PSDiagenetic Processes in Clastic Pre-salt Reservoirs, Onshore Espírito Santo Basin, Eastern Brazil*

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Abstract

Fluvial and estuarine sandstones of the AptianMucuri Formation are major reservoirs in the onshore Espírito Santo Basin, eastern Brazil. They are temporally equivalent to the huge offshore pre-salt reservoirs under exploration. The quality of the Mucuri reservoirs is strongly impacted by intense diagenetic processes. The sandstones are dominantly medium to coarse-grained, and very rich in detrital feldspars, biotite, garnets and other heavy minerals. The main diagenetic process involved the authigenesis of rims, coatings and microcrystalline aggregates of smectitic clays, as intergranular cement and replacing grains of feldspars, biotite and unstable heavy minerals, in places also dissolved and replaced by kaolinite. Cementation by coarse calcite was very heterogeneous, and concentrated in the sandstones with less smectite. Coarse pyrite replaced biotite, mud intraclasts, and previous diagenetic constituents. Minor diagenetic constituents include dolomite, K-feldspar overgrowths and Ti minerals. Porosity is mostly primary, dominantly reduced by cementation, although secondary intragranular and moldic pores from grain dissolution are locally significant. Diagenesis promoted the development of very heterogeneous, complex and irregularly-connected pore systems, which strongly impacts oil recovery from the reservoirs. The intense and complex diagenetic processes are interpreted as product of the interaction between the unstable primary composition and reactive pore fluids. Meteoric fluids related to the alluvial setting promoted grain dissolution and kaolinite authigenesis. The voluminous authigenesis of smectite and calcite was caused by reactions between the feldspars, heavy minerals and micas, and brines derived from the adjacent saline environments and from overlying Aptian evaporites. The precipitation of replacement pyrite was related to fluids charged in H_2S derived from thermal sulfate reduction. The characterization of the types, amounts, and time and space distribution of the major diagenetic processes responsible for porosity modification in the Mucuri sandstones is of paramount importance for increasing oil recovery from producing reservoirs, as well as for the reduction of exploration risks through the development of quality-predictive models. Furthermore, the understanding of eodiagenetic conditions taking place in pre-salt marginal settings should shed light on the origin and evolution of the voluminous offshore reservoirs.

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Geological Setting

Aptian sandstones are major reservoirs in the onshore platform areas of the Espírito Santo Basin, eastern Brazil (Fig. 1).

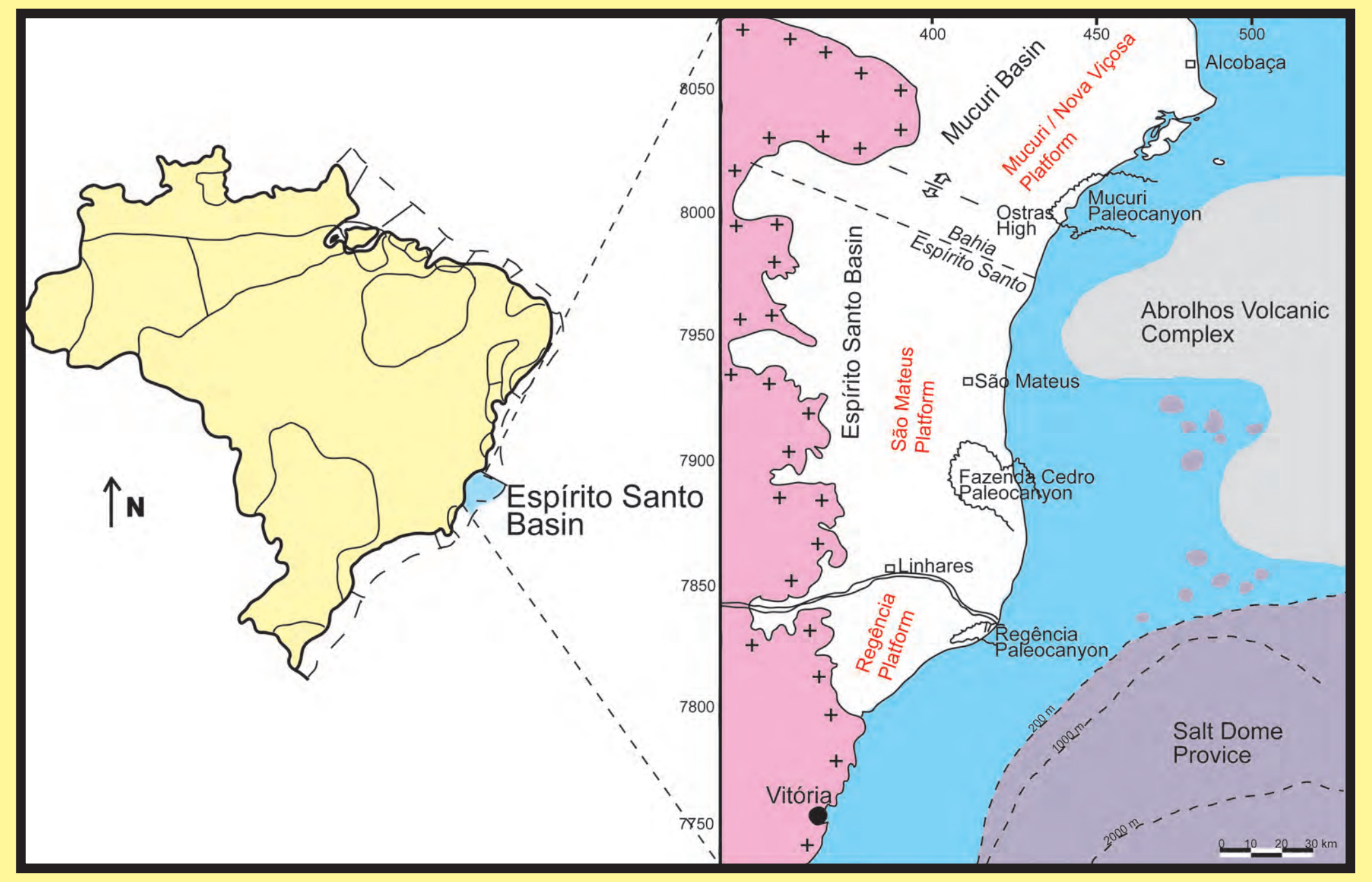

Figure 1 – Map of the Espírito Santo and Mucuri basins, where the Mucuri sandstones constitute the major reservoirs in the onshore platform areas (modified from Carvalho et al., 1989).

The Mucuri Member of the Mariricu Formation is constituted by sandstones, conglomerates and shales, deposited during the Aptian by fluvial and estuarine systems, together with minor limestones and anhydrites, representing short transgressive periods (Fig. 2). The sandstones are covered by the evaporites of the Itaúnas Member, precipitated at the end of the Aptian in a large restricted sea under arid climatic conditions. They are temporally equivalent to the huge offshore pre-salt reservoirs under exploration (Fig. 2).

