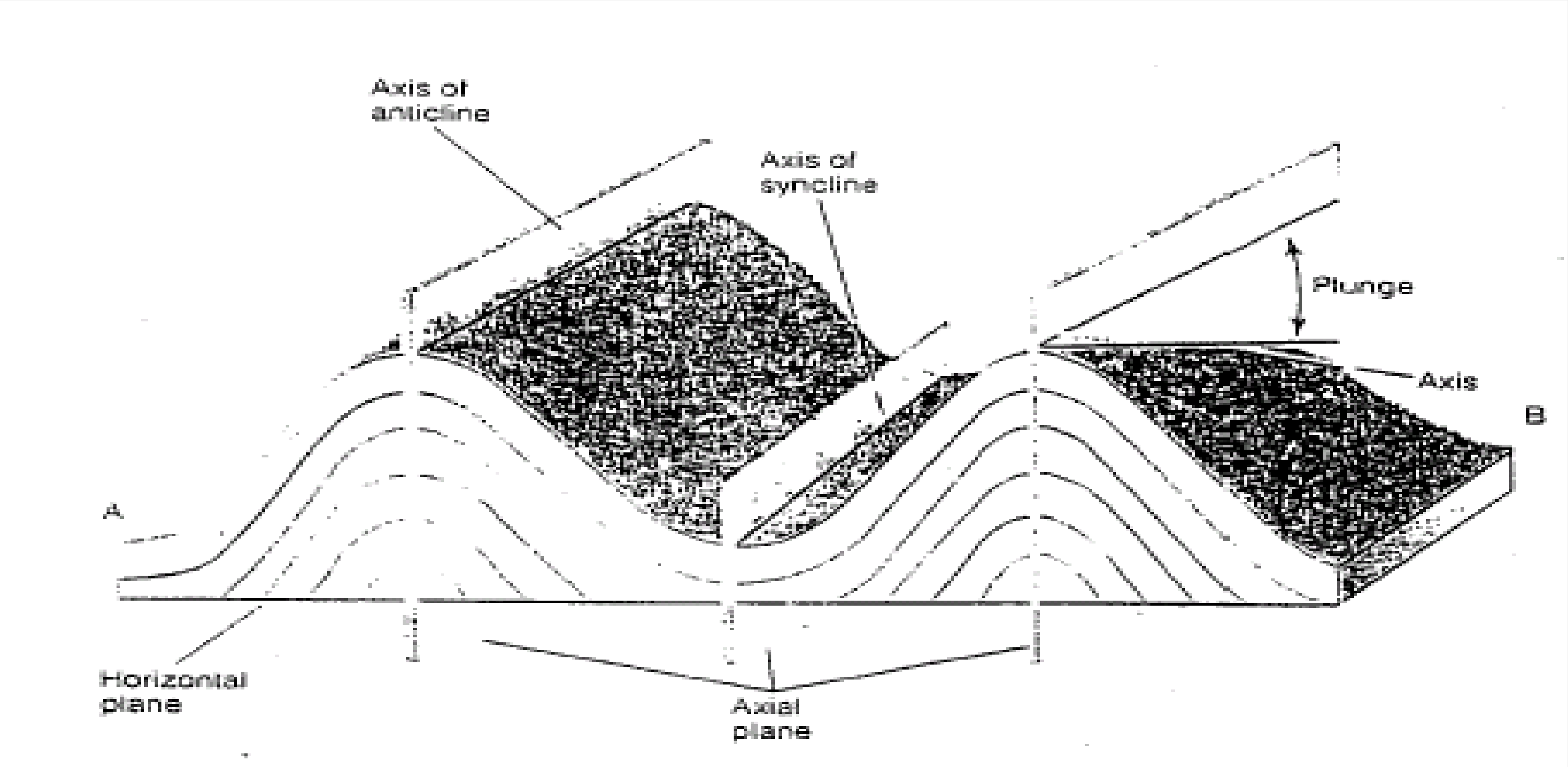
Fold Geometry



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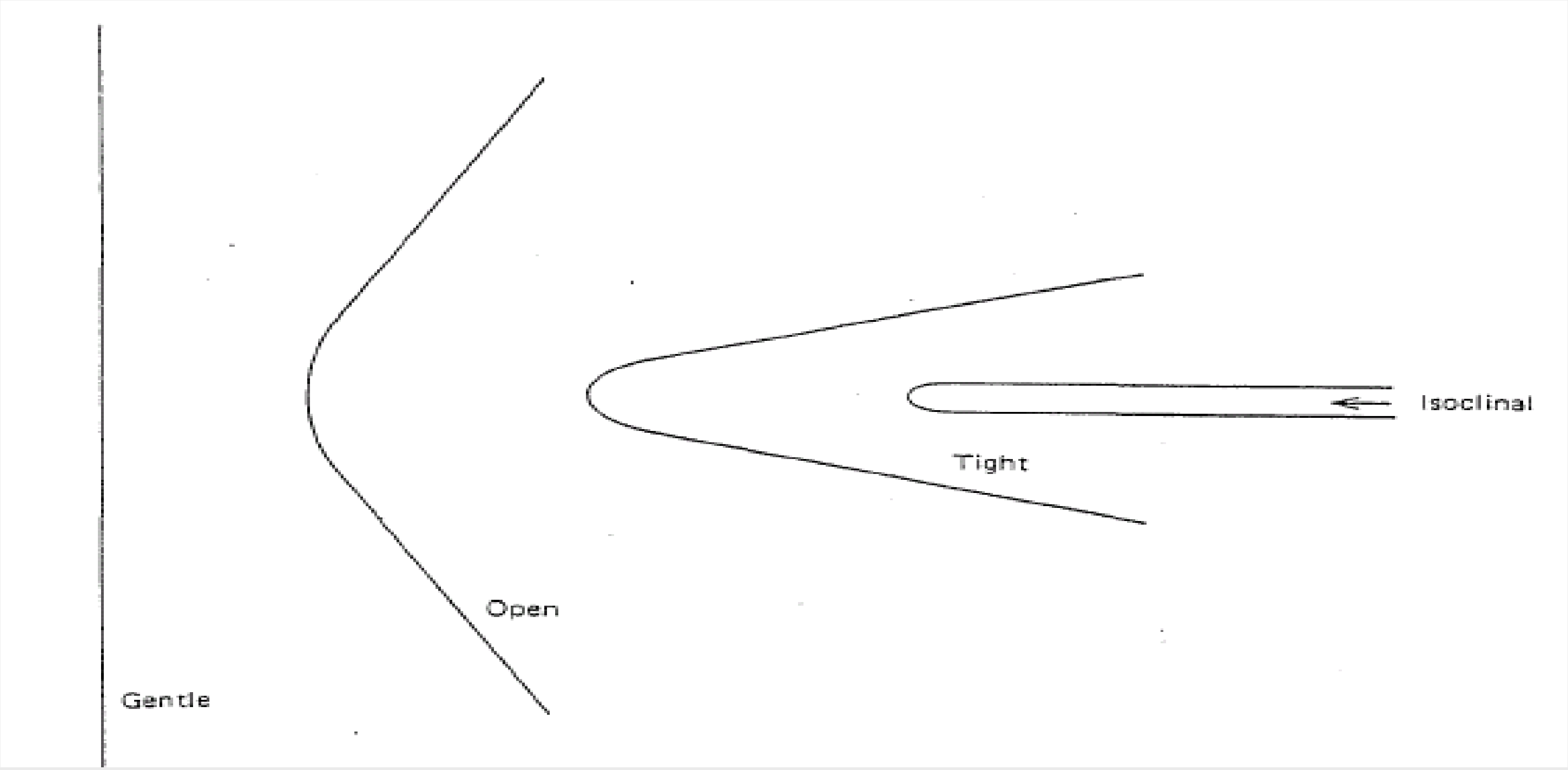
Fold Geometry – Inter-limb Angle



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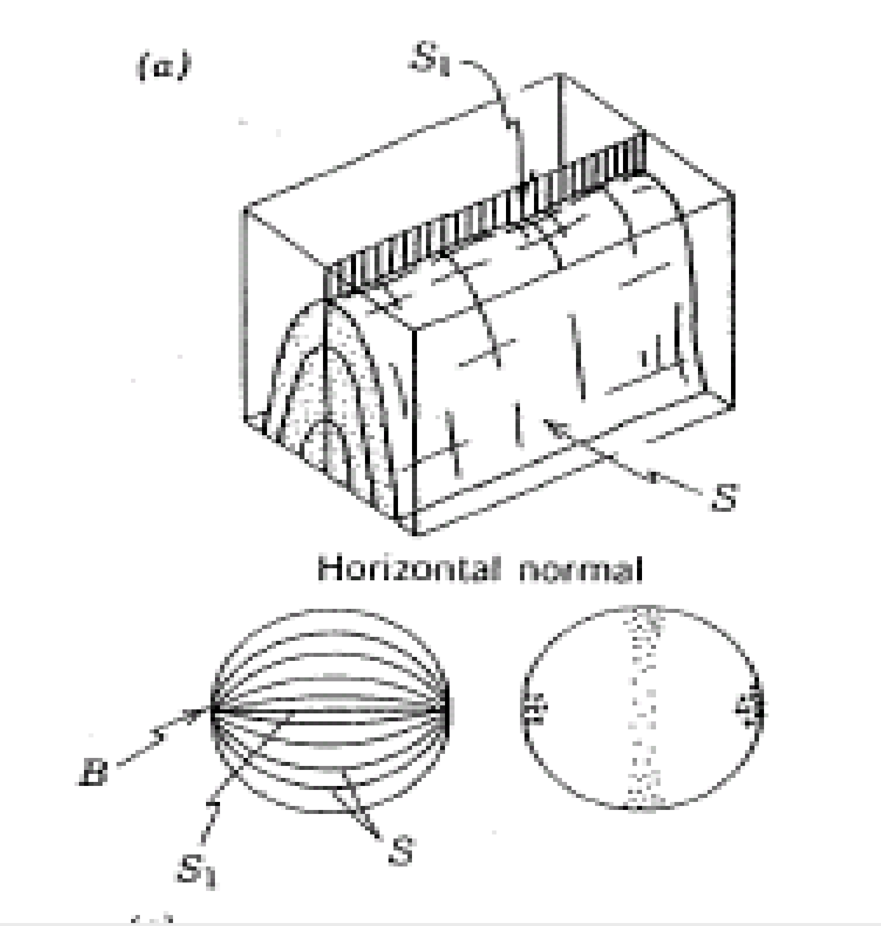
Fold Geometry – Horizontal Normal



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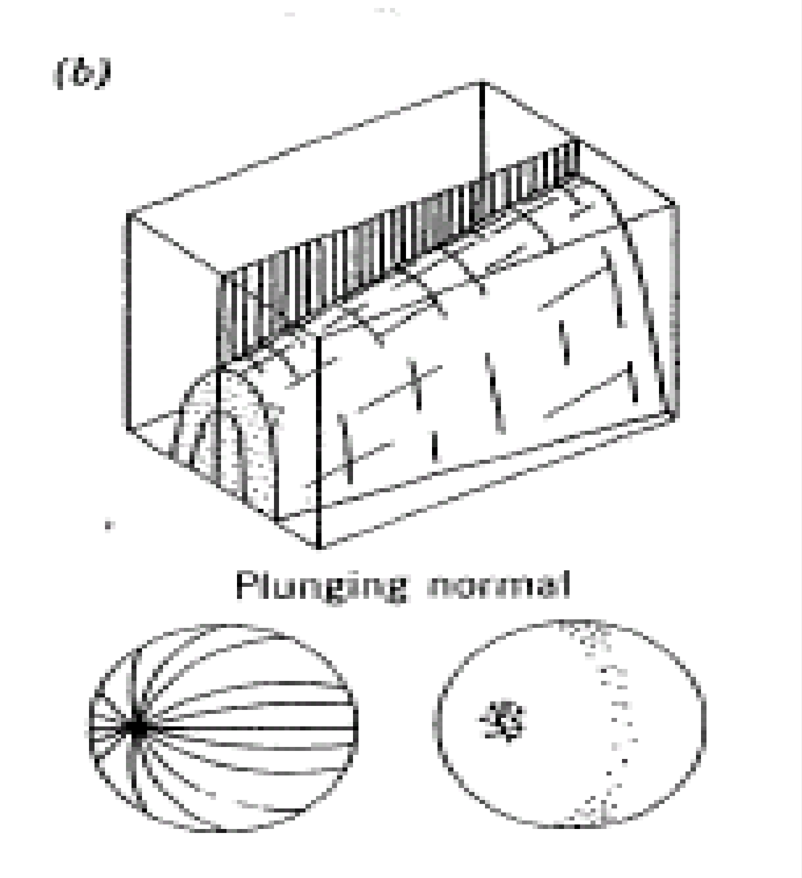
Fold Geometry – Plunging Normal



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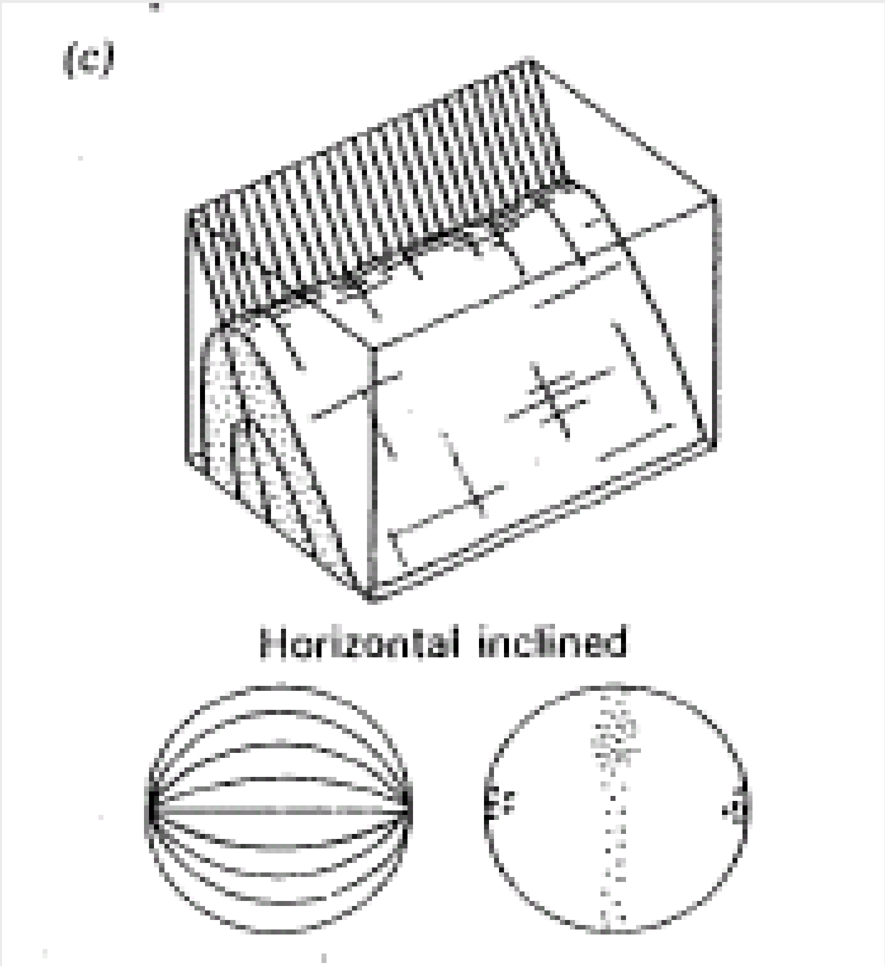
Fold Geometry – Horizontal Inclined



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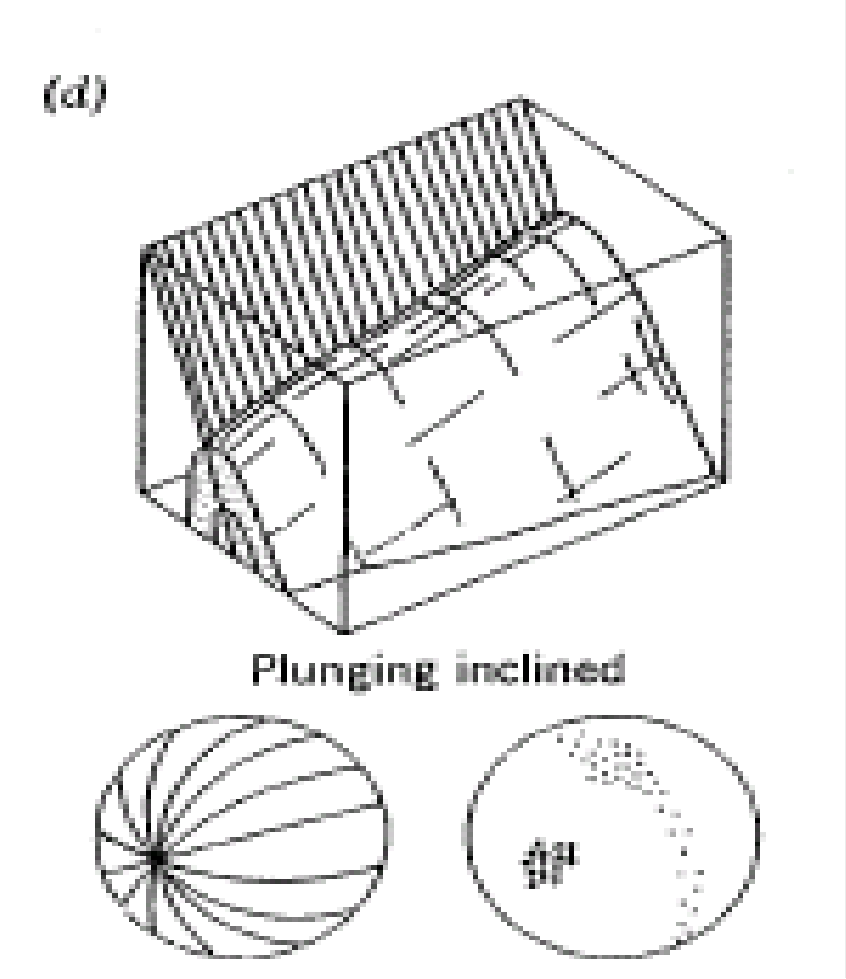
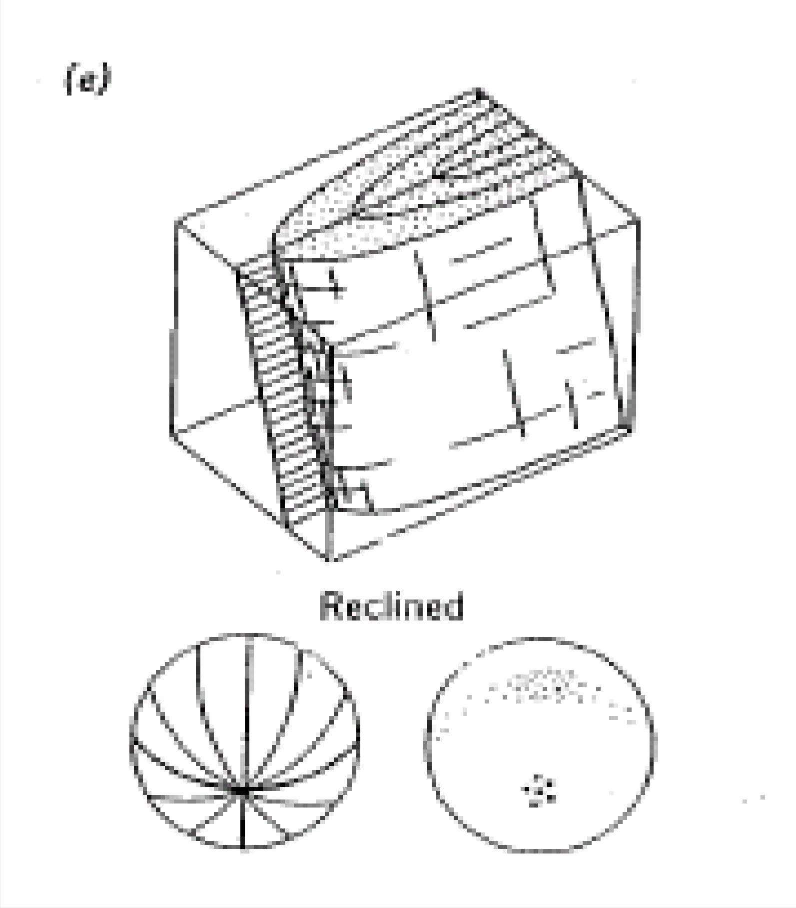
Fold Geometry – Plunging Inclined



Fold Geometry – Reclined



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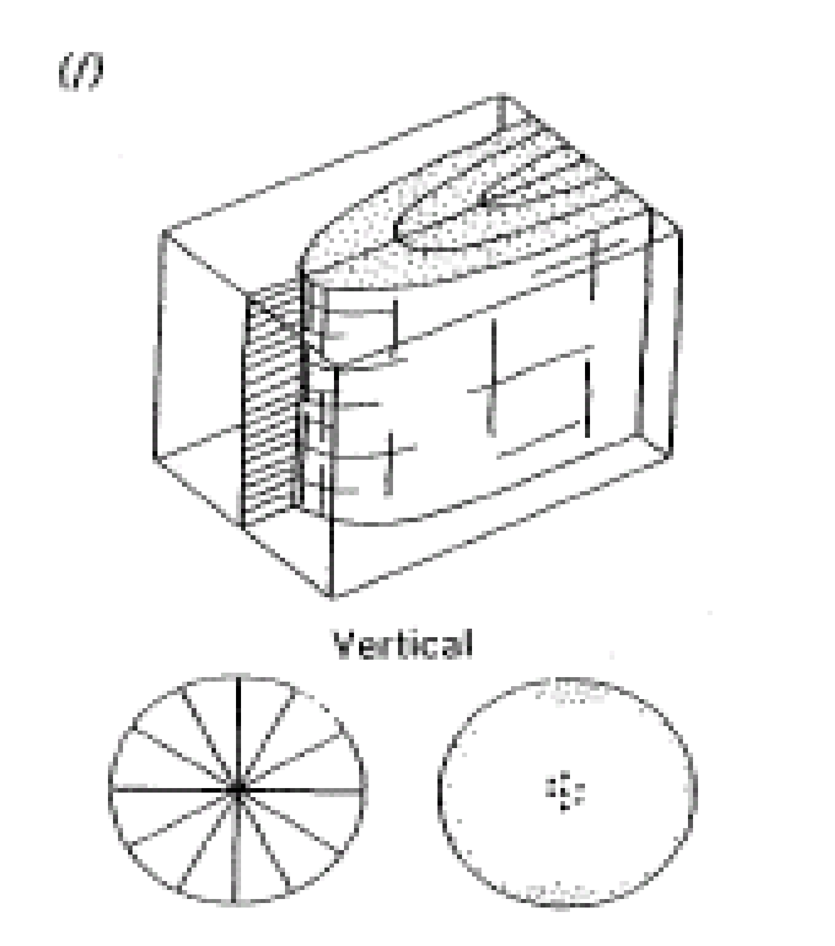
Fold Geometry – Vertical



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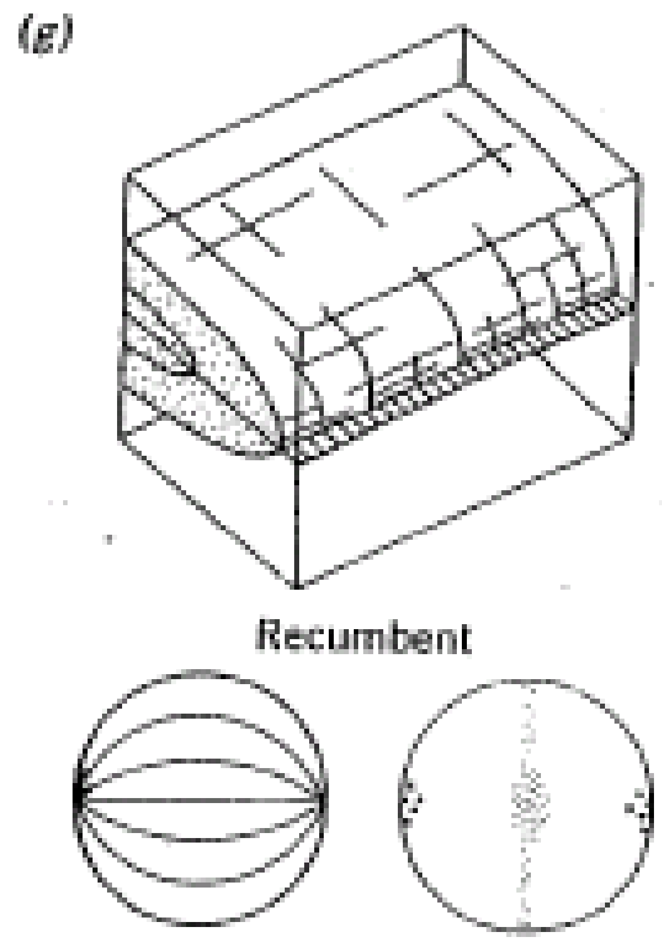
Fold Geometry – Recumbent



Foliation

During deformation of a rock mass, pressure and temperature effects can result in the separation of different minerals into bands based upon their individual ductility. This banding is referred to as *Foliation*.

Slaty Cleavage occurs in fine-grained rocks as a fissility allowing the rock to be split into thin planar slabs due to the preferred orientation of inequant grains (often silicates).

Schistosity varies somewhat but typically refers to the alignment of silicates in a preferred orientation visible to the eye. This is particularly noticeable in coarse grained rocks such as schist or gneiss.

In an engineering sense *foliation* will typically form a pre-existing low strength orientation, and in the case of landsliding may form a preferential plane of failure.

Schistosity - Schist

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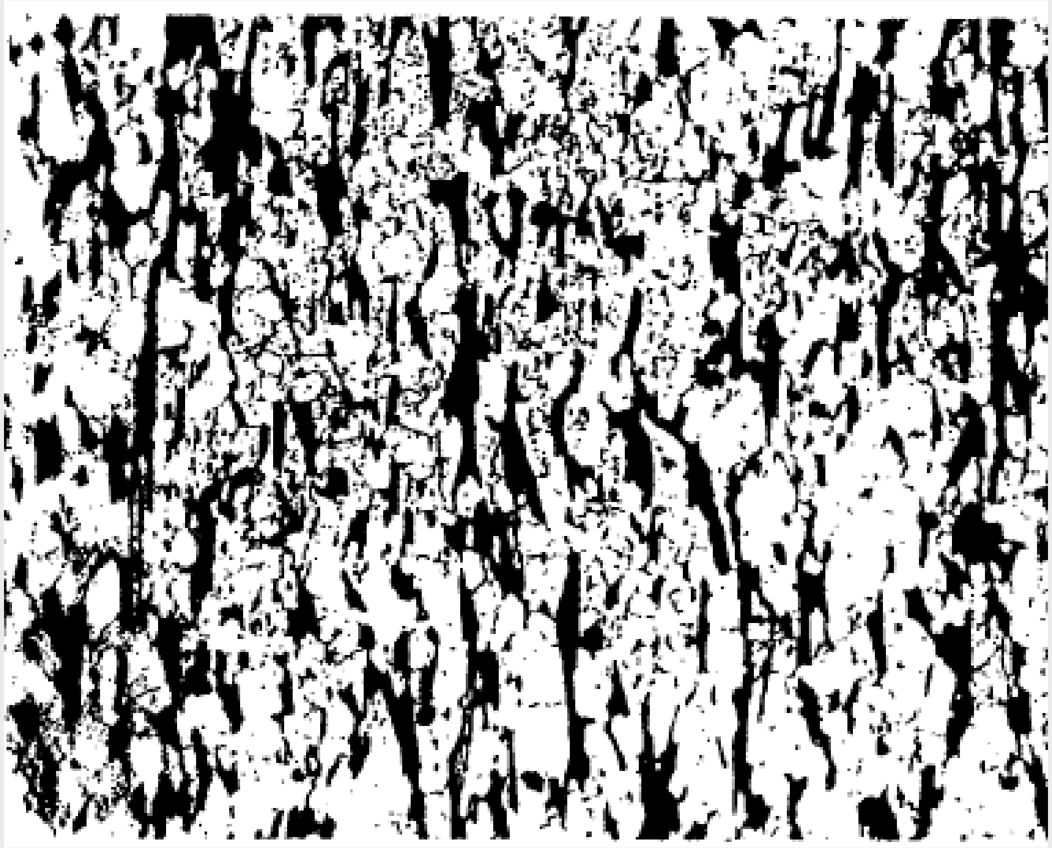
Schistosity - Gneiss



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Joints

Joints are perhaps the most common structures exposed in a rock face. They are the result of brittle behavior of rock and are defined as fractures along which no appreciable displacement has occurred. Joints generally occur in parallel or sub-parallel *joint sets*. Joints of several sets commonly occur together and the resulting geometric pattern is known as a *joint system*.

Typically the characteristics of a joint set, such as length, spacing and orientation, vary to some degree across contacts between rocks of different lithology; in some cases one rock type may be jointed and the other has no joints. Joints which form regular, planar, sub-parallel sets are known as *systematic* whereas curved, conchoidal, discrete and non-parallel are *non-systematic* joints. It is common to find both types developed together in a rock mass. In terms of engineering significance the systematic joints are the most important; however, sometimes non-systematic joints form irregular links between systematic joints which can have implications in the development of rupture surfaces in hard rock slope failures.

Joints - Origin

Joints are probably the least well understood of any structures – the reasons for their formation and origin are often very obscure. In certain environments they form as a result of material contraction; for example, *columnar joints* during cooling of basalt. However, joints which form large scale – sometimes regionally consistent patterns – are of the most interest in engineering. The regularity of these joint systems implies they must have formed under stress states which showed some consistency both in orientations and magnitudes of the principal stresses, probably related to regional tectonic stresses. The major implication of this theory is that once the regional tectonic setting and stresses are understood, the expected principal joint directions should be predictable.

Joints - Origin

Joints systems in igneous rock bodies may be quite different from joint systems in the surrounding rocks. They are often symmetrically related to the contacts of the body suggesting an origin during emplacement and cooling. One prominent joint set is also commonly seen at a high angle to the nearest contact – columnar jointing in flows, dykes and sills is an example of this.

Faults and Shears

Faults are fracture discontinuities within a rock mass along which significant differential displacement has occurred, typically evidenced by displaced lithological layers.

- A *fault* is a planar discontinuity between blocks of rock that have been displaced past one another, in a direction parallel to the discontinuity.
- A *fault zone* is a tabular region containing many parallel or anastomosing faults.
- A *shear zone* is a zone across which blocks of rock have been displaced in a fault like manner, but without development of visible faults.

Essentially a shear zone is a localized zone of ductile deformation whereas a fault zone is a localized zone of brittle deformation.

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Faults – Terminology

- *Hanging Wall*: That part of the rock mass directly above any non-vertical fault plane
- *Footwall*: That part of a rock mass directly below any non-vertical fault plane.
- *Net slip*: The displacement vector joining originally contiguous points in the hanging wall and footwall.
- *Dip slip*: Component of the net slip parallel to the dip of the fault plane.
- *Strike slip*: Component of the net slip parallel to the strike of the fault plane.
- *Throw*: vertical component of the dip separation,
- *Heave*: horizontal component of the dip separation.

Normal Faults

These are inclined faults with a typical dip exceeding 50° where the dip-slip component of movement is considerably larger than the strike-slip component and where the *footwall* is moved downwards relative to the *hanging wall*.

Normal faults often occur in conjugate systems and the overall geometric features of the conjugate movements on faults inclined towards or away from each other lead to the sinking of a trough or *Graben* and the relative uplift of a linear elevated block or *Horst*. Horst and graben structures are typical of extensional environments within the Earths crust such as rift valleys.

Reverse Faults

These are inclined faults with inclinations typically less than 45°, with a zero or small strike slip component and with a dip slip component, that elevates the footwall with respect to the hanging wall.

Low angle reverse faults are referred to as *thrusts* or *thrust faults*, and are particularly abundant in the upper levels of the of the external parts of compressional orogenic zones as the first formed major tectonic structures.

Conjugate sets of thrust faults or *back thrusts* often appear at the same time or at a late stage of the tectonic evolution of the main reversed fault structure.

Thrust faults often show variation in dip as they pass from one lithology to another. *Ramps* climb more steeply across lithological layers and typically occur in the more competent beds, while *flats* lie close to the planar lithology of more incompetent layers.

Strike Slip Faults

Strike slip faults are usually steeply orientated, often vertical with differential displacement between the walls that is predominantly horizontal. The movements on a strike slip fault are either *sinistral* (left hand) or *dextral* (right hand) depending on the relative movement of the wall opposite to that of the observer.

