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Diagenetic Controls upon the Quality of Giant Gas Reservoirs of Brazilian Amazonia

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Abstract

Eolian, transitional and shallow marine sandstones of the Juruá Formation (Carboniferous of the Solimões Basin, western Brazilian Amazonia) are the largest gas reservoirs of Brazil, containing over 120 x 10^9 m^3 gas in place and 170 x 10^6 of associated bbl of oil. Despite the large reserves, the intensity, heterogeneity and complexity of the diagenetic processes that directly control their porosity and permeability trouble the development and production of these reservoirs. The major diagenetic processes are mechanical and chemical compaction and cementation by microcrystalline and blocky dolomite, poikilotopic anhydrite, and quartz overgrowths. Detrital composition, depositional facies, stratigraphic sequence limits and structural evolution control the spatial distribution of these processes. Diagenetic heterogeneity is related to the complex interbedding of sandstones, shales, evaporites and dolomites within three 4th order depositional sequences. The time distribution is constrained through analyses of fluid inclusions, radioactive dating of associated illite, and stable oxygen isotopes. Conceptual and empirical models of the distribution of porosity and permeability in the Juruá reservoirs relative to the petrographic, petrologic, geochemical and geological parameters will contribute for the efficiency of the development and production of the reservoirs, as well as for the reduction of exploration risks within the basin.

1. Geological Setting:

The Solimões Basin is a large Paleozoic intracratonic basin, comprising around 600,000 Km^2 in the Amazonas State (North Brazil). The basin is limited to South by the Brazilian shield, to North by the Guyanas Shield, to West by the Acre Basin, and to east by the Amazonas Basin (Caputo and Silva, 1991). The Solimões Basin was filled by six 2nd order depositional sequences: Ordovician, Silurian-Devonian, Devonian-Carboniferous, Carboniferous-Permian, Cretaceous and Tertiary (Eiras et al., 1994). This study is focused in the Juruá Formation, basal part of the Carboniferous-Permian sequence.

The Juruá Formation is the most important gas reservoir of Brazil, containing over 120 x 10^9 m^3 gas in place and 170 x 10^6 of associated bbl of oil. The most important accumulations of the Juruá Formation are aligned along a N70^o-80^{o}E fault-and-fold system structured by Jurassic-Cretaceous right-lateral wrenching (Caputo and Silva, 1991). The sedimentary-tectonic evolution in the studied area starts with an Eohercinian extension characterized by normal faults and source area uplift, followed by a Jurassic-Cretaceous transpressional tectonism, originating reverse faults and folds.

2. Facies and Stratigraphy

The Juruá Formation is constituted of sandstones, mudstones, evaporites and dolostones that were deposited within a 3rd order transgressive cycle (Becker, 1997), in eolian and fluvial-deltaic environments with increasing marine influence, in a hot and arid climate (Cunha et al., 1988). Eolian sandstones are the best reservoirs of the Juruá Formation.

The part of Juruá Formation analyzed in this study is divided into five operational reservoir sub-units, from top to base: JR-70A, JR-70B, JR-80, JR-85 and JR-90A. The JR-70A sub-unit corresponds basically to eolian sandstones, with associated sabkha evaporites and mudstones. These sandstones are bimodal with fine-coarse grain-size lamination, moderate to poor sorting, and climbing translatent strata. The evaporites consist of 1 to 3m thick, amalgamated nodular anhydrite, interbedded with dolostones and mudstones.

The JR-70B sub-unit is constituted of eolian sandstones similar to those of JR-70A, with some associated evaporites and marine reworking towards the top. These sub-units correspond to a 4th order depositional sequence (S3), composed of a transgressive systems tract (JR-70B) and a highstand systems tract (JR-70A). The transgressive systems tract is characterized by sabkha evaporites covered by eolian sandstones, in retrogradational pattern, while the highstand systems tract shows a progradational distribution (Fig. 1).

The JR-80 sub-unit is constituted of sabkha and eolian sandstones with some associated mudstones and marine reworking towards the top. The mudstones of JR-80 sub-unit are generally massive with some horizontal trace-fossils, and probably lagoonal. This sub-unit represents a retrogradational 4th order depositional sequence (S 2) related to the transgressive systems tract (Fig. 1).

