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The role of fracturing and mineralogical alteration of basement gneiss in the oil exhsudation in the Sousa Basin (Lower Cretaceous), Northeastern Brazil

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ABSTRACT

This work focuses the geological context of an oil sample obtained from an exhsudation in a superficial well, located at Salguinho Farm, Sousa Basin, at the central Borborema Province, Brazil. It is a light oil, with 81,1% of saturated compounds and a predominance of C17 and C23 n-paraffins, in which biomarkers point out to a non-biodegraded mature oil. Although the source rocks of this oil are unknown, the reservoir are metamorphic rocks from the basement, in a structural arch nearside the depocenter area of the basin. This lithology corresponds to ortho-derived gneiss strongly modified by ductile and brittle deformation (fracturing), as well as mineralogical alteration due to retrometamorphic and hydrothermal reactions. Here we emphasize and discuss the importance of such modifications underwent by the gneiss in the development of a propitious porosity and permeability for the further oil accumulation.

1. Introduction

The Sousa Basin is part of a sedimentary basin system, known as the intracontinental basins of Northeast Brazil (Ponte, 1992). These basins are mainly sites of Cretaceous sedimentation, whose origin and evolution were controlled by the reactivation of pre-existing tectonic structures in the basement (Precambrian rocks) during the Jurassic and Cretaceous. This reactivation was closely related to the opening of the South Atlantic Ocean and normal and transcurrent faults were the main structural style for the opening of grabens and half grabens in the central region of Northeast Brazil during the Early Cretaceous. They show an SW–NE orientation determined by the structures of competent supracrustal rocks within the Borborema Province. This lowlying trend has been called the Araripe-Potiguar depression (Mabesoone, 1994; Valença et al., 2003). The Sousa Basin is a half graben, and together with the neighboring Vertentes, Uiraúna-Brejo das Freiras and Pombal basins, are known as the Rio do Peixe Basins.

They were originated as a consequence of the tectonic movements which resulted in the separation of South America and Africa (Mabesoone, 1994; Valença et al., 2003). The region was periodically affected by the formation of intracontinental rifts, for the last time from Callovian onwards (Matos, 1992). As a consequence, several sedimentary basins resulted from the differential reactivated fault movements within the ancient Precambrian belt zone (Fig. 1). The crustal extension gave rise to the generation, along the preexisting Precambrian fault lines, of SW-NE oriented, tilted half-grabens (Ponte, 1992; Valença et al., 2003).

In Rio do Peixe Basins, the combination of the current level of erosion with the geometry of major faults and bedding dips shows the existence of different half-grabens (Vertentes, Uiraúna-Brejo das Freiras, Sousa and Pombal). The structural and geophysical data presented by Córdoba et al. (2008) indicate that the sediment column may be more than 2 km thick in the deep portion of depocenters, or even attain 2.5–3 km thick in the case of Brejo das Freiras half-graben. Segments of Brasiliano-Pan-African EW-trending (Patos lineament) or NE (Portalegre lineament) shear zones, acted as brittle shear zones during the Early Cretaceous reactivation. The combination of slickenlines and kinematic indicators helped to establish the displacements along the faults, normal in NE structures, such as the Brejo das Freiras fault (which defines the faulted border of the homonym half-graben) and oblique, normal-sinistral, in the EW trending São Gonçalo; this fault defines the faulted border of a transtractive block, in the case of Sousa half-graben (Córdoba et al., 2008). In each half-graben, the layers are tilted to the faulted borders, in whose vicinity may occur syntectonic conglomerates. Both border faults are structured in steps, which usually represent relay ramps.