Strike slip faults are occasionally referred to as *wrench*, *tear*, *lateral* or *transcurrent* faults.

Although strike slip faults are generally found in sub-parallel sets, a conjugate set is sometimes developed at an angle of 60° to the initial set. These are referred to as either right hand or left hand en-echelon patterns, depending on whether the adjacent faults show a right of left hand sense of strike shift.

Strike Slip Faults

Faults planes are often filled with fragmental material known as *fault breccia* or *microbreccia* if the fragments are microscopic. Some microbreccias are soft and may show significant clay development due to a combination of crushing weathering and alteration, this infill is known as *fault pug* or *gouge*. Other microbreccias (particularly in metamorphic rocks) are hard and characterized by platy or streaky "flow" structure in thin section, these are known as *mylonites*.

A diagnostic feature of many fault planes are the smoothed or polished surfaces of easy parting known as *slickensides*, these may be featureless but often display prominent parallel ribbing or *striations*. The striations are considered to be parallel to the direction of relative movement during their formation. Small steps orientated normal to the striations are often apparent, these may or may not indicate the direction of movement of the opposite block, but careful microscopic study of individual examples may reveal the sense of displacement.

Faults – Shear Zones

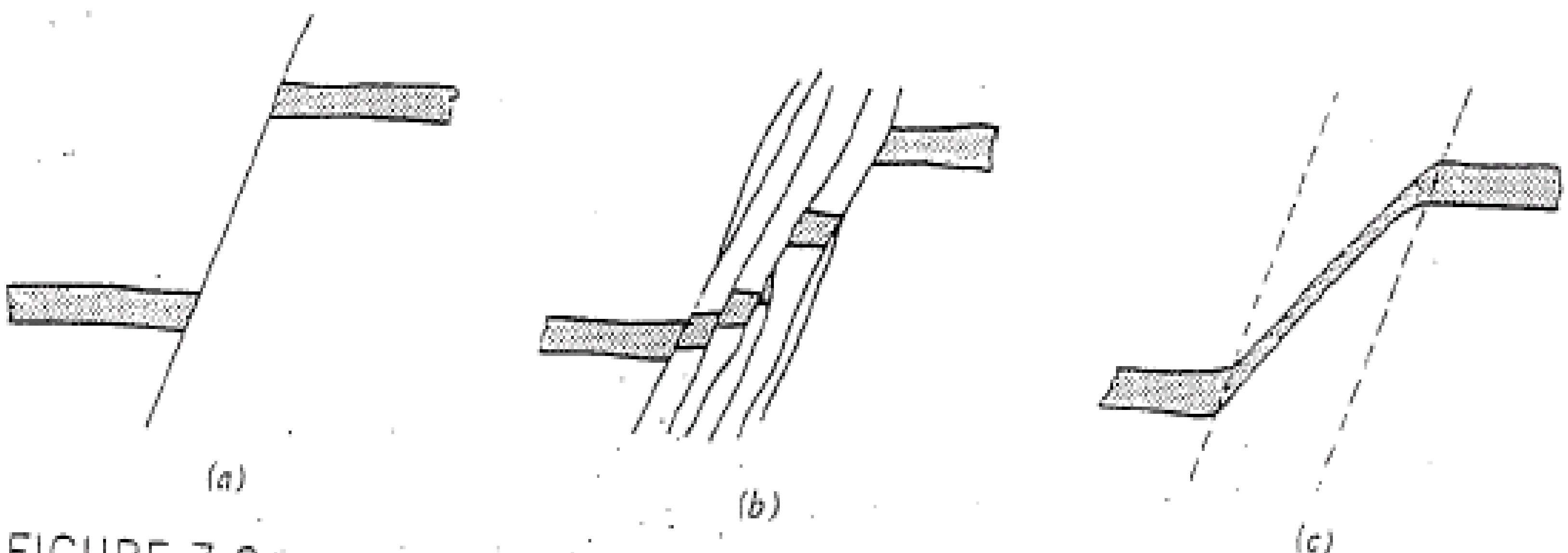
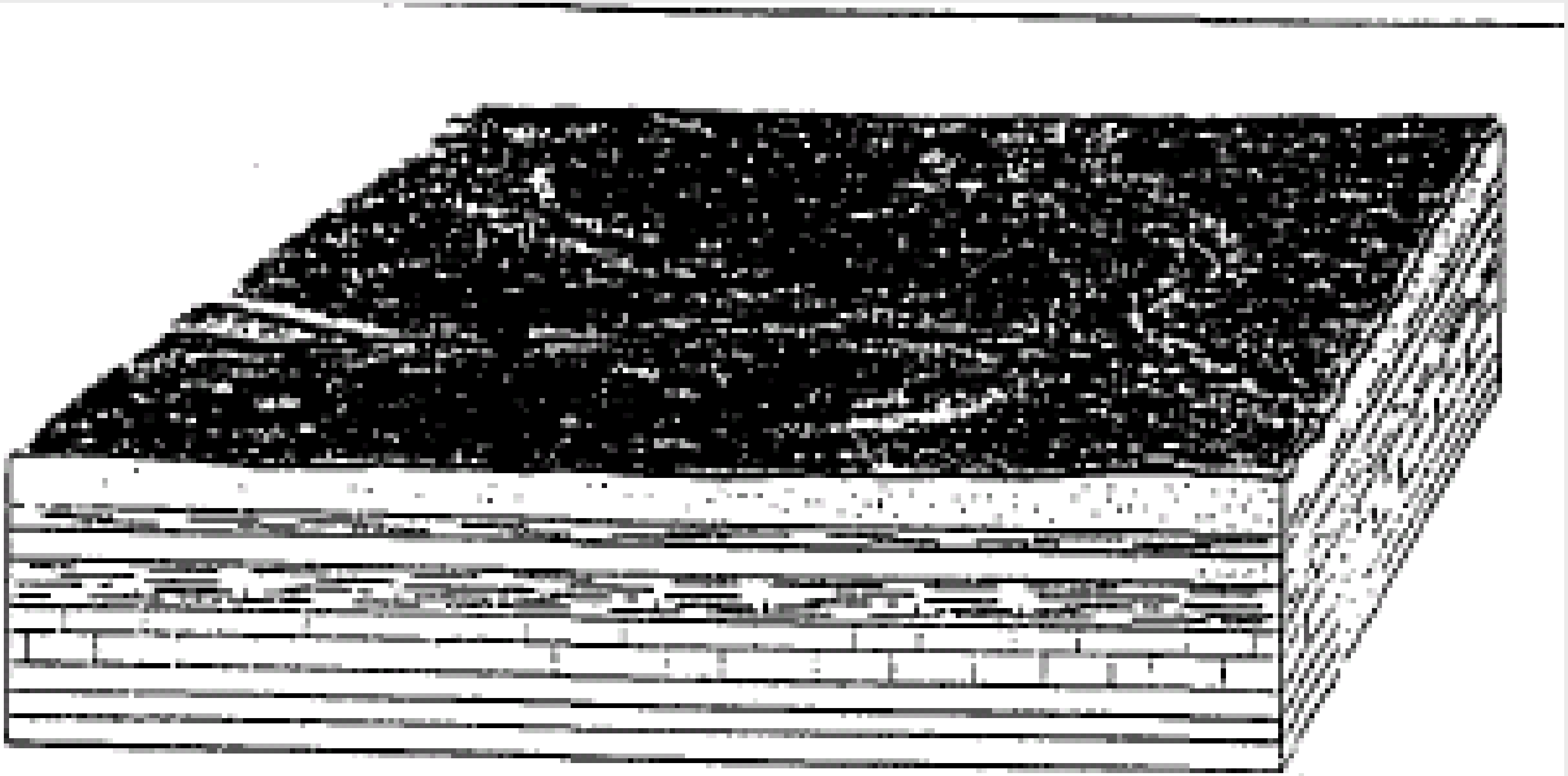


FIGURE 7.9 (a) Fault. (b) Fault zone. (c) Shear zone.

Faults – Undisturbed Block



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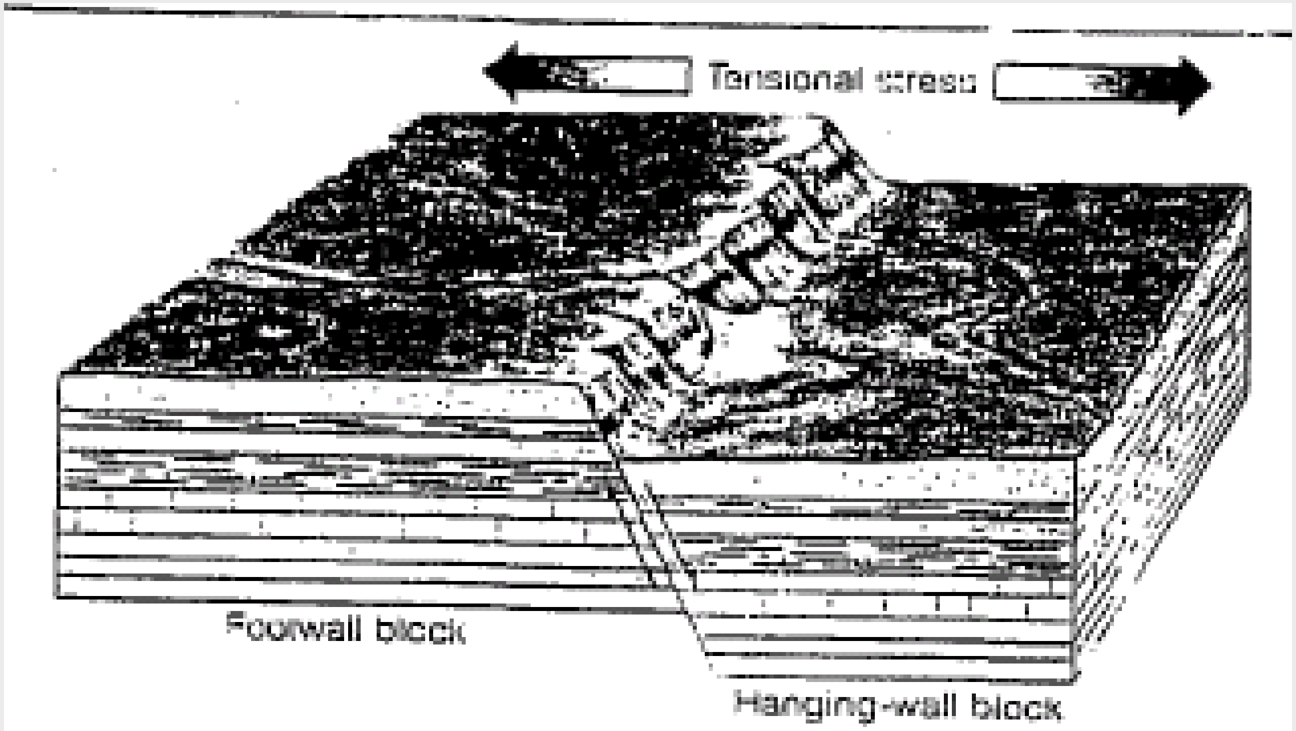
Faults – Normal



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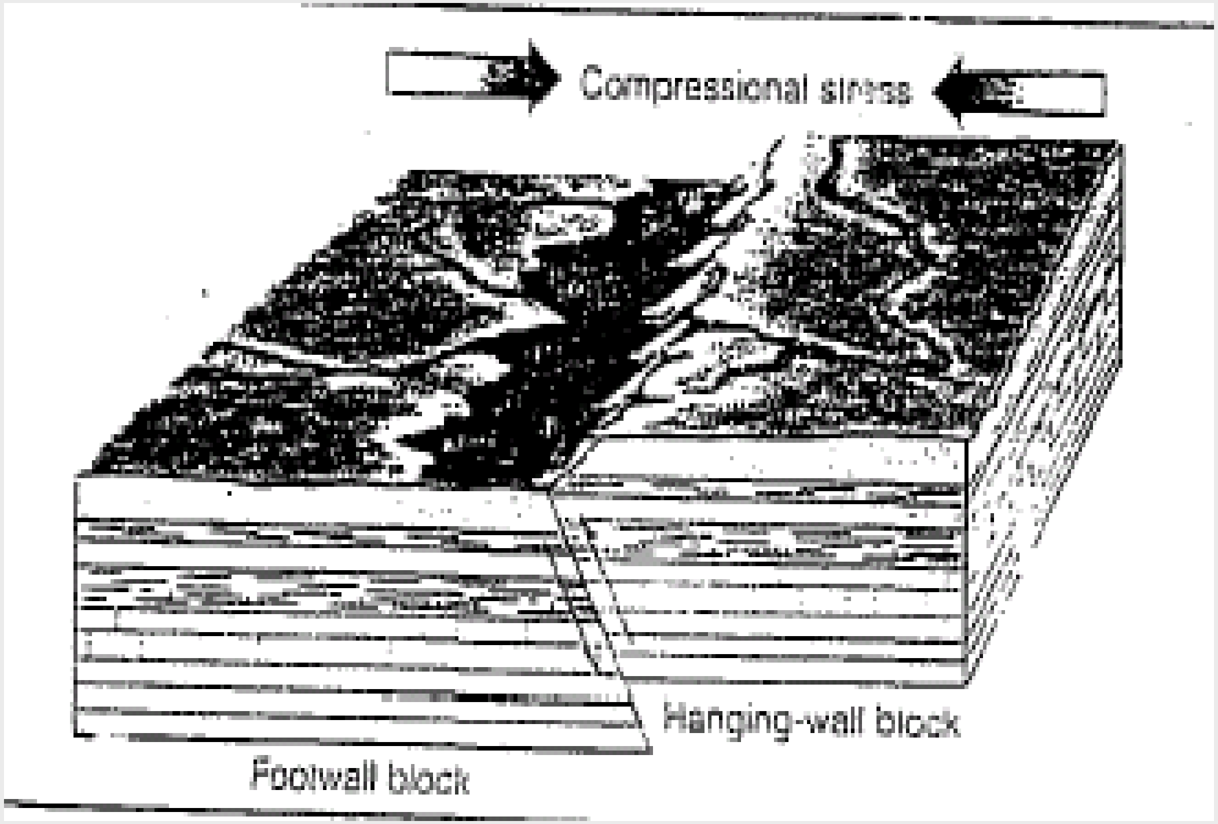
Faults – Reverse



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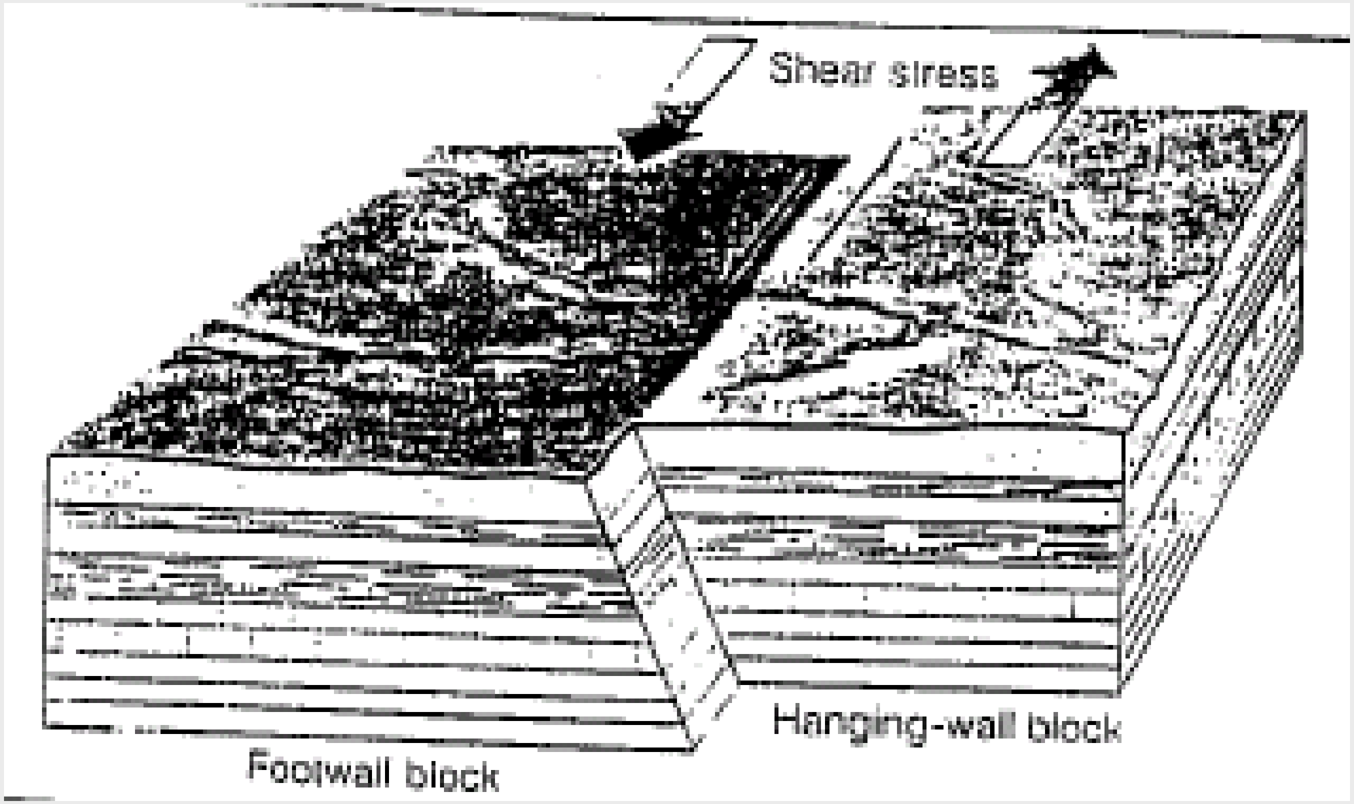
Faults – Strike Slip



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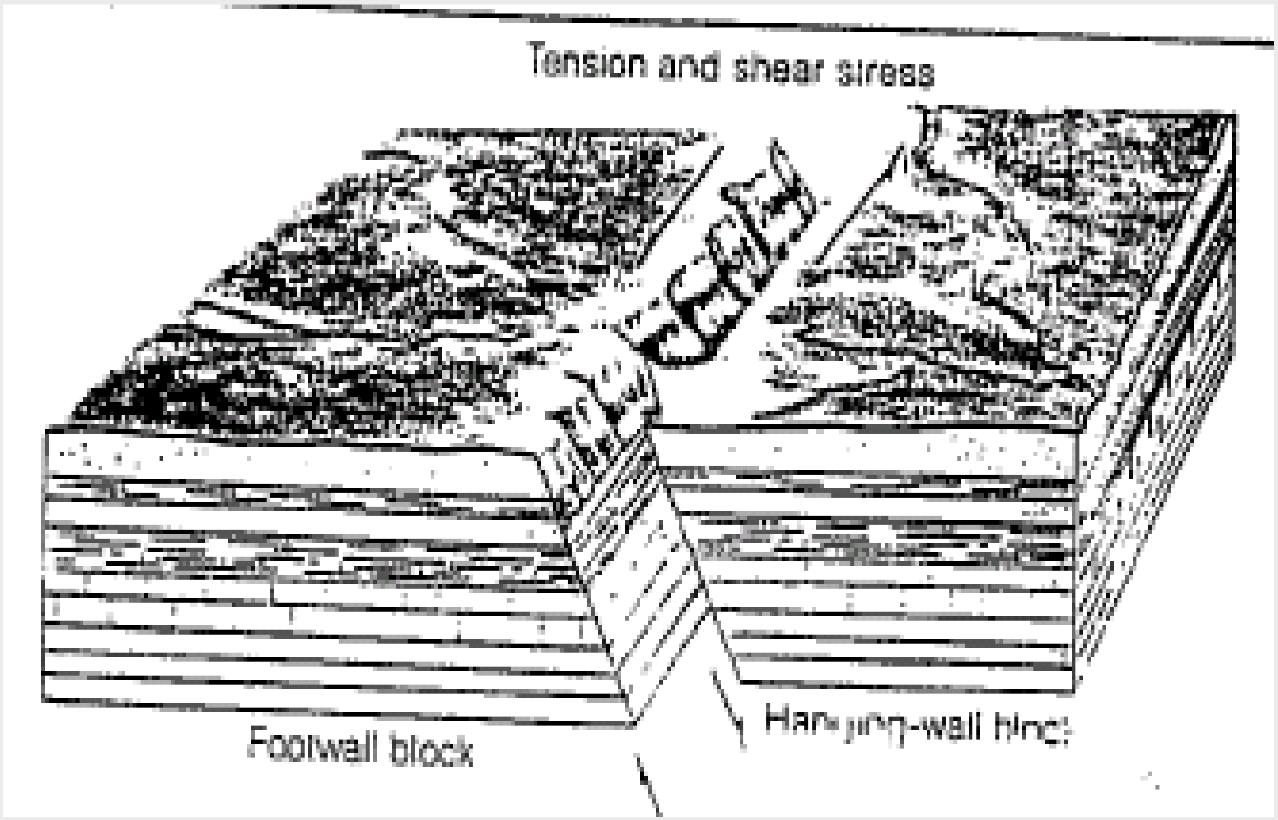
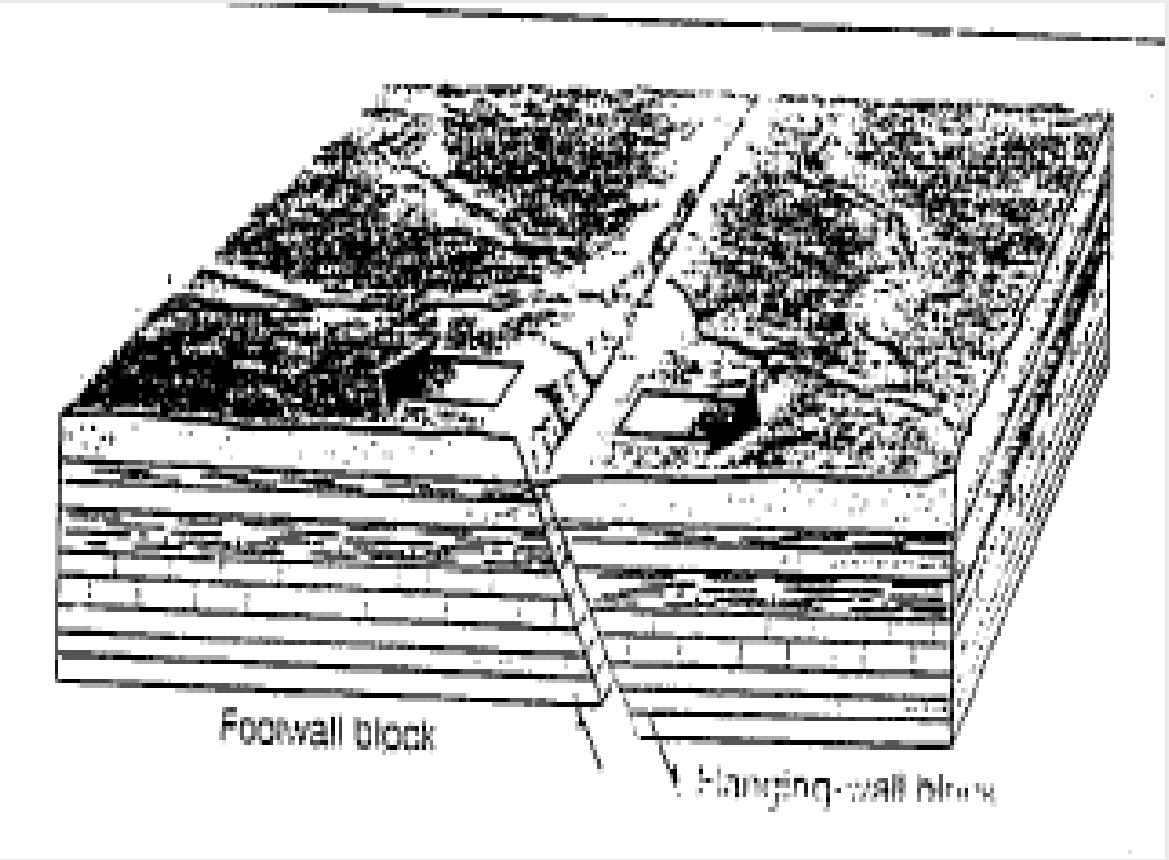
Faults – Oblique Slip



Faults – Hinge



Rock Mass Classifications

- Terzaghi
- Q
- RMR
- RMR Variations
- Sydney Sandstone Classification
- USE ALL WITH CAUTION

Sydney Opera House Car Park

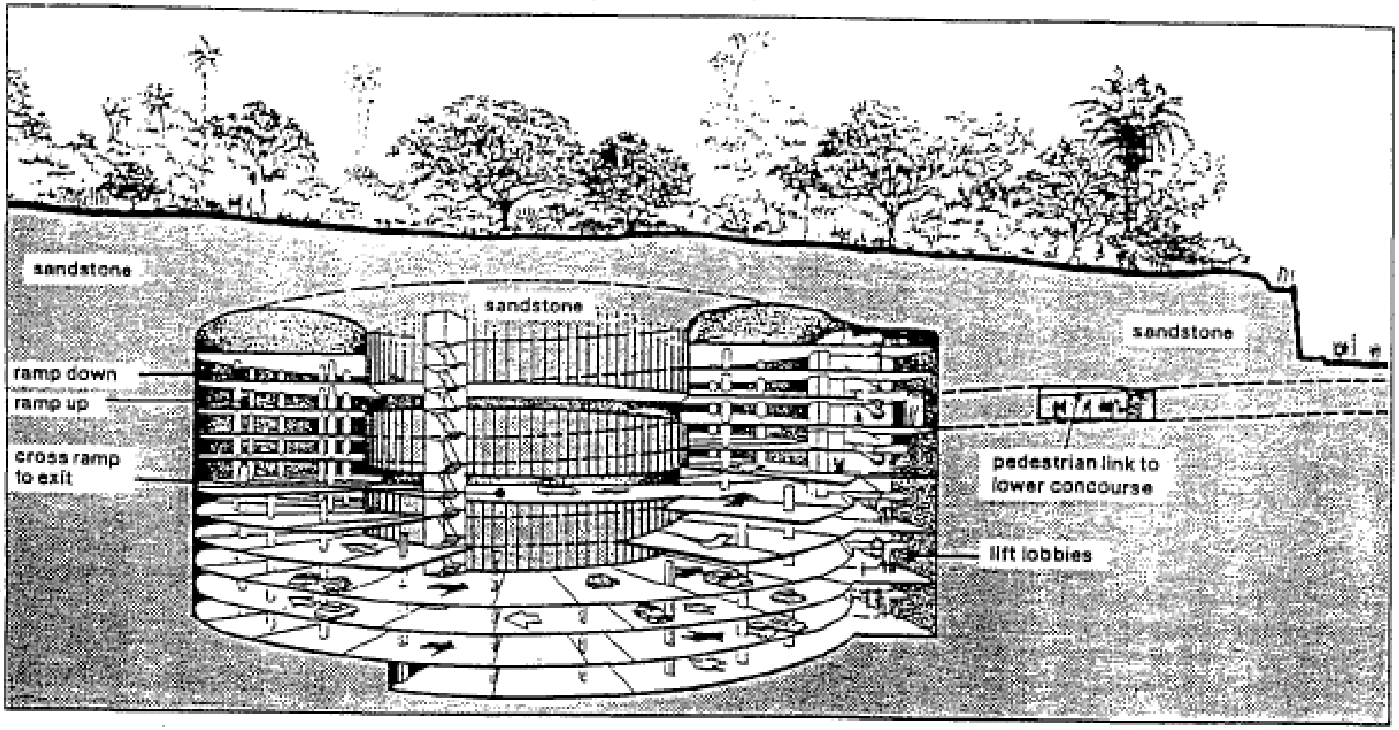


FIGURE 2 : THE SYDNEY OPERA HOUSE CAR PARK

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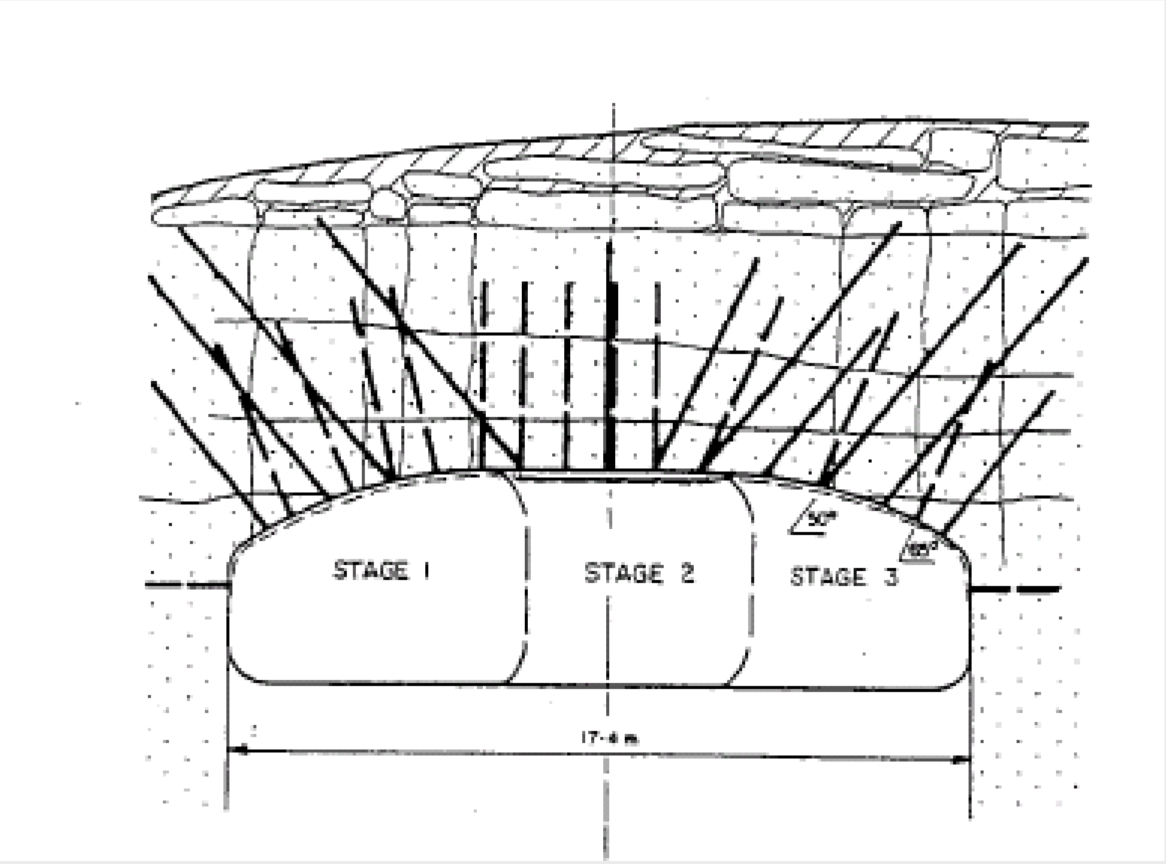
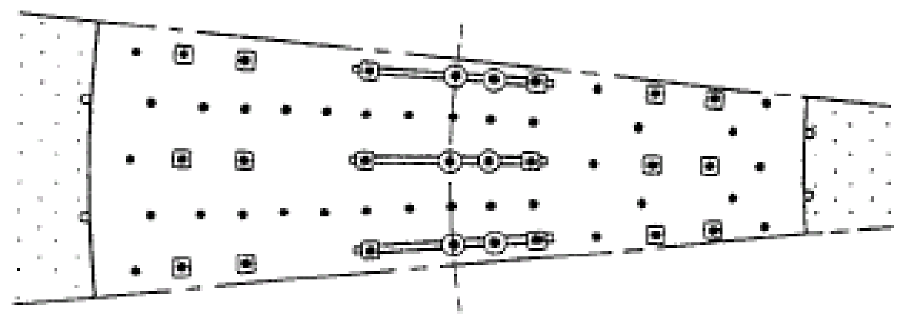
Sydney Opera House Car Park



Sydney Opera House Car Park



LEGEND

- MACALLOY BARS 7·5m
- MACALLOY BARS 5·5m
- 4·4 m Y24 DOWEL
- 2·0m Y24 DOWEL IN SIDEWALL
- 152 x 76 GALVANISED CHANNEL
- F41 MESH & 50mm SHOTCRETE

FIGURE 5 : ROOF SUPPORT FOR OPERA HOUSE CAVERN

Sydney Opera House Car Park

The design and construction of this cavern is described in detail in (Refs 12 and 13). The crown of the cavern comprised 6m to 8m of Class I and Class II sandstone, (using the Sydney System). This rock classified as:

Q- system	20 to 60;	design value = 50	(ESR = 0.8)
RMR-system	60 to 55;	design value = 65	

TABLE 6
CLASSIFICATION BASED SUPPORT DESIGN
FOR THE 18m SPAN OPERA HOUSE CAVERN

SYSTEM	RATING	PREDICTED PRIMARY SUPPORT
RMR*	65	3m bolts at 2.5m centres with occasional mesh and 50mm shotcrete where required.
Q	50	6m bolts at about 3m centres, no shotcrete.

