PS Diagenetic Model Related to Unconformity Surfaces and Application in the Exploration of Deep Reservoirs in Sergipe-Alagoas Basin, Brazil*

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Abstract

Sergipe-Alagoas Basin in northeastern Brazil is one of the oldest petroleum basins in operation in this country, with its first exploratory activities in the 1930s. The geological complexity of the basin is related to exploratory difficulties but also to a series of attractive possibilities. Studies were conducted to understand the geological context related to the presence of significant porosity values at great depths, such as 4200 m, where values of 20% of porosity were found in offshore shallow water. An important contribution for these studies was developed on the Serraria Formation reservoirs, resulting in predictive diagenetic models for hydrocarbon exploration. These studies integrated lithofaciologics analysis, depositional conditions, paleogeographic and paleoclimatic reconstructions and the burial history control on the diagenetic evolution and porosity distribution. This permitted recognition of important factors responsible for the best porosities in Serraria reservoirs in some oil fields.

Two deep reservoir models of increment and/or preservation of porosity in deep reservoir conditions can be recognized. The conditions of each model can occur combined with consequent improvement of its efficiency. The Caioba Model is directly related to direct meteoric fluids infiltration in sandstone reservoirs during an exposition time related to an uplift phase in part of the basin. The solvent action of the meteoric water infiltrated from areas of unconformity surfaces and/or along fault zones and provided a considerable increase of porosity by dissolution of feldspar grains and carbonate cements. The Furado Model is related to the early occupation of oil in the reservoir. The process of preservation of porosity by early occupation by oil can be extremely efficient, since the closing of the structure persists throughout later burial history. In terms of Petroleum System Analysis, two sets of reservoirs are

considered: 1) Pre-salt reservoirs, and 2) Post-salt reservoirs. Two Pre-salt reservoir oils from continental and marine source rocks are present in different sectors of the basin under different burial history controls. Significant oil accumulations could be preserved in basin sectors where the seals superimposed (salt, for example) were preserved. The Post-salt reservoirs are positioned relatively distant from the main source rock intervals, situated below the salt, only accessible by migration routes associated with the faulted and basculated blocks.

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Introduction

Sergipe-Alagoas basin, in northeastern region of Brazil (Fig. 1), is one of the oldest petroleum basin in operation in this country, with its first exploratory activities in the 30. The geological complexity of the basin is related to exploratory difficulties but also a series of attractive possibilities. Deep prospects in some structural low sectors and in the deep waters situations still awaiting a exploratory decision to be developed.

Since the launch of oil exploration in the Sergipe-Alagoas Basin the fluvial sandstone of the Serraria Formation (Lower Cretaceous) has been regarded as a hydrocarbon reservoir. Despite the abrupt porosity reduction with depth of the onshore portion of the basin, the Serraria Formation sandstones show a much better porosity offshore in deeper levels (Garcia, 1992).

The main diagenetic processes, controlled by paleogeography, paleoclimate and burial history of the Serraria Formation, include (1) an eodiagenetic carbonate cementation of continental sandstone, important for preservation during later burial history of the initial loose packing of the deposits, and (2) the association of this eodiagenetic cementation with secondary porosity formation, the latter mostly due to telodiagenetic processes ascribed to surface exposure after uplifting during the syn-rift phase (~114-74 Ma) of the basin.

The exploratory potential of the Serraria Formation reservoirs is also constrained by tectonics and distance from hydrocarbon source rocks within different sectors of the basin. Based on these aspects, two groups of sandstone reservoirs can be distinguished in the Serraria Formation: (1) deep reservoirs (deeper than 2500-3000 m) and (2) non-deep reservoirs (shallower than 2500 m) (Garcia et al., 1990).

