Non-Marine Carbonates - Facies, Diagenesis and Porosity Development*

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Abstract

The discovery of major non-marine carbonate reservoirs in the South Atlantic offers new challenges for carbonate sedimentologists and reservoir geologists. Non-marine carbonate precipitation originates in a wide spectrum of settings, e.g. ambient temperature freshwater fluvial and lacustrine systems, alkaline and saline in lakes, and hydrothermal water springs. Such variability has limited the understanding of non-marine carbonate facies models and little information is available about their diagenetic pathways. This review aims to emphasize the specific properties of non-marine carbonate reservoirs. Their depositional environments include river cascades, barrages and channels, lake shorelines and epilimnion zones, sub-lacustrine groundwater springs, palustrine settings, and thermal water springs. Main external controls are basin morphology and hydrology, tectonic setting and climate.

As for marine carbonates, non-marine precipitation can be: 1) an abiotic process, driven by CO_2 degassing in cooling, flowing or wave agitated water or by mixing of bicarbonate-rich and Ca-rich waters at sub-lacustrine springs; 2) a biologically-induced process via biomineralization or organomineralization mechanisms associated to cyanobacteria, heterotrophic bacteria and EPS; 3) a biologically-controlled process in skeletal biota, e.g. molluscs, ostracods and algae. Unlike marine carbonate systems, where environmental and temporal controls on the carbonate factory, its original mineral composition, primary and secondary porosity are relatively well understood, non-marine carbonates have setting-specific mineral suites, build-up morphologies, microfabrics and porosity developments. Water chemistry, in particular its Mg/Ca ratio (and eventually temperature), play a key role in determining the primary carbonate mineralogy and the associated minerals, including clays. The primary mineralogy affects the diagenetic potentials of the carbonates, producing different diagenetic pathways and porosity development. Non-marine carbonates also exhibit a wider range of primary pore systems reflecting complex interactions between abiotic and biologically-induced precipitation processes: novel framework porosity, i.e. within dendritic and shrub-like growth forms, and unusual forms such as coated-bubble porosity. Secondary

porosity includes biomoldic (after degradation of vegetation and aragonitic shell dissolution), and vuggy porosity due to meteoric dissolution.

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NON-MARINE CARBONATES – FACIES, DIAGENESIS AND POROSITY

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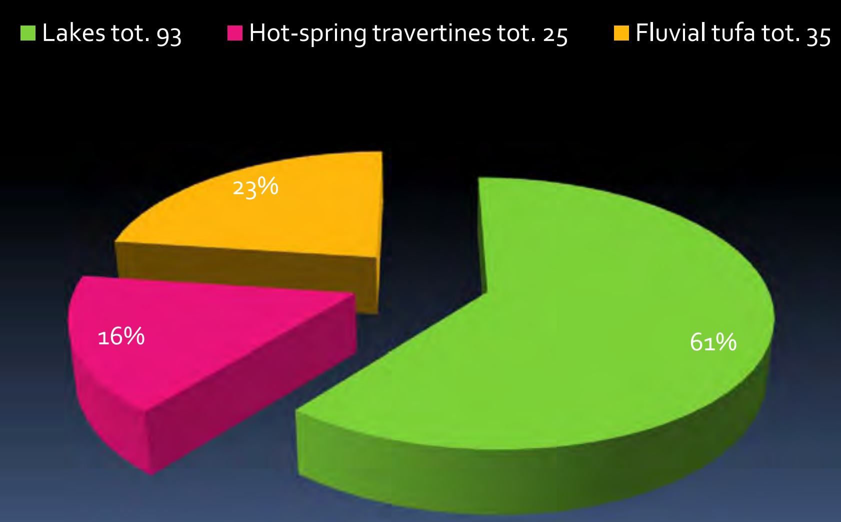
Non-marine carbonate buildups

- literature review of 400 publications + selected studies
- 153 case studies worldwide from Holocene to Paleozoic including carbonate buildups (both ABIOTIC and BIOLOGICALLY INDUCED/INFLUENCED)
- **wide spectrum of depositional settings**

a) subaqueous lacustrine settings (FRESHWATER, ALKALINE, SALINE LAKES)

b) subaerial flowing-water systems : freshwater ambient temperature fluvial systems (TUFA) and hydrothermal (> 20°C) vents (TRAVERTINE).

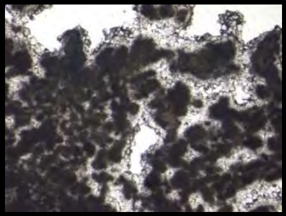
Non-marine carbonate types



WHAT ARE THE DIFFERENCES IN TERMS OF GEOMETRY, FABRICS AND DIAGENESIS?

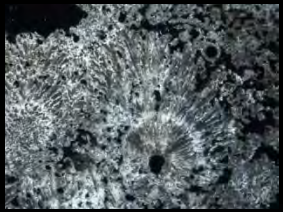
Key points.....

Different depositional settings and geometry of buildups (both abiotic and biologically induced/influenced)



Not all fabrics are diagnostic of depositional settings: laminated and clotted peloidal micrite (biologically induced/influenced) occur across the marine and non marine record

Shrubs: dendritic clotted peloidal fabrics (biologically induced/influenced) dominate but are not exclusive of slow-flowing hot-spring travertine pools and ponds



Crystalline crusts (rapid abiotic precipitation): diagnostic of lake spring mounds and hydrothermal subaerial systems (e.g. ikaite in lake spring mounds; feather and radial crystals in fast-flowing slopes, crystalline dendrites and spherulitic pisoids).

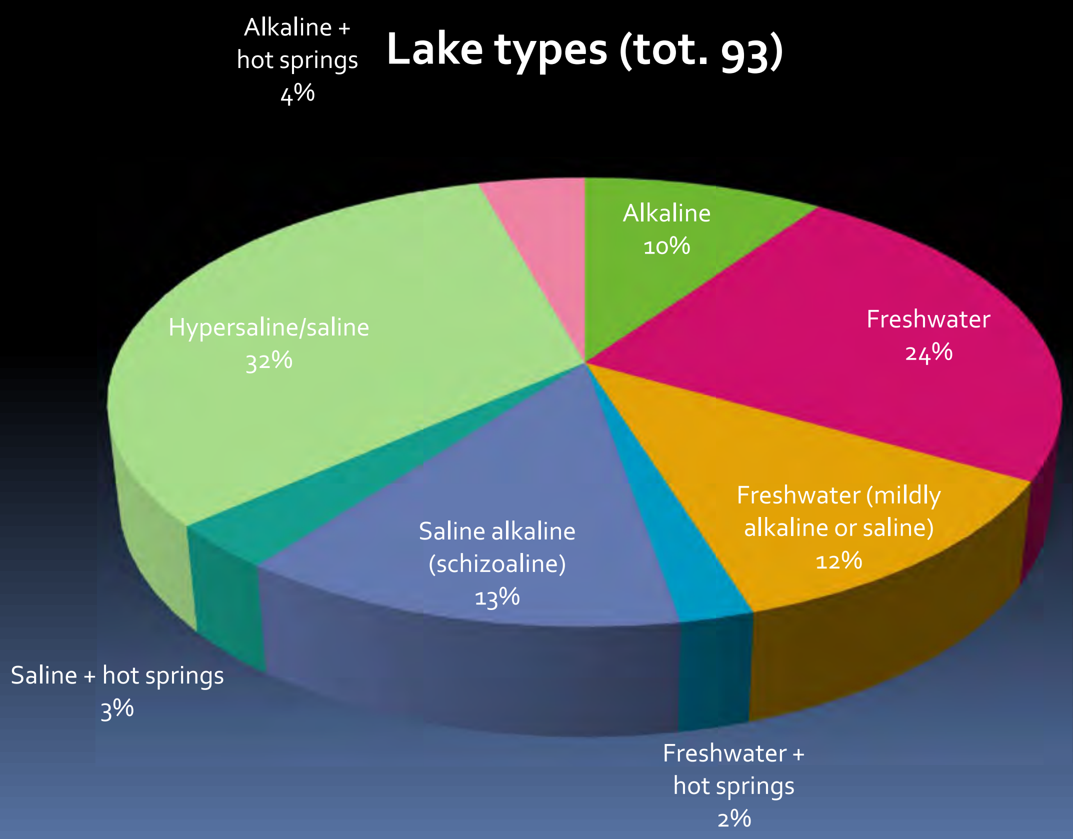
Primary mineralogy controlled by Mg/Ca ratio in lakes, by T in hot-spring travertine

Dolomitization and silicification rare in hot-spring travertine, common in lakes with high Mg/Ca and silica from volcaniclastic deposits

Wide range of primary porosity (framework porosity, bubbles); secondary (biomoldic, vuggy meteoric dissolution, fractures)

Carbonate buildups: in what type of lakes?

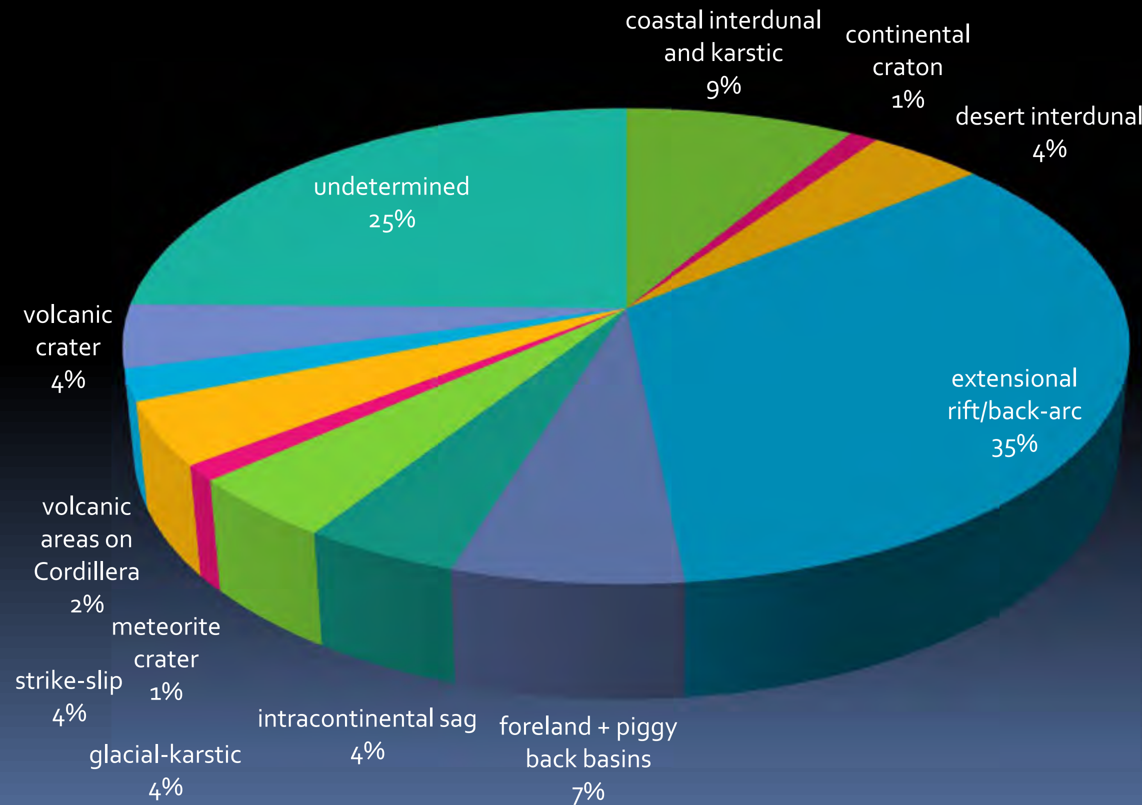
- Mostly systems with **hydrologic closure (no permanent outflow)**
- Commonly **highly to moderately alkaline or saline**; limited fauna
- 9% associated with **hot springs**
- **arid climate** contributes to increased salinity (high evaporation)



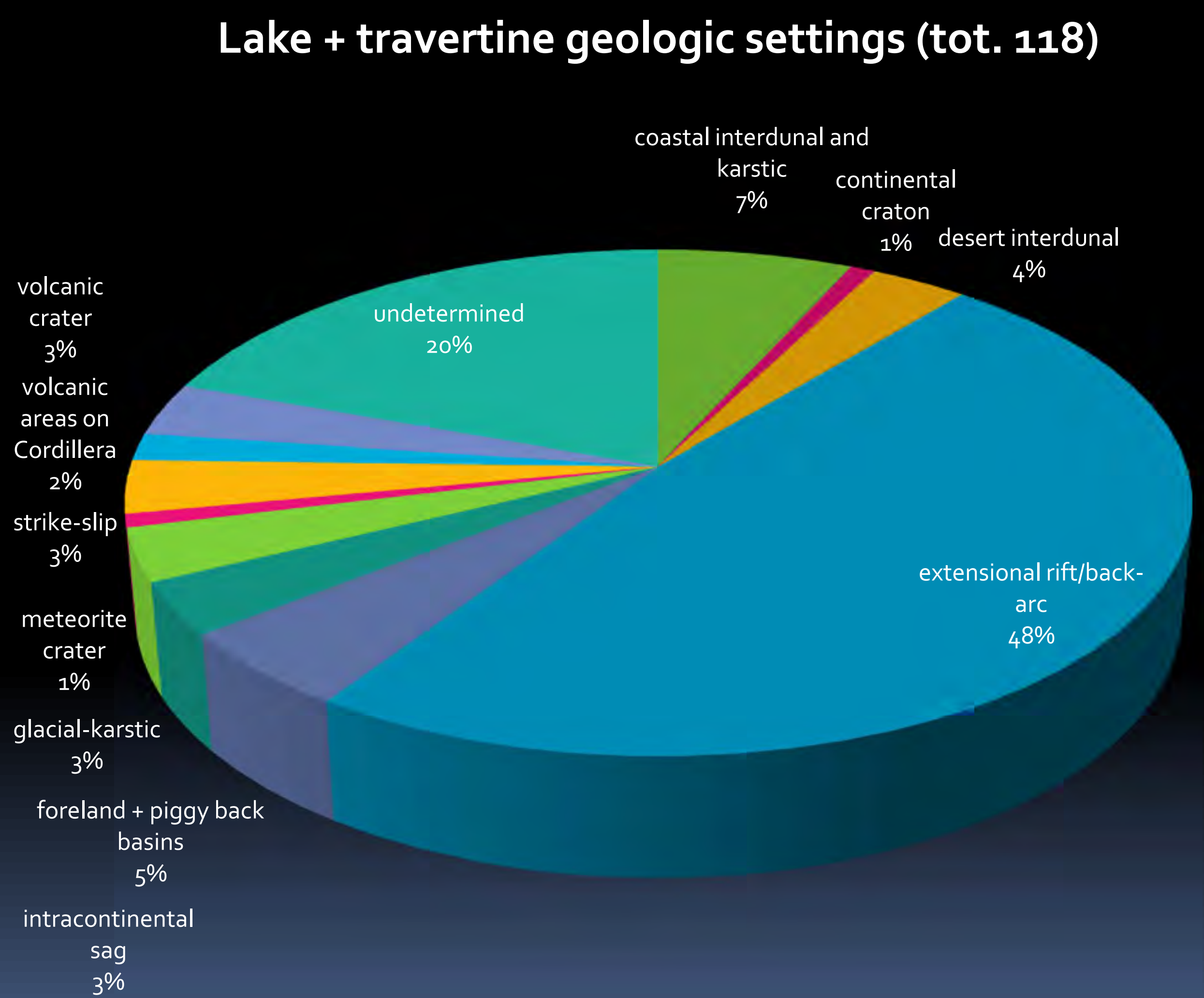
Lakes with carbonate buildups: where do they occur?

