A Geochemical Model for the Formation of the Pre-Salt Reservoirs, Santos Basin, Brazil: Implications for Understanding Reservoir Distribution*

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Abstract

An evaporitic geochemical model is presented for the Aptian Barra Velha Formation reservoirs, Santos Basin, offshore Brazil. This has to explain the paucity of "normal" carbonate precipitates, the dominance of unusual calcitic morphologies and the presence or former presence of Mg-silicate matrices in the reservoir. The occurrence of metre-scale cyclothems with repetitive mineralogical, textural, micro-textural and early diagenetic changes is explained by invoking the evolution of highly alkaline lake waters with a high dissolved silica, Mg and Ca content. Several modern lakes provide partial indicators of how the evaporation of the Barra Velha lakes would have progressed in stages. Initially Mg-silicate precipitation, as a hydrous poorly crystalline gel, triggered by evaporation, produced a "chemical divide". This resulted in the near complete depletion of Mg, but allowed evaporative concentration of residual SiO_2 (aq), influencing the subsequent stages of brine development and sedimentation. The depletion of Mg limited the production of Mg-silicates but lowered the Mg/Ca favoring LMC precipitation, as is observed in some lakes such as Lake Chad. The nucleation of LMC within the gels led to the growth of spherulites. CO_2 degassing, driven by solubility decreases with evaporation, drove up pH and CO32- but coupled with low Ca2+, still favored $CaCO_3$ crystal growth, the kinetics of which were inhibited at very high pH. This favored an increase in crystal size over new nuclei, explaining the lack of other precipitates (e.g. micrite). The spherulites grew to large size and extended beyond their gel matrix producing crystal shrub cementstones with dendritic crystals reflecting high SiO2 (aq) in high pH fluids. The shrub units have the best reservoir quality. Continued evaporation led to increased levels of SiO (aq) but pluvial events caused a drop in the pH led to the growth of interstitial silica. This model predicts that even though the more porous shrub facies represents the shallowest facies, it was not restricted to the more proximal settings but to areas where lake waters ponded during evaporation, such as depositional lows as in the higher accommodation zones of half-grabens. Variations in the initial composition of the lake waters over the South Atlantic basins due to differences in catchment geology and hydrology would have resulted in significant differences in the final assemblage of carbonates and silicates.

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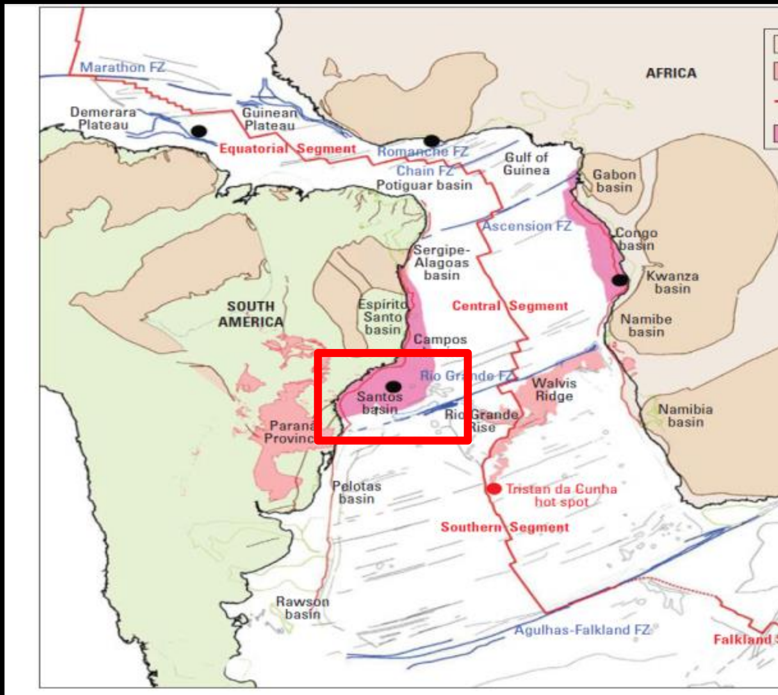
Take away points –

- The key characteristics seen in the early Cretaceous Barra Velha Fm carbonates of Santos Basin (misnamed the "Microbialite" reservoir) can be reproduced by geochemical modelling

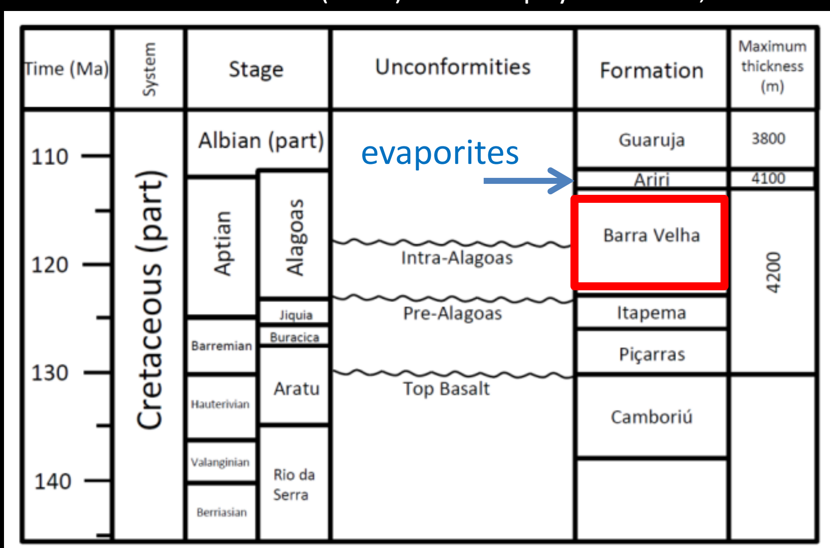
- This lends support for the interpretation that the reservoirs formed in hyper-alkaline shallow lakes, abiotically, and not as large, microbial carbonate platforms in deep lakes

- We emphasize that there are several different reservoir types in the South Atlantic Pre-Salt and that a clearer picture is now emerging of their diversity and of what was controlling their compositions, architectures, porosity types and diagenesis

South Atlantic Basins: Cretaceous lacustrine carbonates: the "Microbialite"

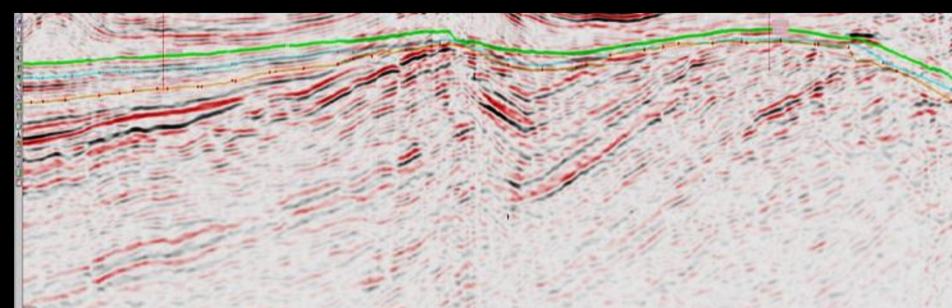


From: Aslanian et al. (2009). Tectonophysics v. 468, 98-112.



Main production from this interval is from the Santos Basin, with estimates of recoverable reserves in multi-billion barrels . Some wells produce >25K BLPD.

= Barra Velha Fm. Which is ***up to 550m***



Carbonates developed during late rift to sag stage; Coquina reservoirs occur below

And discoveries in the conjugate Kwanza Basin

Facts

There are currently two different models for the depositional settings, seismic geometries, stratal architectures and porosity evolution in the Barra Velha reservoirs (so called “Microbialites”) in Santos Basin

One published model invokes shallow evaporitic lakes, with the carbonates of largely abiotic origin produced with Mg-silicate gels, which later formed clay matrices, which later dissolved creating much of the porosity and impacting on later diagenetic events

The other model (unpublished) being used by several companies is of deep lakes, with seismically identified carbonate platforms with distinct margins and relief of up to several hundred metres, built by microbialites