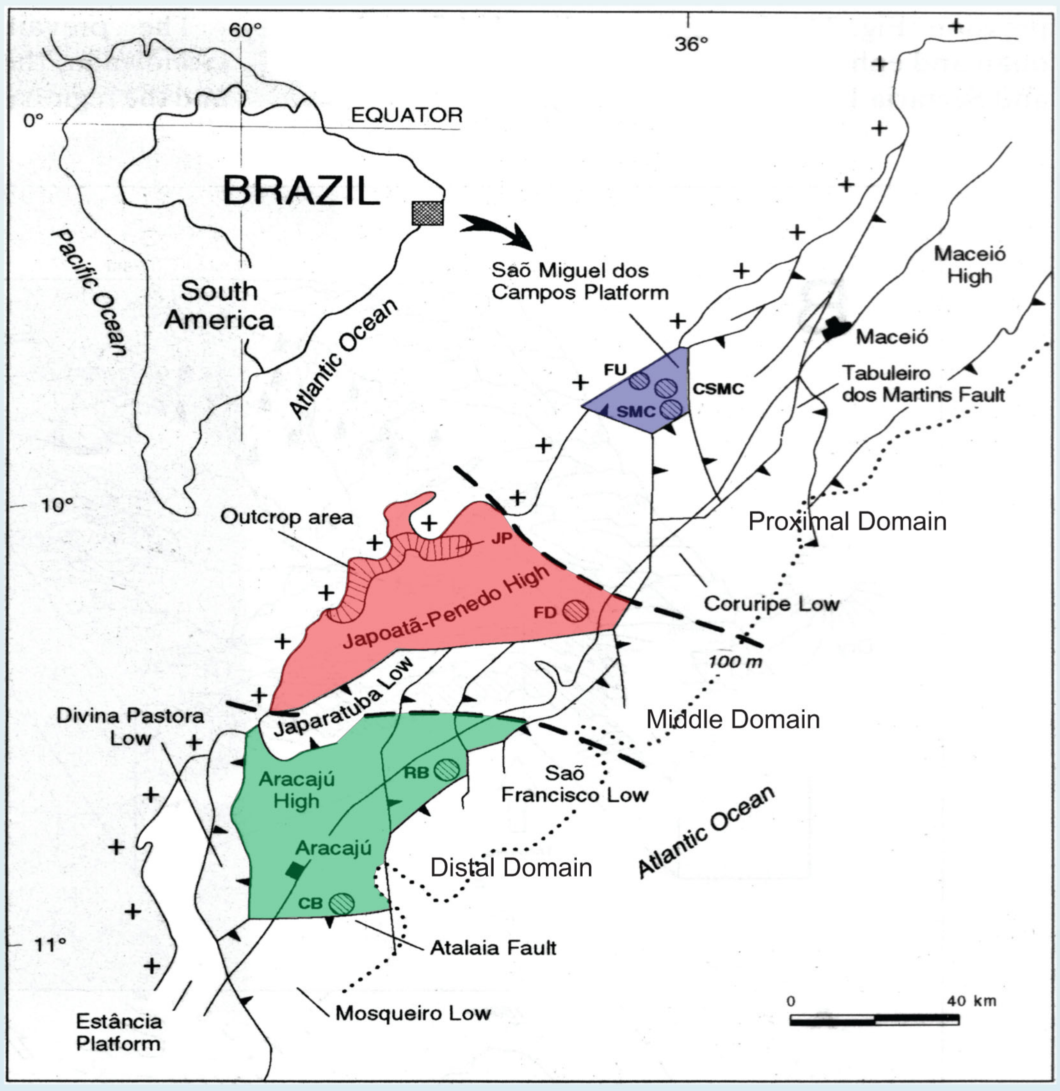

Figure 1. Structural compartments of the Sergipe-Alagoas Basin and studied areas. Distal Domain: CB: Caioba area; Aracajú High and RB- Robalo area; Middle Domain: JP- Japoatã-Penedo area (including outcrops); Proximal Domain: FU- Furado, SMC: São Miguel dos Campos and CSMC- Cidade de São Miguel dos Campos areas.

Geological Setting

Deposited under a dry climate, the Serraria Formation includes a lower and an upper one finer-grained interval, both ascribed to shallow lacustrine systems, and a coarser-grained, middle interval deposited by high energy fluvial systems associate with eolian reworking. Provenance analysis has revealed a mature quartz-feldspathic (Fig. 2) detrital composition credited to steady weathering and long-distance transport from a basically plutonic source-area. As a result of diagenetic dissolution, secondary quartz-arenite was produced in some basin sectors (Fig.2).

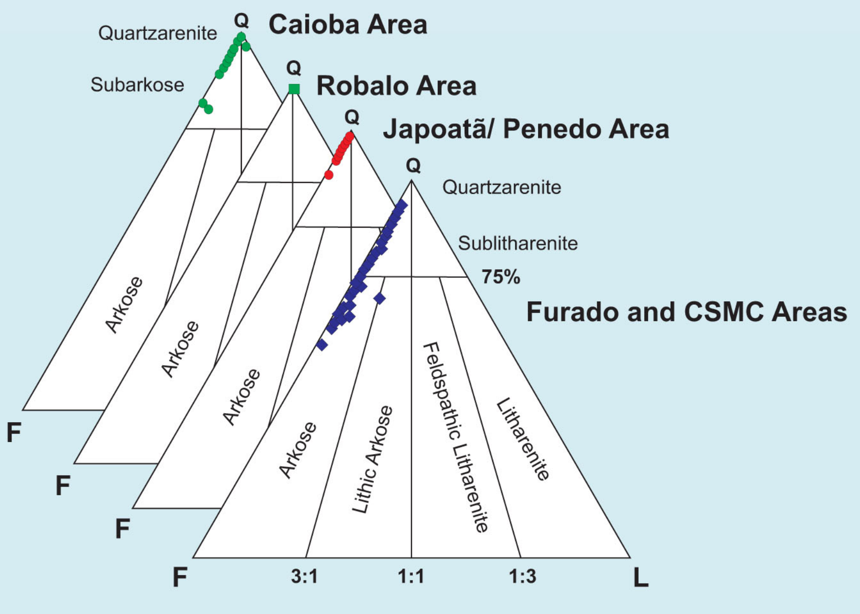

Figure 2. QFL detrital composition of the sandstones of the diagenetic domains of Serraria formation plotted on Folk (1968) classification diagram. Proximal Domain is closer to the original detrital composition.

The burial history of different structural blocks in the basin (Fig. 3A, 3B and 3C) controlled the paragenetic sequence and porosity / permeability evolution in the Serraria Formation.

Thin sections of core and fresh outcrop samples from different structural sector were examined under a standard petrographic microscope. Burial history was used to understand diagenetic processes within different diagenetic domains.

