Classifying Reservoir Carbonates When the Status Quo Simply Does Not Work: A Case Study from the Cretaceous of the South Atlantic*

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Abstract

The limitations of current limestone and porosity classifications are brought into sharp focus with the discoveries of unusual Aptian lacustrine carbonates, offshore South Atlantic. A range of textures and pore types are found which have no direct analogue with other carbonate successions and reservoirs, including such idiosyncrasies as highly labile matrices. By constraining these unusual rock types into existing classifications, the interpreter is led into false interpretations by the conceptual "baggage" associated with many existing terms and concepts. For example, one critical problem is that existing classifications are based on the concept of textural maturity whereby the presence or absence of a matrix is seen as an indicator of energy levels. What happens when the carbonate grains grew in a matrix, which later dissolved producing what appears to be primary intergranular porosity? In existing classifications boundstones are textures, which show signs of having been bound biologically during deposition, but what if these features indicating binding are in fact diagenetic? A pragmatic approach is needed to identify textural and pore types and to do this for these important Cretaceous carbonates involves identifying ghost matrices by comparing the same grain frameworks between units with preserved matrices and those lacking it. A robust, practical and tested classification of these lacustrine carbonates has been developed based on distinguishing in situ precipitates (biotic and abiotic) from reworked material. A crucial step was to identify and refine criteria for ghost matrices, which have created much of the porosity, and to relate these criteria to a precursor silicate. The application of the approach has facilitated the formulation of a successful depositional model, now substantiated by geochemical modeling, and a practical means for rock fabric determination and for interpreting diagenetic pathways and petrophysical properties.

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Classifying reservoir carbonates when the status quo simply does not work: a case study from the Cretaceous of the South Atlantic

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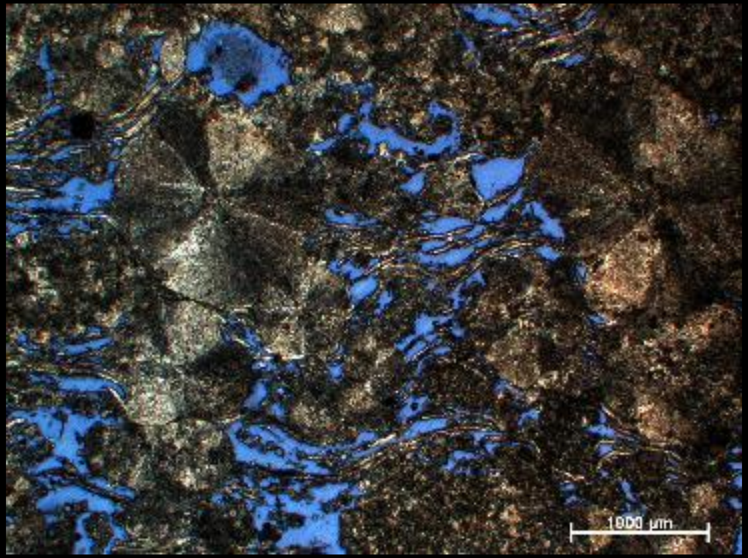

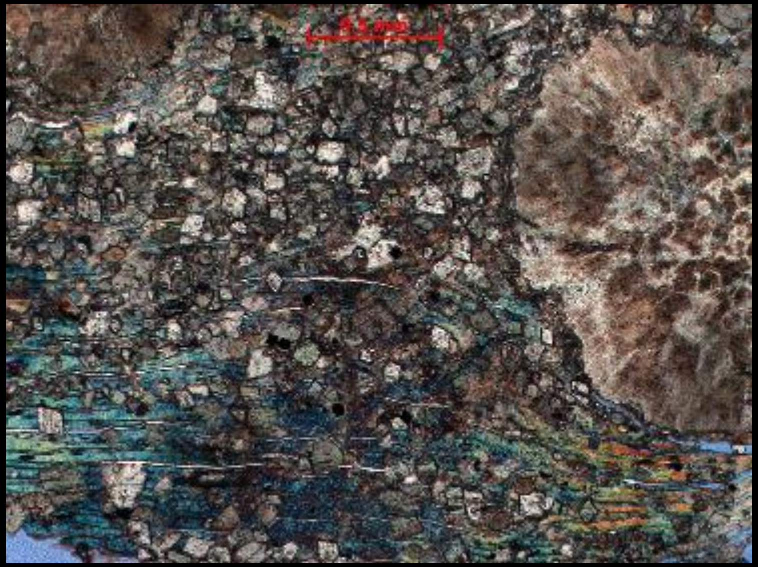

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- This presentation offers a methodology for characterising the highly unusual carbonates from the Cretaceous lacustrine Pre-Salt Barra Velha Fm giant oil fields of Santos Basin and its equivalents in other South Atlantic basins, which has provided a robust system for rock fabric determination linked to understanding pore system evolution, diagenetic pathways and petrophysical properties.

- Many textures and pore types found in the Barra Velha Fm appear to have no direct analogue with other carbonate successions and reservoirs.

- Applying industry standard terminology (e.g. Dunham, 1962) carries conceptual “baggage” and can mislead the interpreter to make incorrect interpretations leading to erroneous facies and even seismic interpretations.

- The crucial step in understanding these reservoirs was to identify the former presence of labile Mg-silicate matrices whose dissolution played a key role in producing porosity and influencing later diagenesis.

- Textures resembling boundstones are diagenetic and what have been regarded as microbial growths (shrubs) can be distinguished from microbial forms which are VERY rare.

Why does it matter?

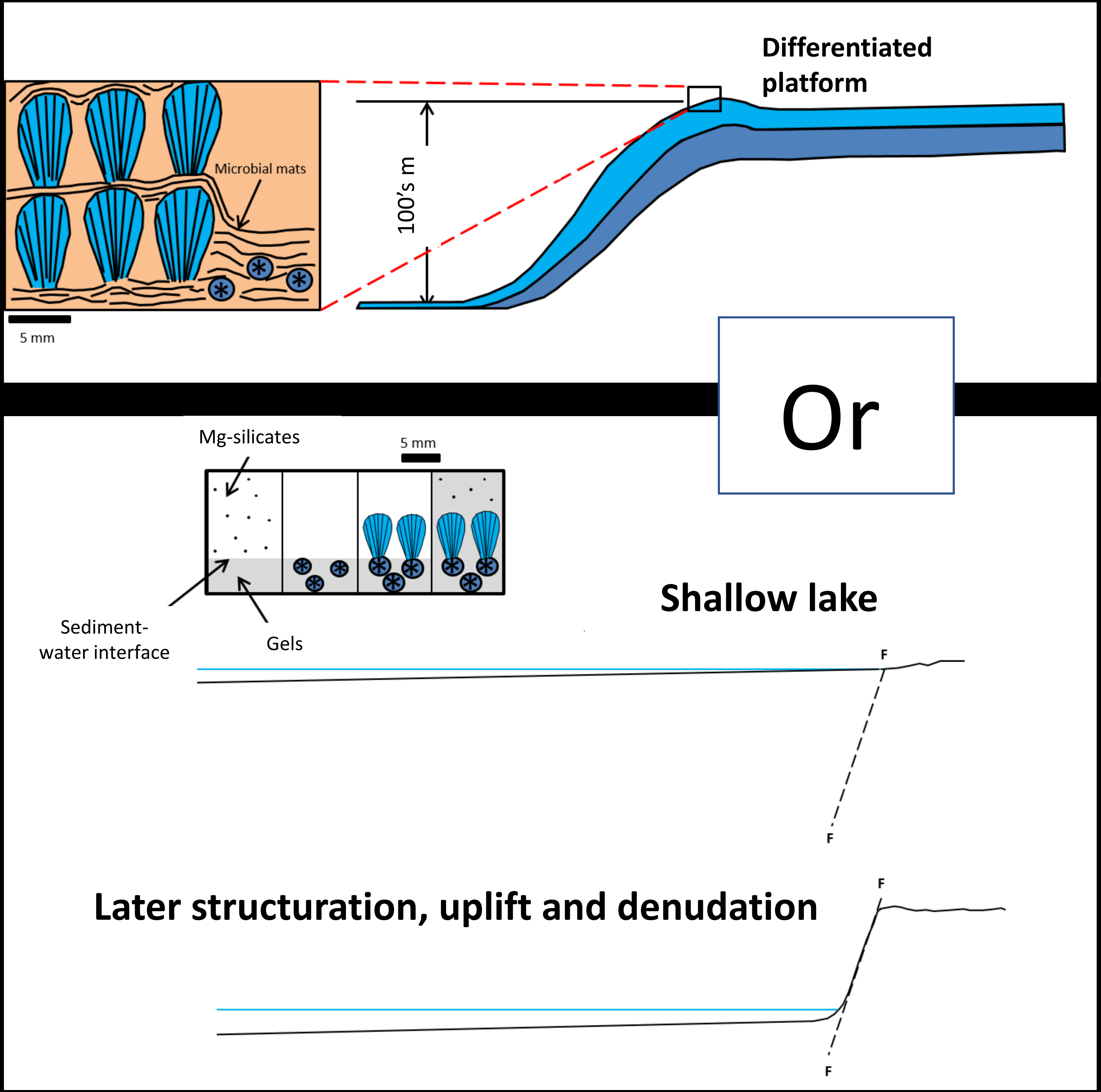
There are currently two almost diametrically opposite Barra Velha Fm models in terms of understanding seismic expression and reservoir architecture:

1. The microbial platform - deep lake model, is based on seismic data suggesting marine-like platforms. The textures and facies are slotted into a simple, intuitive model with biotic factories (microbial), slopes, platform margins and platform interiors.

2. The shallow lake model is evidence-based, derived from detailed process-based textural comparisons, then interpreting the key facies from their positions in metre-scale cycles, supported by geochemical modelling.

Our practical classification is fundamental to supporting the shallow lake model.

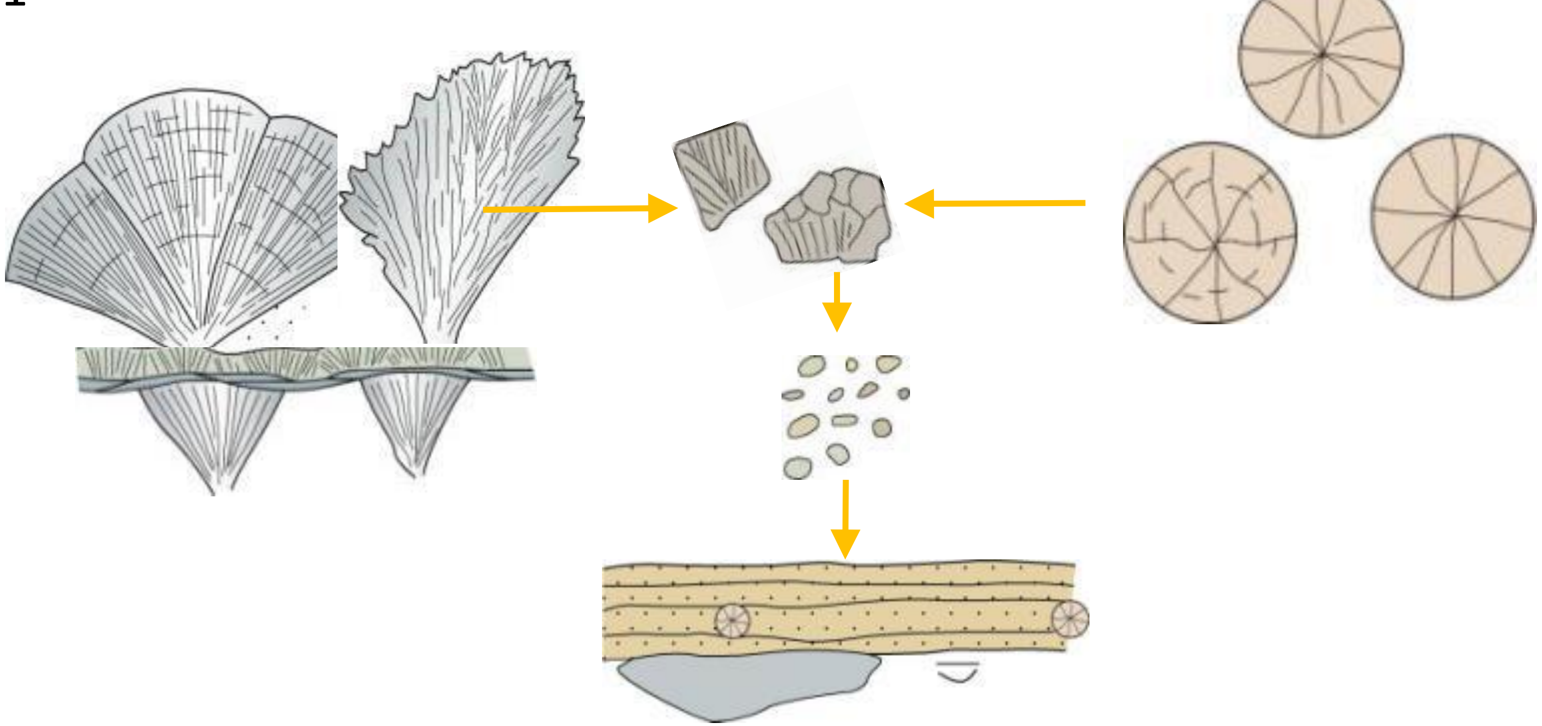
In this model seismic relief is explained by extensive largely post-carbonate structuration.

