Critically Evaluating the Current Depositional Models for the Pre-Salt Barra Velha Formation, Offshore Brazil*

V. Paul Wright[1] and Andrew Barnett[2]

Search and Discovery Article #51439 (2017)**
Posted November 20, 2017

*Adapted from Keynote Address given at AAPG/SEG International Conference and Exhibition, London, England, October 15-18, 2017

[1]PW Carbonate Geoscience, Cardiff, UK (vpw@pwcarbonategeoscience.com)
[2]Shell, Canary Warf, London, UK

Abstract

This presentation assesses approaches for evaluating the two contrasting models for the depositional settings for the Cretaceous Barra Velha Formation carbonate reservoirs of Santos Basin, and their impact upon exploration strategies and reservoir modelling. One model invokes deeper lakes with differentiated microbial platforms having relief of hundreds of metres, as well as smaller buildups. The other model is of very shallow, evaporitic, hyper-alkaline lakes with predominantly abiotic carbonate and Mg-silicate precipitates. The case for the former has been based on the perceived presence of shelf-like margins resembling marine carbonate platforms, whereas the latter is based on detailed sedimentological analysis from a large data set supported by geochemical modelling.

The hydrology of the Barra Velha lakes can be assessed by proxy using carbon and oxygen stable isotopes, by comparison with extensive studies from Quaternary lake deposits from East Africa. Co-variant trends in these Barra Velha isotopes suggest the former presence of shallow, evaporitic lakes which were likely very extensive or sourced from a uniform aquifer.

Identifying isolated carbonate buildups is now facilitated by scoring using work flows, but this approach relates to marine systems and may not be appropriate for nonmarine ones as the absence of modern or ancient large scale, nonmarine buildups limits this approach. Instead the evidence shows that the large platform-like features are largely post-Barra Velha and structural in origin affected by varying degrees of subaerial erosion (denudation).

While available sedimentological and geochemical evidence does not support the presence of platform-like features with hundreds of metres of relief, this does not preclude the presence of large carbonate mounds and ridges analogous to those seen in modern extensional systems. However, as such features can be sub-lacustrine, subaerial or periodically both, their presence and interpreted relief cannot be used to draw reliable conclusions about palaeobathymetry

Facies and well logs allow correlations to be made in the Barra Velha Formation from what appear to have been lows (lake floor) to highs (platform) within the basin, as defined beneath the base salt. This implies that these apparent topographic differences of hundreds of metres or more were not being reflected in any lithological differences at the time of deposition. This suggests that what appear to be paleotopographic differences are due to later structuration, post-deposition of the lake sediments, and prior to salt deposition.

References Cited

Bohacs K.M., et al., 2000, Lake-basin type, source potential, and hydrocarbon character: An integrated sequence–stratigraphic-geochemical framework; *in* E.H. Gierlowski-Kordesch and K.R. Kelts, editors, Lake Basins through Space and Time: AAPG Studies in Geology no. 46, p. 3-34.

Buckley, J.P., et al., 2013, Carbonate buildups in the Santos Basin, offshore Brazil, *in* Microbial Carbonates in Space and Time: Implications for Global Exploration and Production: Geological Society, London, Conference, 19-20 June 2013, p. 36-37.

Buckley, J. P. et al., 2015, Tectonic setting and stratigraphic architecture of an Early Cretaceous lacustrine carbonate platform, Sugar Loaf High, Santos Basin, Brazil: *in* D.W.J. Bosence et al., editors, Microbial Carbonates in Space and Time: Implications for Global Exploration and Production: Geological Society, London, Special Publications no. 418, p. 175-191. Website accessed November 14, 2017, http://dx.doi.org/10.1144/SP418.13 (subscription required).

Carroll, A.R., and K.M. Bohacs. 1999, Stratigraphic classification of ancient lakes: balancing tectonic and climatic controls: Geology, v. 27, p. 99-102.

Della-Porta, G. 2015, Carbonate build-ups in lacustrine, hydrothermal and fluvial settings: comparing depositional geometry, fabric types and geochemical signature, *in* D.W.J. Bosence et al. (eds), Microbial Carbonates in Space and Time: Implications for Global Exploration and Production. Geological Society, London, Special Publications no. 418, p. 17-68. Website accessed November 14, 2017, http://dx.doi.org/10.1144/SP418.4 (subscription required).

der Mann, J., and J.W.D Rigg, 2012, New geological insights into the Santos Basin: Geo ExPro February, 2012, p. 38-40.

Goldberg, K., et al., 2017, Re-sedimented deposits in the rift section of the Campos Basin: Marine and Petroleum Geology, v. 80, p. 412-431. Website accessed November 14, 2017, doi.org/10.1016/j.marpetgeo.2016.11.022 (subscription required).

Hasiuk F.J., and S.E. Kaczmarek, 2015, Geochemical evidence of biotic influence in Brazilian pre-salt carbonates: AAPG Search and Discovery Article #51190 (2015). Website accessed November 14, 2017, http://www.searchanddiscovery.com/documents/2015/51190hasiuk/ndx_hasiuk.pdf.

Kattah, S., 2017, Exploration opportunities in the pre-salt play, deepwater Campos Basin, Brazil: The Sedimentary record, v. 15/1, p. 4-8. Website accessed November 14, 20017, https://www.sepm.org/CM_Files/SedimentaryRecord/SedRecord15-1-Final-lo.pdf.
Playton, T.E., et al., 2010, Carbonate slopes, *in* N.P. James and R.W. Dalrymple, editors, Facies Models 4: Geological Association of Canada, p. 449-476.

Poros, Z., et al., 2017, Origin of silica in pre-salt carbonates, Kwanza Basin, Angola: Search and Discovery Article #51413 (2017). Website accessed November 14, 2017, http://www.searchanddiscovery.com/documents/2017/51413poros/ndx_poros.pdf.

Sabato Ceraldi, T., and D. Green, 2017, Evolution of the South Atlantic lacustrine deposits in response to Early Cretaceous rifting, subsidence and lake hydrology, *in* T. Sabato Ceraldi et al., editors, Petroleum Geoscience of the West Africa Margin: Geological Society, London, Special Publications, no. 438, p. 77-98. Website accessed November 14, 2017, http://doi.org/10.1144/SP438.10 (subscription required).

Saller, A., et al., 2016, Pre-salt stratigraphy and depositional systems in the Kwanza Basin, offshore Angola. AAPG Bulletin, v. 100/7, p. 1135-1164.

Terra, G.J.S., A.R. Spadini, A.B. Franca, C.L. Sombra, E.E. Zambonato, L.C.da S. Juschaks, L.M. Arienti, and M.M. Erthal, 2010, Carbonate rock classification for Brazilian sedimentary basins: Boletim de Geociencias da Petrobras, v. 18/1, p. 9-29.

Williams, H.D., et al., 2011, Investigating carbonate platform types: Multiple controls and a continuum of geometries: Journal of Sedimentary Research, v. 81, p. 18-37.

Wright, V.P., and A.J. Barnett, 2015, An abiotic model for the development of textures in some South Atlantic Early Cretaceous lacustrine carbonates, *in* D.W.J. Bosence et al., editors, Microbial Carbonates in Space and Time: Implications for Global Exploration and Production: Geological Society, London, Special Publications no. 418, p. 209-219. Website accessed November 14, 2017, http://dx.doi.org/10.1144/SP418.3 (subscription required).

Wright, V.P., and N.J. Tosca, 2016, A. Geochemical Model for the Formation of the Pre-Salt Reservoirs, Santos Basin, Brazil: Implications for Understanding Reservoir Distribution: Search and Discovery Article #51304 (2016). Website accessed November 14, 2017, http://www.searchanddiscovery.com/documents/2016/51304wright/ndx_wright.pdf.

Critically evaluating the current depositional models for the Pre-Salt Barra Velha Fm, offshore Brazil

V Paul Wright[1], Andrew J Barnett[2]

1. PW Carbonate Geoscience, Cardiff, United Kingdom.
2. Shell, London, United Kingdom

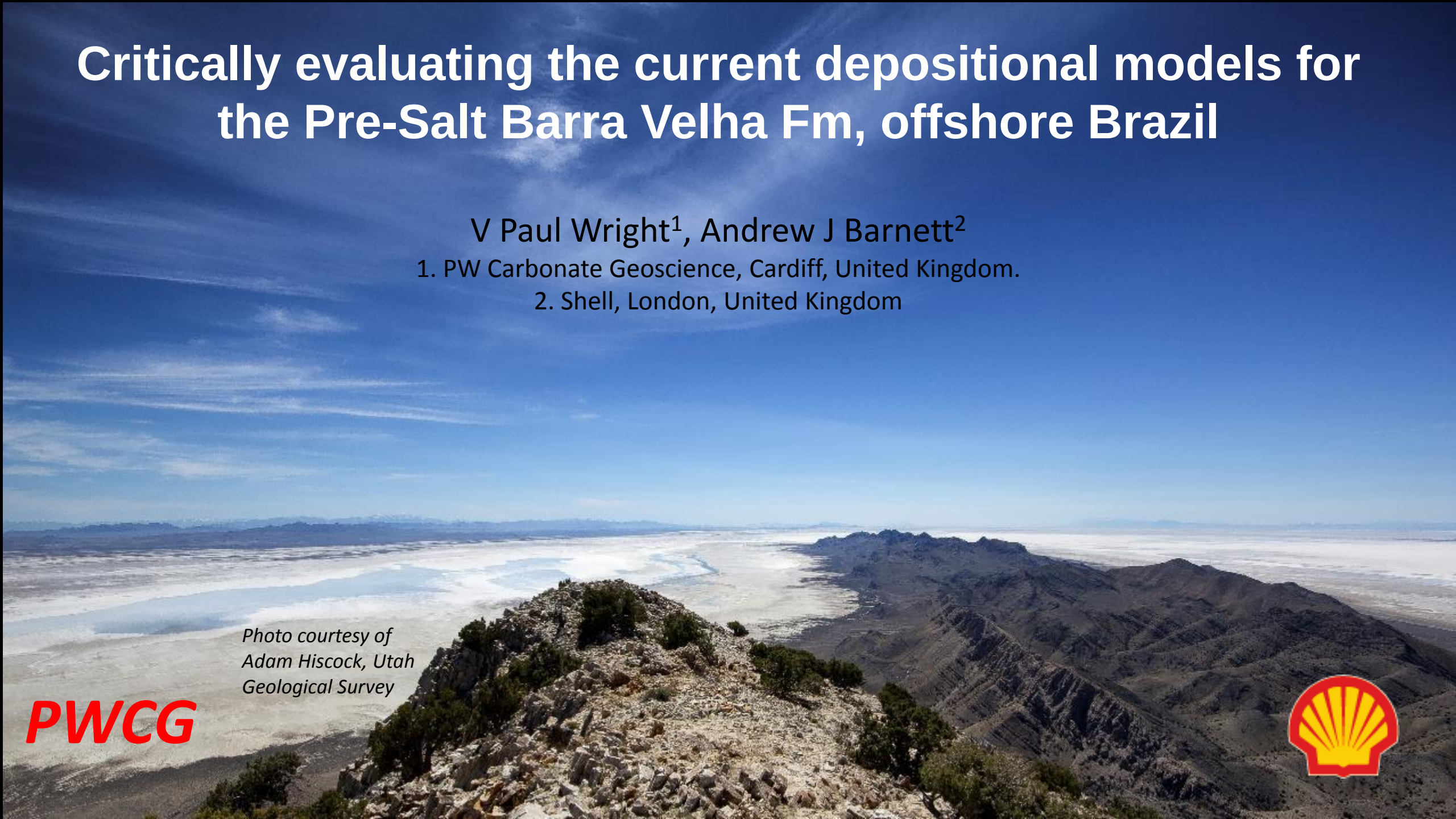


Photo courtesy of Adam Hiscock, Utah Geological Survey

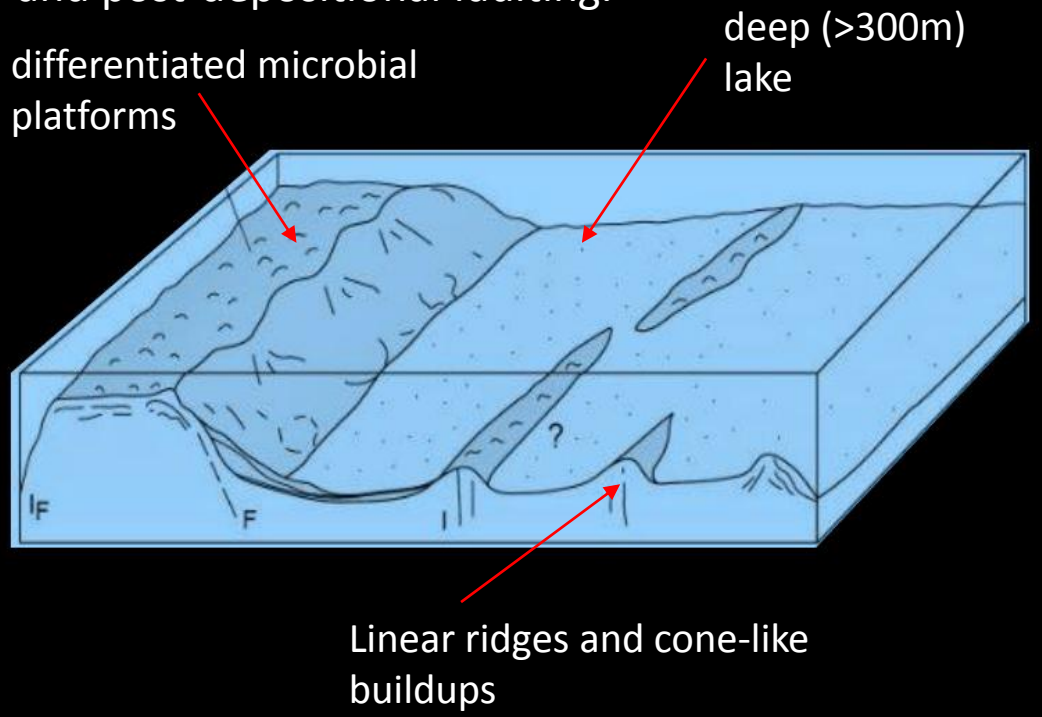
PWCG

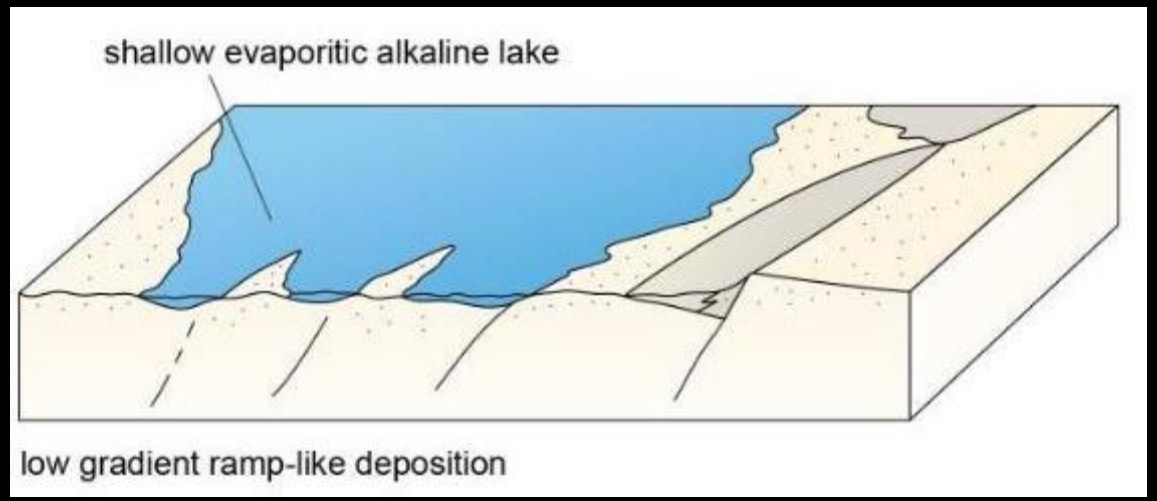
The problem

The Pre-Salt **Barra Velha Fm** (BV) (so-called Microbialites), **Santos Basin** hosts giant oil and gas fields and two conflicting models exist for its depositional setting with huge implications for exploration and production –

- deeper lake, 100's m deep with microbial platforms and isolated microbial buildups
- shallow evaporitic lake

What is known is that the Barra Velha is closely associated with volcanics and formed in a rift setting affected by syn- and post-depositional faulting.