- predominantly **tectonically and volcanic active areas** , e.g. extensional + strike slip settings (fault controlled)
- hypersalinity in **coastal lakes and lagoons**

Lake geologic setting (tot. 93)

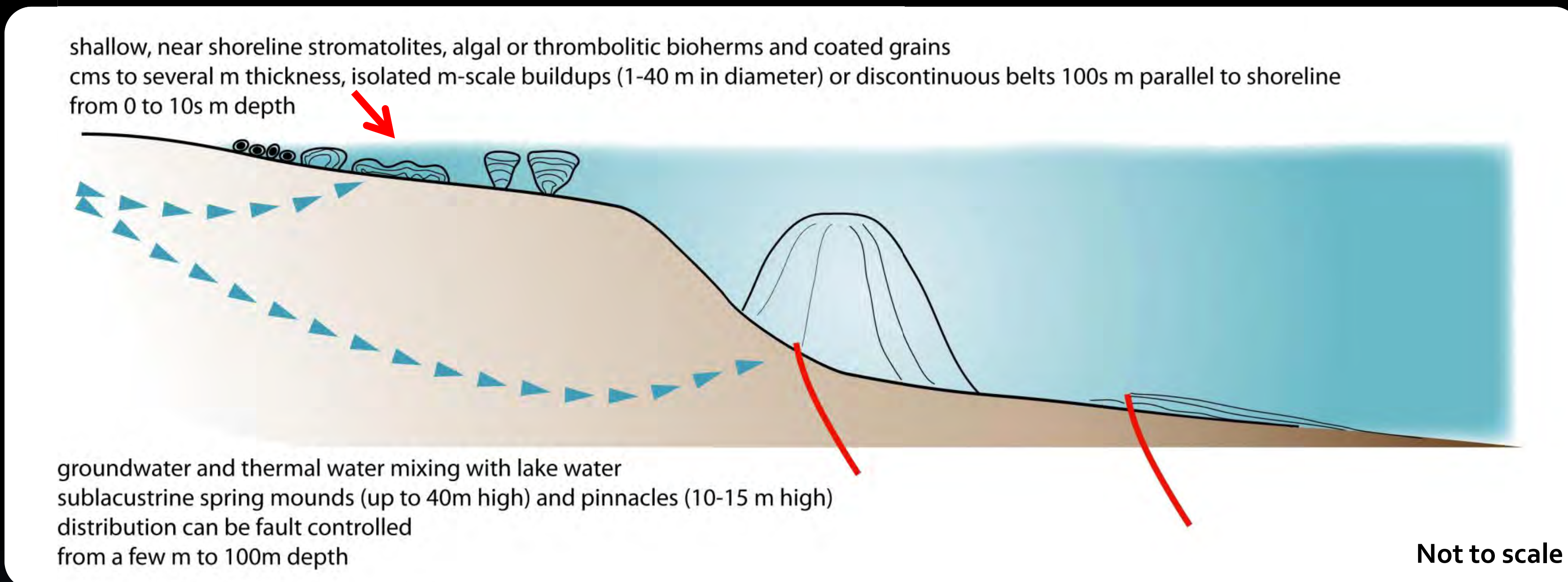


Hot-spring travertines: where do they occur?



- **Hot-spring travertine mostly from rift and back-arc basins (e.g. Pleistocene-Holocene Central Italian travertines)**

Lacustrine buildups: depositional environments and geometry



- Lacustrine carbonate buildups and bioherms at shallow shorelines or at sub-lacustrine groundwater springs.

- In rift lakes and active volcanic areas precipitation is eventually associated with hydrothermal springs.

Shoreline bioherms: Great Salt Lake

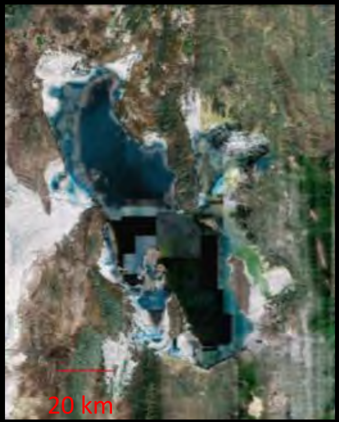
- **Great Salt Lake, Utah**: closed **hypersaline** (6-32%) , with low-angle high-energy lake margin, N-S oriented faults (cf. Eardley 1938; Carozzi 1962; Pedone & Folk 1996)

- Bioherms cover 160-280km2 ,on W high-energy shorelines (0.3-5m depth)

+ ooids; limited fauna (brine shrimps, gastropods ,ostracods)

- Elongated perpendicular to shoreline or sub-circular and coalesced
- Aragonite, calcite and early dolomite replacement; halite , gypsum ,

mirabilite



Google Earth image

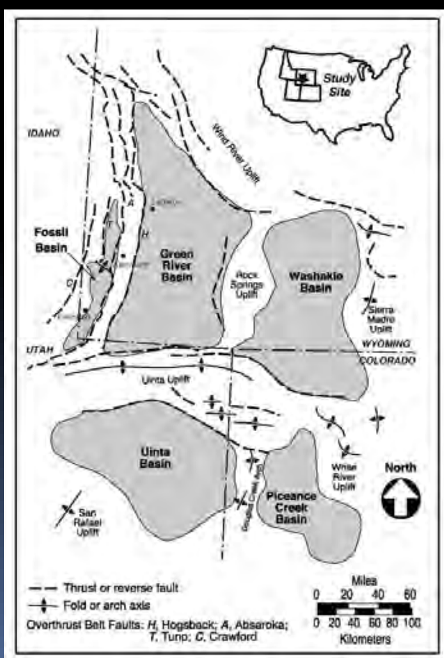
Great Salt Lake, Promontory Point

Shoreline bioherms: Great Salt Lake

Great Salt Lake, Bridger Bay, Antelope Island

Shoreline bioherms: Green River Fm.

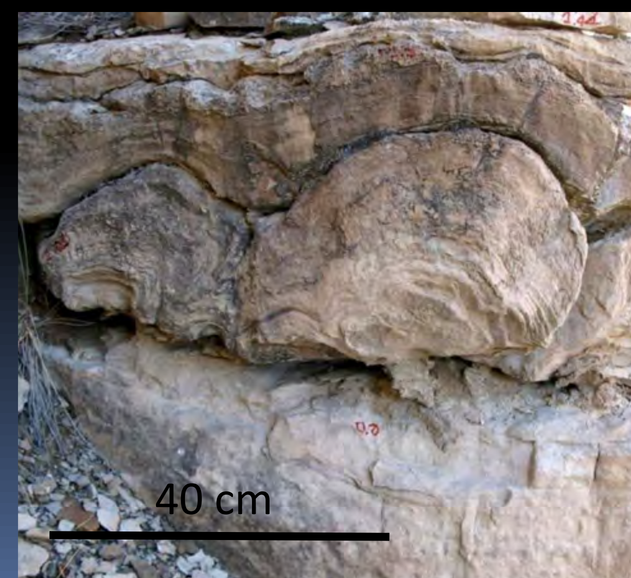
- **Green River Fm.,** Eocene, 4 basins across Wyoming, Utah and Colorado, **schizohaline (fluctuating from freshwater to saline alkaline lake with trona evaporites)**
- meter-scale caddisfly bioherms (Wyoming; cf. Leggitt & Cushman 2001)
- dm-scale laminated stromatolites (Utah)
- irregularly spaced 10s-100s m apart, discontinuous belts sub-parallel to shorelines for several 100s m



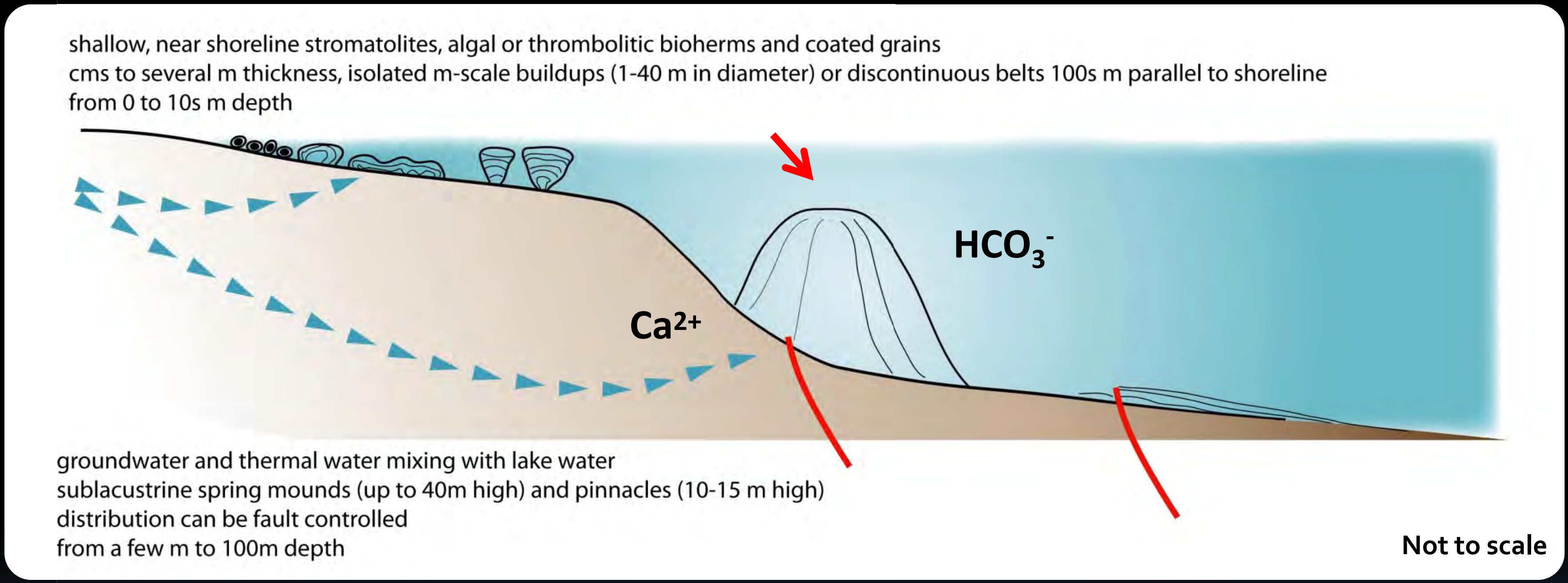
After Leggitt & Cushman (2001)

Caddisfly bioherms, Laney Mb., Wyoming

Stromatolites with ooidal grainstone, Utah



Lacustrine buildups: depositional environments and geometry



- Lacustrine carbonate buildups and bioherms at shallow shorelines or at sub-lacustrine groundwater springs.

- In rift lakes and active volcanic areas precipitation is eventually associated with hydrothermal springs.

Sub-lacustrine spring mounds: Pyramid Lake

- **Pyramid Lake, Nevada**: **freshwater to mildly alkaline**, hydrologic closure most of the time except at spill points, lake bottom oxygenated, depth 100 m; extensional tectonics Basin and Range Province.
- Upper Pleistocene mounds at groundwater (thermal, Ca2+ rich) discharge; spatial distribution fault controlled (Needle Rocks).
- Build-ups (meter to decameter scale) of dm-thick concentric layers (nodular, ikaite, dendritic, laminated; cf Benson 1994; Arp 1999); isolated with 100s m to kms spacing

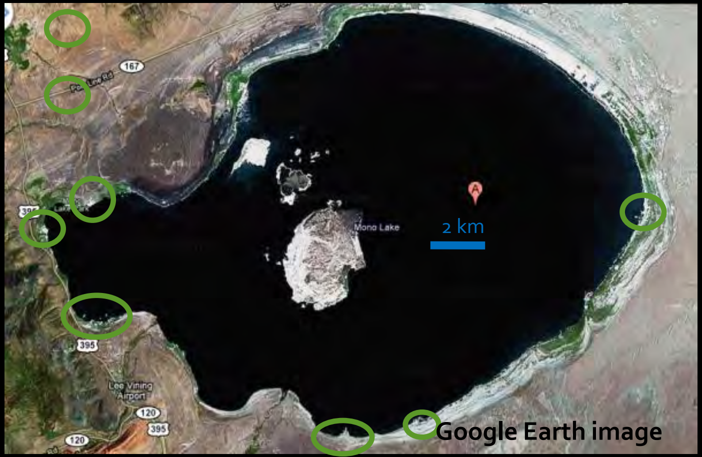
Google Earth image

Sub-lacustrine spring pinnacles: Mono Lake

•**Mono Lake, California**: closed **alkaline** (pH = 9.7) saline (50-90‰) meromictic lake, 38 m deep, only shrimps and alkali flies;
•volcanically active extensional structural depression.

•Upper Pleistocene pinnacles (1-7.5m high, 1.5-15 m in diameter; Scholl & Taft, 1964) , clustered in areas kms apart along faults and groundwater (thermal) discharge

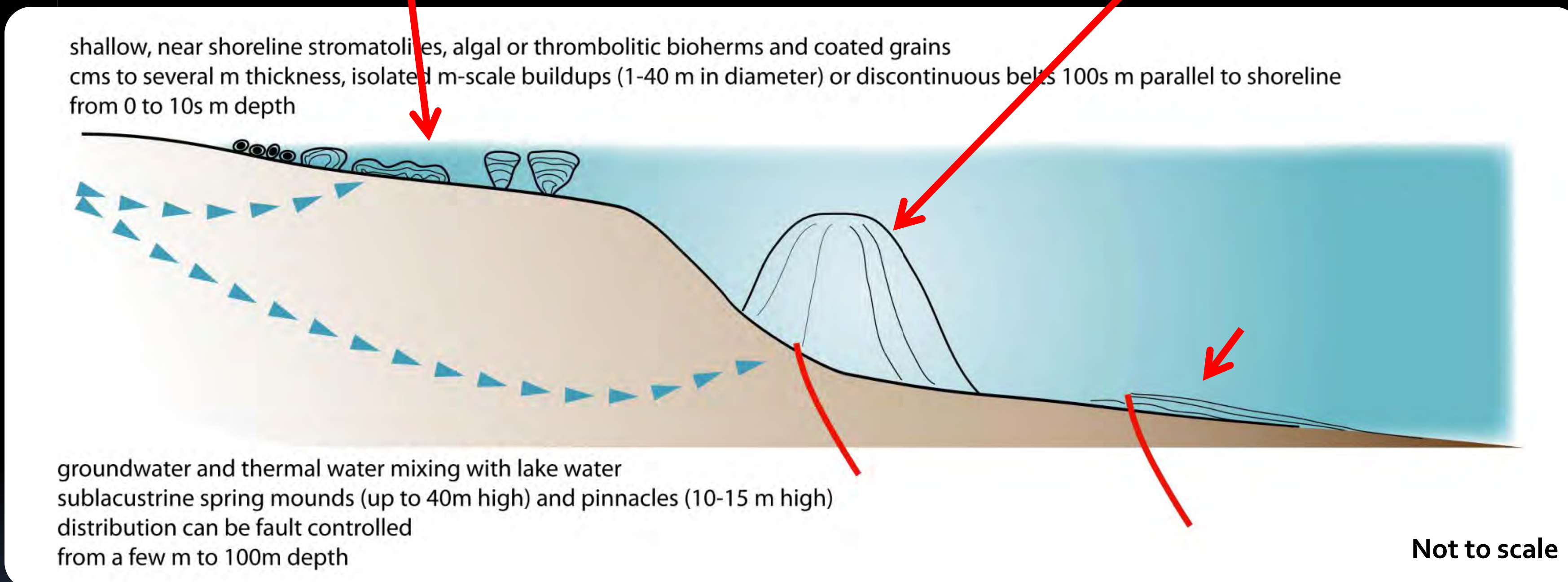
•calcite, aragonite , ikaite (Bischoff et al. 1993).



Lacustrine buildups: depositional environments and geometry

Discontinuous belts parallel to shorelines for 100s of meters

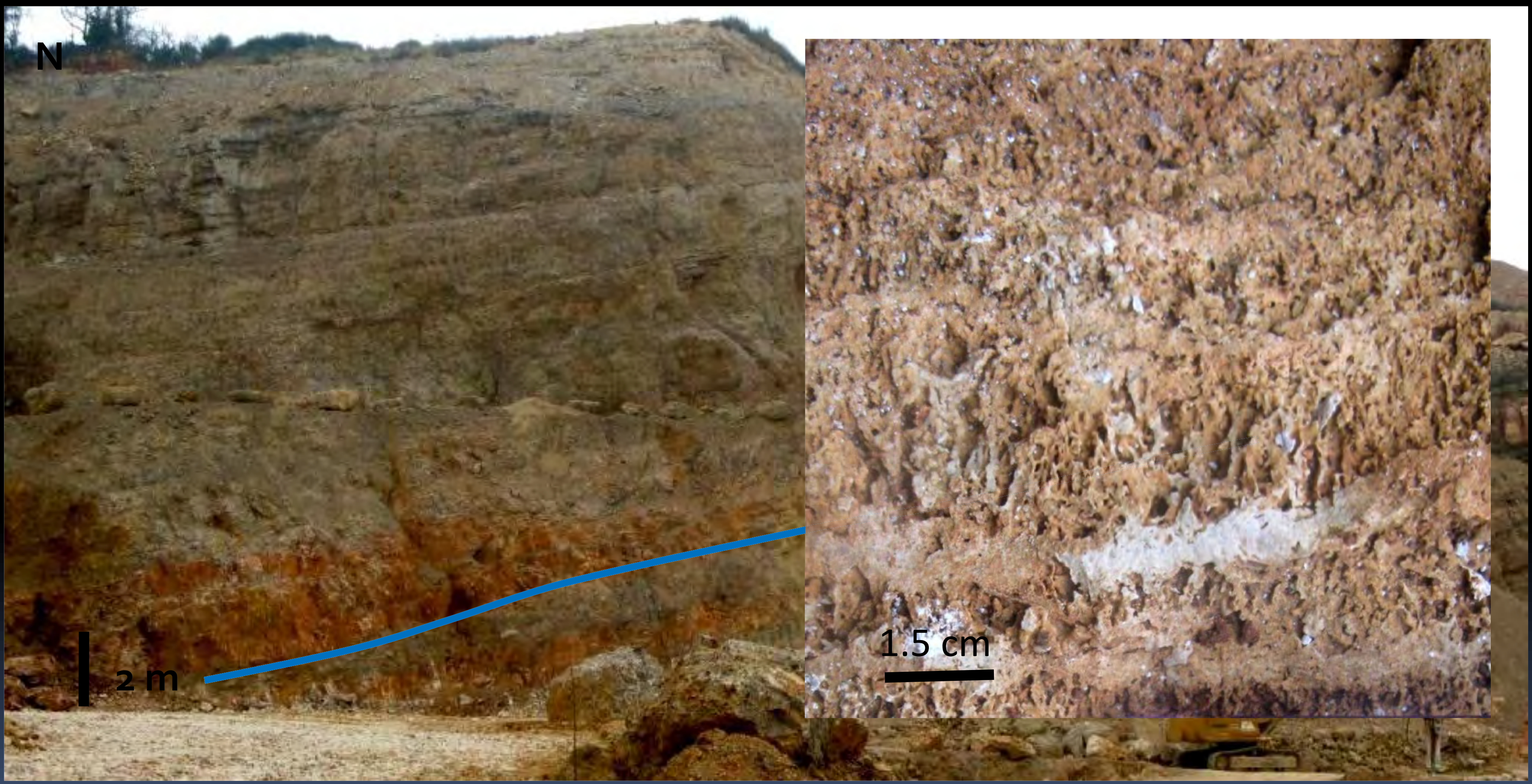
Isolated, up to km-scale spacing
Location controlled by groundwater springs and faults



•Lacustrine carbonate buildups and bioherms at shallow shorelines or at sub-lacustrine groundwater springs.