*Recommendations only really apply for 10m span

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Sydney Opera House Car Park

The design comprised 3.6m (230 kN) and 7.5m (450 kN) dowels and stressed anchors at an average spacing of 1.3m, plus 100mm x 100mm x 4mm weldmesh and 150mm shotcrete.

Comparing this support with the predictions in Table 6 suggests that either the designers of the cavern were very conservative (which the author does not believe to be true) or predictions based only on the classification systems were dangerous.

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NGI Q System

CLASSIFICATION OF TYPICAL RANGE OF SYDNEY SANDSTONE USING NGI Q-SYSTEM

ITEM	PARAMETER	SANDSTONE CLASS ACCORDING TO SYDNEY SYSTEM				
		I	II	III	IV	V
1	RQD	90	80	65	25	5
2	J_n*	2	4	4	6	12
3	J_r	3	3	1.5	1	1
4	J_a	0.75	1.0	20.	3.0	6.0
5	J_w	0.8	0.8	0.8	0.66	0.66
6	SRF	2.5	2.5	1.0	5.0	7.5
Q-value		57.6	19.2	9.75	0.18	0.006
Description		Very Good	Good	Fair	Very Poor	Exceptionally Poor

*Practitioners in Sydney find this parameter difficult to assess.

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Hawkesbury Sandstone Bedding

Facies Bedding

This defines the major near horizontal bedding discontinuities which have a spacing of between 1m and 2.5m. These may be continuous for hundreds of metres and may be marked by continuous partings, clay seams or petrographic changes. Facies bedding marks major depositional horizons. Local increase in the dip of the Facies Bedding occurs where sand has been deposited in channel structures. Minor shale bands or shale breccias frequently occur in the base of these channel structures.

Clay seams typically between 5 and 25mm thick are very common within the sequence. The origin of these seams is not clearly understood but they provide the major weakness within the Hawkesbury Sandstone sequence.

Cross Bedding

Cross bedding (also termed current bedding) is almost an ubiquitous feature and forms the close layering (2mm to 20mm) observed within each major unit or facies. Cross bedding planes are often marked by the deposition of flakes of mica, graphite, and carbonaceous matter which settle as the current velocity decreased between influxes of sand. The cross bedding usually does not represent planes of weakness in fresh or slightly weathered sandstone. However, in moderate to highly weathered sandstone the cross beds can form surfaces of incipient parting or relatively low shear strength ($\phi' = 35°$).

Limestone

1. INTRODUCTION

Chemical and or biochemical sedimentary rocks originate by precipitation of minerals from water through various chemical or biochemical processes.

Distinguished from clastic sedimentary rocks by their chemistry, mineralogy and texture. May be divided into five basic groups:

1. Carbonates,
2. Evaporites,
3. Siliceous sedimentary rocks, eg Cherts,
4. Iron rich sedimentary rocks and
5. Phosphorites.

Carbonates are the most abundant rocks by far and the focus for this lecture. They comprise about 20% of all sedimentary rocks; although some sources quote 10%.

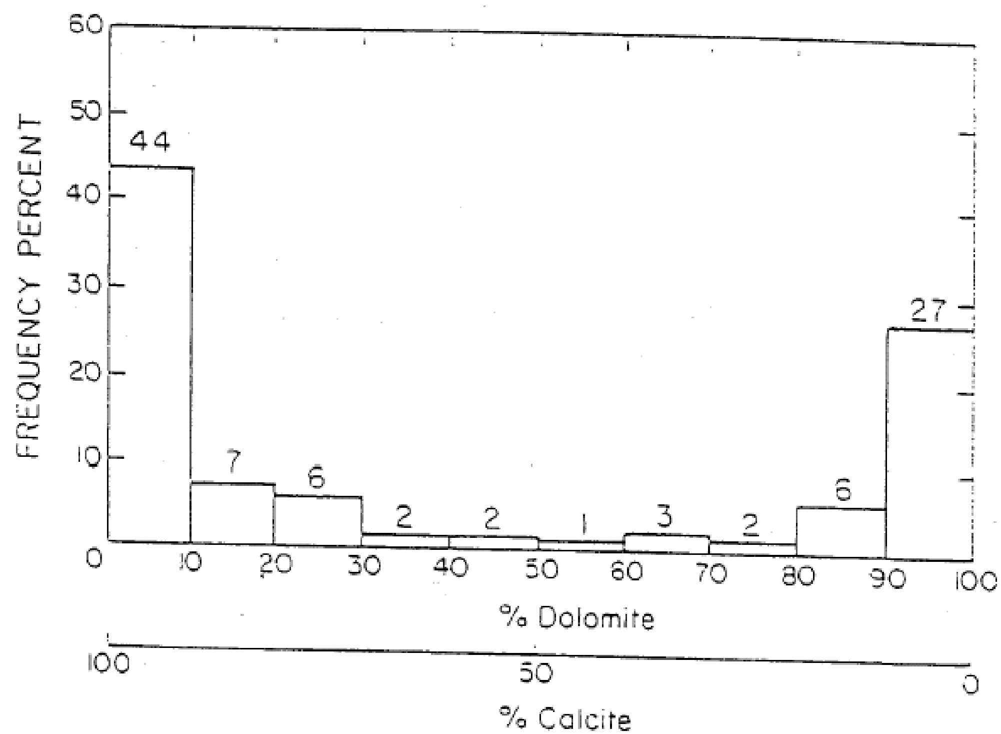
Evaporites are also covered because of their engineering significance.

Carbonate Rocks

Carbonates may be divided into limestones and Dolomites on the basis of mineralogy, with limestones mainly formed from calcite ($CaCO_3$) and Dolomites mainly formed from Dolomite ($CaMg(CO_3)_2$). Dolomites are more common in very old rocks. Paleozoic and Precambrian, while calcite dominates in younger Cenozoic and Mesozoic rocks.

Table 1 gives a classification system for carbonate rocks and Figure 1 shows the continuum between the two end members, although most samples are either limestone or dolomite Figure 2.

Carbonate Rocks



Computed percentages of calcite and dolomite for 1148 analyses of North American carbonate rocks. (Steidtmann, 1917)

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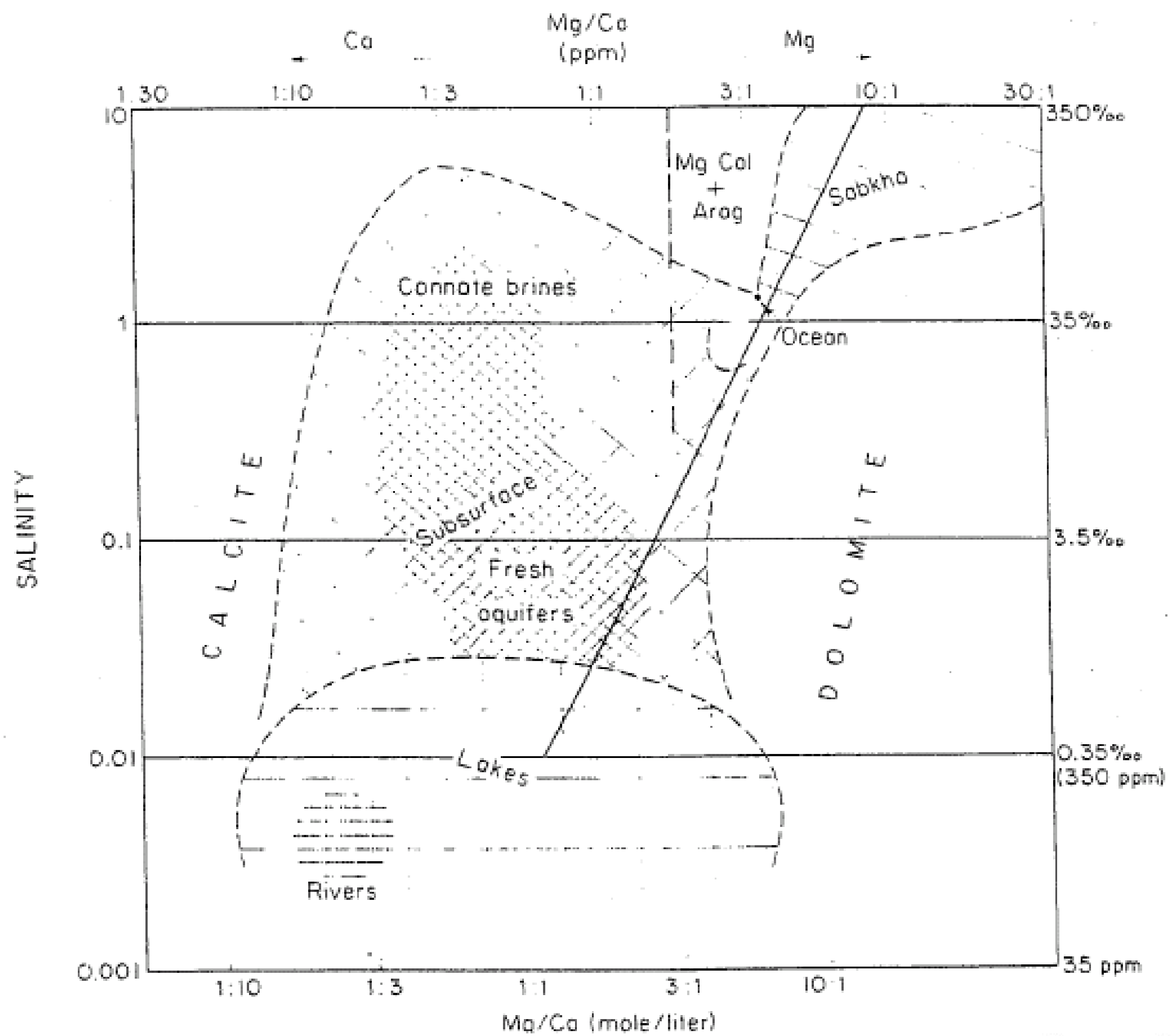
Carbonate Rocks



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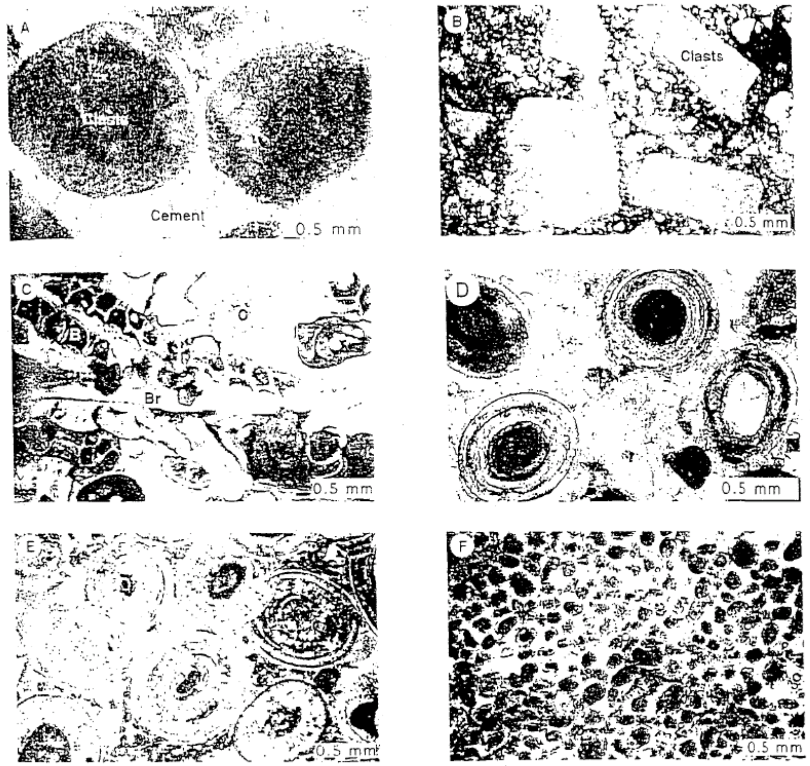
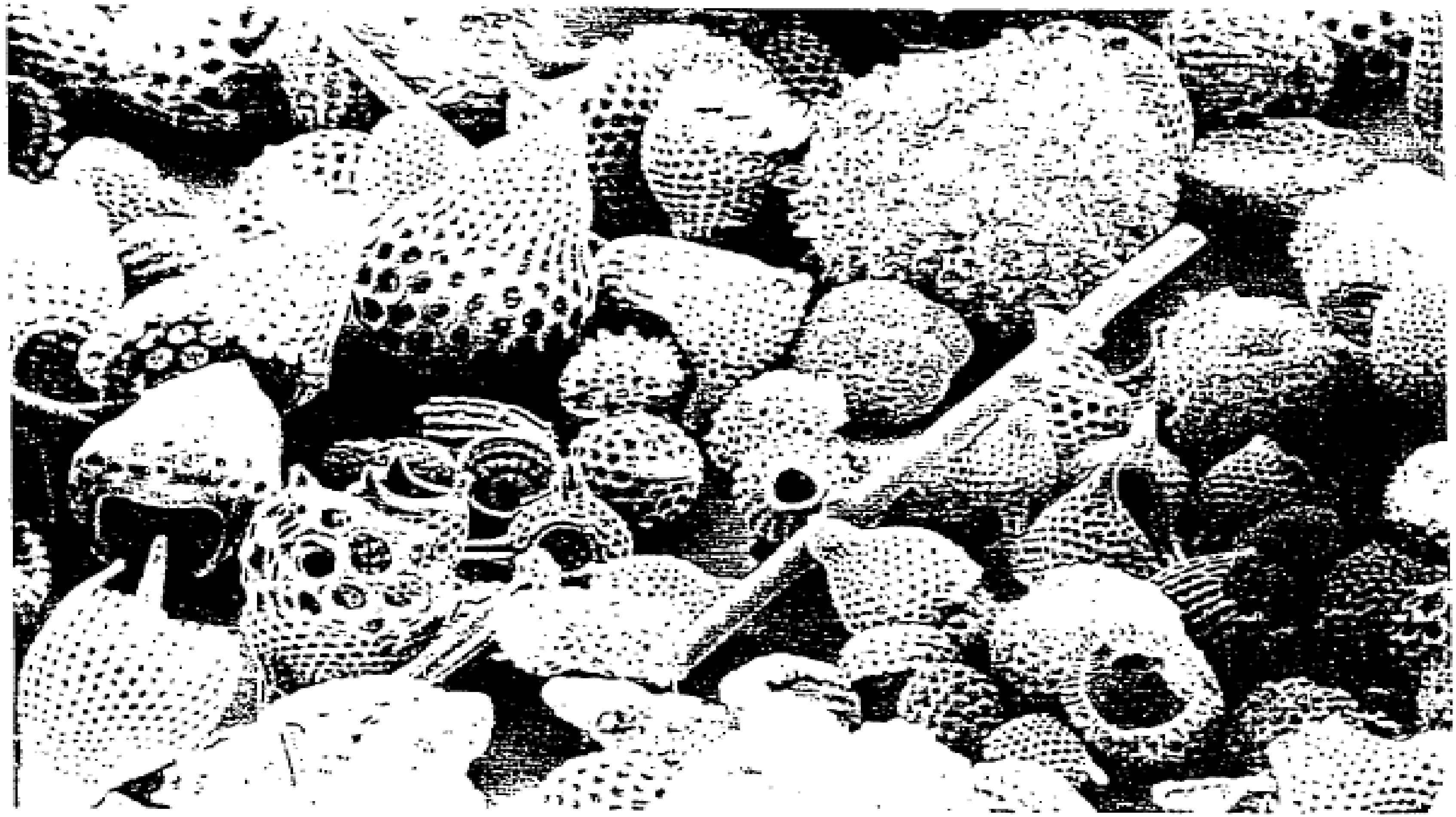
Carbonate Rocks



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), Miama 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.



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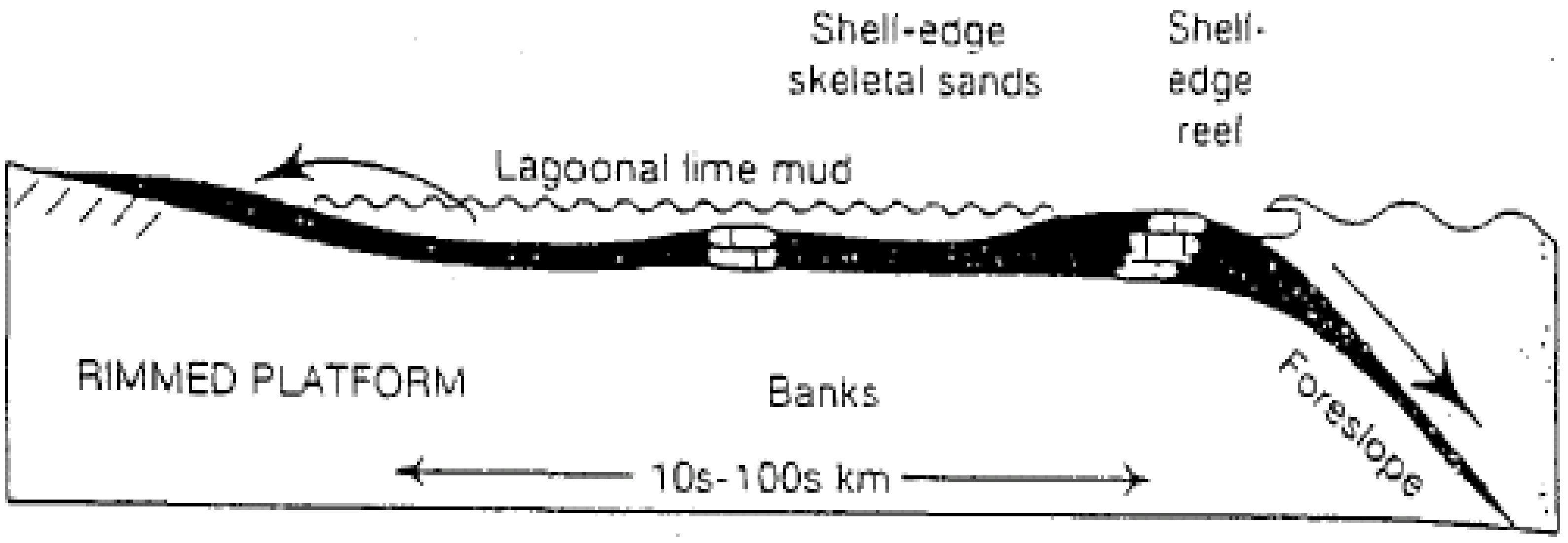
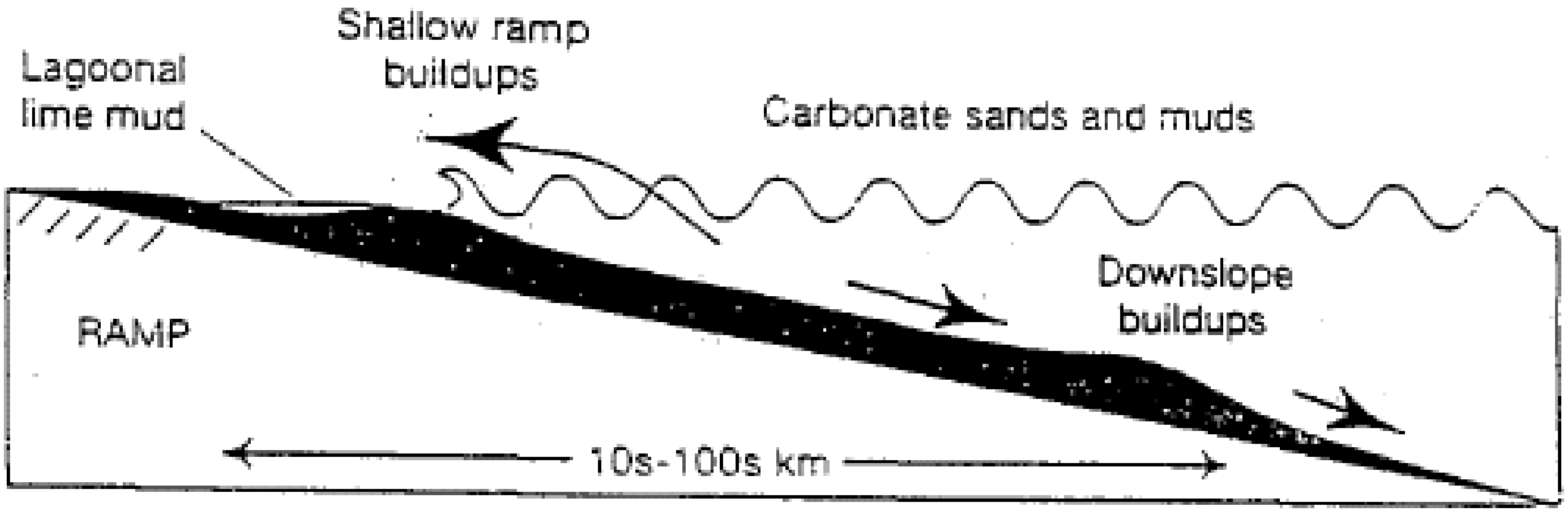
Carbonate Platforms - 1



Carbonate Platforms - 3



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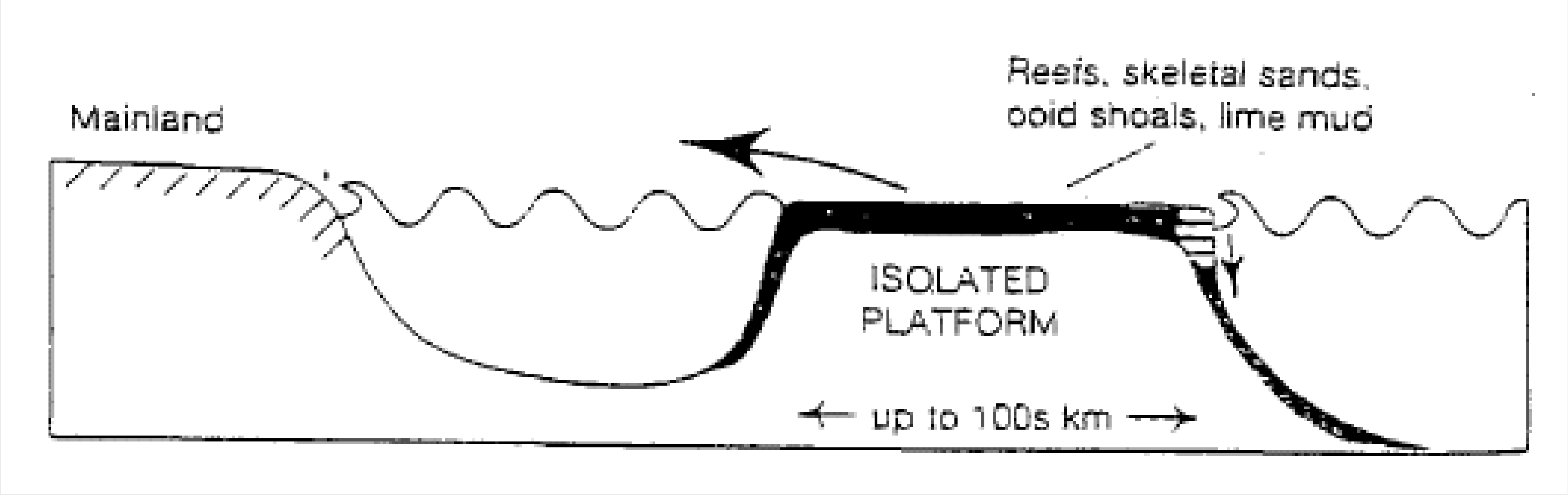
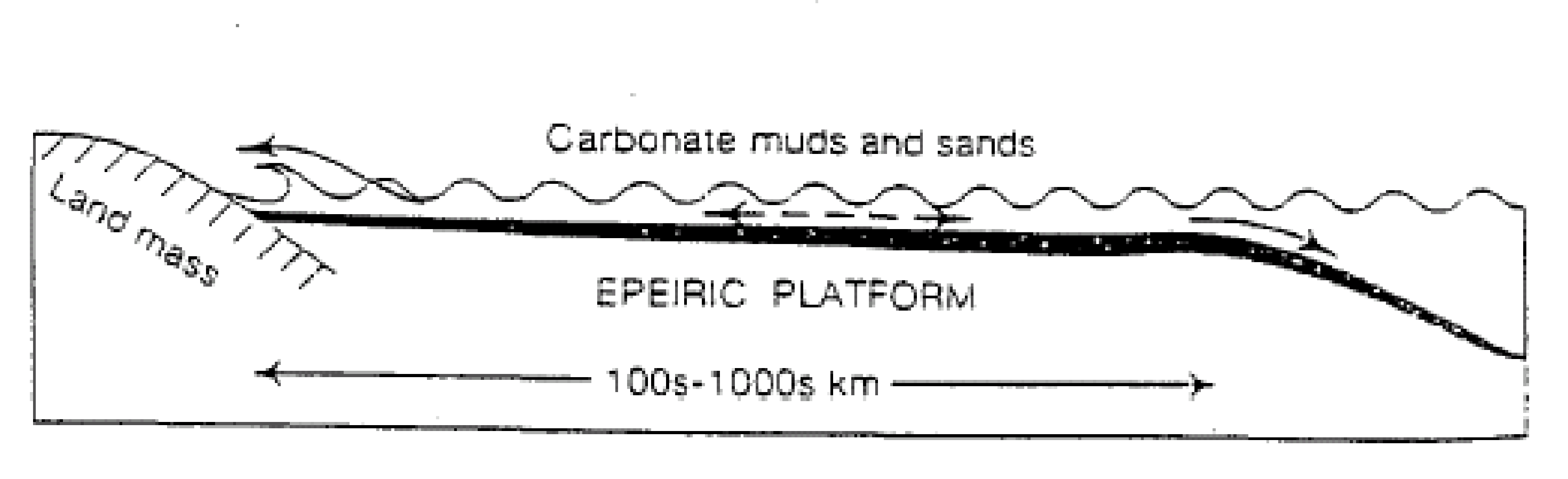
Carbonate Platforms - 4



Carbonate Platforms - 5



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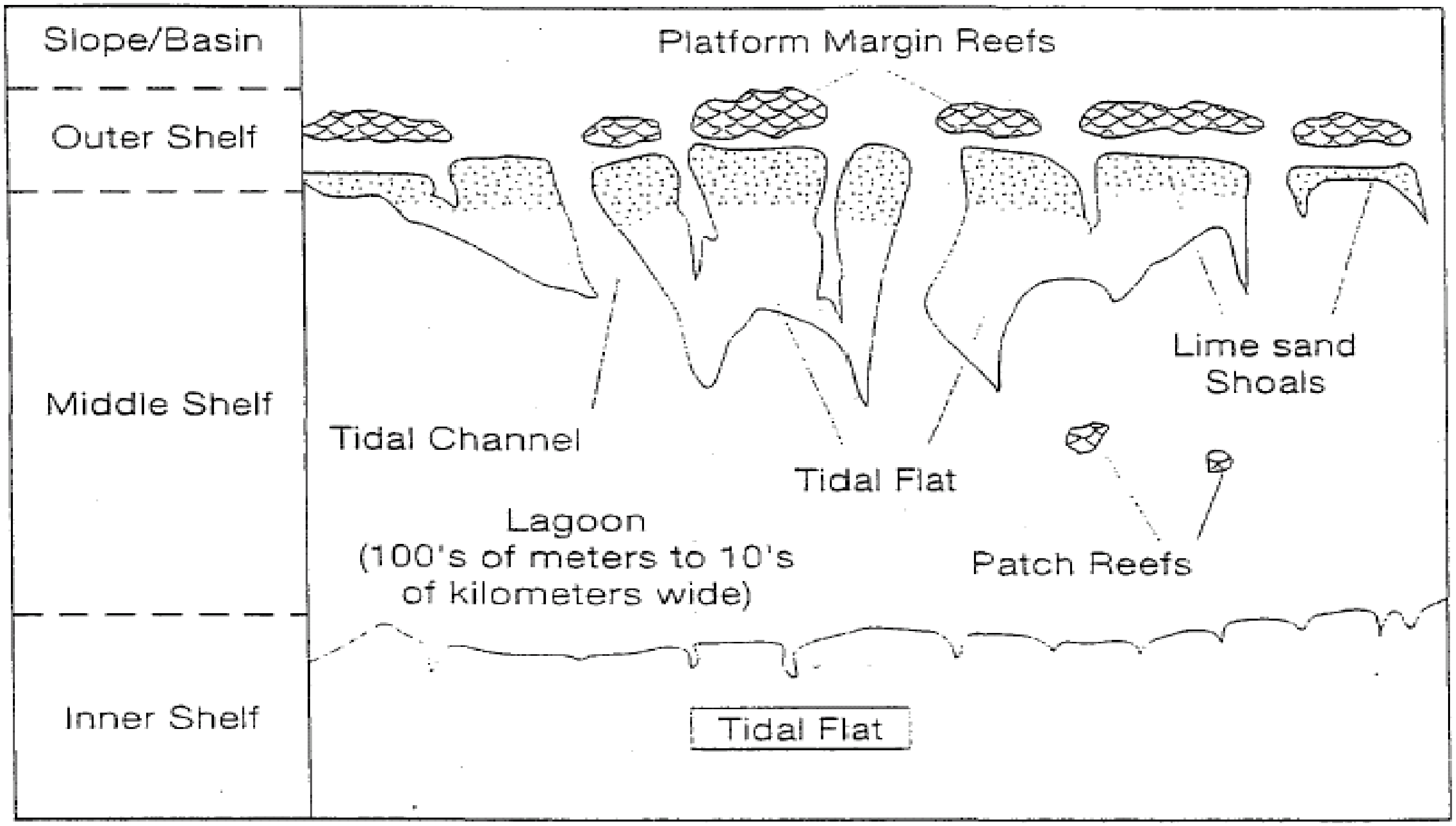
Carbonate Platforms - 6



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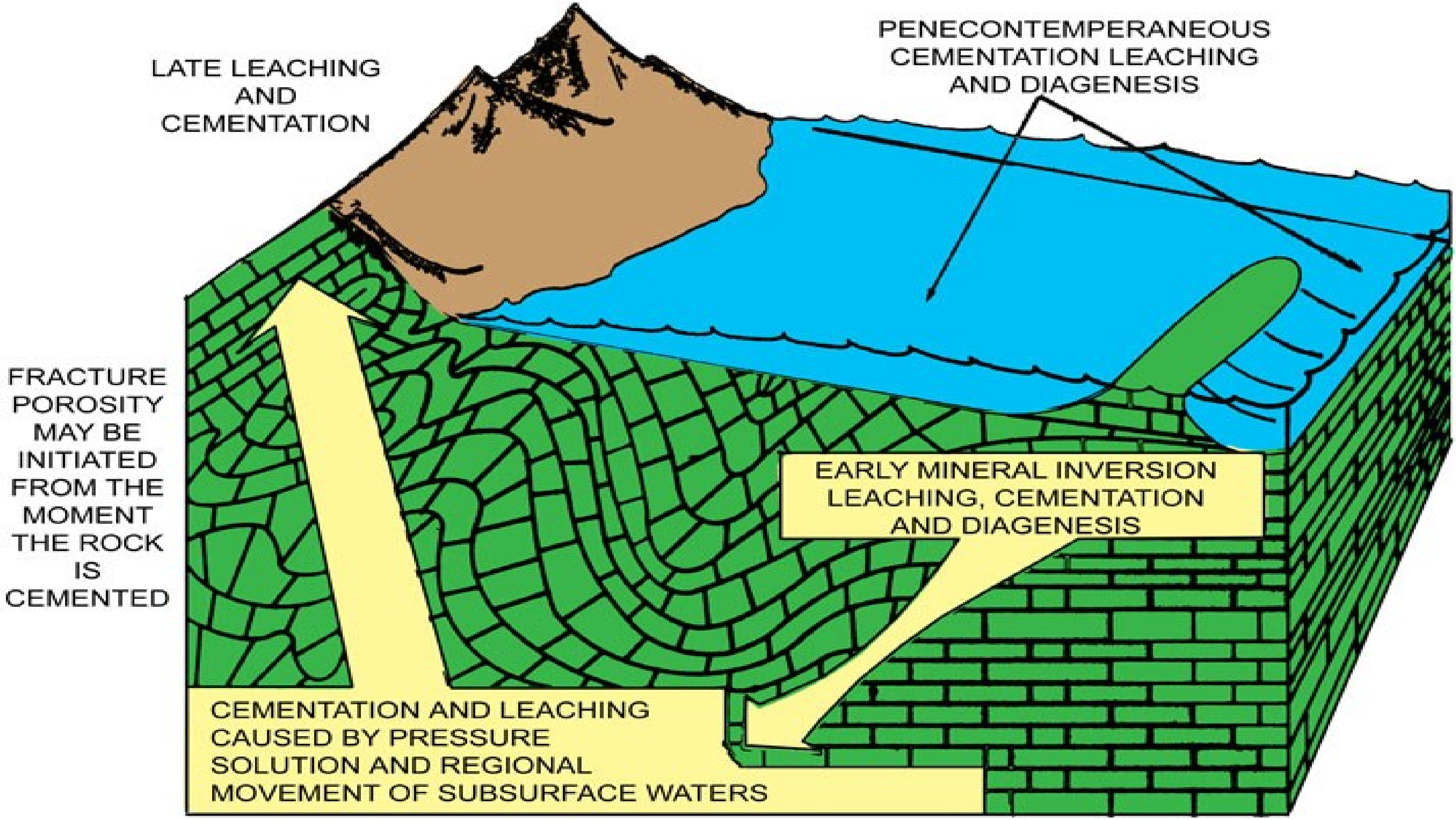