Take-away points

For Santos Basin the weight of evidence suggests the main reservoir interval, the Barra Velha Formation did not develop as high-relief carbonate platforms

Relief on the base salt was largely structural and post-Barra Velha in origin, not due to high relief platforms and deep lake basins during Barra Velha deposition

As regards the isolated ridge-like and conical mounds, the main origins of such topography in closed rift basins are likely to be spring mounds and volcanoes

Syn- and post-Barra Velha faulting, erosion and volcanism created features, such as clinoforms, more likely representing rotated onlap geometries, lava deltas and alluvial fans and fan deltas, but mis-interpreted as related to high-relief buildups

The evidence comes from:

- *Re-evaluation of seismic data*
- *Long-range correlations*
- *Facies interpretations*
- *Isotopic data*

Many studies have identified carbonate platforms and isolated buildups

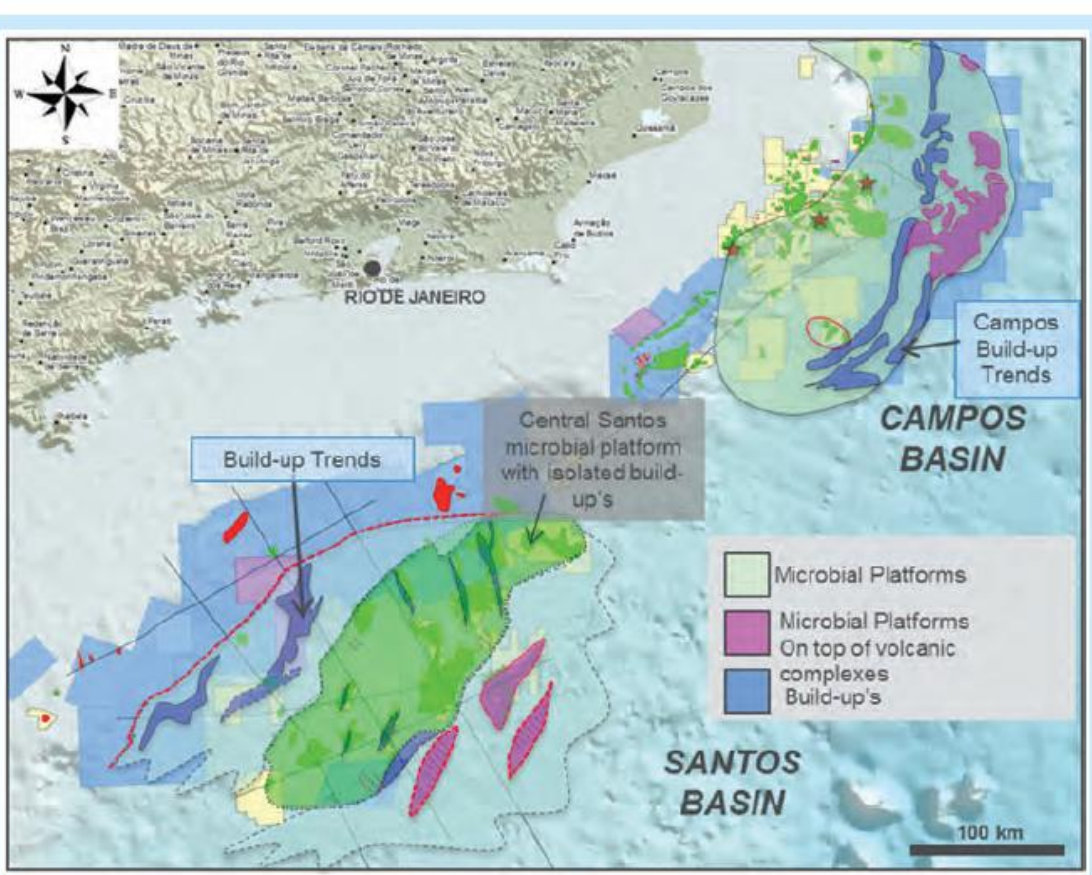
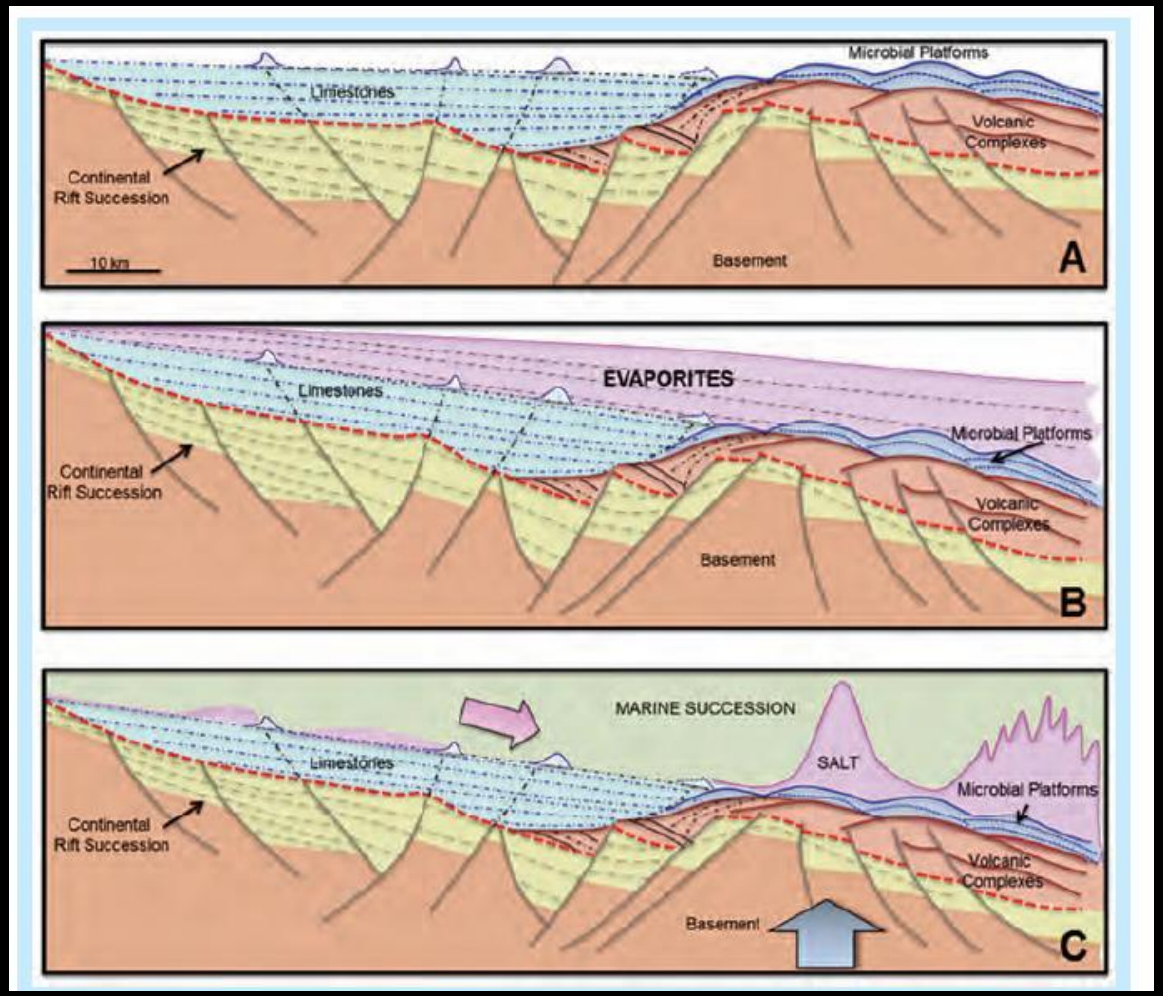


Figure 2: Location, Seismic dataset and pre-salt Environments of Deposition (EOD's) for the Santos and Campos basins.

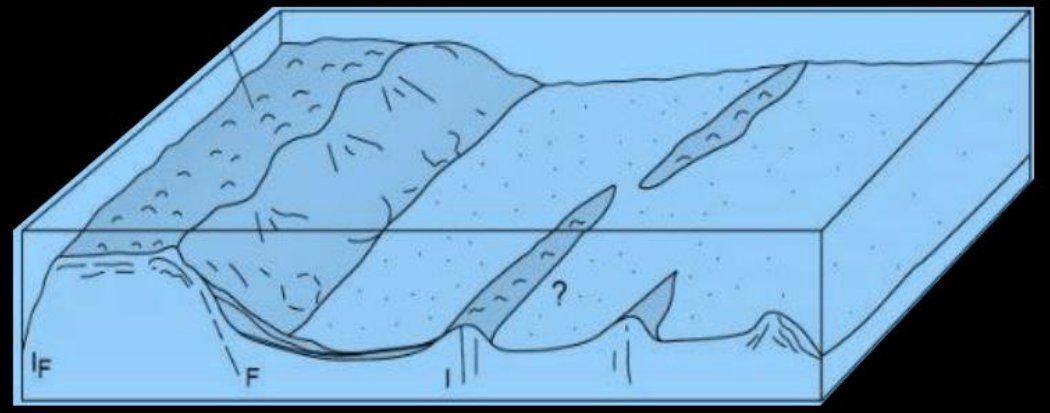
Kattah, S. 2017. Exploration Opportunities in the Pre-Salt Play, Deepwater **Campos Basin**, Brazil. The Sedimentary record, 15,1, March 2017, p.4-8 doi:10.21110/sedred.2017.1



Deeper Lake Microbial Platform-Buildup Model

The evidence for larger platforms comes from seismic interpretations showing relief on the base of the salt and on the presence of clinoforms

For Santos Basin no evidence has been provided for differentiated platform-like buildups, or for the potential for the carbonate factories seen in the BV to produce such buildups



The clinoforms suggest progradation but closed lakes in rift basins are dominated by aggradational strata generated mainly by evaporation. Progradation of the type that might produce clinoforms is limited to lake-margin alluvial fans or fan deltas, but morphologically similar features could be produced by, for example, lava deltas which are known in the Santos Basin.

The isolated conical-ridge-like features seen on seismic could be sub-lacustrine vent/spring-related, subaerial travertine cones or volcanoes; seismic-scale sub-lacustrine buildup formation in lakes requires significant water depth

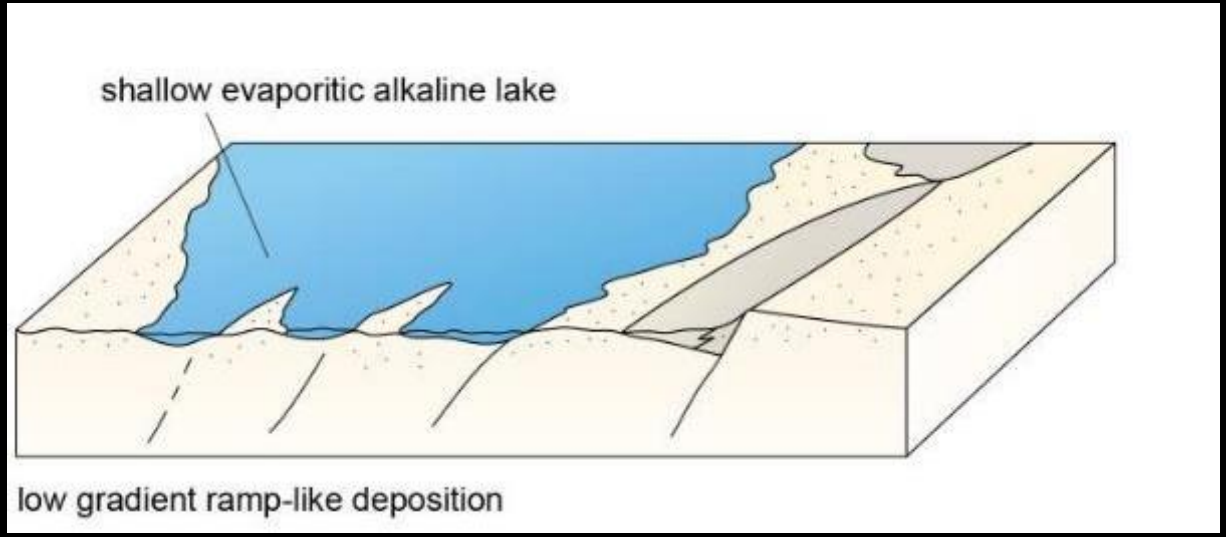
The case for a shallow, as against a deep lake with high relief platforms, is based on 4 lines of evidence –

1. Most seismic features attributable to carbonate buildups do not meet the standard criteria, and in most cases the features can be explained by syn- and especially post-Barra Velha faulting, including local inversion, and erosion, rotated onlap geometries and may even be volcanic in origin including lava deltas