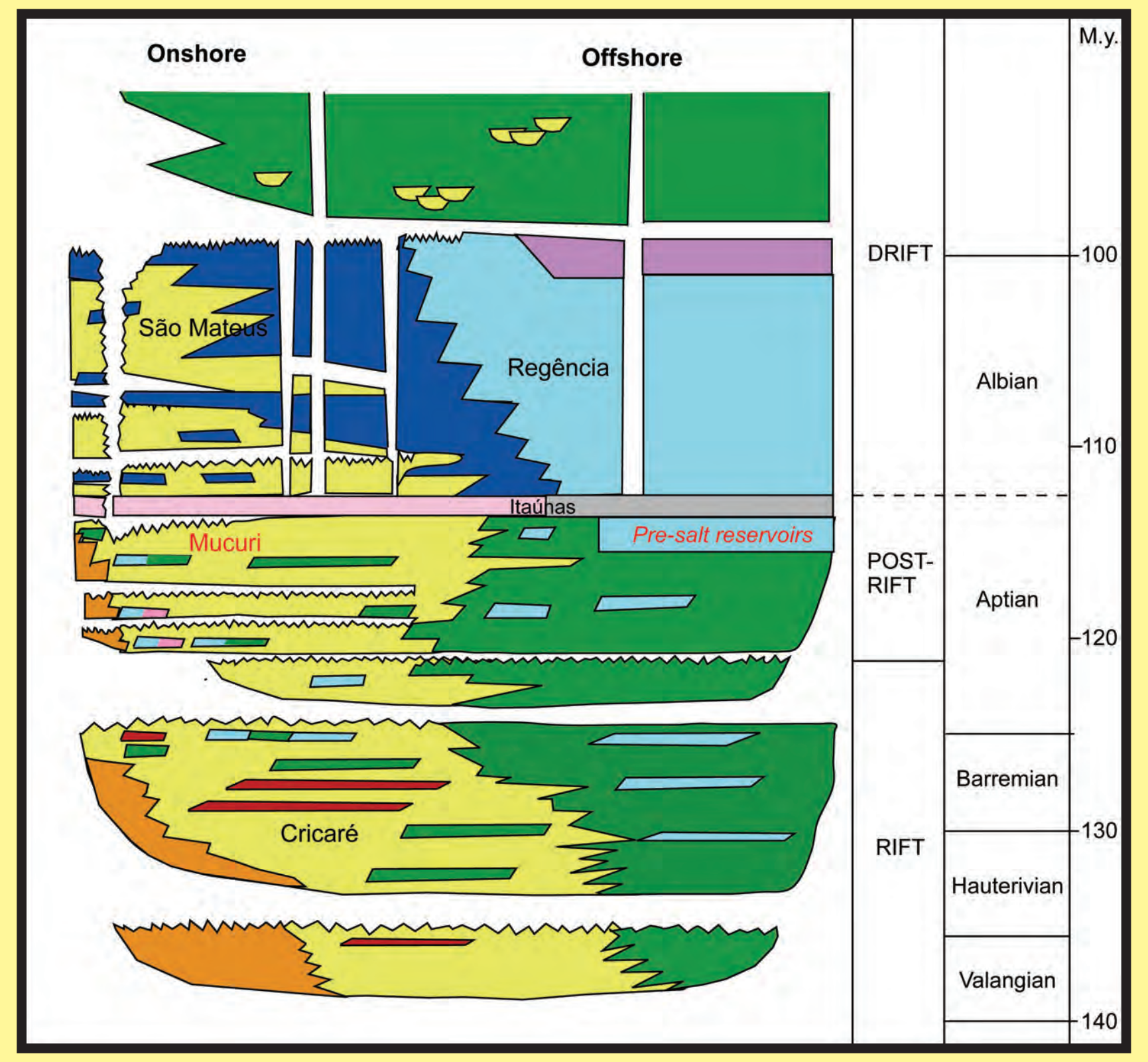

Figure 2 - Stratigraphic column of the Espírito Santo Basin, showing the equivalence between the Mucuri sandstones and the offshore pre-salt reservoirs.

Primary Texture and Composition

The sandstones are dominantly medium to coarse-grained, often conglomeratic arkoses (Fig. 3), and very rich in detrital feldspars, biotite (Fig. 4), garnets and other heavy minerals. Finer-grained sandstones are always very micaceous (Fig. 5), frequently bimodal with coarser fraction corresponding to the micas, and laminations defined by concentrations of biotite and/or heavy minerals.

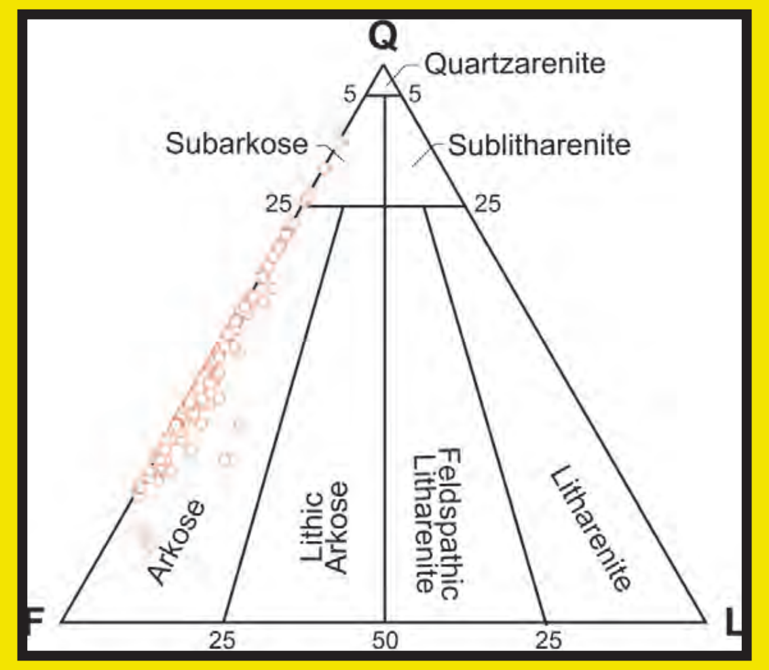

Figure 3 - Major composition of 453 Mucuri sandstones plotted on Folk (1968) diagram.

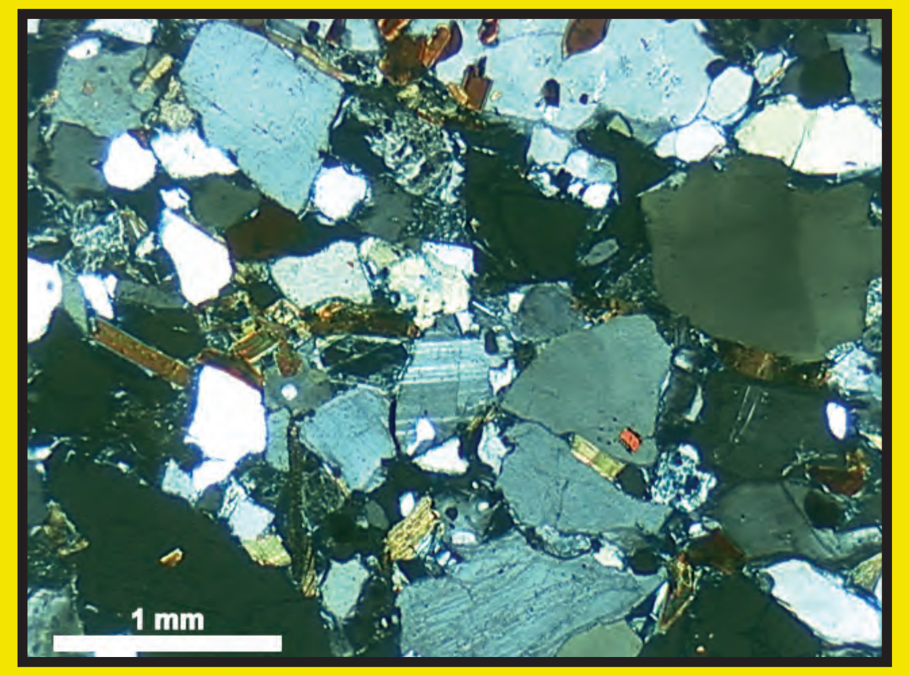

Figure 4 - Poorly-sorted, coarse arkose, rich in biotite, with angular grains. Crossed polarizers. (XP).

Figure 5 - Very fine-coarse sandstone with crossed laminations defined by levels of biotite or heavy mineral concentrations. Uncrossed polarizers (//P).

Intrabasinal constituents correspond to mud intraclasts, eroded from flood deposits (Fig. 6), and carbonate intraclasts, some with features indicative of microbial origin (Fig. 7; cyanobacteria?)

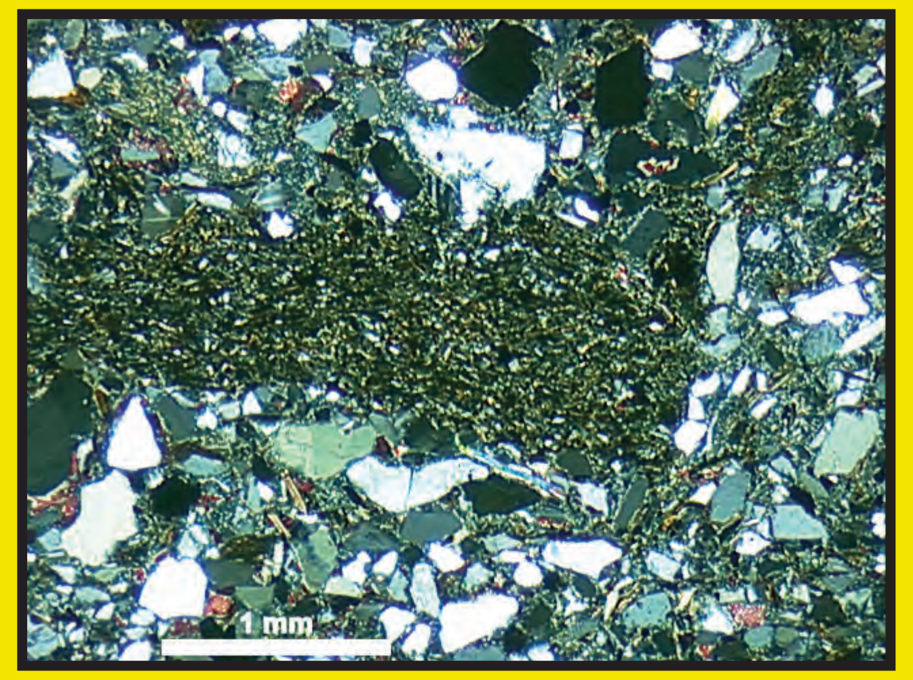

Figure 6 - Intraclastic conglomerate constituted by mud intraclasts and feldspathic-micaceous sand. (XP).