LATE LEACHING AND CEMENTATION
PENECONTEMPERANEOUS CEMENTATION LEACHING AND DIAGENESIS
FRACTURE POROSITY MAY BE INITIATED FROM THE MOMENT THE ROCK IS CEMENTED
EARLY MINERAL INVERSION LEACHING, CEMENTATION AND DIAGENESIS
CEMENTATION AND LEACHING CAUSED BY PRESSURE SOLUTION AND REGIONAL MOVEMENT OF SUBSURFACE WATERS

DURING LIMESTONE

DEPOSITION

BURIAL

AND SUBSEQUENT UPLIFT

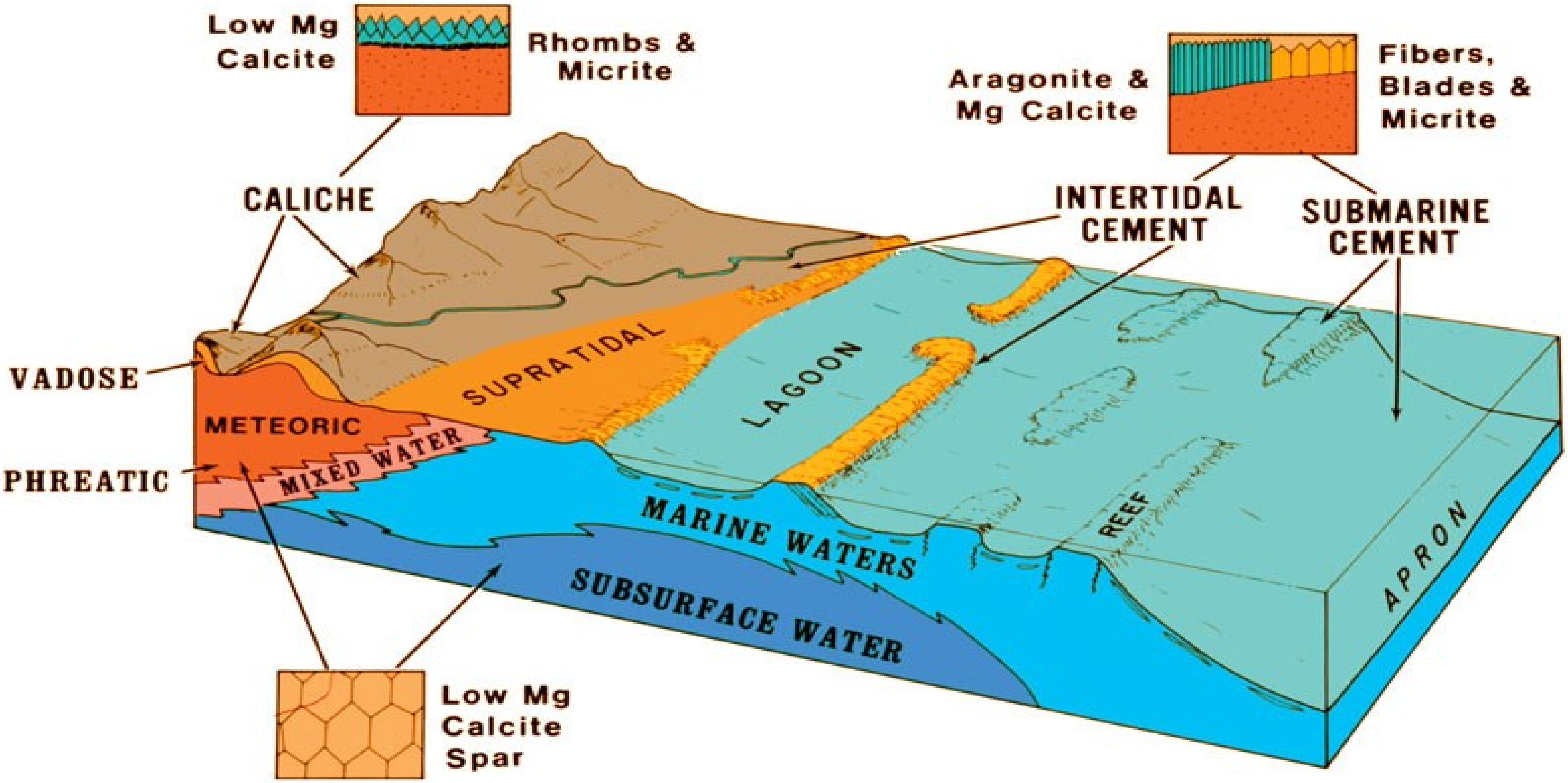
THEY UNDERGO

A. CEMENTATION

B. LEACHING

C. DIAGENESIS
- i) MINERAL ALTERATION
- ii) MINERAL INVERSION
- iii) NEOMORPHISM (RECRYSTALLIZATION GRAIN GROWTH)

Holocene Calcium Carbonate Cementation



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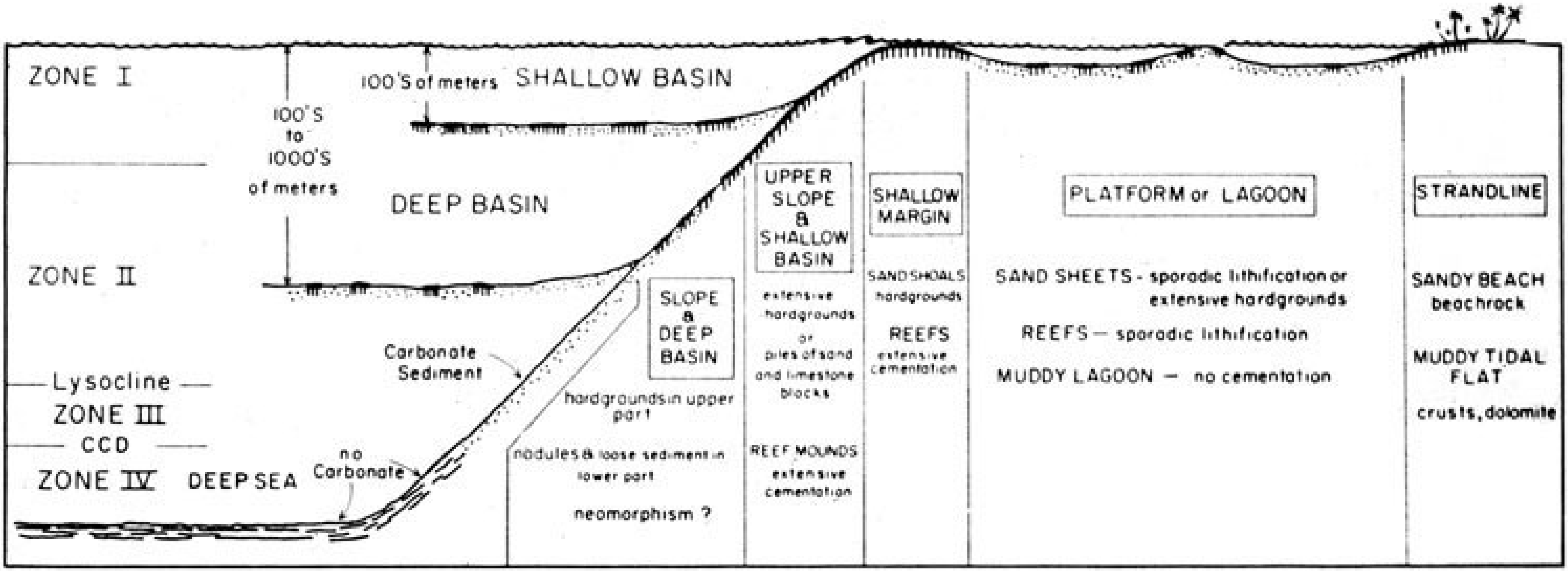


After James, 1984

Figure 5 *The locations of seafloor precipitation on a shallow, carbonate platform and in adjacent deep-water settings. In all of these habitats, most sediments are unlithified.*

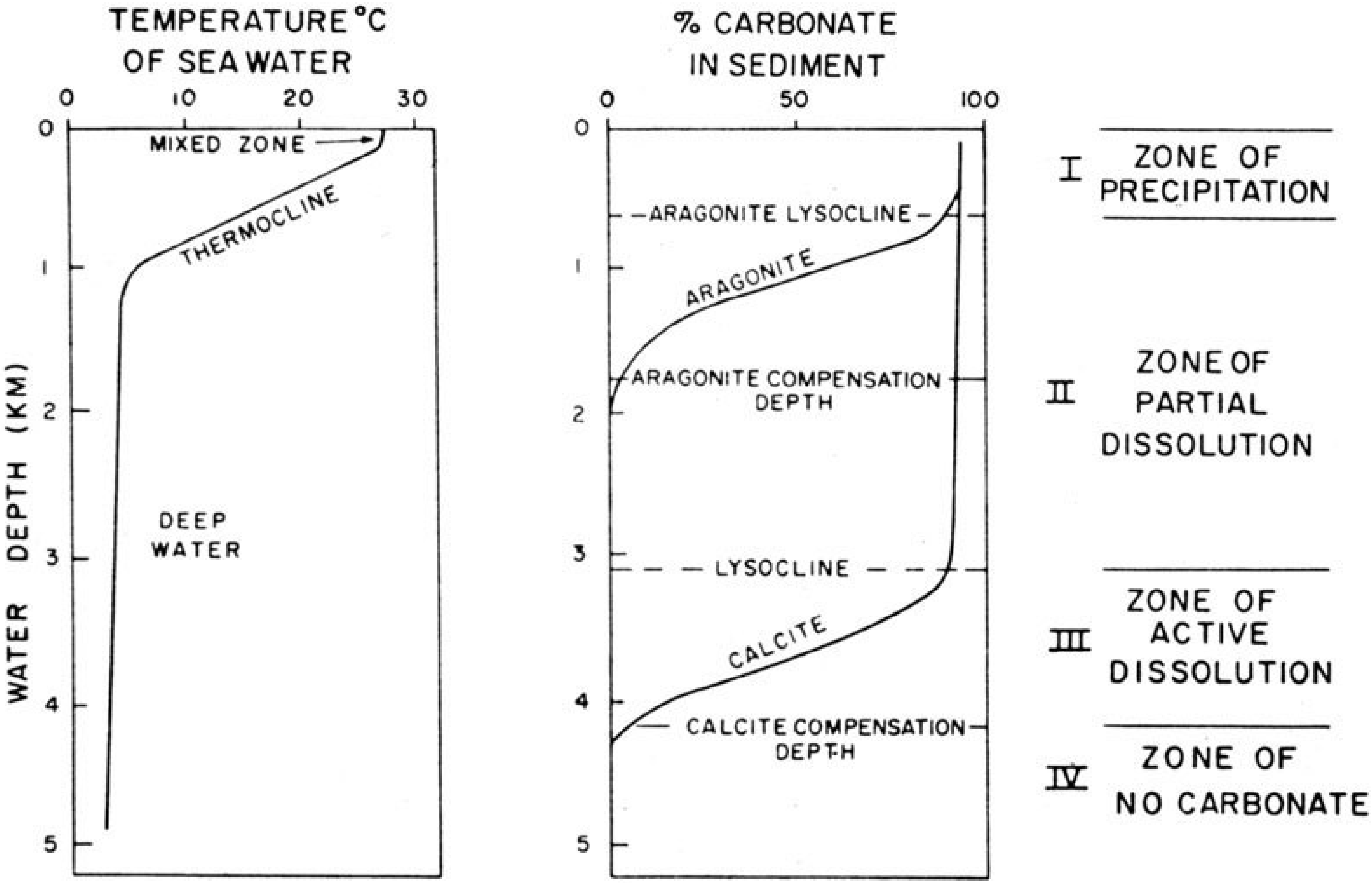
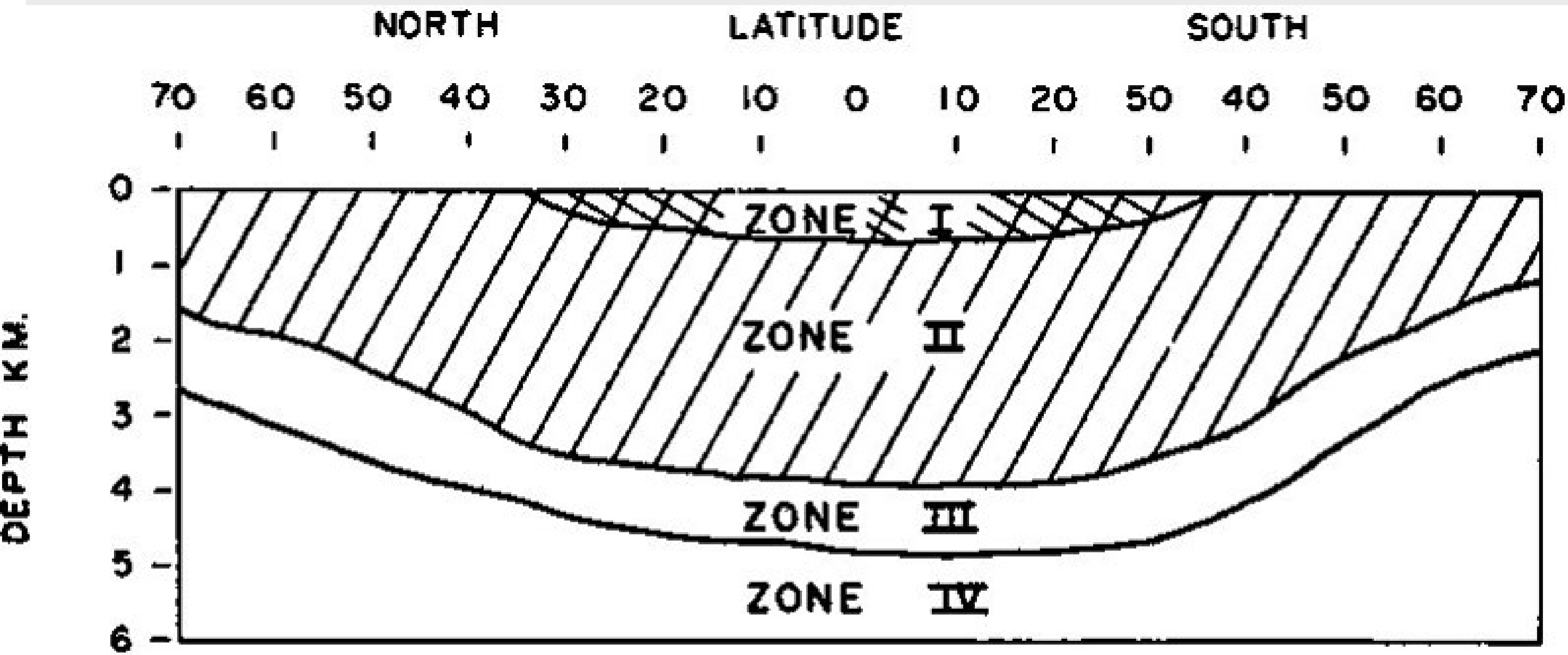


Figure 1 *Generalized diagrams illustrating the relative positions of calcite and aragonite solubility profiles in the modern tropical ocean and the variation in temperature with depth. The major zones of diagenesis are plotted to the right.*

After James, 1984



After James, 1984

Figure 2 *Variations in the different zones of seafloor diagenesis in the modern ocean.*

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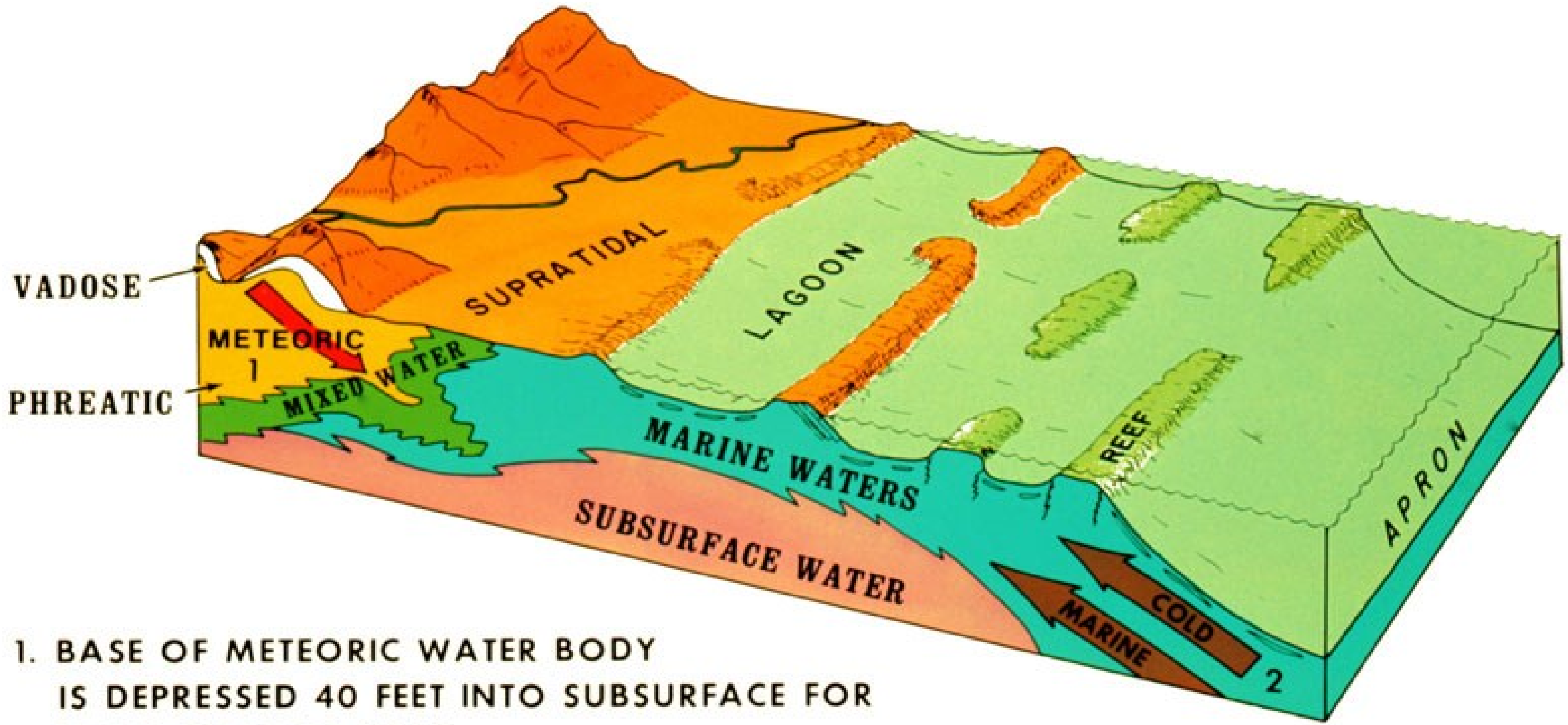
Water Movement within Carbonate Sediments During and Just After Deposition

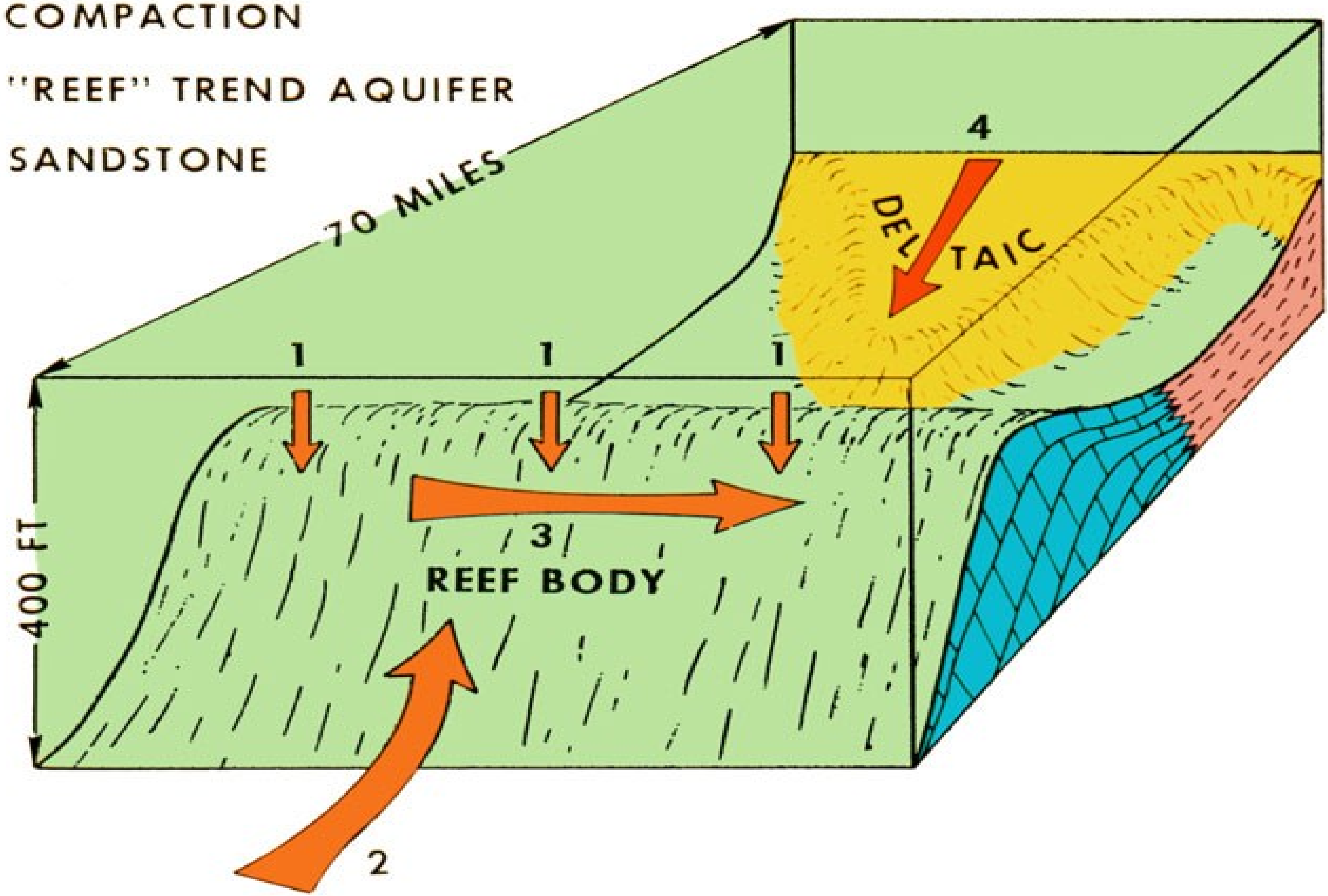


1. BASE OF METEORIC WATER BODY IS DEPRESSED 40 FEET INTO SUBSURFACE FOR EVERY FOOT OF HEAD

2. COLD MARINE WATER SUCKED INTO POROUS PLATFORM SEDIMENTS TO REPLACE CONVECTING WARM SURFACE WATERS

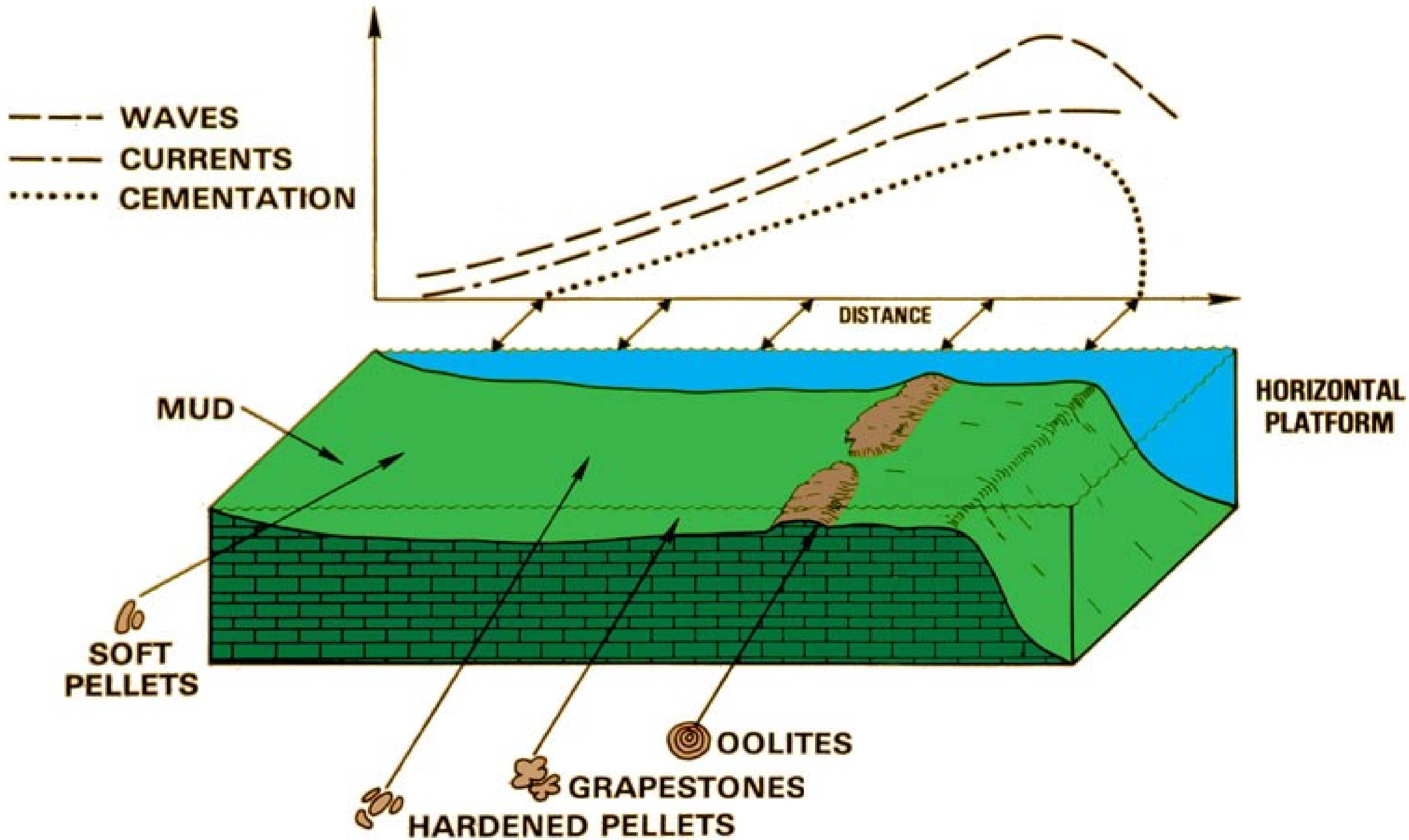
Possible Subsurface Water Movements

1. LOCAL METEORIC
2. OFFSHORE COMPACTION
3. REGIONAL "REEF" TREND AQUIFER
4. REGIONAL SANDSTONE AQUIFER



THERE CAN ALSO BE STRUCTURALLY CONTROLLED REGIONAL MOVEMENTS OF WATER UNRELATED TO LITHOLOGY

RELATIONSHIP OF GRAIN MORPHOLOGY TO CEMENTATION AND WAVE AND CURRENT REGIME



CEMENTATION DURING SEDIMENT DEPOSITION

MARINE ENVIRONMENT:

1. FORMATION OF { OOLITES, GRAPESTONES, PELLET HARDENING }
2. SUBMARINE
   - A. REEF CAVITY CEMENT
   - B. SEDIMENT SURFACE CRUSTS
3. INTERTIDAL
   - A. SUBSURFACE CRUSTS
   - B. SEDIMENT SURFACE CRUSTS

STABLE MARINE CEMENTS:

ARAGONITE —— FIBERS, AND MICRITE

HIGH MAGNESIUM CALCITE —— FIBERS, BLADES AND MICRITE

OOLITE FORMATION

ALGAE AND BACTERIA INVEST OOLITE
IN MUCILAGENOUS ENVELOPE

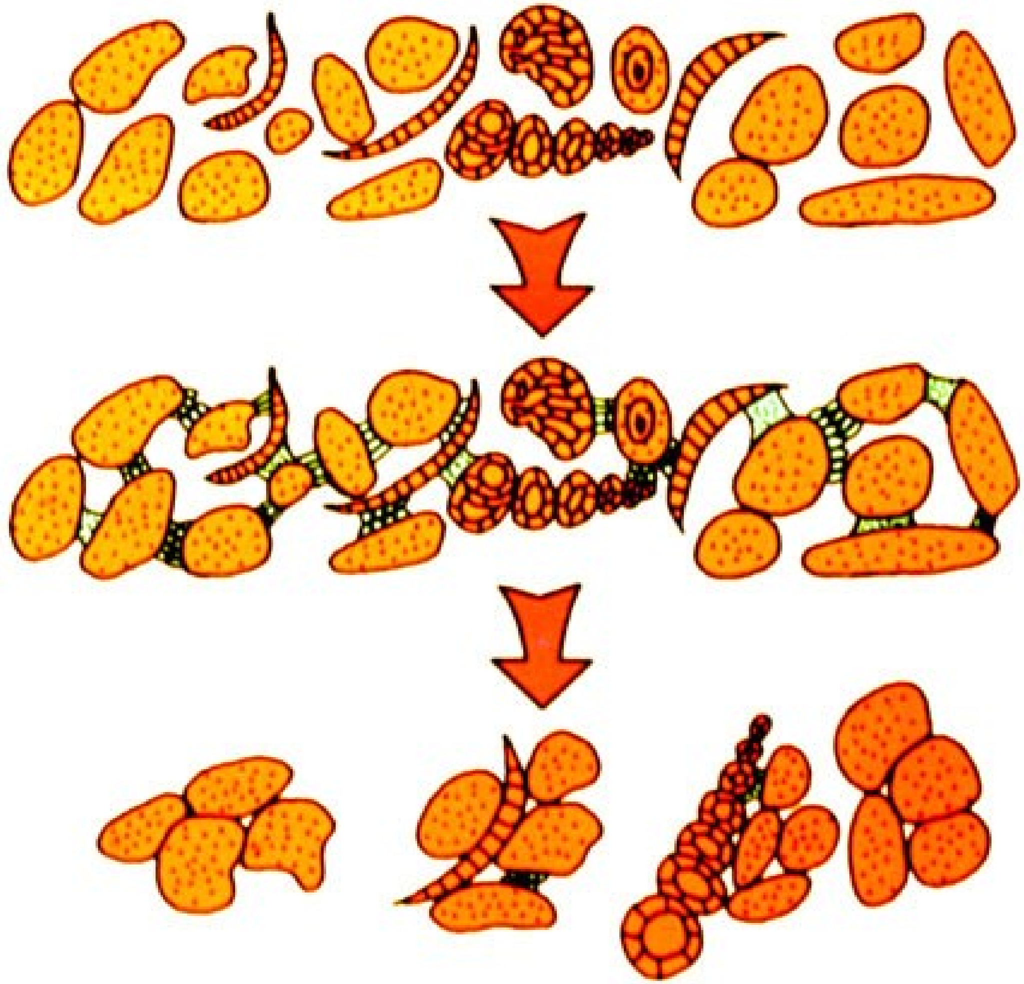
STAGE 1 | STAGE 2 | STAGE 3

OOLITE COMES TO REST

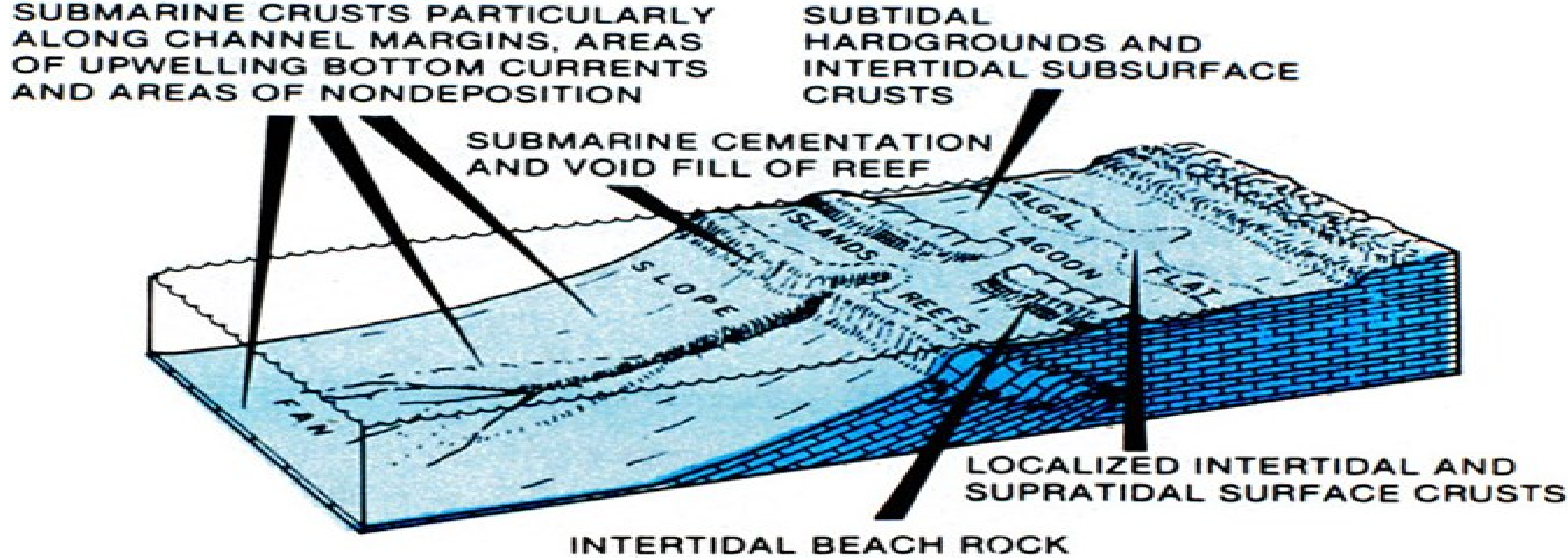
ARAGONITE FIBERS ARE PRECIPITATED ON SURFACE

ABRASION FLATTENS TANGENTIAL CRYSTALS AND REMOVES OTHERS. POLISHED ORIENTED SURFACE PRODUCED

SOURCE OF CARBONATE LUMPS



1. ACCUMULATION OF LOOSE CARBONATE SAND
2. PRECIPITATION OF MARINE CARBONATE CEMENT WHILE AT REST
3. BREAK UP OF LAYER BY STORM INTO LUMPS