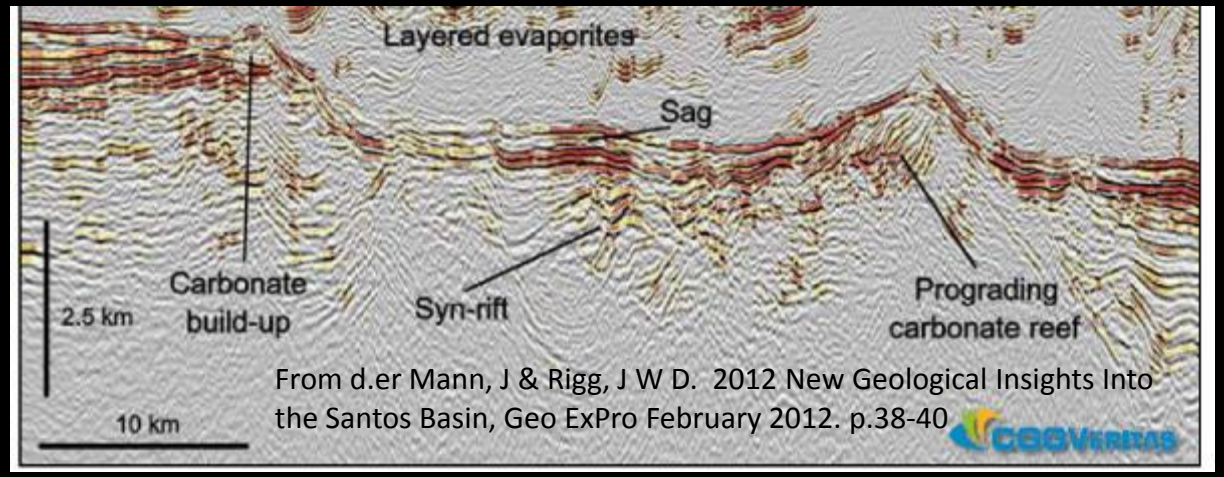
2. Long-range correlations using well logs indicate that current relief across the basin did not exist at the time of deposition and is due to post-Barra Velha structuration

3. The facies model, supported by geochemical modelling, suggests shallow evaporitic lakes

4. Provisional isotopic data suggest the lakes were shallow and evaporitic, with no large water body nearby



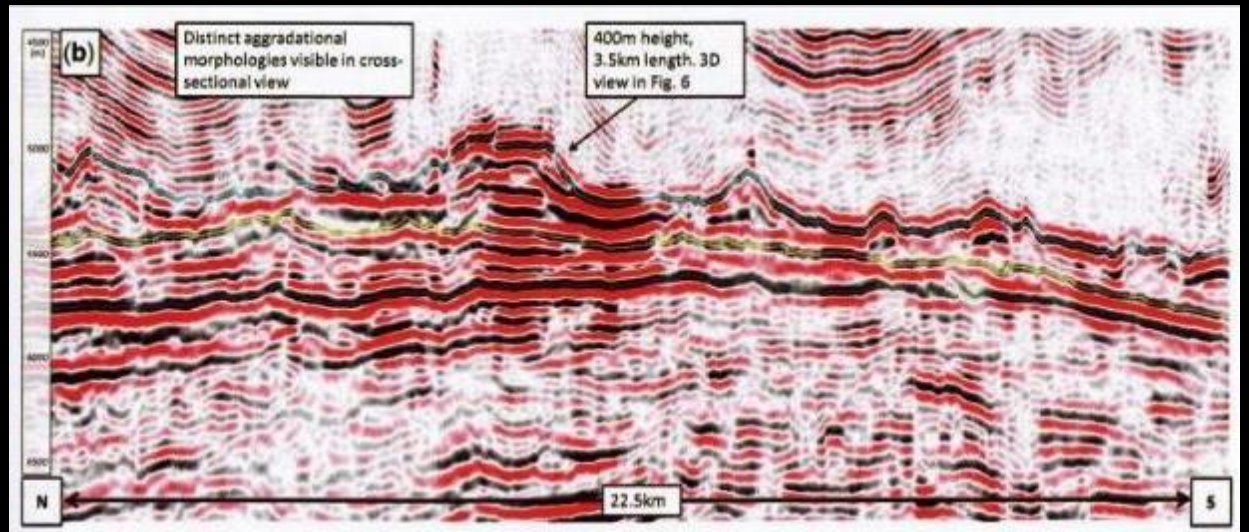
Evidence for the Platforms model



From d.er Mann, J & Rigg, J W D. 2012 New Geological Insights Into the Santos Basin, Geo ExPro February 2012. p.38-40

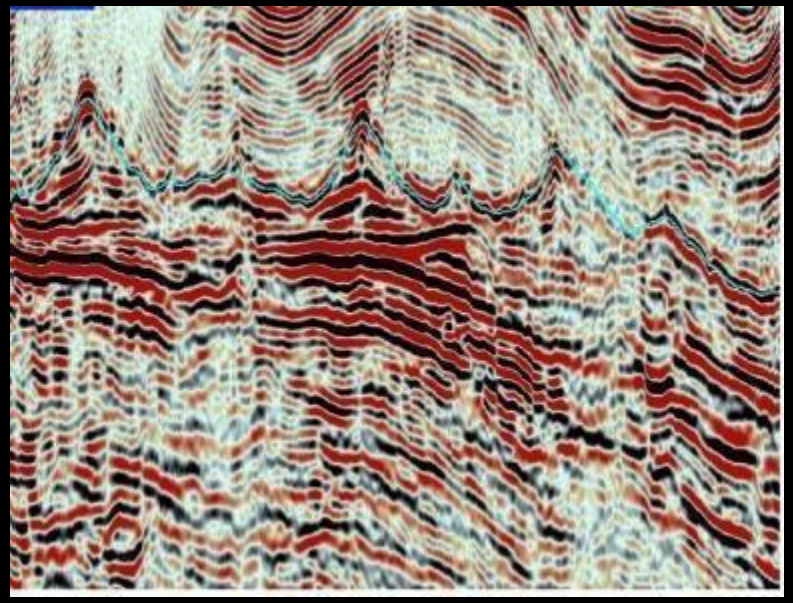
Clinoforms –

- Could be subaqueous carbonate aprons
- Could be artefacts or even rotated onlap features
- Could be subaerial fans, lava deltas



Isolated mounds -

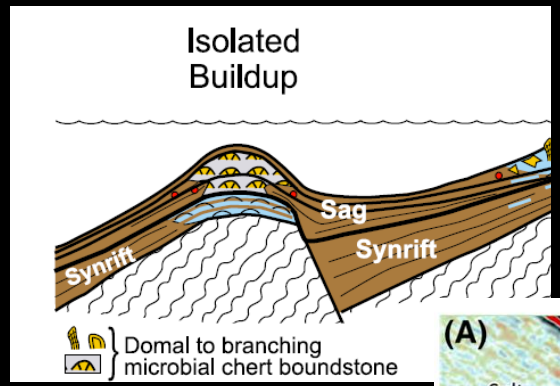
- Could be sub-lacustrine buildups
- Could be subaerial travertine buildups
- Could be volcanoes



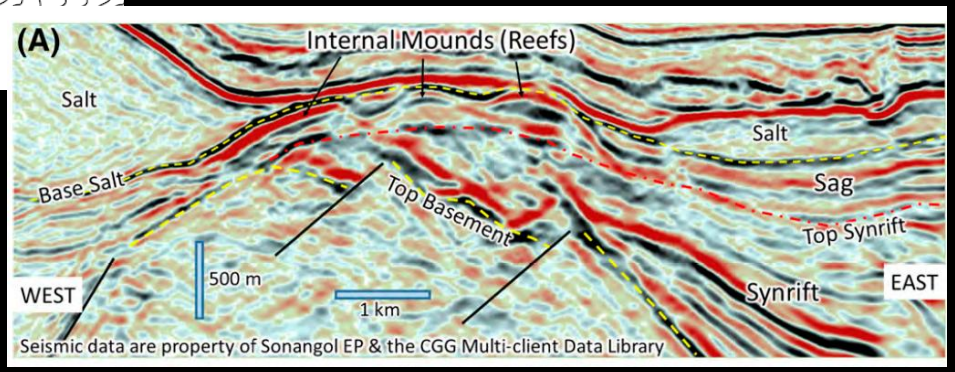
Buckley, J. P. et al. 2013 Carbonate Buildups in the Santos Basin, Offshore Brazil In Microbial Carbonates in Space and Time Implications for Global Exploration and Production. Geological Soc. Lon. Conference 19-20 June 2013, p36-37

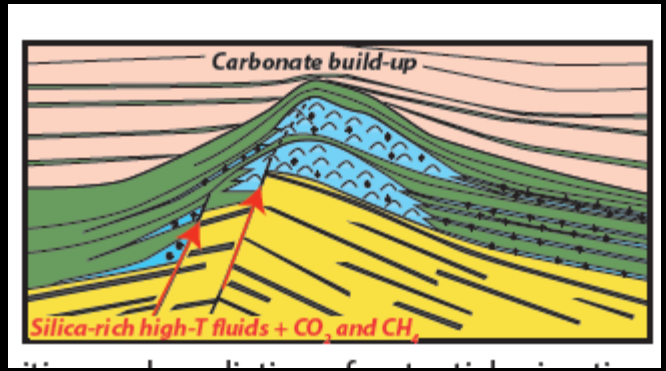
Buckley, J. P. et al. 2015 Geol Soc London, Spec Publ. 418, 175-191

Isolated mound-like buildups have been proposed from Kwanza Basin – very closely associated with faults



Kwanza (Cameia): Saller A. et al. 2016. Pre-salt stratigraphy and depositional systems in the Kwanza Basin, offshore Angola. AAPG Bulletin, v. 100, no. 7, pp. 1135–1164





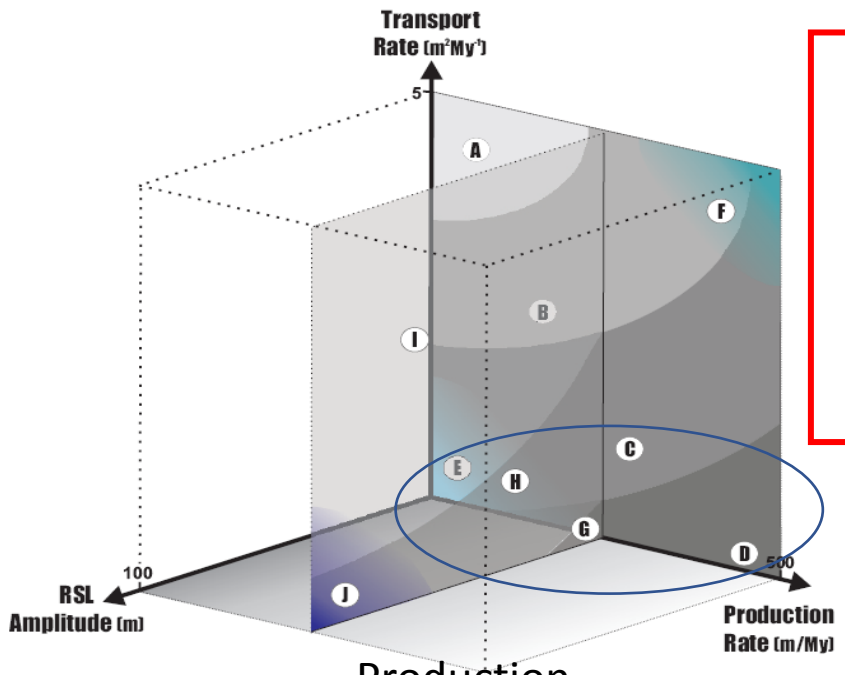
Poros et al. (2017) for Omosi-1 well identify; Poros, Z. et al. 2017, Origin of Silica in Pre-Salt Carbonates, Kwanza Basin, Angola, AAPG ACE Houston Abstract 2612742; courtesy of ConocoPhillips

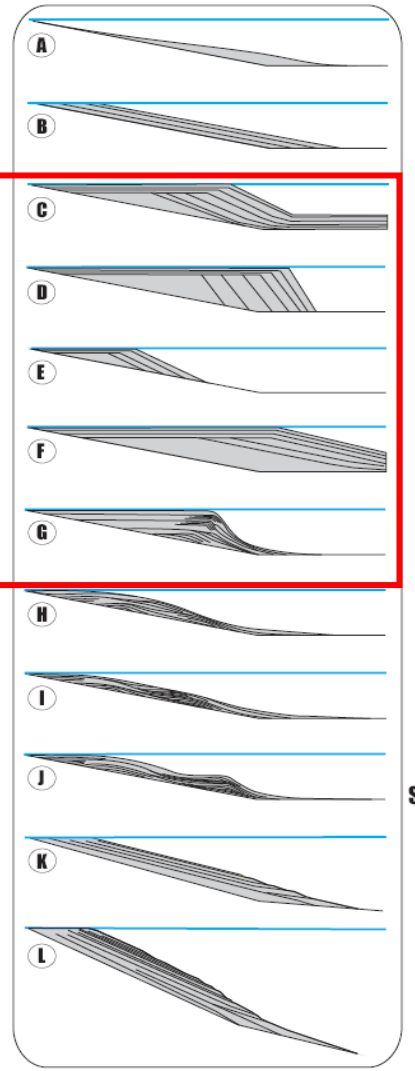
What is not clear is whether or not the large platforms are actually carbonate accumulations, as in many Phanerozoic marine platforms, or are simply carbonates that accumulated on antecedent topography.

In the case of the former modelling, studies have shown what key parameters affect the geometry of marine carbonate platforms.