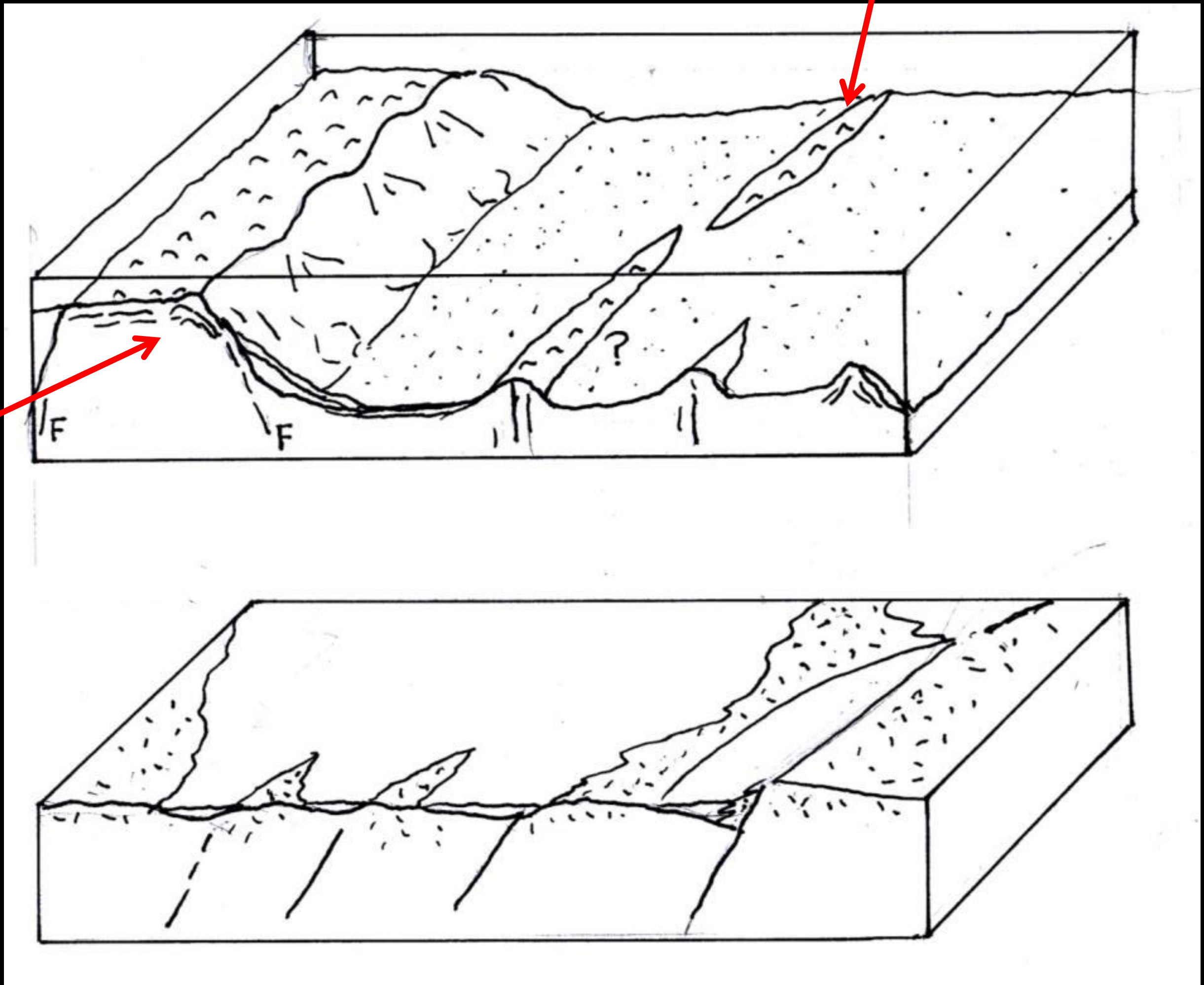
Two end–member models? -

Linear buidlups along major faults with vents

Microbial carbonate platform model

Deep (>300m?) perennial lakes with microbialite platforms on fault blocks and sub-lacustrine isolated buildups possibly along vents or around volcanoes

Carbonate platform margins rims and mounds and slope clinofroms



Abiotic shallow evaporite lake model

Can we independently test the evaporite model?

How?

Isotopes – look for evaporation signals in the C & O isotopes

insufficient data in the public domain

Modelling - can geochemical modelling reproduce the key characteristics seen in the Barra Velha Fm

What are those characteristics?

Main components of the Barra Velha Fm

- Cm-scale “shrubs”, in situ and reworked; when in situ form porous shrub framestones,
- Mm-scale spherulites, in situ and reworked; when in situ produce porous floatstone (quasi-boundstones)
- Laminated carbonate muds

These can be found in cyclothems

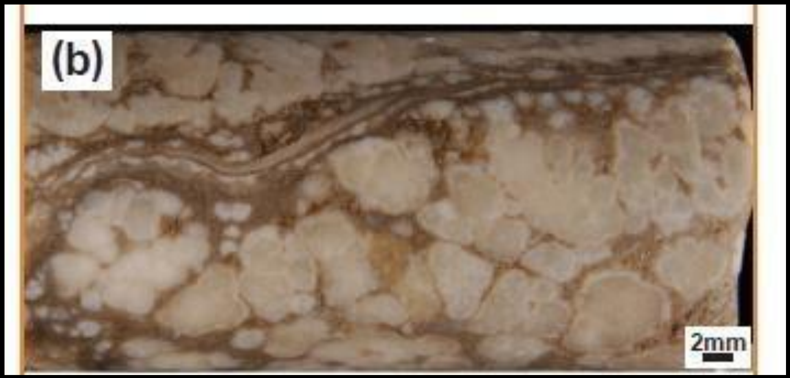
- Various very mature grainstones/rudstones

The carbonates seem to have been originally LMC

See - Wright V P & Barnett 2014 Cyclicity and Carbonate-Silicate Gel Interactions in Cretaceous Alkaline Lakes. AAPG Search and Discovery Article #51011

Shrubs - Campos & Santos Basins

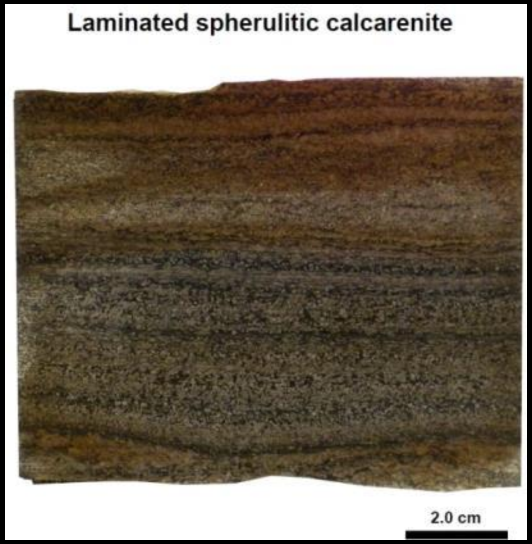
From: Diaz J L B. Geoci. Petrobras, Rio de Janeiro, v. 13, n. 1, p. 7-25, nov. 2004/maio 2005



Shrub-like growths – Barra Velha Fm, Cretaceous, Santos Basin. From Terra et al 2010, Boll. Geosci. Petrobras, 18, 1, 9-29

Spherulites

Range up to 16mm in diameter



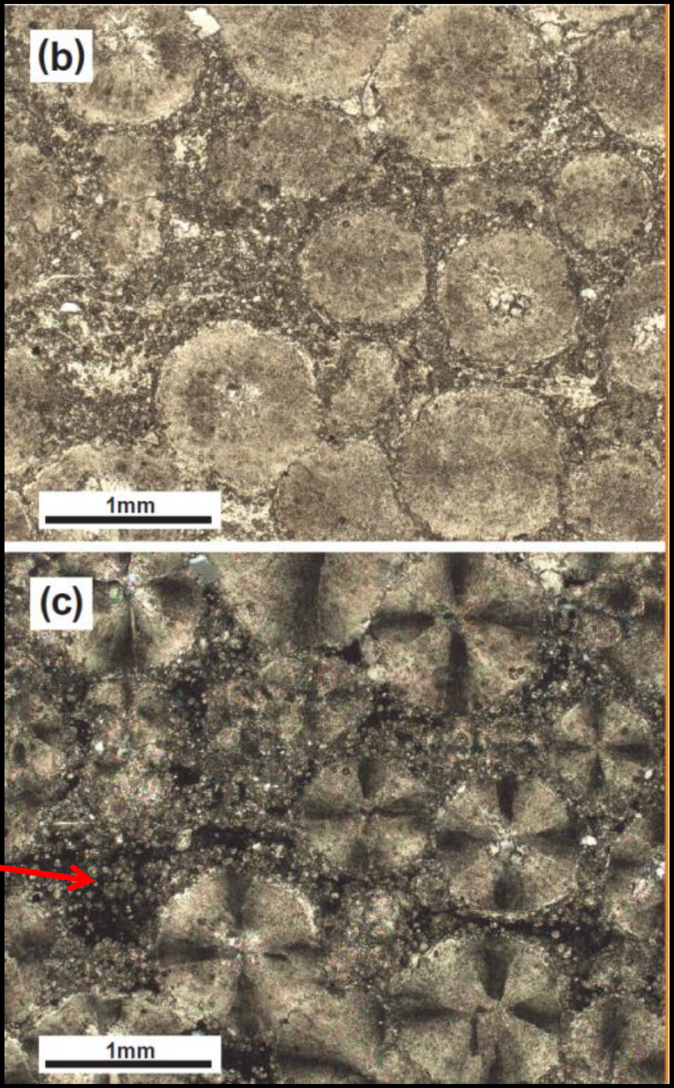
Source – ANP Pre-Salt Libra Geological Assessment : 17/9/2013