Deposition of the Serraria Formation started ~144 My and lasted for ~ 10 My whereas the syn-rift subsidence phase started ~140-135 My. During this burial phase the maximum depth attained in the Distal Domain ranges from 750 to 1500 m, with a residence time of around 13 My. In the Caioba and Robalo areas, subsidence was fast during this phase. The maximum depth attained in the Robalo area was of 2500 m with a residence interval of 60 My. After the syn-rift subsidence phase (~118 My) the Caioba area was uplifted and exposed to subaerial conditions during 10 My (and up to 40 My with the more strongly affected blocks). The erosional surface that developed during this subaerial exposure was named Pre-Muribeca (Neo-Alagoas) Unconformity (Fugita, 1974 – Fig. 4). The distribution of the outcropping areas played an important part relative to meteoric-water infiltration and sandstone porosity enhancement. During this exposure, Serraria Formation sandstone in most of the Caioba area was located between the surface and 500 m of depth (Fig 4). A post-rift subsidence bringing the Serraria Formation in the Caioba area to the present-day maximum depths of ~2500m. In the Robalo area during this time interval, the Serraria Formation sandstone was buried down to ~4200 m. In the proximal Furado area, subsidence was fast and continuous from the beginning of the syn-rift burial phase (i.e. 140-135 Ma) to about 125 My, bringing the Serraria Formation close to its present maximum depth of ~2500 to 3000m in the deepest faulted blocks.

Currently the Serraria Formation is exposed in some portions of the Middle Domain. From outcropping to shallow buried sectors (Japoatã-Penedo Area) of this domain, the present-day burial depth ranges from 50 to 900m. Depths down to ~2000m in this domain are estimated for the syn-rift subsidence phase. After the Lower Cretaceous uplift, depths of about 3500m were attained in the deepest blocks.

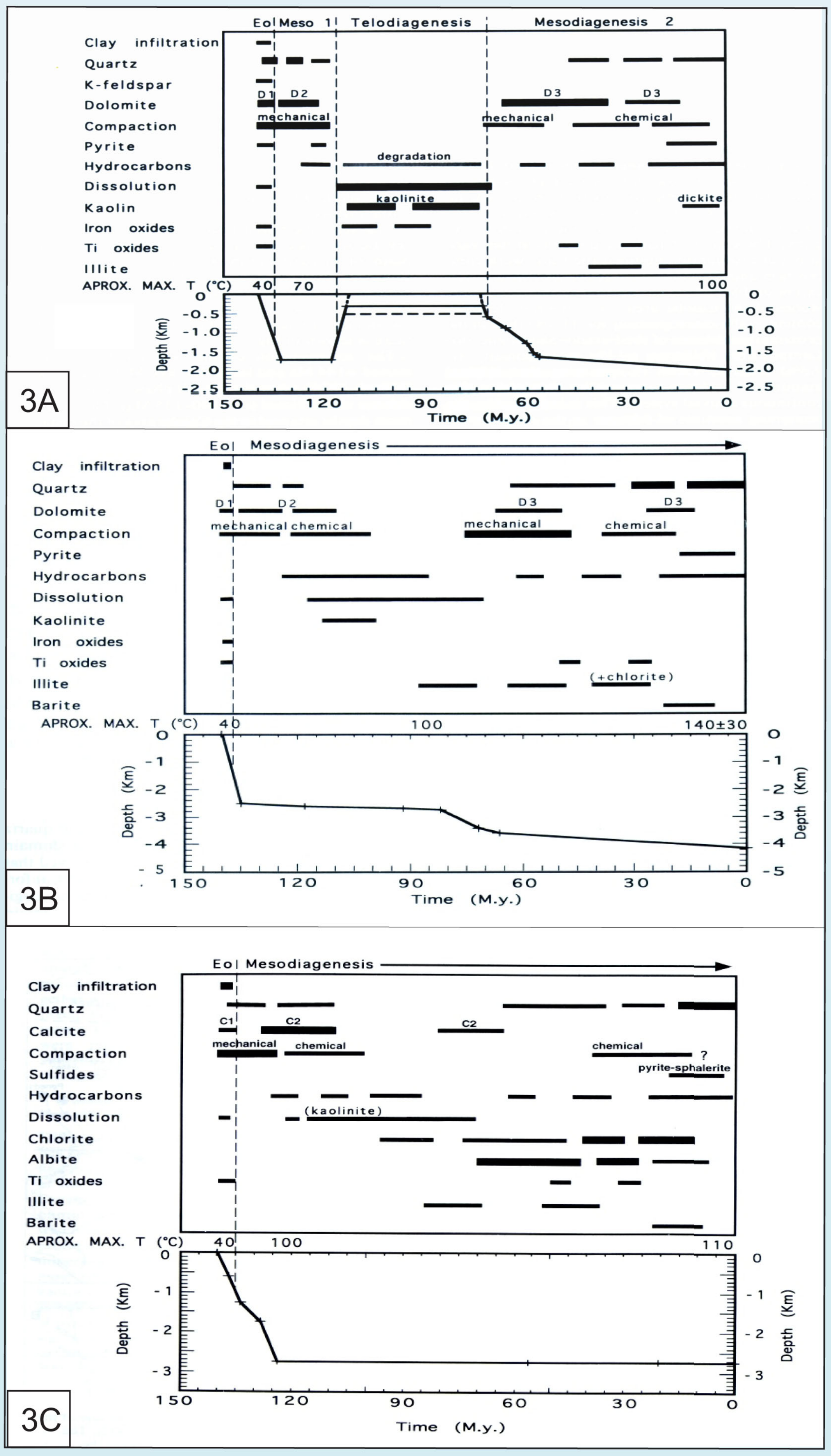

Figure 3. Paragenetic sequence and burial history in the: 3A) Caioba Area; 3B) Robalo Area; 3C) Furado Area.