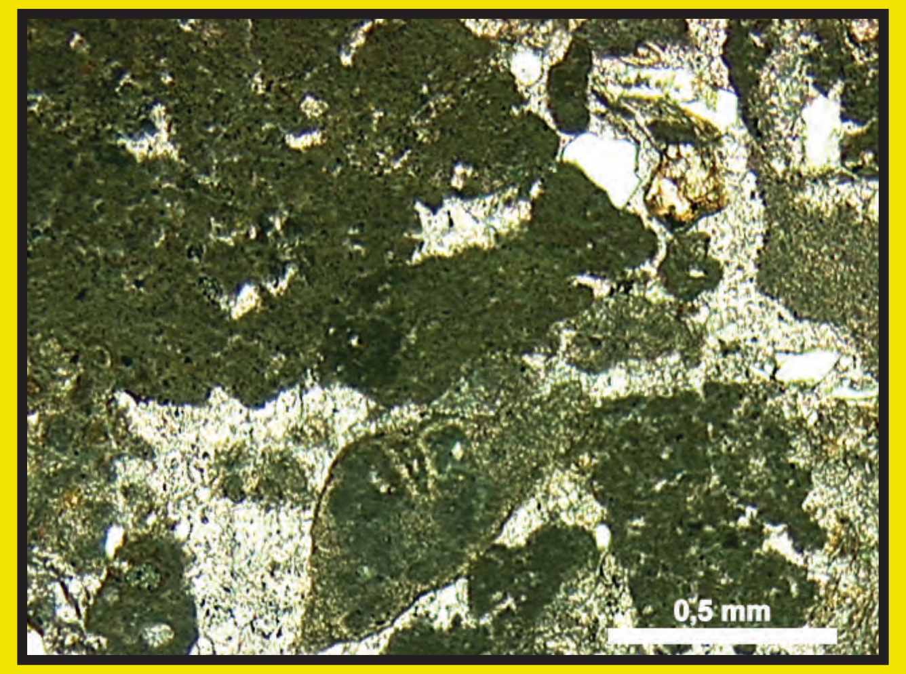

Figure 7 - Carbonate intraclasts with clotted fabric, indicative of microbial formation, probably by cyanobacteria, cemented by calcite. (//P).

Immature paleosols with argillaceous horizons with root marks (Fig. 8) and sandy horizons containing cutans with pendular features (Fig. 9) are locally interbedded with the sandstones, and may constitute local flow barriers.

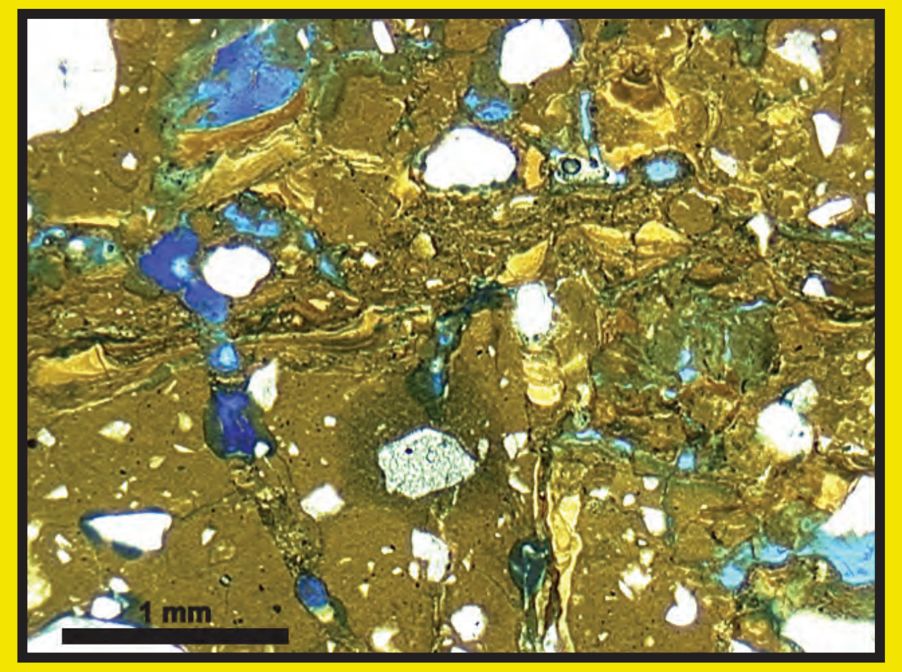

Figure 8 - Muddy paleosol with abundant pedogenic matrix, root marks and shrinkage fractures partially filled by Clay cutans. (//P).

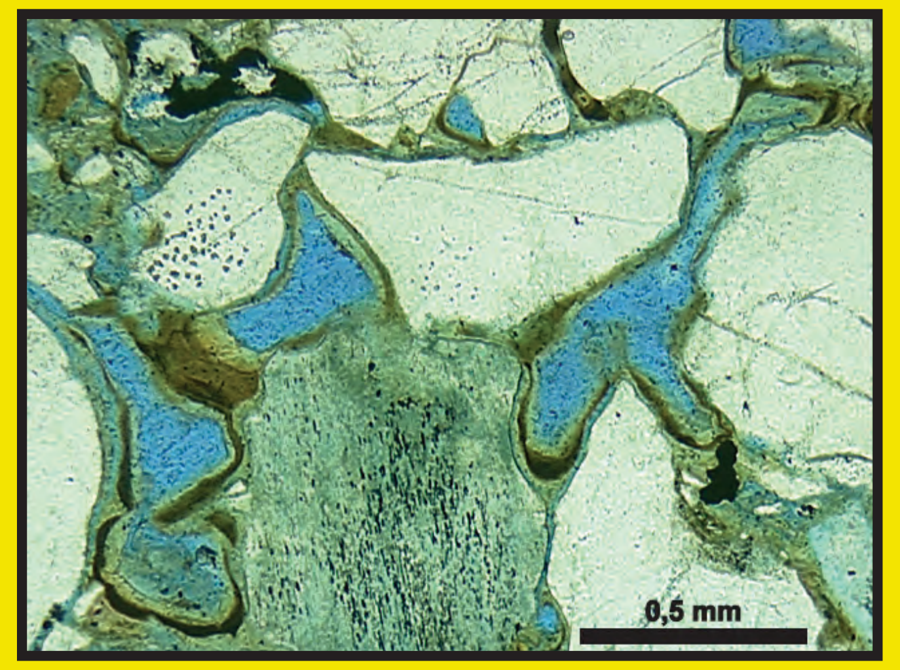

Figure 9 - Sandy paleosol with Clay and oxides cutans in pendular display. (//P).

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Diagenetic Processes

The reservoir quality of the Mucuri reservoirs is strongly impacted by diagenesis. Intergranular cementation and replacement of feldspars, micas, mud intraclasts and heavy minerals by kaolinite was the earliest diagenetic process in some sandstones, following thin smectite coatings in others (Fig. 10 and 11).

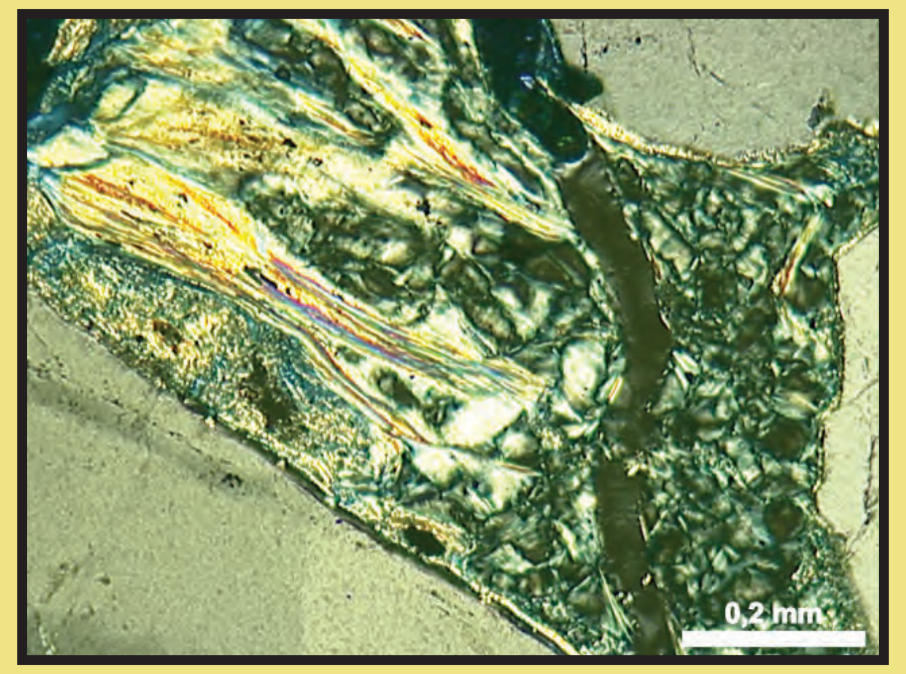


Figure 10 – Intergranular pore-filling cementation, replacement and expansion of micas by kaolinite. Thin, discontinuous smectite coatings. (XP).

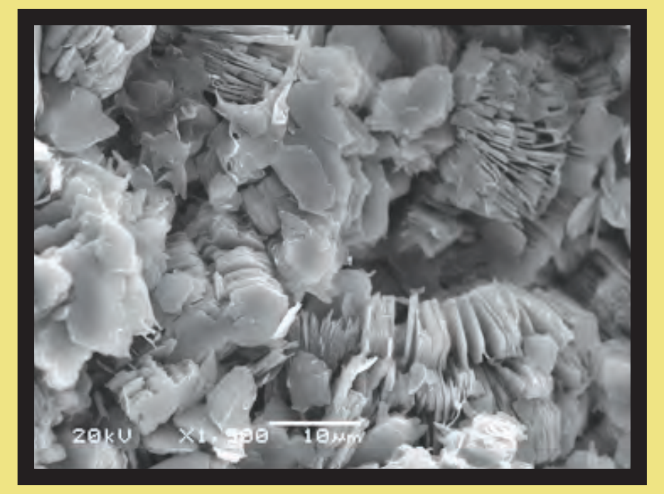


Figure 11 - Scanning electron microscopy (SEM) image showing vermicular kaolinite aggregates incipiently covered by fibrous illite.