The sandstones of JR-85 sub-unit are medium-grained and poorly to moderately sorted, presenting low angle cross-bedding and mud drapes. The gray-to-red associated mudstones show linsen bedding, and some horizontal trace-fossils. This sub-unit corresponds mainly to tidal-plain and tidal-channel facies, with some associated eolian sandstones. This sub-unit is absent in the eastern part of the studied area, probably due tectonic uplift.

The marine sandstones of JR-90A sub-unit are medium-grained, moderately sorted, and present low angle cross-bedding and mud drapes. JR-90A eolian sandstones are mostly bimodal with fine-coarse grain-size lamination. Marine reworking increases upward in the eastern area. Associated evaporites are amalgamated nodular anhydrite, 1 to 3m thick. JR-85 and 90A sub-units correspond to a 4th order depositional sequence (S 1). The transgressive systems tract (JR-90A) shows a retrogradational pattern, with eolian deposits progressively reworked by marine processes (Fig. 1), and the highstand systems tract (JR-85) corresponds to a progradational pattern of transitional to eolian environments.

3. Diagenetic Processes

The Juruá Formation sandstones are mainly arkoses and subarkoses. Quartz grains are dominantly monocrystalline, making in average 51% of rock volume. Polycrystalline quartz grains average 4%. Detrital feldspars are mainly microcline (av. 4%), orthoclase (av. 3%) and less often plagioclase (av. 0.7%) and perthite (av. 0.5%). The rock fragments are plutonic (av. 3.6%), acid volcanic (av. 2%), sedimentary (av. 0.4%) and low grade metamorphic (av. 0.1%). The accessory components are usually heavy minerals, mostly tourmaline, micas, mud intraclasts and peloids, and dolomite intraclasts.

The diagenetic evolution of the sandstones is characterized by eodiagenetic hematite, clay coatings, pyrite, dissolution, dolomite, barite, compaction, k-feldspar and quartz overgrowths; by mesodiagenetic anhydrite, dissolution, albite, halite, illite, chlorite, quartz, calcite, dolomite/ankerite, siderite, TiO_2 and pyrite; and by telodiagenetic hematite and kaolinite.

Dolomite is the most abundant diagenetic constituent within Juruá Formation (av. 7.5%; up to 68%), ocurring most commonly as microcrystalline, precompactional pore-filling cement with 0.8 to 4% of $FeCO_3$ (Fig. 2A). Pore-filling dolomite also occurs as blocky and poikilotopic crystals. Blocky dolomite (0.05-0.1mm; av. 2%; up to 26%) shows compositional zonation between 5.4% and 25% of $FeCO_3$ (ankerite). Dolomite crystals are covered and engulfed by anhydrite pore-filling cement and quartz overgrowths (Fig. 2B). Poikilotopic dolomite has a heterogeneous distribution (av. 0.1%, up to 3.7%), 4 to 5% of $FeCO_3$, and commonly replaces detrital grains and quartz overgrowths. Poikilotopic, pore-filling calcite (1to 4% $FeCO_3$), siderite (9 to 10% of $MgCO_3$) and barite are very scarce.

Cementation by quartz overgrowths (av. 1.7%; up to 21%) occurred during and after compaction (Fig. 2D). The presence of sutured intergranular contacts and stylolites (Fig. 2E) in some samples suggests that part of the silica was internally derived. K-feldspar overgrowths are less common (av. 0.1%; up to 0.7%) than quartz overgrowths. Poikilotopic anhydrite is very common (av. 5.5%; up to 24.7%), and engulfs quartz overgrowths and dolomite (Fig. 2B and 2C). Isotopic analysis of anhydrite suggests a Carboniferous seawater origin with the most of values between +16‰ and +18‰ $\delta^{34}S_{CDT}$.

Mixed-layer illite-smectite, mechanically infiltrated clay coatings are more common and thicker in the transitional sandstones. Illite (av. 0.3%; up to 2.3%) occurs as fibrous aggregates “bridging” between grains through the pores (Fig. 2F), and replacing volcanic rock and feldspar grains. Microcrystalline halite occurs locally associated to illite. Chlorite was observed in only two wells as rims and replacing feldspar grains. Kaolinite was identified locally as pore-filling intergranular aggregates.