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Diagenetic Features

The paragenetic sequence and porosity / permeability evolution of the Serraria Formation sandstone were controlled by several chief factors that include facies, climate and burial history differences. The diagenetic domains were discriminated from petrologic features that reflect these main controls.

Paragenetic sequence attributes were correlated to burial history diagrams of the Caioba, Robalo, Japoatan-Penedo and Furado-Sao Miguel dos Campos areas. Precipitation of eodiagenetic cements (dolomite **A** and quartz) was more extensive in the Caioba area. Conversely, eodiagenetic clay infiltration, associated with smaller amounts of carbonate precipitation (calcite), was more profuse in the Furado-Sao Miguel dos Campos Area. Dissolution / kaolinization of detrital feldspars and micas **B** occurred mainly in the Caioba and Japoatan-Penedo areas due to meteoric infiltration in these regions. In the Furado-Sao Miguel dos Campos area detrital feldspars were partially to entirely albitized. Late illitization of detrital or authigenic (kaolinite) clay minerals occurs in the Caioba Area, while smectite chloritization is observed in the Furado-Sao Miguel dos Campos area. Dickitization is observed in Robalo area.

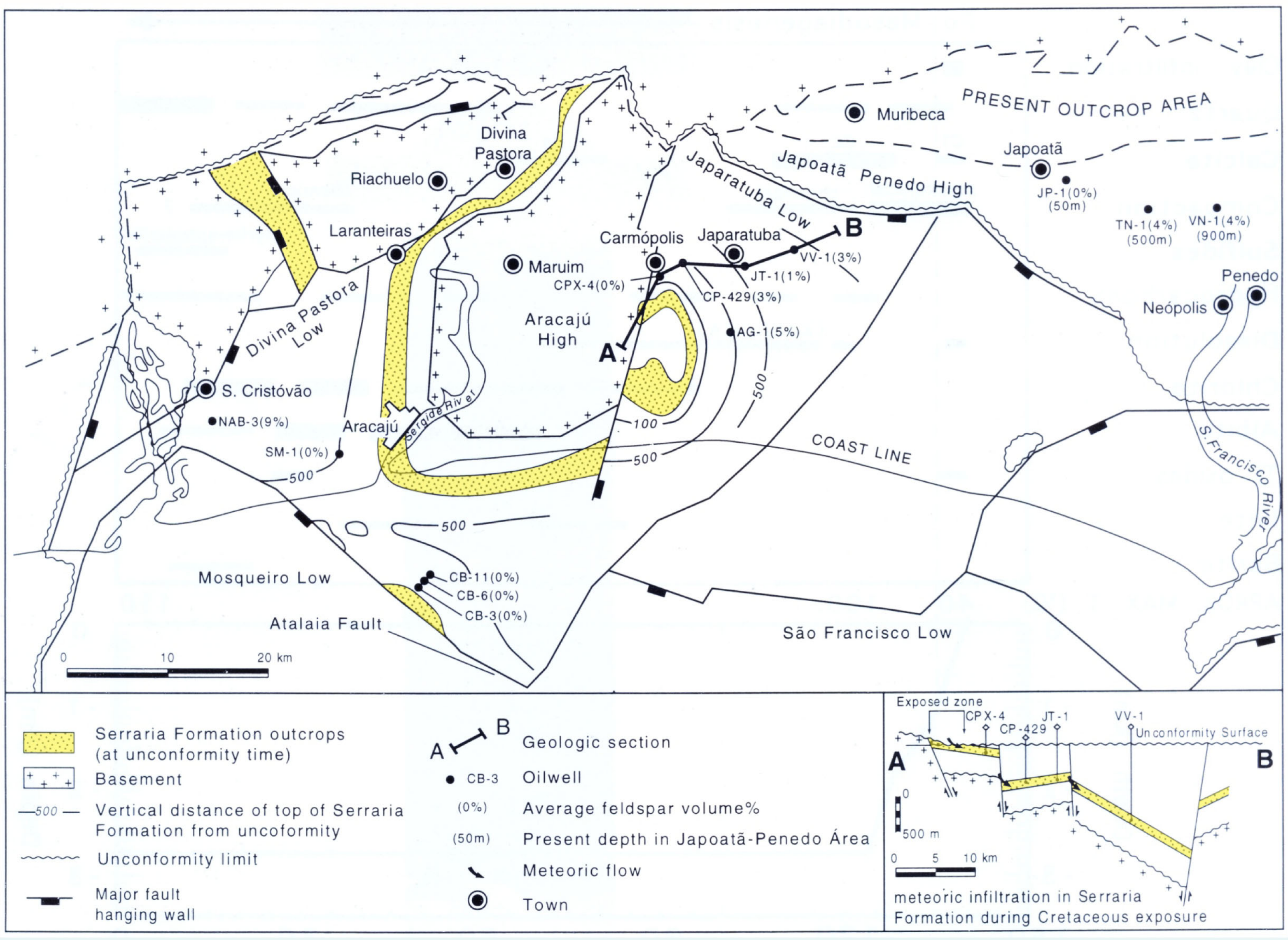


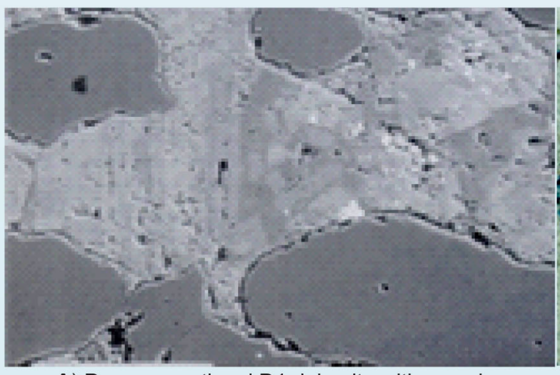
Figure 4. Paleogeologic map of the southern Sergipe-Alagoas Basin at _ 74 Ma showing the areas of exposure of the Serraria Formation at the maximum development of the post-rift, Pre-Muribeca (Neo- Alagoas) unconformity (Ojeda, 1982). The average remaining feldspar content after meteoric flushing in the studied wells increases with distance to the unconformity, as illustrated by the section A-B.

Authigenic kaolinite occurs as booklet and vermicular aggregates **C** of thin, stacked lamellar crystals, a morphology typical of meteoric origin (Osborne, et al., 1994). Kaolinite fills intergranular and secondary pores after dissolved carbonate cements **D** and feldspar grains **E**, and replaces detrital clays and micas **F**. Kaolinite lamellae with replace infiltrated clays and pseudomatrix are commonly irregular. Kaolinite is more common in fluvial sandstone of the Caioba area (avg. 6.0%). It occurs in smaller amounts in sandstone of the Japoatã-Penedo area(_avg. 2.4%).