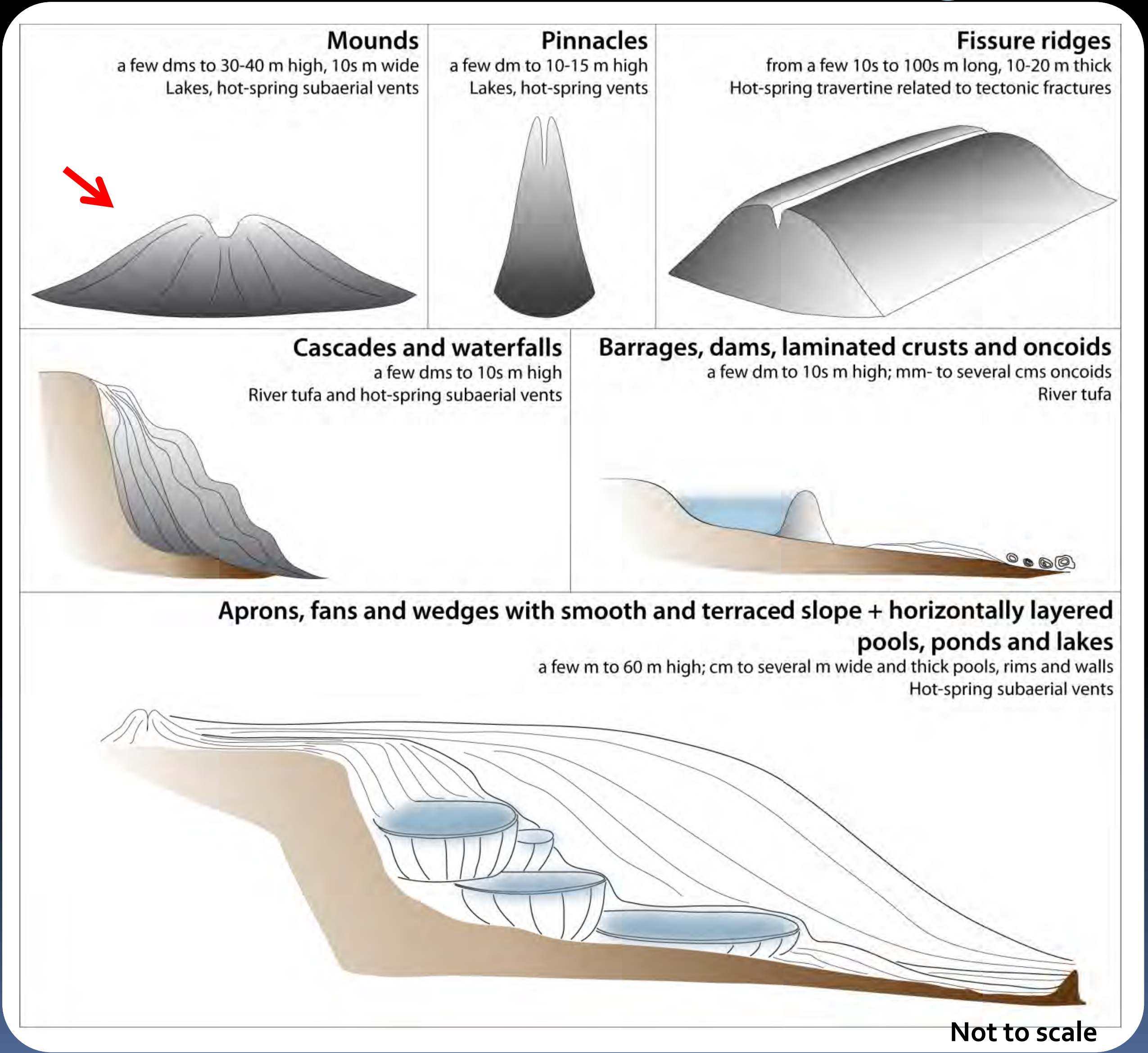
•In rift lakes and active volcanic areas precipitation is eventually associated with hydrothermal springs.

Fault-controlled lacustrine to palustrine basin with hot springs



- Dm- to m-scale bedded wedge-shaped succession (70 m thick) with hot-spring travertine, packstone/grainstone, marls, shales, breccia units: upper Miocene (Messinian), Tuscany, Central Italy

Hot-spring travertine and fluvial tufa: depositional environments and geometry

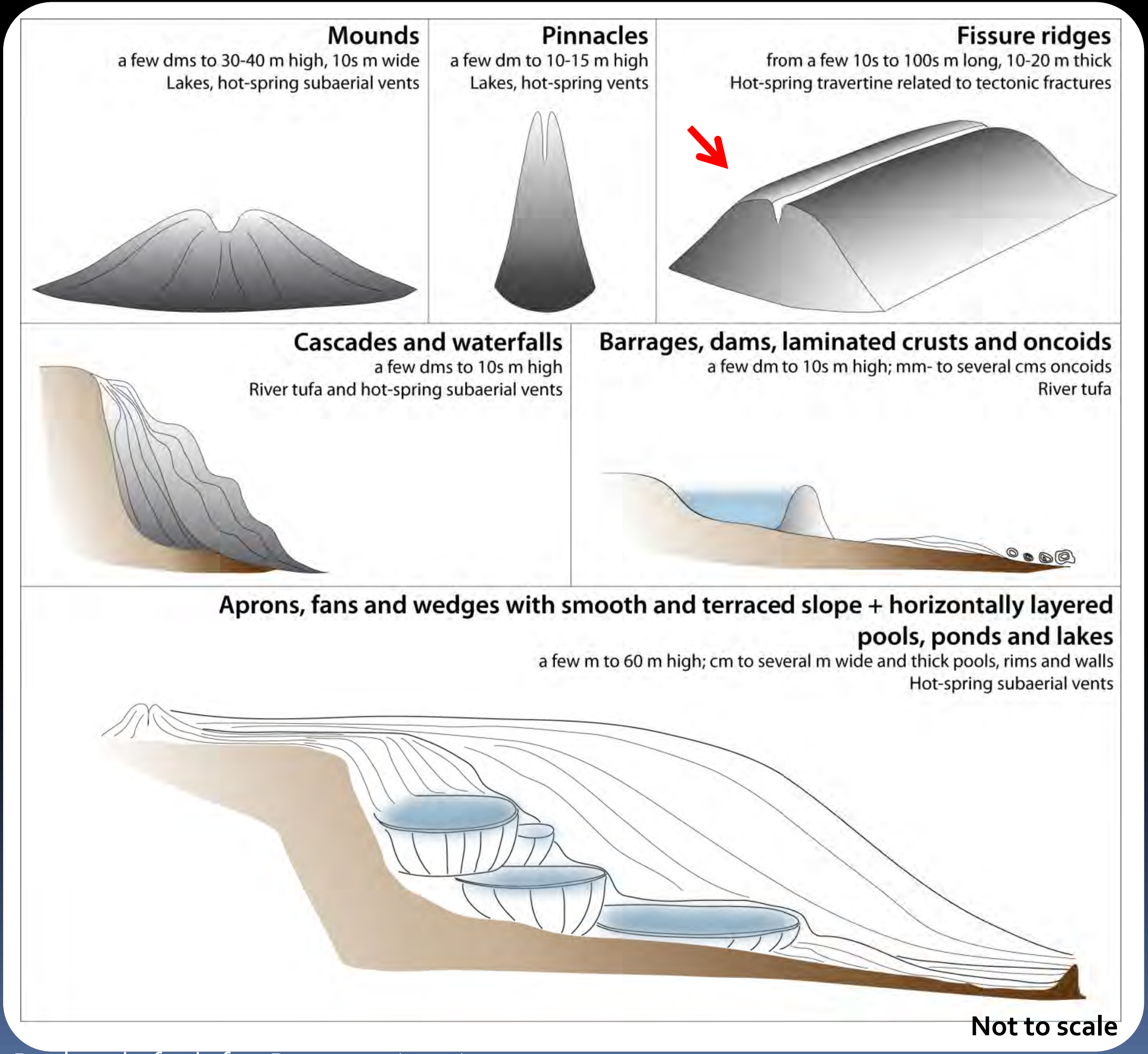


Partly redrafted after Pentecost (1995)

Hot-spring mounds

- **Castel di Luco (Marche, Central Italy), Pleistocene hot-spring travertine mound**
- cm-thick crystalline crusts (precipitated by fast-flowing thermal water sourced by punctual subaerial hydrothermal vent).

Hot-spring travertine and fluvial tufa: depositional environments and geometry



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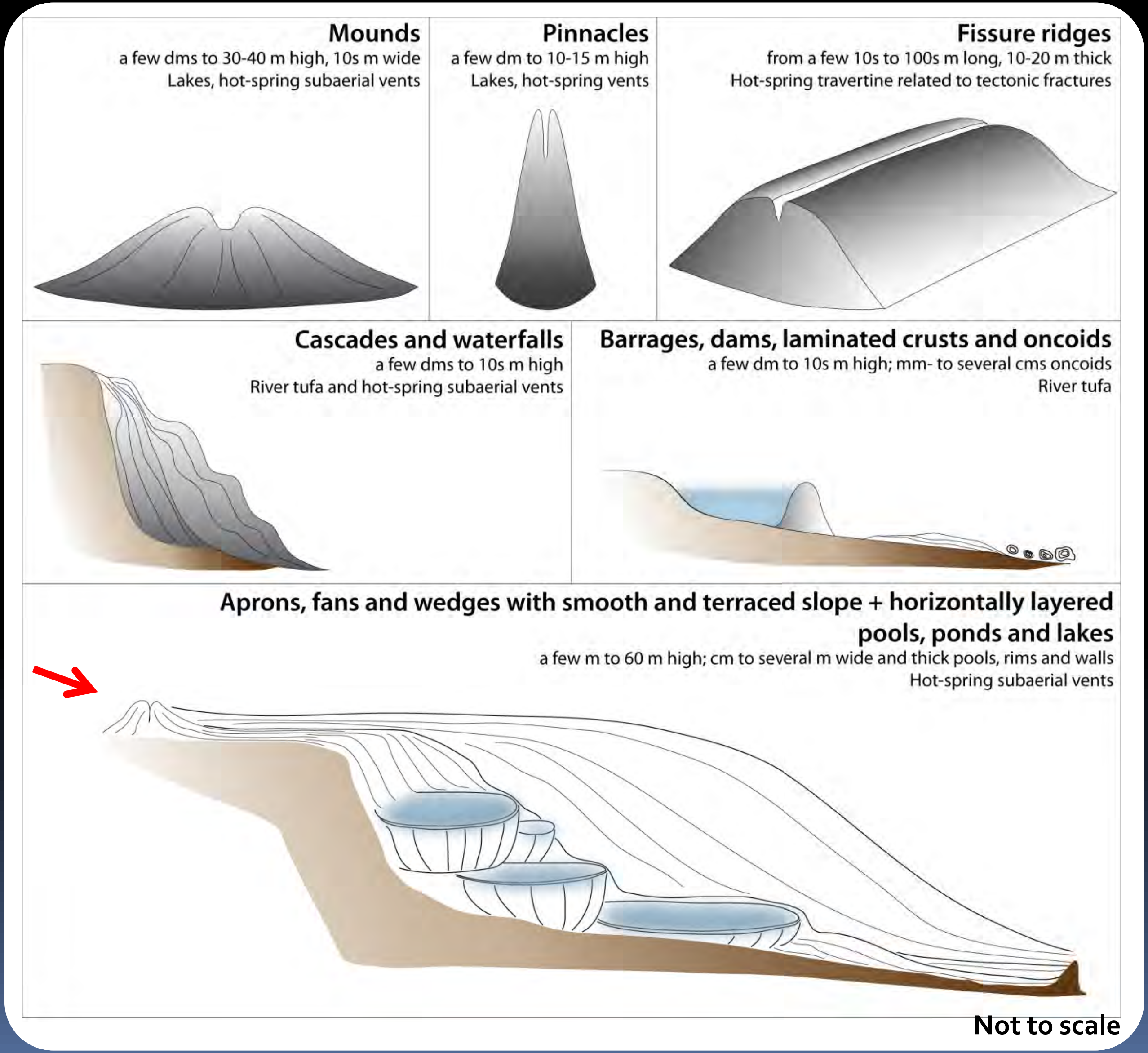
Hot-spring travertine and fluvial tufa: depositional environments and geometry



Partly redrafted after Pentecost (1995)

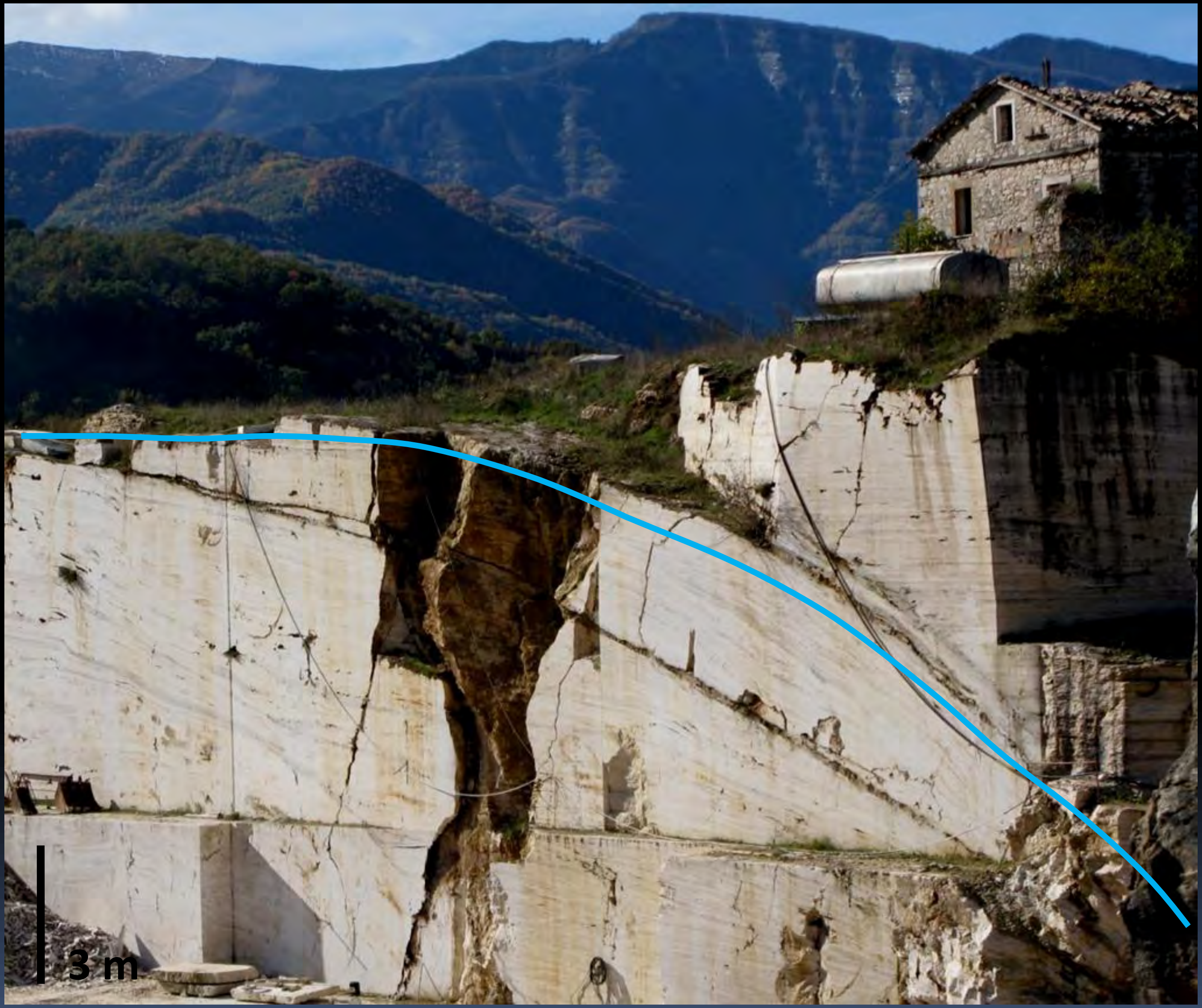
Hot-spring terraced slope

- **Present –day Bagni di Saturnia, Southern Tuscany, Central Italy**
- Hydrothermal vent , water H_2S rich, T 37°
- Meter-scale wide pools, 0.1-1.5 m deep with cm-size pisoids; pool rims and walls from dm to 1 m high

Hot-spring terraced slope

- **Saturnia travertine**, Tuscany, Central Italy, upper Pleistocene

Hot-spring travertine smooth slope and clinoforms



•**Pleistocene Acquasanta hot-spring travertine, Marche, Central Italy**

•Clinoforms built by 5-15 cm alternation of feather crystal crusts and mm-thick laminated microsparitic crusts

Non-marine carbonate buildups: depositional geometry vs. fabrics

ARE CARBONATE FABRICS A DIAGNOSTIC PROXY FOR NON-MARINE CARBONATE DEPOSITIONAL SETTINGS AND GEOMETRY?