Forward modelling (2D) using large numbers of multi-parameter runs to define parameter space distributions of typical platform geometries

Diffusion – transport rate





The key characteristic of these high relief systems is low-sediment diffusion and is linked to the sediment producers being less transportable = large metazoans or metaphytes or microbial boundstones

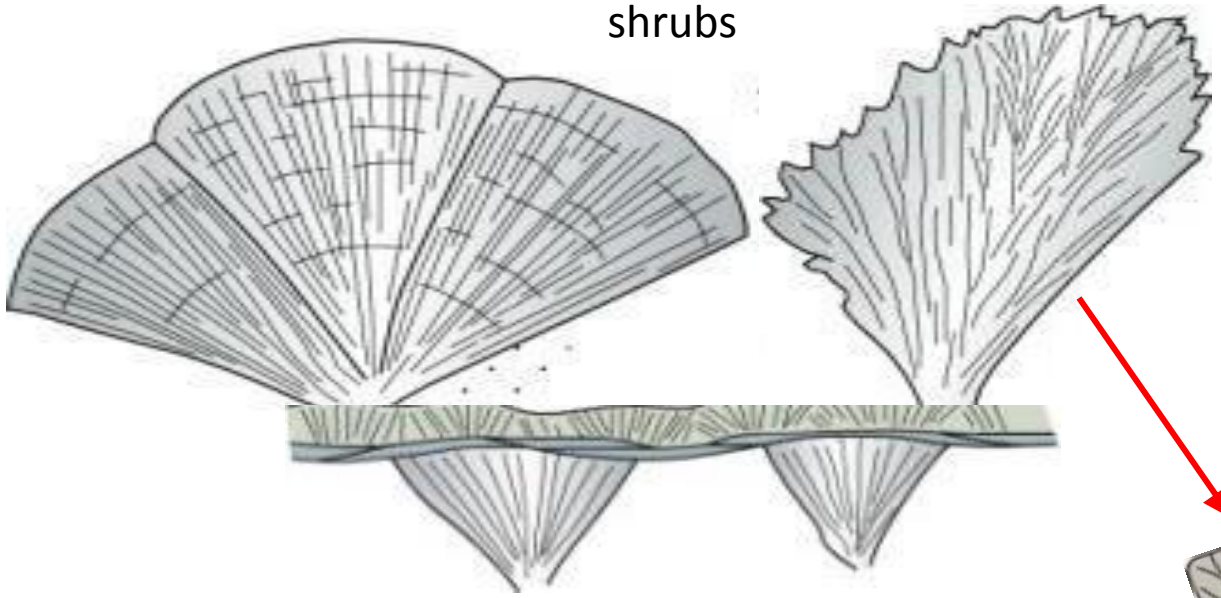
•Amplitude of relative base-level change

Production rate (linked to depth profile)

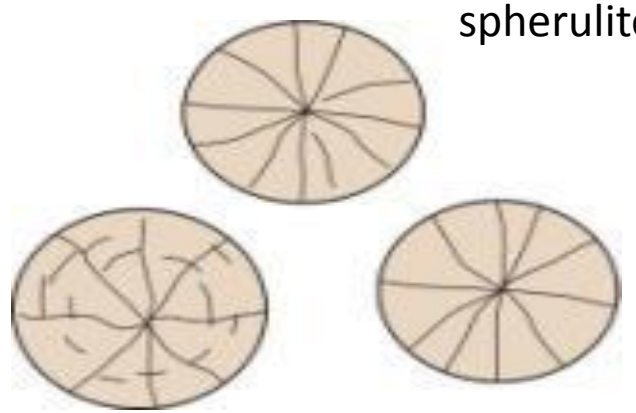
Williams H D et al. 2011 Journal of Sedimentary Research, 81, 18-37.

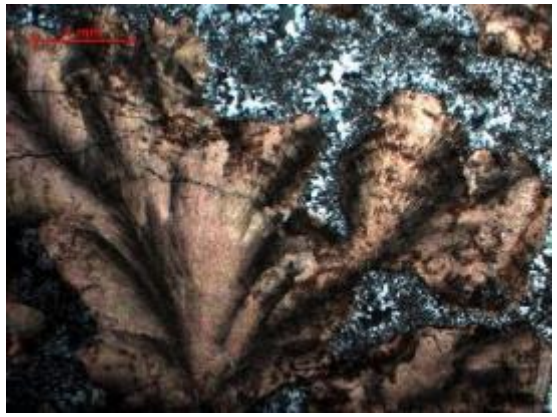
So do the Barra Velha sediments have high or low transportability?
Only two key components: -

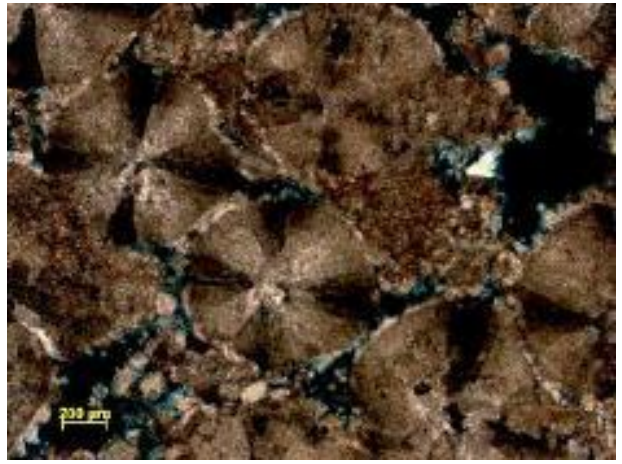
Mm-cm sized shrubs



Mm-sized spherulites

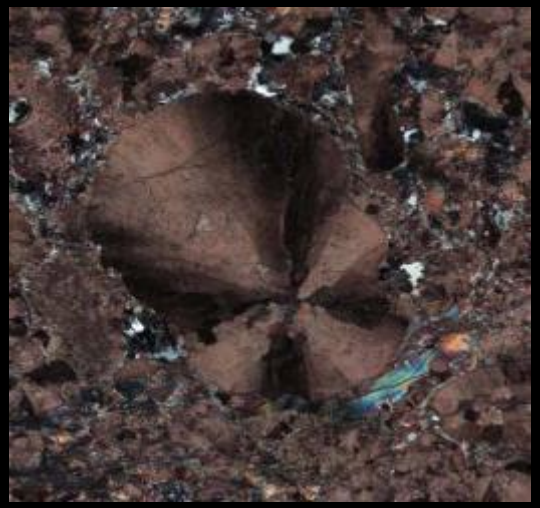






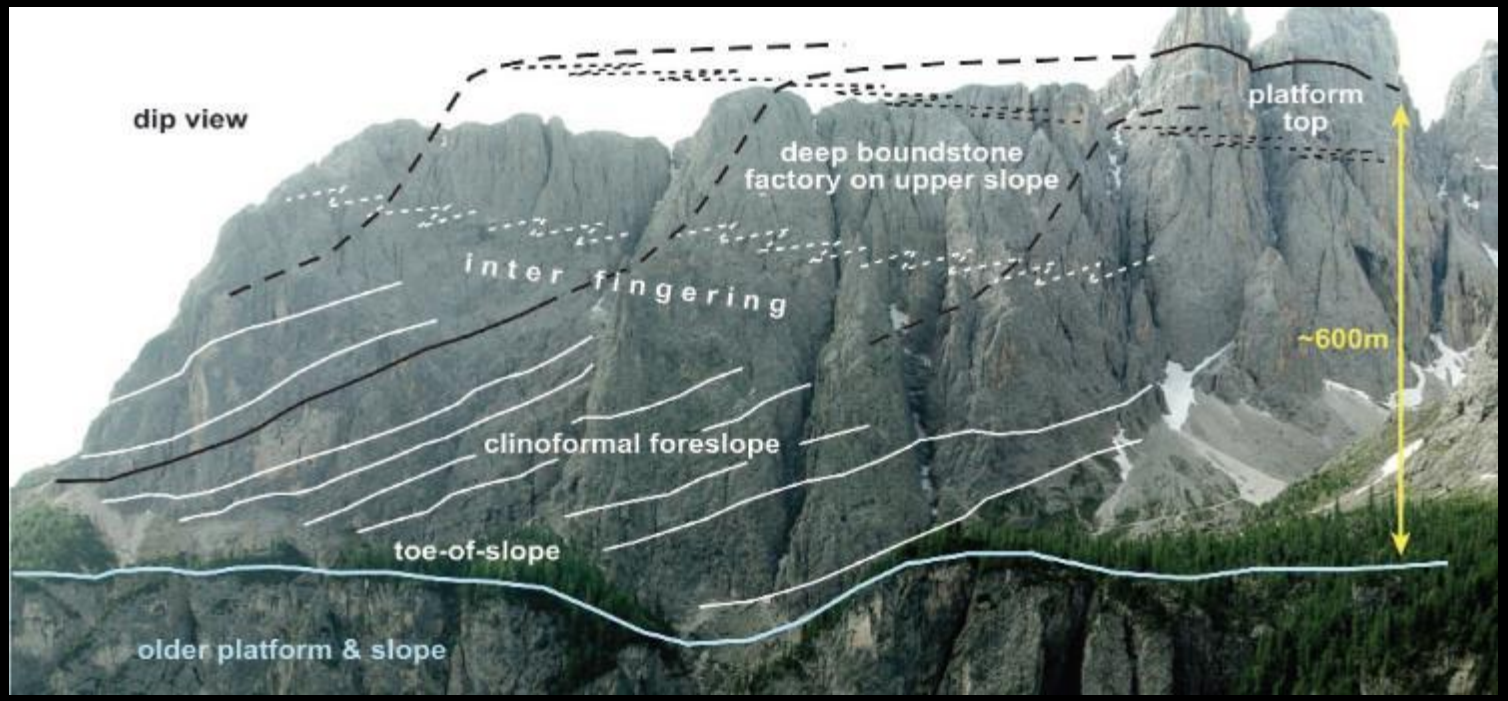
Both components are frequently reworked, layered units, not massive, or reefal

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



From Dorobek S et al. 2012
AAPG Hedberg conference
"*Microbial carbonate reservoir characterization*"
June 4-8, 2012 – Houston

Microbial factories ARE capable of building platforms and isolated buildups with hundreds of metres of relief and the Formation is also known as the “Microbialites”



- Carboniferous of N Spain and Kazakhstan
- Triassic of Dolomites
- Jurassic of Morocco
- Albian of N Spain
- etc…

From Playton T E et al 2010 Carbonate Slopes- in Facies Model 4 (ed by N P James & R W Dalrymple), p.449-476

BUT in the Barra Velha

- microbial macrostructures which resemble classical stromatolites are **rare** (<0.5% of thickness of logged sections)
- as are microbial planar laminites (<1%)
- and oncoids (<0.1%)
- Within the key textural components such as shrubs microbial microstructures are **very rare** with as few as 0.05 to 0.1% of shrubs showing features such as microbial filament moulds

In addition –

No modern lacustrine carbonate systems produce large differentiated platforms and seismic-scale clinoforms

No analogues are currently known from the geological record of lakes

There are examples of isolated, sub-lacustrine and subaerial mounds, the former at least of seismic-scale

Pyramid Lake, Nevada

1-3km long

Large sub-lacustrine spring mounds develop in perennial lakes – they need the space (depth) in which to grow

What about subaerial mounds – spring mounds and travertines?

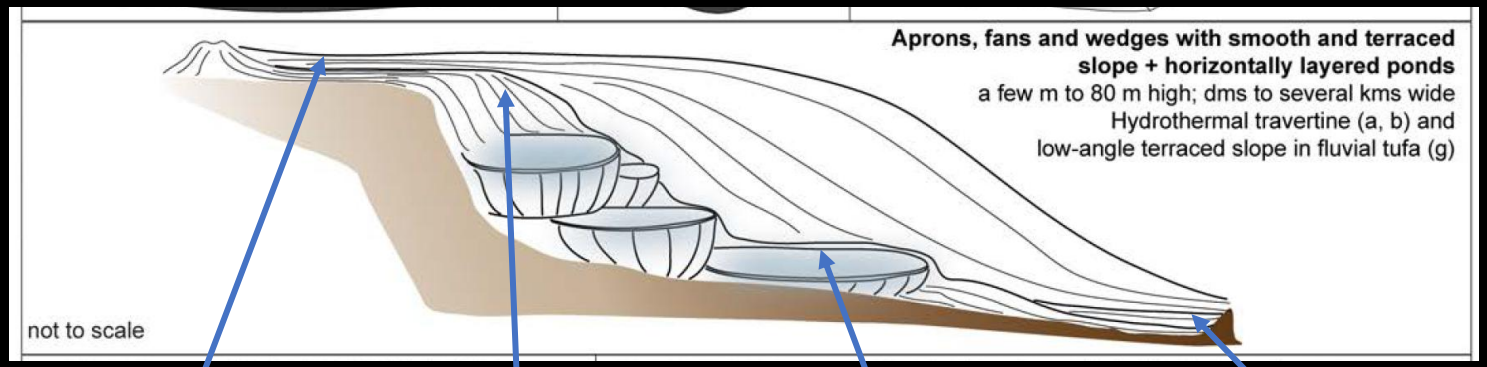
Individual mounds today seem to reach a maximum height of 30m

But can occur in complexes covering 100's km^2 and 250m thick

But are subject to erosion

Main travertine facies – e.g., ridge-terrace association

These produce distinctive facies associations not recorded in the bulk of the Barra Velha and C & O isotopic data shows non-thermal signatures



Della-Porta, G. 2015. Geological Society, London, Special Publications, 418,17-68. http://dx.doi.org/10.1144/SP418.4

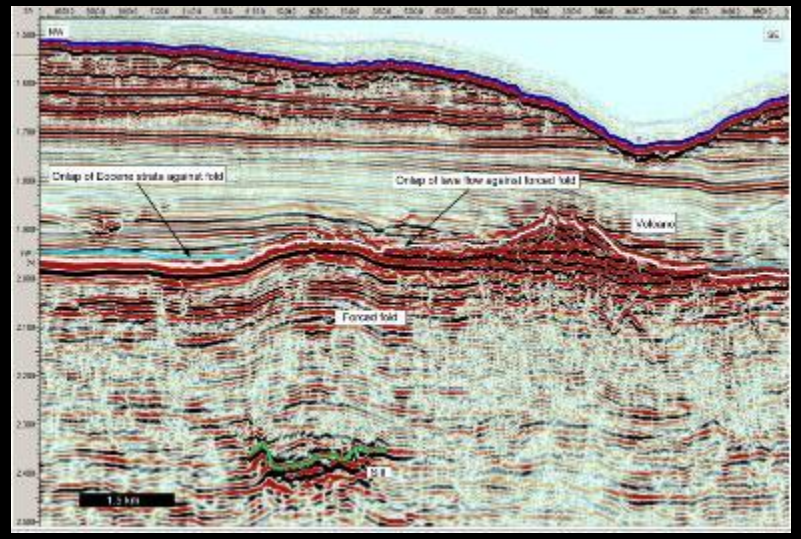
Shrubs – bacterial and crystal formed on terraces