Diagenetic albite with a nearly pure composition commonly replaces partially detrital K-feldspar (av. 1.3%; up to 3%) and plagioclase (av. 0.1%; up to 1%). Iron oxide coatings occur mostly associated to the JR-90A sub-unit in the eastern area, and average 0.3% (up to 1.3%). Scarce anatase and framboidal pyrite replace grains and fill some pores.

4. Depositional Controls on Diagenesis:

Depositional facies, stratigraphic units and sequence boundaries, hydrocarbon/water contacts, and magmatism control the heterogeneous and complex pattern of distribution of diagenetic processes.

Depositional facies: Microcrystaline dolomite is more common in eolian sandstones (av. 3.4%, up to 11% in the JR-70A sub-unit). On the other hand, blocky dolomite is dominantly associated to the non-eolian sandstones (av. 2.4%, up to 26% in the JR-80 sub-unit). The abundance of eodiagenetic dolomite within Juruá sandstones is in line with other eolian/sabkha units (e.g. Purvis, 1992; James, 1992). The dominance of microcrystaline dolomite cements under these conditions is most probably related to the depletion in Ca^{2+} by the precipitation of evaporitic sulfates, and/or to the mixing of marine and meteoric waters. However there is no clear relationship between dolomite distribution and stratigraphic sequence boundaries or present hydrocarbon/water contacts in the Juruá reservoirs. Quartz overgrowths, similarly to blocky dolomite, are more abundant in non-eolian sandstones (av. 2.8%, up to 21%), but their distribution is also controlled by stratigraphic boundaries.
Stratigraphic units and boundaries: Anhydrite is more commonly associated to the JR-70B sub-unit both in the eolian (av. 7%, up to 18.7%) and non-eolian (av. 10.4%, up to 24.7%) sandstones. This is certainly related to the frequency and thickness of evaporite beds within this sub-unit. Quartz overgrowths are more commonly associated to the JR-80 (av. 3%, up to 15%), JR-85 (av. 5.6%, up to 21%) and JR-90A (av. 2.1, up to 16.3%) sub-units, probably due their stronger chemical compaction through intergranular and stylolitic pressure dissolution. This suggests that at least part of the silica for quartz cementation was internally derived. Both anhydrite and quartz cements are more abundant close to the boundaries of stratigraphic sequences (Fig. 1). This might suggest an enhanced fluid circulation along the coarser, more permeable sequence-basal sands during burial. It is also quite evident, however, a positive correlation between anhydrite cementation and evaporitic sulfate layers, and between quartz cementation and mudstone layers, which occur at sequence limits, indicating a direct derivation of ions from these interbedded lithologies.

Added to the depositional parameters, other controls have exerted their influence on the heterogeneity of cementation patterns within Juruá reservoirs:
Oil-water contacts: Both anhydrite cementation and quartz overgrowths are more abundant along present oil/water contacts (see Fig. 1). This is possibly related to the

gradual stagnation and concentration of fluids with decreasing water saturation towards O/W contacts.

Magmatism: A basic magmatism in the form of diabase sills and dykes occurred during late Triassic to early Jurassic which played an important role in hydrocarbon generation from Devonian source rocks (Caputo and Silva, 1991). K/Ar dating of Juruá Formation illites (Mizusaki et al., 1990) yielded ages of 150 to 205 ± 23 Ma in JR-70A, and of 210 to 243 ± 3 Ma in JR-70B of western area, and ages of 185 to 199 ± 25 Ma in JR-70B of eastern area. The convergence between the K/Ar ages of illites and of diabase intrusions (Mizusaki et al., 1990) suggests that, besides hydrocarbon generation and emplacement, magmatism provided the conditions for enhanced fluid circulation through thermal convection.