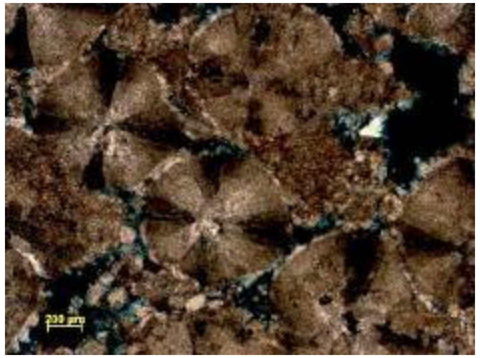


The Barra Velha Fm, locally >550m thick consists mainly of two components

Crystal calcitic shrubs = mm-cm-sized
= Facies 1

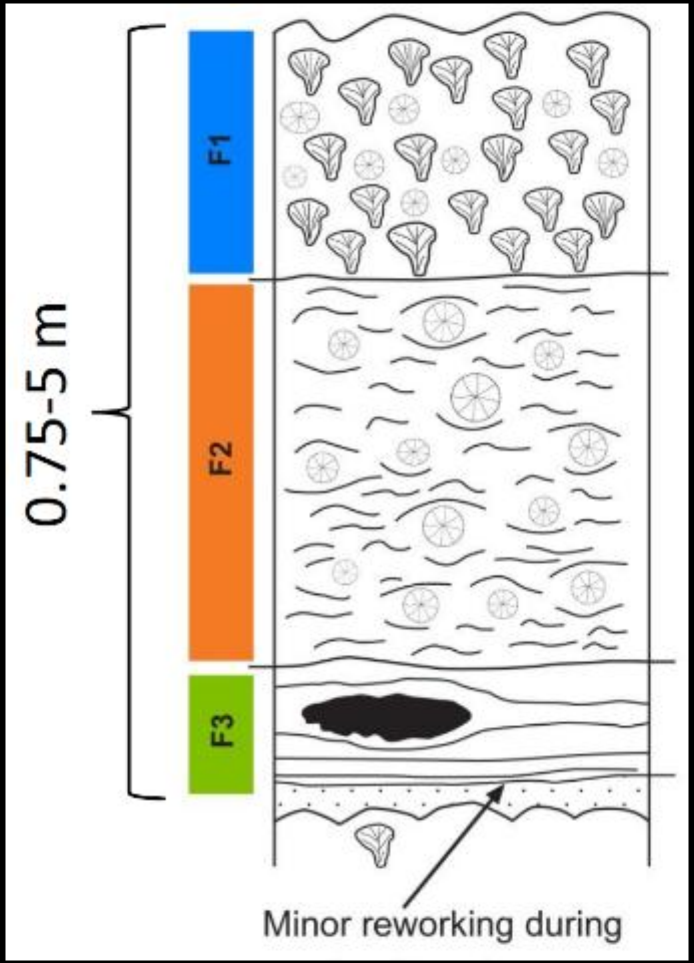
Mm-sized calcite spherulites
= Facies 2





Laminated silt-grade reworked shrub-spherulite debris and micrite with ostracodes, vertebrate fragments and “early” silica nodules = Facies 3

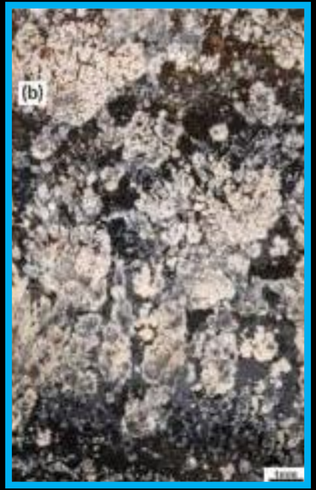
The facies we define occur in evaporative alkaline lake cyclothems

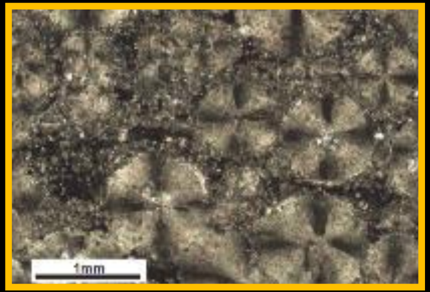


Facies 1: Calcite shrub framestones, with Mg-silicates or patchy traces of former Mg-silicates

Facies 2: Calcite spherulite floatstones, with Mg-silicates or traces of former Mg-silicate matrices

Facies 3: Laminated calcimudstones with prominent ostracodes and vertebrate debris, early silica nodules



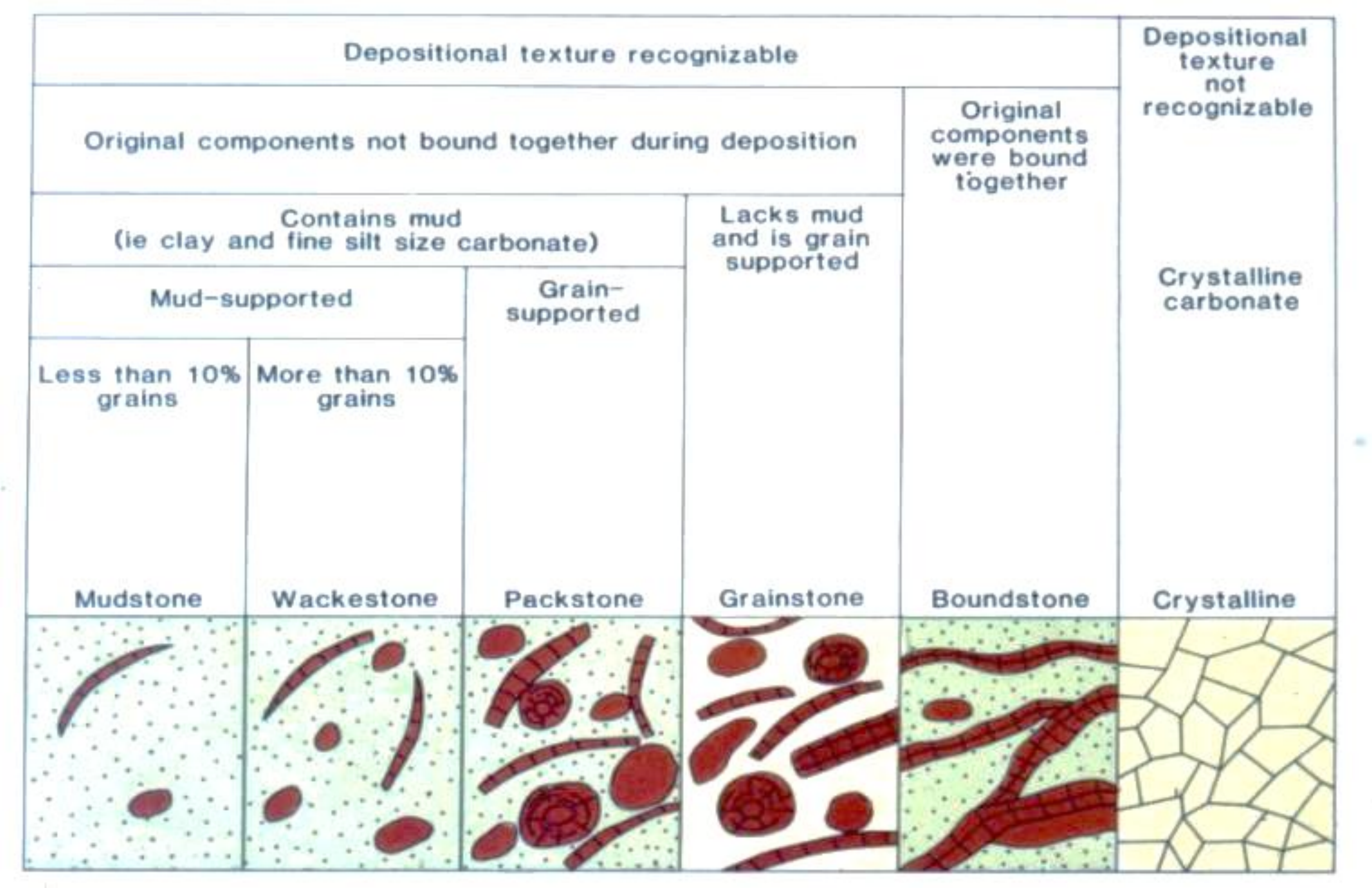


Photos from Terra et al 2010, Boll. Geosci. Petrobras, 18, 1, 9-29

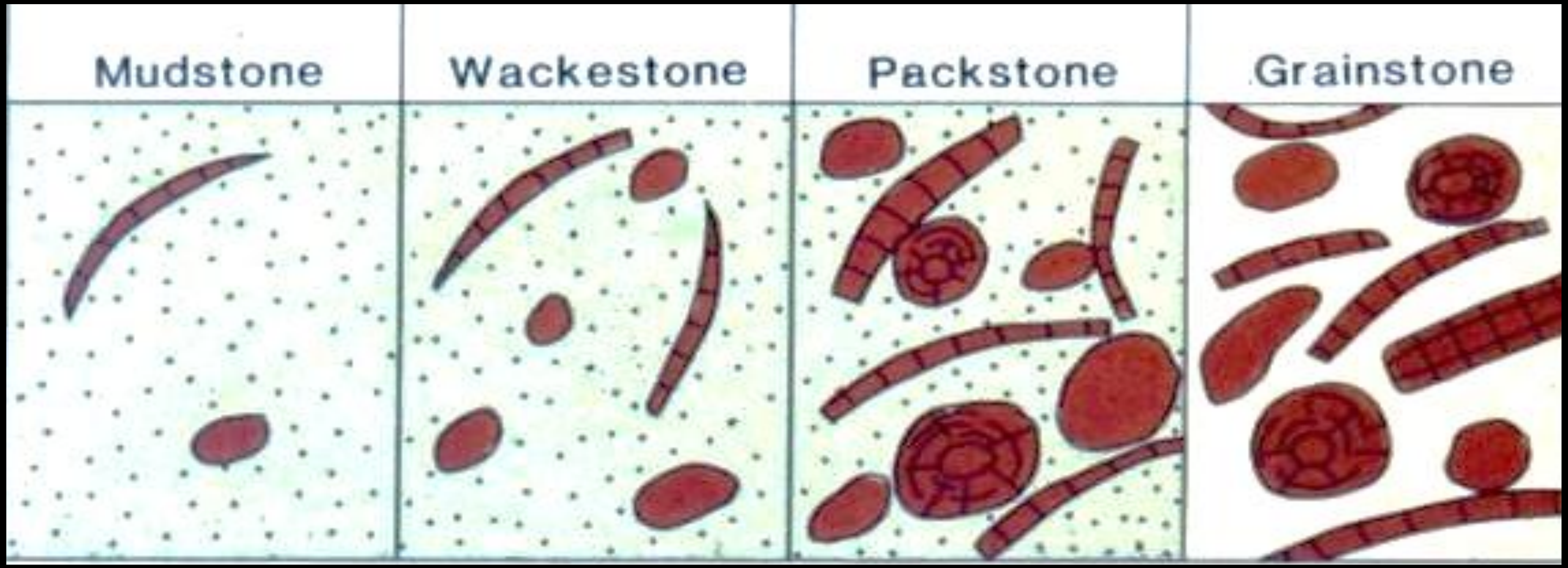
From - Wright, V. P. & Barnett, A. J. 2015 An abiotic model for the development of textures in some South Atlantic early Cretaceous lacustrine carbonates. In Bosence, D. W. J. *et al*. (eds.), Microbial Carbonates in Space and Time: Implications for Global Exploration and Production. Geological Society, London, Special Publications, 418, 209–219.

Geochemical modelling – Wright, V. P. & Tosca, N. J. 2016. Geochemical Model for the Formation of the Pre-Salt Reservoirs, Santos Basin, Brazil: Implications for Understanding Reservoir Distribution . Search and Discovery Article #51304

Existing classifications of carbonates are based on the concept of textural maturity whereby the presence or absence of a matrix is seen as an indicator of energy levels



