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 SiO₂(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. CO₂ degassing, driven by solubility decreases with evaporation, drove up pH and CO₃²⁻ but coupled with low Ca²⁺, still favored CaCO₃ 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.

References Cited


Tosca, N., and V.P. Wright, 2014, The formation and diagenesis of Mg-clay minerals in lacustrine carbonate reservoirs: AAPG Search and Discovery Article #51002.


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

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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.
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? -

**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**

Linear buildups along major faults with vents
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


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

Inter-shrub porosity
Spherulites

Range up to 16mm in diameter

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

Terra G J S et al. B.

Dolomite matrix

Cpl

Ppl
Facies 3

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

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

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

Two possible explanations for the cyclothsms

Waltherian

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

Evaporation

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.

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 H₂O 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**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tr>
<td>pH</td>
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<td>log P_{CO₂}</td>
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<tr>
<td>Ca</td>
<td>0.3 mmolal</td>
</tr>
<tr>
<td>Mg</td>
<td>0.2 mmolal</td>
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<tr>
<td>SiO₂</td>
<td>0.5 mmolal</td>
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<tr>
<td>SO₄</td>
<td>0.04 mmolal</td>
</tr>
<tr>
<td>Cl</td>
<td>0.08 mmolal</td>
</tr>
</tbody>
</table>

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

- pH
- $H_4SiO_4$
- $CO_3^{2-}$
- $SO_4^{2-}$
- $Ca$
- $Mg$
- $K$
- $Cl$
- $Na$

Concentration factor (log)

$mol/kg$ (log)
**Stage I: 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”

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*Mg-silicate precipitation acts as a “chemical divide”*
**Stage 2: Mg-consumption & LMC nucleation**

- Mg-silicates remove Mg & lower Mg/Ca ratio ($\text{SiO}_2(aq)$ increases)

- Low-Mg calcite nucleates

- Mg-silicate $\rightarrow$ 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

- CO₂ degassing w/ evaporation drives pH up (Eugster & Jones, 1979)

- High pH & CO₃²⁻ but low Ca²⁺ lowers saturation, still favouring CaCO₃ crystal growth

- CaCO₃ 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, SiO₂(aq) is still increasing...

Result is carbonate precipitation limited to earlier sites = shrubs
Stage 4: pH increase & growth in high-SiO₂ solution

- High pH retains SiO₂(aq)

- CaCO₃ growth at high pH & SiO₂(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
Influx and freshening

Evaporation

0.75-5 m

F1

F2

F3

Minor reworking during
Porosity development – dissolution of Mg-clays

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

**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
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

BIOGENICALLY CONTROLLED

- Coquinas – importance of physical processes (internal waves and seiches?)
- Moldic and intergranular pore systems

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

BIOGENICALLY INDUCED

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

- Prone to early silica precipitation
- Cameia Field, Kwanza

- Aragonite loss & and calcite cementation

- Mg-silicates

ABIOTIC

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

- Barra Velha Fm
- Santos Basin

+/-

- Meteoric dissolution
- HTD & corrosion
- Late silica cements

- Toca Fm, Congo, Cabinda

- Biogenic calcite precipitation suppressed

pH
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