1. Lake shoreline bioherms

2. Sublacustrine spring mounds (mixing with lake water)

3. Lakes with dominant hydrothermal input

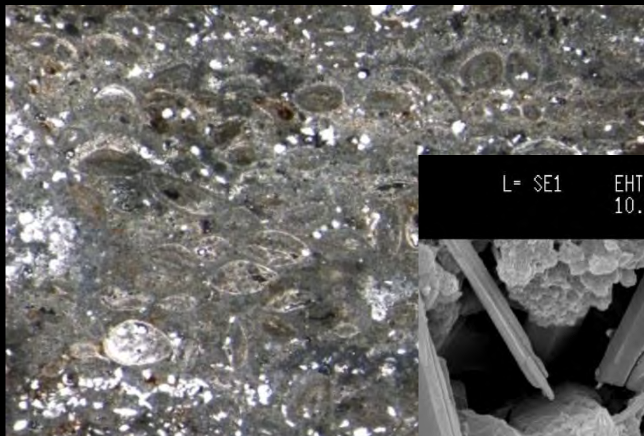
4. Subaerial hot-spring travertine

→

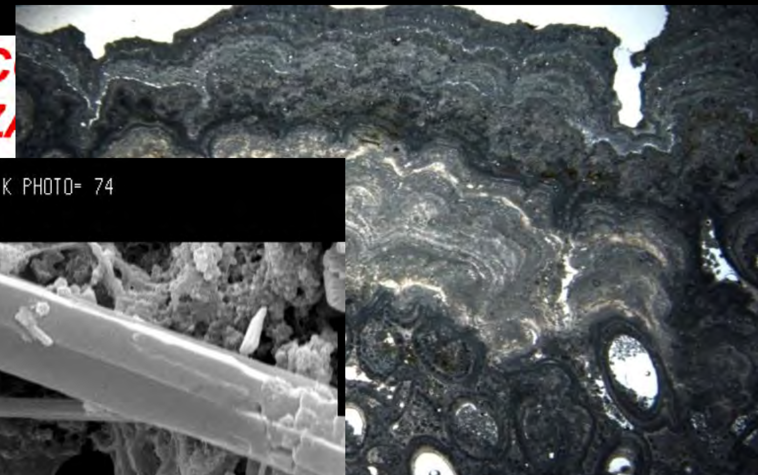
Wide spectrum of fabrics

- Crystalline crusts and cements: *abiotic*
- Coated grains (ooids, oncoids, pisoids): *abiotic or biomediated*
- Laminated stromatolitic : *biologically induced/influenced = microbially mediated*
- Clotted peloidal micritic: *biologically induced/influenced = microbially mediated*
- Dendritic and shrubby: *abiotic or biomediated*

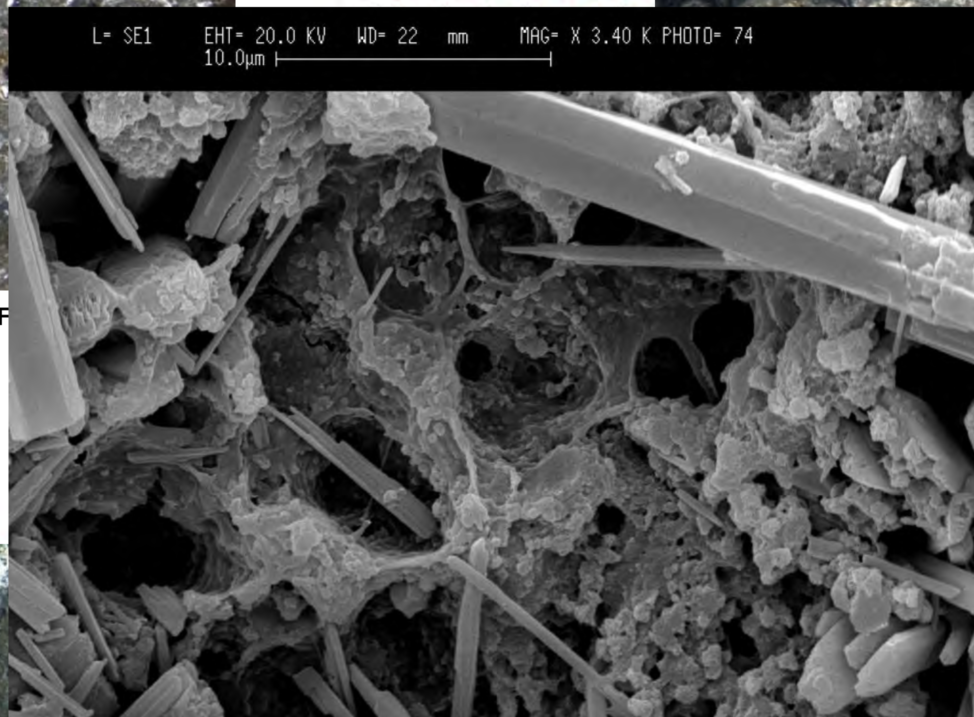
Modes of carbonate precipitation: shoreline bioherms in lakes



Ostracod Packstone, Green River F
Eocene (FoV 5.5 mm)

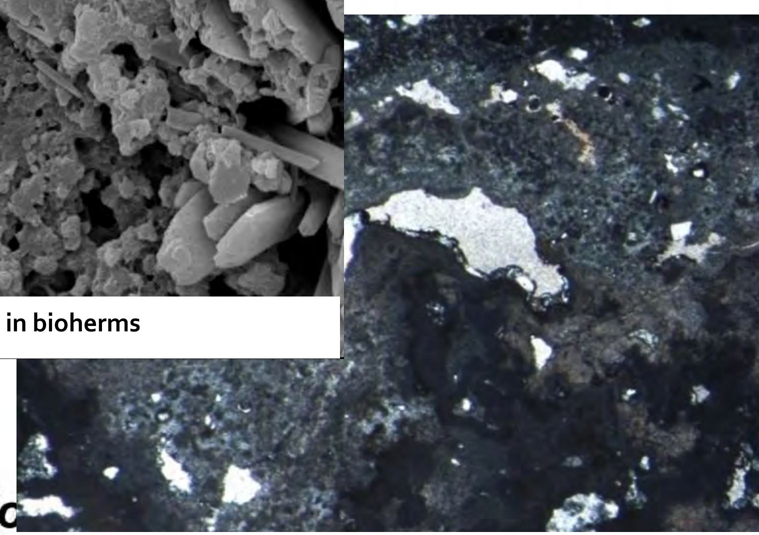


., Wyoming, Eocene, laminated
e bioherms (FoV 28mm)



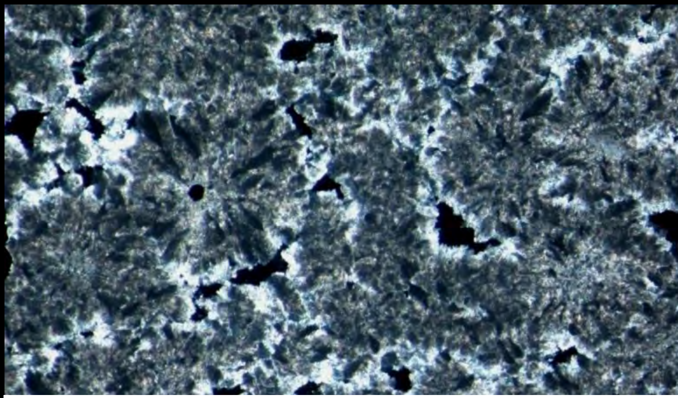
Great Salt Lake, Utah, present-day EPS and aragonite in bioherms

Great Salt Lake, Utah present-day bioherms (FoV 4.5 mm)

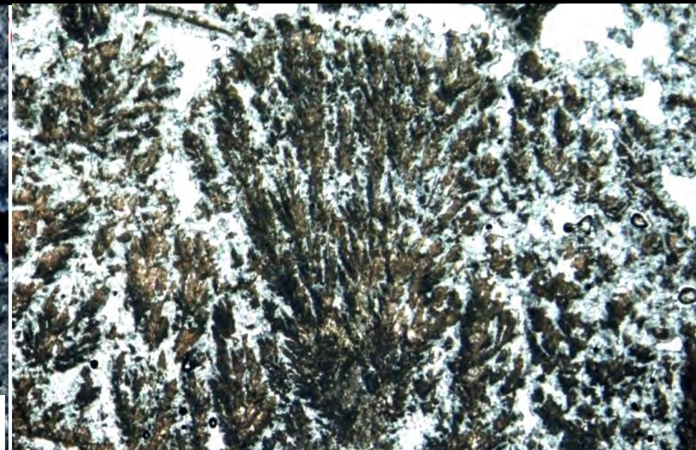


Great Salt Lake, Utah, present-day bioherms (FoV 4.5 mm)

Modes of carbonate precipitation: subaerial hot-spring travertine

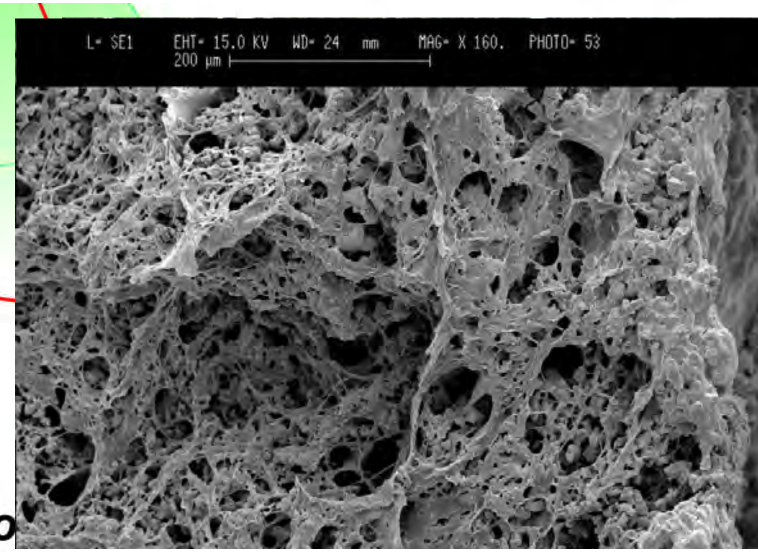


Hot-spring travertine pisoids, Acquasanta, Pleistocene, Marche Central Italy (FoV 4.5 mm)



Saturnia Pleistocene travertine, Tuscany, Central Italy (FoV 7mm)

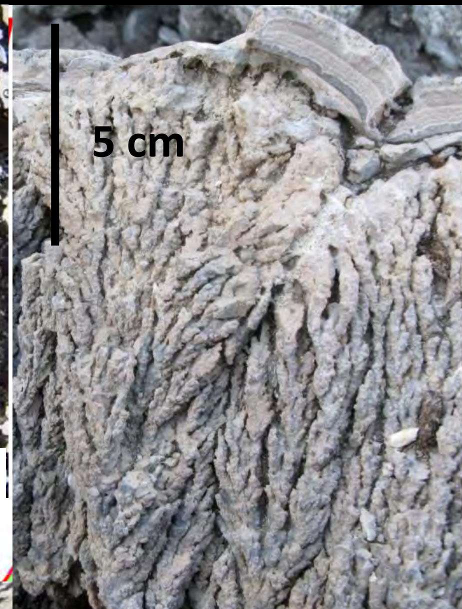
Saturnia terraced slope travertine, Pleistocene, Central Italy (FoV 4.5 mm)



Saturnia Bath, Central Italy, present-day travertine, EPS and calcite micrite

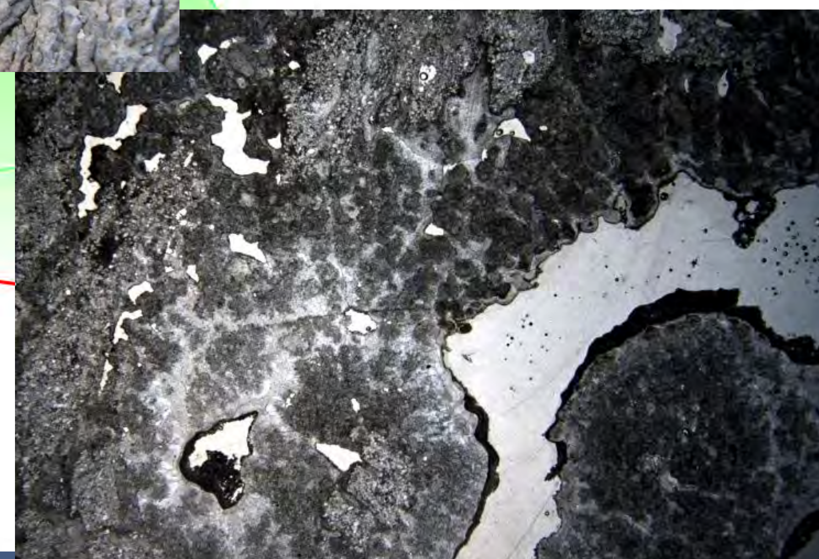
Modes of carbonate precipitation: sub-lacustrine spring mounds

Gstropods in srping mounds (FoV 14 mm)



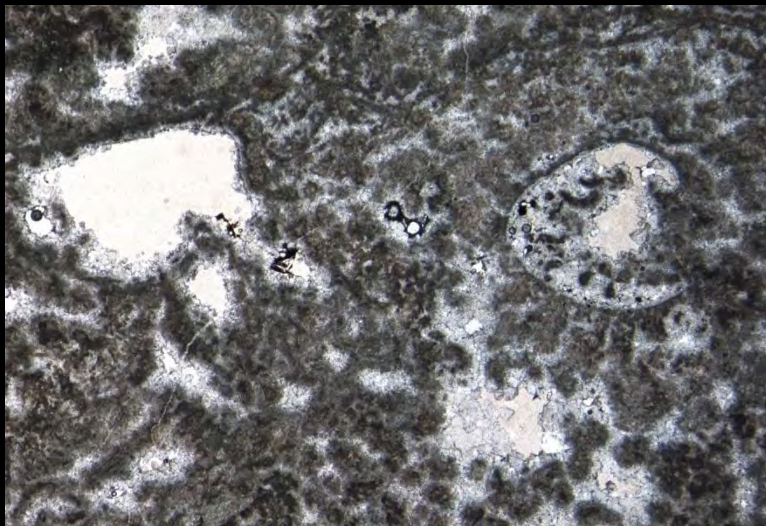
Dendritic sublacustrine spring mounds, Pleistocene (FoV 11 mm)

89)



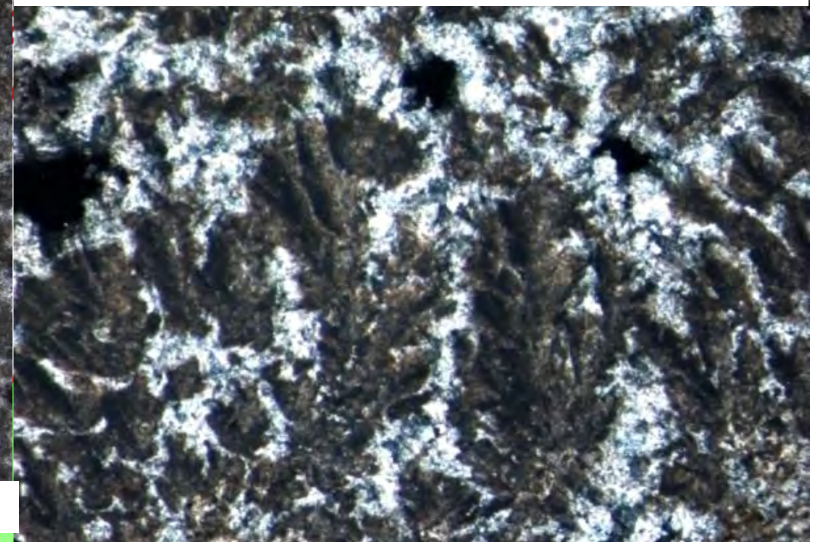
Clotted peloidal in sring mounds (FoV 21 mm)