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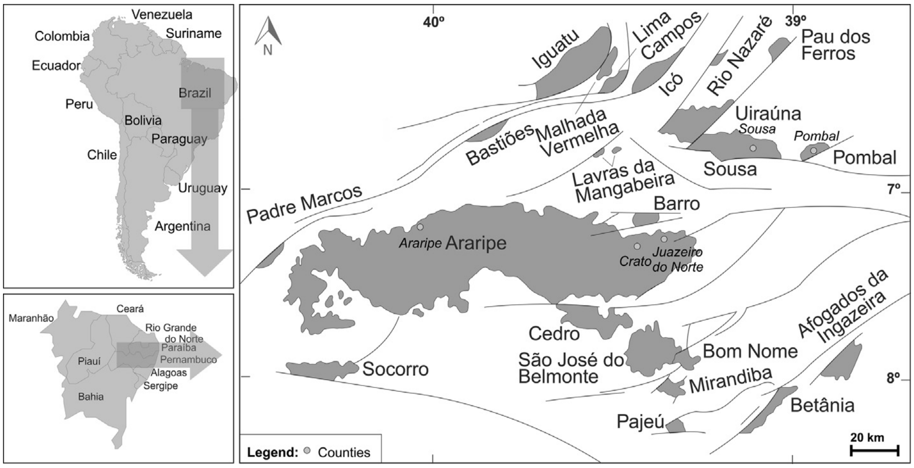

Fig. 1. Location area of the Sousa Basin and the distribution of the intracratonic basins of NE Brazil (modified from Fortier and Schultz, 2009).

Based on the structural style and petrographic-diagenetic features, Córdoba et al. (2008) inferred larger original dimensions for this basin and similar counterparts in the region, which were reduced (with exposure of the crystalline highs) by the significant erosion that occurred in late to post-rift and subsequent evolutionary stages. Two alternative hypotheses try to explain the evolution of these rift basins, either by a model considering NW extension during Neocomian-Barremian times, or by a model involving reactivation of EW and NE strike-slip Precambrian lineaments, but also involving NW extension.

Considering the existence of oil accumulated in gneissic rocks as a reservoir, this work aims an overview of the Sousa Basin stratigraphy, paleoenvironmental and architecture, as-well-as a broad description of its basement gneiss. The study of this rock was provided using a 3.01 m of a core obtained from a drilling – 2-SS-PB (core diameter 1.5″) which reached the metamorphic rock in a structural dome of the basement after 28 m from surface. The drill location is the Sítio Salguinho (Salguinho Farm) at 6° 43′25,7″S and 38° 20′17,1″W, Sousa County, Paraíba State.

The investigation on the basement rocks of the basin is relevant because the fractures system found in those rocks probably act as a natural way to the oil flux and, at least, resulting in loss of part of this oil. Taking into account the occurrence of oil and gas in igneous and metamorphic rocks, this article also presents a brief description of some important oil fields from around the world located in basement rocks.

2. The Borborema Province: a summary

The Borborema Province (Almeida et al., 1981) is characterized by zones of supracrustal rocks embedded among ortho-derived gneissic-migmatitic terrains. Paleoproterozoic and rare Archaean blocks of the gneissic basement are covered by Meso to- Neoproterozoic metasedimentary rocks. Hence it consists of a complex mosaic constituted by fold systems and crustal segments separated by an expressive set of shear zones (Brito Neves et al., 2000). The rocks present diverse structural trends that are grouped into fold systems, resulting in the superposition of diverse tectonic, metamorphic and magmatic events upon the sedimentary and volcanic rocks accumulated since the Mesoproterozoic (Almeida and Hasui, 1984). A Neoproterozoic age has been obtained for the majority of these fold systems. Granitoid rocks of Brasiliano age crosscut almost all the units of the province. The Brasiliano orogeny has been considered the main event which controlled the structural and low to- high grade metamorphic style of the province, although the Transamazonian orogeny was the main crust forming event of the region (Van Schmus et al., 1995).

According to Trompette et al. (1993) the Borborema Province belonged to a larger Precambrian paleocontinent extending into Africa, formed by convergence and collision of the São Luís/West African and São Francisco/Congo-Kasai cratons. This Precambrian basement was characterized by thermal and tectonic-magmatic processes which took place during the Meso- and Neoproterozoic continuing into the Cambrian-Ordovician (Matos, 1992).

The Borborema Province is characterized by large shear zones of predominantly NE-SW and E-W trend, which divide the province in three distinct segments, North, Central and South Domain (Van Schmus et al., 1995). The study area of this work is located at the North Domain. Two important crustal scale lineaments, Patos and Pernambuco (Ebert, 1970) cut the Borborema Province from east to west and the former is the southern border of the Rio do Peixe Basins (Fig. 1).