Based on Dunham R J 1962 AAPG Memoir 1, 108-121



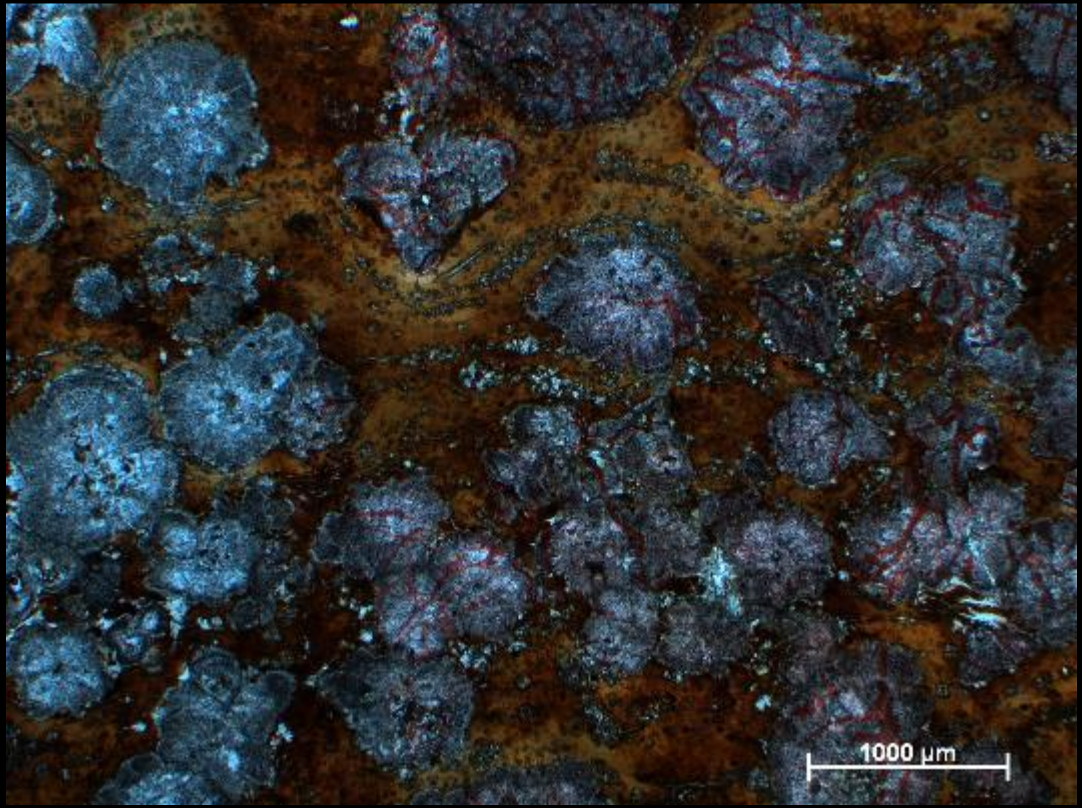
Porosity and/or cement

Grains and matrix were deposited

No matrix - fines winnowed away

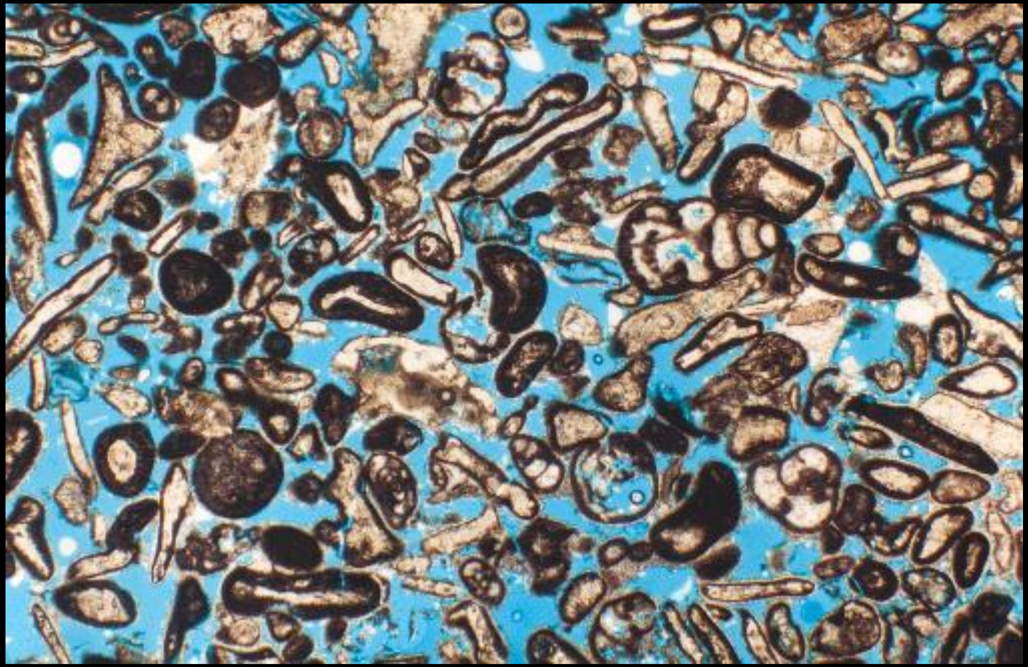
But what if the carbonate grains grew in a matrix?

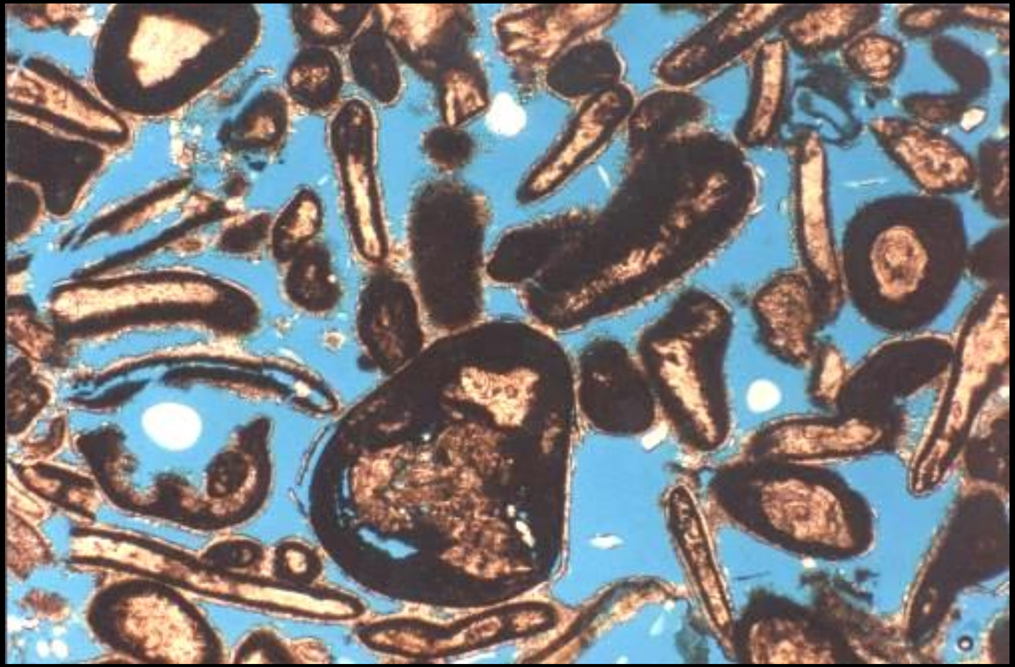
The matrix is or
was a Mg-silicate



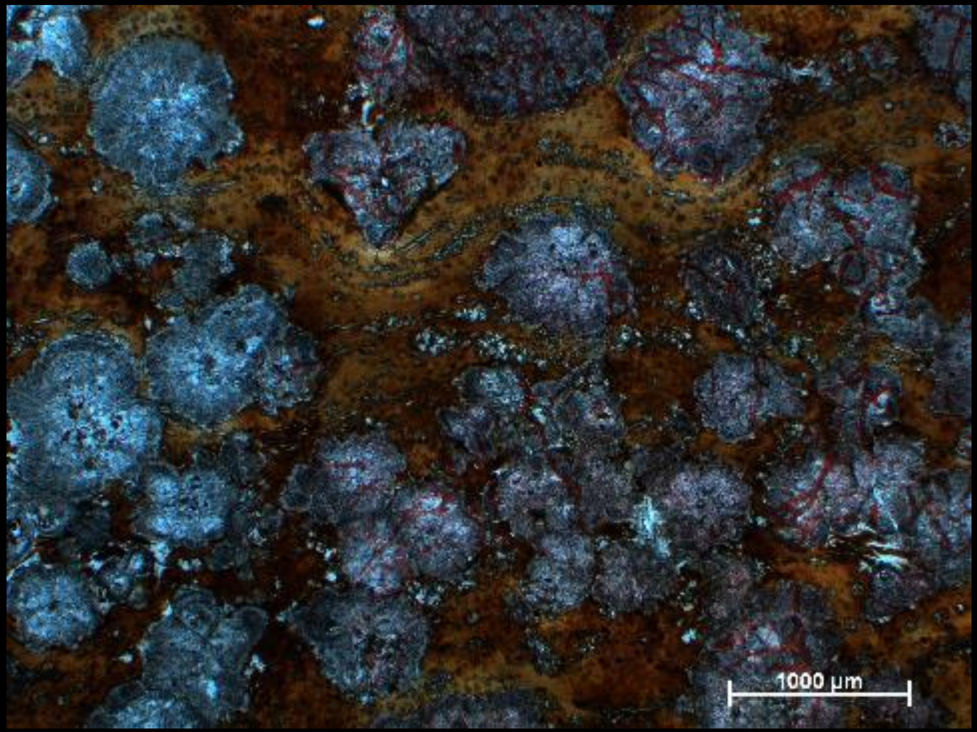
Such silicates form initially as gels = hydrated aggregates of Mg-silicate nanoparticles, which convert to crystalline clays

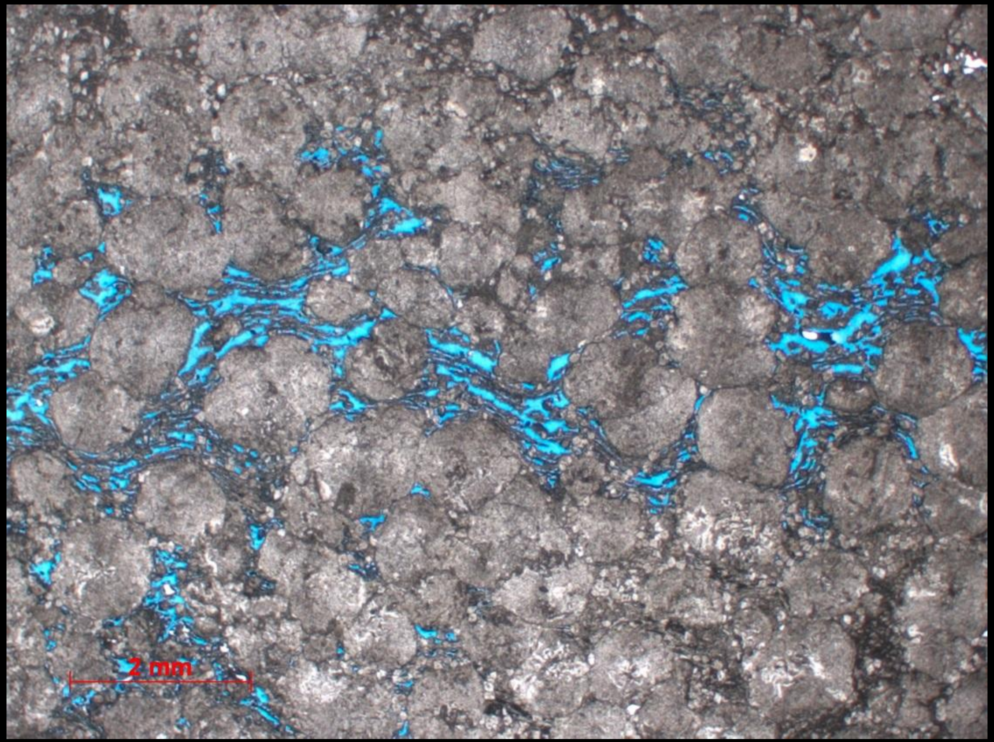
Grainstones, with primary intergranular porosity or cement between grains are interpreted as higher energy deposits





But what if ….. the porosity was due to the dissolution of the matrix





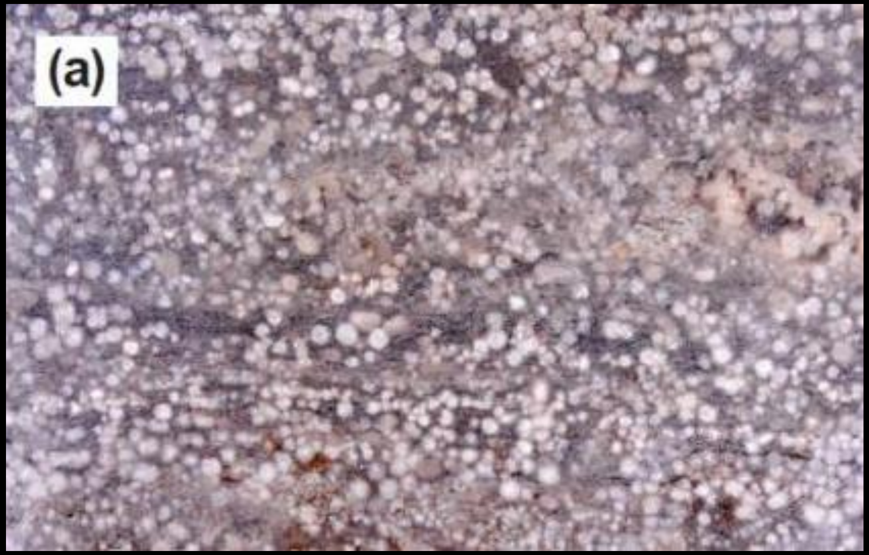
producing what appears to be primary intergranular porosity?

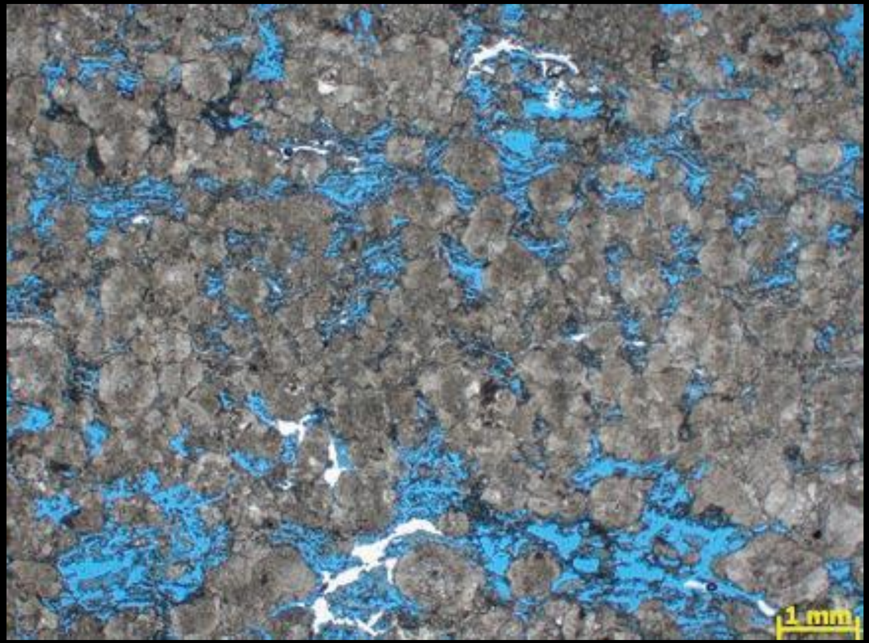
Dunham's 1962 classification

Boundstone – "carbonate rocks showing signs of being bound during deposition….."