DIAGENETIC EFFECTS OF MARINE WATERS

MICRITIZATION

NEOMORPHIC GRAIN GROWTH

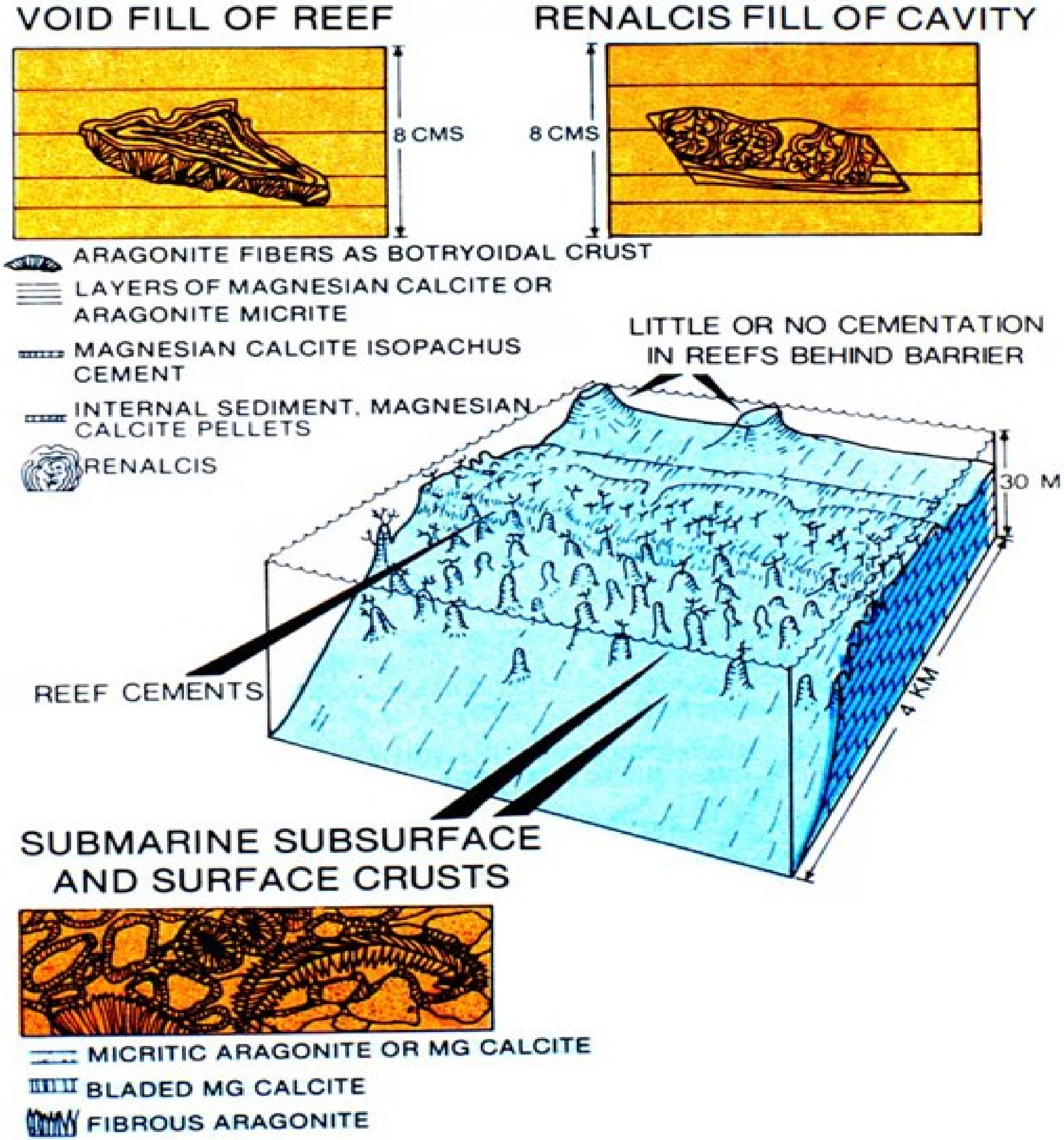
CEMENTATION DURING SEDIMENT DEPOSITION

FORMATION OF { OOLITES, GRAPESTONES, PELLET HARDENING

SUBMARINE, INTERTIDAL } CRUSTS

STABLE MARINE CEMENTS

ARAGONITE — FIBERS AND MICRITE
MG CALCITE — FIBERS. BLADES AND MICRITE



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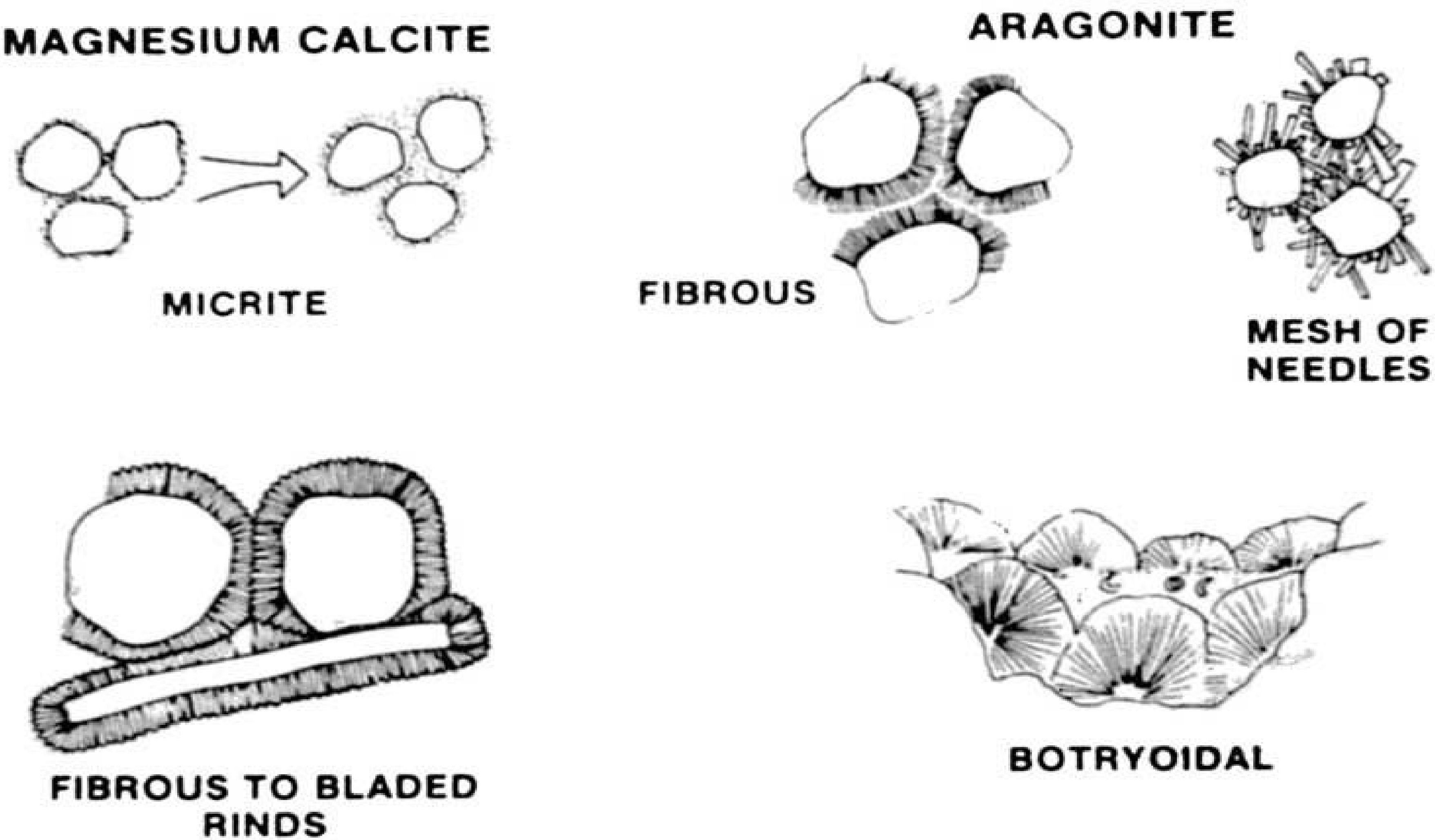
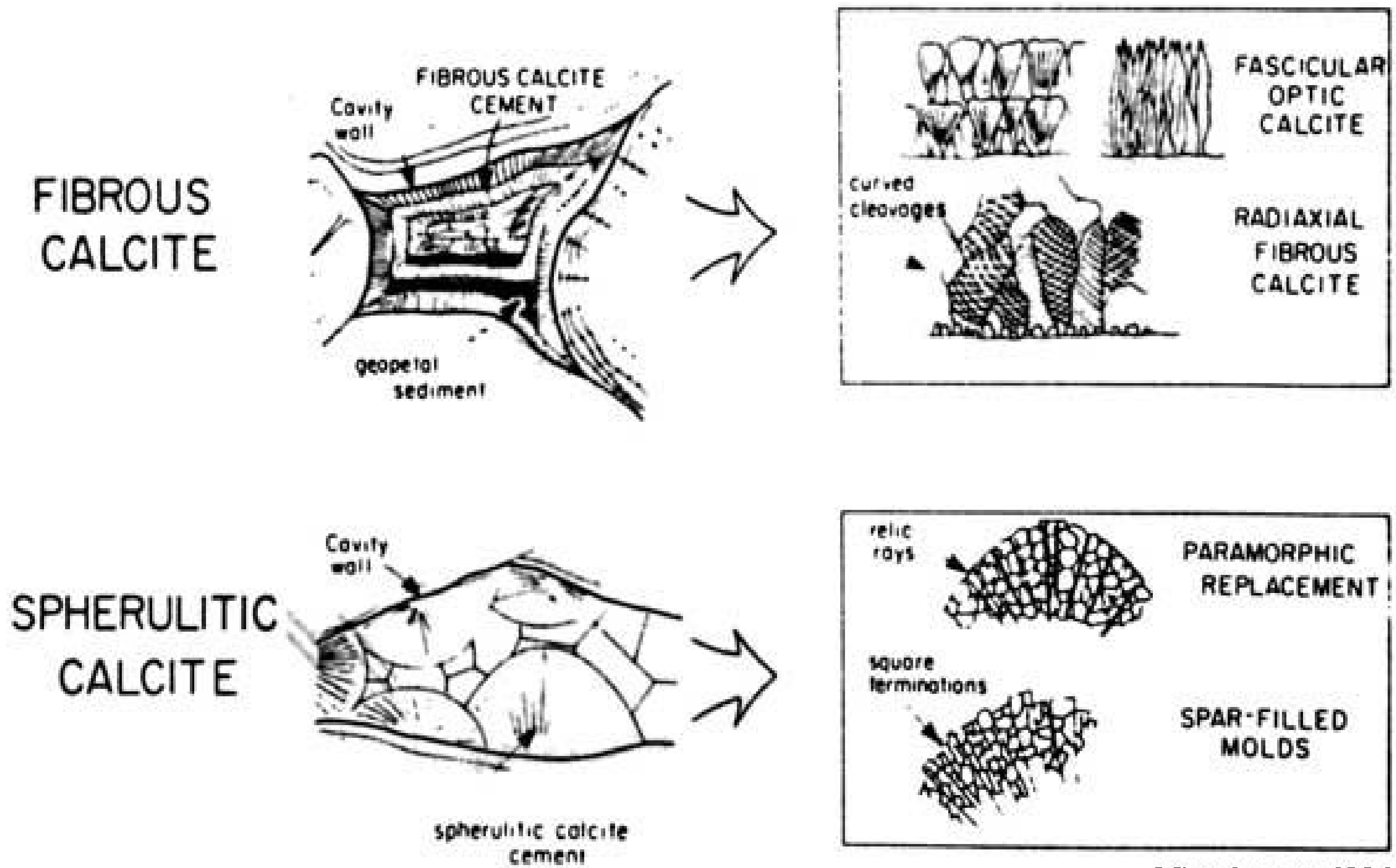


Figure 3 *Different types of modern seafloor carbonate cements.*

After James, 1984



After James, 1984

Figure 16 *Fabrics and morphologies of coarse marine cements. Fibrous calcite is generally interpreted as derived from Mg-calcite and spherulitic calcite from botryoidal aragonite.*

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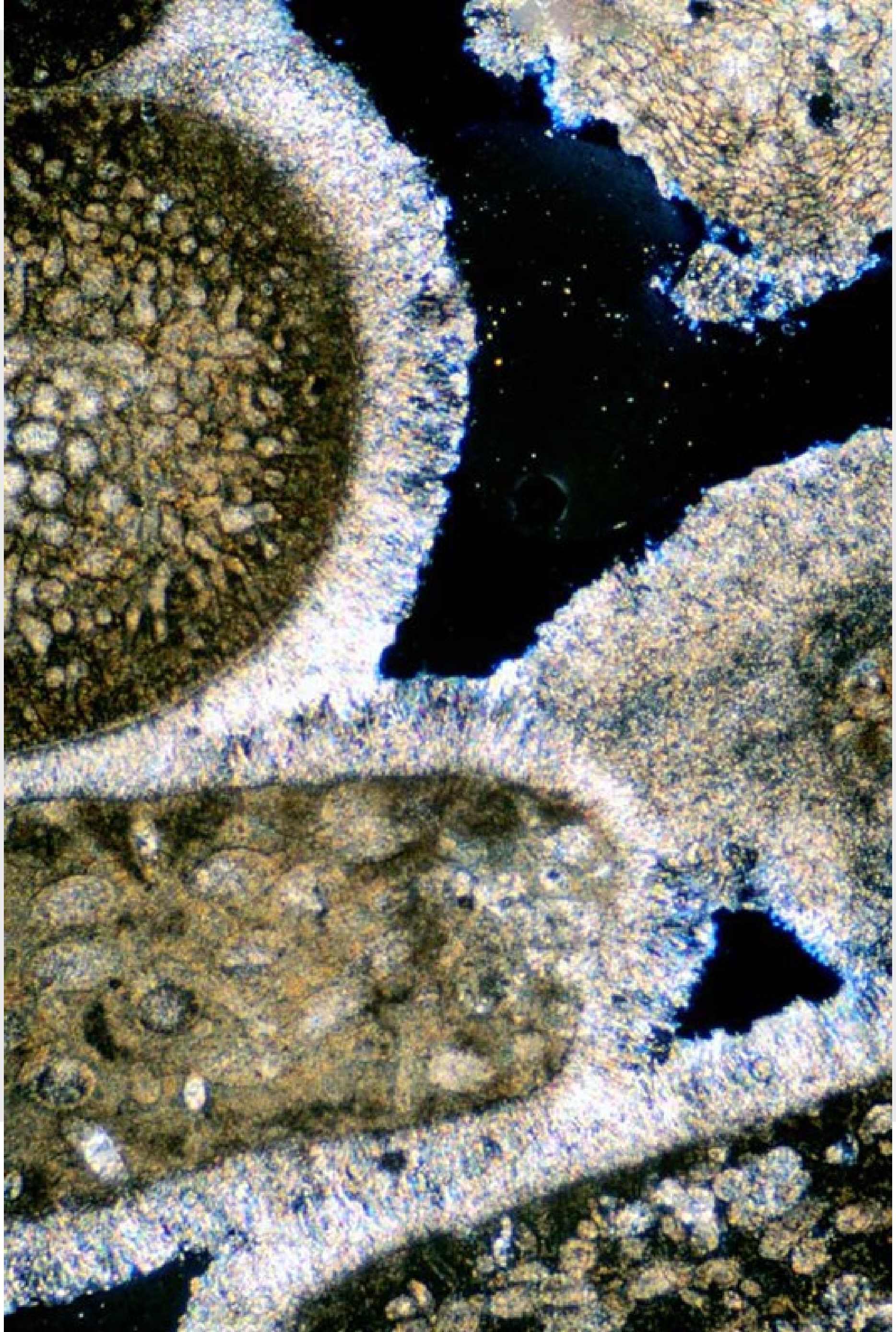

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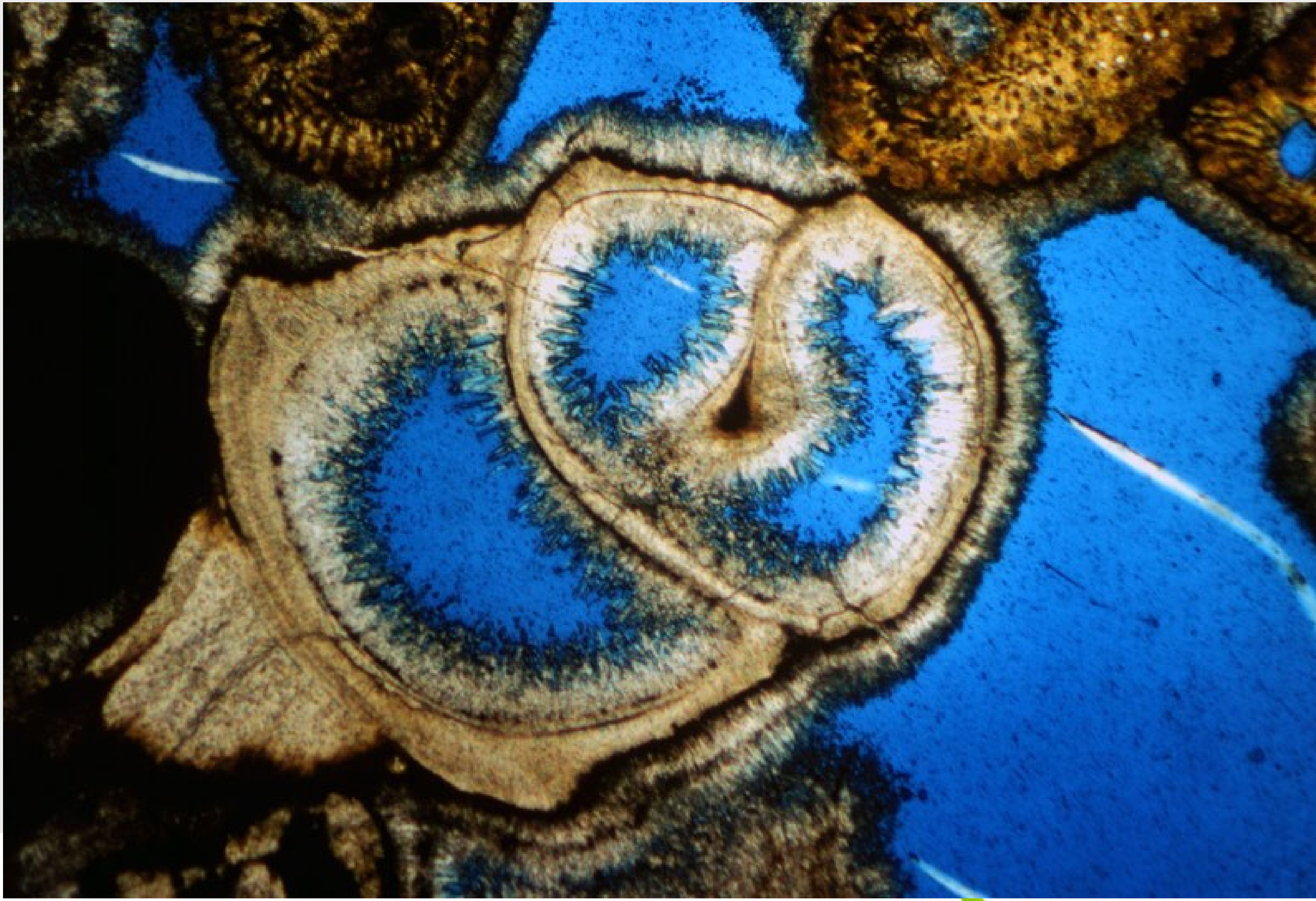

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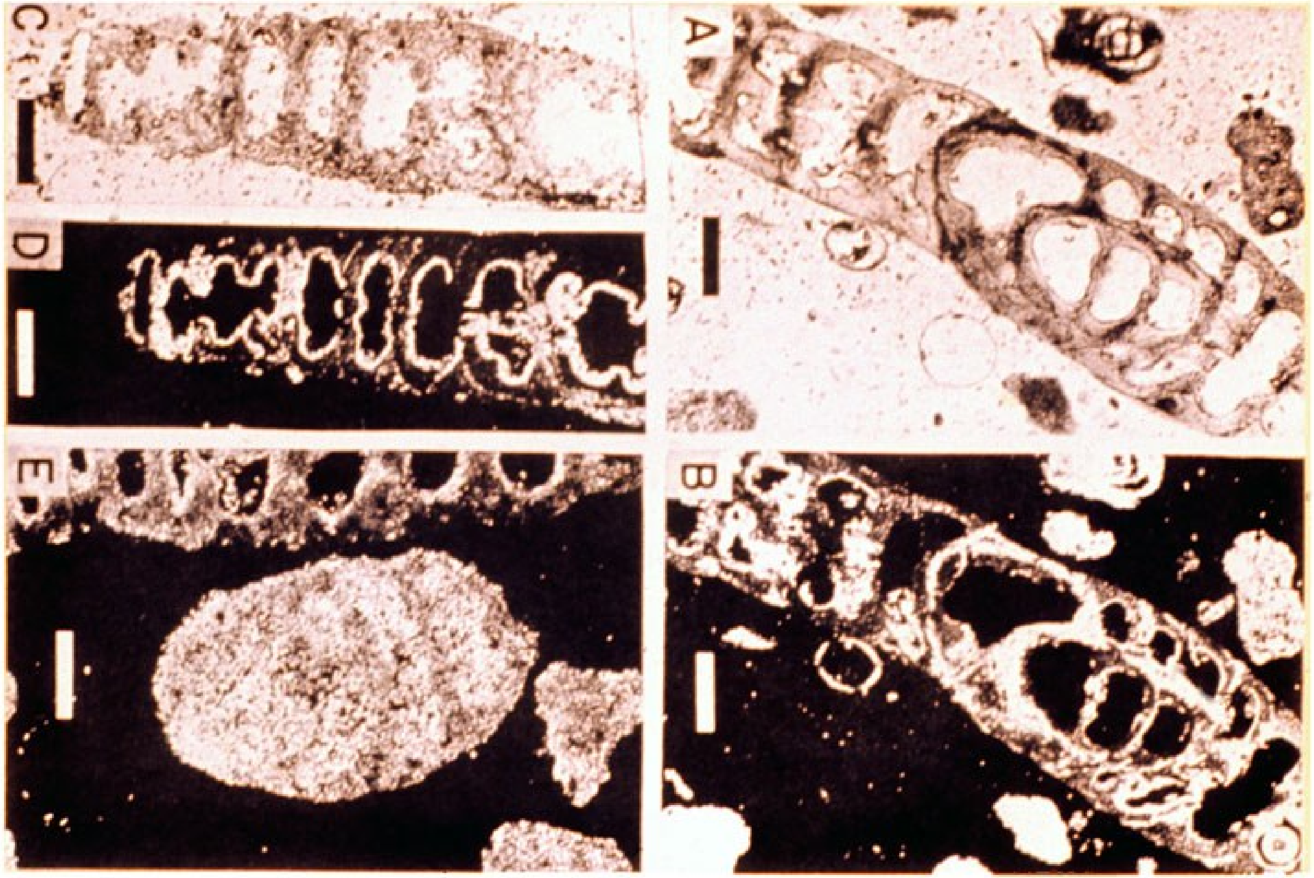
CRYPTOCRYSTALLINE GRAIN ALTERATION



Pusey, 1964

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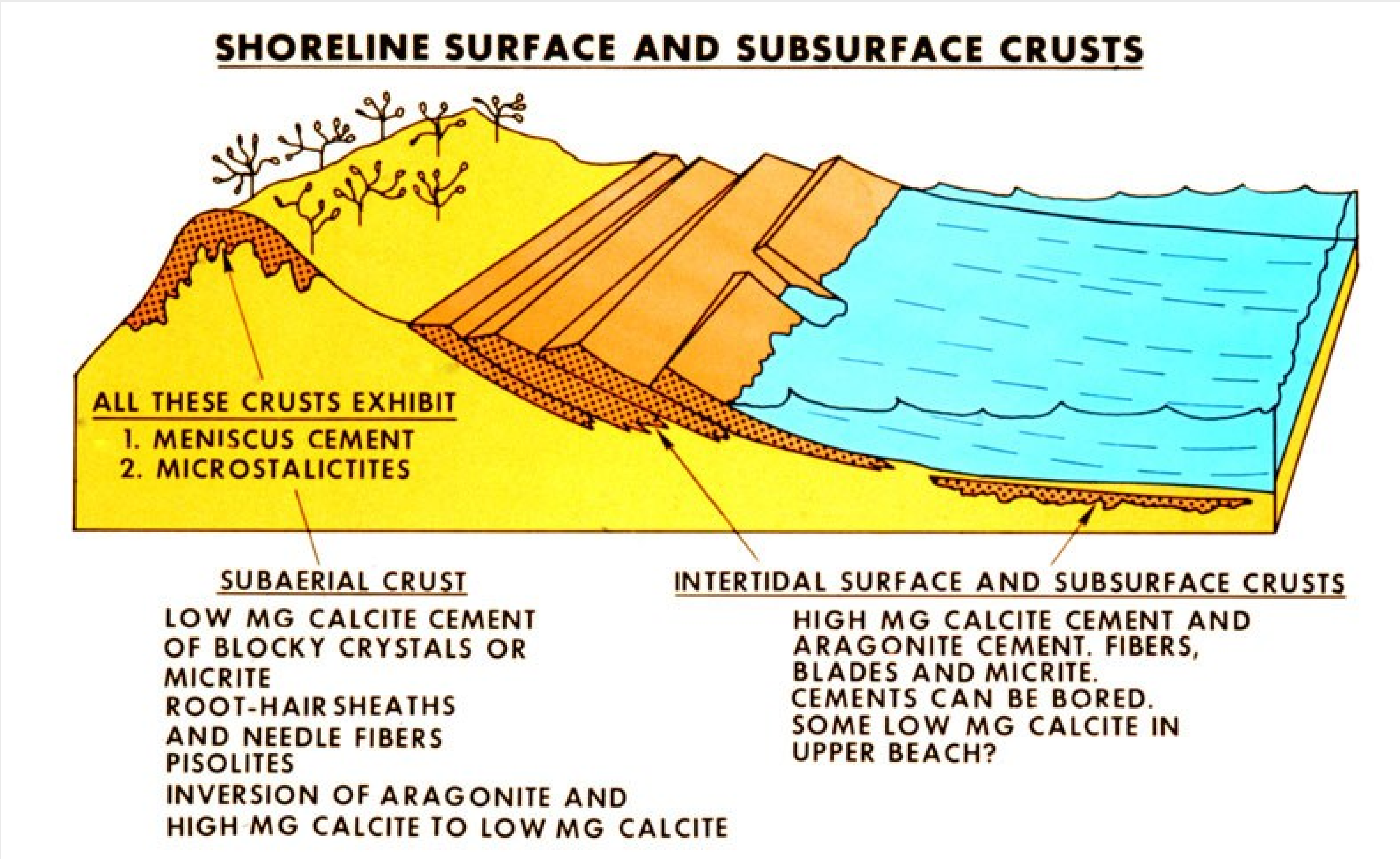
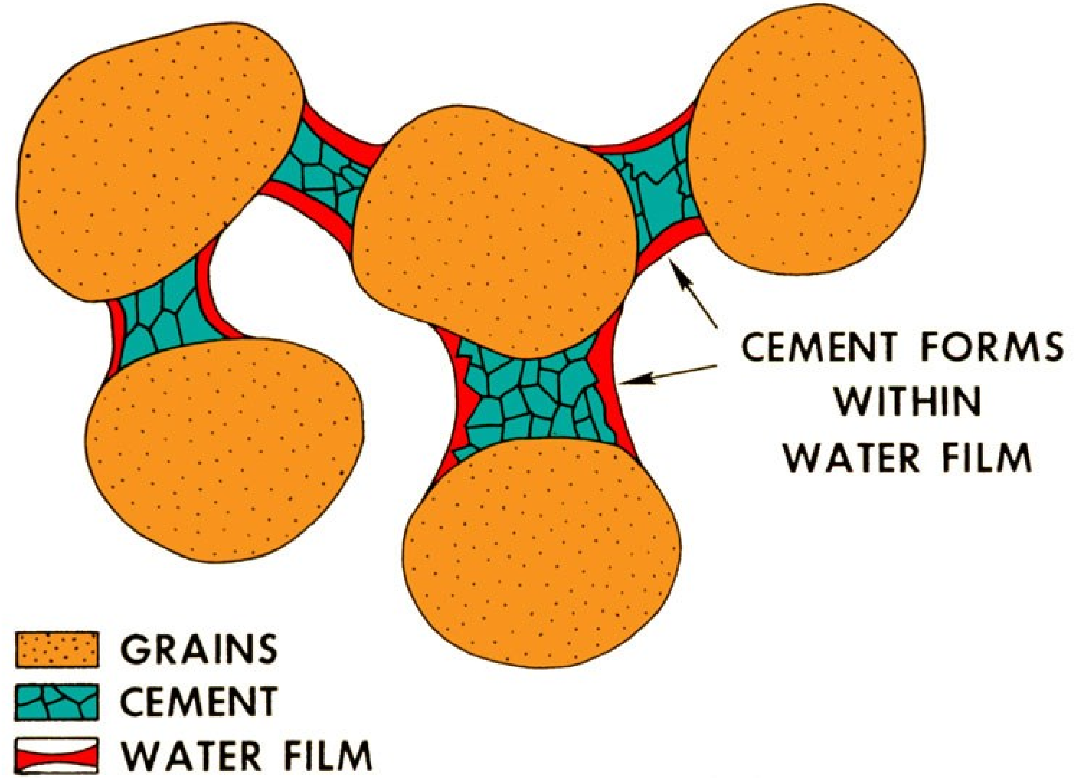
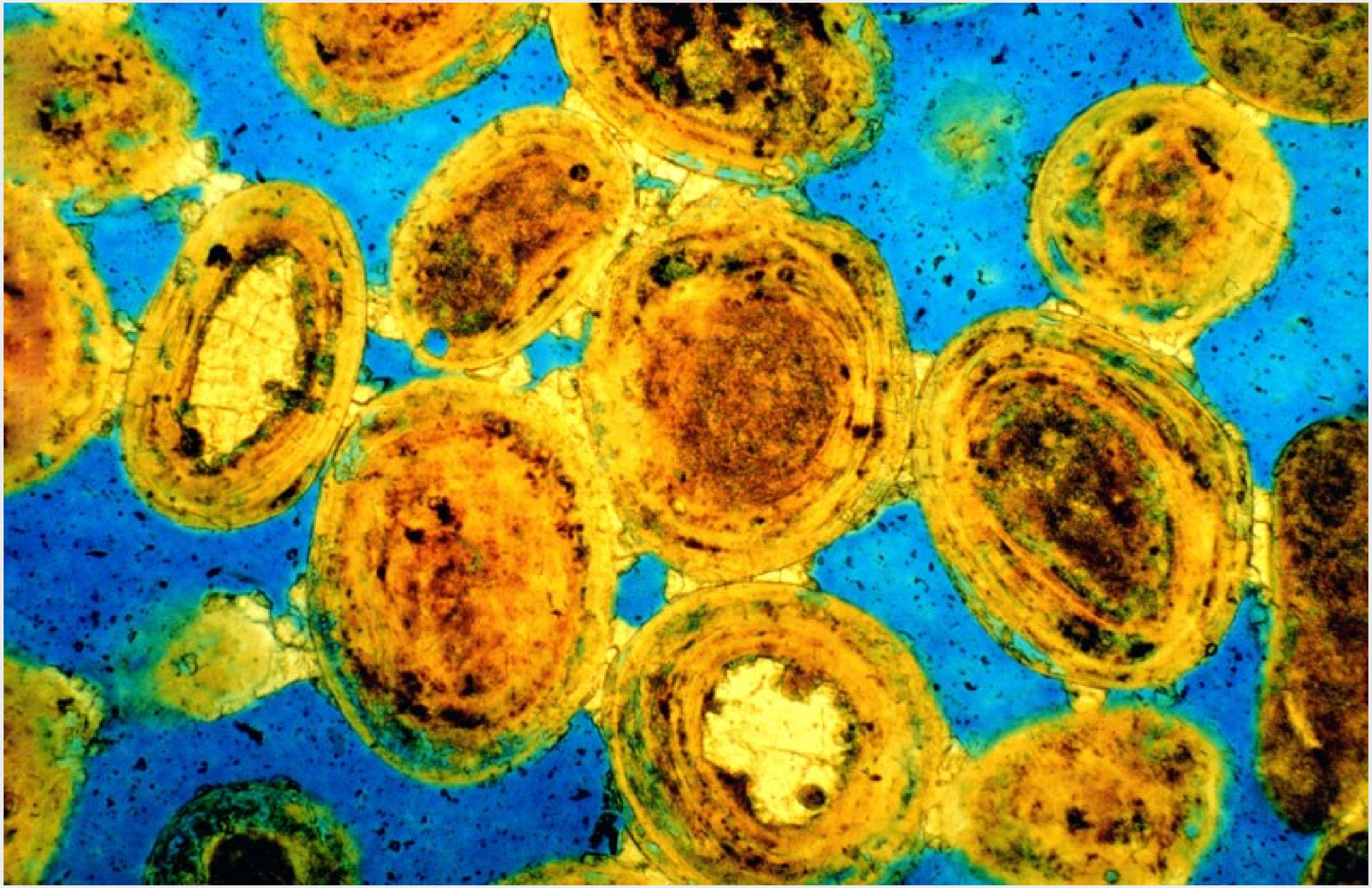

SHORELINE SURFACE AND SUBSURFACE CRUSTS
ALL THESE CRUSTS EXHIBIT
1. MENISCUS CEMENT
2. MICROSTALICTITES
SUBAERIAL CRUST
LOW MG CALCITE CEMENT OF BLOCKY CRYSTALS OR MICRITE
ROOT-HAIR SHEATHS AND NEEDLE FIBERS
PISOLITES
INVERSION OF ARAGONITE AND HIGH MG CALCITE TO LOW MG CALCITE
INTERTIDAL SURFACE AND SUBSURFACE CRUSTS
HIGH MG CALCITE CEMENT AND ARAGONITE CEMENT. FIBERS, BLADES AND MICRITE.
CEMENTS CAN BE BORED.
SOME LOW MG CALCITE IN UPPER BEACH?