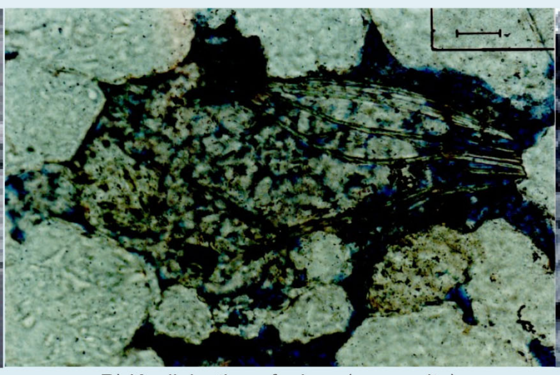
The relationship between meteoric dissolution processes and ferroan dolomite and pyrite oxidations is observed **G**, associated with partial dissolution of dolomite on ferroan zones **H**.

Is observed partial dissolution of the first dolomite phase associated with kaolinite filling the secondary porosity **I**. Detail of the relation between partial dissolved dolomite and kaolinite **J** with kaolinite filling partially secondary porosity **K**. Late dolomite filling secondary pores before filled by kaolinite **L**.

The average overall intergranular porosity ranges from 14.7 to 4.9%. Intragranular, moldic and oversized pores derived from partial to complete dissolution of detrital feldspar are common. The extent of feldspar dissolution has variably but profoundly modified the framework composition and macroporosity of the sandstones. The extent of dissolution was larger in sandstones of the Caioba area (avg. remaining feldspar content < 1%; macroporosity avg. 11.7%) than in proximal sandstones of the Furado-São Miguel do Campos area (feldspars _ 13%; macroporosity avg. 7.3%). In addition to framework grain dissolution, intergranular secondary pores have also resulted from the partial to pervasive dissolution of carbonate cements. Partially-dissolved dolomite cements in the distal sandstones display intracrystalline pores. According to the paragenetic relationships between carbonate and other cements in secondary pores, some samples show evidence of more than one dissolution phase (Garcia *et al.* 1998) .

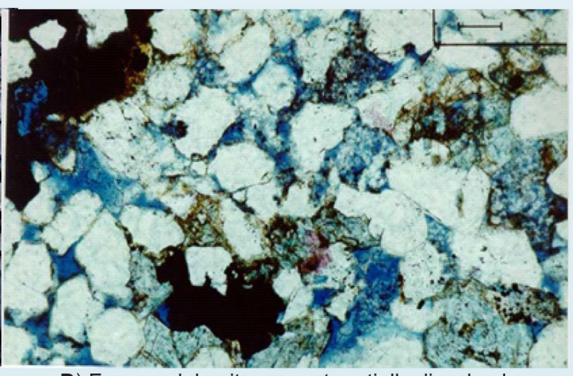


A) Pre-compactional D1 dolomite with complex zonation and displacive texture in relation to the grains.

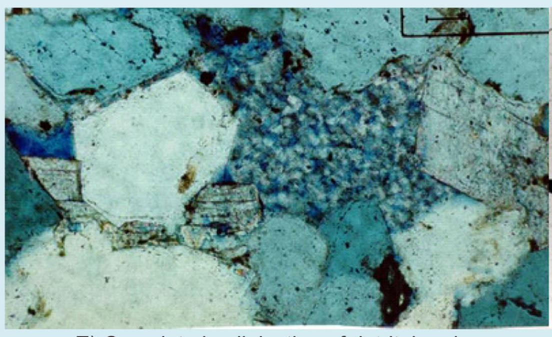


B) Kaolinization of micas (muscovite).