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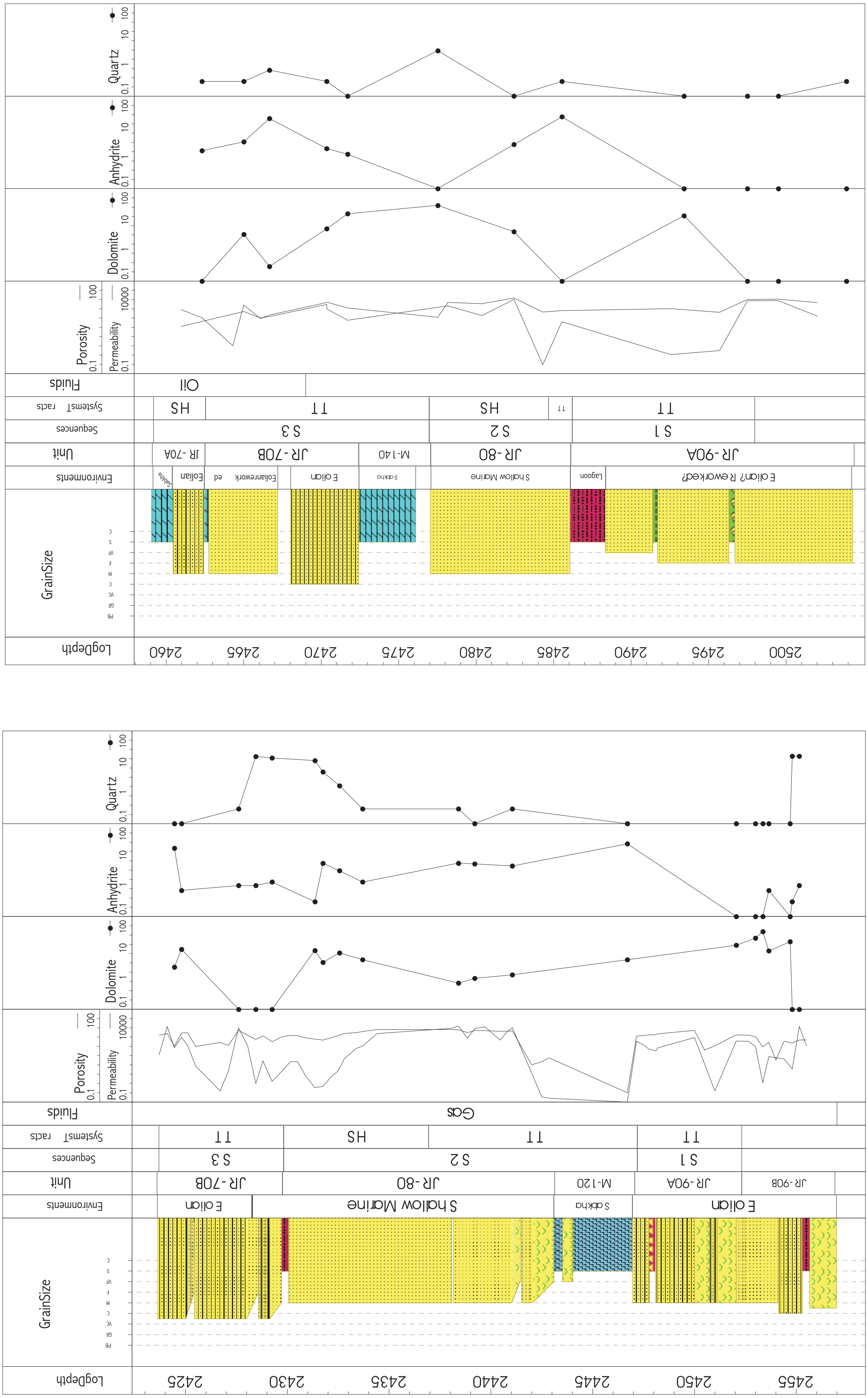

Fig. 1 - Stratigraphy, petrophysics and major diagenetic composition in two representative wells cored in Juruá reservoirs, showing patterns of stratigraphic/depositional control on diagenesis.