2.1. The Precambrian geology around Sousa Basin

The Sousa Basin is inserted in the Borborema Province, which partially corresponds to Neoproterozoic Brasiliano/Pan-African belts. The complex network of NE–SW and E–W-trending shear zones is one of the outstanding structural features of this province, which show brittle reactivation associated with Gondwana breakup in the Early Cretaceous (Castro et al., 2007; Françolin and Cobbold, 1994).

The Precambrian geological framework of the region adjacent to the Sousa Basin was described by Medeiros (2008). Archean to Paleoproterozoic basement rocks covered by Paleoproterozoic to Neoproterozoic metavolcanic and metasedimentary units delineate three large crustal domains, which are denominated as Jaguaribeano, Rio Piranhas-Seridó and Zona Transversal Domains. A significative number of plutons of Ediacarian age are widespread in the neighborhood of the Rio do Peixe Basins, being concordant and/or crosscutting the structures of the ancient units. Brasiliano age deformation is pervasive in all the lithologies, strongly obliterating older deformation phases (Fig. 2).

The main structural features of the region correspond to the dextral Malta (a branch of the Patos shear zone), Portalegre, Jaguaribe and Orós shear zones, which resulted from Brasiliano age transcurrent deformation. The Malta and Portalegre shear zones set bounds for the southern and western Rio do Peixe Basin margins, respectively. Pre- transcurrent deformation event is locally characterized as folds and penetrative foliation in the

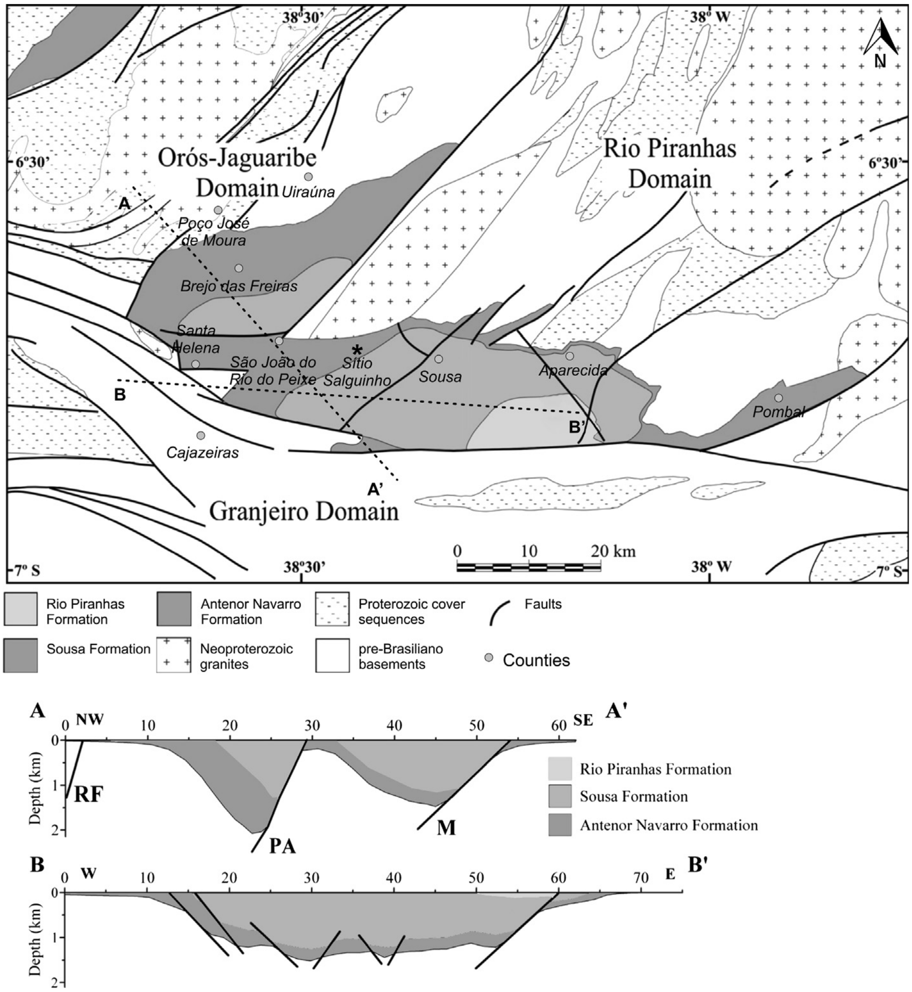

Fig. 2. Geological framework of the region adjacent to the Rio do Peixe Basins and geological sections (A–A′ and B–B′) through Brejo das Freiras and Sousa Basins (modified from Castro et al., 2007).