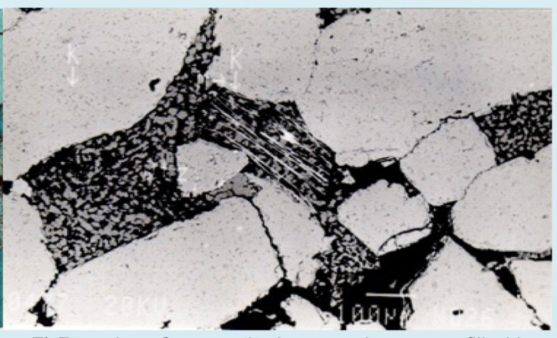
C) SEM photo of vermicular kaolinite replaced by euhedral dickite; thin remnants of kaolinite.



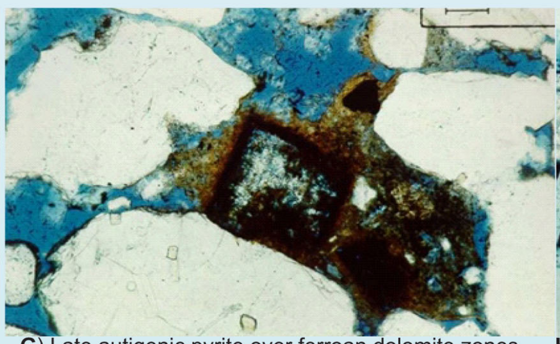
D) Ferroan dolomite cement partially dissolved resulting in secondary porosity filled by kaolinite. Pyrite cement is partially oxidized.



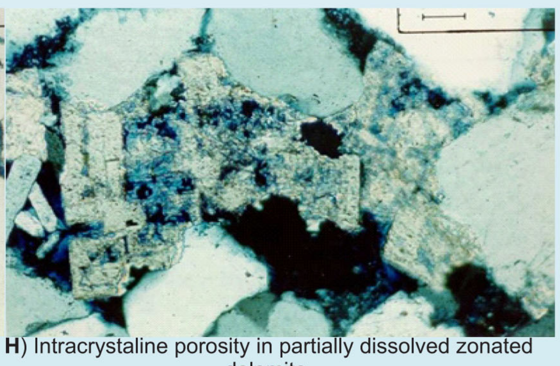
E) Complete kaolinization of detrital grains (feldspars, micas and lithic fragments). Kaolinite filled secondary porosity after carbonate dissolution.



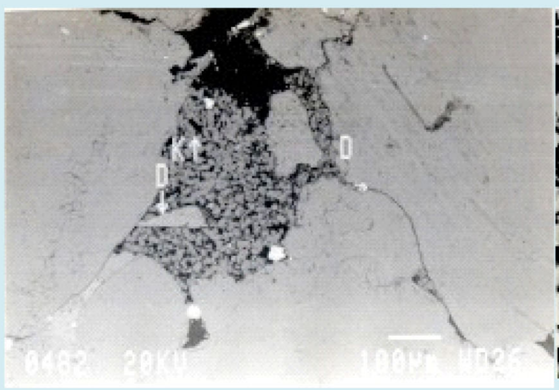
F) Remains of muscovite in secondary pores filled by kaolinite.



G) Late autigenic pyrite over ferroan dolomite zones partially oxidized. Secondary pores partially filled by kaolinite.

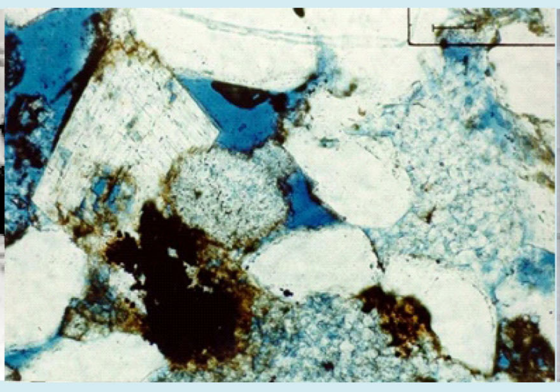


H) Intracrystaline porosity in partially dissolved zonated dolomite.

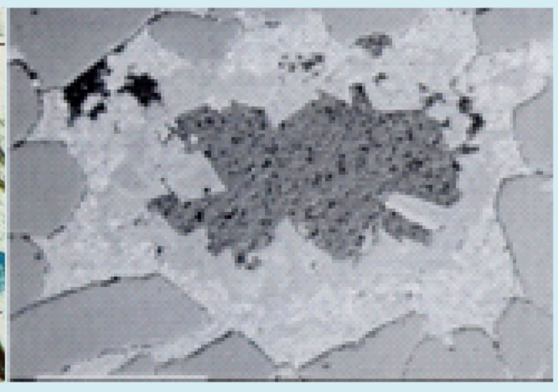


I) Thinly-zoned dolomite D1 with dissolution pores partially filled by vermicular kaolinite.

J) Details of the relationship between kaolinite pore filling and partially dissolved dolomite D1.



K) General relationship between partially dissolved dolomite, intergranular secondary porosity and pore filling kaolinite.



L) Oversized pore rimmed by finely- zoned-crystalline dolomite D1, followed by coarse blocky dolomite D3. Vermicular kaolinite filled the secondary pore before the late dolomite precipitation.