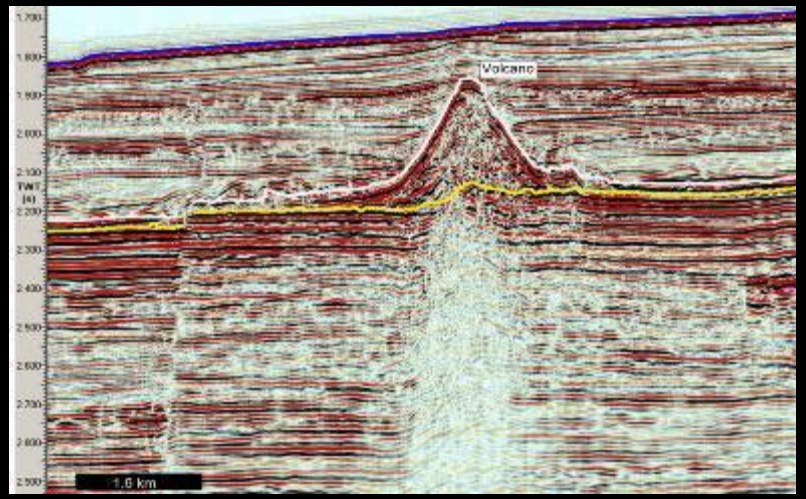
Large crystal fans

Plant stems

Coated grains , pisoids, coated bubbles and rafts

But volcanoes are another possibility





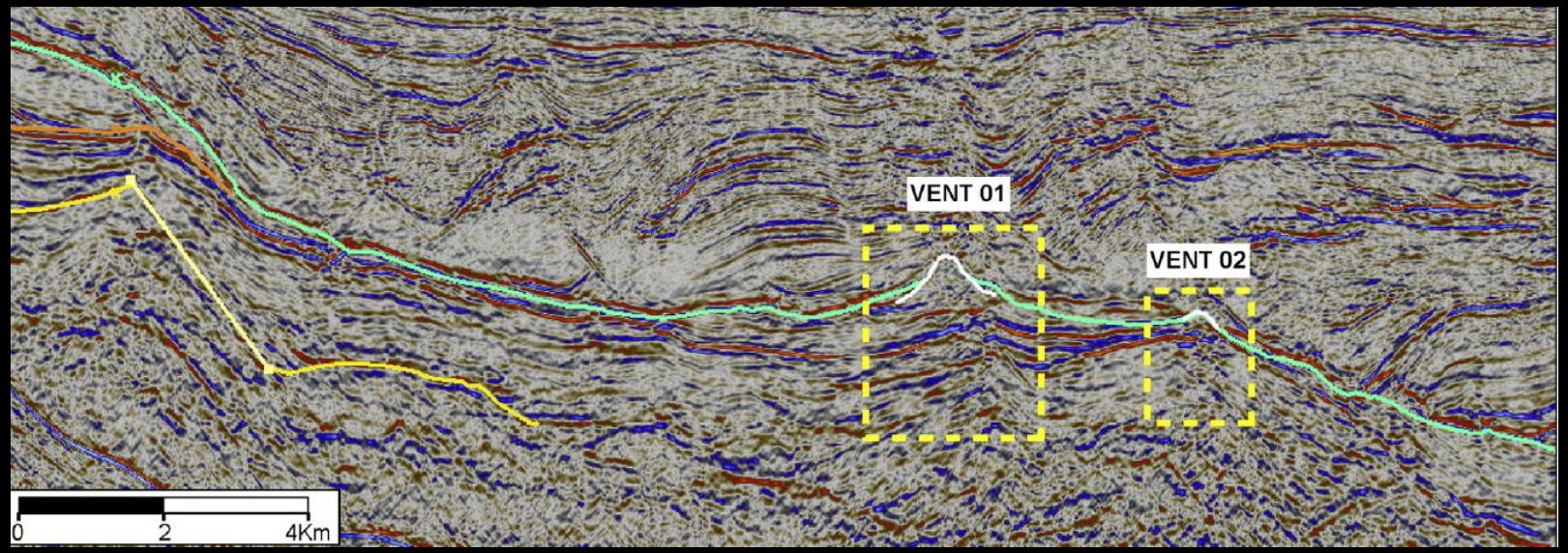
Gada Ale volcano. Source: Smithsonian Institute

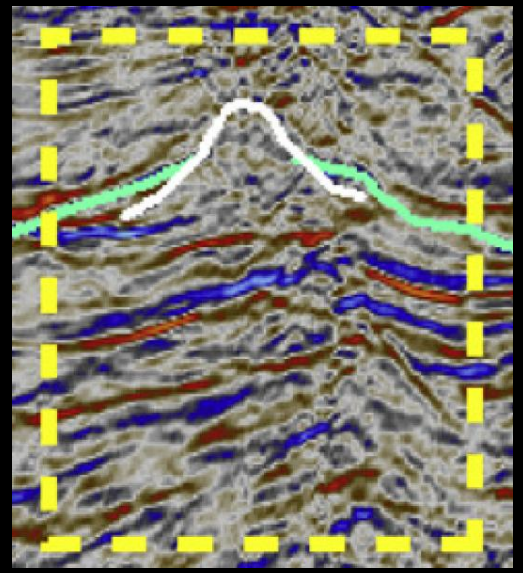
Lake Assale (syn. L. Karum). Afar region, Danakil Depression, Ethiopia

Volcanics from VSA web site

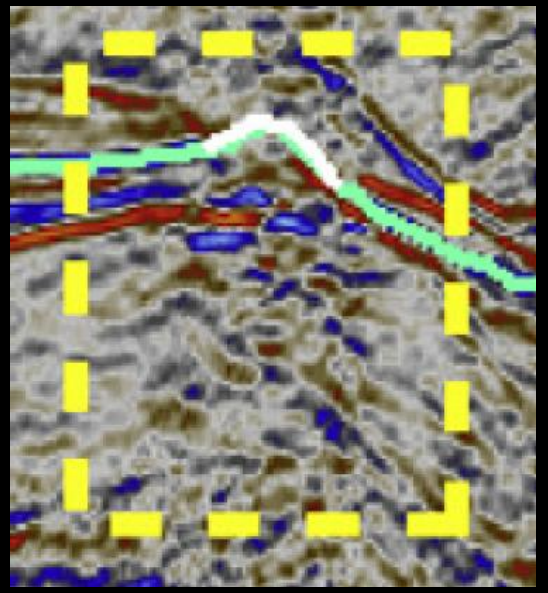
Hydrothermal vent complexes

In Campos basin some seismic features, including what appear to be isolated mound-like buildups in the rift stage, have been interpreted as hydrothermal vent complexes by Alvarenga R. S. et al., 2016 (Marine and Petroleum Geology 74, 12-25)





From - Alvarenga R. S. et al., 2016 Seismic characteristics and distribution of hydrothermal vent complexes in the Cretaceous offshore rift section of the Campos Basin, offshore Brazil. Marine and Petroleum Geology 74, 12-25



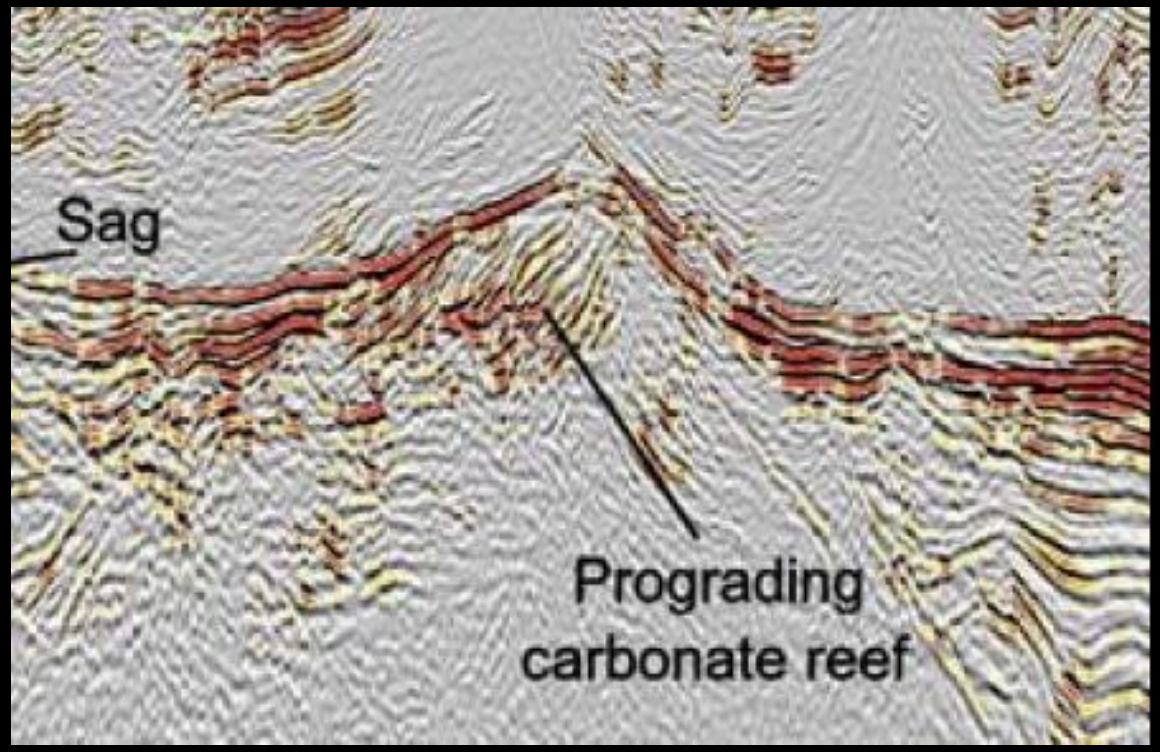
Clinoforms –

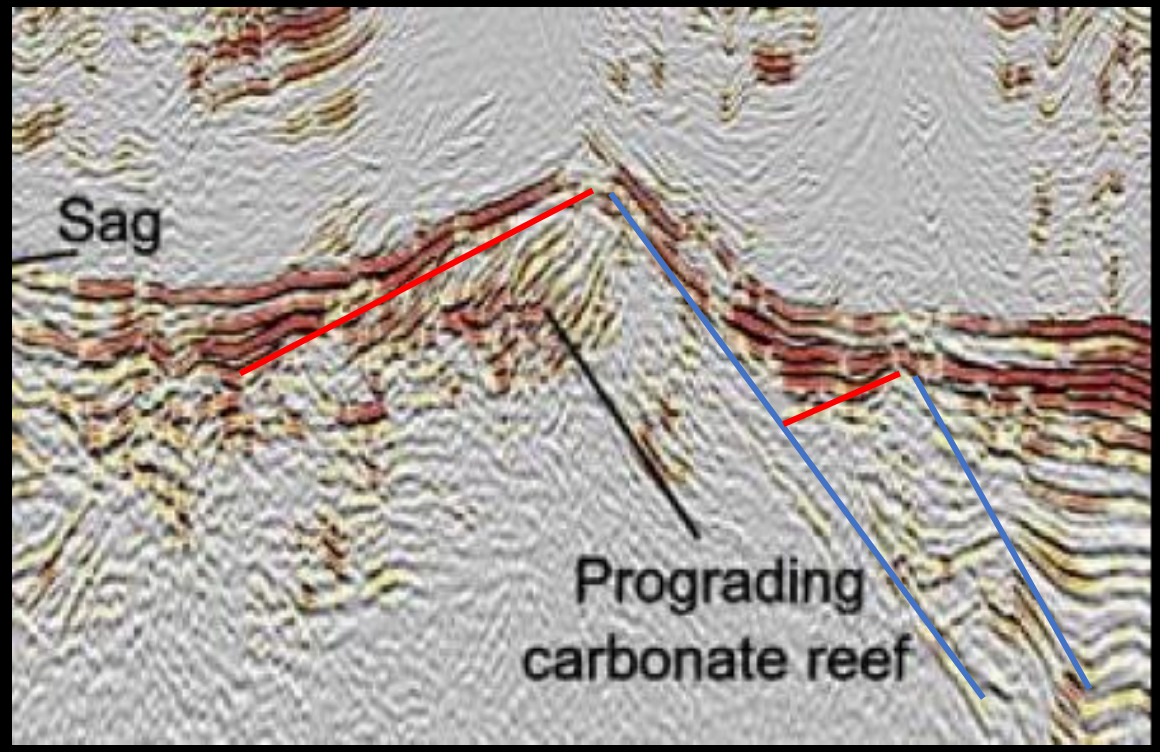
Do they exist?

Composition?

And in the absence of evidence that lacustrine carbonate factories could produce major high relief platforms and shed enough sediment to generate clinoforms, what could they be?

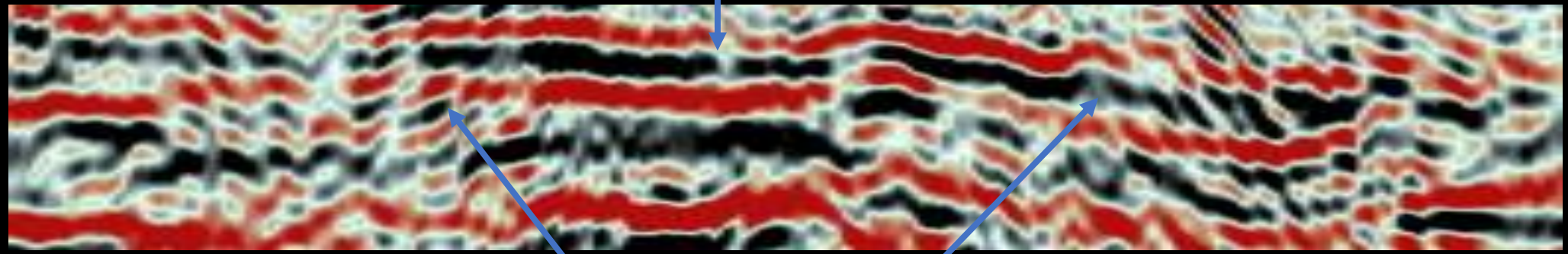
Are these rotated onlapping reflectors?





From der Mann, J & Rigg, J W D. 2012 New Geological Insights Into the Santos Basin, Geo ExPro February 2012, p.38-40

Platform-interior topsets?