metasediments and low angle foliation associated with high rake lineation in the orthogneisses. A former deformation phase of difficult recognition has been identified mainly in the basement lithotypes. Castro and Castelo Branco (1999) and Castro et al. (2007) based on well-acquired gravity, magnetic, and radiometric data analyzed the basin architectural elements and the tectonic evolution of the Rio do Peixe Basins, in which Sousa Basin is included. NW–SE-trending extensional forces acting over an intensively deformed Precambrian basement yielded a composite basin architecture strongly controlled by preexisting, mechanically weak fault zones in the upper crust. The reactivated NE–SW and E–W ductile shear zones are of Brasiliano age (0.6 Ga).

In accordance to the map presented by Medeiros (2008), the Sousa Basin is surrounded by rocks of the units Caicó Complex and Poço da Cruz Suite of Rhyacian to Orosirian age, that belong to the Rio Piranhas-Seridó Domain, and Neoproterozoic granitoid plutons. The Caicó Complex comprises granitic to tonalitic calc-alkaline orthogneisses and migmatites interleaved with metavolcanosedimentary rocks and the Poço da Cruz Suite is characterized by granitic augen gneisses of calc-alkaline nature. In both units, stretching centimeter feldspar crystals are described in the orthogneisses, and hence the ortho-derived gneiss focused in this work as the basement of the Sousa Basin could belongs to one of these units.

3. The Lithostratigraphy of the Sousa Basin

The Sousa Basin comprises an area of 1250 km^2, located in the west of Paraíba state, in the counties of Aparecida, Sousa and Uiraúna. The basement corresponds to highly metamorphosed Precambrian rocks structurally aligned in a northwest–southeast or east–west direction. These rocks are granitic and gabbroic migmatitic gneisses and amphibolites.

The main lithologies in the Sousa Basin are clastic rocks, including breccias and conglomerates, sandstones, siltstones, mudstones and shales. In some cases the carbonate content is high in the form of marls and thin (cm-thick) limestones.

The oldest register of sediments is Early Devonian, identified through palynological analysis from boreholes drilled by PETROBRAS. These rocks are potentially chronocorrelative with a stratigraphic interval of the neighboring Parnaíba Basin, including parts of the Jaicós Formation (uppermost sub-unit of the Serra Grande Group) and possibly also the lower part of the Itaim Formation (Roesner et al., 2011).

A formal lithostratigraphic subdivision of the Cretaceous in the Sousa Basin, and the neighboring Uiraúna/Brejo das Freiras and Pombal basins, was erected by Mabesoone (1972) and Mabesoone and Campanha (1973/1974). These authors identified the Rio do Peixe Group, with a total thickness of 2870 m, and subdivided it into the Antenor Navarro, Sousa and Rio Piranhas formations. The

Antenor Navarro and Rio Piranhas formations are composed of immature sediments, including breccias and conglomerates, with pebbles of metamorphic and magmatic rocks in a coarse arkose matrix. These lithotypes are located near the faulted margins of the basin. Toward the basin-depocenter, there are conglomeratic and fine sandstones, sometimes interbedded with siltstones and shales. The Sousa Formation is composed of reddish sandstones, siltstones, mudstones and carbonate nodules; marls also occur. Cross-channel and planar stratification, climbing-ripples and ripple marks are the main sedimentary structures, but mud cracks, convolute structures, rain prints and evidence of bioturbation are also common.