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

Ppl

Dolomite matrix

Cpl



Facies 3

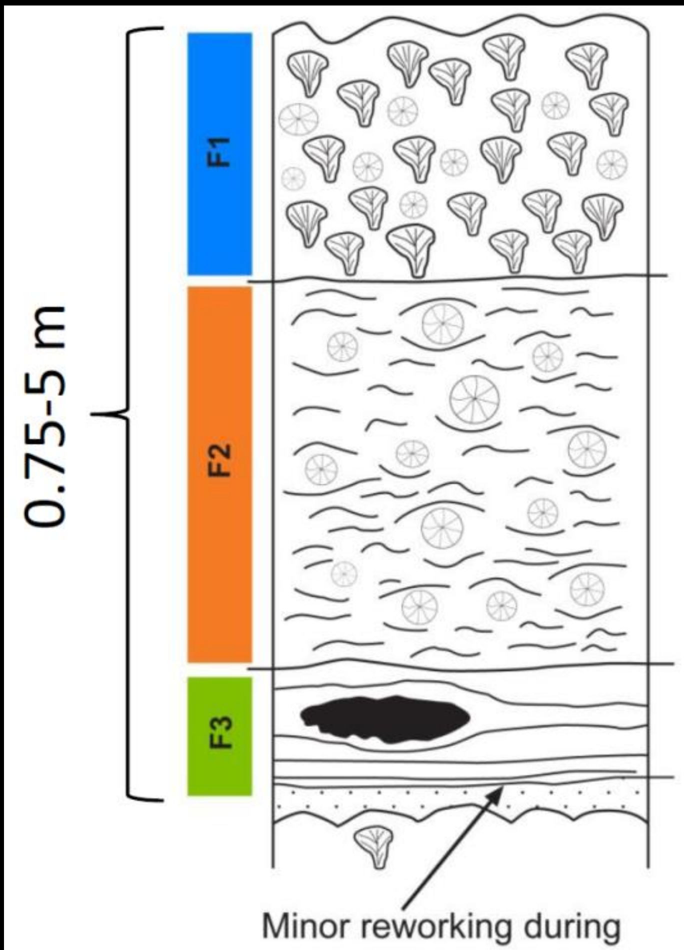
Laminated carbonate muds – Barra Velha Fm, Cretaceous,
Santos Basin. From Terra et al 2010, Boll. Geosci. Petrobras, 18, 1, 9-29

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

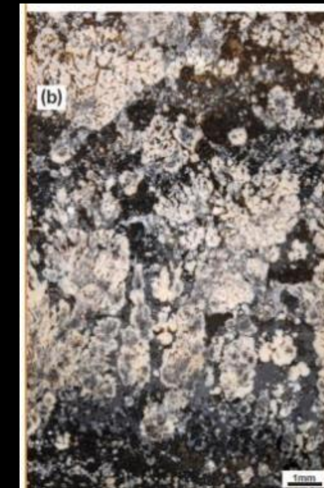
Depositional origin of Facies 3:

- Detrital, finer grained - lower energy, deeper (lakes commonly have shallow wave base cf marine basins) with some desiccation cracks, no paleosols
- Elevated concentrations of ostracodes suggest lowered salinities/alkalinities
- Influx of phosphatic debris - vertebrates invade during lowered salinity/alkalinity phases
- Early silica nodule growth suggests lowered pH triggering silica precipitation

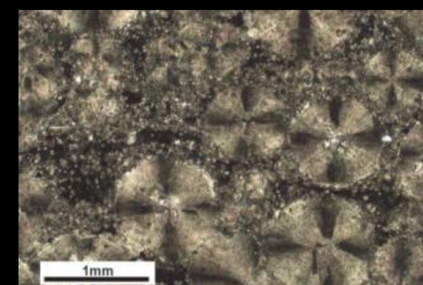
The Cyclothems in the Lacustrine Barra Velha Fm



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



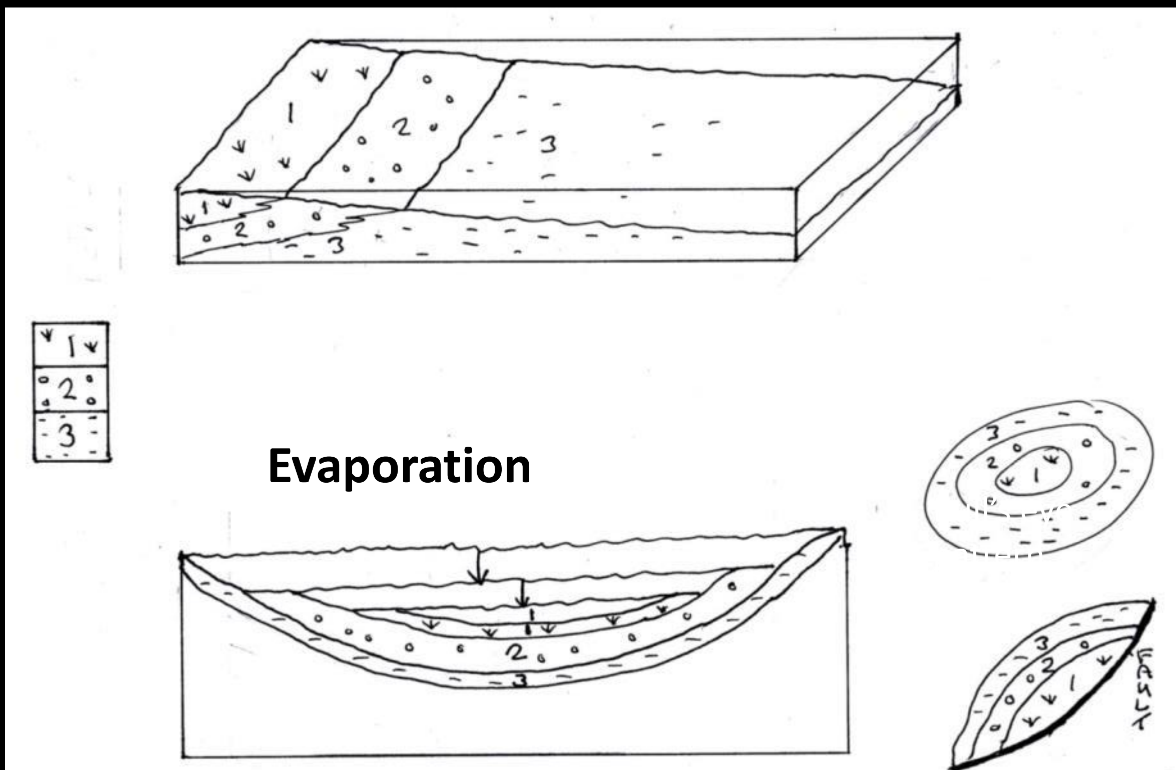
Facies 3: Laminated calcimudstones with prominent ostracodes and vertebrate debris, early silica nodules

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.

Two possible explanations for the cyclothems

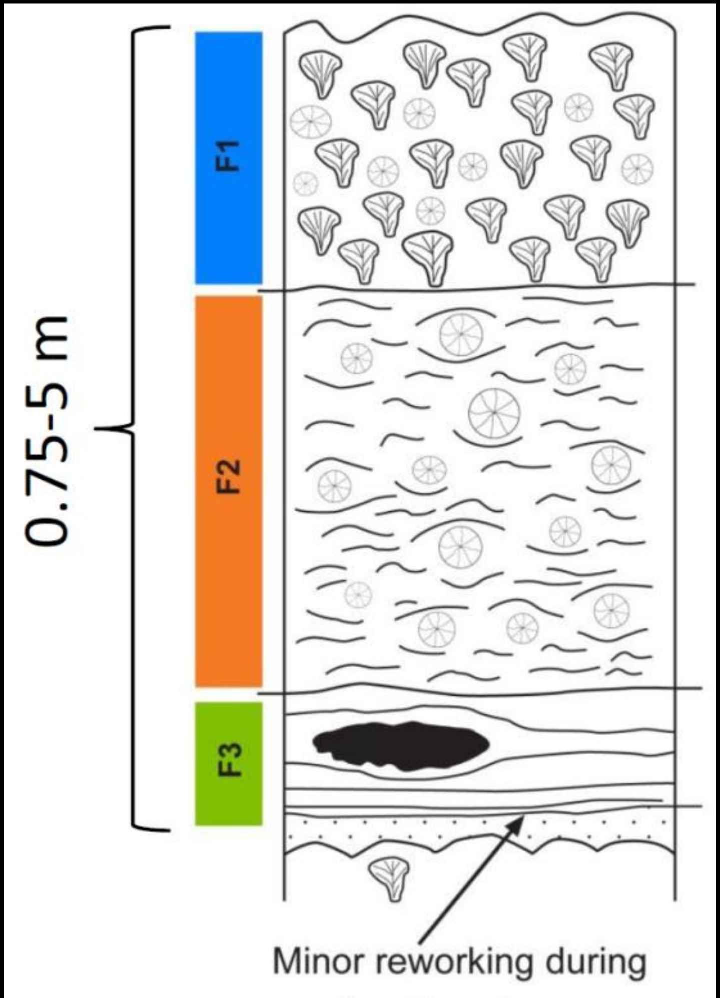
Waltherian



Implies that the facies see in a stratigraphic sequence were time equivalents and the cyclothem represents lake level change

Each facies type represents a different stage of brine evolution caused by evaporation – the facies are not time equivalents and likely occupy different sized areas

Evaporitic interpretation of the lacustrine cyclothems in the Barra Velha Fm



No sulphates and no chlorides!

Facies 1: Reduction of gel precipitation allows rapid growth of calcite crystal shrub framestones by asymmetric growth of spherulites into lake waters

Facies 2: Evaporation triggers Mg-silicate gel precipitation; pH >9.5. Mg rapidly depleted. = low Mg/Ca. Spherulites grew in Mg-silicate gels, in low densities.

Facies 3: flooding phase; reduced alkalinity-salinity allows influx of ostracodes and vertebrates; also triggers silica precipitation as pH drops

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.

What is missing?

Typical carbonate features are rare or absent –

- Such as ooids, intergranular cements, carbonate muds and microbialites
- Something suppressed these common types of precipitate, and microbes were likely present
- Sulphates and chlorides are absent
- BUT Mg-silicates (now talc-stevensite) are/were widespread

Is there a geochemical explanation to support this model?