"Original components were bound together during deposition….roofed over by organic or questionably organic matter…"

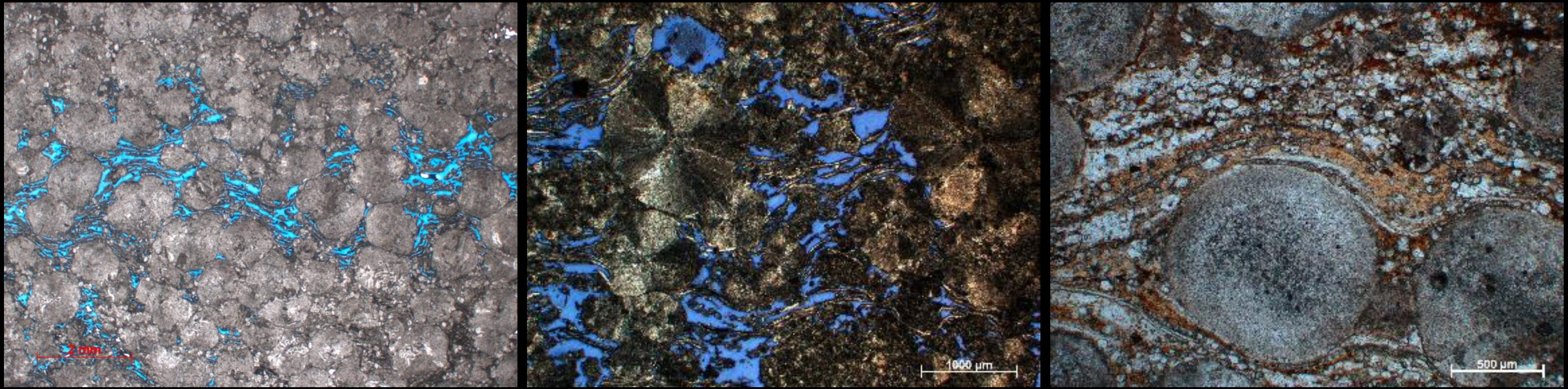
Source – ANP   Pre-Salt Libra Geological Assessment : 17/9/2013





Boundstones of Terra G J S *et al*. B. Geoci. Petrobras, Rio de Janeiro, v. 18, n. 1, p. 9-29, nov. 2009/maio 2010

But what if these features suggesting binding are in fact diagenetic?



The bridges create unusual pseudo-fenestral pores

F1 = Shrubs (crystal shrubs)

F2 = spherulites

Precipitated
suffix a

In situ growth

Shrubs
F1a

Spherulites
F2a

F1/2a^1

With Mg-silicate matix

F1/2a^2

Porous

F1a = framework or moldic

F2a = moldic

F1/2a^3

Silica or dolomite replacement and cement

F3

Laminated carbonate mudstones

a = with ostracodes, early silica nodules
b= varved, graded laminae

Detrital

Fragmented

F1

F2

wackestone
packstone

suffix **c**

grainstone
rudstone

suffix **b**

F5

Super-mature – well sorted and rounded

a = porous +/- rare sparite

b = condensed & fitted fabrics =/- minor porosity

Microbial

Rare

F4

Stromatolite
Dendrolite
Thrombolite
Leiolite

F1 = Shrubs (crystal shrubs)

F2 = spherulites

Precipitated

suffix a

In situ growth

Shrubs **F1a**

Spherulites **F2a**

F1/2a^1 — With Mg-silicate matix

F1/2a^2 — ***Porous***

F1/2a^3 — Silica or dolomite replacement and cement

F1a = framework or moldic

F2a = moldic

This is the critical element

F3

Laminated carbonate mudstones

a = with ostracodes, early silica nodules
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Microbial

Rare

F4

Stromatolite
Dendrolite
Thrombolite
Leiolite

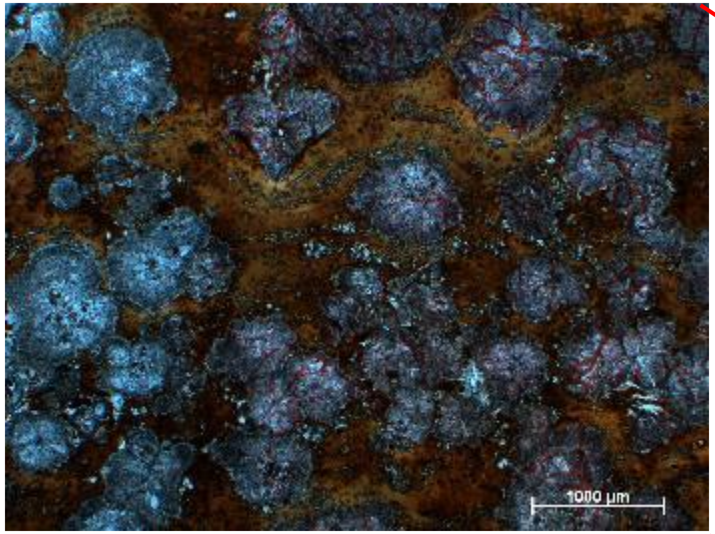
What evidence is there that a matrix dissolved and left features that can be misinterpreted as primary porosity or for evidence of binding during deposition?

Initially this was achieved by comparing units with preserved matrices and those lacking it, and refining the criteria for ghost matrices.

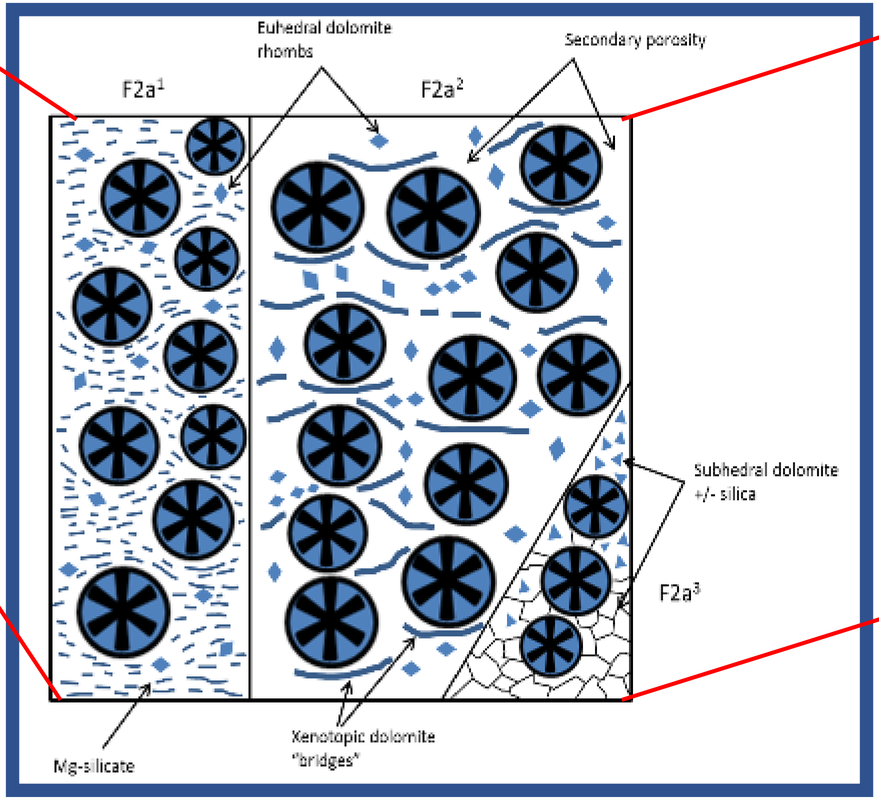
And why would a Mg silicate dissolve?

There are Mg-silicate clay matrices preserved but in the reservoir units this matrix was dissolved

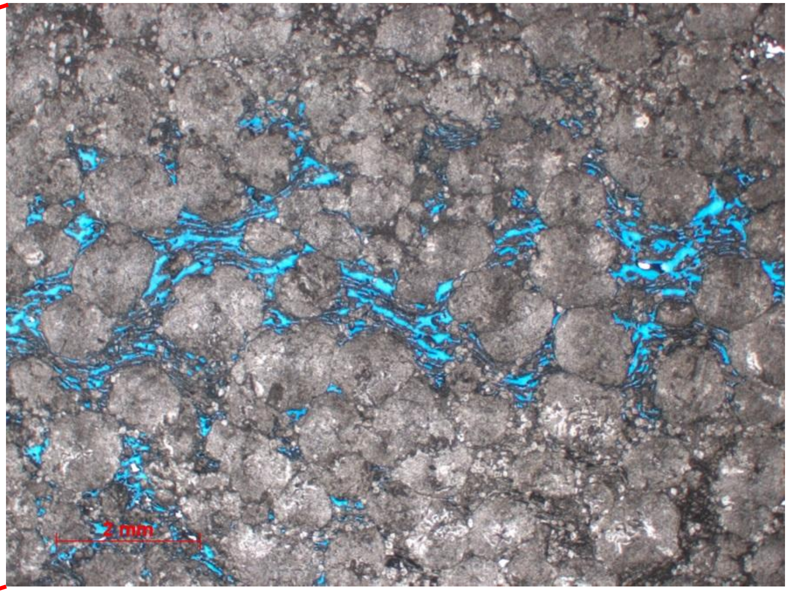
F2a[1]



Spherulites with Mg-silicate matrix preserved



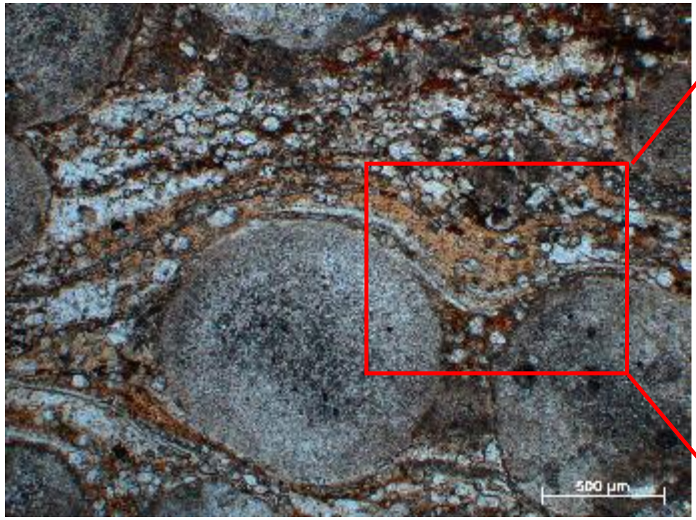
F2a[2]

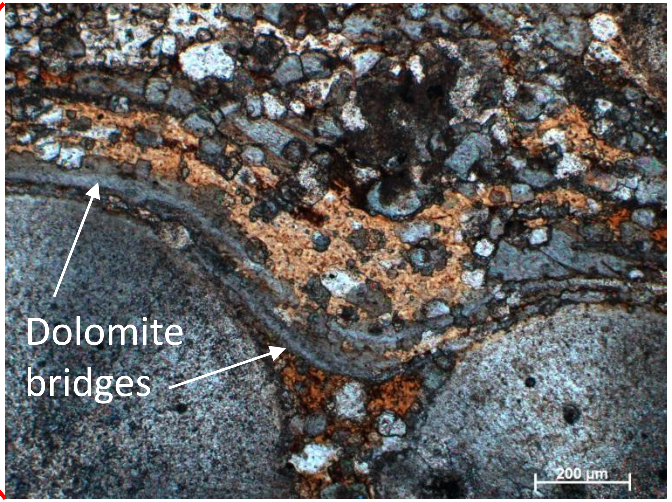


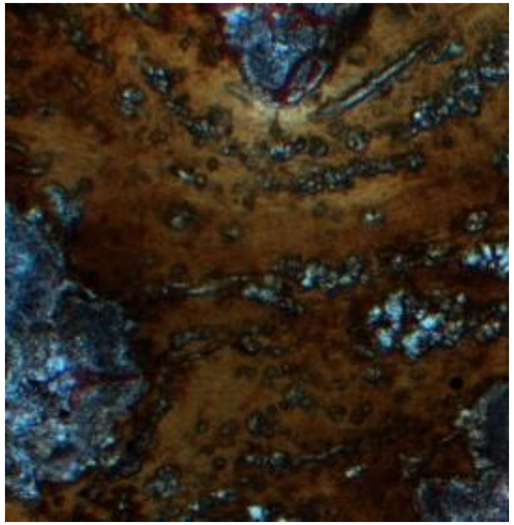
Spherulites with Mg-silicate matrix dissolved

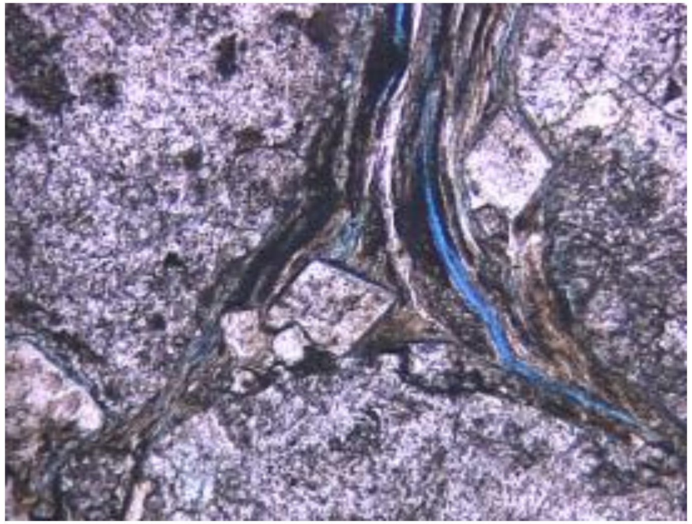
F2a[1] Where the Mg-silicate clay matrices are preserved loose “floating” dolomite rhombs and xenotopic dolomite “bridges” are seen. The “ bridges” mimic the shapes and orientations of clay plates wrapped around grains. These dolomite rhombs and “bridges” are never found reworked and are interpreted as diagenetic features.