Sedimentation in the basin was controlled by regional tectonic processes (Lima Filho, 1991). During Dom João time (latest Jurassic 'Purbeckian' stage), because of crustal extension, a sigmoidal basin developed at the inflection of the northwest–southwest and east–west faults. During Rio da Serra time (Berriasian–Hauterivian), under the same tectonic stress pattern, the basinal area increased, and its shape became rhomboidal. Eventually, probably at the end of Aratu time (Lower Barremian Stage), there was a change in the tectonic pattern and the sediment accumulation rate began to decline. The deposits reflect direct control of the sedimentation by tectonic activity. Along the faulted borders of the basin, deposition consisted of alluvial fans (Mabesoone et al., 1979), which pass distally into an anastomosing fluvial system. In the central region of the basin, a meandering fluvial system with a wide floodplain was established where perennial and temporary lakes were developed.

4. Paleoenvironments and the Sousa oil

Throughout the Early Cretaceous, hot climatic conditions were widespread, although there was probably a wide range of humidity. According to Petri (1983) and Lima (1983), in the earliest Cretaceous the climate was more humid in regions located to the south of the tropical domain (Recôncavo-Tucano-Jatobá basins). Despite a hotter and drier climate to the north, interpretations of depositional environments and fossils suggest the existence of some lakes that locally provided more humid conditions during the Neocomian.

The lithofacies, sedimentary structures and geometry of the beds of Antenor Navarro and Rio Piranhas formations point to sedimentation in fan-delta, alluvial fan and anastomosing fluvial environments. In the Sousa Formation the generally finer grain size of the sediments points to lacustrine, swampy and meandering-braided fluvial palaeoenvironments (Leonardi, 1989; Machado et al., 1990; Carvalho and Leonardi, 1992; Garcia and Wilbert, 1994; Da Rosa and Garcia, 2000). Despite the strong reddish color of Sousa Formation, typical of sediments that accumulated in subaerial environments, there are some outcrops with levels of greenish shales, mudstones and siltstones where fossils are common, which indicates organic-rich environments. The fossils are ostracods, conchostracans, plant fragments, palynomorphs and fish scales. The big-sized conchostracans *Palaeolimnadiopsis reali* (up to 3.5 cm in length), that have been described from some lacustrine facies of Sousa Basin, show optimum conditions for this group in a context of abundant freshwater, warm and wet climate (Carvalho, 1989). The dimensions of these conchostracans suggest an ecological optimum with a large amount of nutrients and chemical ions such as calcium and phosphorus (Carvalho, 1993, 2000, 2004). The palynological assemblages are characteristic of the Rio da Serra (Berriasian–Hauterivian) and Aratu (Lower Barremian) local stages (Lima and Coelho, 1987; Regali, 1990).

The oil exhsudation from Sousa Basin (Fig. 3), comes from Salguinho Farm, Sousa County. Although the region is surrounded by rocks mapped as Sousa Formation, the oil is found in metamorphic rocks from a structural dome of the basement. An expressive system of normal faults at the southeastern border of the basin caused the uplift of the basement.

Although the source rocks of the Salguinho oil are unknown, ANP data (2008) indicated that the petroleum systems of Sousa Basin has the source rocks black shales from the Sousa Formation and as reservoir rocks the sandstones of this same lithostratigraphic unit and also from the Antenor Navarro Formation. The seals are pellites and limestones from the Sousa Formation and the traps are of structural, stratigraphic a paleogeomorphic origin.

The oil sample from the well located at Salguinho Farm, was analyzed with chromatography. It has characteristics of a light oil, with 81,1% of saturated compounds and a predominance of C17 and C23 n-paraffins. The analysis of biomarkers indicates the presence of tricyclic and tetracyclic terpanes, the dominance of the 17α(H), 21β(H), 30-Hopane (C30), gammacerane/C30 17α(H), 21β(H), 30-Hopane (C30) ratio of 0.23, and C30 αβ-Hopane/C30 βα-Hopane (moretane) ratio reaching 80%. These aspects pointing out to a non-biodegraded mature oil from a lacustrine freshwater environment (Mendonça Filho et al., 2006), that probably would be