Modes of carbonate precipitation: hot-spring lakes

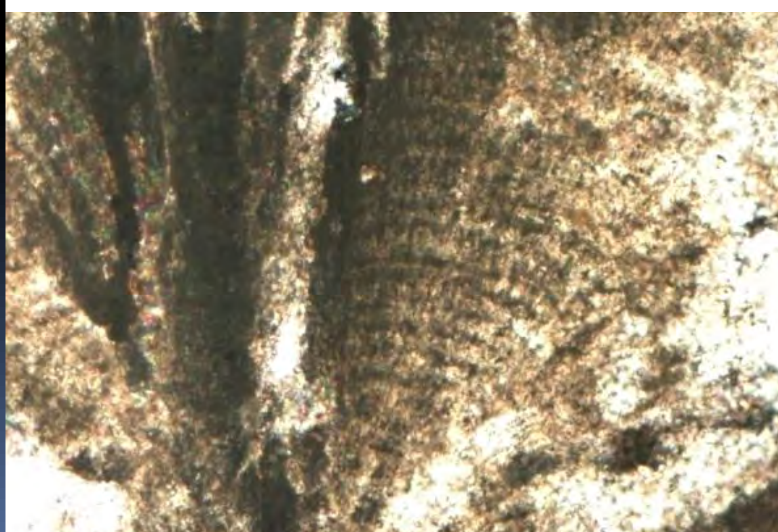


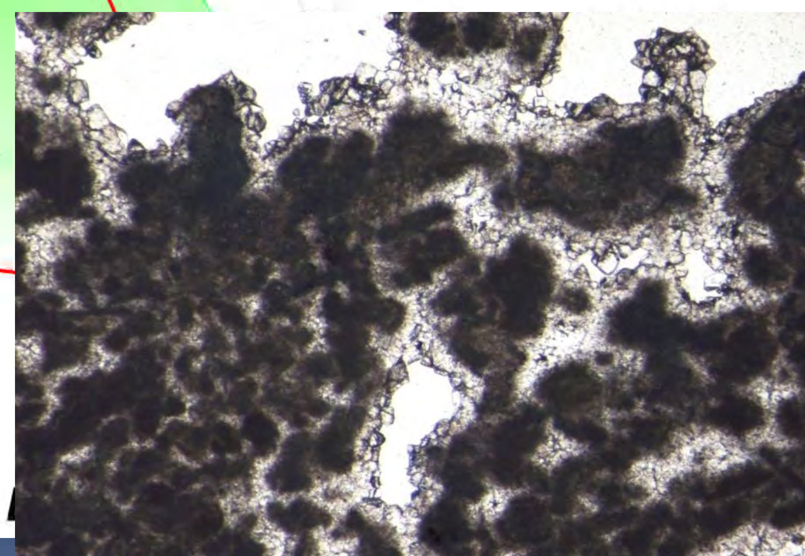
Hot spring lake upper Miocene, Central Italy (FoV 9 mm)

Miocene lake + hot springs, Tuscany, Central Italy (FoV 4.5mm)



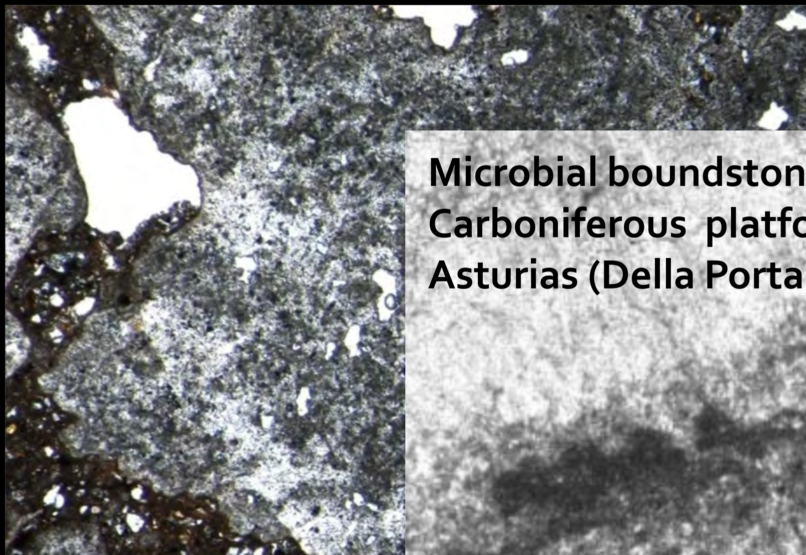
Miocene lake+hot springs, Tuscany, Central Italy (FoV 0.8 mm)



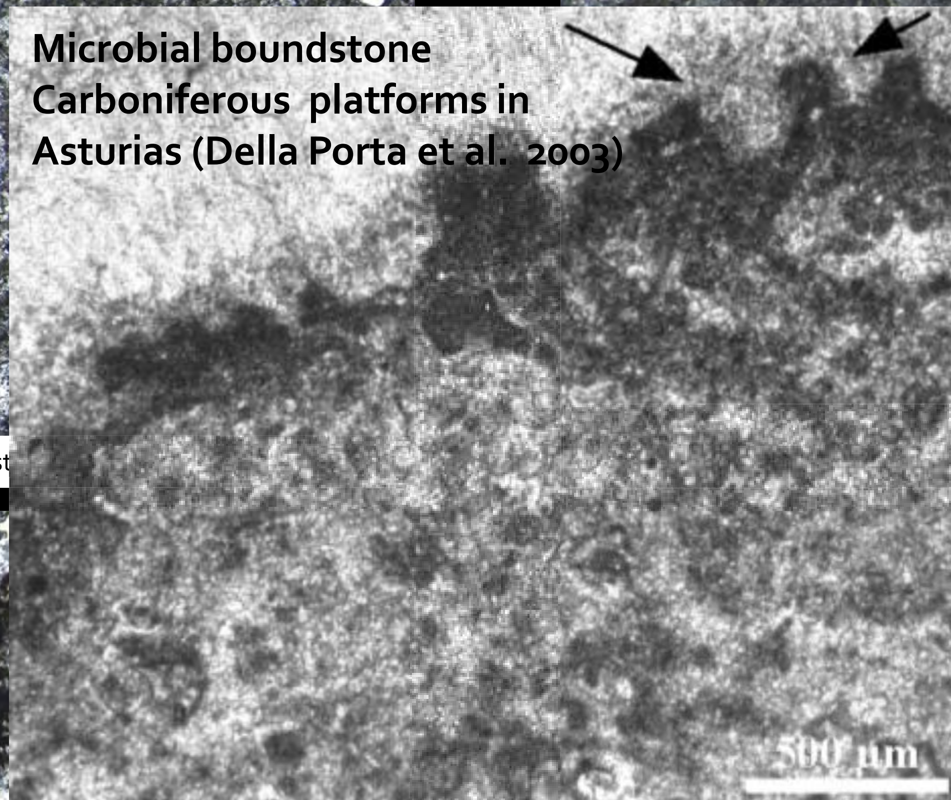


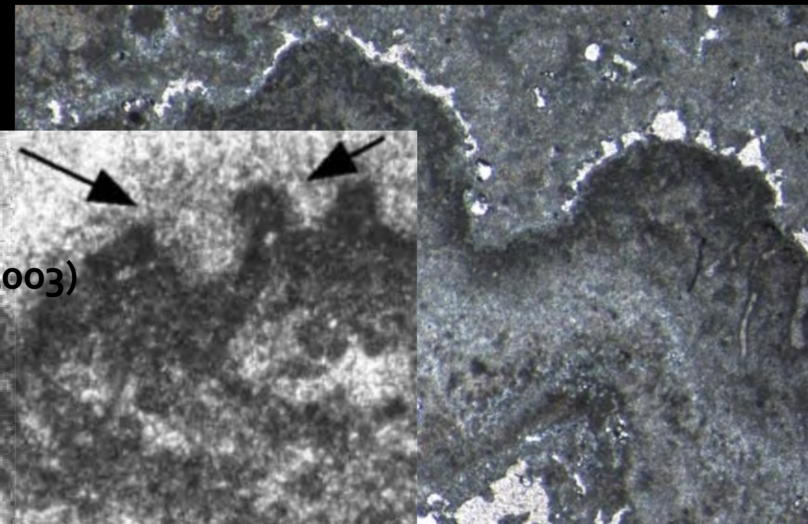
Hot spring lake (Upper Miocene), Central Italy (FoV 7 mm)

Biologically induced fabrics: not diagnostic

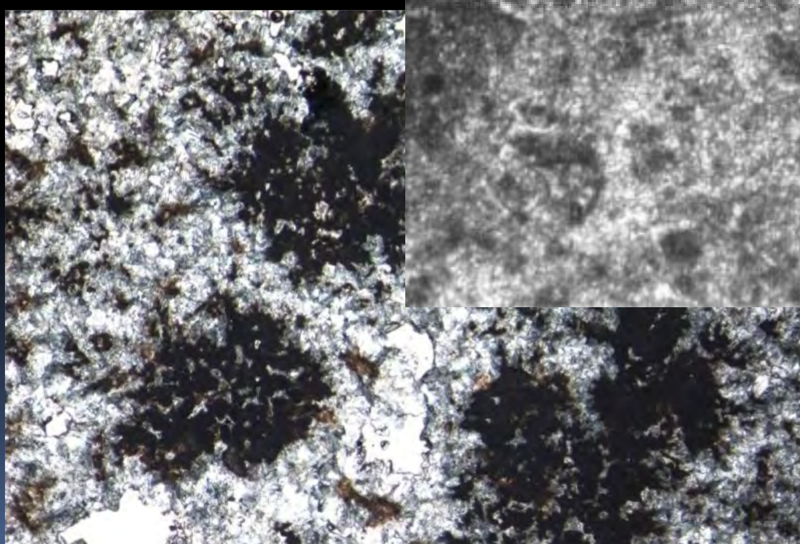


Sublacustrine spring mound, Pleist

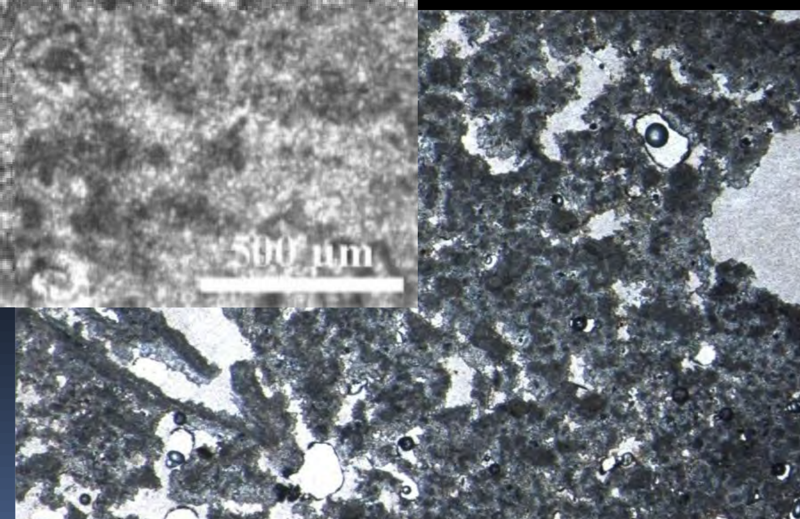




adophorites bioherms, (FoV 4.5



Pleistocene Saturnia , Tuscany, Central Italy (FoV 4.5 mm)



Tufa, Tuscany, Central Italy, Pleistocene (FoV 5.5 mm). cf. Capezzuoli et al. (2010)

Clotted peloidal shrub fabrics typical of hot-spring travertine pools..

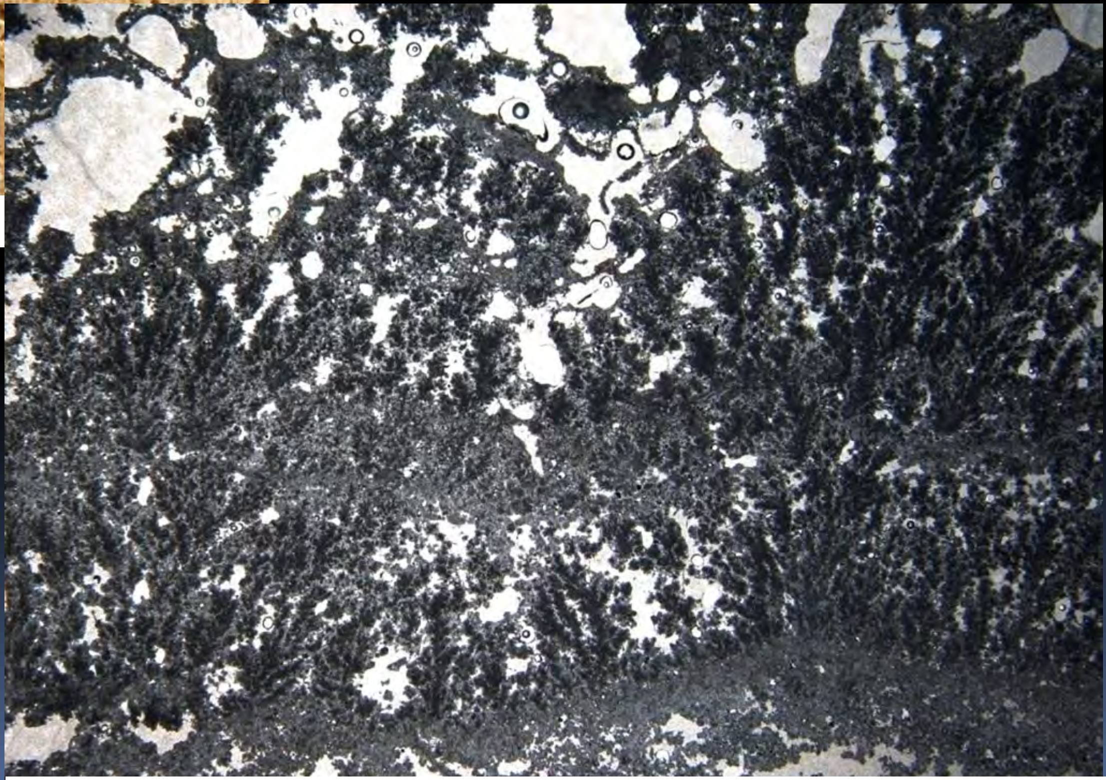
Bacterial shrubs *sensu* Chafetz and Folk (1984); Guo and Riding (1998); Chafetz and Guidry (1999)

Saturnia Pleistocene travertine, Central Italy

Microbial?

- attributed to bacterial mediated precipitation (Chafetz & Folk 1984)

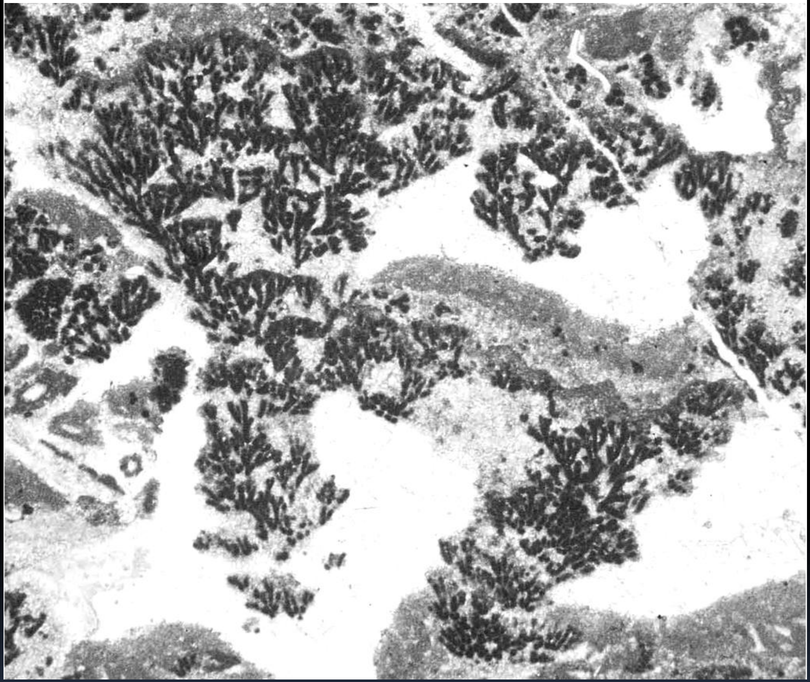
- or abiotic (Pentecost 1990).