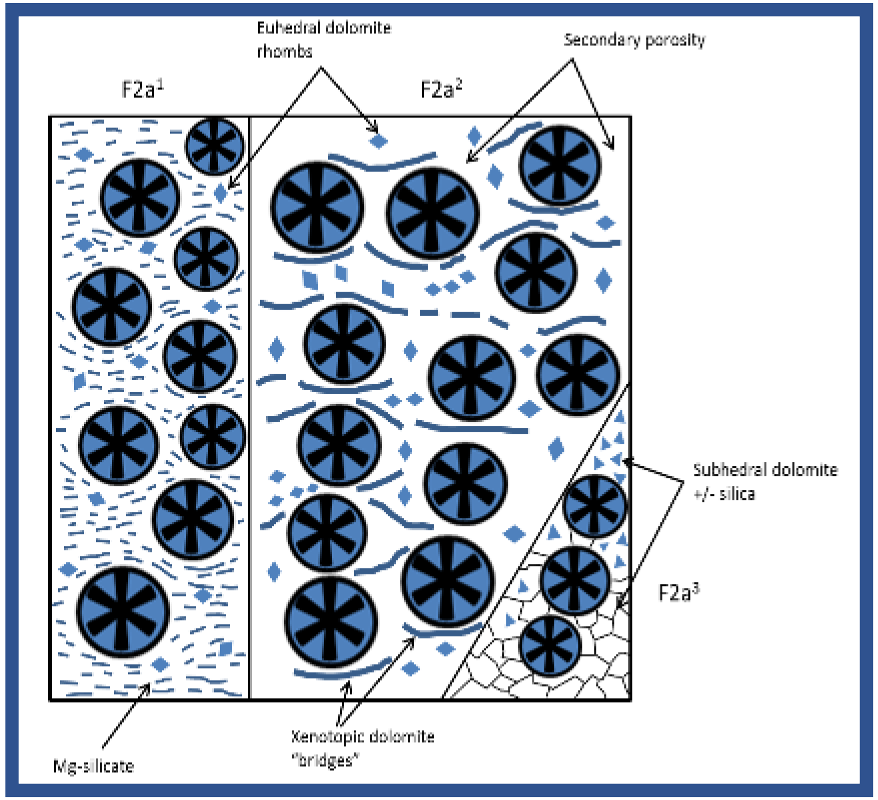
F2a[1]





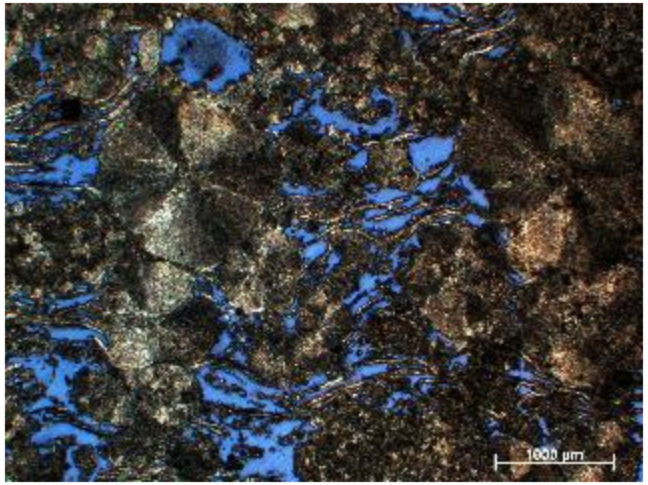


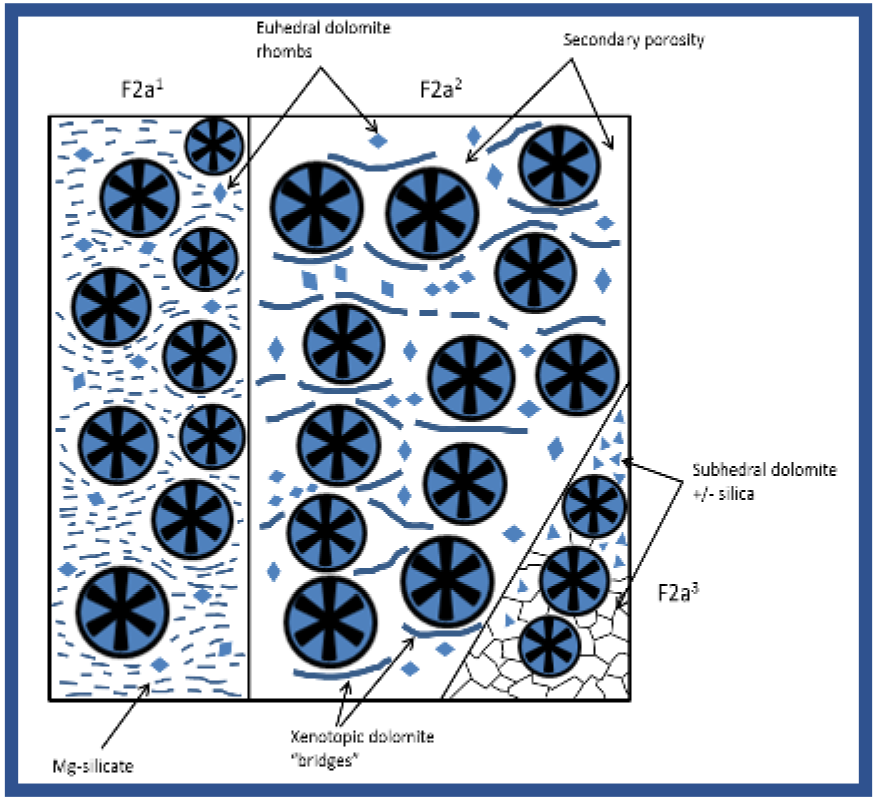


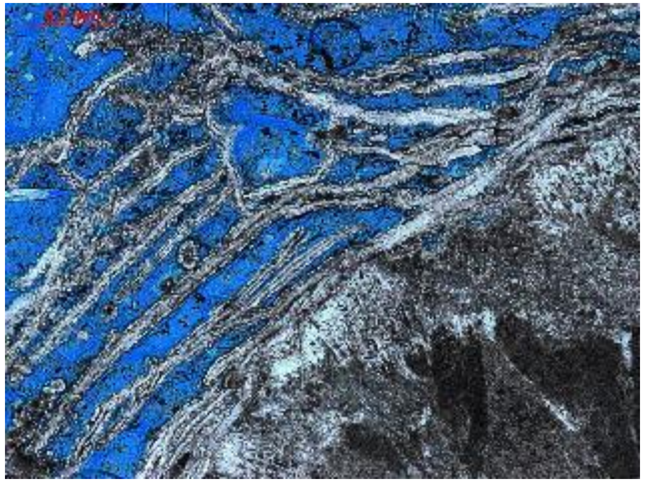


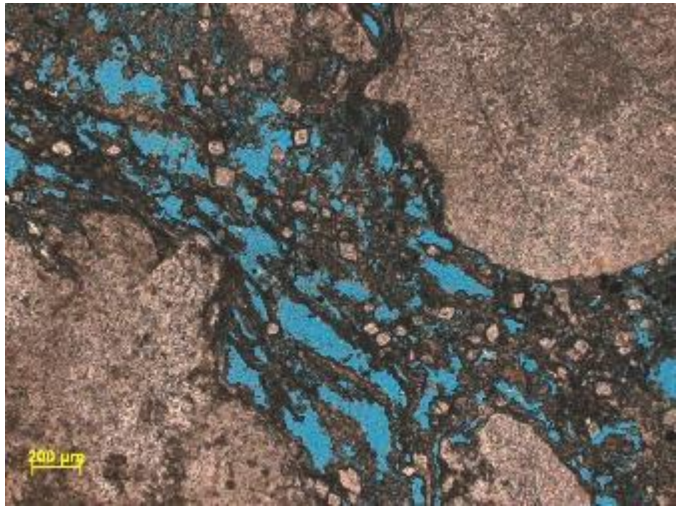
F2a^2 The rhombs and bridges are clearly visible where the matrix has been dissolved – a pseudo-boundstone

F2a^2

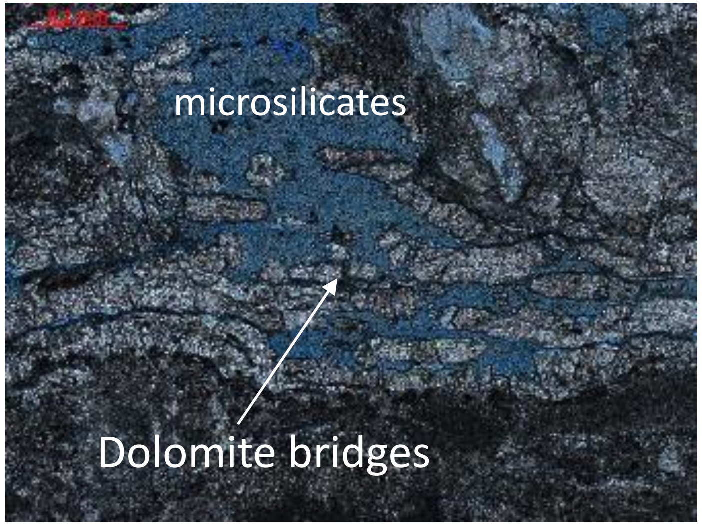


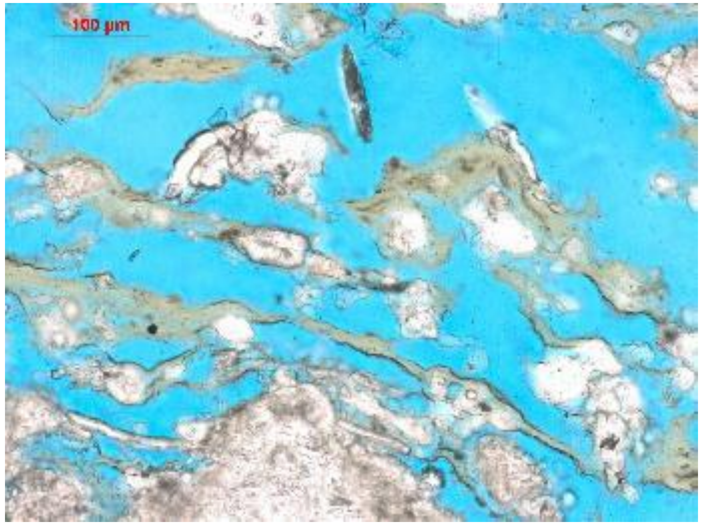


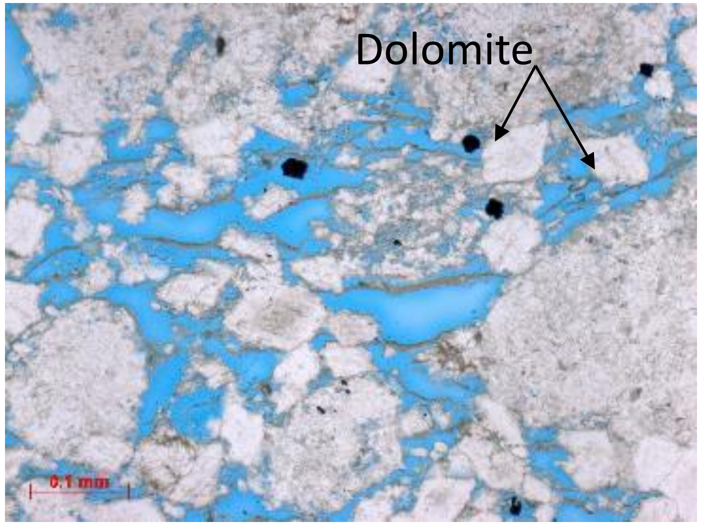


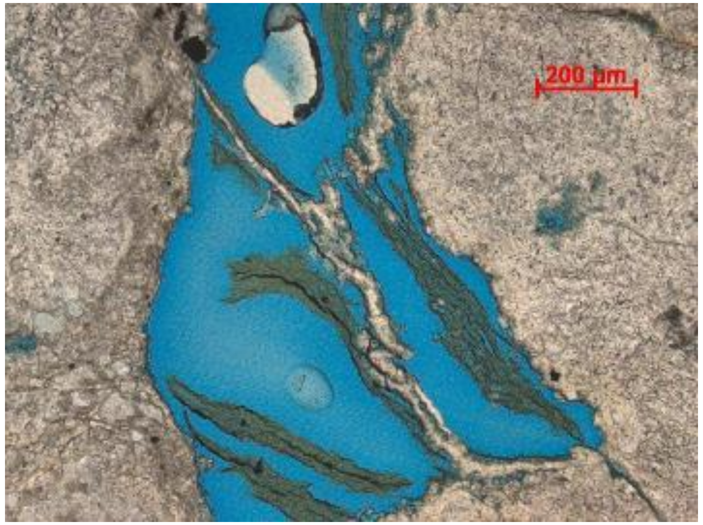


F1a^2 In some cases relict patches of platy and granular microsilicates are found in the pore spaces previously filled by the Mg-silicates. But organic matter does not constitute the matrices when present and no microbial structures have been encountered between any of the spherulites