Lake water evaporation: Thermodynamic modelling

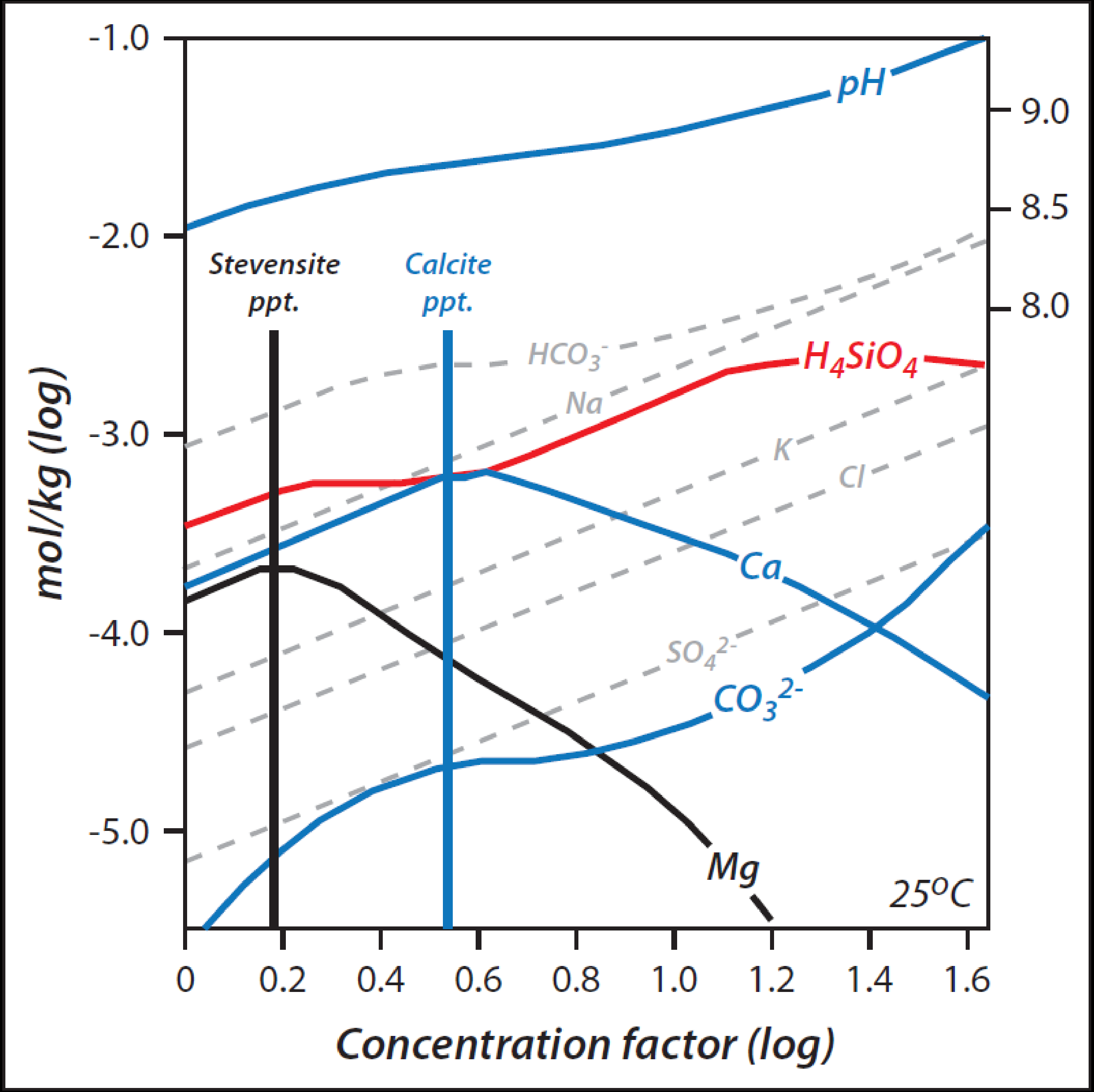
- Begin with dilute water from Lake Chad (*Gac et al., 1977*)
- Remove H_2O through evaporation at 25°C
- Activities calculated with Pitzer ion interaction model for high ionic strength
  - Mg-silicate solubility estimated from Tosca (2015)
- Assume no "back-reaction" between precipitated minerals & evaporating fluid

Initial fluid composition

pH	8.2
log P_{CO2}	-3.5
Ca	0.3 mmolal
Mg	0.2 mmolal
SiO2	0.5 mmolal
SO_4	0.04 mmolal
Cl	0.08 mmolal

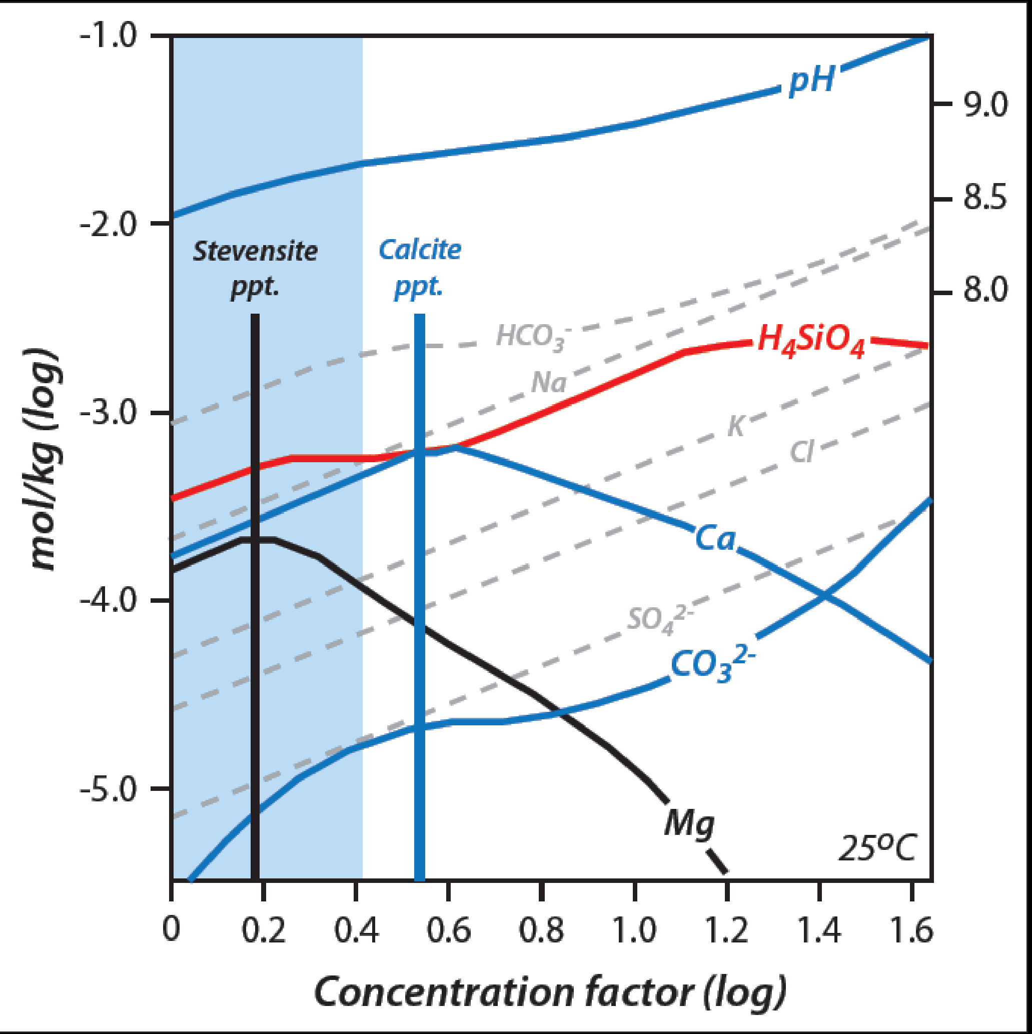
There are 4 key stages of evaporation that sequentially influence Mg-silicate / carbonate sedimentation