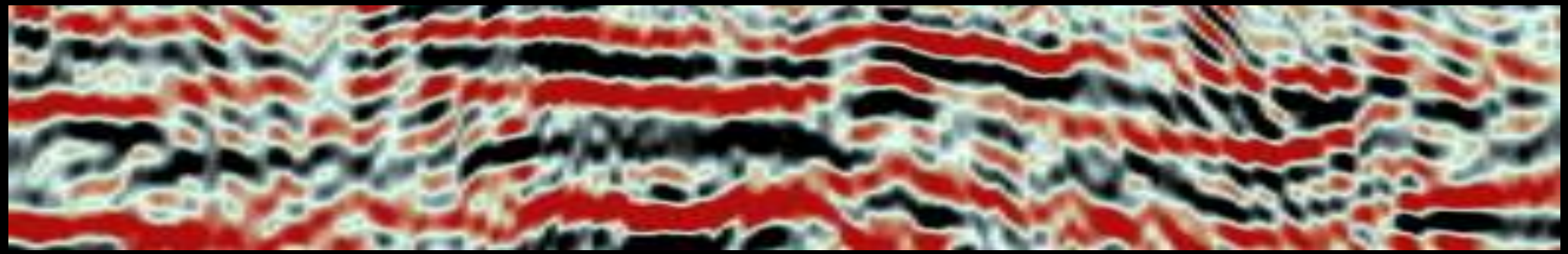


salt

Barra Velha

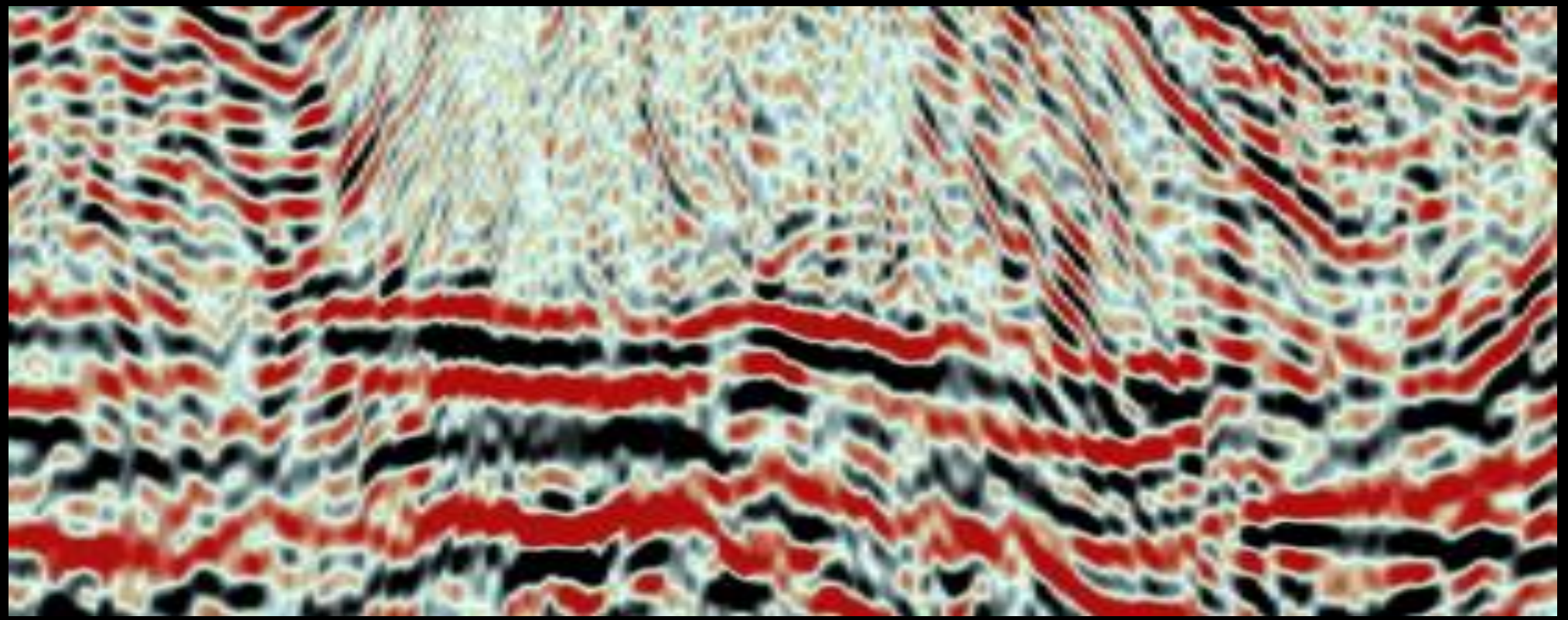
Platform-margin prograding clinoforms

Some clinoforms are artefacts caused by steeply dipping salt

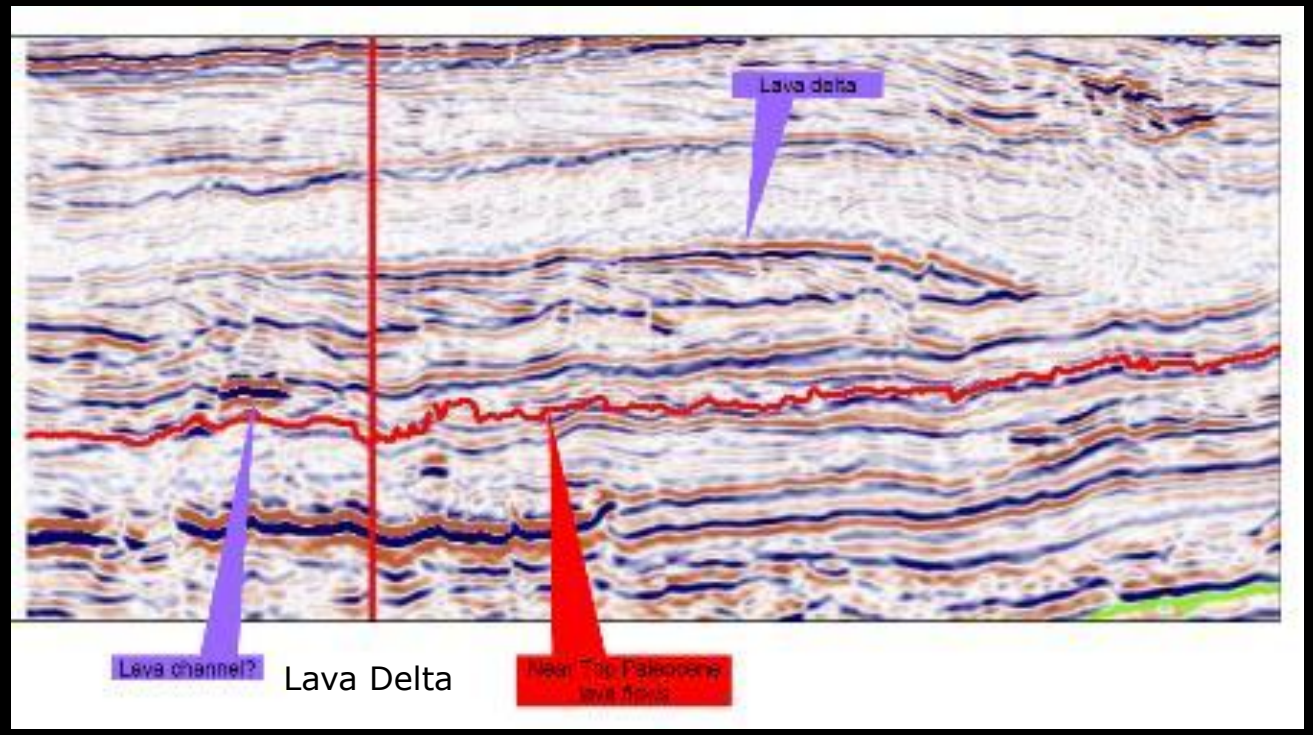


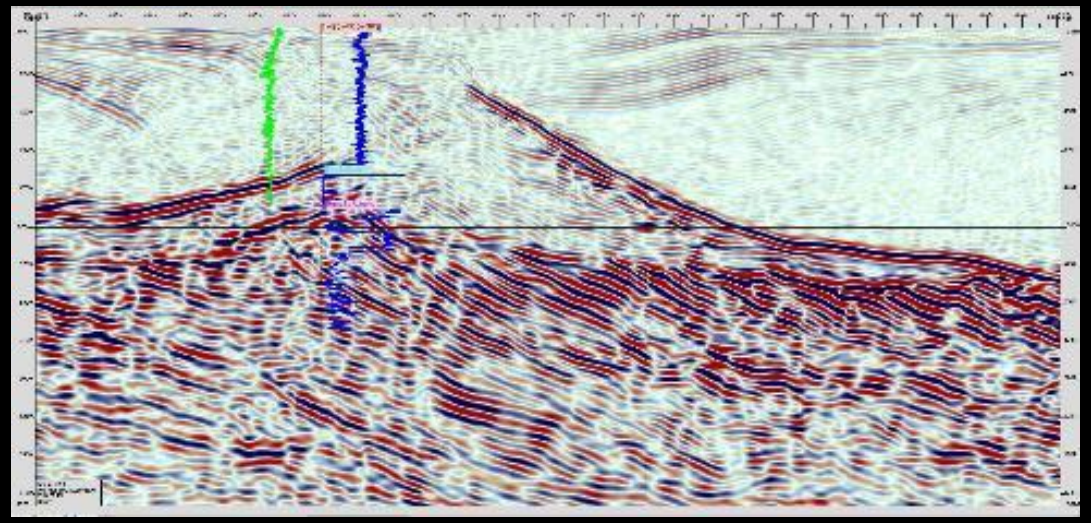
salt

Barra Velha



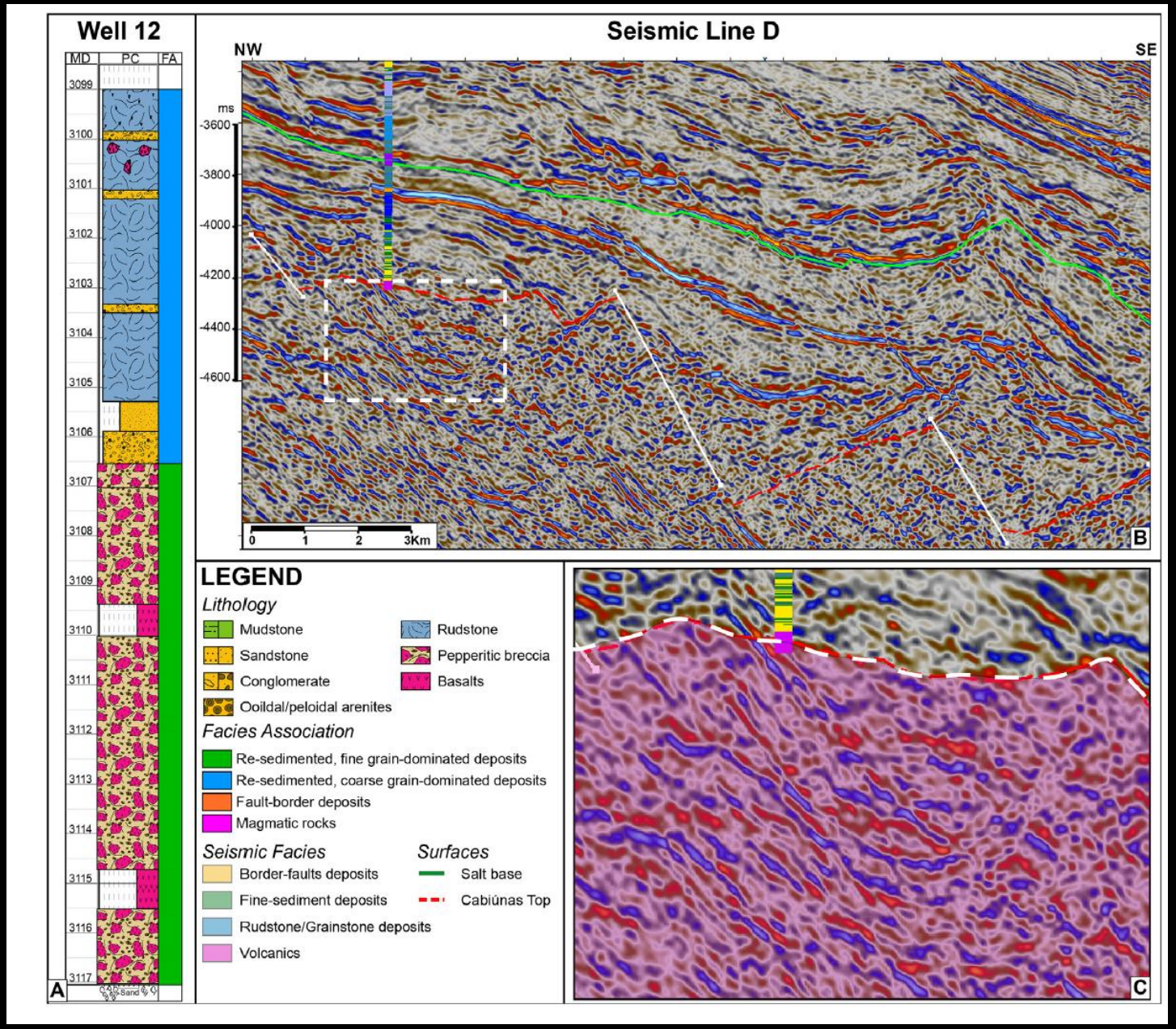
Clinoforms in volcanics - lava deltas





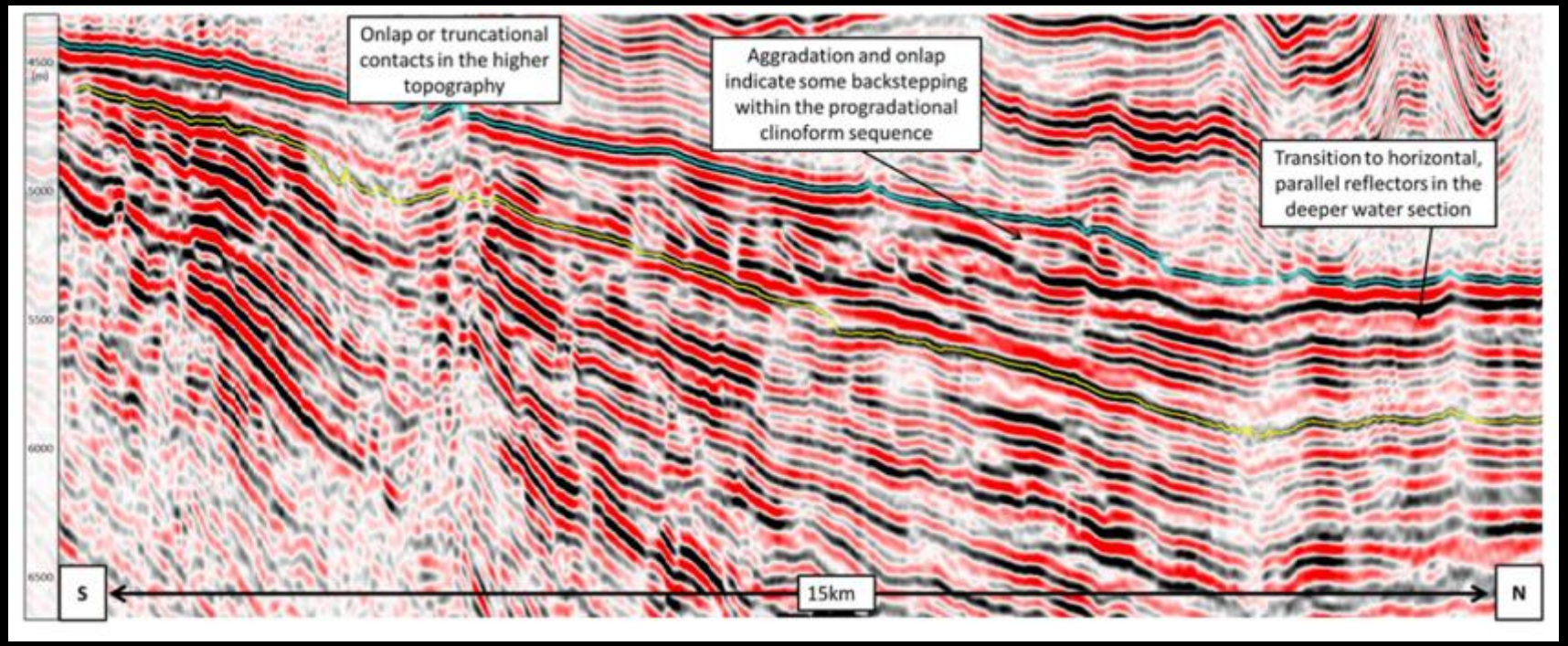
Clinoforms in Santos Basin - basalt, from the Pre-Salt, and other lava clinoforms have recently been described from the Rift stage in Campos Basin

Clinoforms in basalts and diorites, Rift section, Campos Basin



From: Goldberg K. et al., Re-sedimented deposits in the rift section of the Campos Basin Marine and Petroleum Geology 80 (2017) 412-431 doi.org/10.1016/j.marpetgeo.2016.11.022

Clinoform geometries - carbonates or lavas?