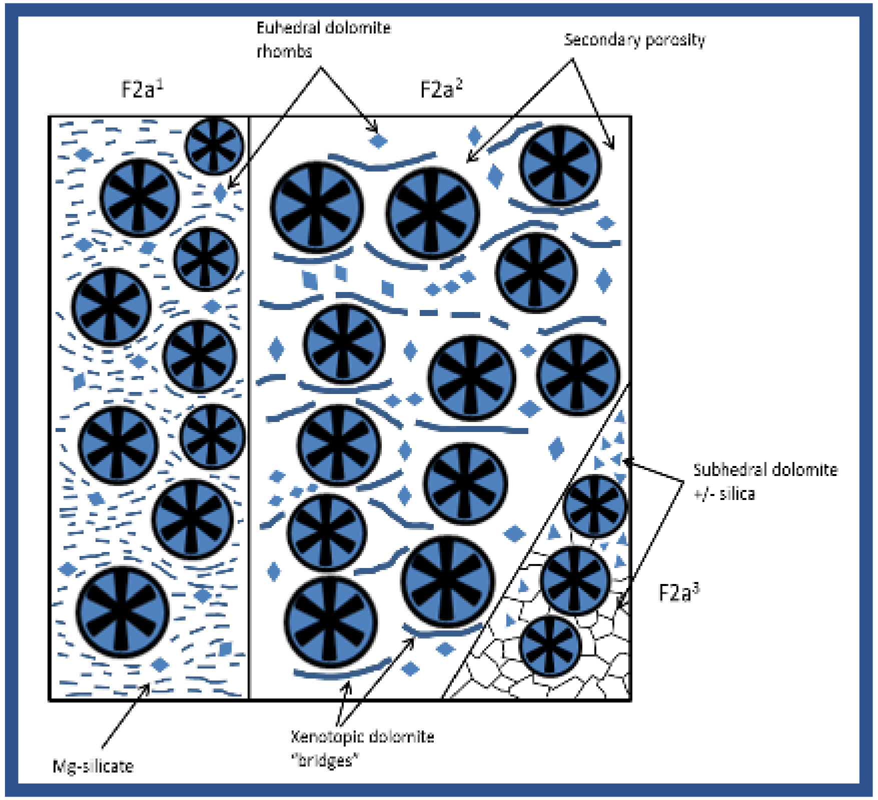




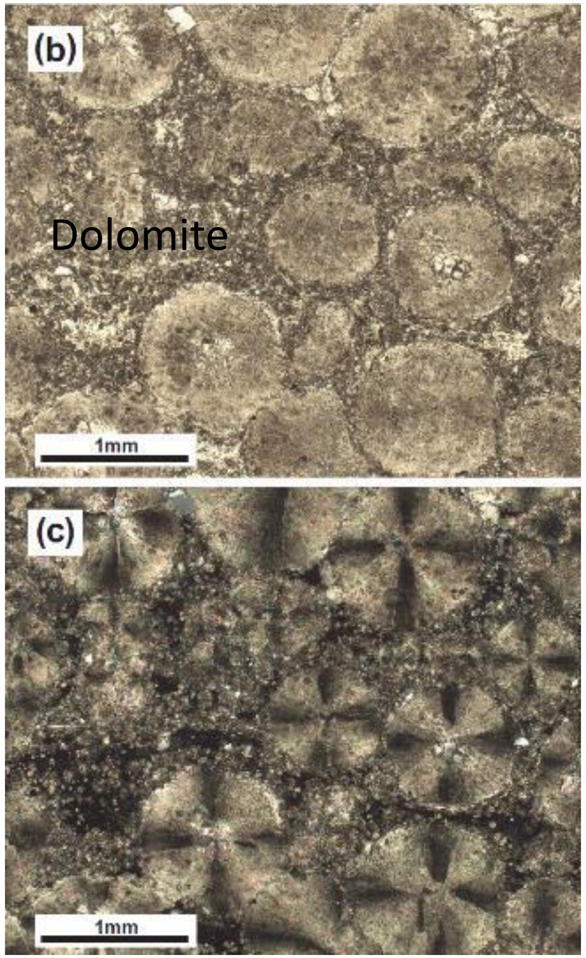




F1a^2



F1a^{3} - In some cases the matrix was replaced by dolomite or silica, or the porosity was filled by silica cement



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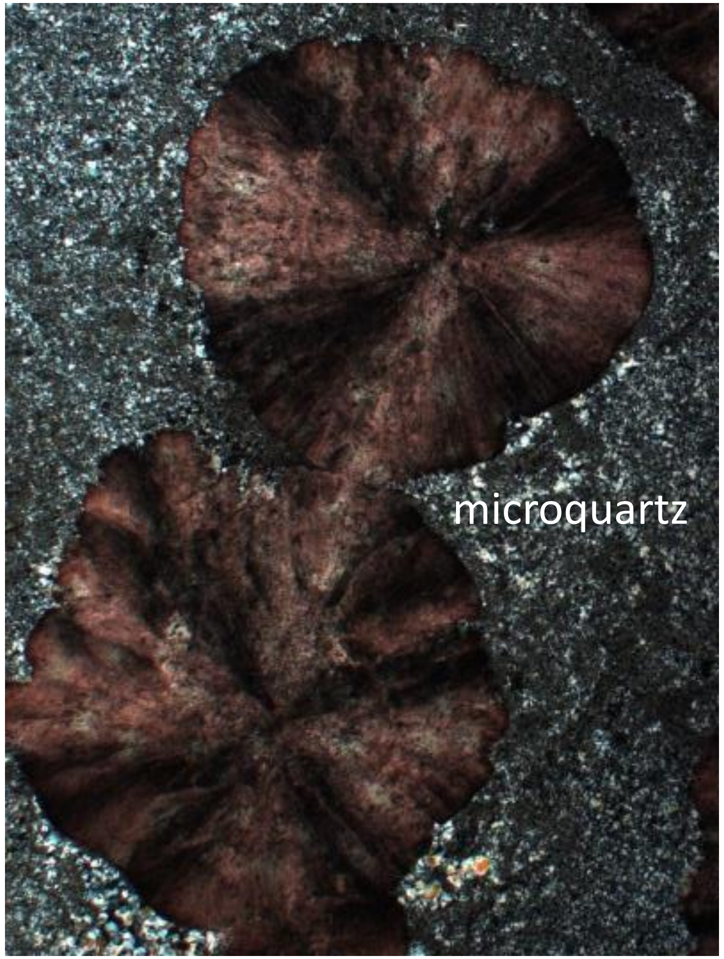
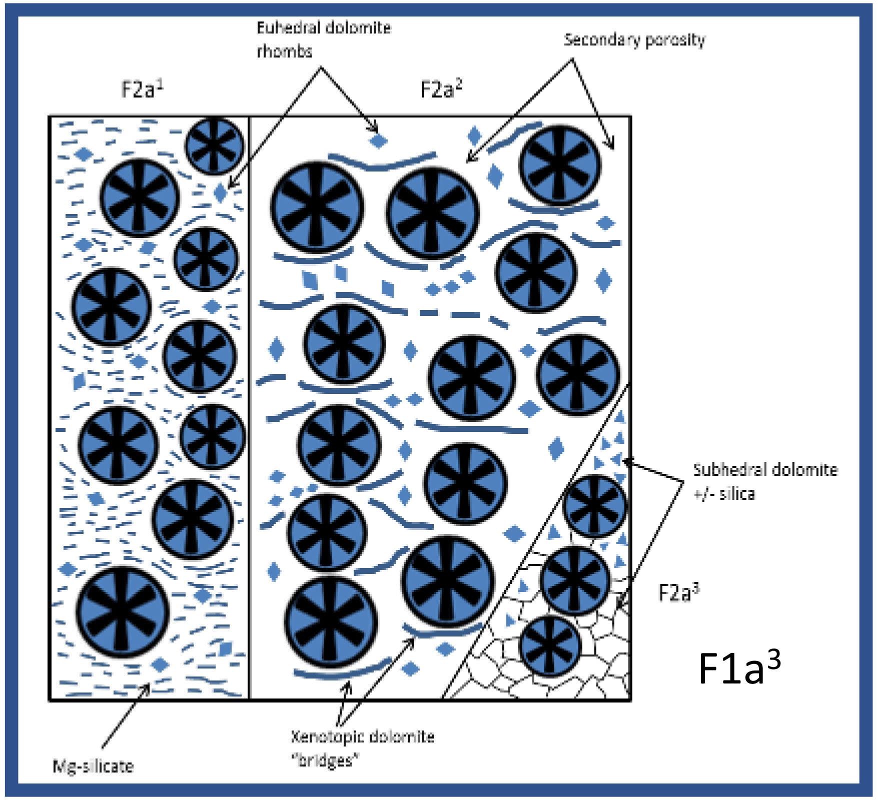
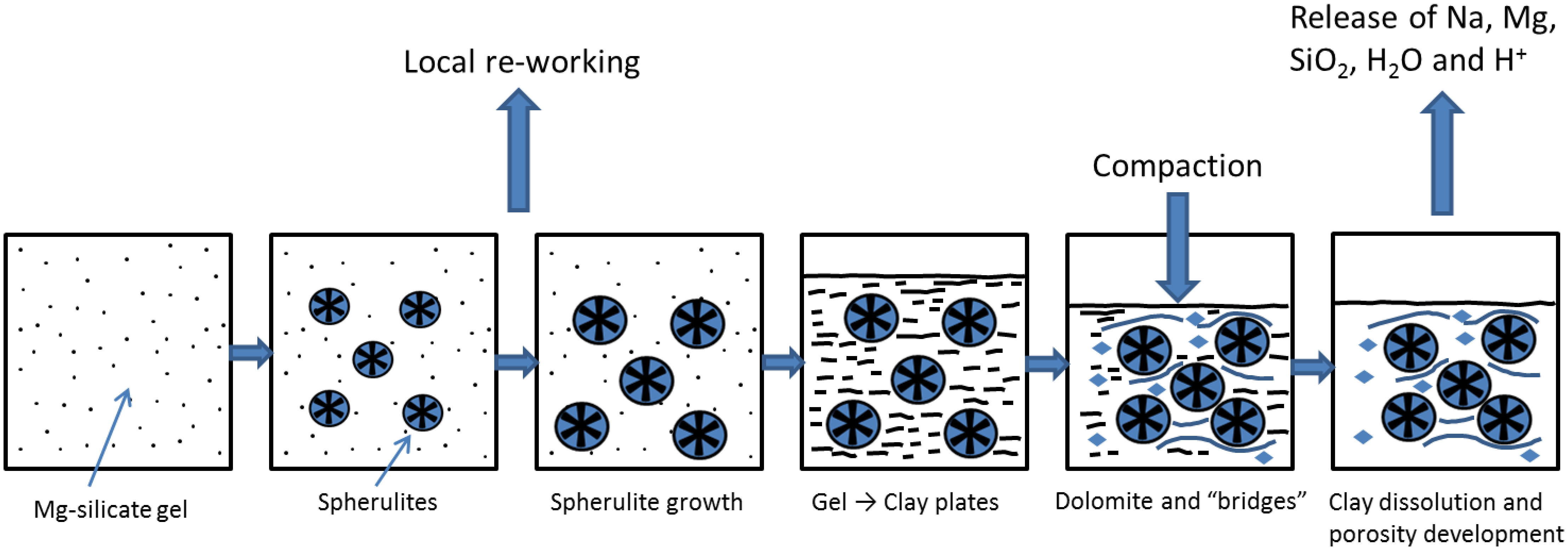




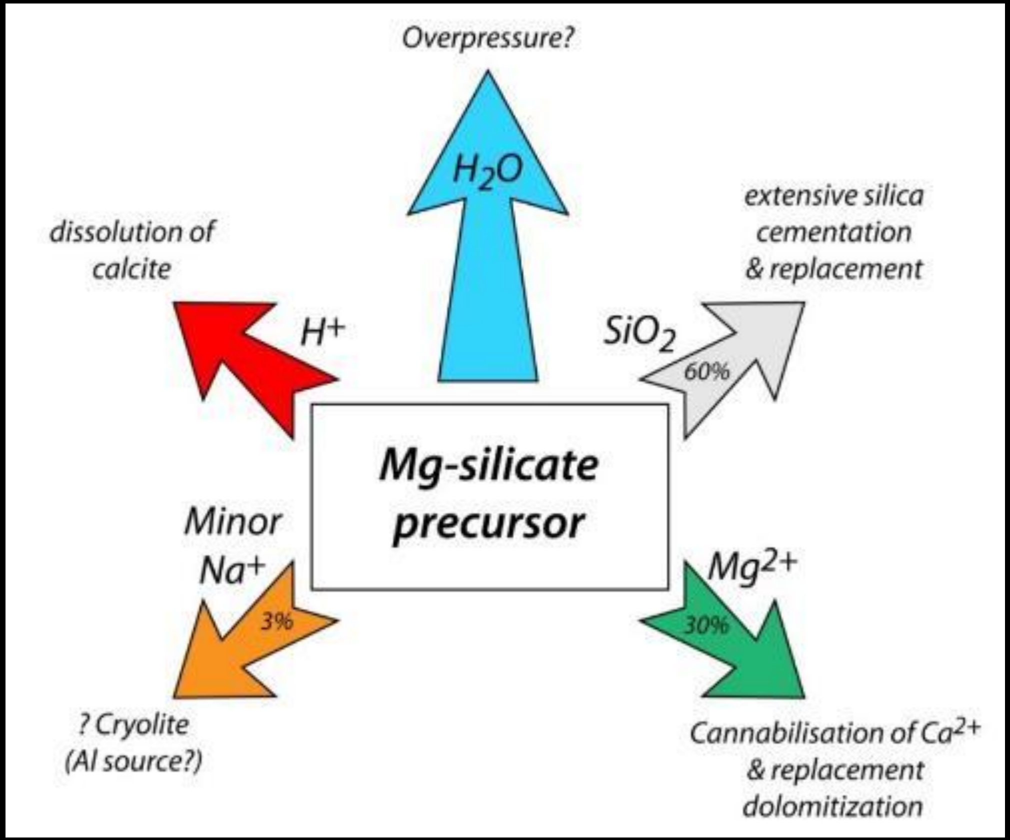
From published experimental work spherulitic growth can be abiotic, and is favoured by high levels of Mg and silica in highly alkaline solutions, coupled with rapid calcite crystal growth, in viscous media, with or without any microbial influence.

Proposal is that the spherulites grew “floating” in a Mg-silicate gel which converted to clay, associated with dolomite. Geochemical modelling shows this resulted from evaporation in highly alkaline waters most likely in shallow lakes.



So what are these textures – wackestones, packstones, floatstones?

Dissolution of Mg silicates - stevensite



Why does stevensite dissolve, congruently?