Changes in chemistry with evaporation



Stage 1: Mg-silicate nucleation & crystal growth

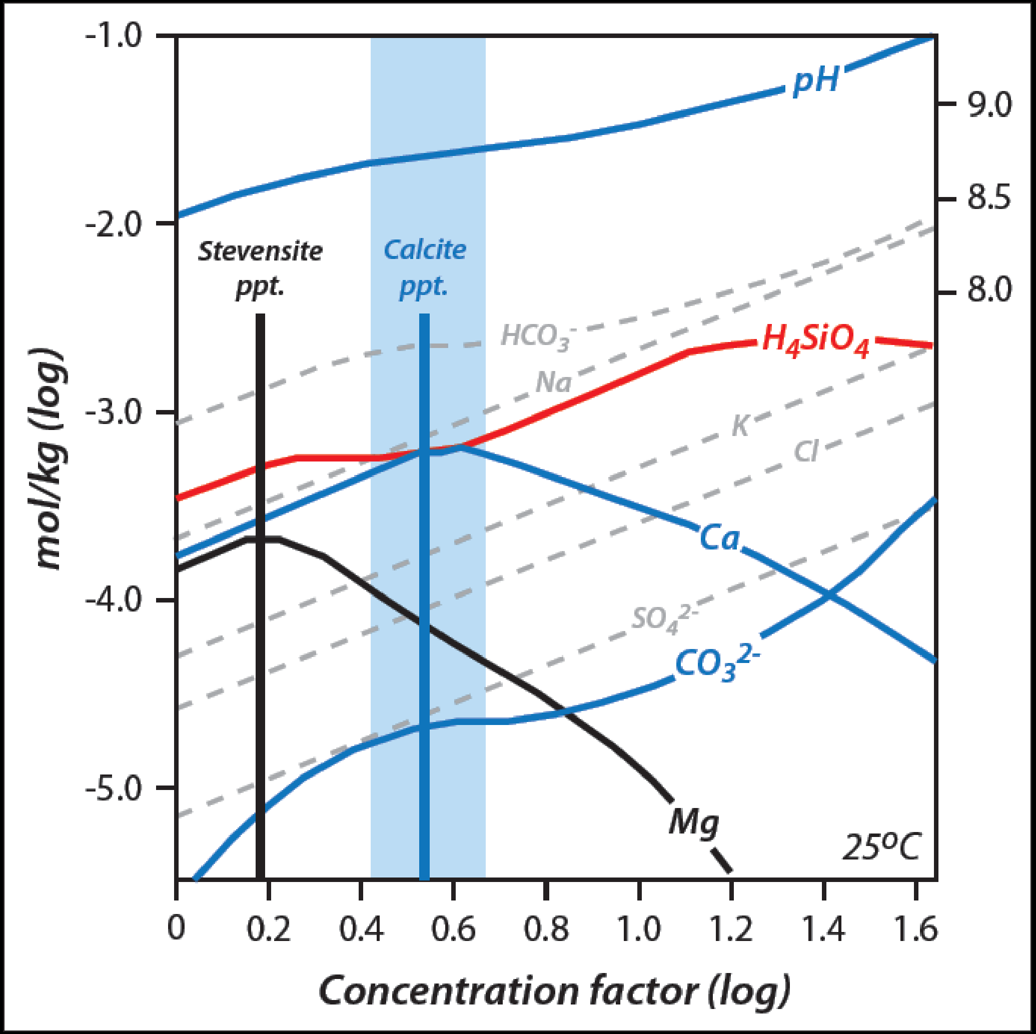
- *Al-free Mg-silicates* (i.e., stevensite, kerolite, sepiolite) are common in lacustrine carbonates
- Laboratory syntheses constrain solubility / stability
- In modern lakes, evaporation triggers regional-scale precipitation
- Precipitates initially as hydrous, poorly crystalline "gel"



Mg-silicate precipitation acts as a "chemical divide"

Stage 2: Mg-consumption & LMC nucleation

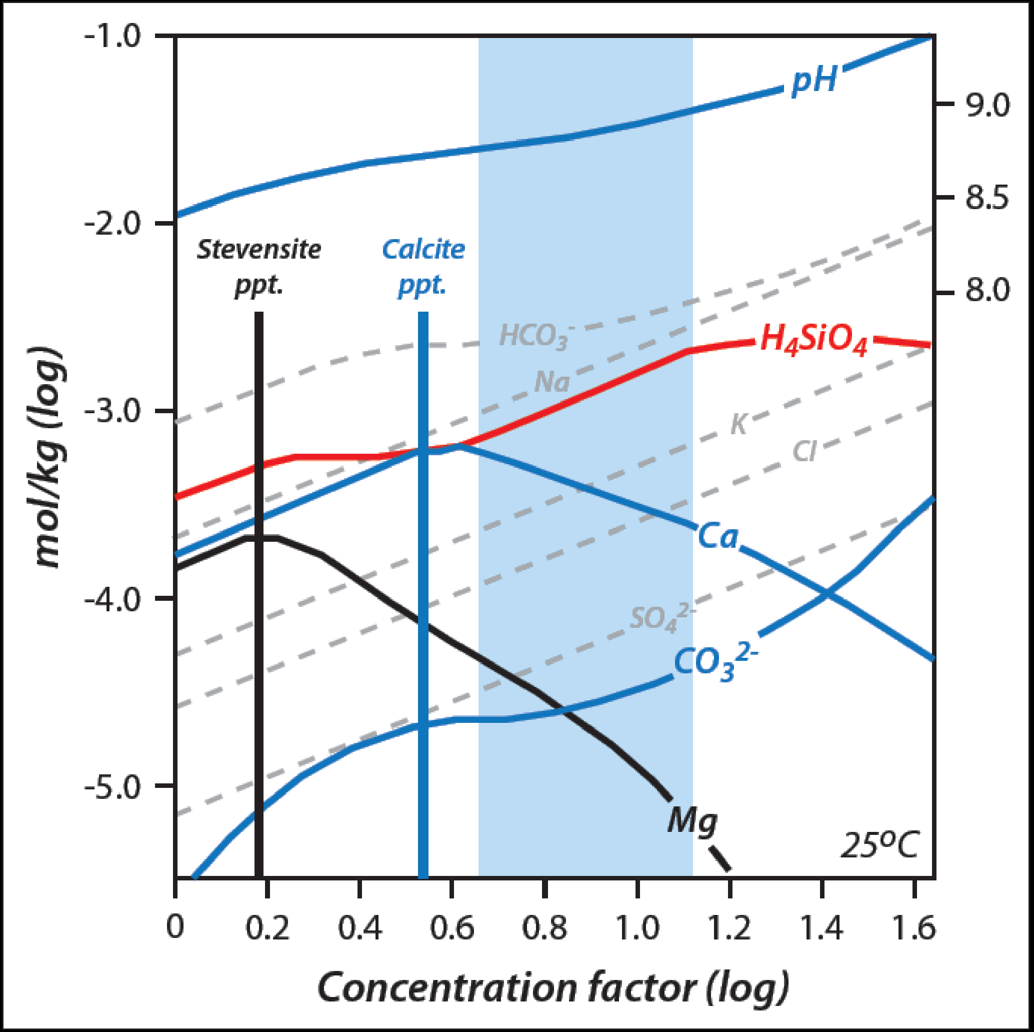
- Mg-silicates remove Mg & lower Mg/Ca ratio (SiO_2(*aq*) increases)
- Low-Mg calcite nucleates
- Mg-silicate → LMC sequence observed in several modern systems (e.g., Lake Chad)
- Consistent w/ LMC spherulitic growth in Mg-silicate gel (Barra Velha Fm)
  - Rapid nucleation of ACC?



Result is spherulite growth in gels

Stage 3: pH increase & decline in LMC saturation

- CO_2 degassing w/ evaporation drives pH up (*Eugster & Jones, 1979*)
- High pH & CO_3^{2-} but low Ca^{2+} lowers saturation, still favouring $CaCO_3$ crystal growth
- $CaCO_3$ nucleation kinetics inhibited at high pH (*Ruiz-Agudo et al., 2011*)
- Favours increase in crystal size over new nuclei (consistent w/ lack of micrite in Barra Velha Fm)