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Reservoir Potential

According to this case study, two deep reservoir models of increment and/or preservation of porosity in deep reservoirs conditions can be recognized. The conditions of each model can occur combined with consequent improvement of its efficiency: The Caioba Model was directly related to meteoric fluids infiltration in sandstone reservoirs during a exposition time related to uplift phase in part of the basin. The solvent action of the meteoric water infiltrated from areas of unconformities surface and/or along fault zones, provided considerable increase of porosity by dissolution of feldspar grains and carbonatic cements. The Furado Model, not discuted in this paper, was related to the early occupation of reservoir by oil. The process of preservation of porosity by early occupation by oil can be extremely efficient, since the closing of the structure, persist throughout later burial history.

The best reservoirs of the Serraria Formation comprise distal sandstones, early cemented by poikilotopic carbonate and later affected by widespread telodiagenetic dissolution. Dissolution took place in the beginning of the post-rift uplift under a warm and humid climate.

Sandstone petrology allowed for the definition of three main diagenetic domains, one of them showing potential for deep sea reservoirs. The most porous domain, including the offshore Caioba oilfield and adjacent onshore fields, experienced an impressive porosity enhancement due to telodiagenetic meteoric water infiltration. This telodiagenetic event occurred after rift subsidence was interrupted due to general faulting, tilting and uplifting of blocks in the Aptian. Nearby in the pre-Muribeca (Neo-Alagoas) unconformity and major faults (Fig. 5), meteoric flushing dissolved most of the dolomitic cement and feldspar grains, precipitated abundant authigenic kaolinite, oxidized pyrite and ferroan carbonates, and degraded part of the oil generated in the Neocomian shales. From the Late Cretaceous, the Serraria Formation was again buried to shallow depths (~1000 to ~1500m), reaching about 2500m in the Caioba field only in the Tertiary. During this new burial episode, part of the abundant secondary porosity was reduced, by late ferroan dolomite and quartz cementation, and the oil generated in transitional Aptian shales migrated into the reservoirs.

In the Robalo area, the Serraria Formation reservoirs reach up to 18 % of porosity at depths larger than ~4200m. Their diagenetic evolution shows that the very rapid subsidence during the rift stage allowed for the generation and migration of the Neocomian oil into the reservoirs before any severe reduction of porosity could take place. Whereas porosity in the oil-saturated zone was preserved, a massive quartz cementation occluded nearly all the pores under the oil-water contact.

Prediction capacity of this kind of porosity firstly relies on the identification of unconformity surfaces cutting potential reservoir units of the basin. The mapping of these surfaces added by detailed petrologic studies of core samples will confirm or not the validity of this porosity model to others reservoir units.

The exploratory potential of the Serraria Formation reservoirs in the Sergipe-Alagoas Basin is also controlled by structural features and distance from hydrocarbon source rocks in the basin.

In terms of Petroleum System Analysis two sets of reservoirs are considered: 1. Pre-salt Reservoirs and 2. Post-salt Reservoirs (Fig. 6).

Tthe Pre-salt Reservoirs with oils from continental and marine source rocks are presents in different sectors of the basin under different burial history controls. Significant oil accumulations could be preserved in basin sectors where the seals superimposed (salt, for example) were preserved.

The Post-salt Reservoirs, are positioned relatively distant from the main source rocks intervals, situated below the salt. Only accessible by migration routes associated with the faulted and basculated blocks.

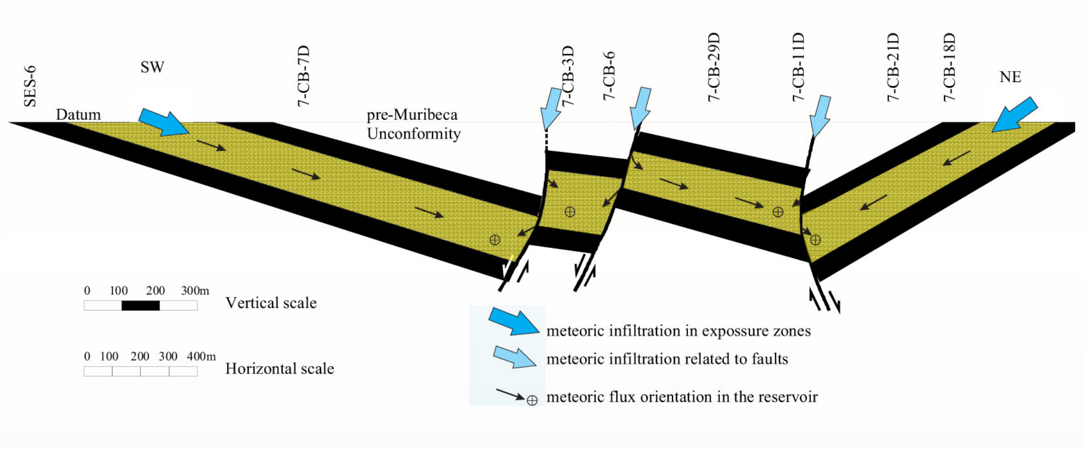

Figure 5. Structural section on Caioba Area , illustrating the meteoric influence in the Serraria reservoir.