- Al –poor (<2%wt)
- Weak Mg-O bonds

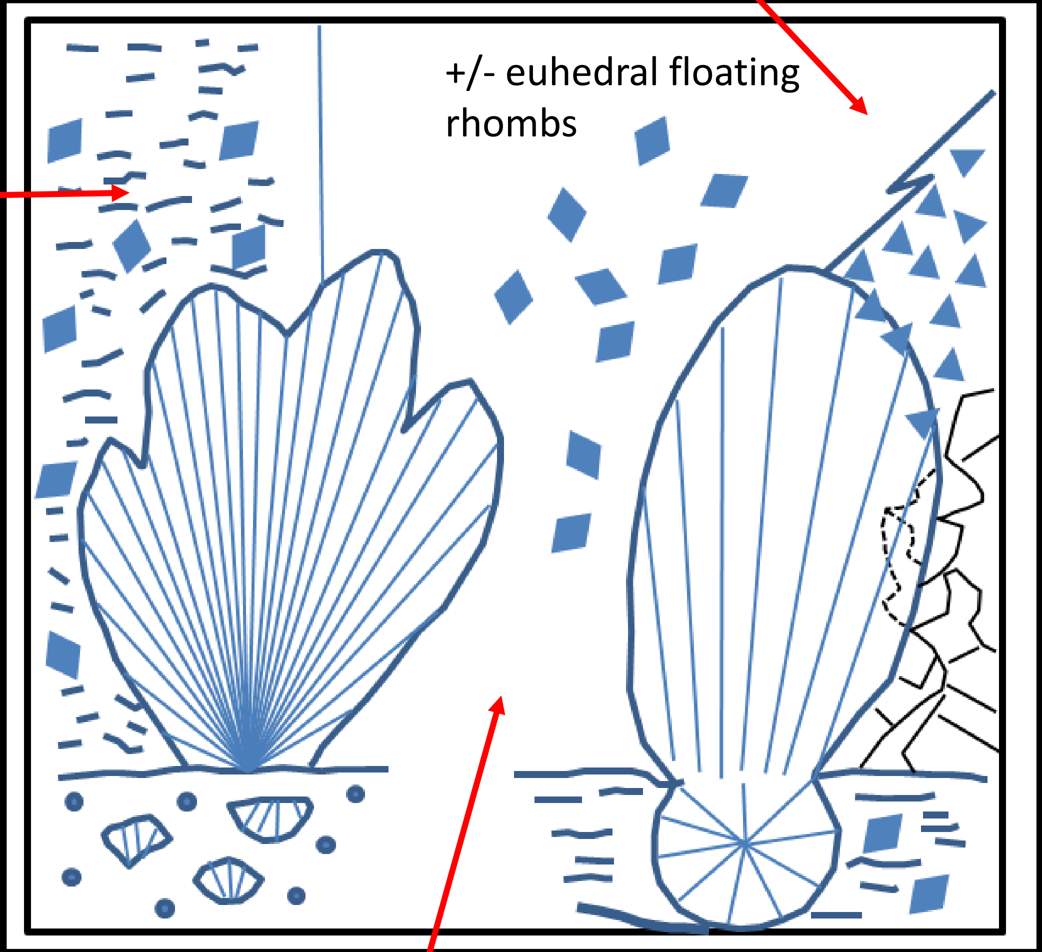
The result of its decay is to trigger the other diagenetic effects seen the formation.

Additionally, stevensite may be particularly prone to acid generation and dissolution because it contains vacancies which, when filled by migrating interlayer cations, cause deprontonation of surface -OH groups. This is known as the Hofmann-Klemen effect.

From: ***Tosca N & Wright V P 2015***, in press & Tosca N 2015-2017 Diagenetic pathways linked to labile Mg-clays in lacustrine carbonate reservoirs: A model for the origin of secondary porosity in the Cretaceous Pre-Salt Barra Velha Formation, offshore Brazil. In Armitage, P et al (eds) Reservoir Quality of Clastic and Carbonate Rocks: Analysis, Modelling and Prediction. Geological Society, London, Special Publication 435, doi.org/10.1144/SP435.1 and ***Tosca N & Wright V P 2014*** The formation and diagenesis of Mg-clay minerals in lacustrine carbonate reservoirs. AAPG Search and Discovery Article #51002

What about the shrubs?

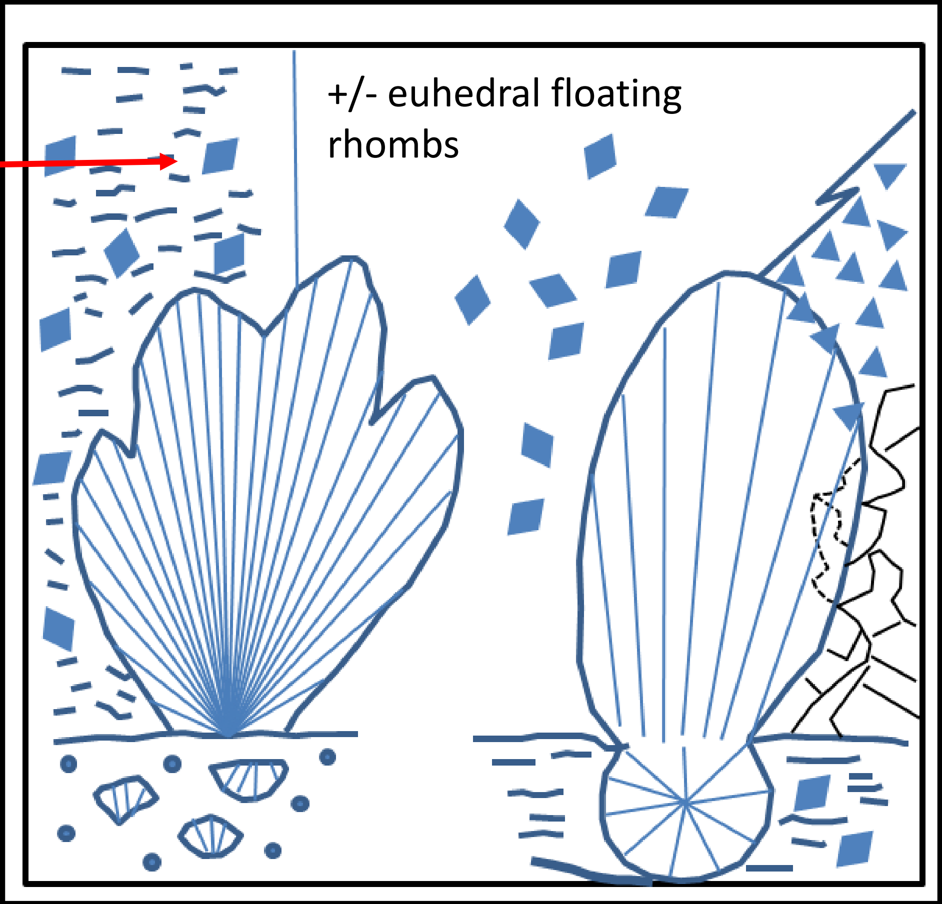
These have the best reservoir quality and appear to have primary framework porosity and in some case also evidence of some former Mg-silicate matrix



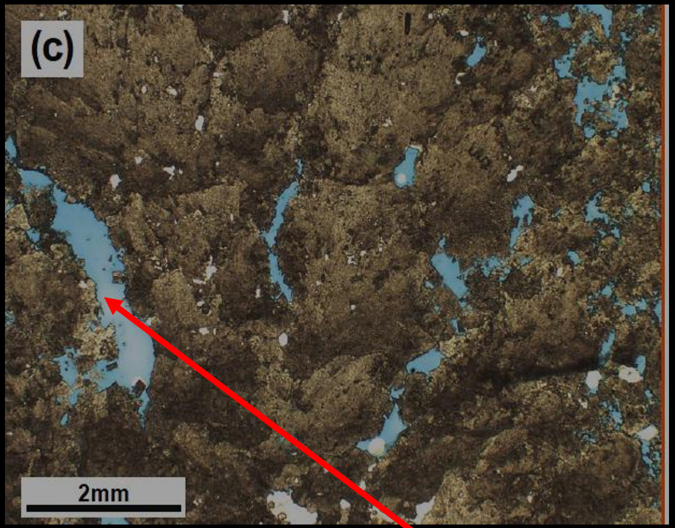
Facies F1a[1] – in situ shrubs with inter-shrub areas filled with Mg-silicates

Mg
silicate

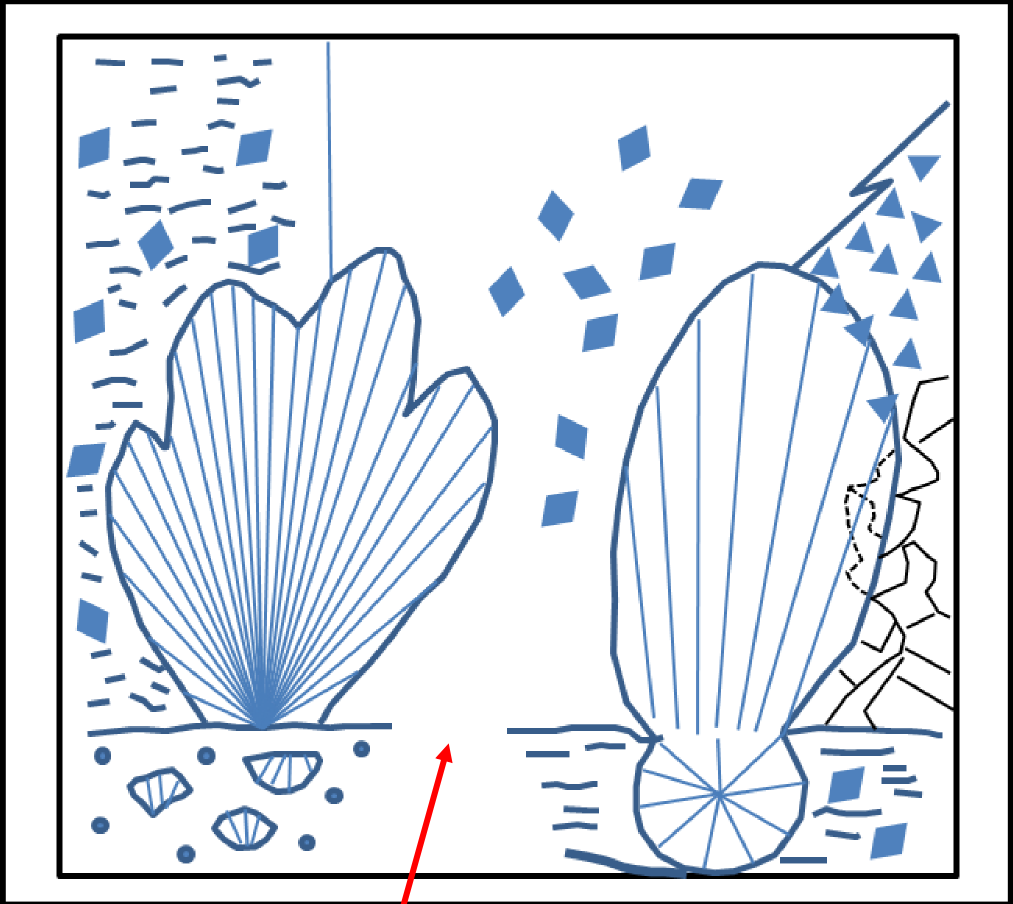
F1a[1]



Facies F1a^2 – in situ shrubs with primary inter-shrub porosity with no evidence of any precursor matrix



Terra G J S et al. B. Geoci. Petrobras, Rio de Janeiro, v. 18, n. 1, p. 9-29, nov. 2009/maio 2010

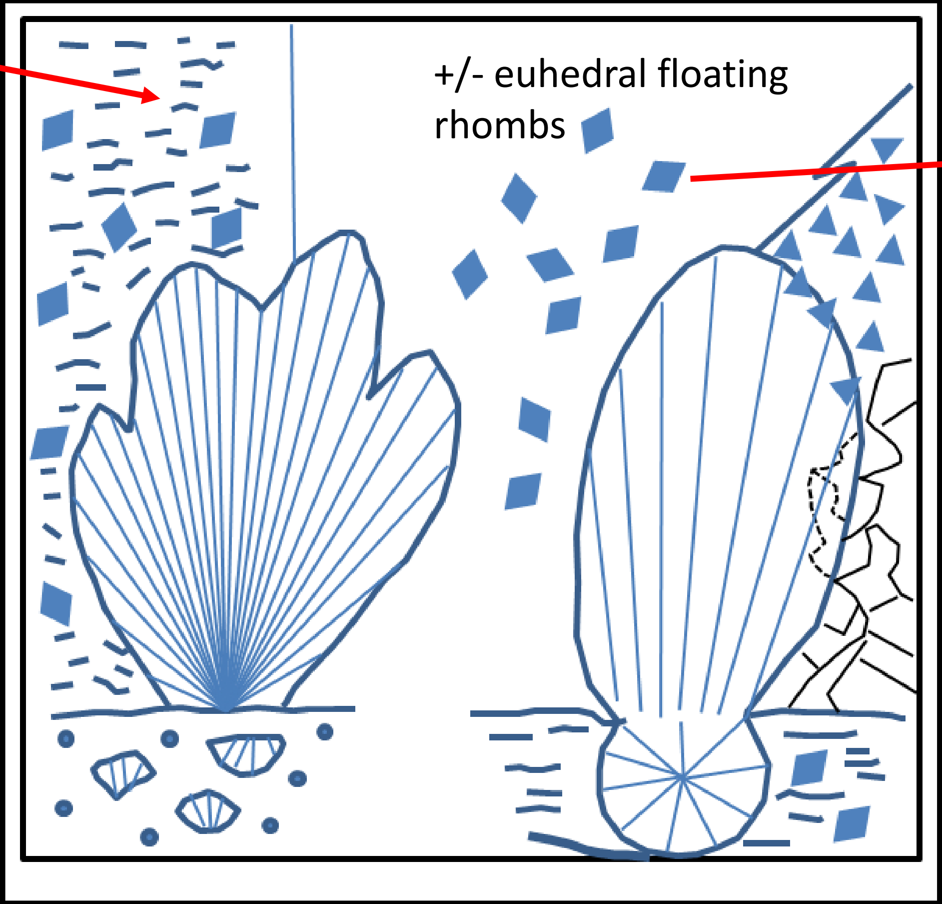


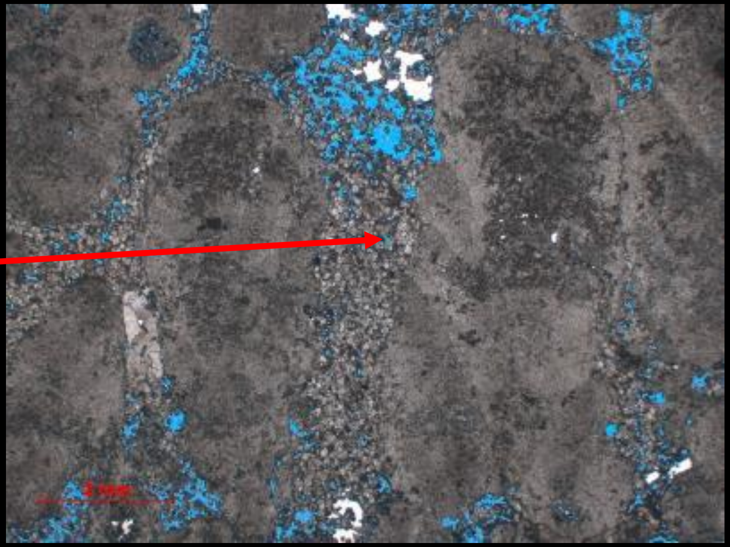
F1a^2
Primary inter-shrub growth/framework porosity