The main diagenetic process was the authigenesis of rims, coatings and microcrystalline aggregates of smectitic clays, as intergranular cement and replacing grains of feldspars, biotite and unstable heavy minerals (Fig. 12 and 13)

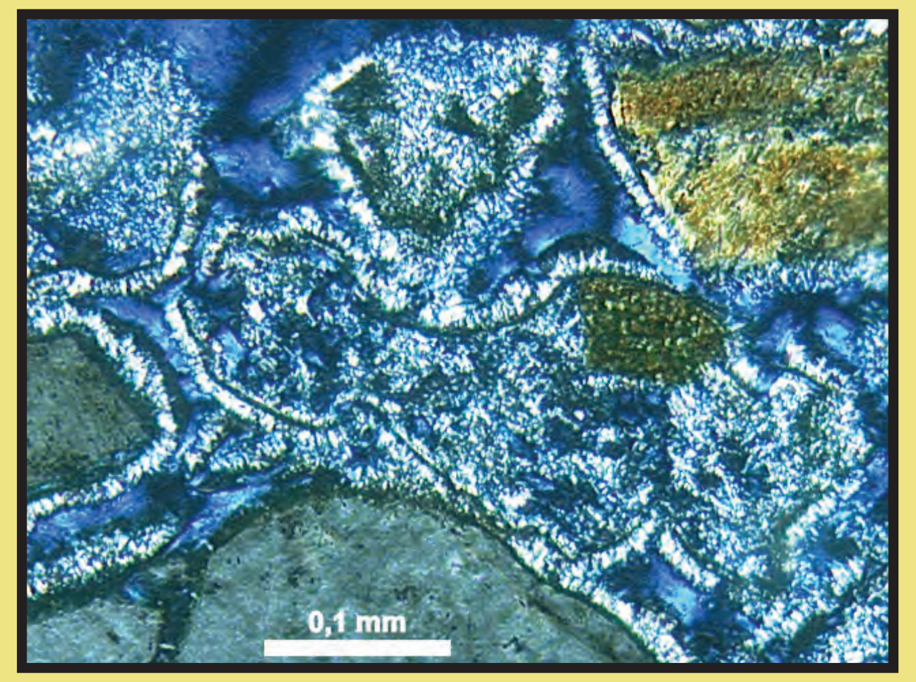


Figure 12 – Rims of smectitic Clay minerals covering thin chloritic coatings, and replacing feldspar and biotite grains. (XP).

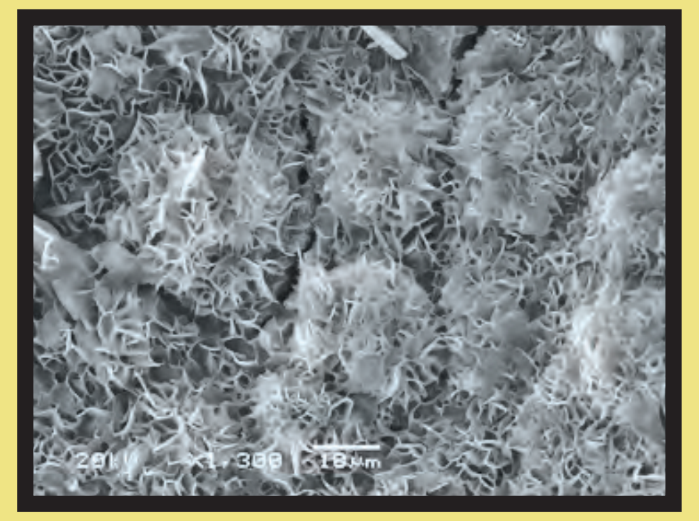


Figure 13 – SEM image of a rim made by honeycombed aggregates of chlorite-smectite

Such smectitic clays are commonly irregular, chlorite-smectite or illite-smectite, mixed-layers (Fig. 14), occurring as double rims covering coatings detached from, or left by the dissolution of grains (Fig. 15). Complex combinations of coatings and rims commonly replace totally grains (Fig. 16).

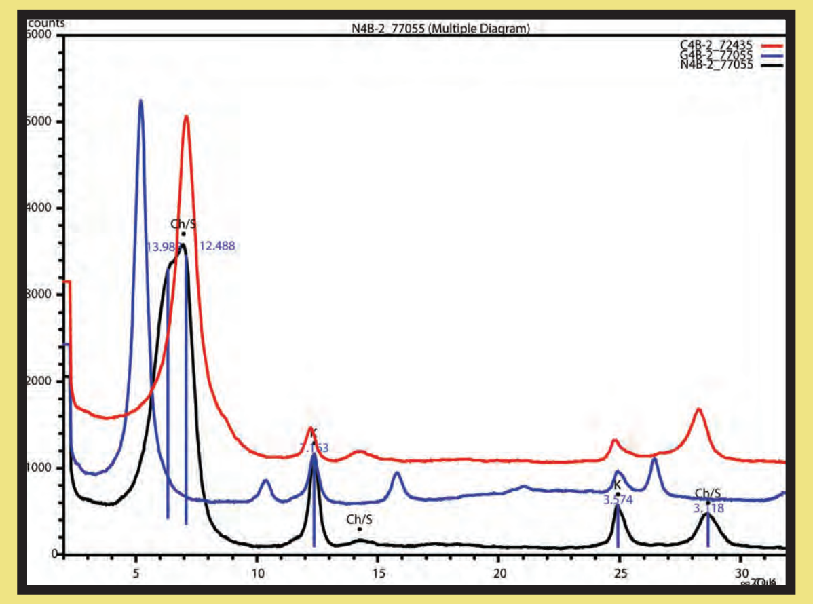


Figure 14 – X-ray diffraction (XRD) diagrams of the ← 20µm, air-dried (black), ethylene-glycol-saturated (blue) and heated (500°C) fraction of a sandstone, constituted by an irregular chlorite-smectite mixed-layer and by kaolinite.

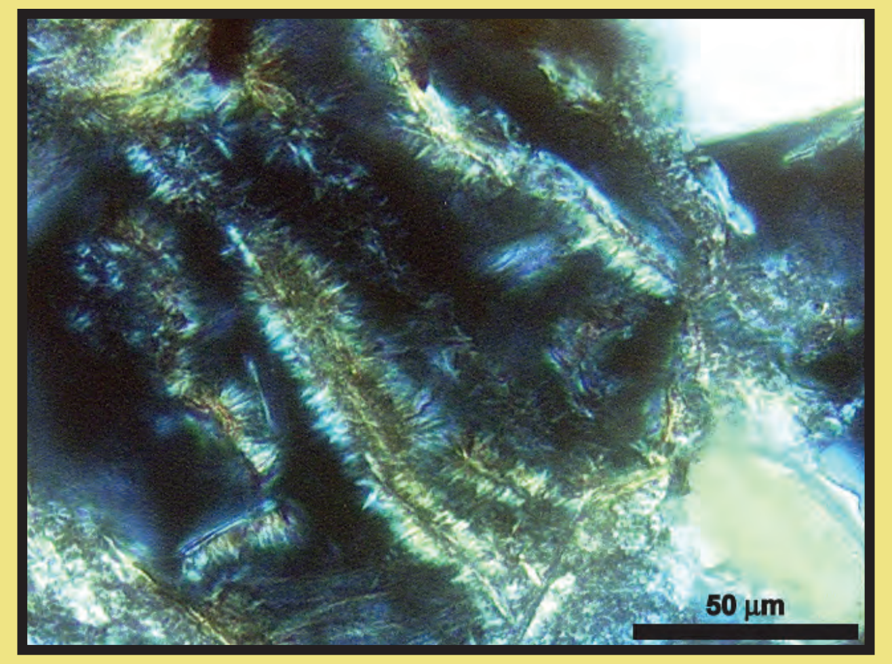


Figure 15 – Detail of Double rims of smectitic clays precipitated on both sides of coatings let loose by the dissolution of grains. (XP).

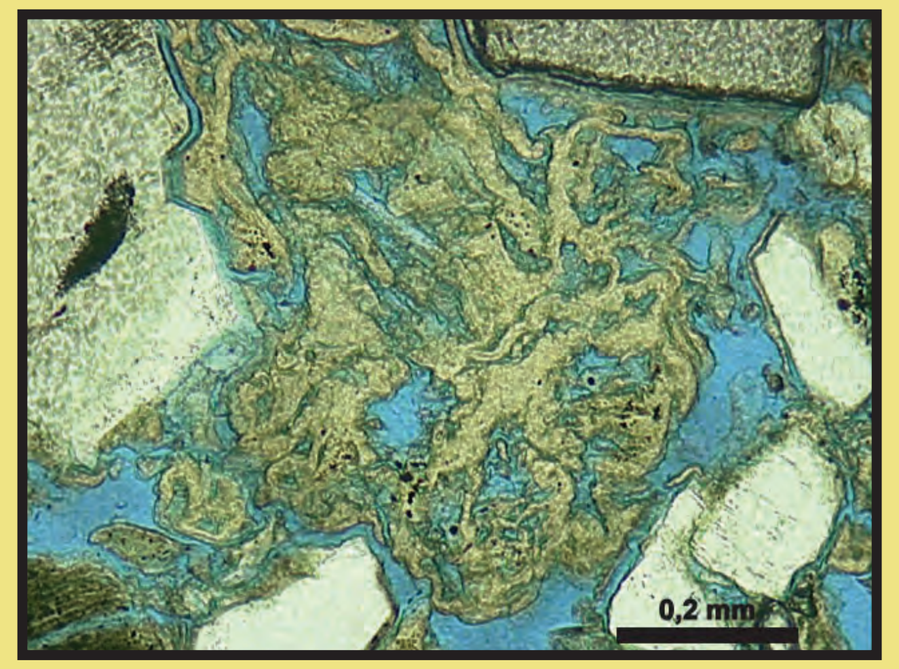


Figure 16 – Grain replaced by a complex combination of coatings and rims of smectitic clays, formed during progressive dissolution. (//P).