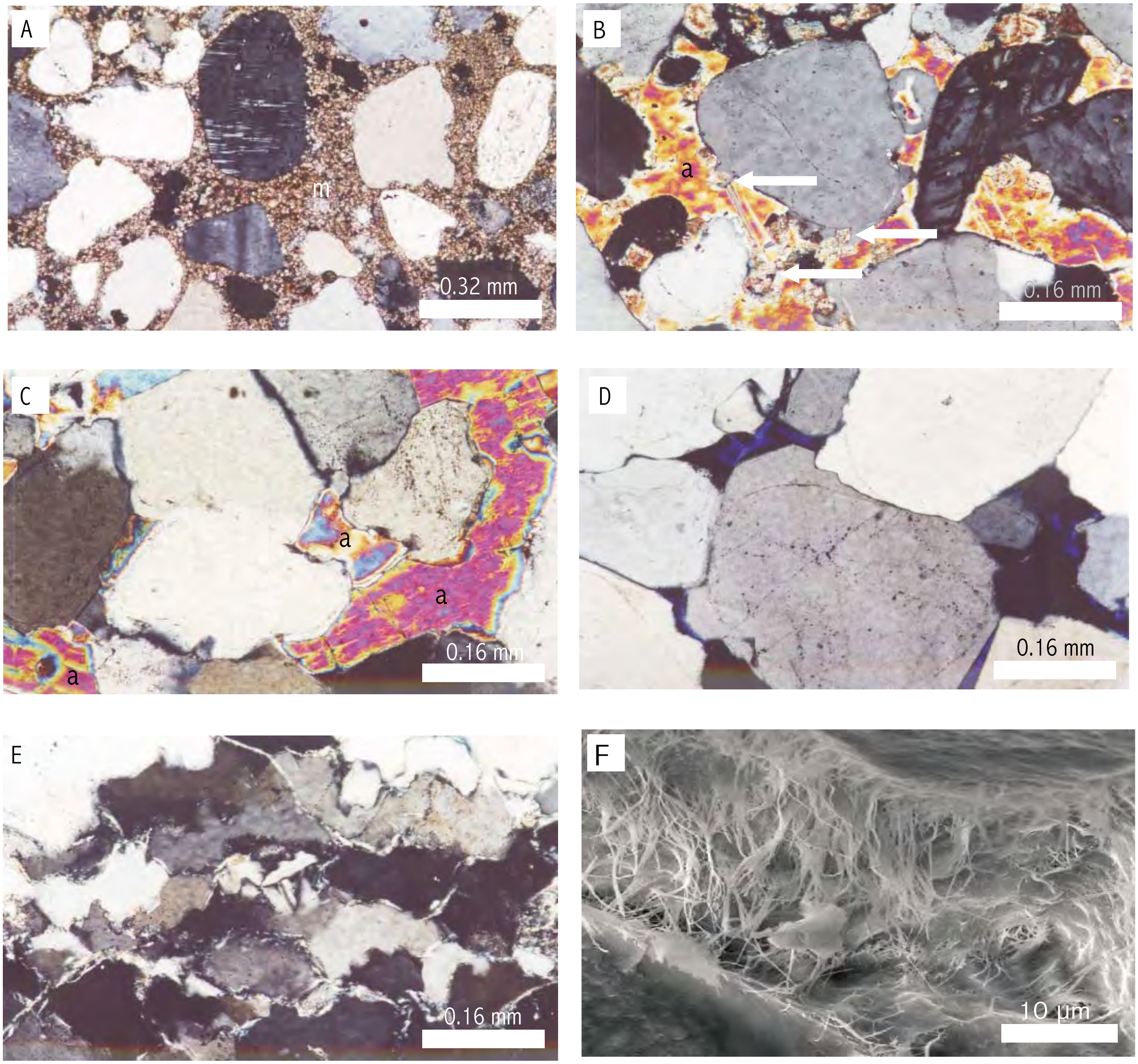

Fig. 2 - Photomicrographs of major diagenetic features of Juruá Reservoirs: A - precompactional microcrystalline pore-filling dolomite (m); B - poikilotopic anhydrite (a) engulfing dolomite rhombs (arrows) and quartz overgrowths; C - quartz overgrowths covered by poikilotopic anhydrite (a); D - well-developed quartz overgrowth cementation; E - sutured intergranular contacts and micro-stylolites; F - fibrous illites forming bridges between grains.