Meniscus Cement Formed in "Wet" Sediment Above Water Table





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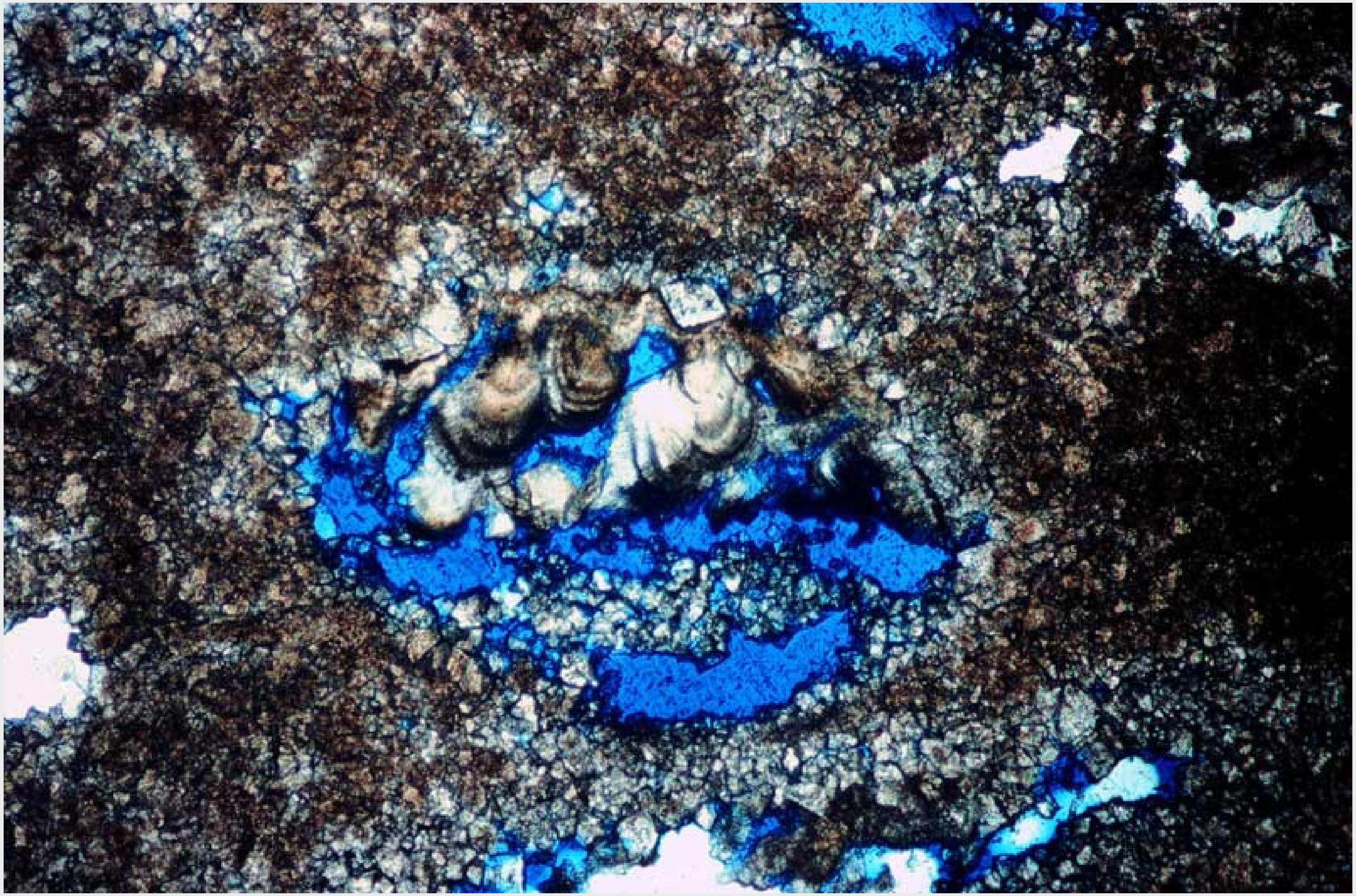

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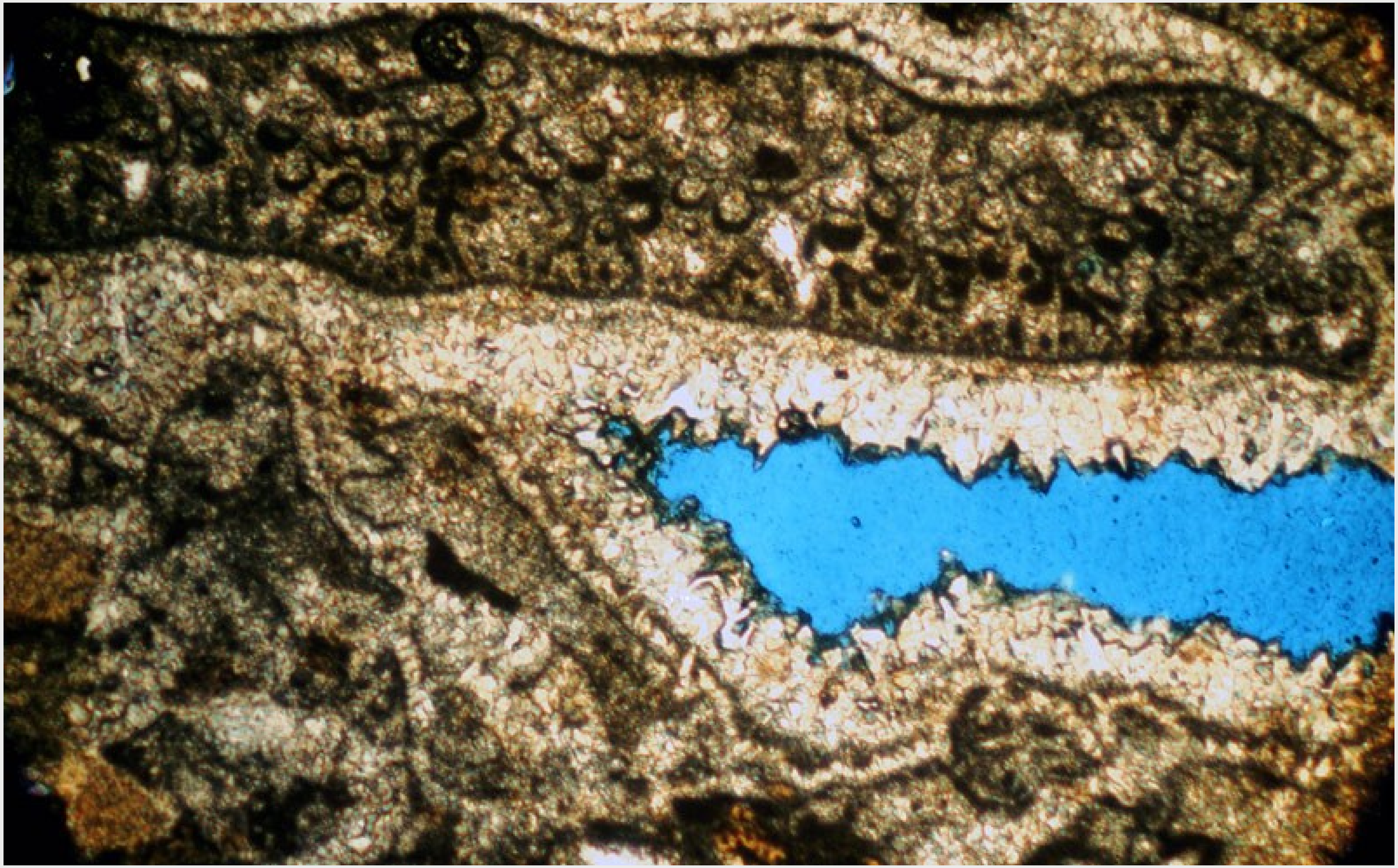

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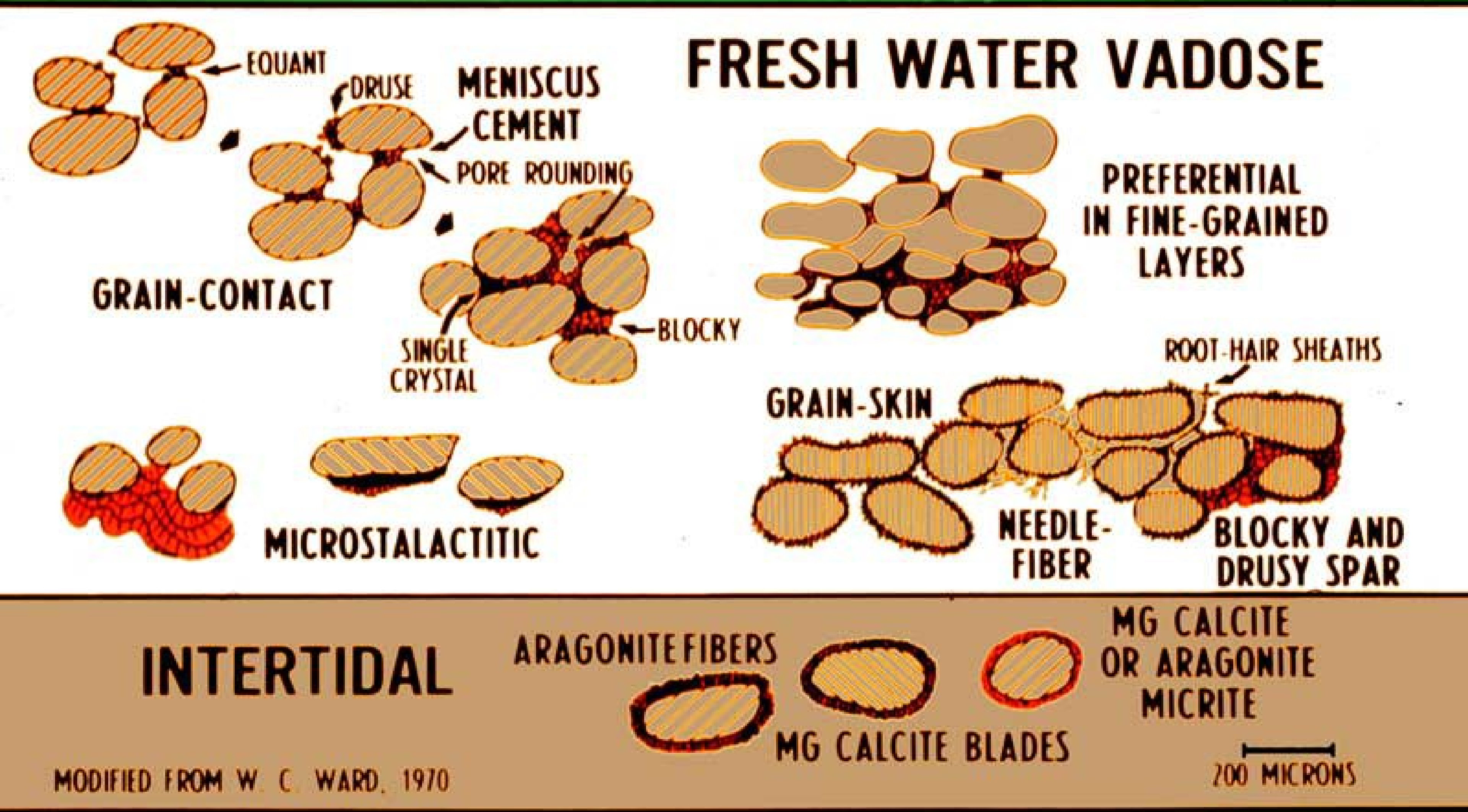
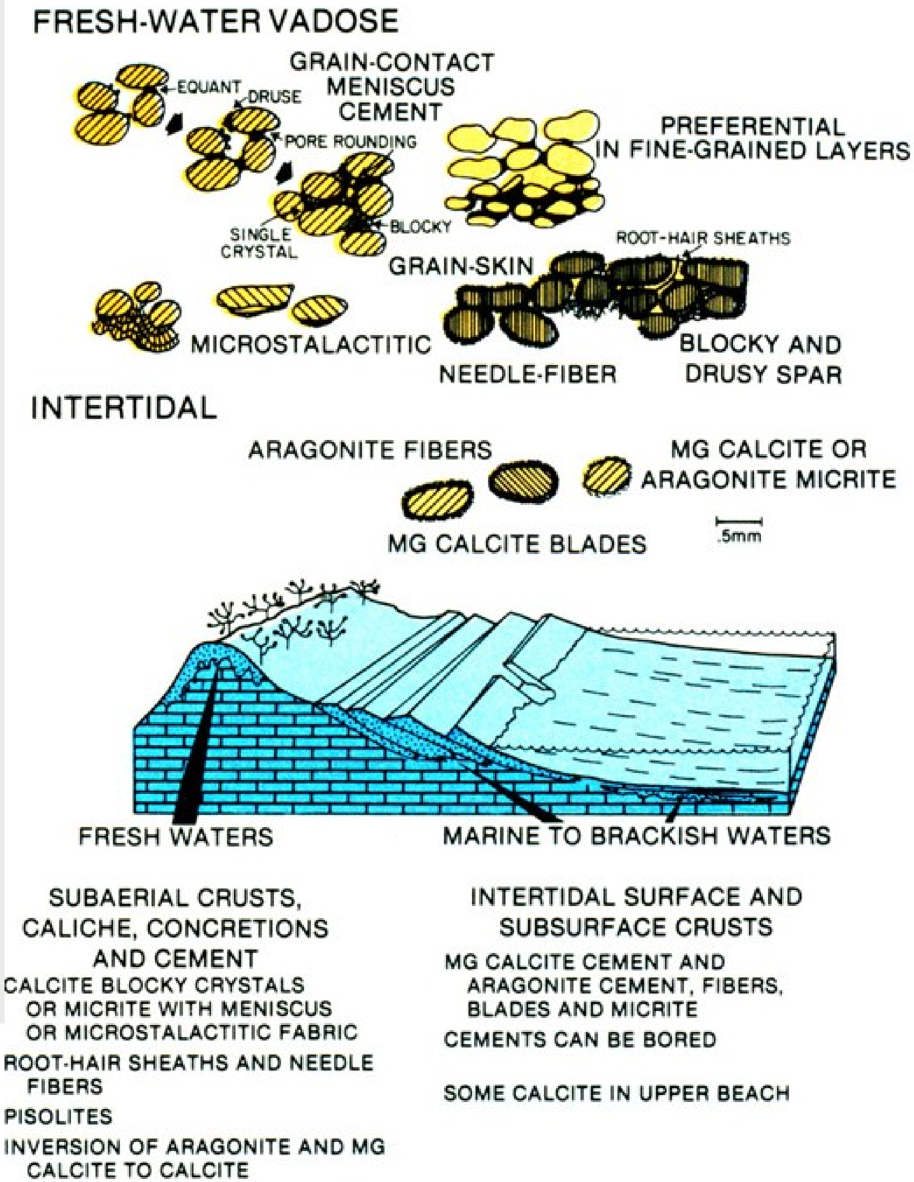
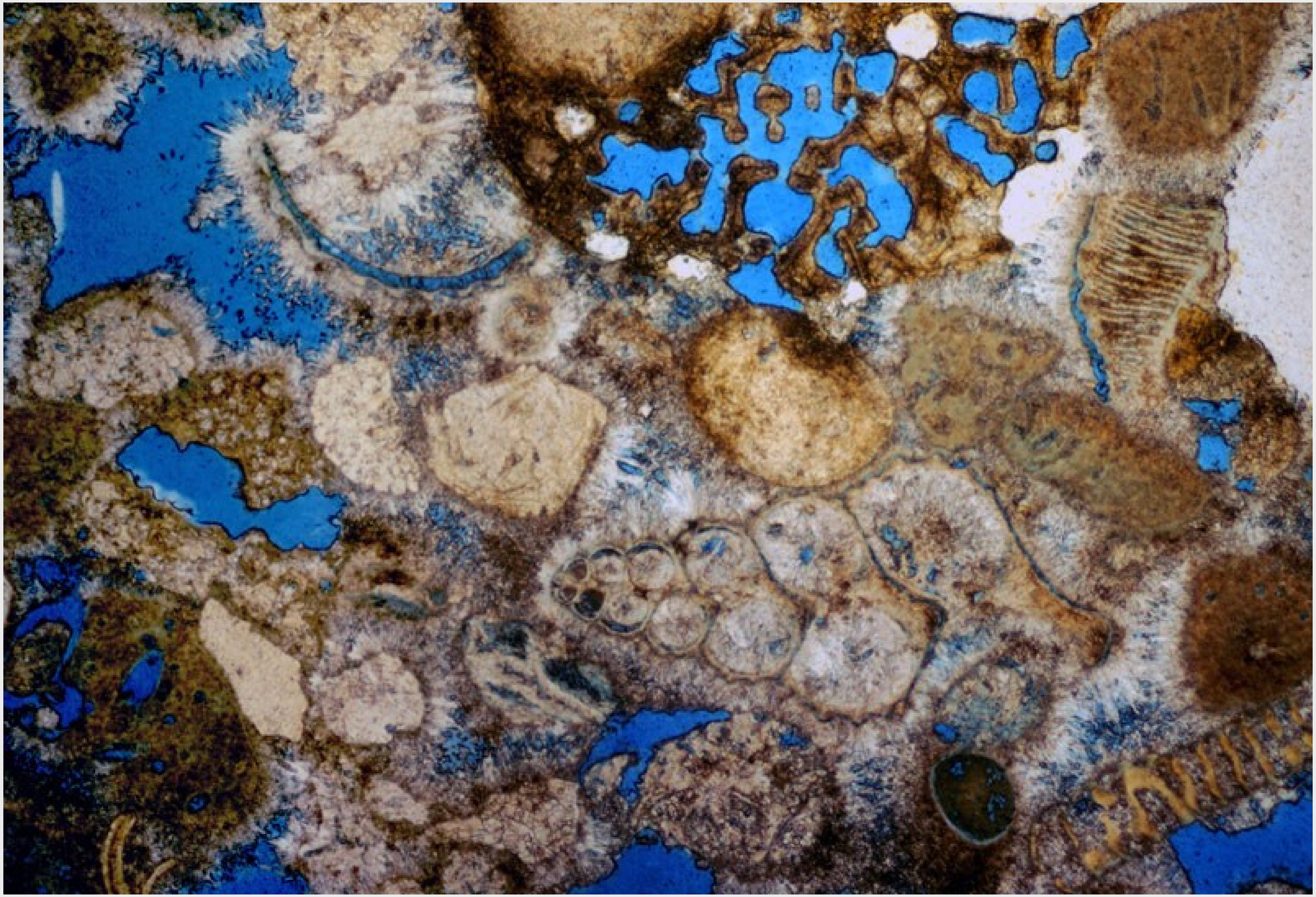
Near Shore Cementation




FRESH-WATER VADOSE
EQUANT
DRUSE
GRAIN-CONTACT MENISCUS CEMENT
PORE ROUNDING
PREFERENTIAL IN FINE-GRAINED LAYERS
SINGLE CRYSTAL
BLOCKY
ROOT-HAIR SHEATHS
GRAIN-SKIN
MICROSTALACTITIC
NEEDLE-FIBER
BLOCKY AND DRUSY SPAR
INTERTIDAL
ARAGONITE FIBERS
MG CALCITE OR ARAGONITE MICRITE
MG CALCITE BLADES
.5mm
FRESH WATERS
MARINE TO BRACKISH WATERS
SUBAERIAL CRUSTS, CALICHE, CONCRETIONS AND CEMENT
CALCITE BLOCKY CRYSTALS OR MICRITE WITH MENISCUS OR MICROSTALACTITIC FABRIC
ROOT-HAIR SHEATHS AND NEEDLE FIBERS
PISOLITES
INVERSION OF ARAGONITE AND MG CALCITE TO CALCITE
INTERTIDAL SURFACE AND SUBSURFACE CRUSTS
MG CALCITE CEMENT AND ARAGONITE CEMENT, FIBERS, BLADES AND MICRITE
CEMENTS CAN BE BORED
SOME CALCITE IN UPPER BEACH



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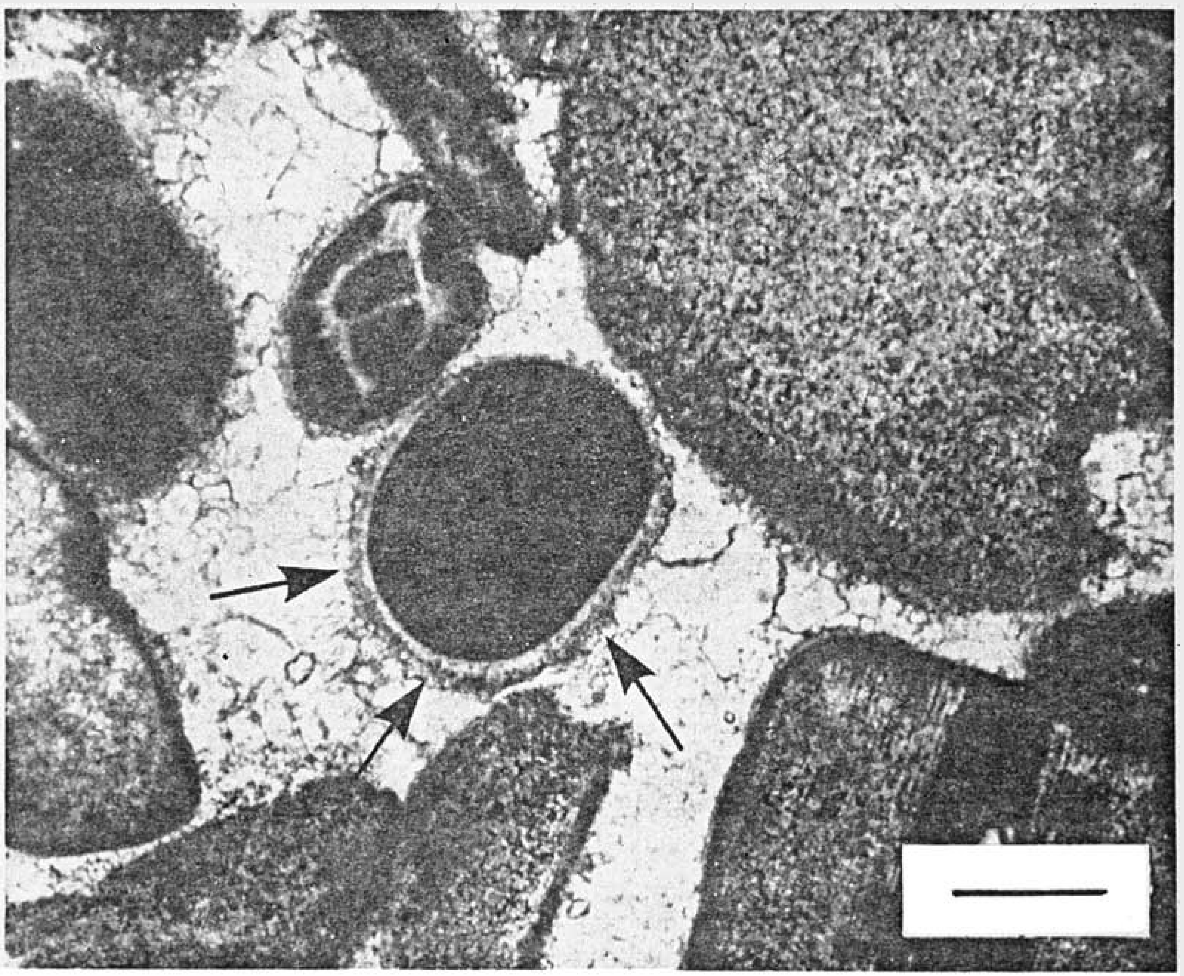

Figure 15 *Photomicrograph of a bioclastic grainstone from the Ste. Genevieve Formation (Mississippian) Bridgeport Field, Illinois Basin, in which the first cement is a fringe of fibrous calcite that is thickest on the undersides of grains (arrows) resembling small stalagtites. This early cement probably developed while the sediment was beachrock. (scale 2 mm).*

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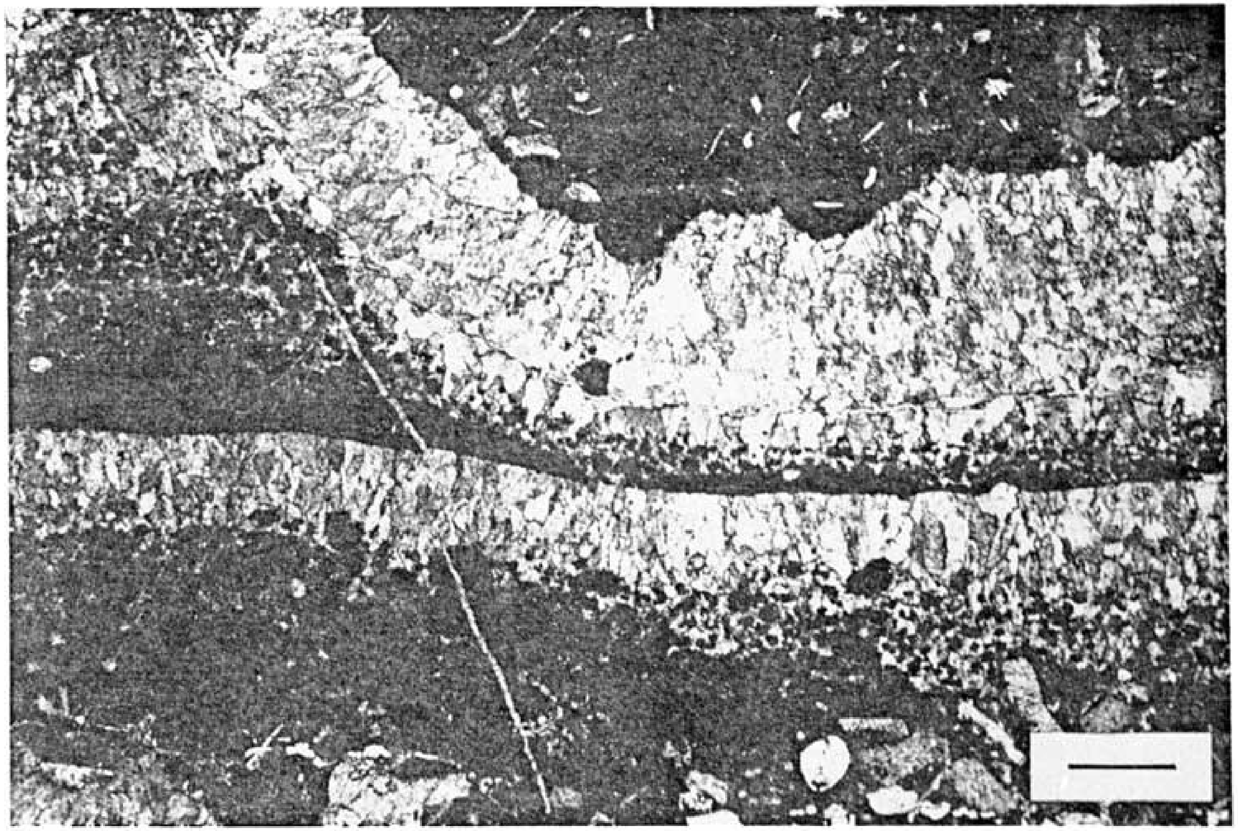


Figure 13 *Photomicrograph of interlayered marine sediment and radiaxial fibrous calcite cement in laminar cavities from a Middle Ordovician reef mound at Meiklejohn Peak, Nevada (scale 1 mm).*