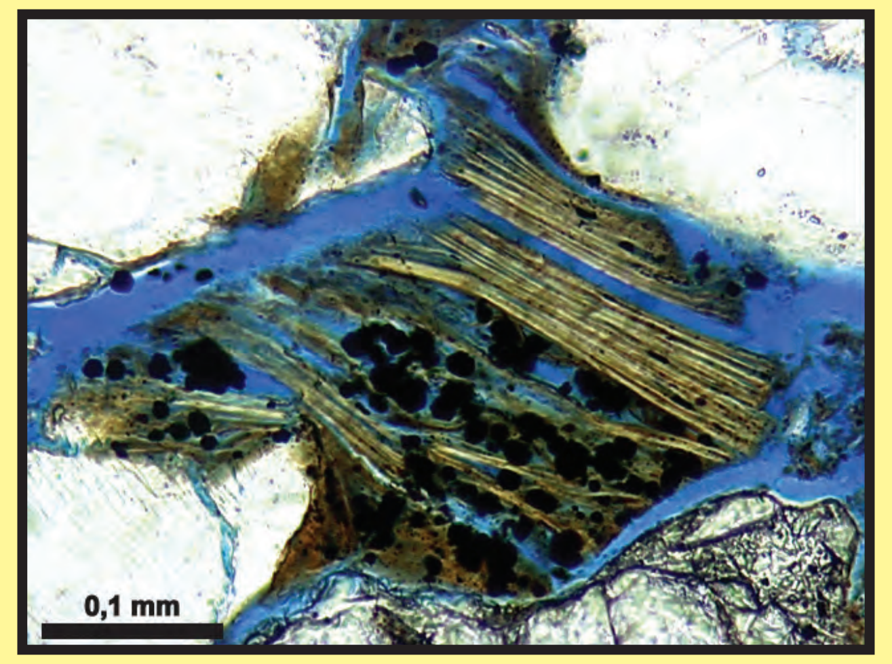


Figure 17 – Biotite flake expanded by precipitation of pyrite framboids and microcrystalline smectite along cleavages. (//P).

Framboidal pyrite aggregates (Fig. 17), overgrowths and discrete crystals of K-feldspar (Fig. 18 and 19) occur commonly associated to the smectitic clays.

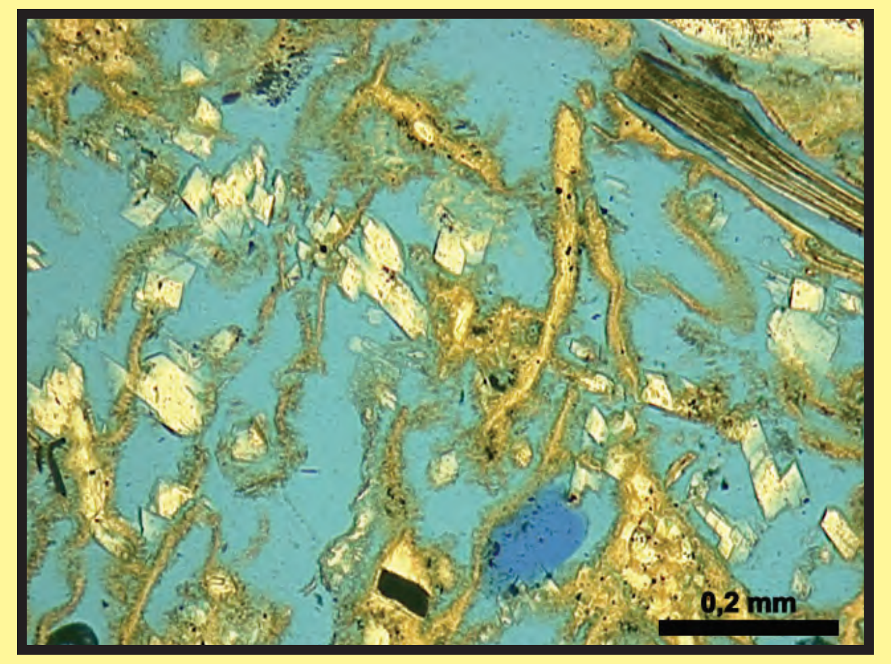


Figure 18 – K-feldspar crystals precipitated within the porosity left by the dissolution of a feldspar grain partially replaced by smectitic coatings. (//P).

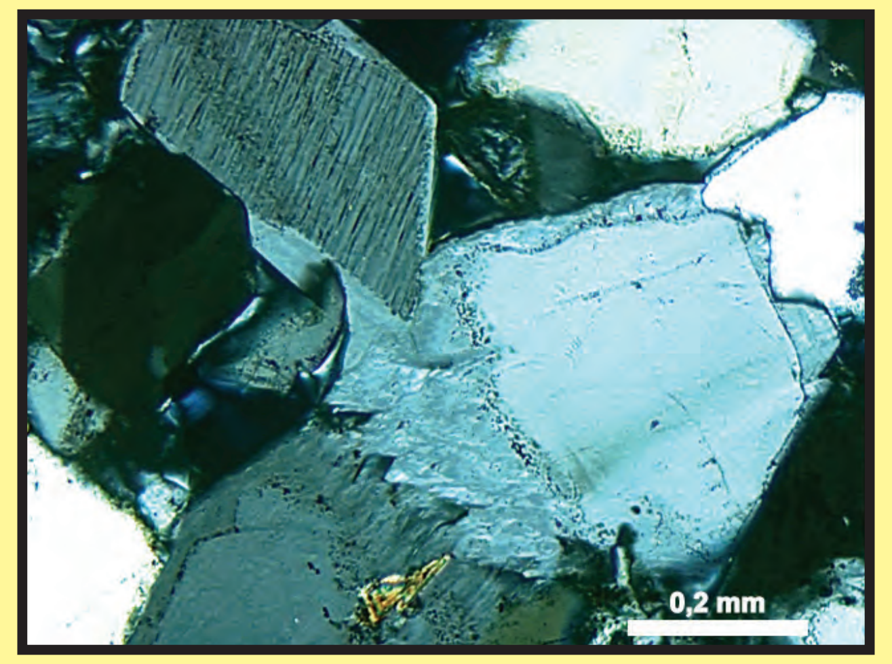


Figure 19 – Large epitaxial K-feldspar overgrowths showing complex zonation. (XP).

Cementation by coarse calcite was very heterogeneous, and more abundant in the sandstones with less smectitic clays, where calcite has extensively replaced grains and diagenetic clays (Fig. 20, 21 and 22).

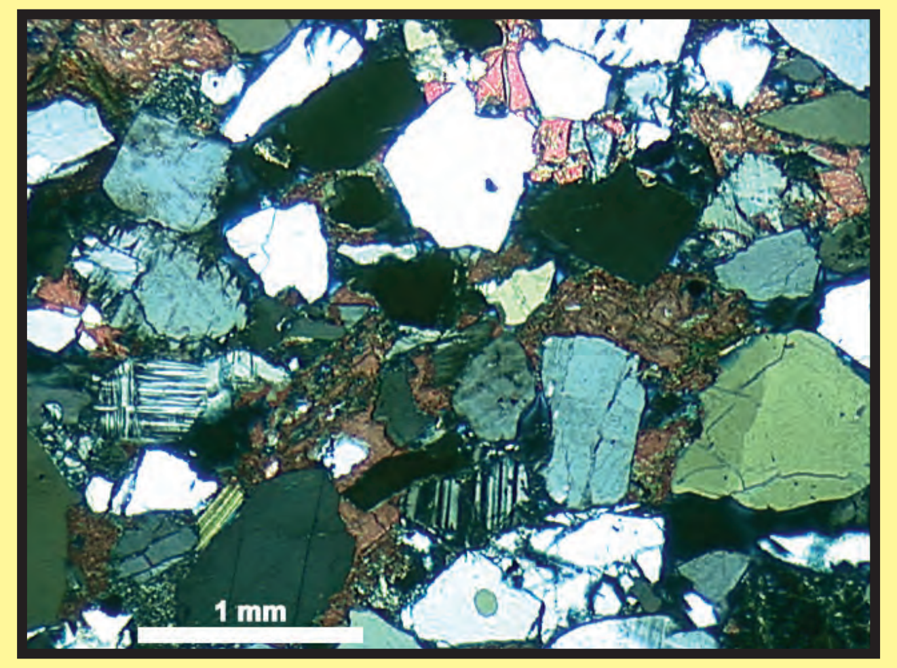


Figure 20 – Coarse sandstone partially cemented by poikilotopic calcite (stained pink). (XP).