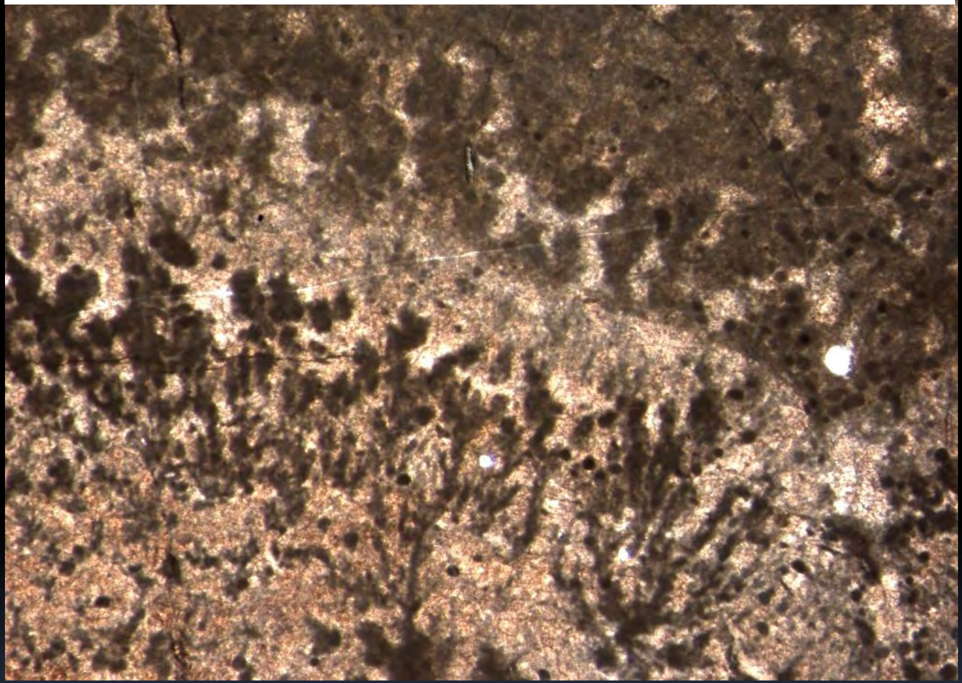
Rapolano travertine, Pleistocene, Central Italy (FoV 21 mm)

..but not only

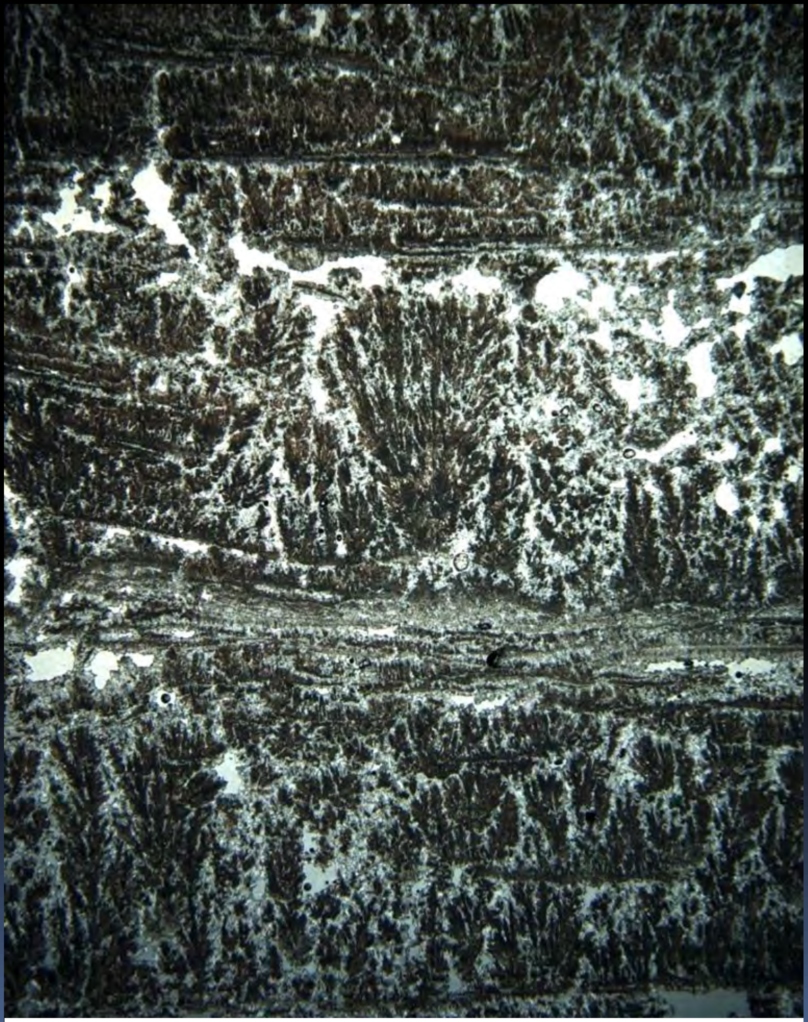
Riding (2000) Mid Cambrian China.
Field of view 8.5 mm



Lower Jurassic Djebel Bou Dahar carbonate platform (Morocco)
intertidal stromatolites (FoV 5.5 mm)



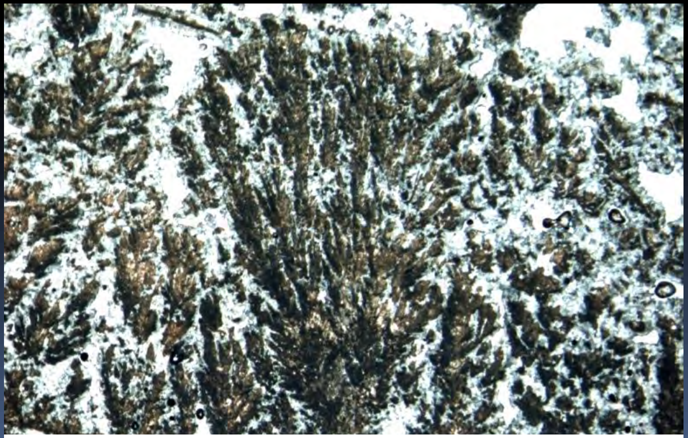
What is typical of hydrothermal water input? crystalline fabrics



Saturnia Pleistocene travertine (FoV 28mm)

Rapolano Holocene travertine, Tuscany, Central Italy (FoV 14 mm); cf. Capezzuoli et al. (2009)

Dendritic feather crystals from fast-flowing slopes

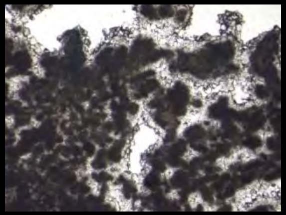


Saturnia Pleistocene travertine, Tuscany, Central Italy (FoV 7mm)

Crystalline shrubs sensu Chafetz & Guidry (1999) from pools

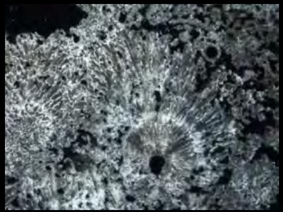
Key points.....

Different depositional settings and geometry of buildups (both abiotic and biologically induced/influenced)

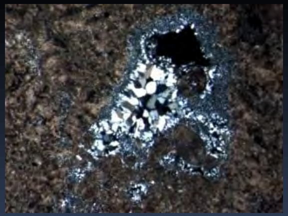


Fabrics not diagnostic of depositional settings: laminated and clotted peloidal micrite (possibly biologically induced/influenced) occur across the marine and non marine record

Dendritic clotted peloidal fabrics (biologically influenced) dominate but are not exclusive of slow-flowing hot-spring travertine pools and ponds



Crystalline crusts (rapid abiotic precipitation): lack in lake shoreline bioherms, diagnostic of lake spring mounds and hydrothermal subaerial systems (e.g. ikaite in lake spring mounds; feather and radial crystals in fast-flowing slopes, crystalline dendrites and spherulitic pisoids).

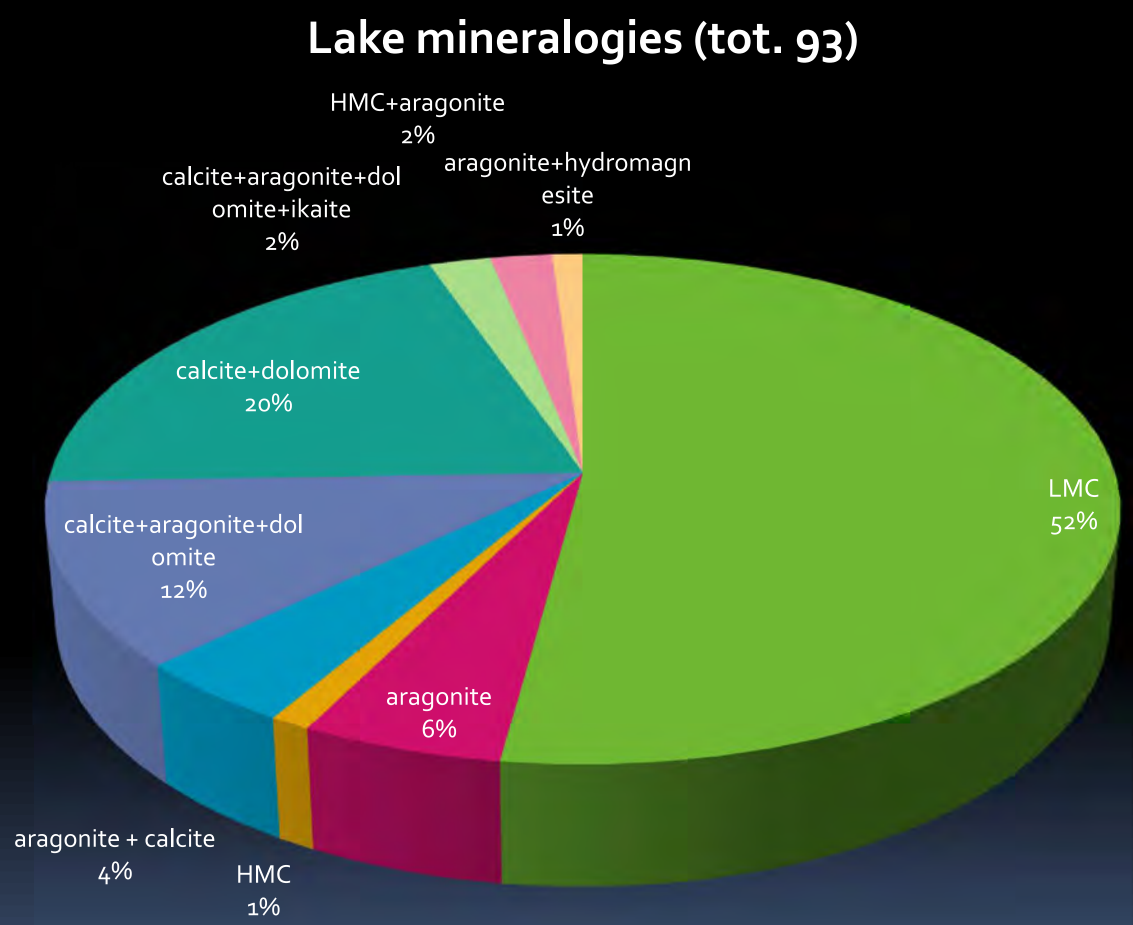


Primary mineralogy controlled by Mg/Ca ratio in lakes, by T in hot-spring travertine

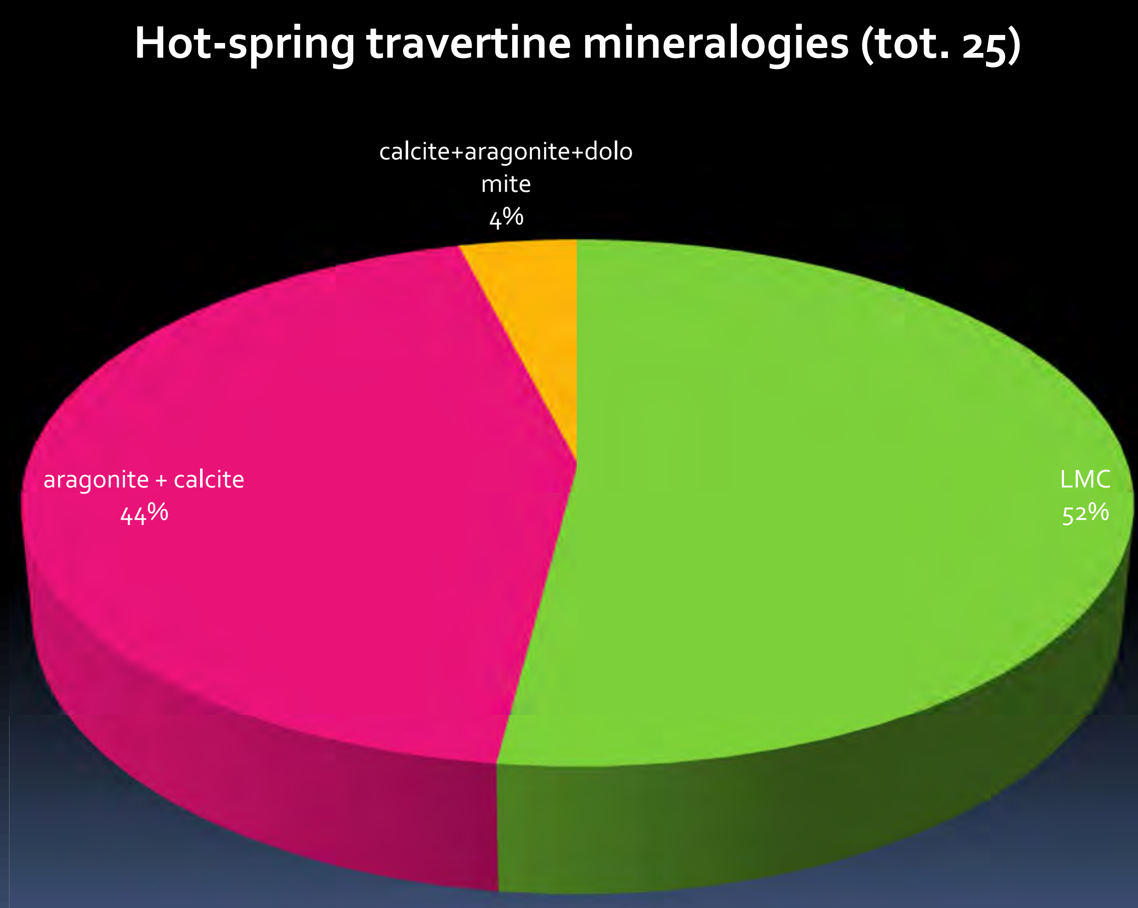
Dolomitization and silicification rare in hot-spring travertine, common in lakes with high Mg/Ca and silica from volcaniclastic deposits

Wide range of primary porosity (framework porosity, bubbles); secondary (biomoldic, vuggy meteoric dissolution, fractures)