Facies F1a^2 – in situ shrubs with open inter-shrub areas typically with "floating" dolomite rhombs

F1a^2

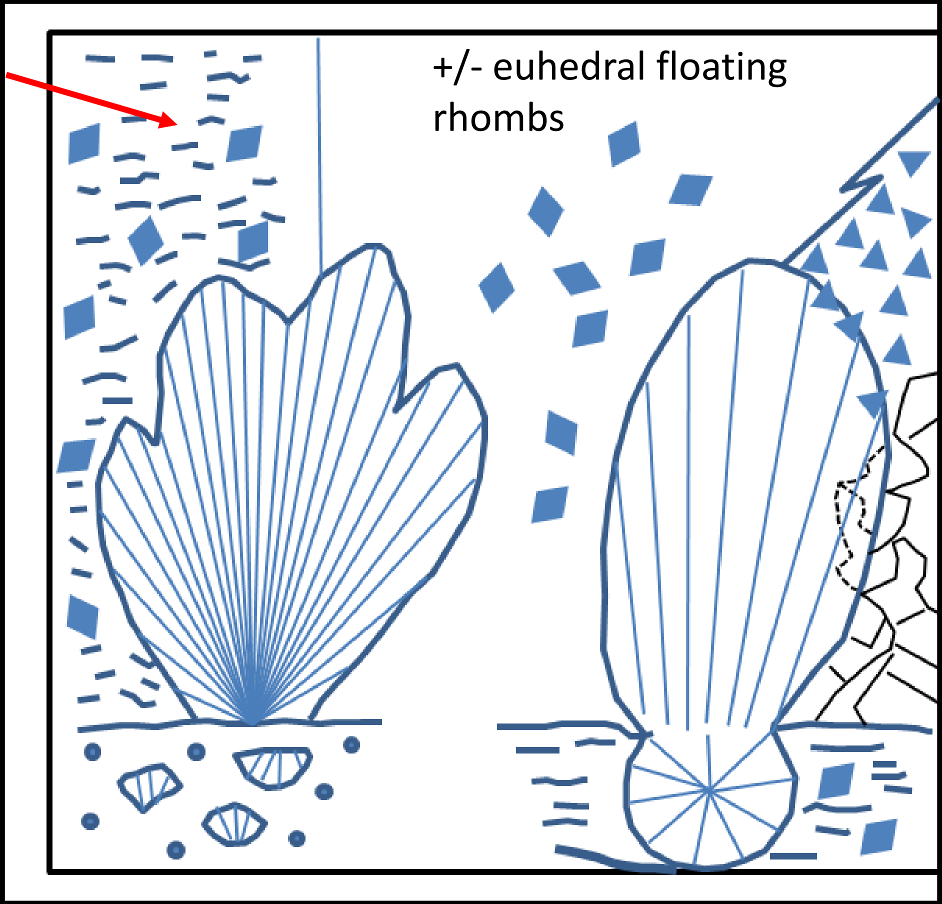
Mg silicate





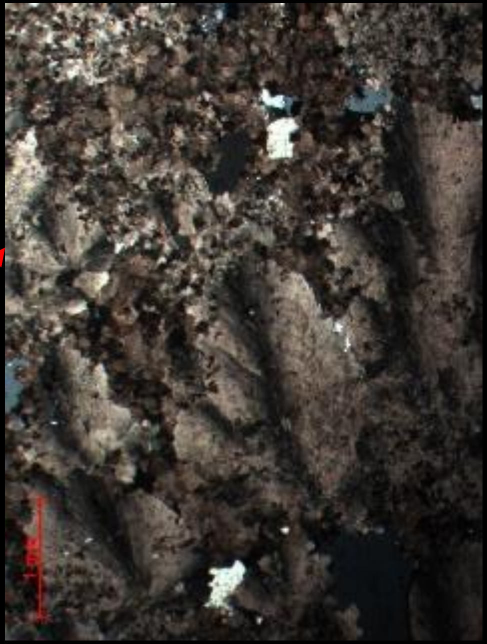
Facies F1a^3 – in situ shrubs with inter-shrub areas largely or wholly filled by dolomite and/or silica; both appear to be partly replacive and partly cement

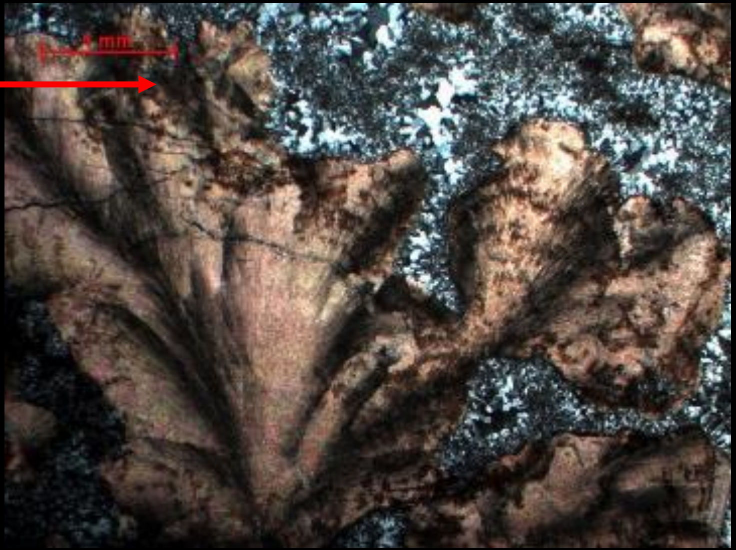
Mg silicate



F1a^3

Dolomite
+/- silica

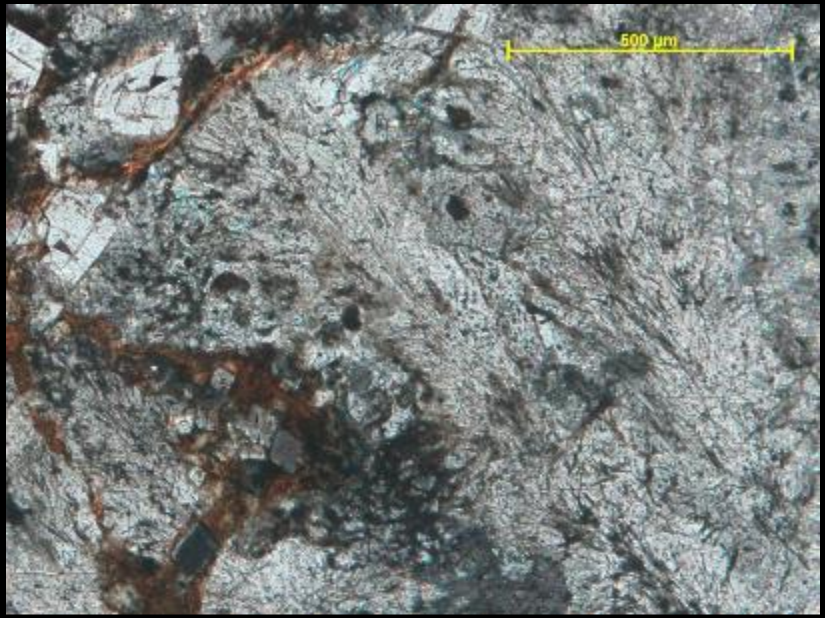


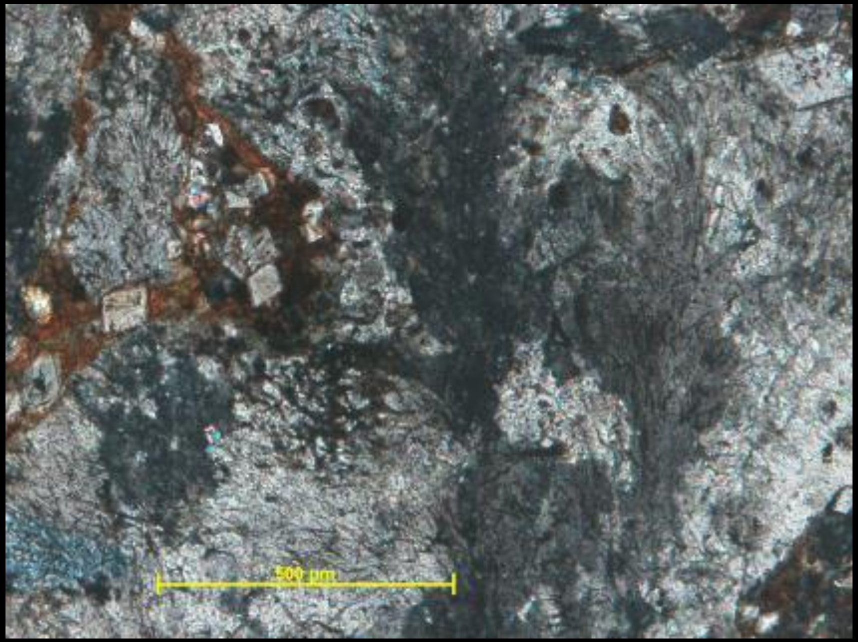


The shrubs are microbial …

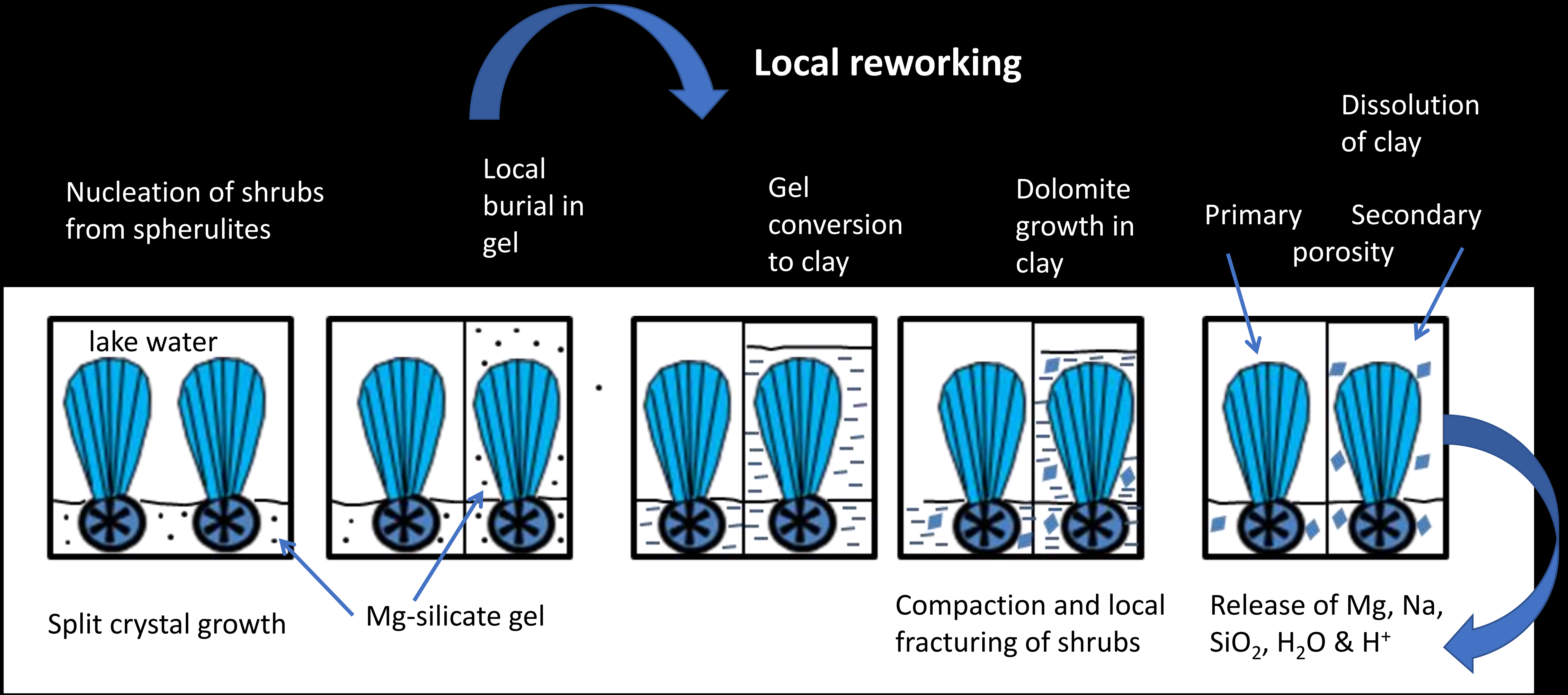
Microbialites do occur but are rare (<1% of core thickness).

They have microbial macro-textures such as dendrolites and microstructures such as filament molds with irregular sparite cements.





The shrubs lack such textures and have split-fibre microstructures with sweeping extinction.



What are these in situ textures? Crystal shrub framestone or cementstones?

Take away points -

An unusual range of textures and pore types are found in the Pre-Salt Barra Velha Fm reservoirs offshore Santos Basin and elsewhere.

Applying standard classifications (e.g. Dunham, 1962) carries conceptual “baggage” and so misleads the interpreter and results in depositional interpretations and erroneous facies and even seismic interpretations.

The key to understanding the reservoir came from appreciating that some of the main rock fabrics resulted from the dissolution of matrices of Mg-silicates, creating much of the porosity.

The application of the approach has provided a practical means for rock fabric determination and for interpreting diagenetic pathways and petrophysical properties.

The resulting model supports the shallow evaporative alkaline lake model and has facilitated the formulation of a successful depositional model, now substantiated by geochemical modelling.