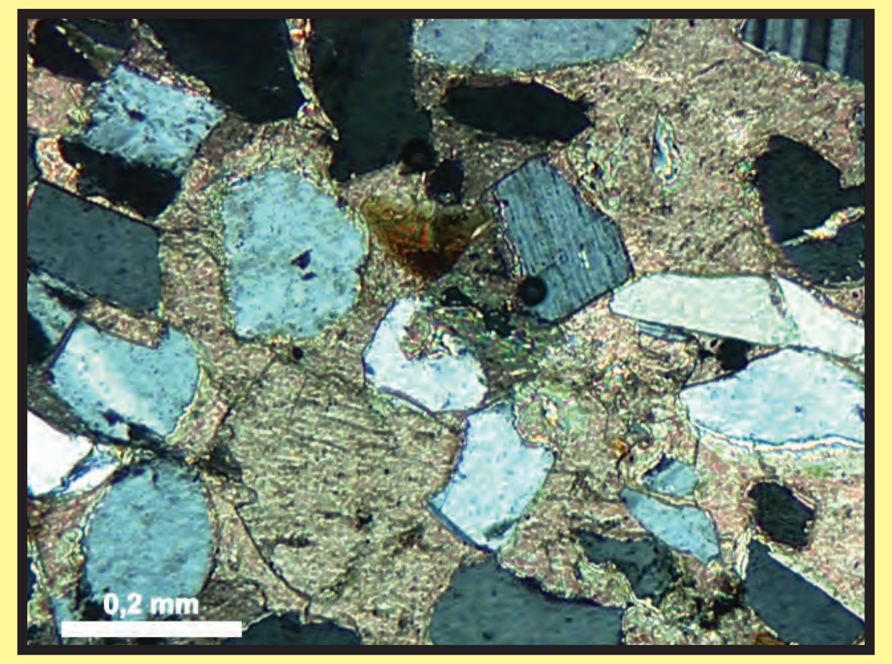


Figure 21 – Poikilotopic calcite (stained pink) filling intergranular pores and replacing grains. (XP).

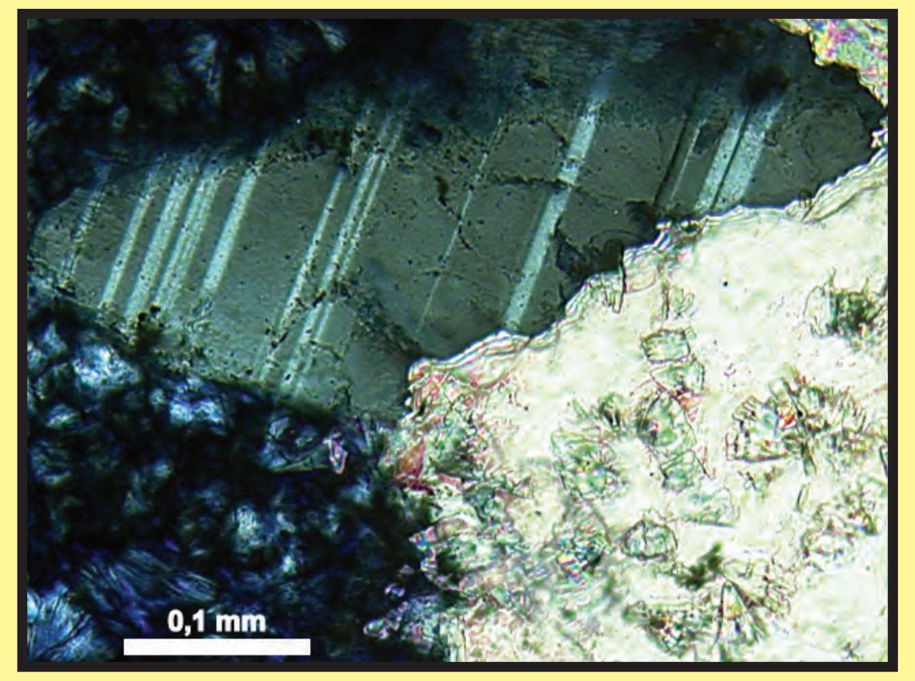


Figure 22 – Poikilotopic calcite (stained pink) filling intergranular pores and engulfing and replacing kaolinite booklets and grains. (XP).

Other diagenetic constituents include dolomite (Fig. 23 and 24), Ti minerals, and coarse pyrite (Fig. 25), which replaced biotite, mud intraclasts, and previous diagenetic constituents.

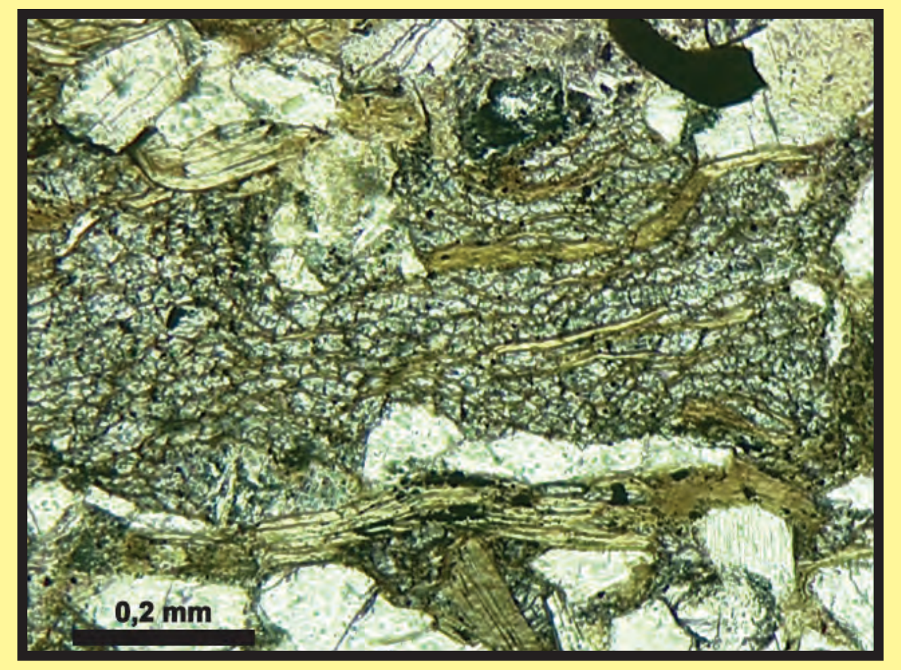


Figure 23 – Biotite flakes expanded by the displacive precipitation of dolomite. (//P).

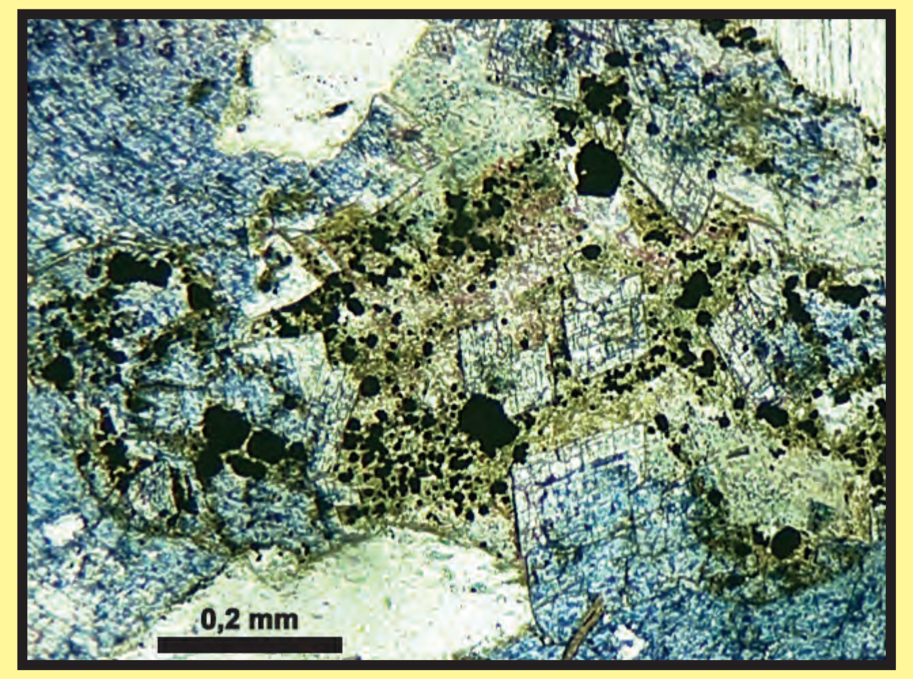


Figure 24 – Zoned ferroan dolomite (stained blue) and framboidal pyrite replacing mud intraclast. (//P).

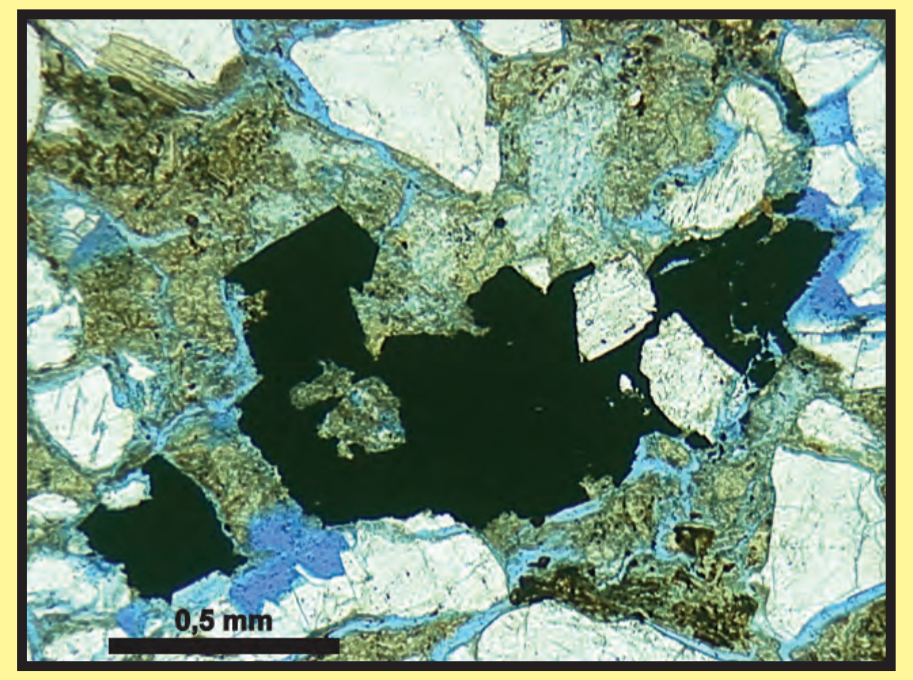


Figure 25 – Coarse blocky pyrite replacing grains and smectitic clays. (XP).