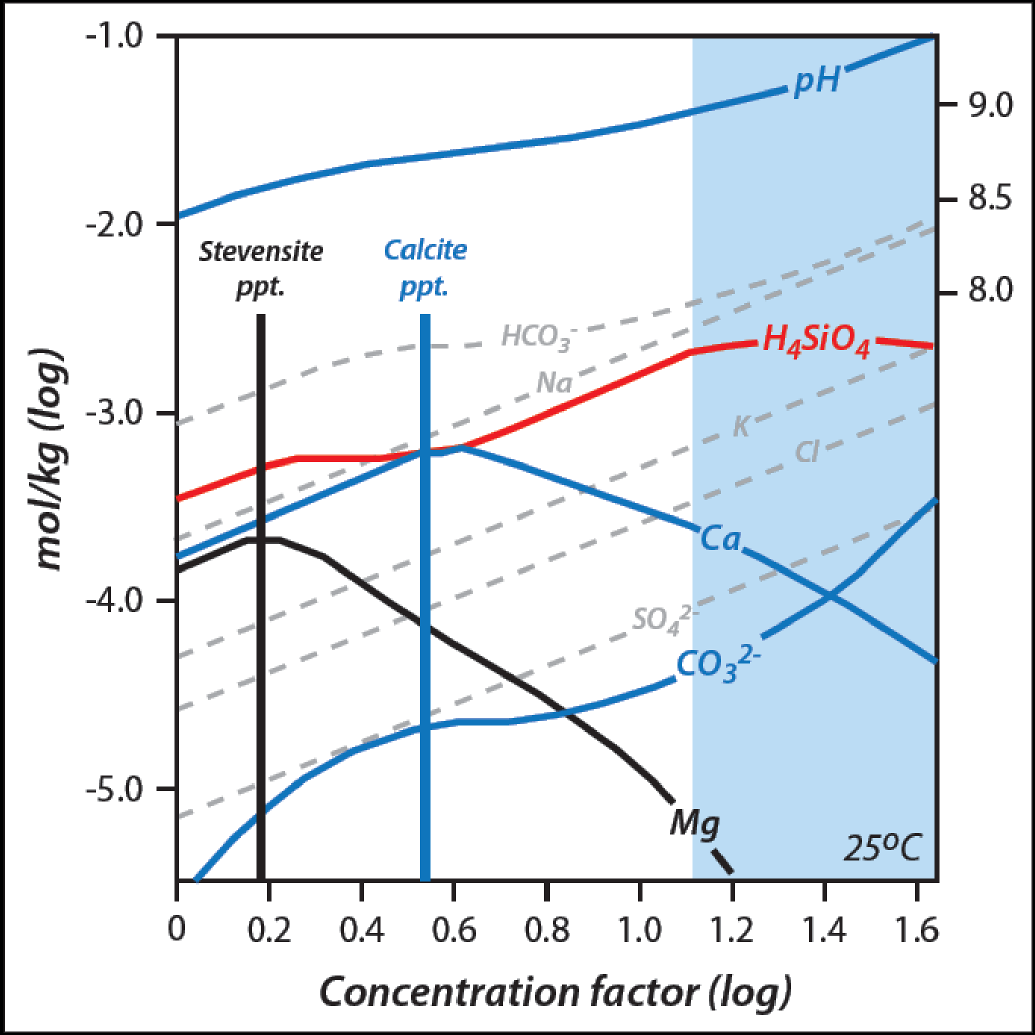


In the meantime, $SiO_2(aq)$ is still increasing…

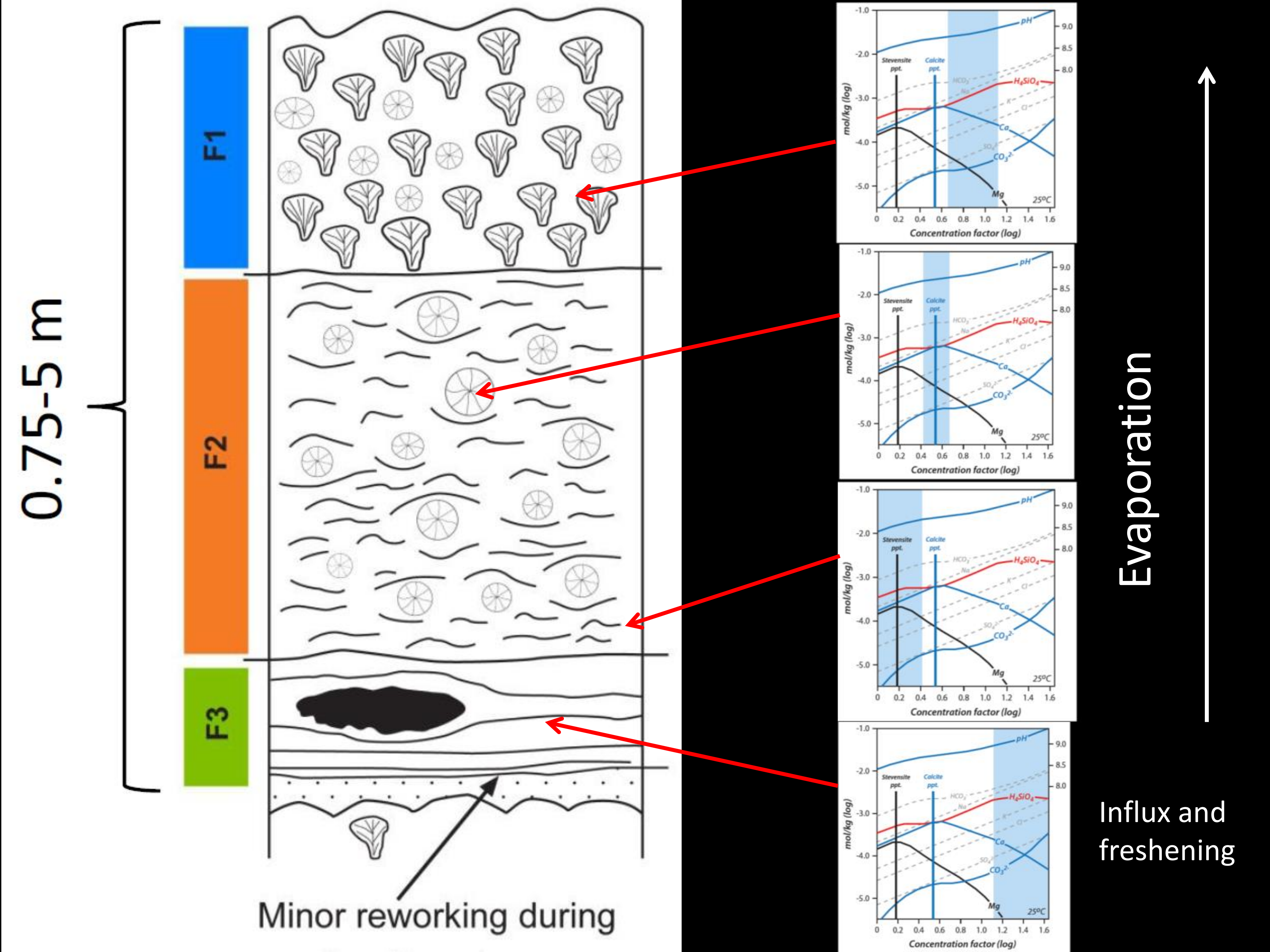
Result is carbonate precipitation limited to earlier sites = shrubs

Stage 4: pH increase & growth in high-SiO_2 solution

- High pH retains SiO_2(*aq*)
- $CaCO_3$ growth at high pH & SiO_2(aq) produces multi-branched dendritic crystals (*Garcia-Ruiz, 2000*)
- Consistent with *crystal shrub growth morphology* in Barra Velha Fm

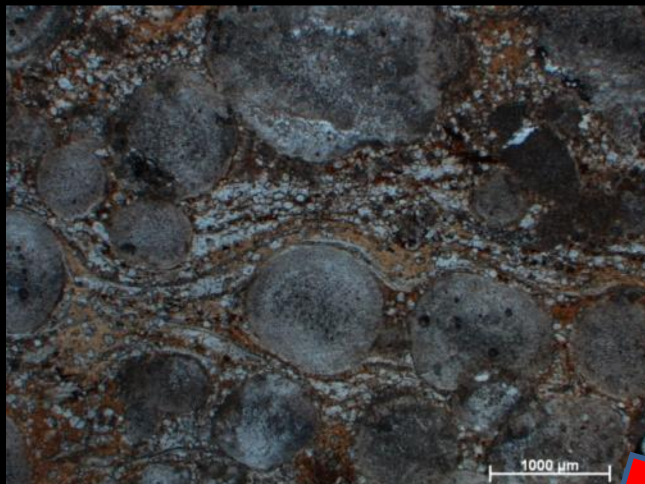


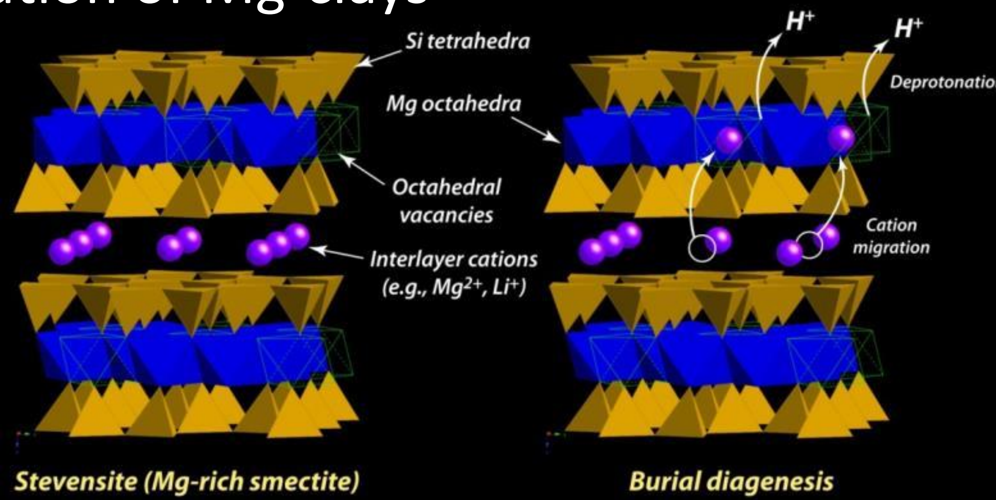
Freshening will lower pH & trigger silicification

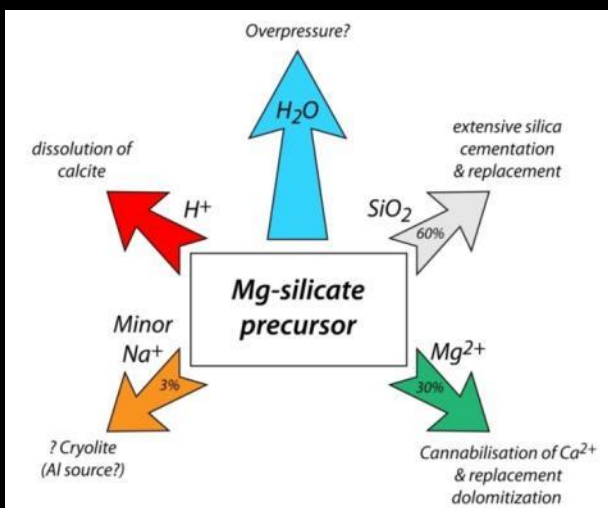


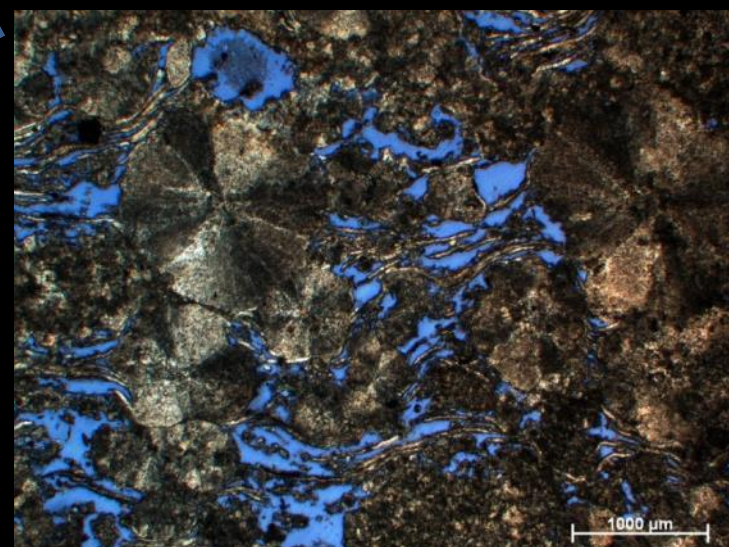
0.75-5 m
F1
F2
F3
Minor reworking during
Stevensite ppt.
Calcite ppt.
pH
H_4SiO_4
Ca
CO_3^{2-}
Mg
25°C
mol/kg (log)
Concentration factor (log)
Evaporation
Influx and freshening