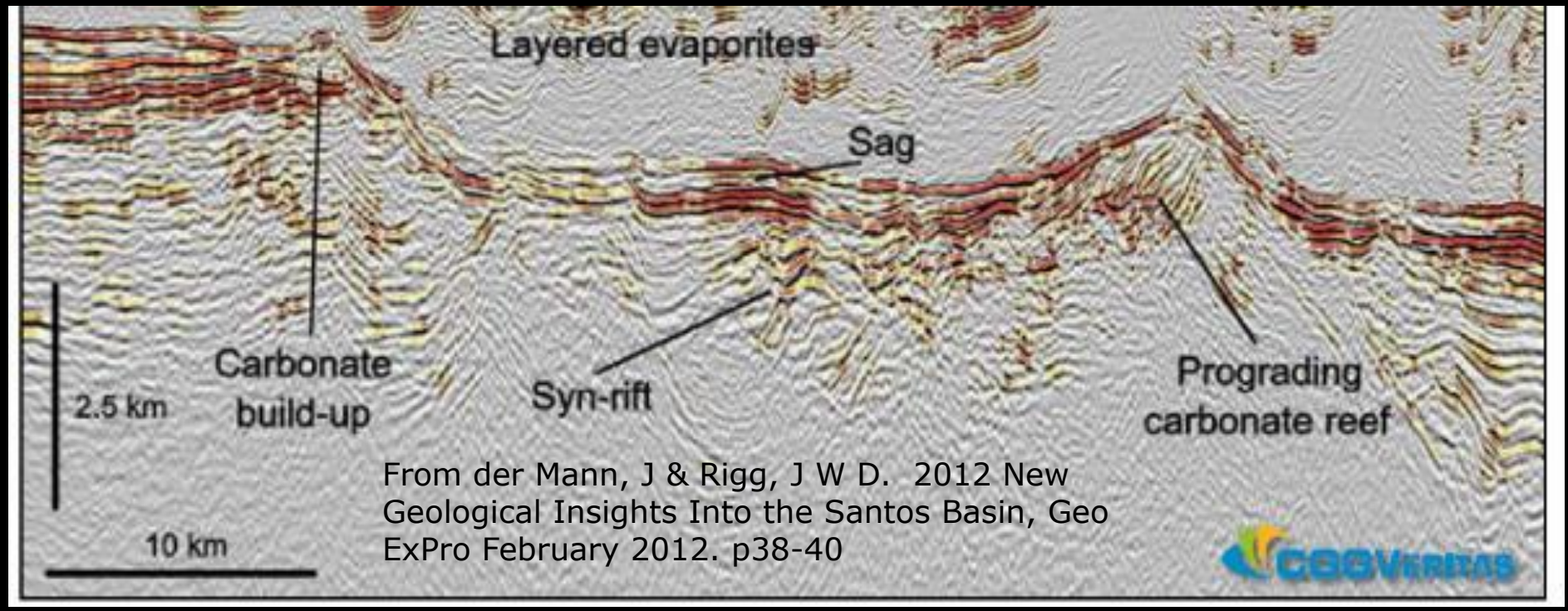


Prograding clinoforms with onlap and aggradation within an overall progradational package, Santos basin. From Buckley, J. P. et al. 2015 Geol Soc London, Spec Publ. 418, 175-191

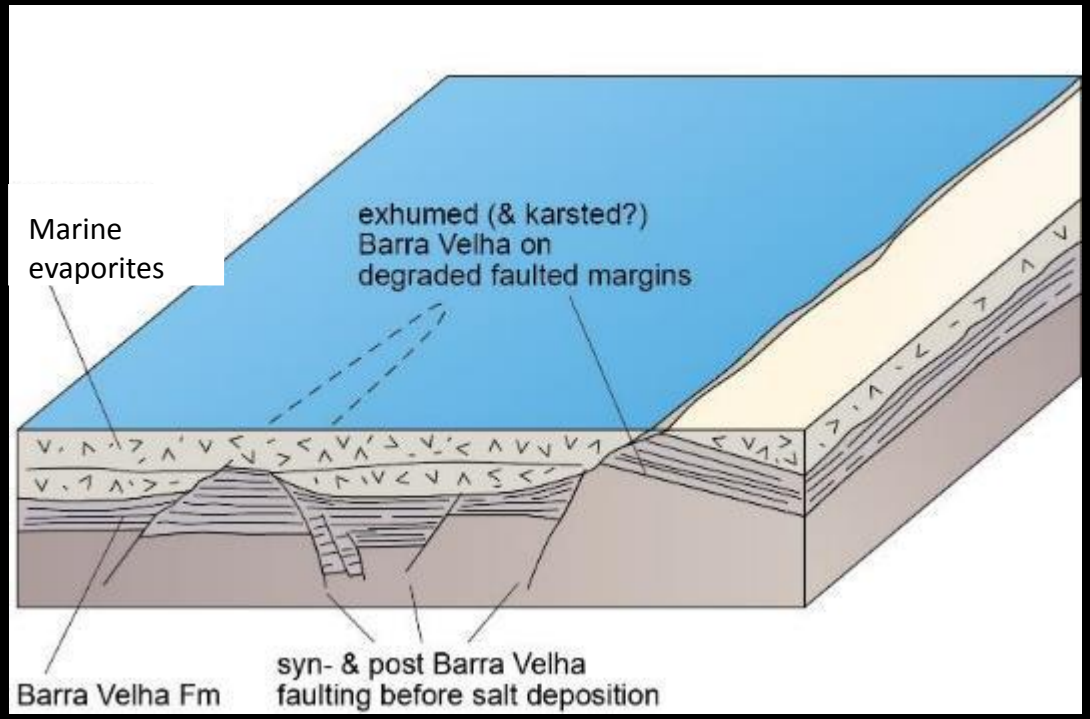
Complex internal geometries from proven lava delta (not from Pre-Salt)

But there clearly is relief on the present base of the salt

How could this have been generated?



Could the relief be largely due to post- (and some syn-) Barra Velha faulting +/- erosion?

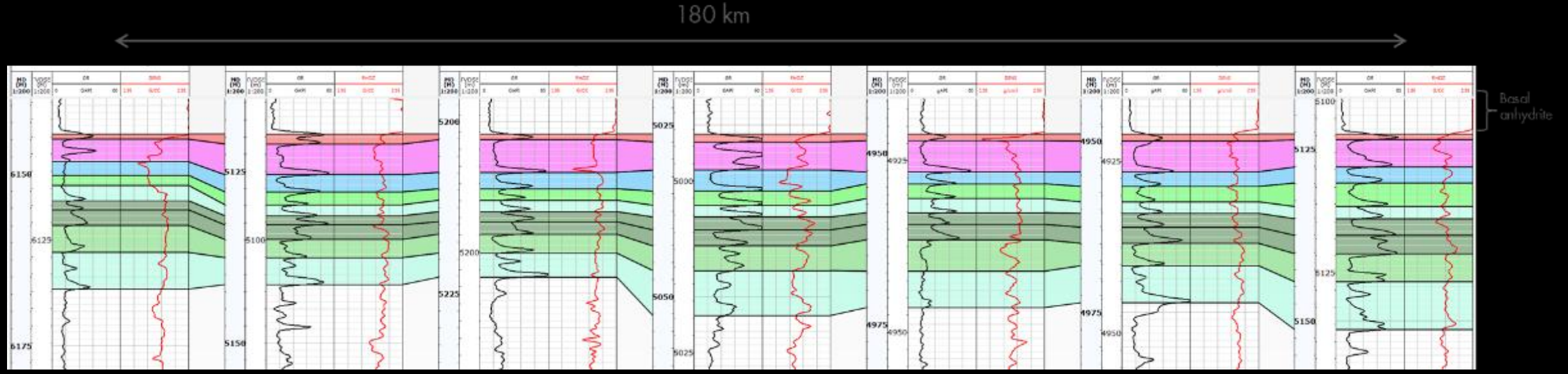


We do know that many researchers have highlighted the lack of significant extensional faulting visible on seismic in the South Atlantic basins, not consistent with the observed amount of thinning and subsidence.

Within the Santos Basin, extensional faulting within the pre-salt sag basin occurs up to the base of the evaporites and locally beyond; extension clearly continued to the late Aptian
Karner, G.D.& Gamboa, L.A.P. 2007. Geological Society, London, Special Publications, 285, 15–35, http://doi.org/10.1144/SP285.2

Is there any hard evidence for structuration after deposition of the Barra Velha?

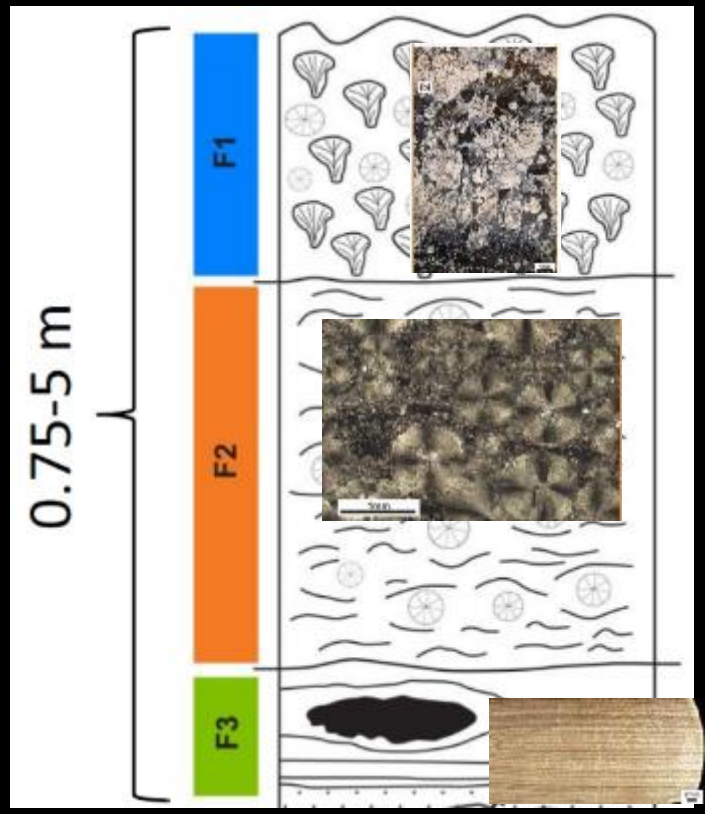
W-E correlation from across Santos Basin



- Total thickness of correlated package (so-called “Lula’s fingers”) varies from 20.8 to 28.5 m (mean = 24.3 m).
- 9 gamma-defined cycles (mean thickness 2.7 m) comprise one or more shallowing-upwards cycles defined by basal laminites.
- Cycles are well sampled by core and SWC, and facies are very similar in all wells and include a range of unequivocally shallow-water facies (e.g., microbial laminites and stromatolites).
- Cycles were deposited at same water depth but are now separated by > 1 km vertical relief, indicating significant post-depositional, but pre-salt structuration.

The Depositional Model

The facies and the occurrence of cyclothems support a shallow evaporitic lake model - Wright & Barnett 2015



Facies 1: Calcite shrub cementstones, 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

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

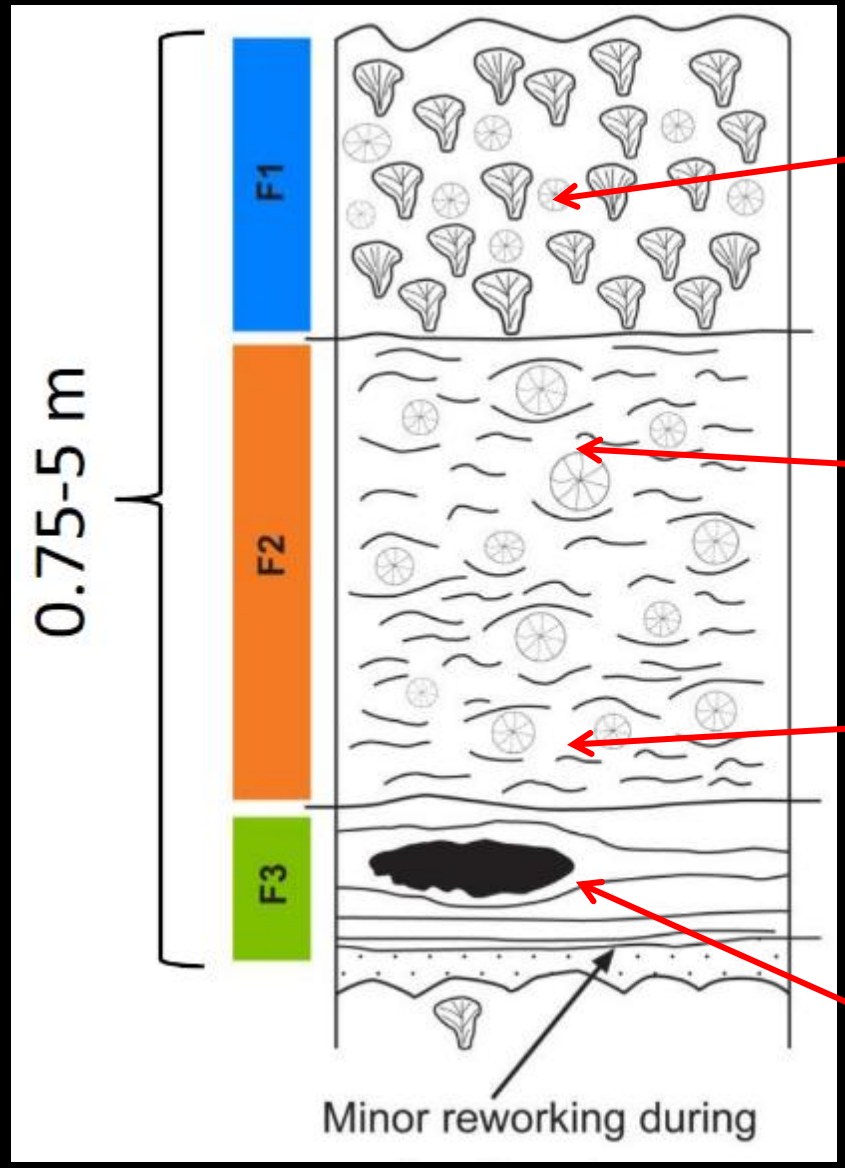
Evaporation triggers Mg-silicate gel precipitation; pH >9.5. Mg rapidly depleted. = low Mg/Ca. Spherulites grew in Mg-silicate gels, in low densities.