Porosity Evolution

Porosity is mostly intergranular primary in most sandstones, although secondary intragranular and moldic pores from grain dissolution, as well as intergranular porosity from carbonate cement dissolution are locally significant (Fig. 26, 27 and 28). Diagenesis promoted the development of very heterogeneous, complex and irregularly-connected pore systems, what strongly impacts oil recovery from the reservoirs (Fig. 26 and 27).

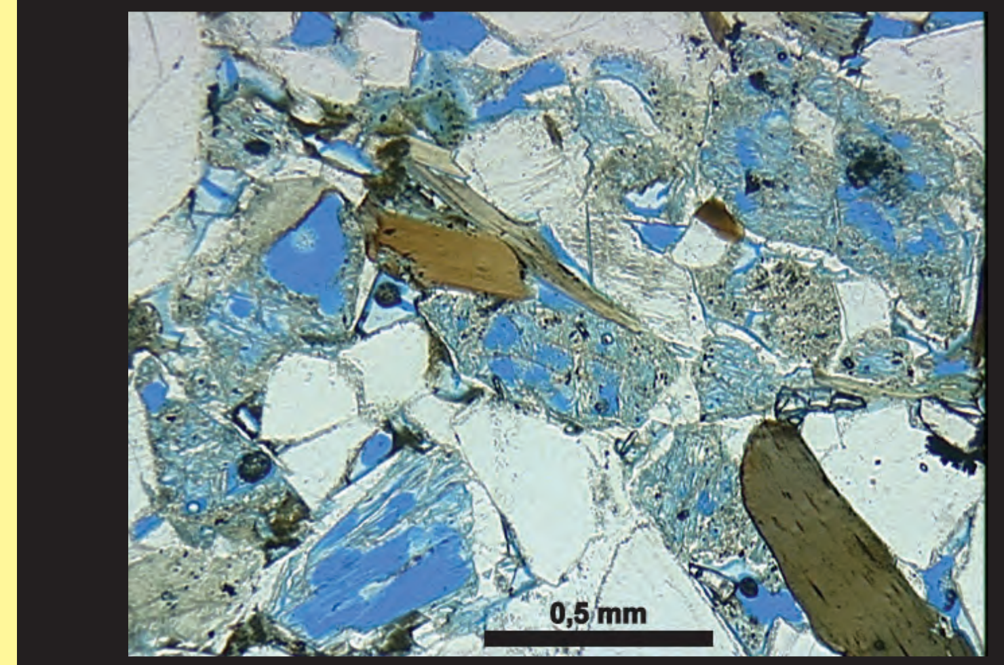


Figure 26 – Intragranular pores generated by the dissolution of feldspar grains surrounded by overgrowths. (//P).

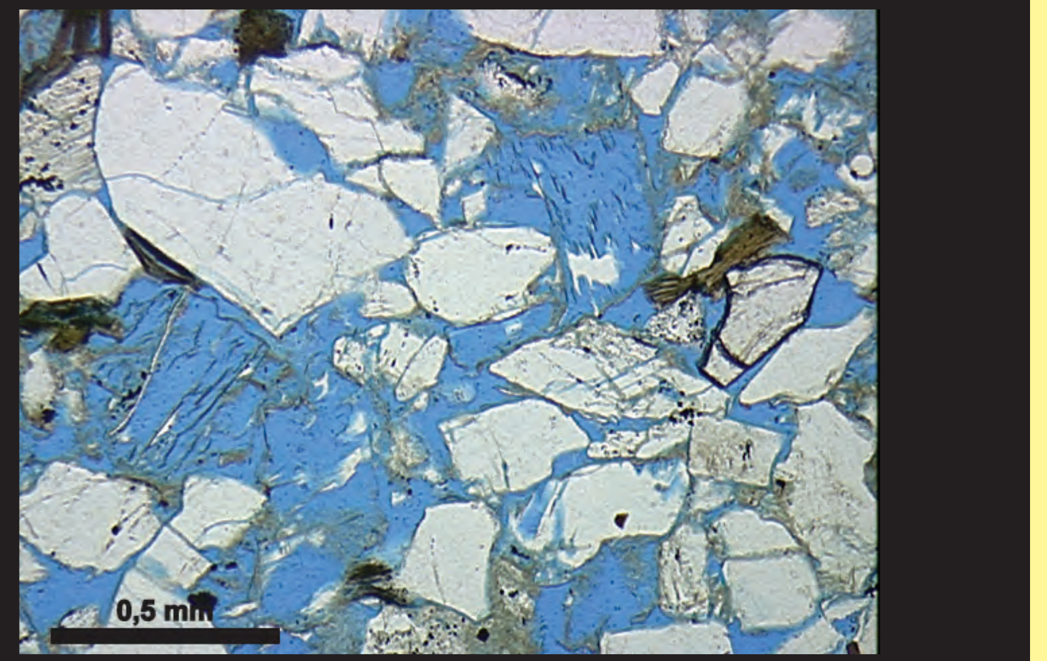


Figure 27 – Intergranular, intragranular and moldic pores. This smectite coatings cover discontinuously the grains. (//P).

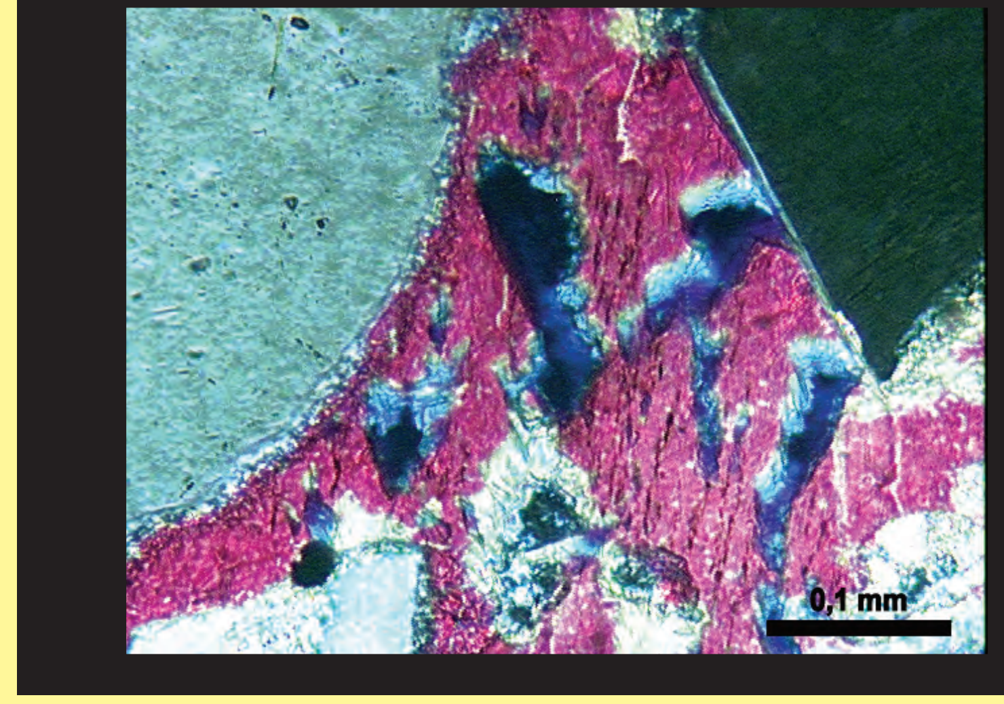
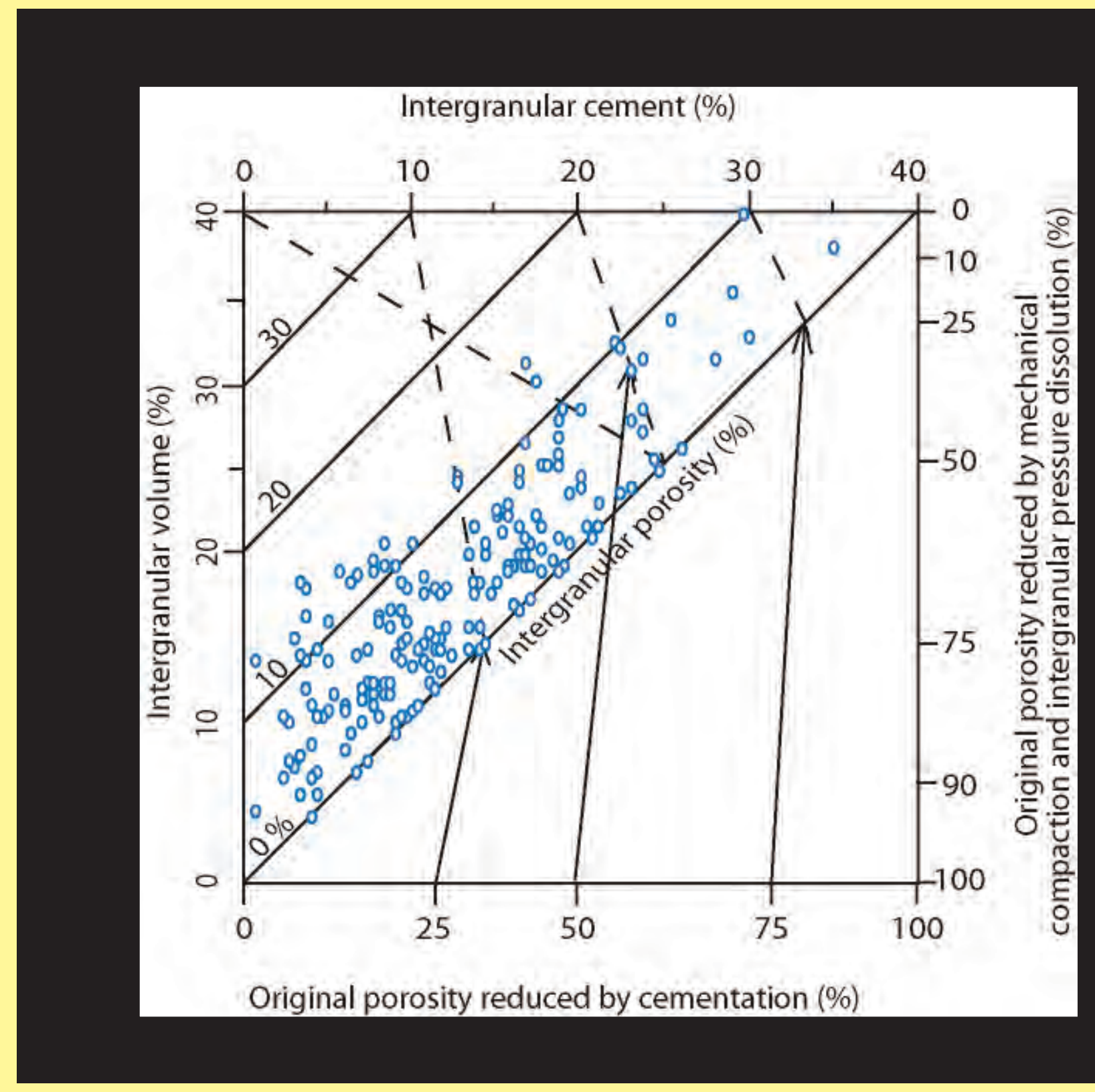