Diagenesis: lake carbonate mineralogy

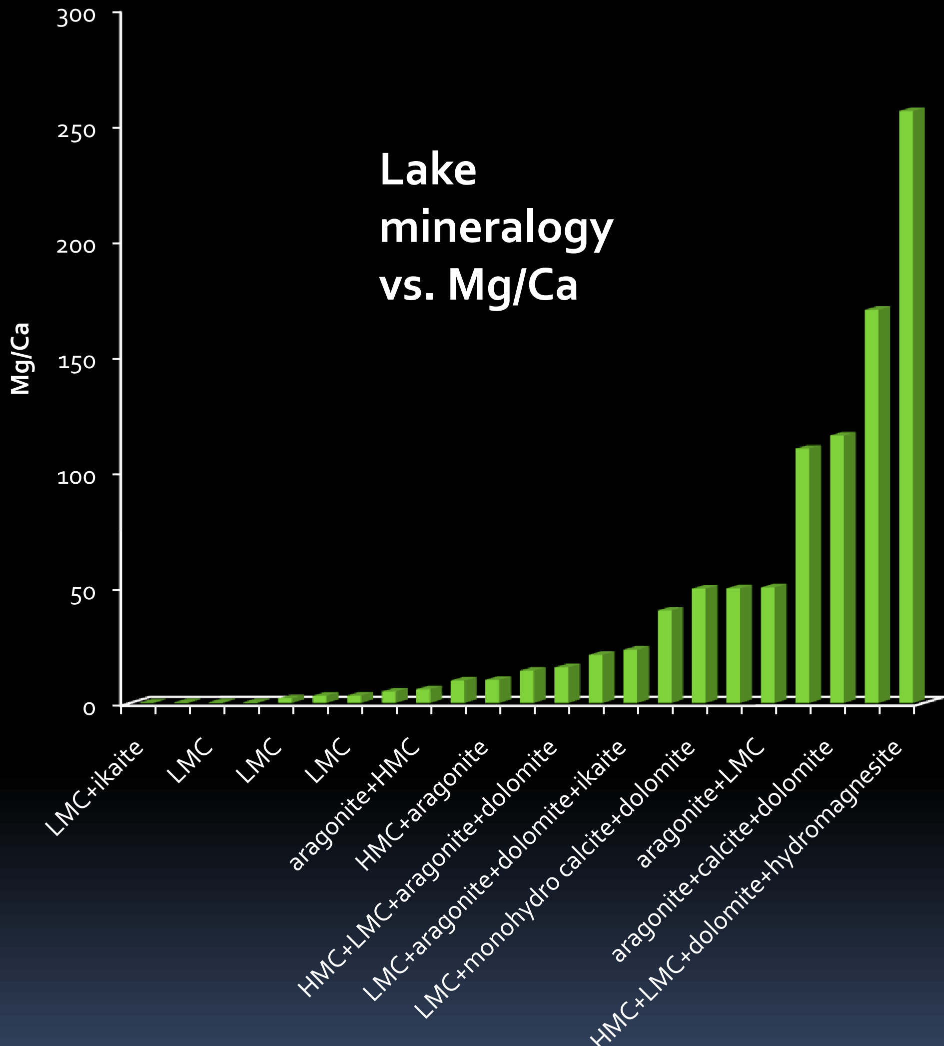


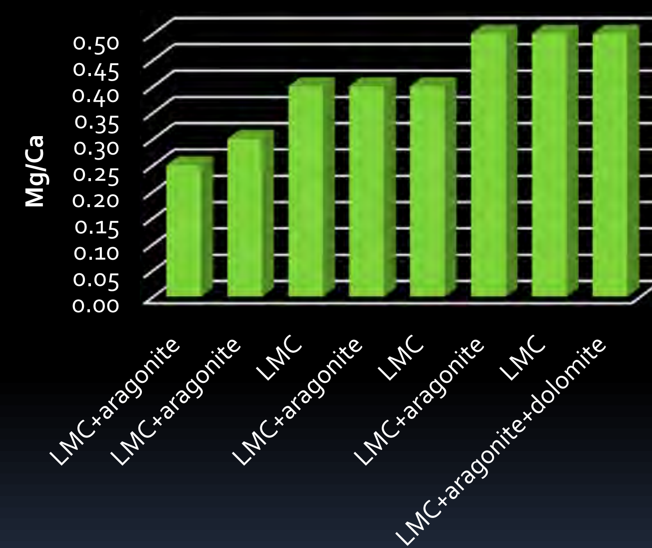
Diagenesis: hot-spring travertine mineralogy



- high temperature (>40-50°) favors aragonite precipitation in hot spring settings

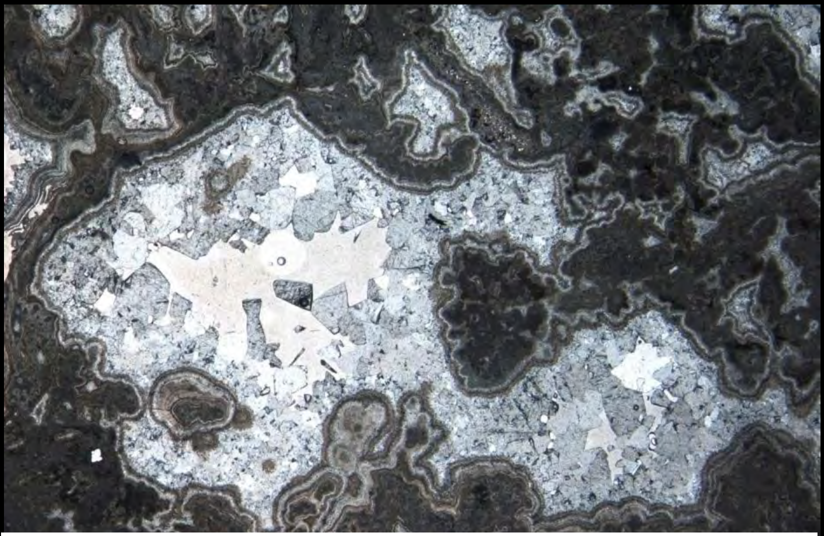
Carbonate mineralogy vs. Mg/Ca ratio

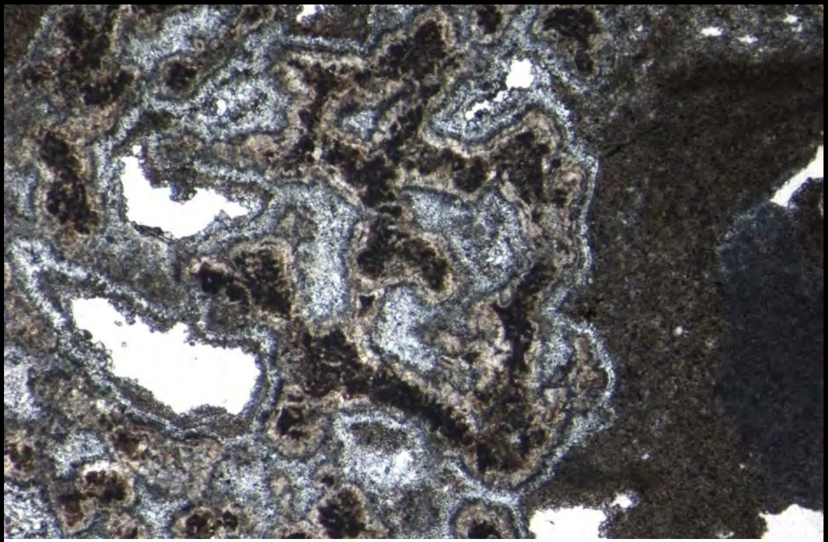


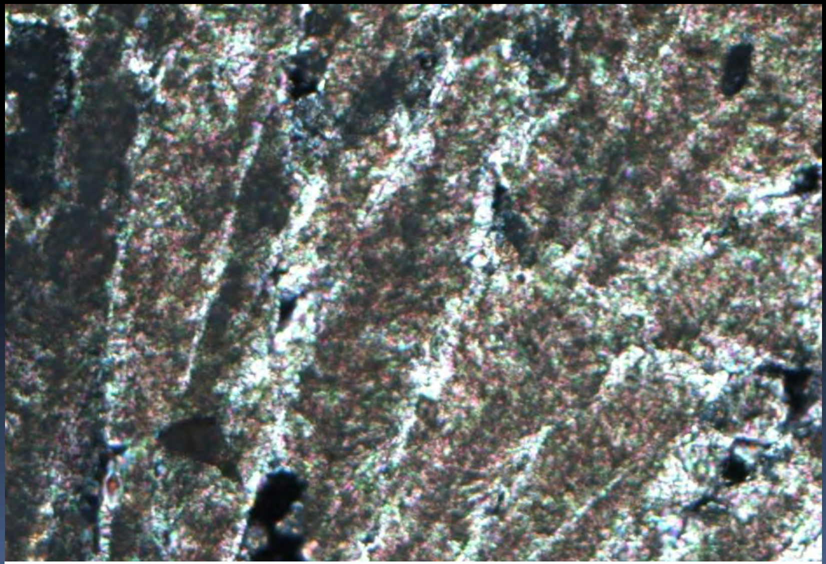


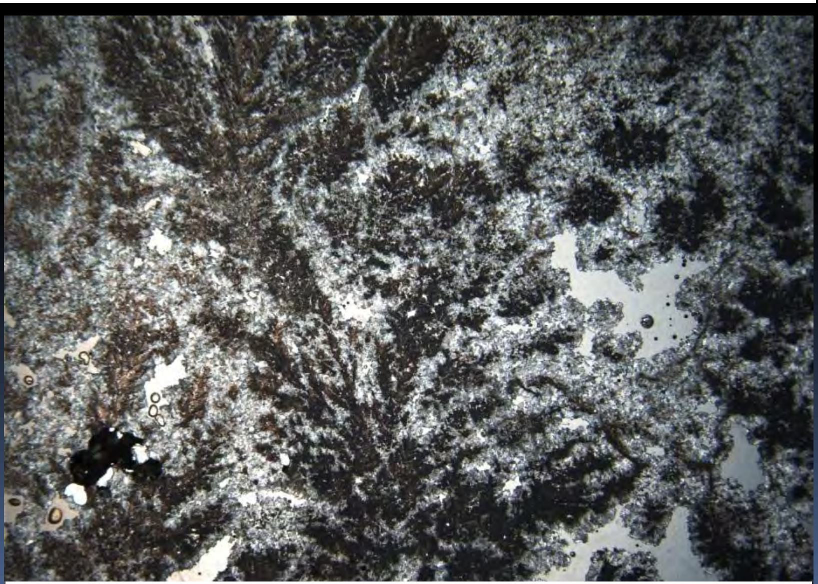
- Water Mg/Ca ratio affects the carbonate mineralogy as in marine settings (Müller et al. 1972)
- Mg/Ca ratio is a function of variable degrees of mixing between lake, ground- or thermal water
- It evolves through time and space following Mg clay mineral formation

Diagenesis: meteoric cementation


Ries Crater, Germany, Miocene, lake spring mound blocky spar cementation (FoV 1.4 mm)

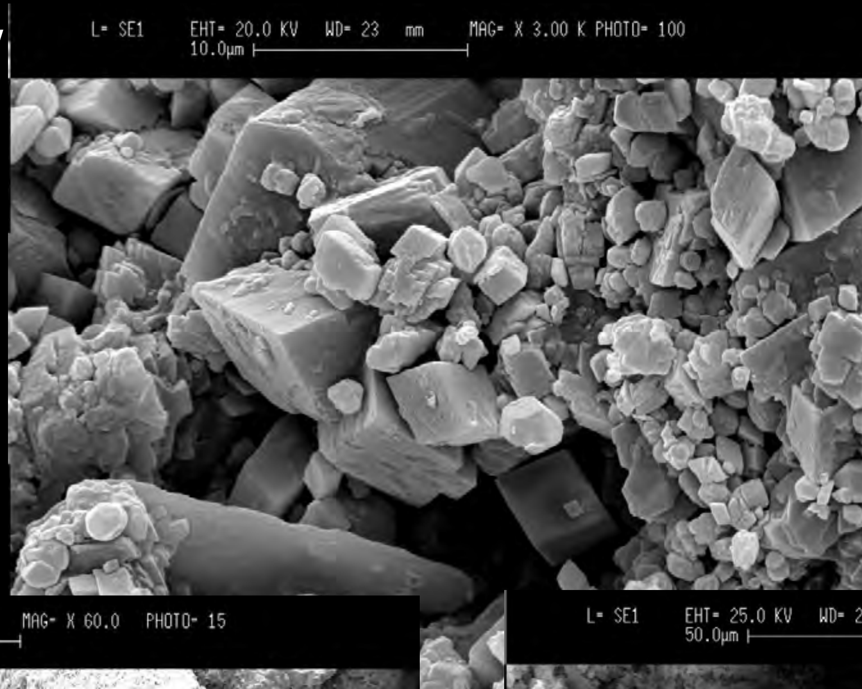

Saturnia lake with hot-spring, dissolution, sparitization, cementation, Miocene (FoV 4.5 mm)


Saturnia travertine, blocky spar cementation between dendritic crystalline crusts Pleistocene (FoV 4.5 mm)

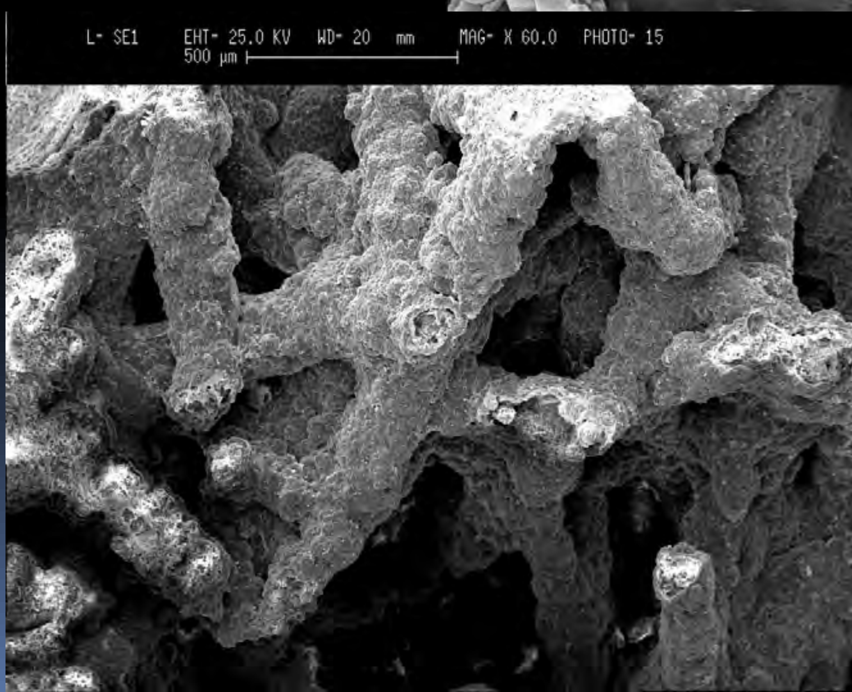

Saturnia travertine, blocky spar cementation between crystalline shrubs Pleistocene (FoV 4.5 mm)

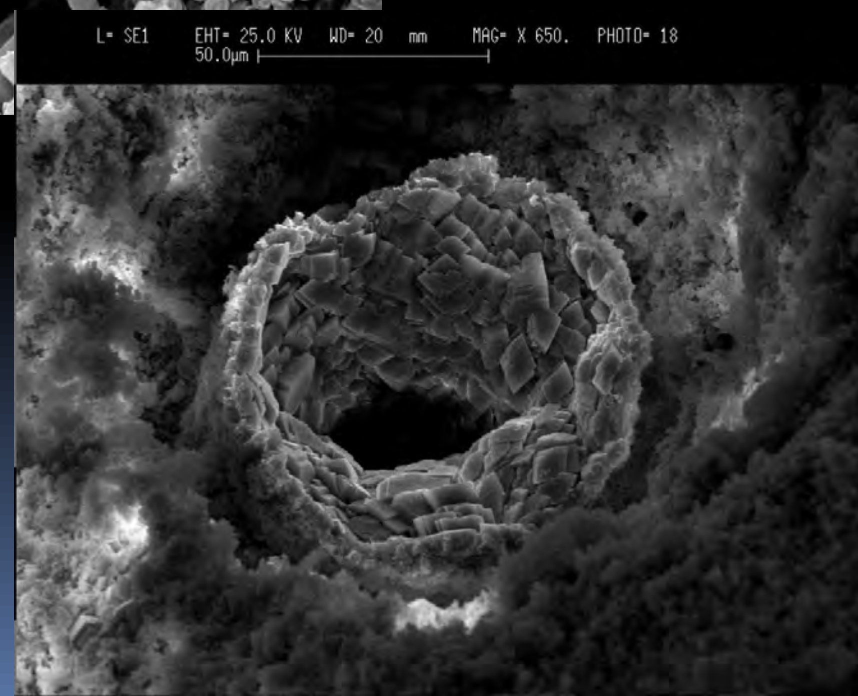
Diagenesis: dolomitization

Green River Fm., Laney Mb., Wyoming, Eocene, caddisfly bioherms

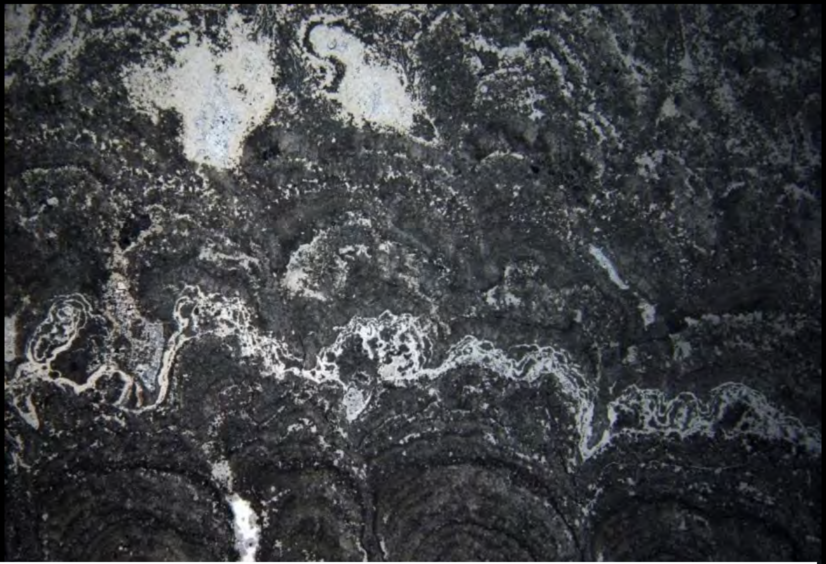


Ries Crater, S Germany,Miocene Cladophorites bioherms



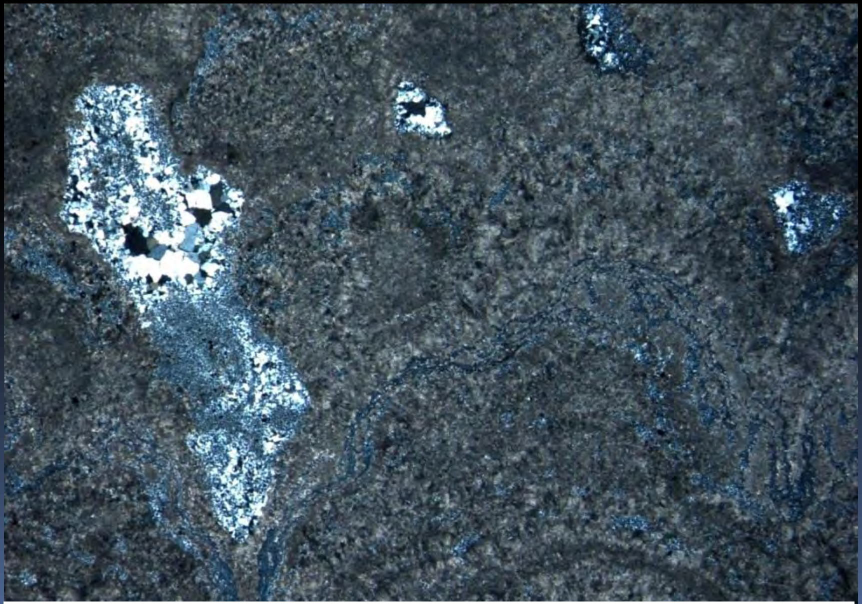


Diagenesis: silicification



Green River Fm., caddisfly bioherms, Wyoming (FoV 21 mm)