Porosity development – dissolution of Mg-clays









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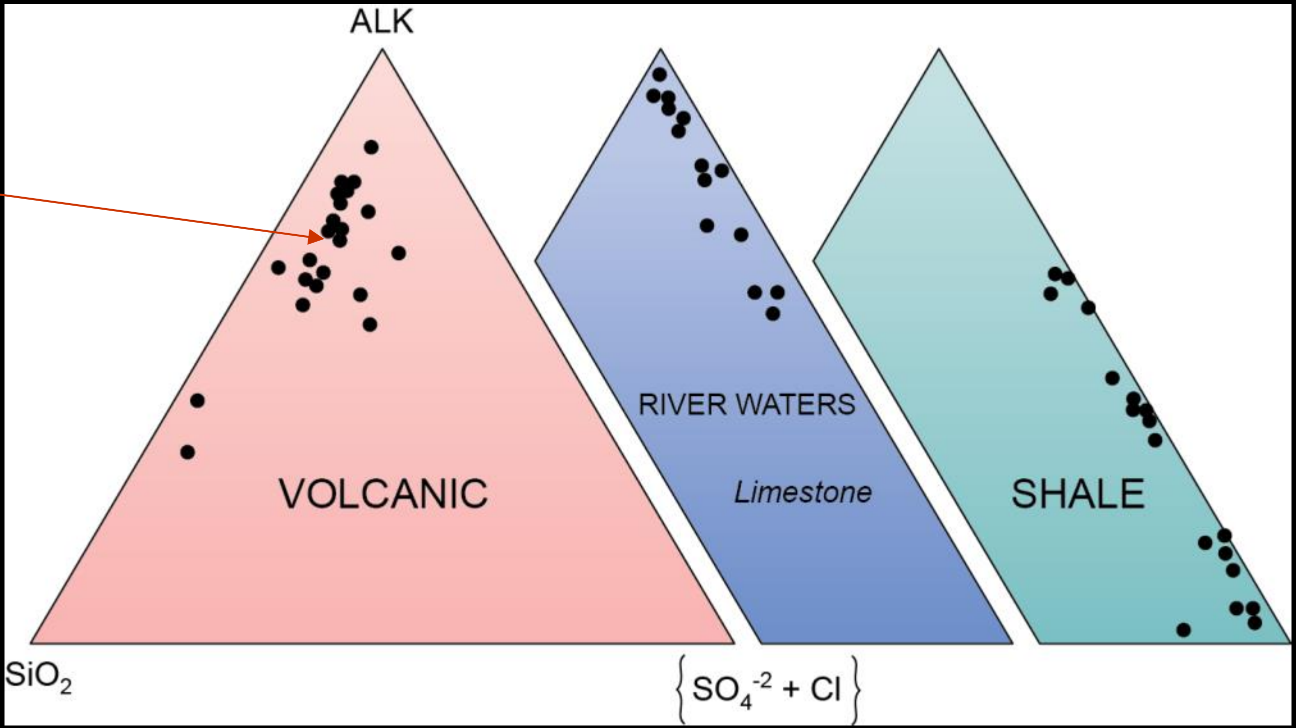
What is special about the Barra Velha Fm?

It required highly alkaline conditions and probably a catchment geology dominated by basic igneous rocks

" calcite, tri-octahedral smectite, analcime (& Na bicarbonates & carbonates) etc…form in lakes where volcanic terrains predominate."

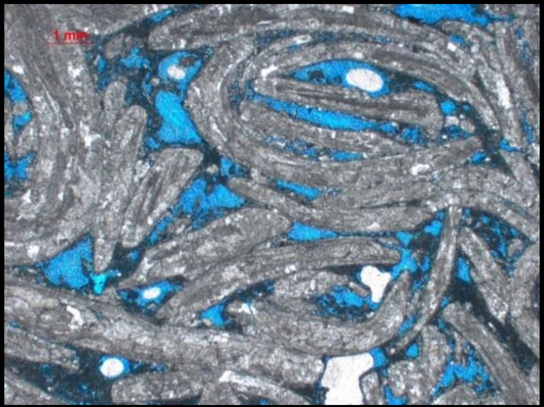


Stevensite - Ca, Mg, Na, K, Fe, & Li silicate…over 30% Mg

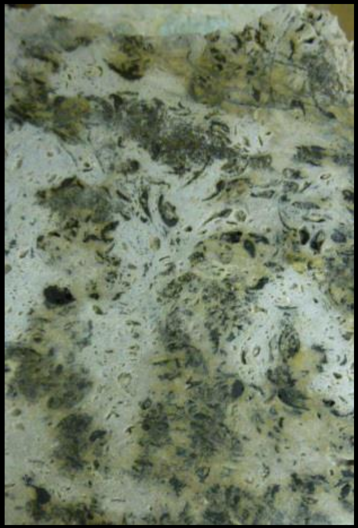
Cerling T 1994 Global Geological Record of Lake Basins Vol 1, page 29

Wright. V.P. 2012 Lacustrine carbonates in rift settings: the interaction of volcanic and microbial processes on carbonate deposition. In Garland, J., Neilson, J E, Laubach S E & Whidden K J (eds) Advances in Carbonate Exploration and Reservoir Analysis. Geological Society Special Publicaion 370, 39-47.

We know there are other types of lacustrine reservoirs in the South Atlantic – but why?



Coquina reservoirs of Brazilian Lago Feia & Itanema Formations



Coquinas and microbialites in West African : Toca Fm

Microbialite cherts, Aptian of Kwanza Basin; Sallet et al. 2016. Bull. AAPG, 100, 1135-1164

Tectonics – rift versus sag (controls water depth, circulation etc)

Climate/Hydrology – fresher (lower pH) versus evaporitic and alkaline (high pH)

Catchment – mixed solutes versus basic igneous source

"Fresh" water dominated -- Alkaline brine dominated

Deeper lakes – rift phase --------------------------------------Shallow lakes – sag phase

Restricted conditions; non-evaporitic; some alkaline phases with minor stevensite and kerolite

More restricted conditions, alkaline but with frequent phases of lowered pH and silica precipitation

Highly evaporitic – rare lowered alkalinity events (early silica in Facies 3 in Barra Velha Fm)

Coquinas

Microbialites

Abiotic

………………………….pH…………………………………

BIOGENICALLY CONTROLLED

BIOGENICALLY INDUCED

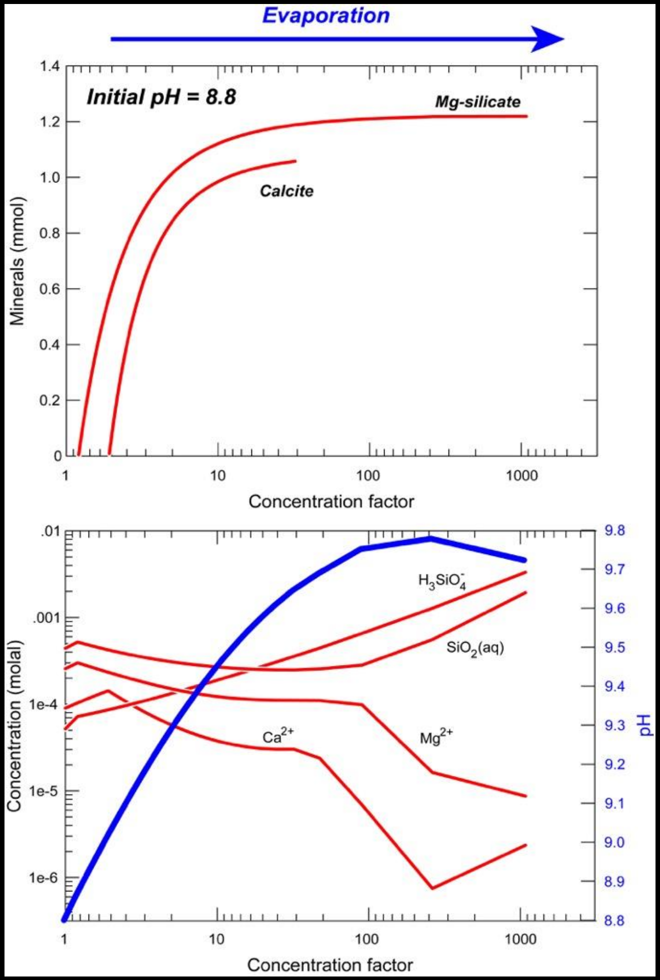
BIOGENIC CALCITE PRECIPITATION SUPPRESSED