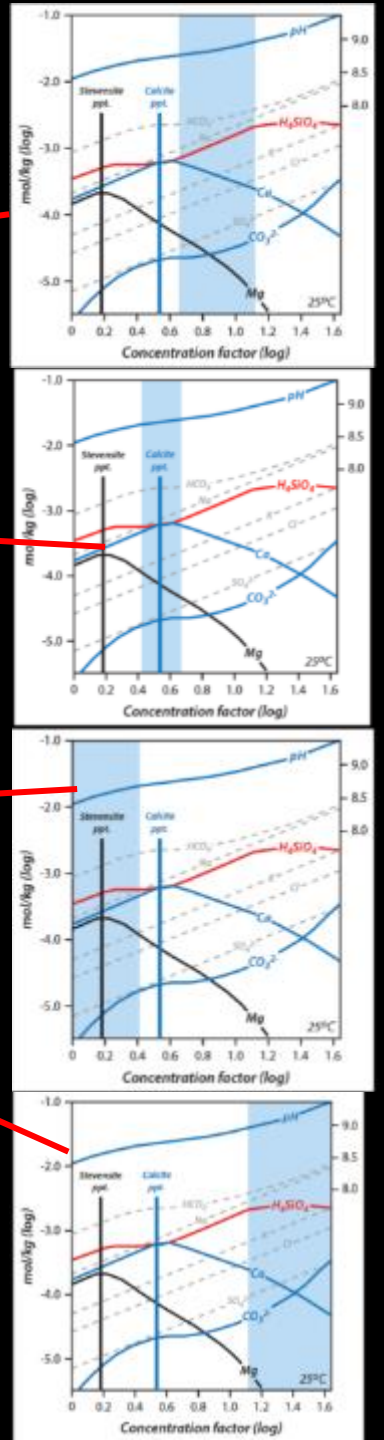
Flooding phase; reduced alkalinity-salinity allows influx of ostracodes and vertebrates; also triggers silica precipitation as pH drops

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.

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

Thermo-dynamic modelling supports the generation of the cycles from evaporation





Evaporation

Influx and freshening

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

Isotopes

Provisional isotopic data supports an evaporitic lake model with water bodies that had high area-depth ratios, that is, very shallow.

Based especially on studies by Talbot (1990) from E African lakes, Sabato Ceraldi & Green (2017) reasoned that a strong covariance is recorded in C & O stable isotope data from carbonates from Kwanza, and suggested that – while *“the correlation line …..which suggests a rather large area to depth ratio of the lake..”*

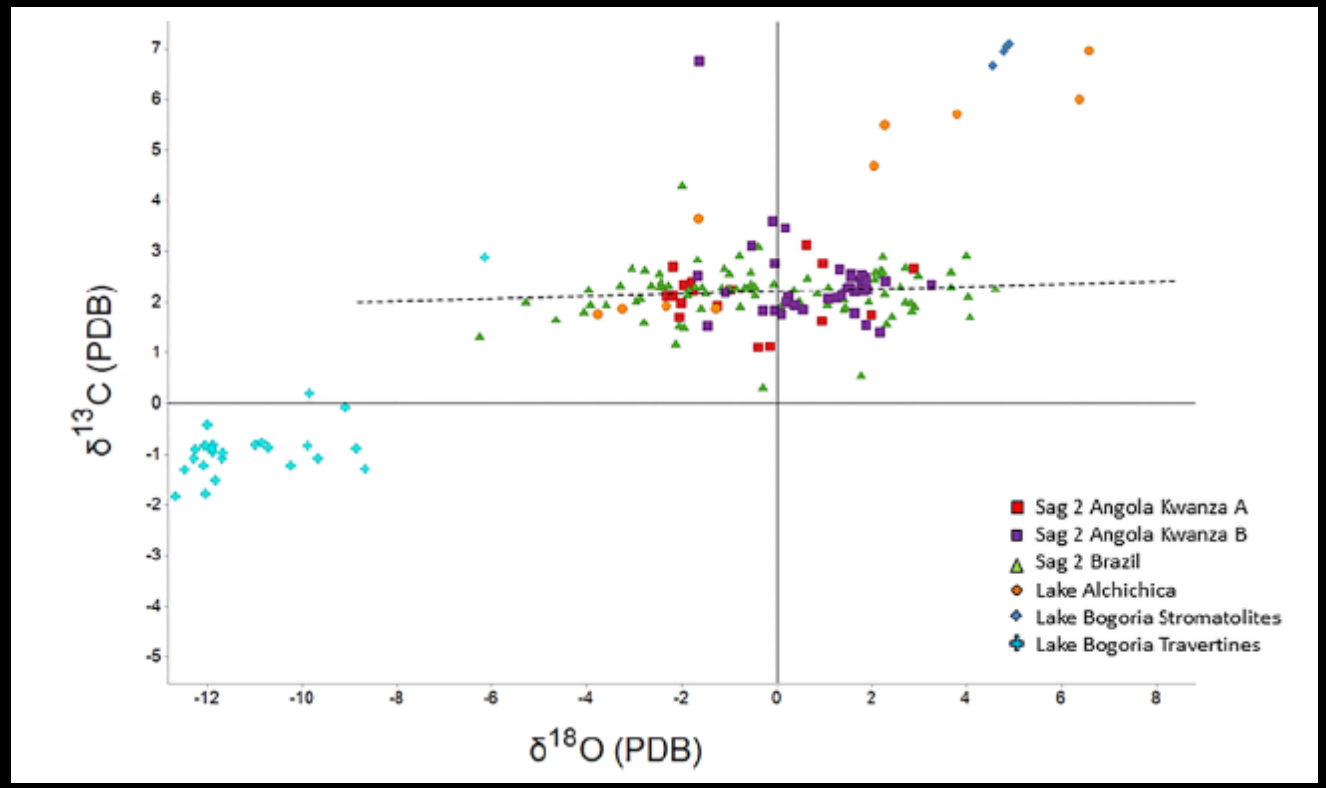
A small data set presented by by Hasiuk & Kaczmarek (2015) from the Barra Velha from Santos Basin also supports this interpretation

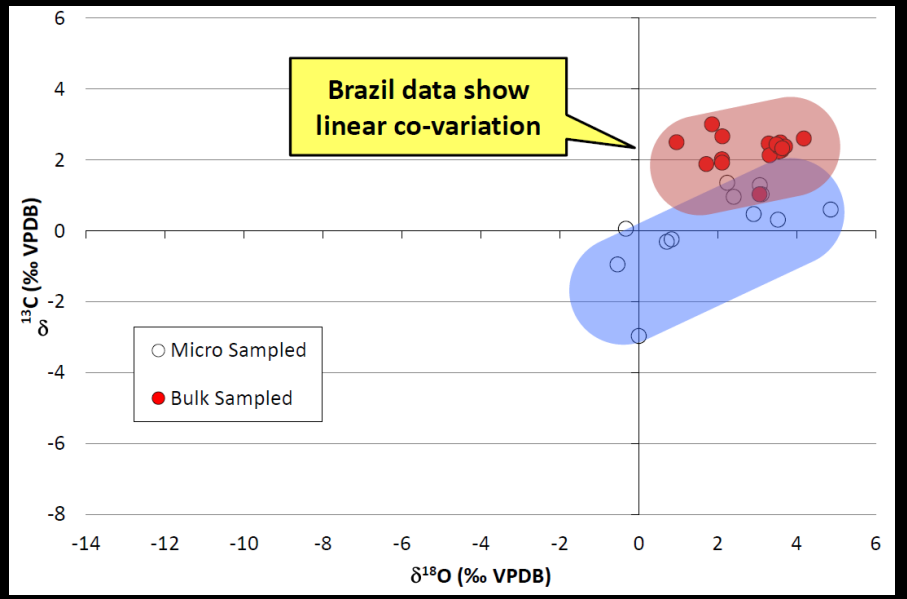
= closed and shallow lakes

Other unpublished data sets support these interpretations, and combined indicate that there was NO large, deep body of water nearby.

Stable Isotope data Kwanza and Santos

Similarities of Brazil data and Kwanza?

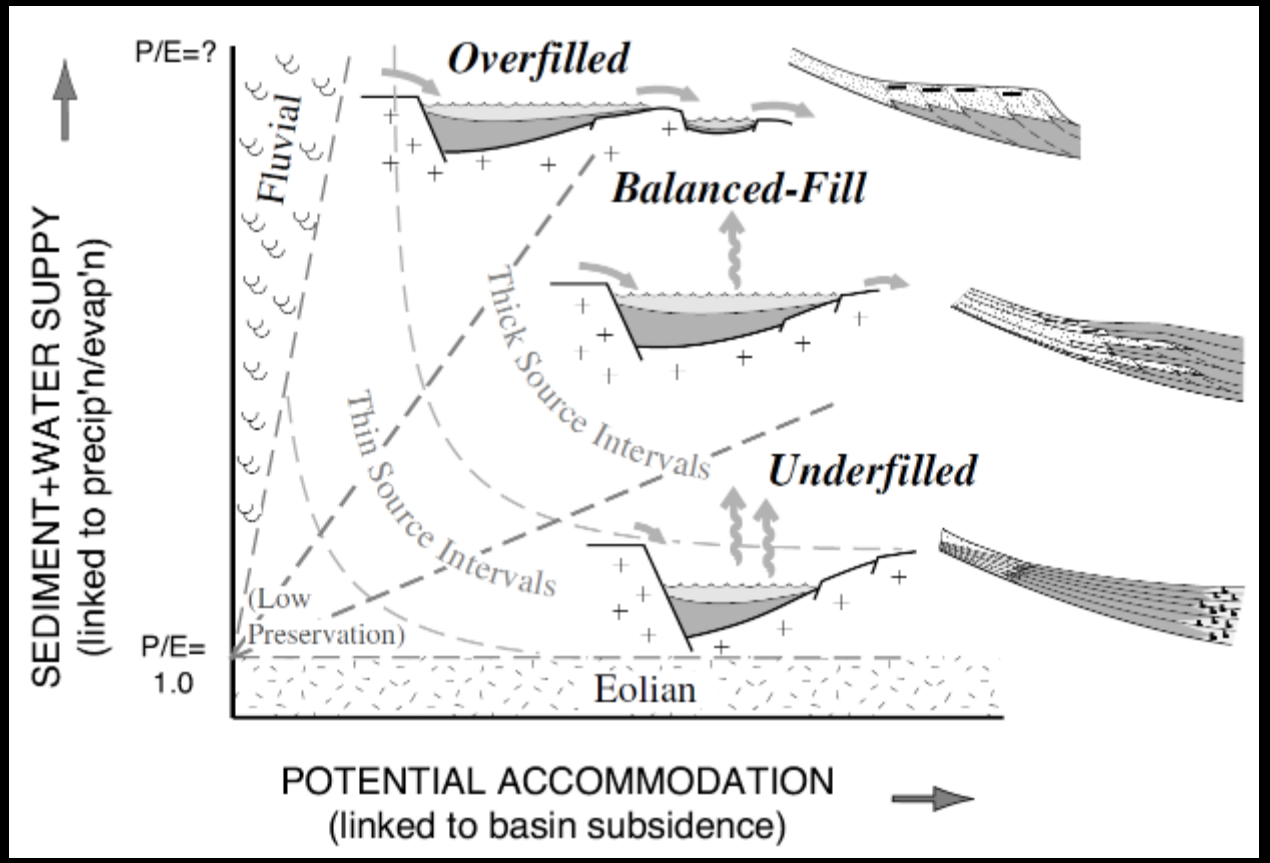




Santos basin Whole rock data from small data set presented by Hasiuk F J & Kaczmarek S E 2015 AAPG Search and Discovery Article #51190

Sabato Ceraldi & Green 2017. Geological Society, London, Special Publications, 438, 77–98. http://doi.org/10.1144/SP438.10

If the sedimentology and geochemistry indicate an evaporitic lake – the Barra Velha was deposited in an under-filled lake basin in the sense of Carroll & Bohacs 1999



Bohacs et al. 2000, AAPG Studies in Geology 46 – underfilled closed basin lakes, with significant chemical sedimentation, produce dominantly aggradational stratal architecture

So how can clinoforms be generated in an evaporitic, underfilled lake?

Alluvial fans-fan deltas are likely candidates. The thick carbonate grainstones and rudstones found locally in the Barra Velha could be shoreline deposits representing wave reworked sheet flood or terminal splay deposits.

In arid extensional basins colluvial-alluvial wedges are a basic component of the deposystem

Alluvial fans being reworked by fluctuating lake shoreline in the Great Salt Desert, Utah

Blair and Macpherson (1994) observed that alluvial fans have average slope values ranging from 1.5° to 25 °, with values of 2° to 12° most typical.

Conclusions

For Santos Basin the weight of evidence suggests the main reservoir interval, the Barra Velha Formation did not develop as high-relief carbonate platforms

Relief on the base salt was largely structural and post-Barra Velha in origin, not due to high-relief platforms and deep-lake basins during Barra Velha deposition

As regards the isolated ridge-like and conical mounds, the main origins of such topography in closed rift basins are likely to be spring mounds and volcanoes

Syn-and post-Barra Velha faulting, erosion and volcanism created features, including rotated onlap geometries, lava deltas and alluvial fans and fan deltas, mis-interpreted as related to high-relief buildups such as clinoforms,

The evidence comes from:

- *Re-evaluation of seismic data*
- *Long-range correlations supporting extensive post-Barra Velha structuration*
- *Facies interpretations based on process-based analysis not on assumptions regarding unsubstantiated microbialite models, the former supported by geochemical modelling*
- *Isotopic data precluding the presence of large water bodies during the deposition of the Barra Velha*