Green River Fm., caddisfly bioherms, Wyoming (FoV 4.5 mm)

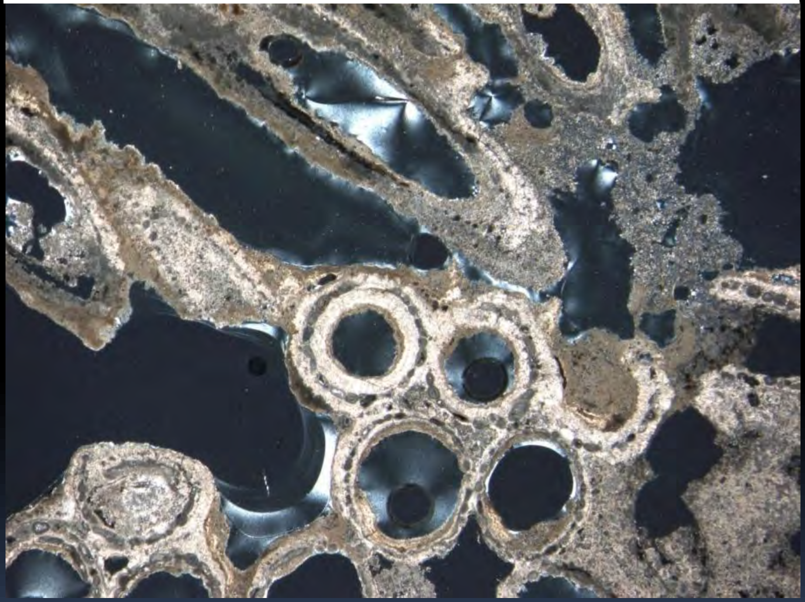


Green River Fm., caddisfly bioherms, Wyoming (FoV 4.5 mm)

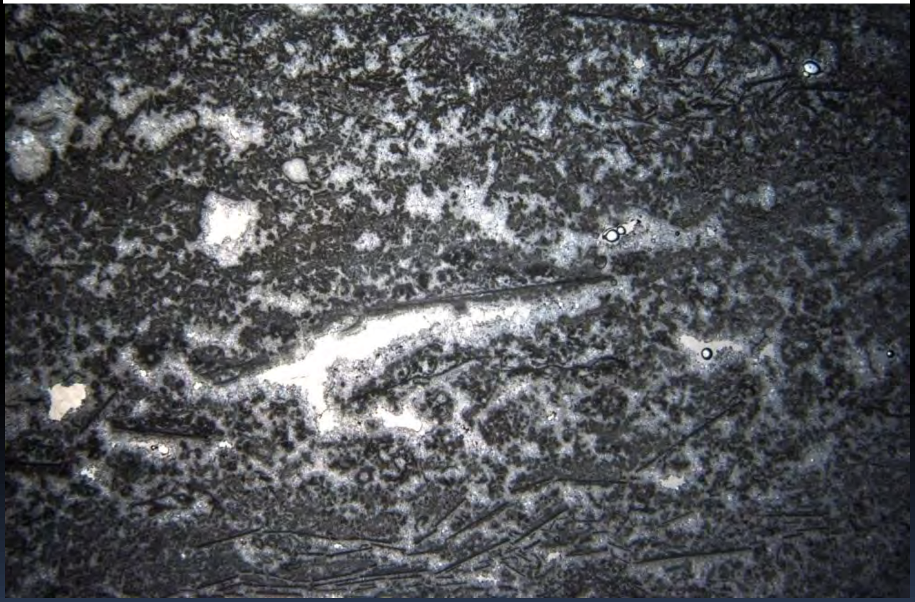
Primary porosity

• wider range of primary pore systems reflecting complex interactions between abiotic and biologically-induced/influenced processes

Green River Fm., insect larval cases porosity, Wyoming (FoV 11 mm)



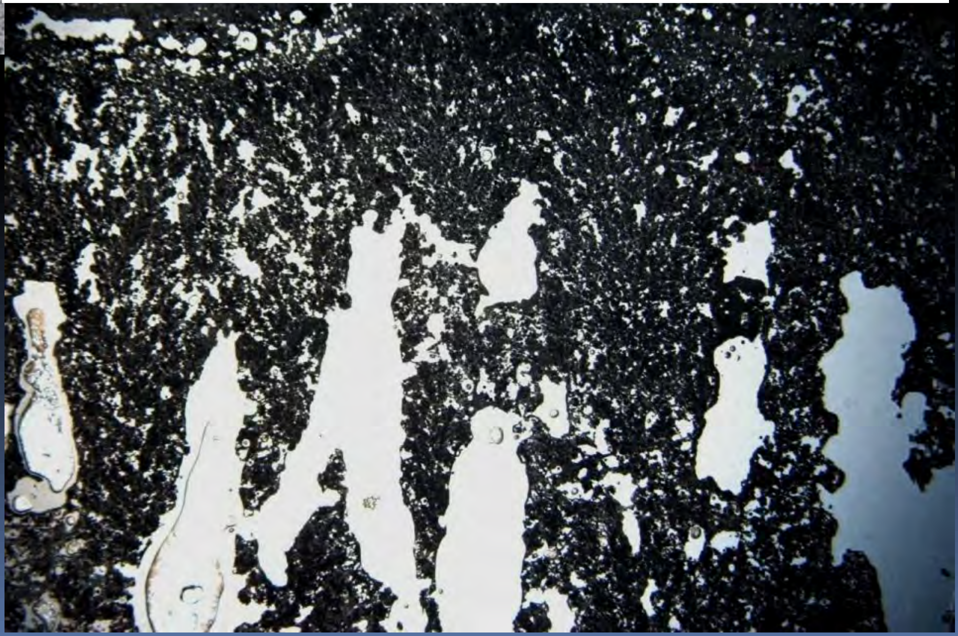
Miocene lake with hot-spring water showing clotted peloidal framework and shelter porosity (FoV 28 mm)



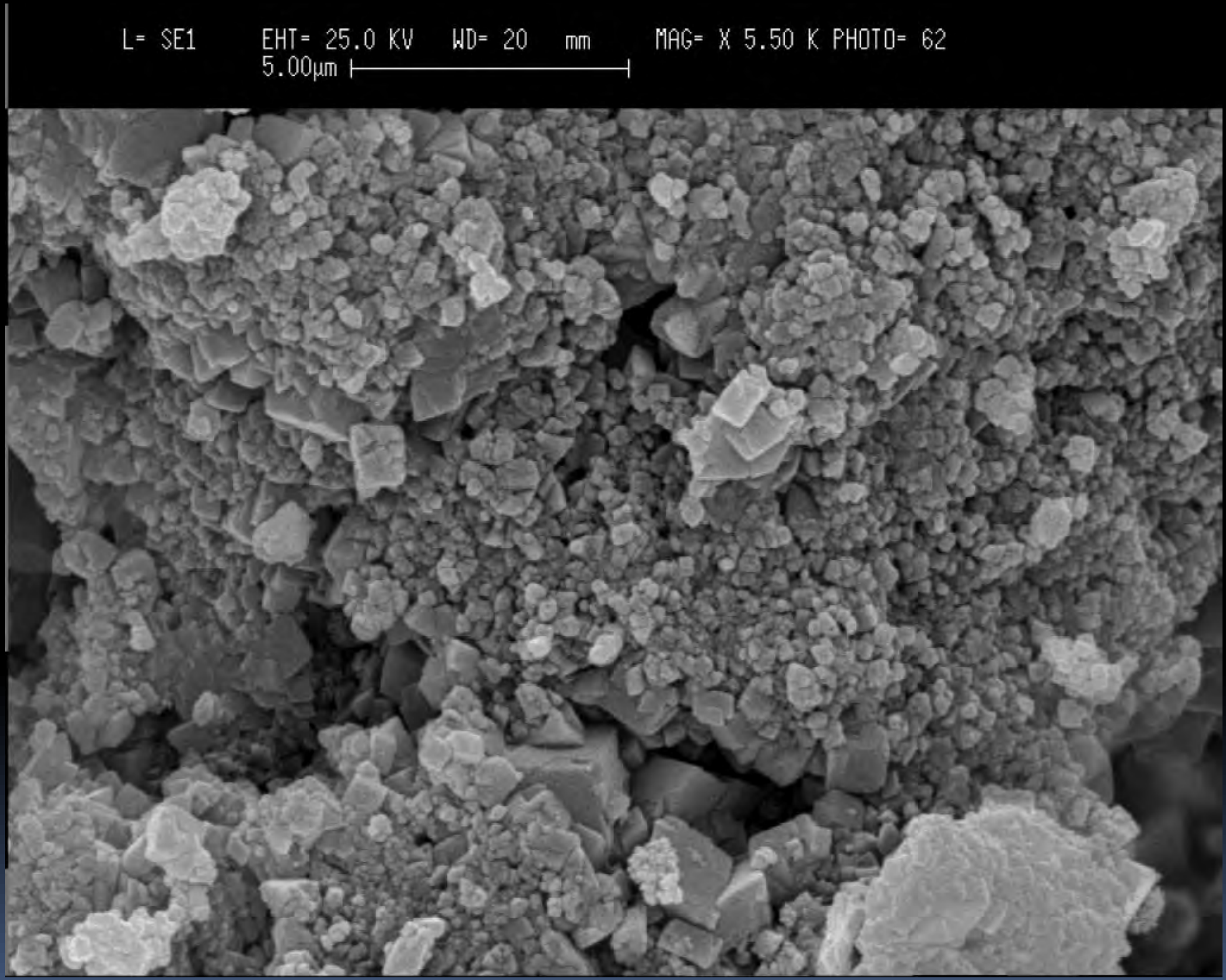
Primary porosity

Inter-shrub and bubble porosity, Pleistocene hot-spring travertine, Acquasanta, Marche, Central Italy

Inter-shrub and bubble porosity, Pleistocene hot-spring travertine, Rapolano, Tuscany, Central Italy (FoV 28 mm)

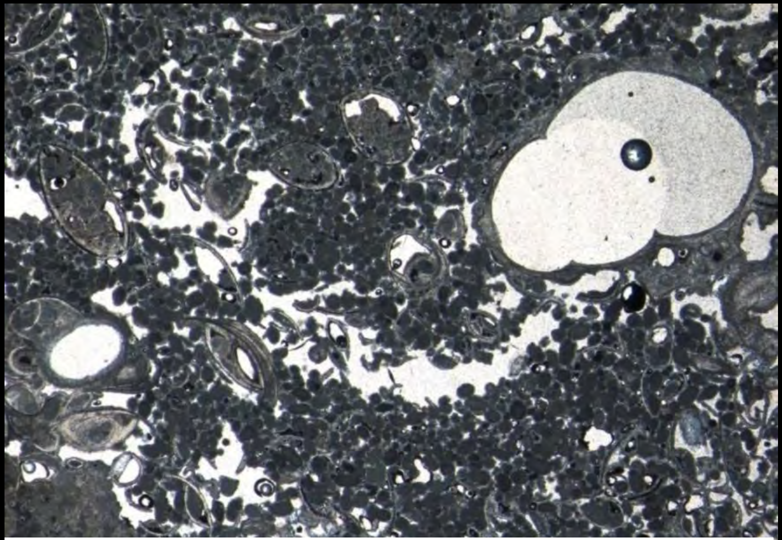


Microporosity

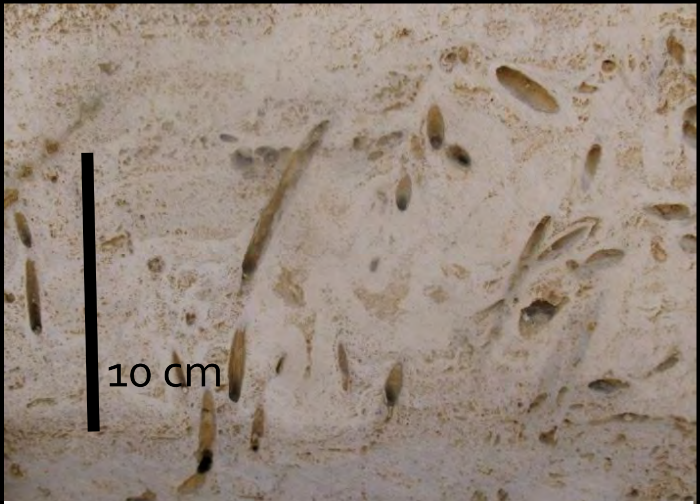


Ries Crater, S Germany, Miocene microporosity between micrite and dolomite crystals.

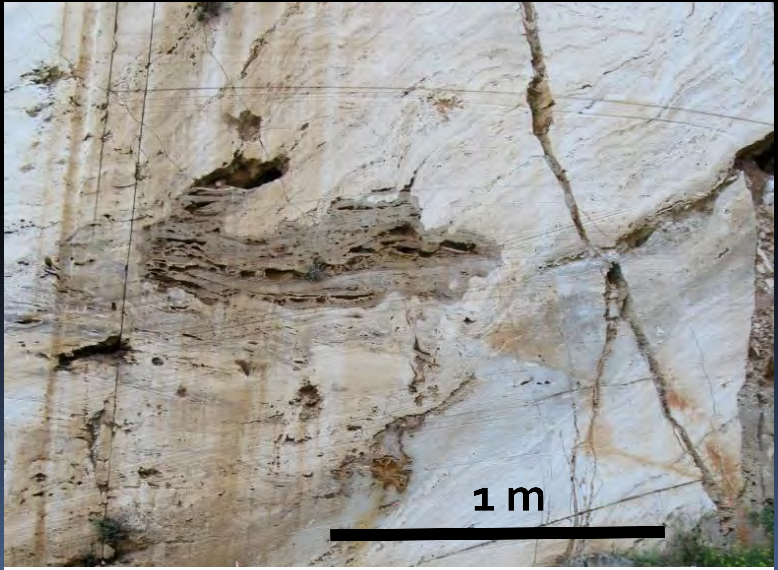
Secondary porosity



Ries Crater, S Germany, Miocene biomoldic porosity (FoV 7 mm)



Vegetation encrusted in hot spring travertine, Saturinia, Central Italy

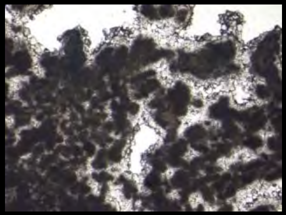


Karstic dissolution and fractures in hot-spring travertine, Acquasanta, Marche, Central Italy

Green River Fm., Eocene, Wyoming, meteoric dissolution vug porosity

Key points.....

Different depositional settings and geometry of buildups (both abiotic and biologically induced/influenced)



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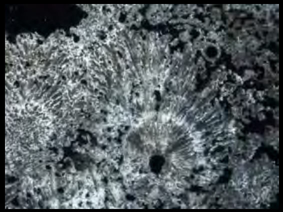

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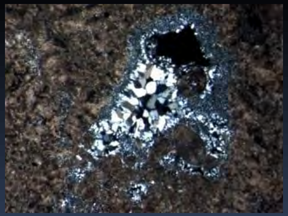

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Many thanks to:
Enrico Capezzuoli, Siena University (Italy)

BG Group, Repsol Brasil & Statoil

Thank you…

Presentation available on http://www.carbonateworld.com