Figure 28 – Secondary intergranular pores formed by the partial dissolution of calcite cement (stained pink). (XP).



Compaction was the main process of porosity reduction in most sandstones, but cementation was the dominant process in some samples cemented by early calcite (Fig. 29).

Figure 29 – Plot of the intragranular volume versus the intergrasnular cement volume for the Mucuri sandstones (diagram after Houseknecht, 1987; mod. Ehrenber, 1989).

Diagenetic Environments and Implications

The intense and complex diagenetic processes are interpreted as product of the interaction between the unstable primary composition and reactive pore fluids. Meteoric fluids related to the alluvial setting promoted grain dissolution and kaolinite authigenesis. The stable isotopic composition commonly observed in the calcite cements suggests precipitation at near-surface to shallow burial conditions, from meteoric fluids moderately modified by water-sediment interaction (Table 1). The voluminous authigenesis of smectitic clays and associated K-feldspar and framboidal pyrite was caused by reactions between the feldspars, heavy minerals and micas, and brines derived from the adjacent saline environments and from overlying Aptian evaporites.

Table 1 – Stable carbon and oxygen isotopic values and calculated precipitation temperatures for calcite cements in Mucuri sandstones.

Well	Prof. (m)	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	δ W*	T °C	δ W	T °C
A	725,55	-23,25	-6,91	-5,0	25,5	-3,0	35,5
A	731,85	-21,49	-7,41	-5,0	27,9	-3,0	38,2
B	651,15	-17,4	-7,41	-5,0	27,9	-3,0	38,2
D	833,9	-20,72	-7,42	-5,0	27,9	-3,0	38,2
B	618,05	-14,24	-7,48	-5,0	28,2	-3,0	38,6
D	829,6	-19,02	-8,48	-5,0	33,2	-3,0	44,2
C	811,25	-14,11	-9,25	-5,0	37,3	-3,0	48,7
C	806,65	-14,7	-9,73	-5,0	39,9	-3,0	51,6
A	732,7	-16,52	-12,31	-5,0	55,2	-3,0	68,2

* δ water ≈ -5 for ≈ 20ºS paleolatitude (cf. Lloyd, 1982)

The precipitation of coarse, replacive pyrite was related to fluids charged in H2S derived from thermal sulfate reduction. The characterization of the types, amounts, and time and space distribution of the major diagenetic processes responsible for porosity modification in the Mucuri sandstones is of paramount importance for increasing oil recovery from producing reservoirs, as well as for the reduction of exploration risks through the development of quality-predictive models.

Furthermore, the characterization of eodiagenetic processes taking place in the pre-salt marginal settings revealed by the mineralogical, chemical and isotopic composition of early diagenetic constituents in the Mucuri sandstones, will contribute to the understanding of the environmental conditions occurring during the formation of the voluminous offshore reservoirs, shedding light on their origin and evolution (Fig. 30).

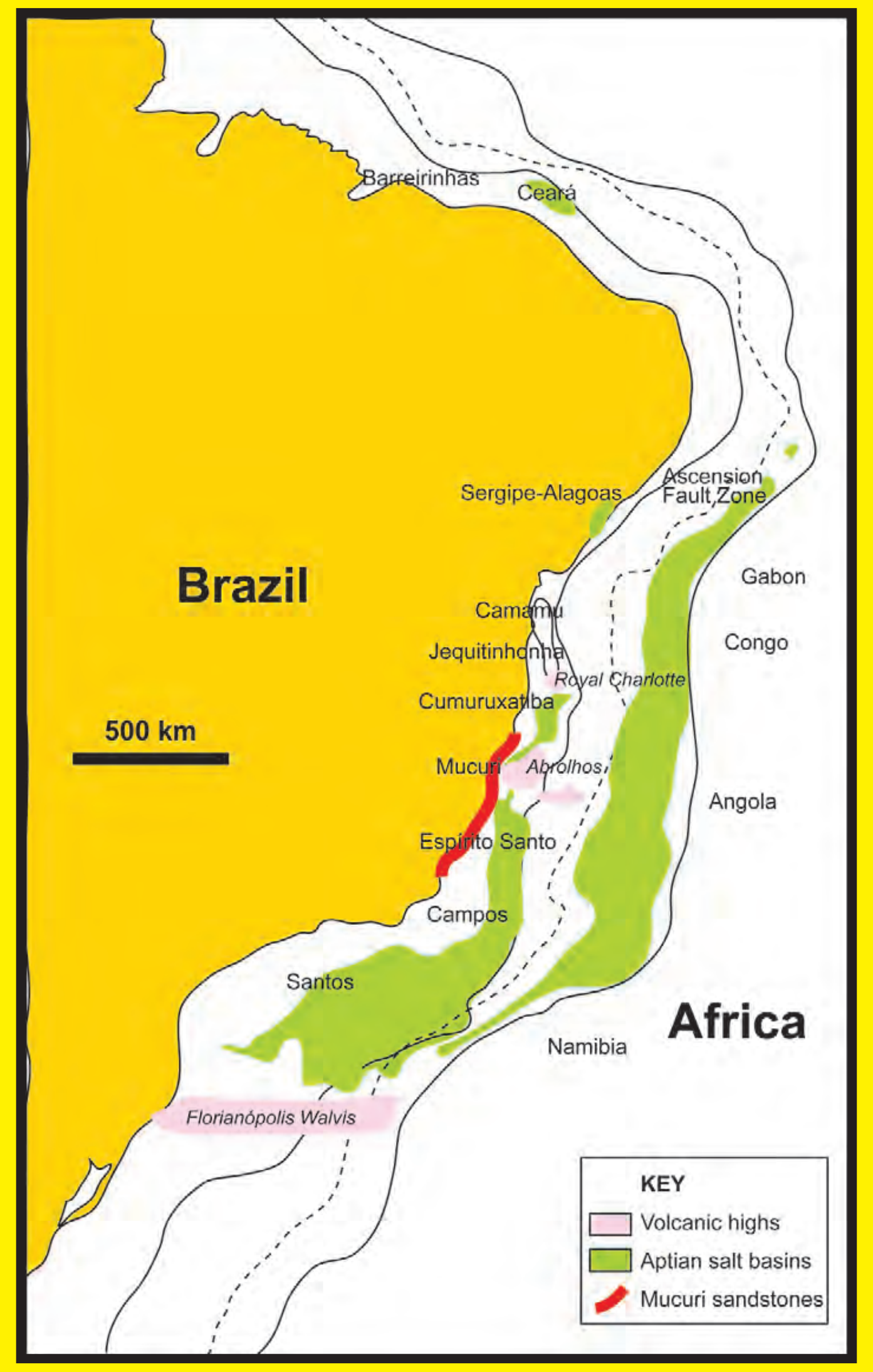


Figure 30 – Schematic paleogeographic reconstruction of the Brazilian-African area during the Aptian, illustrating the salt basins and the approximate occurrence of the Mucuri sandstones (modified from Petrobras presentation).