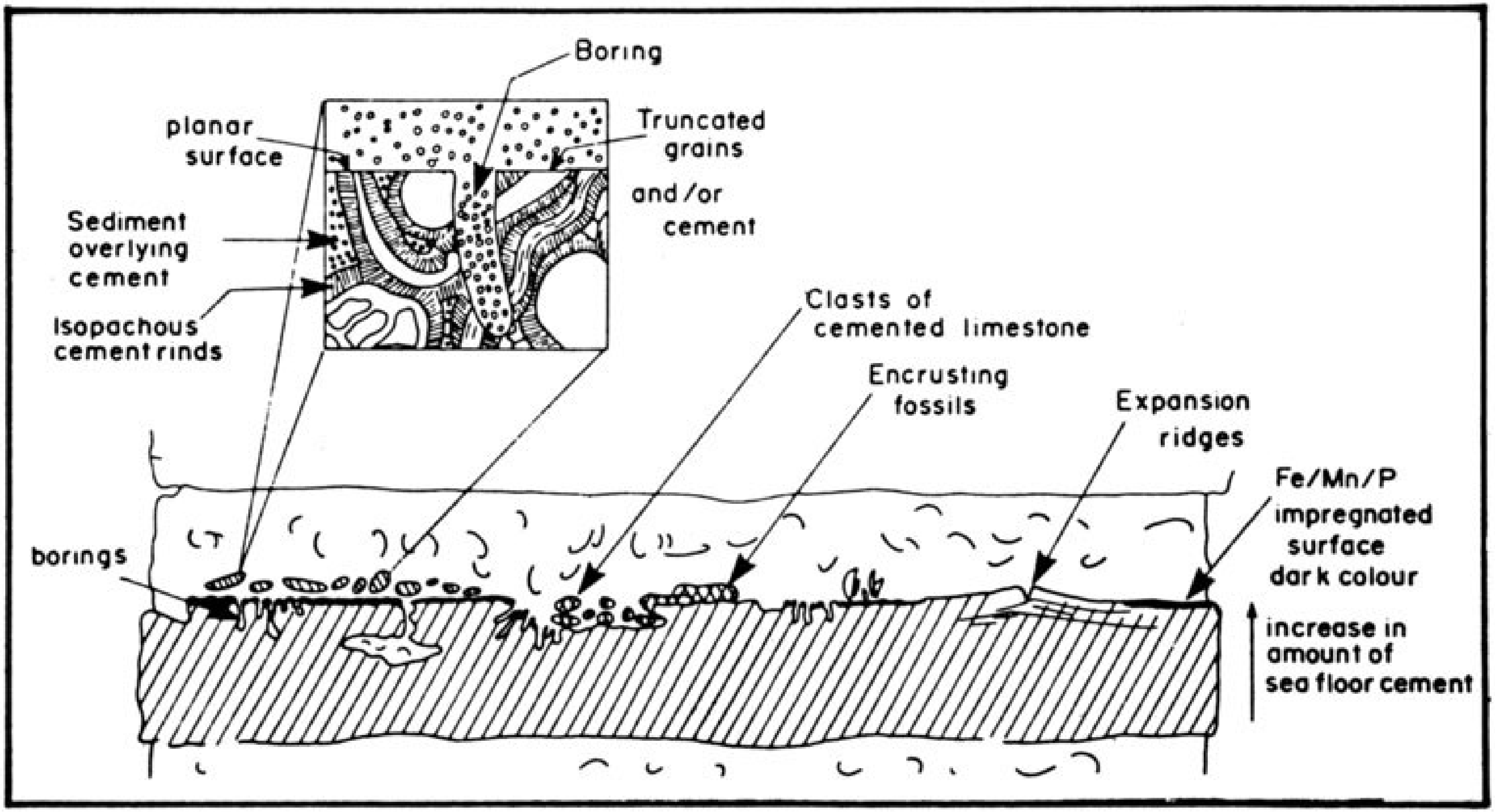


Figure 12 *Criteria for the recognition of seafloor cementation.*

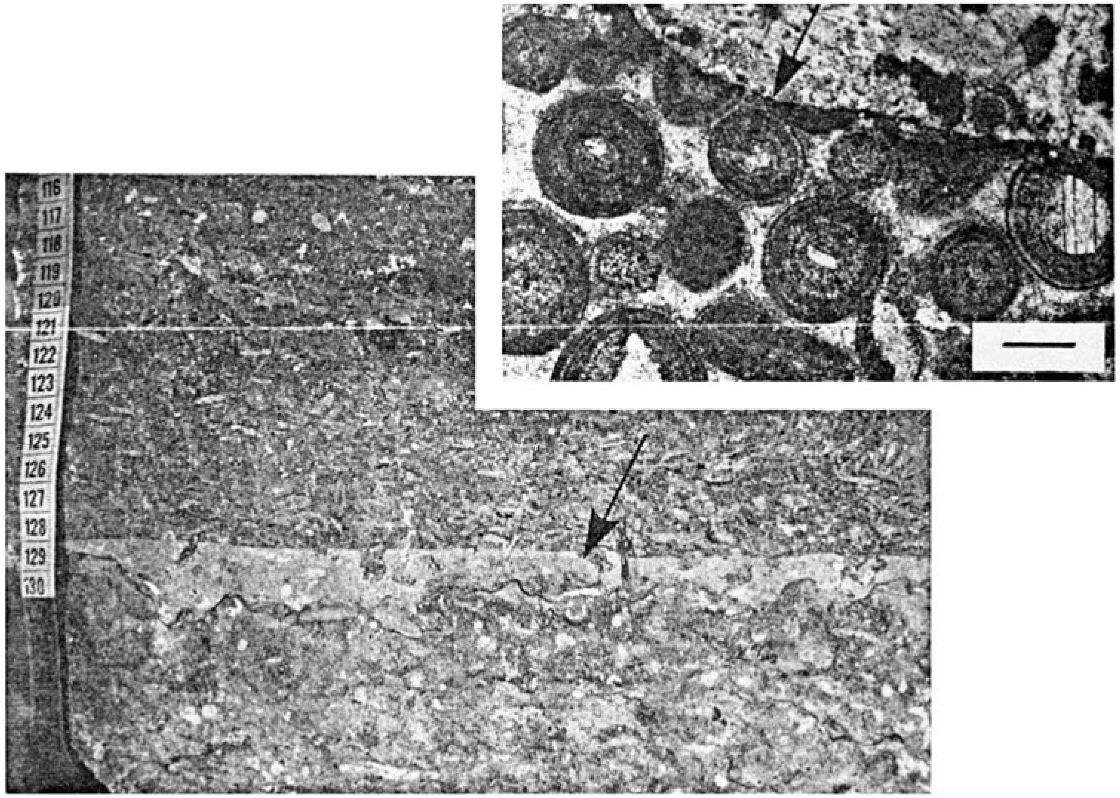
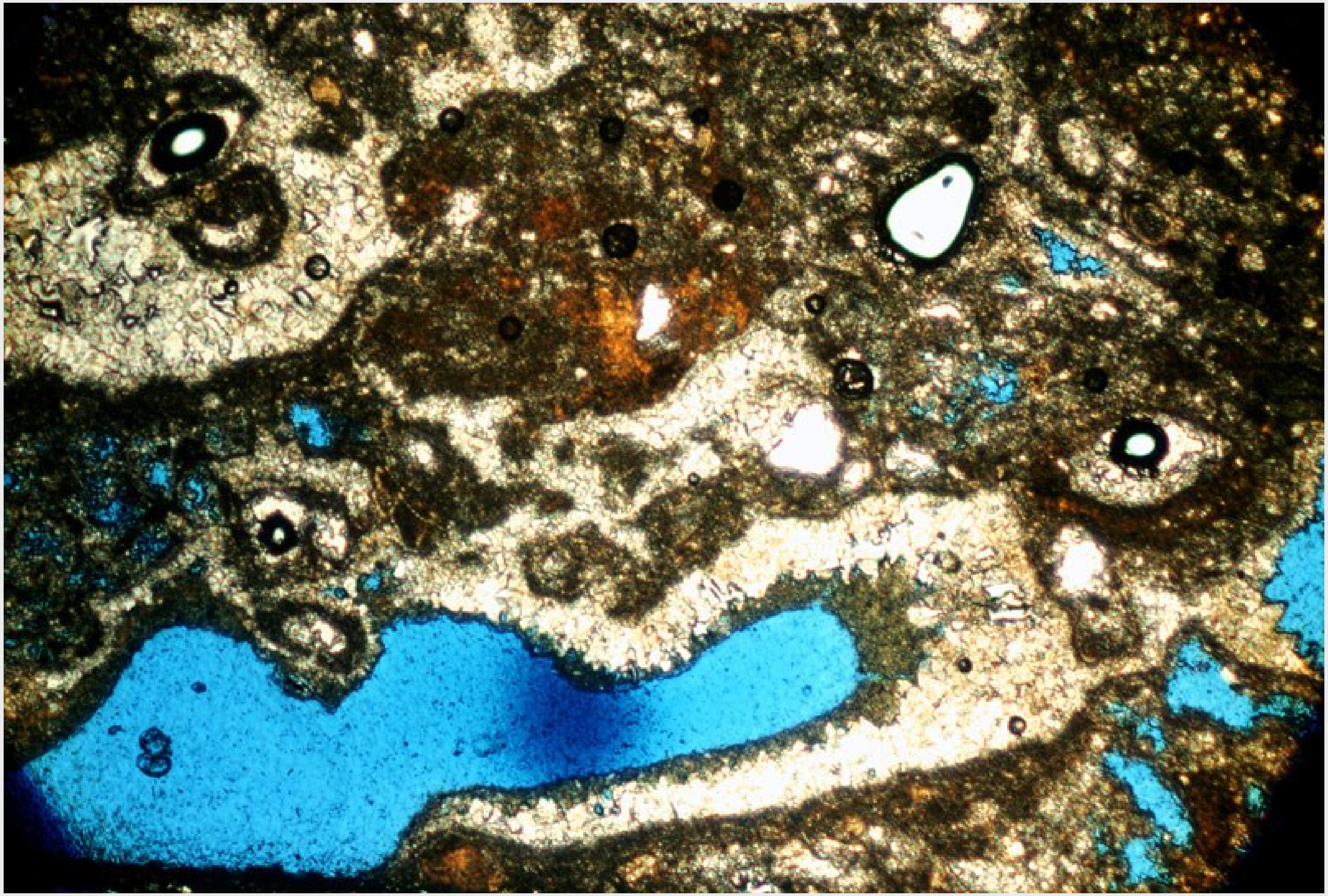


Figure 6 *An irregular submarine hardground (between 129 and 128 cm. on the tape) developed in Lower Cambrian ooid limestones of the Forteau Formation, western Newfoundland. The photomicrograph illustrates the truncated ooids and cements at the hardground surface (arrow indicates location; scale bar 0.5 mm).*



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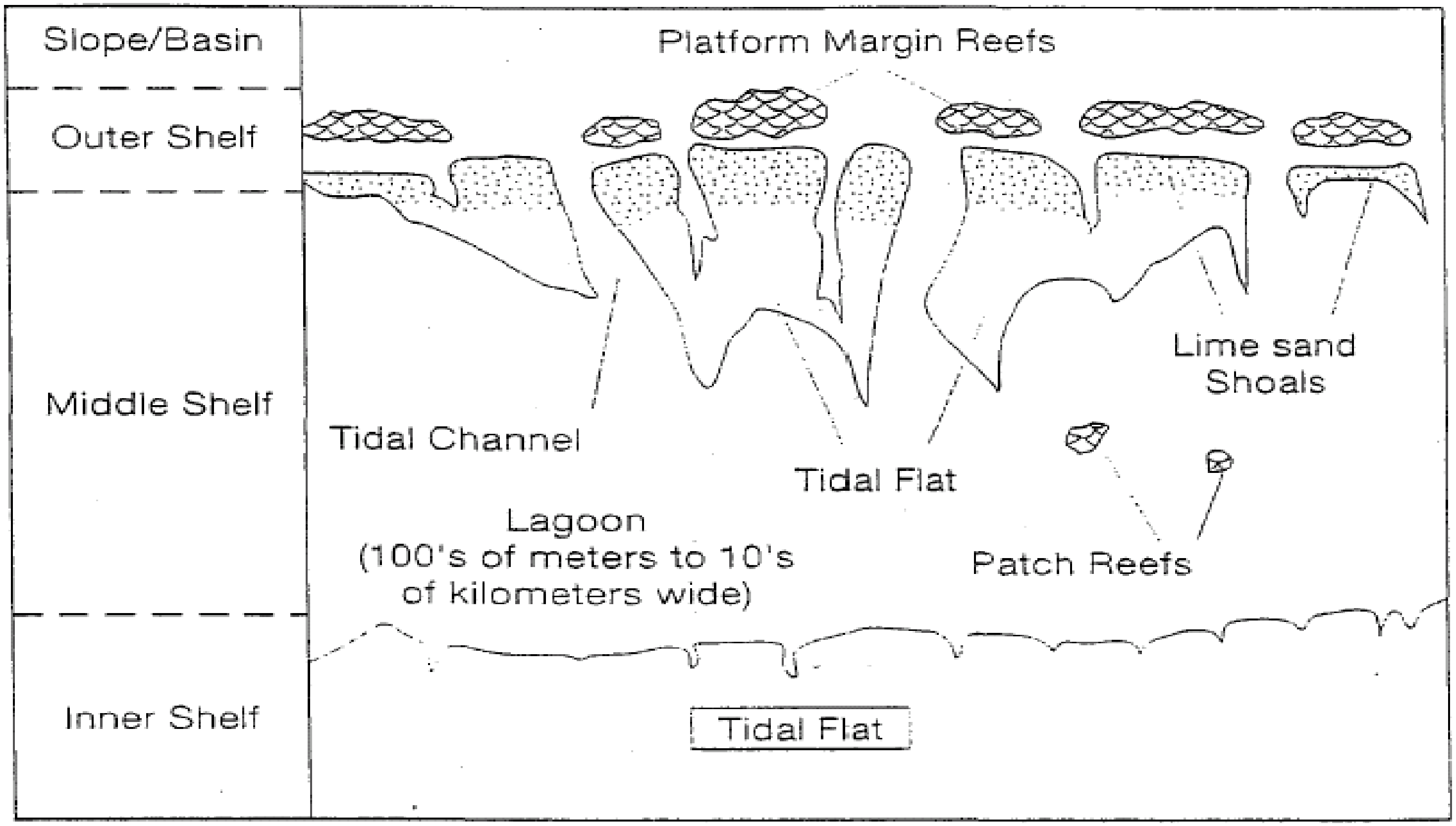
Carbonate Platforms - 6



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Evaporites

Evaporites comprise all rocks that have formed by precipitation from saline solutions concentrated by evaporation. Evaporates have formed under both marine and nonmarine conditions, although the nonmarine formations tend to be much thinner. Marine sequences in the Mediterranean are up to 1km thick.

Evaporites are particularly common in the Cambrian, Permian, Jurassic and Miocene eras.

Evaporite deposits mostly comprise gypsum, halite (rock salt) and anhydrite. Although these rocks are volumetrically much less significant than carbonates they nevertheless are very significant in engineering terms because of their peculiar properties.

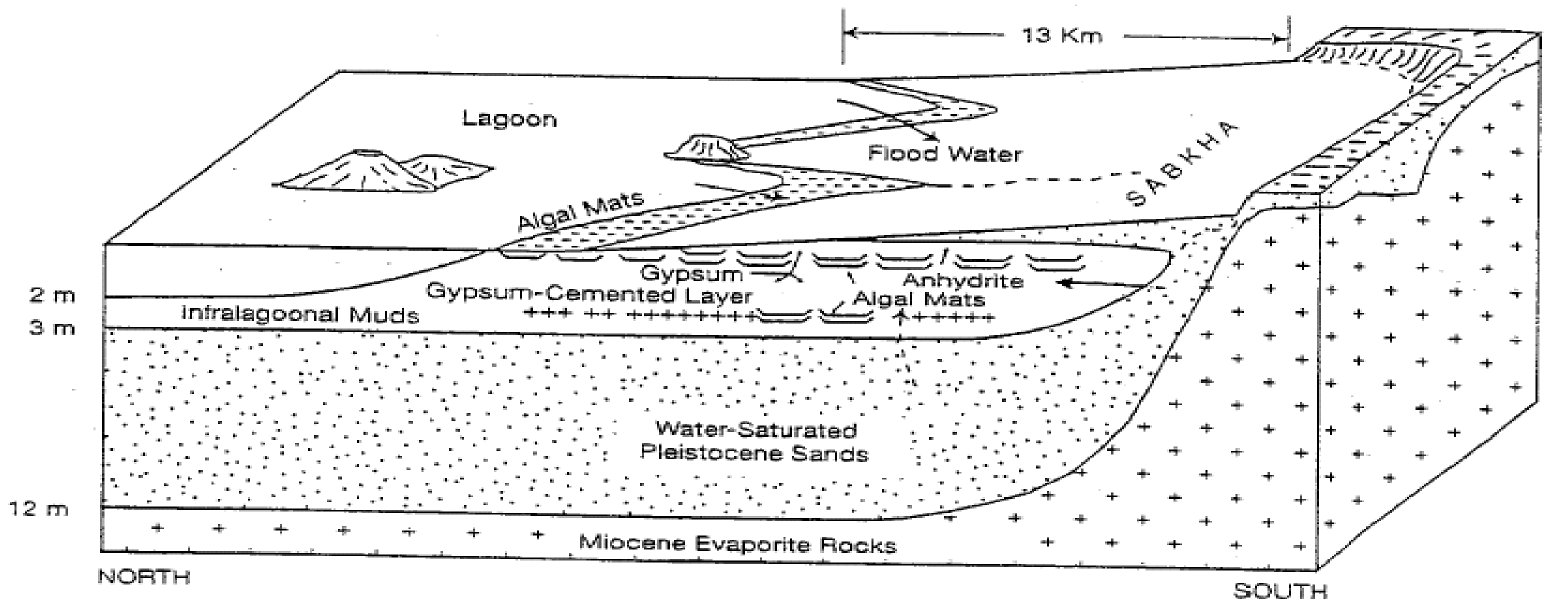
Evaporites – Rock Types

Evaporites may be classified as chlorides sulphates or carbonates on the basis of their chemical composition, Table 2.

Calcium Sulphates (gypsum and anhydrite) are deposited mainly as gypsum, which can then be altered to anhydrite with burial. This process is associated with a 30 to 40% loss of volume. Hence most old deposits are anhydrite. However the process is reversible and uplift and exposure to low-salinity water results in gypsum with a corresponding increase in volume.

Halite forms as crusts in shallow water or as finely laminated deposits in deeper water.

Evaporites – Rock Types



Abu Dhabi sabkha, Persian Gulf. Schematic representation of a typical sabkha environment in which penecontemporaneous dolomite forms, commonly in association with gypsum and anhydrite, owing to evaporitic concentration of Mg. [After Butler, G. P., 1969, Modern evaporite deposition and geochemistry of coexisting brines, the sabkha, Trucial Coast, Arabian Gulf: Jour. Sed. Petrology, v. 39, Fig. 2, p. 72, reprinted by permission of SEPM, Tulsa, OK.]

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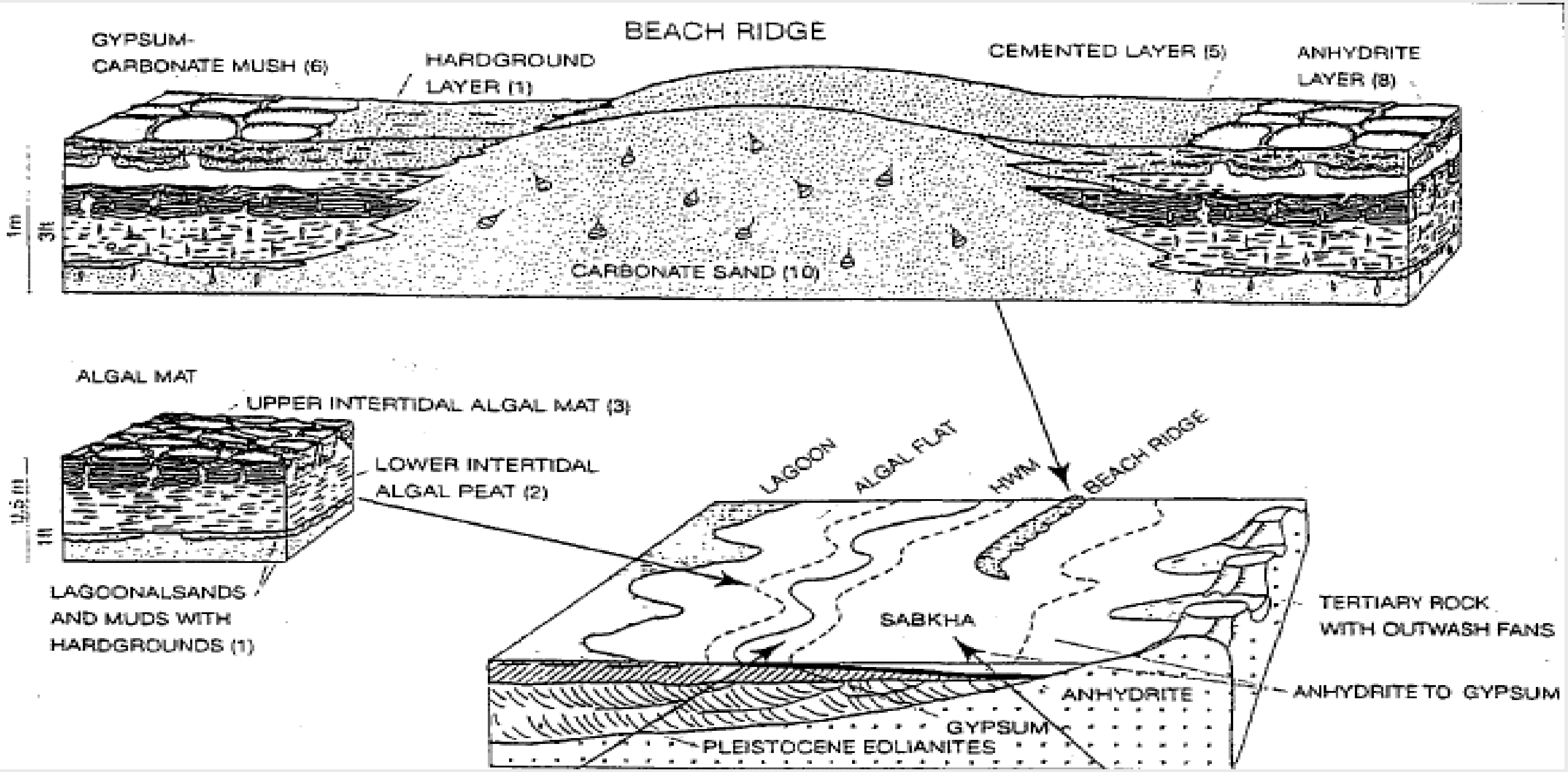
Evaporites – Rock Types



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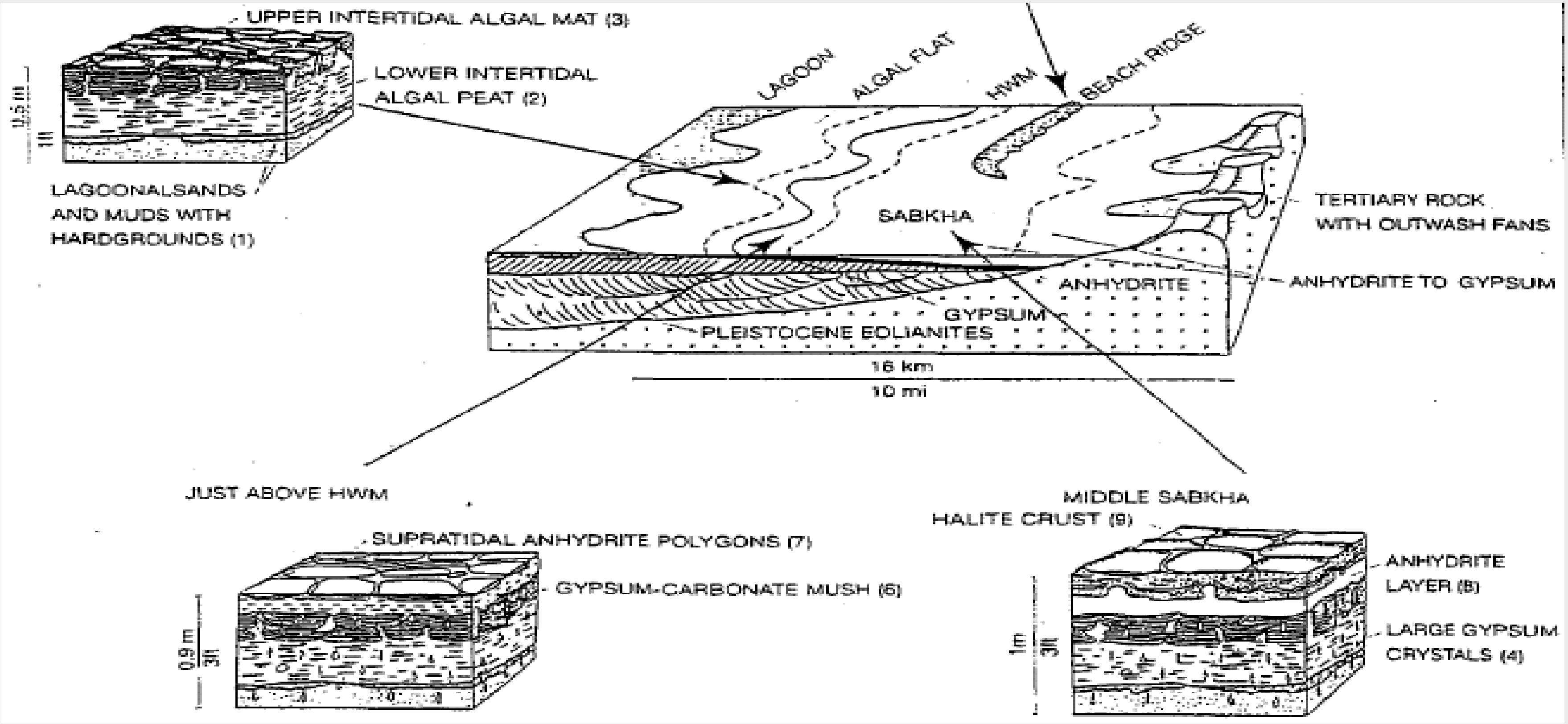
Evaporites – Rock Types



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Engineering Characteristics of Carbonates Structural

The main characteristics are:

1. Long-term solubility.
2. Effects of past solution.
3. Presence of thin argillaceous layers.

The classic problems associated with carbonate rocks include:

- Collapse and subsidence due to sinkholes.
- Questions over whether long-term solution could affect the engineering performance of the rocks.
- Poor foundation conditions, due to high void ratio, low-density granular materials of low strength and high compressibility; and grains themselves, which are of low strength. These features can also result in potential for collapse type behaviour.
- Large-scale landsliding on thin low strength layers that have weathered or been altered at great depth in conjunction with deep solution processes.
- Solution features often occur well below the groundwater table and therefore caves at depth should be expected.

Engineering Characteristics of Carbonates Hydrogeologic

Some hydrogeological implications of limestone/dolomite rocks include:

1. Subhorizontal solution features are usually of more importance than subvertical features, although this may be a sampling issue, Figure 36.
2. Experience has shown that major lineaments and lineament intersections are high success targets for groundwater wells, Figure 37. However deep soils and weathering/solution may make these sites difficult and expensive to drill.
3. Tension zones, eg anticlinal axes, often show more solution features, Figure 38.
4. Permeability may be almost infinite, due to karstic formation.

Engineering Characteristics of Evaporites

Because of their limited distribution as rocks on the earth evapoites are not associated with same widespread issues as carbonates, but there are some particular issues, which practitioners need to be aware of. The main issues are:

1. Volume changes associated with hydration changes.
2. Reaction with other minerals.
3. Solution, often down to depths of 700 to 1000m.

Firstly the volume changes:

ANHYDRITE	+	WATER	=	GYPSUM
Ca SO4	+	2H2O	=	Ca SO4 2H2O
100 Vol. Units	+	78	=	163

Anhydrite is generally deeply buried and drill through Gypsum at the surface into anhydrite at great depth.

The volume changes can be dramatic with significant stresses and uplift, this is one of the formation issues with Sabka's.

The big question is has the volume change from Gypsum to anhydrite fully occurred? When tunnelling through these rocks there could be volume changes 20 years ater construction is completed, leading to collapse of the tunnel sides.

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Solubility

Materials	Solubility in pure water— c_s (kg/m^3) at 10°C
Gypsum	2.5
Halite	360.0
Limestone	0.015
Anhydrite	2.0
Quartz	0.01

Solubility

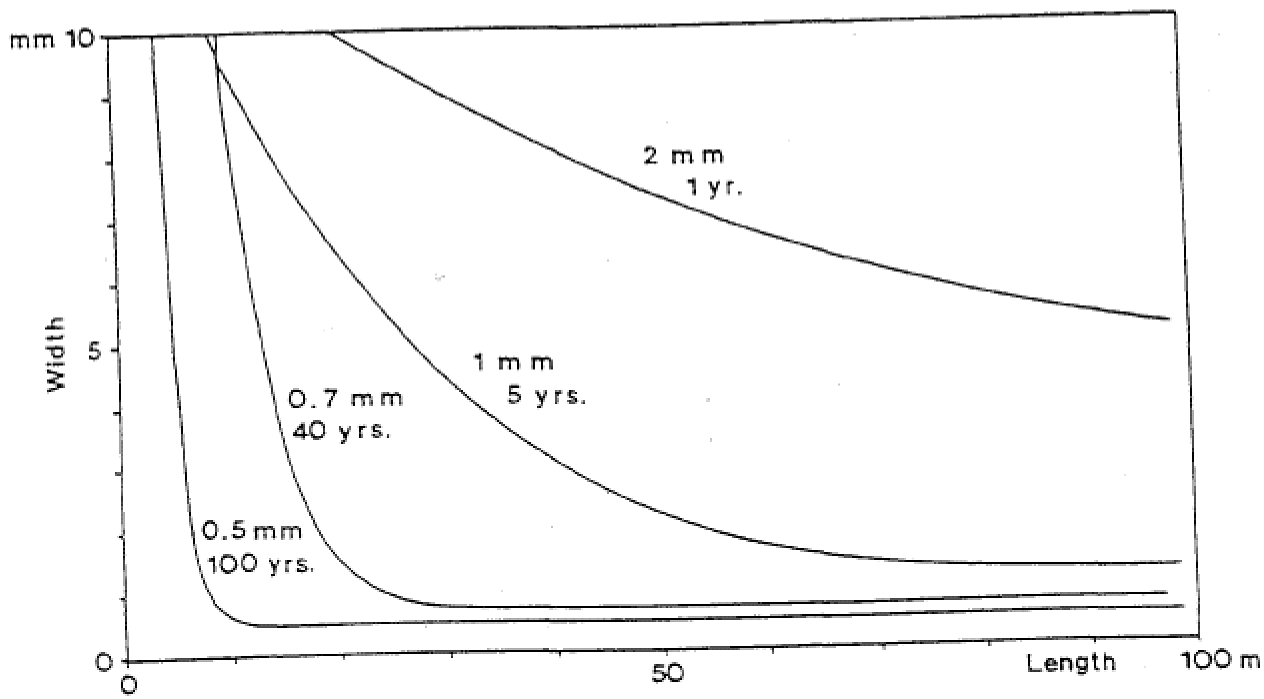

FIG. 3. Enlargement of fissures in calcium carbonate rock by pure flowing water.

Solubility & Grouting

TABLE 3. *Fissure width and seepage control*

	Fissure width (mm)		
	For stable inlet face retreat	For a rate of retreat of 0.1 m/year	Suggested preventive measures
Gypsum	0.2	0.3	Grouting
Anhydrite	0.1	0.2	Cut-off—eg. plastic concrete
Halite	0.05	0.05	Cut-off—eg. plastic concrete
Limestone	0.5	1.5	Grouting

These values are for pure water; at fissure spacing on one every metre and an hydraulic gradient of 0.2.