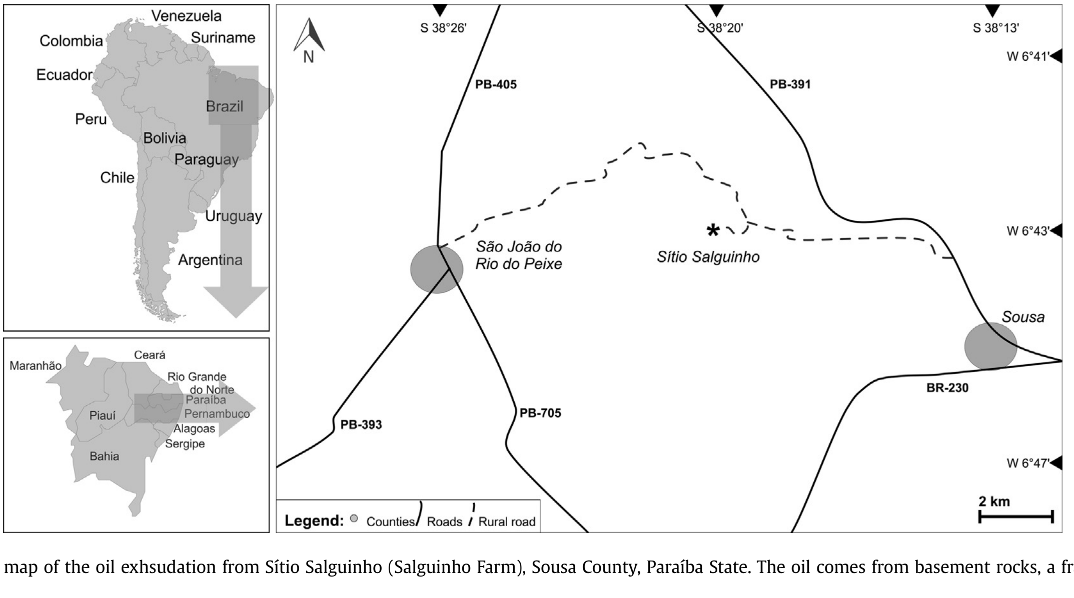

Fig. 3. Location map of the oil exhsudation from Sítio Salguinho (Salguinho Farm), Sousa County, Paraíba State. The oil comes from basement rocks, a fractured gneiss.

in a context similar to the environments interpreted for Sousa Formation.

5. Petrography of the gneissic basement

The recognition and description of the Sousa Basin basement was allowed from a drilling core containing 3.01 m of a gray to red colorful gneissic rock (Fig. 4). Red color is imprinted by superficial oxidizing of minerals, mainly feldspars. Green spots occur as the result of chlorite and epidote concentration. Compositional, granulometric and textural gradation from the bottom to the top of the core is not observed. The rock is leucocratic and presents granulometric variation ranging from ca 0.1 mm–12 mm. A gneissic foliation defined by the orientation of biotite and chlorite is noticeable. This foliation is locally deviated by coarse grains of feldspars and aggregates of quartz. The existence of continuous fracturing along the core filled mainly by chlorite, quartz and epidote, is also a relevant aspect.

Under the microscope, the grain size variation gives to the rock an inequigranular aspect related to the heterogeneous deformation. Along with this feature the texture of the gneiss also varies from lepidoblastic, where biotite and chlorite mark the foliation, to granoblastic in those areas where the concentration of recrystallized quartz and feldspar is conspicuous (Figs. 5A, B). Preservation of previous igneous feature is only punctually observed as the occurrence of subhedral to euhedral plagioclase crystals (Fig. 5C) and relicts of brown hornblende.