Conclusions

The diagenetic evolution trends herein presented allow further discussion on the conditions for optimum porosity preservation and/or enhancement in the Serraria Formation reservoirs. The best reservoirs are in the Distal Domain, which was affected by porosity enhancement due to an extensive detrital feldspar and dolomite cement dissolution related to telogenetic influx of meteoric waters. Similar conditions are also expected, either within other structural blocks also affected by post-rift uplift and erosion or blocks bounded by major fault systems in which the Serraria Formation was at a relatively small distance from the exposure surface. A similar setting is seen in several blocks of the Japoatan-Penedo area as well as along portions of the rift basin margins.

The more intense eogenetic carbonate cementation in the Distal Domain related to the Proximal Domain is likely to have also played an important role on the preservation of larger porosity and intergranular volumes in the former domain. Porosity enhancement through carbonate cement dissolution due to telogenetic meteoric influx into Distal Domain reservoirs is significant if compared to feldspar dissolution.

It is hereby demonstrated that a proper understanding of the diagenetic and porosity evolution of sandstone reservoirs can only be achieved by constraining the combined effects of paleogeography, paleoclimate, facies and burial history.

Both subaerial exposure and a more humid climate in the beginning of post-rift uplift in part of the Distal Domain (Caioba area) resulted in extensive feldspar and carbonate dissolution, kaolinite precipitation and porosity enhancement. Meteoric water infiltration in this area promoted a strong modification of the sandstone framework composition, hence producing diagenetic quartz-arenite from original arkose and subarkose.

The best expected reservoirs in the Serraria Formation are within structural blocks of the Caioba (Fig. 5) and Aracaju High (Fig. 6) areas affected by porosity enhancement via extensive feldspar and carbonate cement dissolution in connection to a post-rift exposure and associated telogenetic influx of meteoric water.

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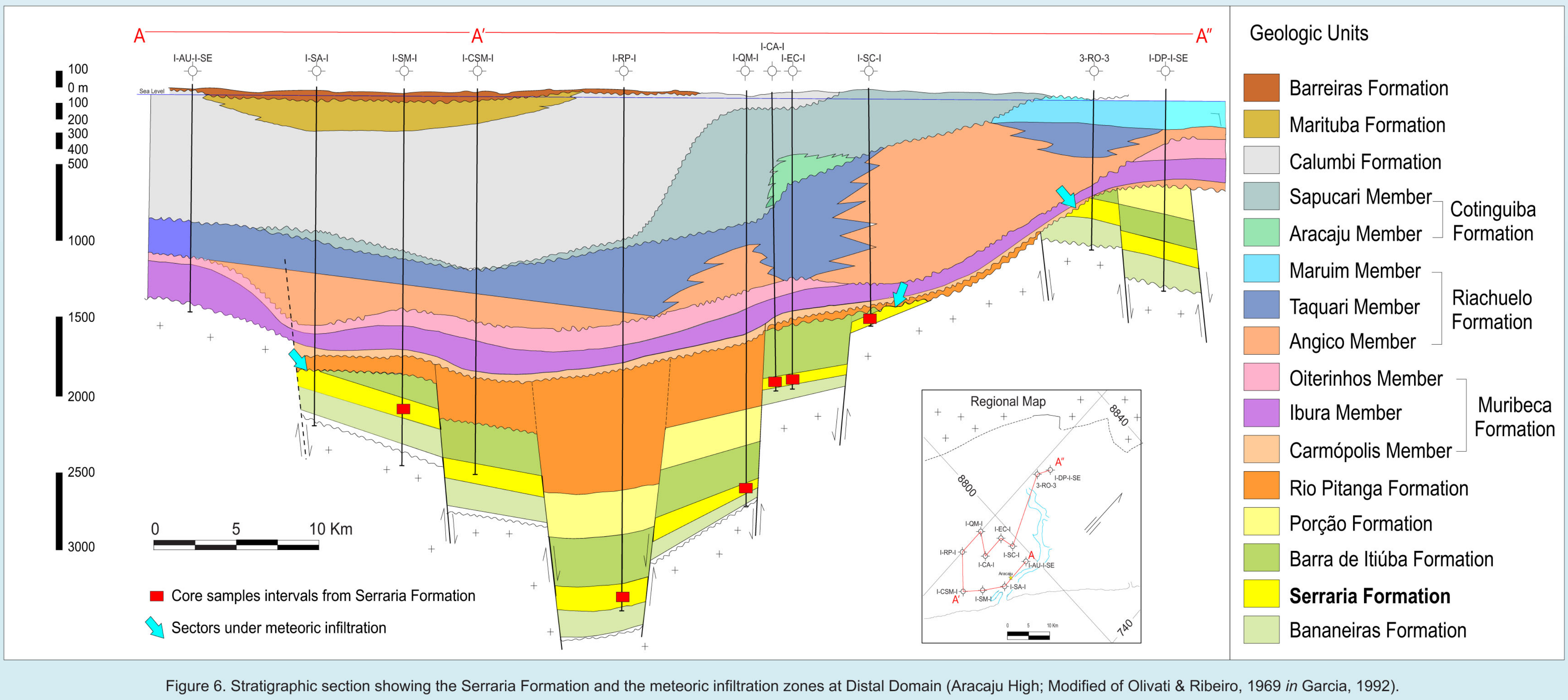

Figure 6. Stratigraphic section showing the Serraria Formation and the meteoric infiltration zones at Distal Domain (Aracaju High; Modified of Olivati & Ribeiro, 1969 *in* Garcia, 1992).