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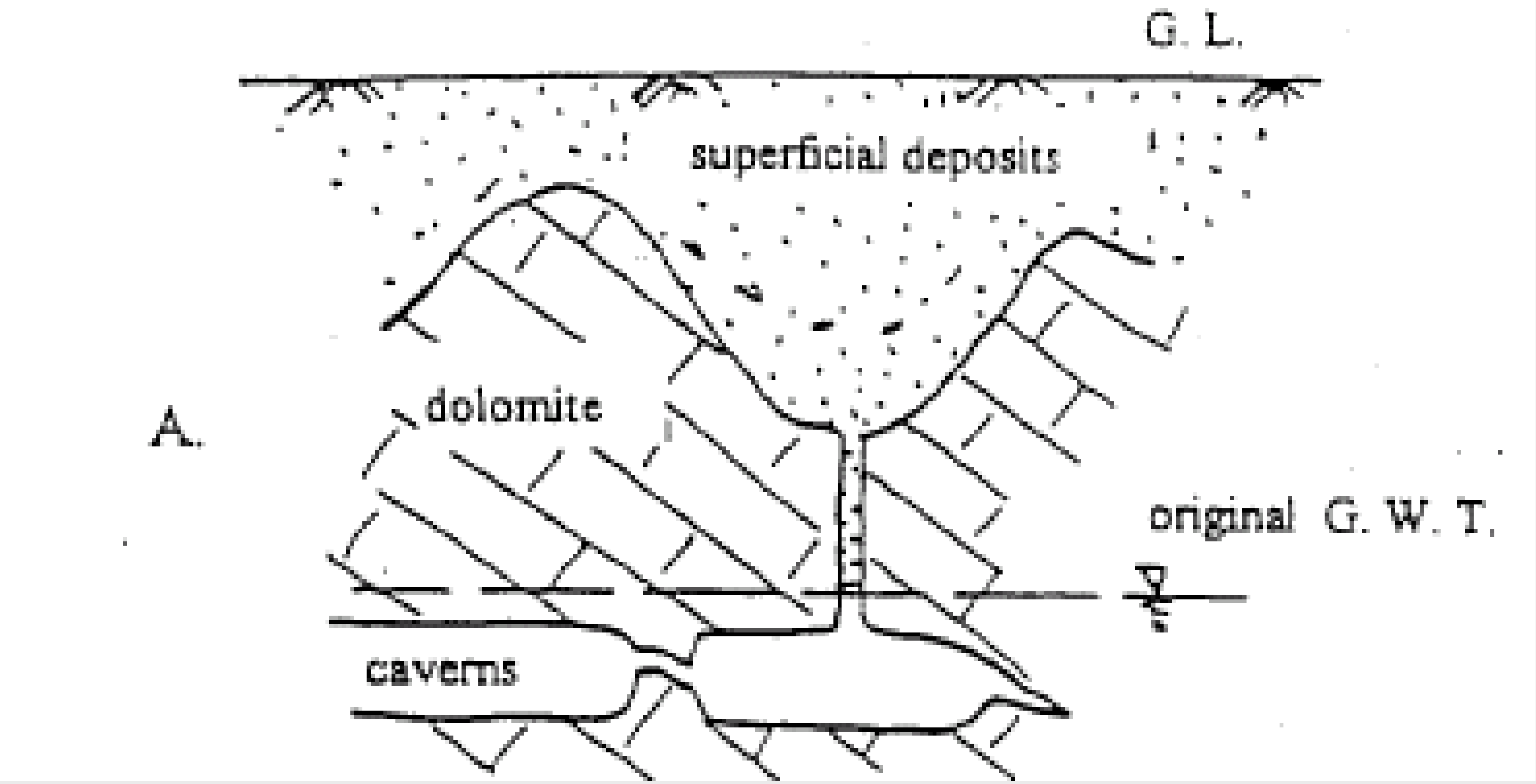
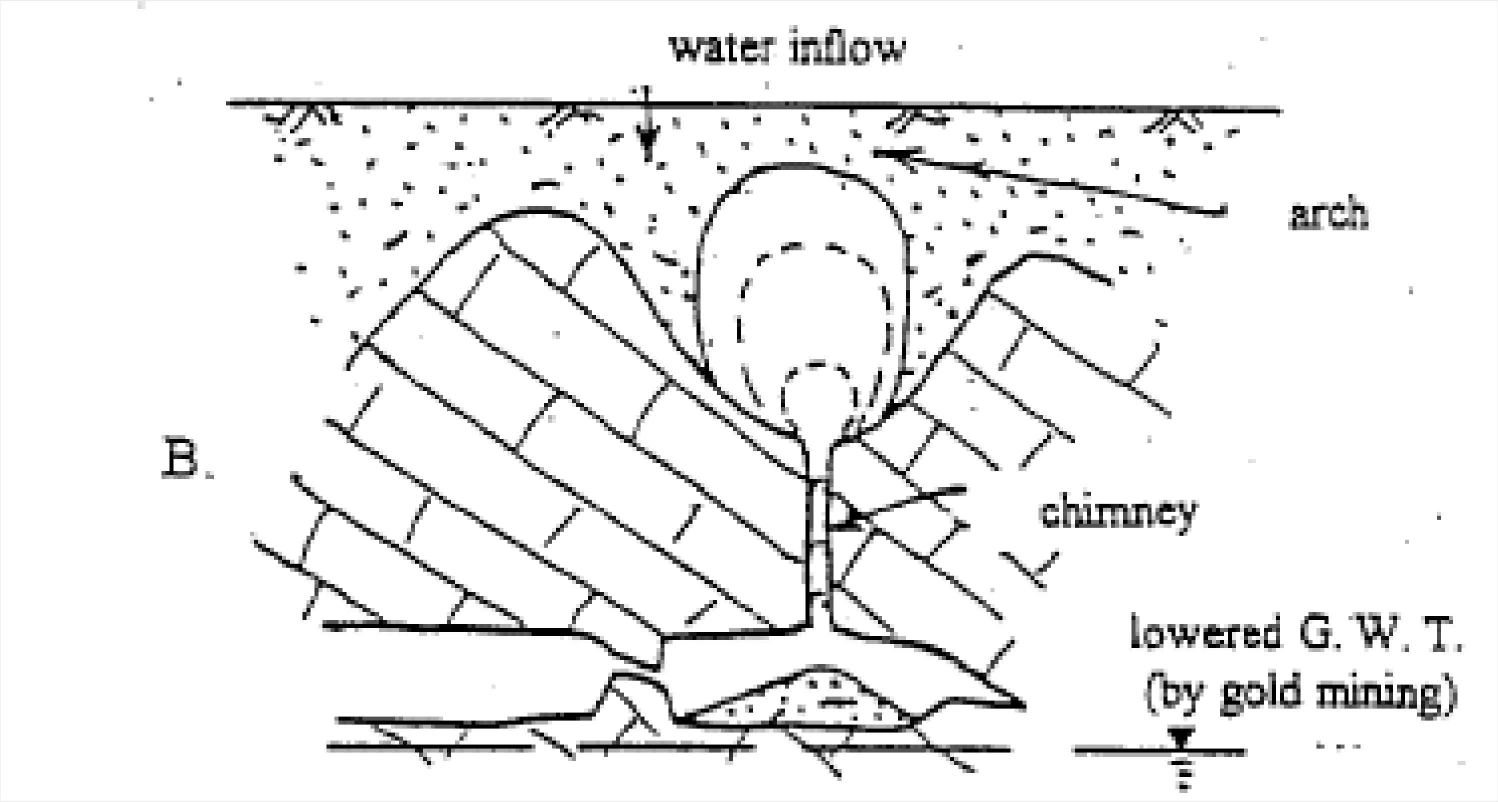
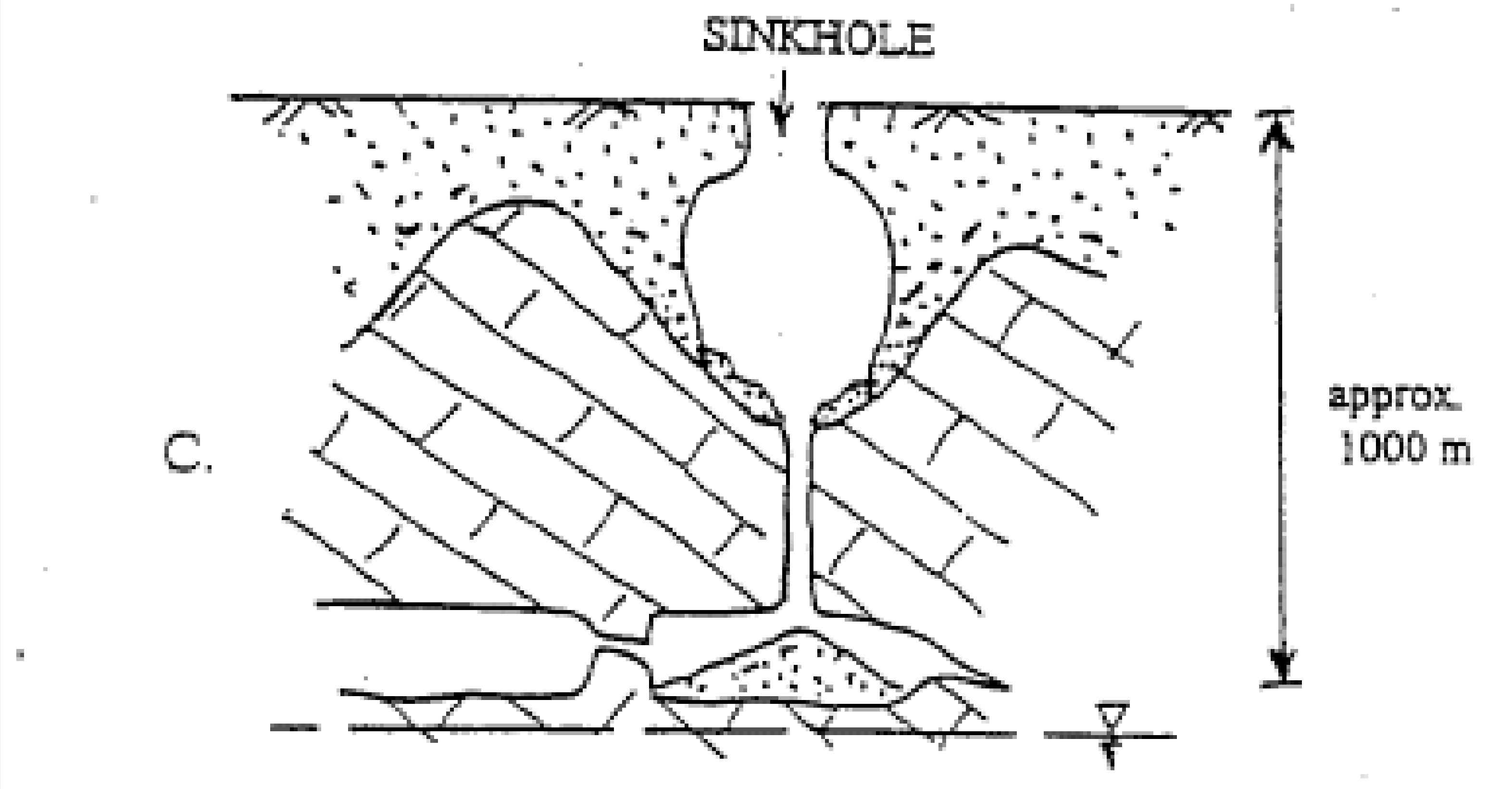
Sinkholes – Stage 1



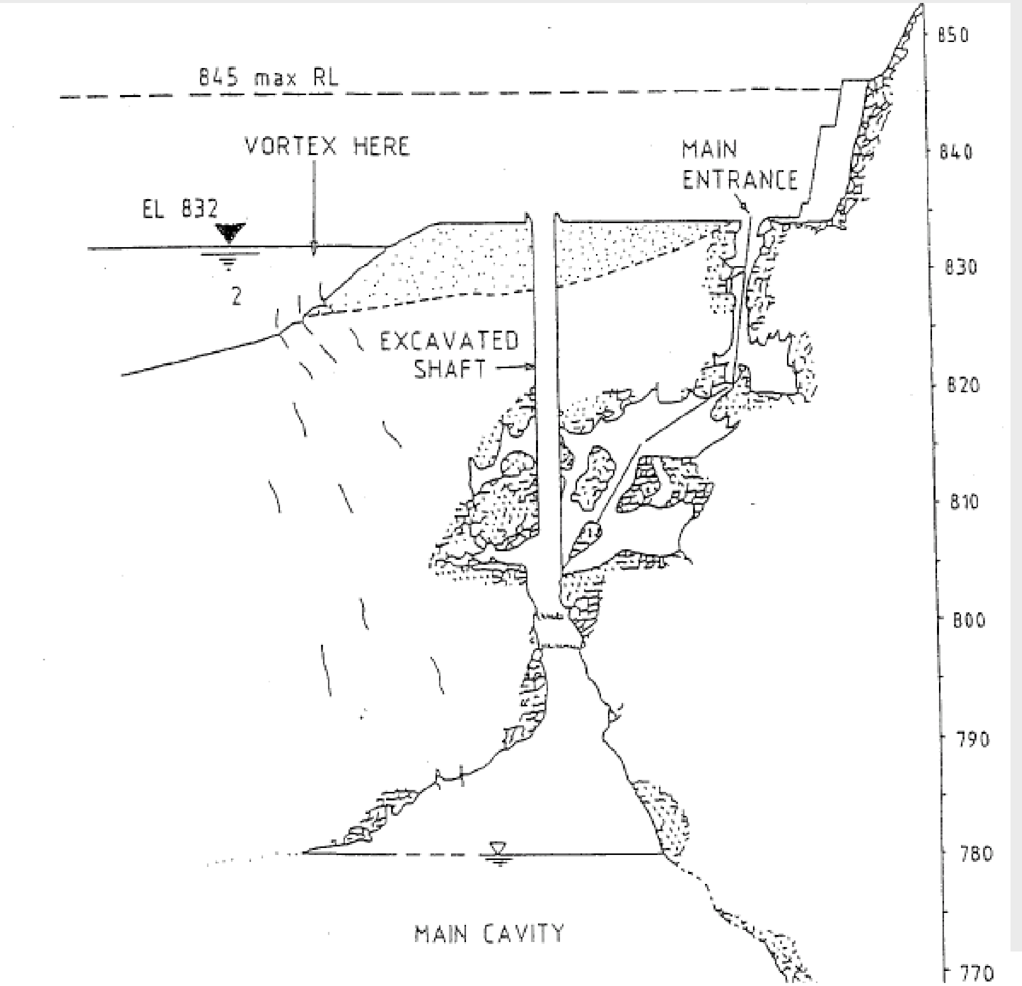
Sinkholes – Stage 2



Sinkholes – Stage 3



Sinkholes – Dam Abutments



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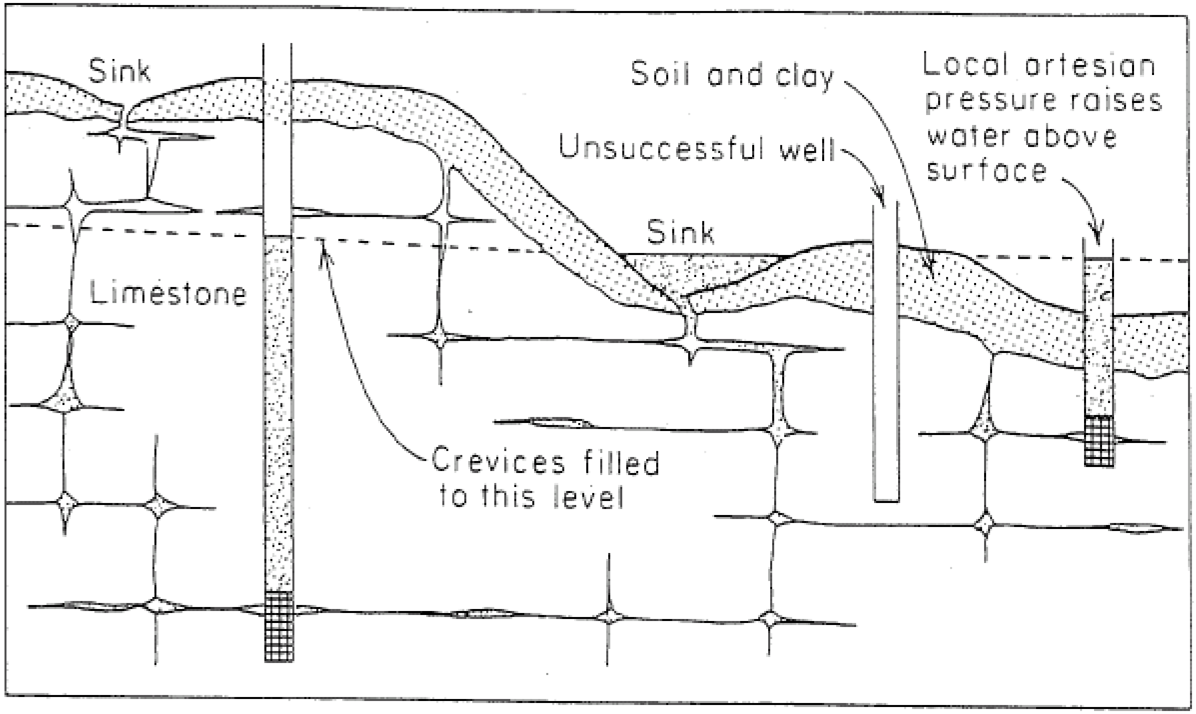
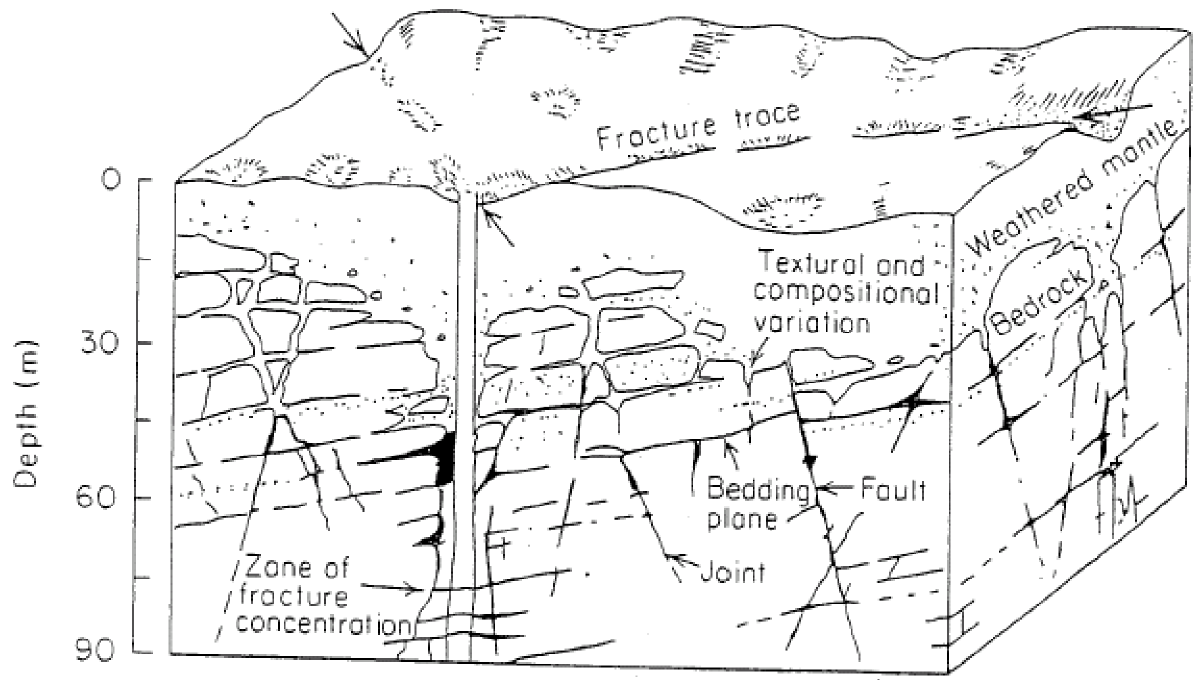
Carbontaes – Groundwater



Schematic illustration of the occurrence of groundwater in carbonate rock in which secondary permeability occurs along enlarged fractures and bedding plane openings (after Walker, 1956; Davis and De Wiest, 1966).

Carbonates – Groundwater



Occurrence of permeability zones in fractured carbonate rock. Highest well yields occur in fracture intersection zones (after Lattman and Parizek, 1964).

Metamorphism

- Metamorphism can be defined as the solid state recrystallisation of pre-existing rocks due to changes in heat and/or pressure and/or introduction of fluids i.e without melting. There will be mineralogical, chemical and crystallographic changes.

- Metamorphism produced with increasing pressure and temperature conditions is known as prograde metamorphism. Conversely, decreasing temperatures and pressure characterize retrograde metamorphism.

Limits of Metamorphism

- The temperature lower limit of metamorphism is considered to be between 100 - 150° C, to exclude diagenetic changes, due to compaction, which result in sedimentary rocks. There is no agreement as for a pressure lower limit. Some workers argue that changes in atmospheric pressures are not metamorphic, but some types of metamorphism can occur at extremely low pressures (see below).
- The upper boundary of metamorphic conditions is related to the onset of melting processes in the rock. The temperature interval is between 700 - 900° C, with pressures that depend on the composition of the rock. Migmatites are rocks formed on this borderline. They present both melting and solid-state features.

Regional Metamorphism

- Regional or Barrovian metamorphism covers large areas of continental crust typically associated with mountain ranges, particularly subduction zones or the roots of previously eroded mountains. Conditions producing widespread regionally metamorphosed rocks occur during an orogenic event.
- The collision of two continental plates or island arcs with continental plates produce the extreme compressional forces required for the metamorphic changes typical of regional metamorphism. These orogenic mountains are later eroded, exposing the intensely deformed rocks typical of their cores.
- The conditions within the subducting slab as it plunges toward the mantle in a subduction zone also produce regional metamorphic effects. The techniques of structural geology are used to unravel the collisional history and determine the forces involved. Regional metamorphism can be described and classified into metamorphic facies or zones of temperature/pressure conditions throughout the orogenic terrane.

Metamorphic Facies

- Metamorphic facies are recognizable terranes or zones with an equilibrium assemblage of key minerals that were in equilibrium under specific range of temperature and pressure during a metamorphic event. The facies are named after the metamorphic rock formed under those facies conditions from basalt. Facies relationships were first described by Eskola (1920).

- Facies:
  - Low T - low P : Zeolite
  - Mod - high T - low P : Prehnite-Pumpellyite
  - High-P low T : Blueschist
  - Mod P - Mod to high T: Greenschist - Amphibolite – Granulite
  - High P - Mod - high T : Eclogite

Metamorphic Grades

In zones of progressive metamorphism in Scotland), metamorphic rades are also classified by mineral assemblage based on the appearance of key minerals in rocks of pelitic (shaly, aluminous) origin:

- Low grade ------------------- Intermediate --------------------- High grade
- Greenschist ---------------- Amphibolite ----------------------- Granulite
- Slate ------ Phyllite ------ Schist --------- Gneiss ----------------------- Migmatite(partial metling) >>>melt

- Chlorite zone
  - Biotite zone
    - Garnet zone
      - Staurolite zone
        - Kyanite zone
          - Sillimanite zone

Contact (Thermal) Metamorphism

Contact metamorphism occurs typically around intrusive igneous rocks as a result of the temperature increase caused intrusion of magma into cooler country rock.

The area surrounding the intrusion (called aureoles) where the contact metamorphism effects are present is called the metamorphic aureole. Contact metamorphic rocks are usually known as hornfels.

Rocks formed by contact metamorphism may not present signs of strong deformation and are often fine-grained.

Contact (Thermal) Metamorphism

Contact metamorphism is greater adjacent to the intrusion and dissipates with distance from the contact.

The size of the aureole depends on the heat of the intrusive, its size, and the temperature difference with the wall rocks.

Dykes generally have small aureoles with minimal metamorphism whereas large ultramafic intrusions can have significantly thick and well-developed contact metamorphism.

Contact (Thermal) Metamorphism

The metamorphic grade of an aureole is measured by the peak metamorphic mineral which forms in the aureole.

This is usually related to the metamorphic temperatures of pelitic or alumonisilicate rocks and the minerals they form.

The metamorphic grades of aureoles are andalusite hornfels, sillimanite hornfels, pyroxene hornfels.

Contact (Thermal) Metamorphism

Magmatic fluids coming from the intrusive rock may also take part in the metamorphic reactions. Extensive addition of magmatic fluids can significantly modify the chemistry of the affected rocks. In this case the metamorphism grades into metasomatism.

If the intruded rock is rich in carbonate the result is a skarn. Fluorine-rich magmatic waters which leave a cooling granite may often form greisens within and adjacent to the contact of the granite.

Metasomatic altered aureoles can localize the deposition of metallic ore minerals and thus are of economic interest

Hydrothermal Metamorphism

Hydrothermal metamorphism is the result of the interaction of a rock with a high-temperature fluid of variable composition. The difference in composition between existing rock and the invading fluid triggers a set of metamorphic and metasomatic reactions.

The hydrothermal fluid may be magmatic (originate in an intruding magma), circulating groundwater, or ocean water. Convective circulation of water in the ocean floor basalts produces extensive hydrothermal metamorphism adjacent to spreading centers and other submarine volcanic areas. The patterns of this hydrothermal alteration is used as a guide in the search for deposits of valuable metal ores.

Prograde and Retrograde Metamorphism

Metamorphism is further divided into prograde and retrograde metamorphism. Prograde metamorphism involves the change of mineral assemblages (paragenesis) with increasing temperature and (usually) pressure conditions. These are solid state dehydration reactions, and involve the loss of volatiles such as water or carbon dioxide.

Prograde metamorphism results in a rock representing the maximum pressure and temperature experienced. These rocks often return to the surface without undergoing retrograde metamorphism , where the mineral assemblages would become more stable under lower pressures and temperatures.

Prograde and Retrograde Metamorphism

Retrograde metamorphism involves the reconstitution of a rock under decreasing temperatures (and usually pressures) where revolatisation occurs; allowing the mineral assemblages formed in prograde metamorphism to return to more stable minerals at the lower pressures.

This is a relatively uncommon processes, because volatiles must be present for retrograde metamorphism to occur.

Most metamorphic rocks return to the surface as a representation of the maximum pressures and temperatures they have undergone.

Foliation

The layering within metamorphic rocks is called foliation (derived from the Latin word folia, meaning "leaves"), and it occurs when a strong compressive force is applied from one direction to a recrystallizing rock.

This causes the platy or elongated crystals of minerals, such as mica and chlorite, to grow with their long axes perpendicular to the direction of the force.

This results in a banded, or foliated, rock, with the bands showing the colors of the minerals that formed them.

Metamorphic Rock Textures

The five basic metamorphic textures with typical rock types are:

- Slaty: slate and phyllite; the foliation is called 'slaty cleavage'
- Schistose: schist; the foliation is called 'schistocity'
- Gneissose: gneiss; the foliation is called 'gneisocity'
- Granoblastic: granulite, some marbles and quartzite
- Hornfelsic: hornfels and skarn

Metamorphic Rock - Slate

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Metamorphic Rock - Slate

Metamorphic Rock - Phyllite

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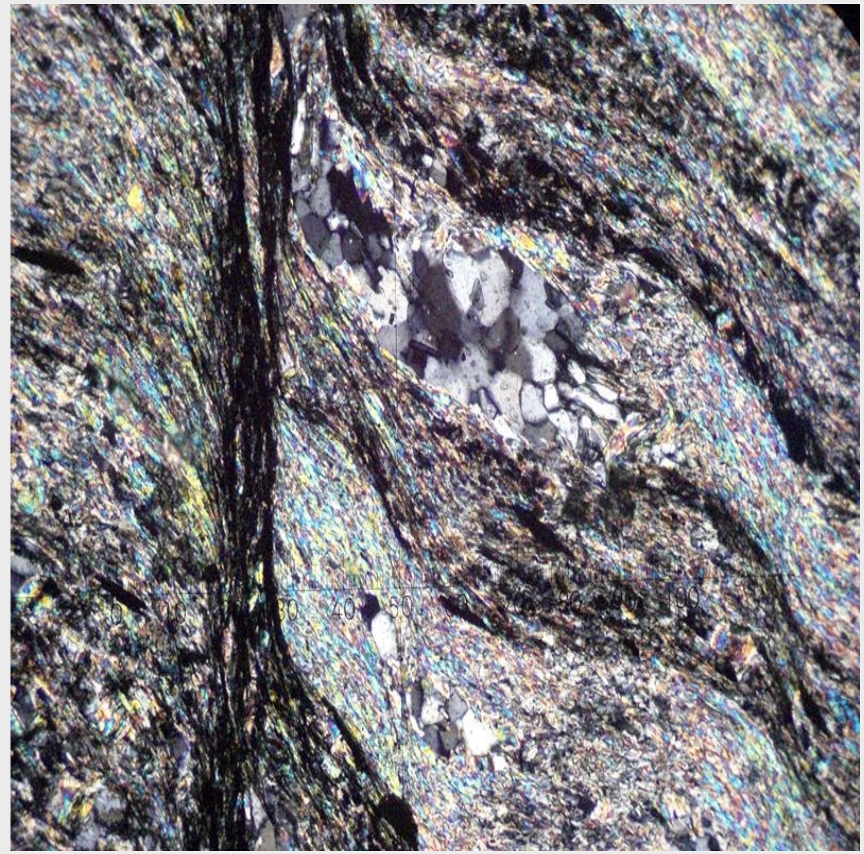
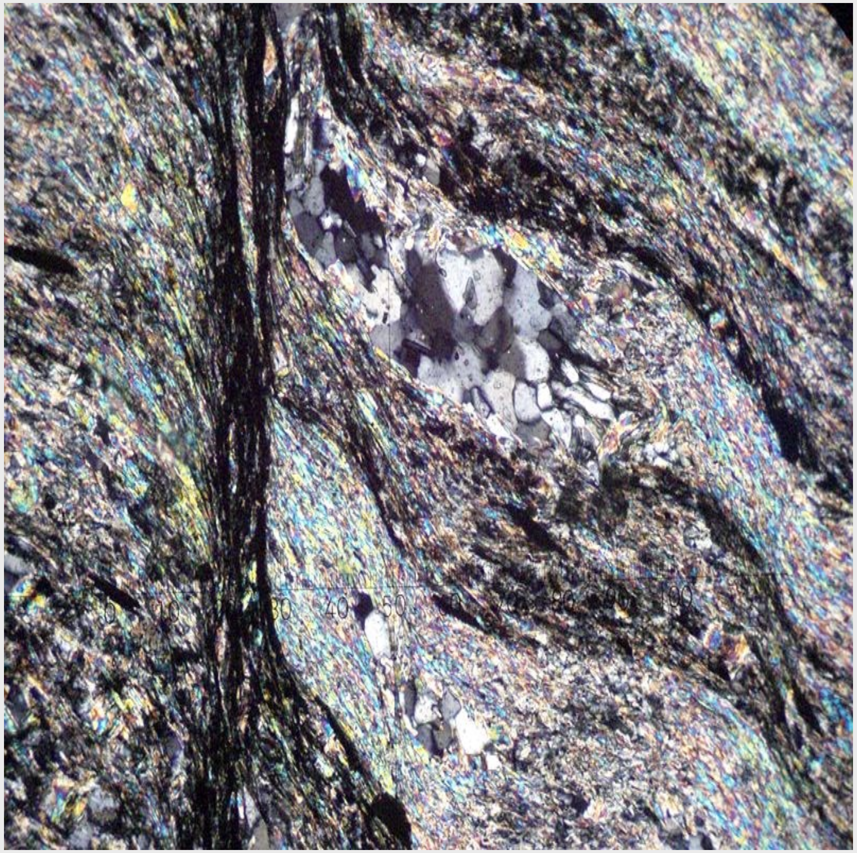
Metamorphic Rock - Phyllite



Metamorphic Rock - Phyllite

Phyllite is a type of foliated metamorphic rock primarily composed of quartz, sericite mica, and chlorite; the rock represents a gradation in the degree of metamorphism between slate and mica schist. Minute crystals of graphite, sericite, or chlorite impart a silky, sometimes golden sheen to the surfaces of cleavage (or schistosity).



Metamorphic Rock - Schist

The schists form a group of medium-grade metamorphic rocks, chiefly notable for the preponderance of lamellar minerals such as micas, chlorite, talc, hornblende, graphite, and others. Quartz often occurs in drawn-out grains to such an extent that a particular form called quartz schist is produced. By definition, schist contains more than 50% platy and elongated minerals, often finely interleaved with quartz and feldspar.

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Metamorphic Rock - Gneiss

Gneissic rocks are usually medium to coarse foliated and largely recrystallized but do not carry large quantities of micas, chlorite or other platy minerals. Gneisses that are metamorphosed igneous rocks or their equivalent are termed granite gneisses, diorite gneisses, etc..

Metamorphic Rock - Granulite

Granulites are metamorphic rocks that have experienced high temperatures of metamorphism. They typically have a granular (granoblastic) texture -- that is, a texture comprised of similarly sized and shaped grains -- and hence the name granulite.

Metamorphic Rock - Marble

Marble is a metamorphic rock resulting from the metamorphism of limestone, composed mostly of calcite (a crystalline form of calcium carbonate, $CaCO_3$).

Metamorphic Rock - Quartzite

Quartzite is a hard, metamorphic rock which was originally sandstone.[1] Sandstone is converted into quartzite through heating and pressure usually related to tectonic compression within orogenic belts. Pure quartzite is usually white to grey. Quartzites often occur in various shades of pink and red due to varying amounts of iron oxide

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