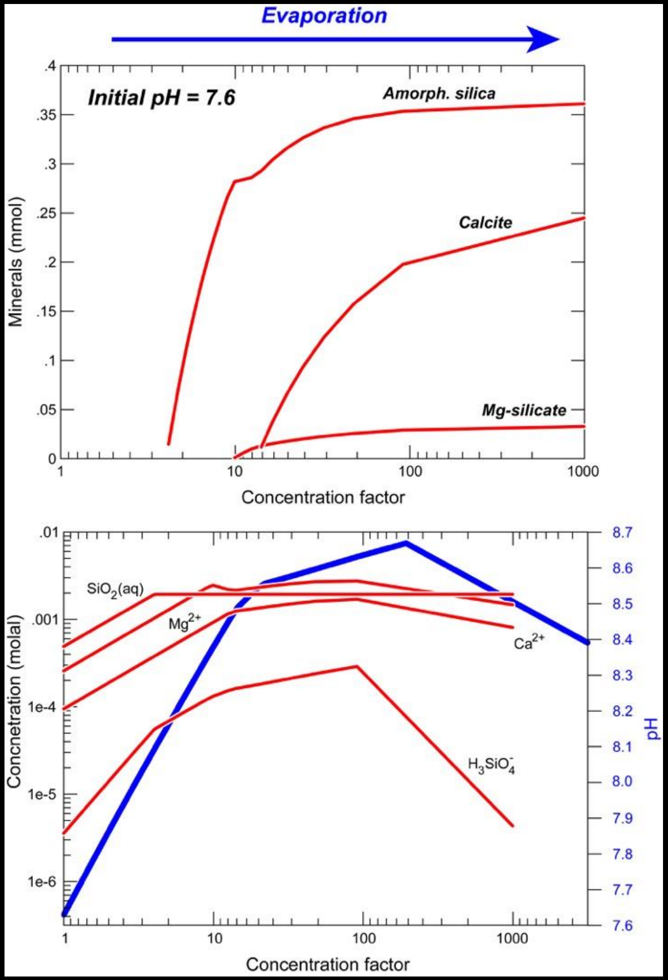
Mixed lithology catchment?? ---------------------- Basic igneous catchment

Alkaline waters, high Mg/Si

Lake Turkana waters

Lowered pH





In modern rift lakes waters such as Lake Turkana (E Africa) changes in pH can favor Mg-silicate precipitation (as In the Barra Velha of Santos Basin) or silica precipitation (microbialite cherts of Kwanza Basin?).

South Atlantic Pre-Salt Factories

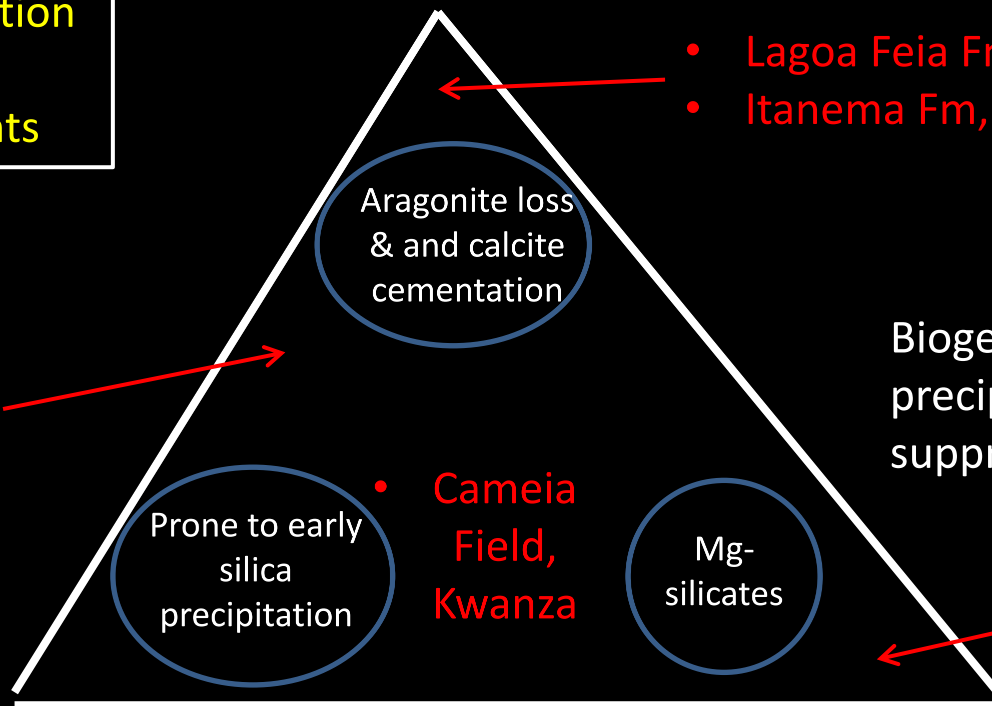
+/-
- Meteoric dissolution
- HTD & corrosion
- Late silica cements

BIOGENICALLY CONTROLLED

- *Coquinas – importance of physical processes (internal waves and seiches?)*
- *moldic and integranular pore systems*

- Lagoa Feia Fm, Campos Basin
- Itanema Fm, Santos Basin

- Toca Fm, Congo, Cabinda



Biogenic calcite precipitation suppressed

- Barra Velha Fm
- Santos Basin

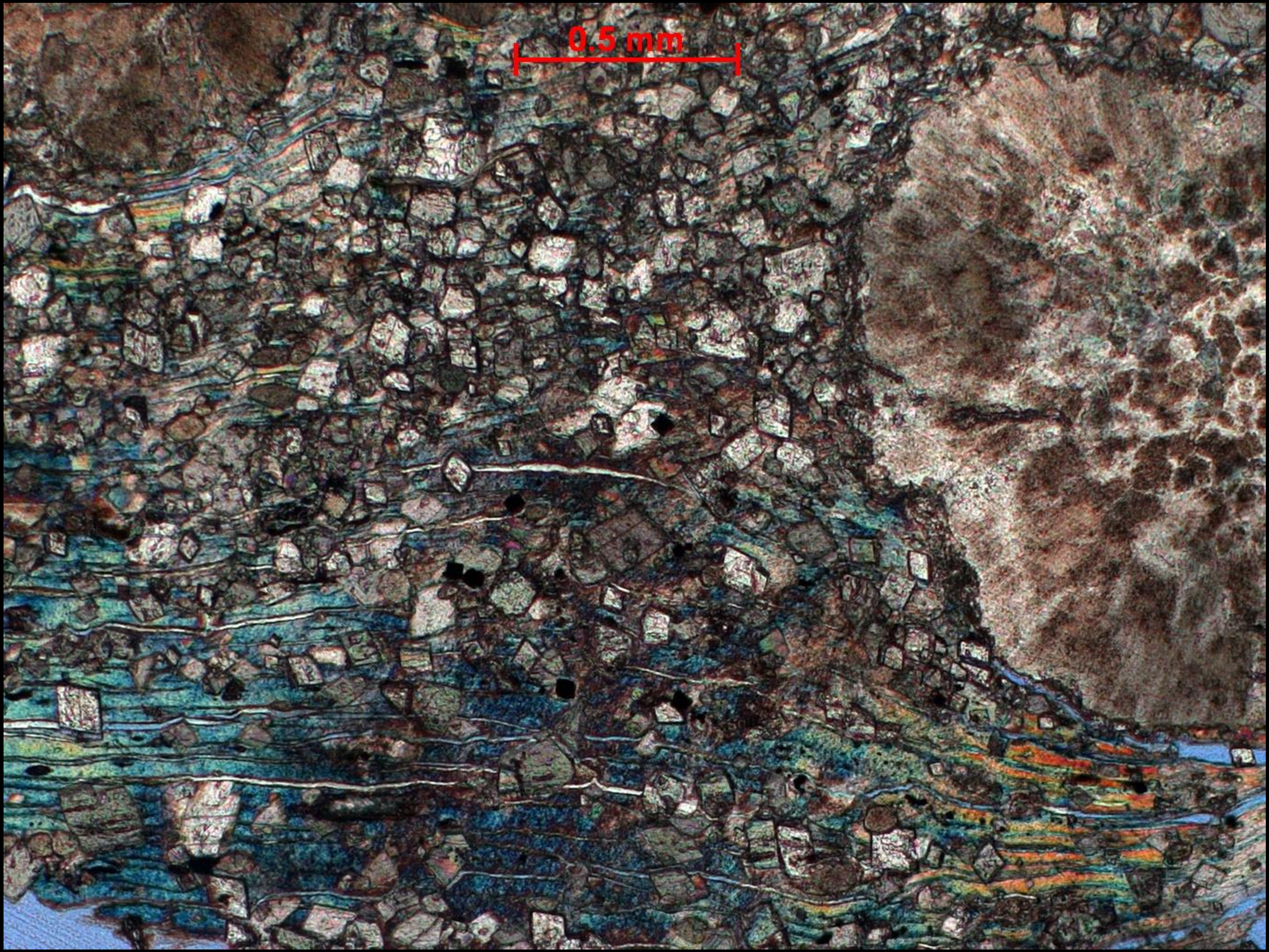
pH

BIOGENICALLY INDUCED
- *Microbialites; constructional margins, buildups, clinoforms*
- *Calcitic and siliceous*
- *Framework porosity*

ABIOTIC
- *Evaporitic, partly cyclic, sheet-like.*
- *Porosity evolution influenced by stevensite decay*

Take away points –

- The key characteristics seen in the early Cretaceous Barra Velha Fm carbonates of Santos Basin (misnamed the “Microbialite” reservoir) can be reproduced by geochemical modelling
- This lends support for the interpretation that the reservoirs formed in hyper-alkaline shallow lakes, abiotically, and not as large, microbial carbonate platforms in deep lakes
- We emphasize that there are several different reservoir types in the South Atlantic Pre-Salt and that a clearer picture is now emerging of their diversity and of what was controlling their compositions, architectures, porosity types and diagenesis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