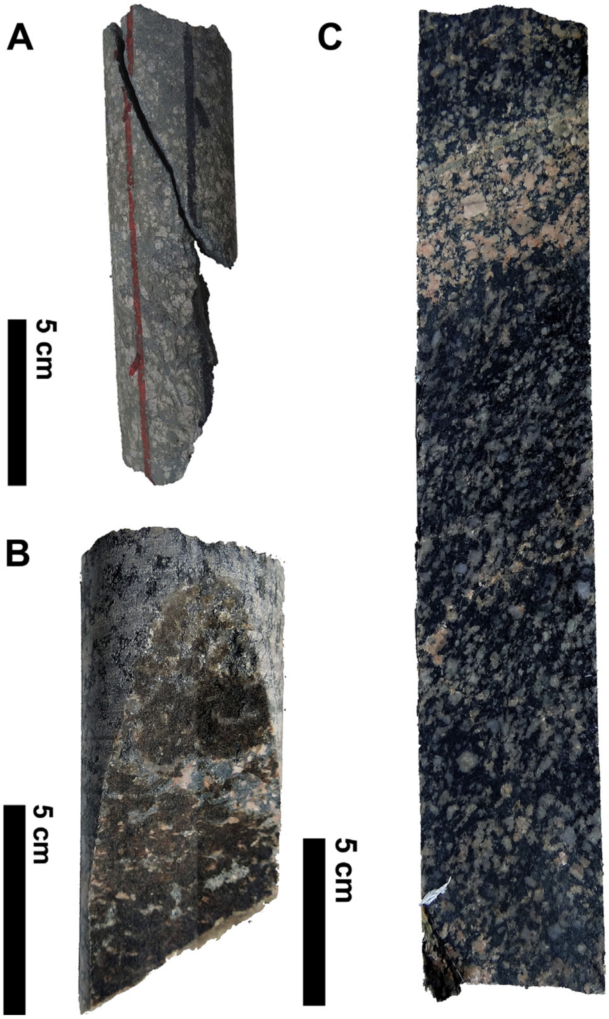

Fig. 4. Core (drilling 2-SS-1-PB) from Sítio Salguinho (Salguinho Farm) where the oil is found in the gneissic basement. (A) Fractured Precambrian basement (Box 8) at 27.40 m depth – an important pathway for fluid migration. (B) Fracture surface covered by oil (Box 9) at 30.95 m depth. (C) Longitudinal section of the core (Box 9) showing the megascopic aspect of the basement at 31.15 m depth.

Deformation textures are to be observed in the common occurrence of quartz grain showing strong wave extinction as well as recrystallized quartz aggregates showing polygonal contacts (Fig. 5B). Feldspar crystals also present important evidences of deformation like as: lobate contacts giving rise to bulging relationship with quartz or another feldspar grain, as a result of grain migration boundary (GMB) or even subgrain rotation, as described by Passchier and Trouw (2005). Such metamorphic reequilibrium of the feldspars enabled the development of nucleus-mantle structures where a large core is involved by a rim of new grains of feldspar (Fig. 5C). Hence, this granulometric heterogeneity resulted from the deformation, together with the existence of a mosaic of polygonal quartz grains allows to interpret such textures as a response of dynamic recrystallization mechanism followed by static recrystallization in temperatures over than 500 °C (Passchier and Trouw, 2005).

The primary mineralogy of the gneiss is represented by plagioclase, quartz, biotite, allanite and opaque minerals, whereas brown hornblende and microcline were identified in only one thin section. Multiple twining characterizes plagioclase grains, but feldspars without twining are common and most of them are replaced by epidote, clinozoisite and sericite, what permit being interpreted as plagioclase. The secondary paragenesis points to low- to medium grade metamorphic overprint generating epidote and clinozoisite replacing plagioclase and hornblende, chlorite overgrowing hornblende and biotite and sericite replacing feldspars, accompanied by quartz of second generation. Chlorite showing purple interference color is widespread in the rock and it may present relict of typical amphibole cleavage (Fig. 5D, E). A common relationship between epidote, chlorite, biotite, opaque minerals and titanite indicates that this last mineral is also related to metamorphic reactions as well as suggests that there is a secondary formation of biotite and opaque minerals. Such mineral association is conformable with metamorphic re-equilibrium in green-schist facies for the gneiss. Apatite and zircon are accessories frequently included in the other phases. Modal analysis displayed in Table 1 reveals tonalitic composition for the gneiss with plagioclase contents up to 50 vol.%.

The studied thin sections also allowed perceiving fractures clearly observed in the core. They affect mainly crystals of quartz and feldspars and are filled by epidote, quartz, clinozoisite and chlorite. In some of these veins one can see that the minerals are oriented parallel to the rock foliation (Fig. 5F), pointing to a pre- to syn-tectonic nature for those minerals. The development of this set of fractures probably gave rise to a secondary porosity for the gneiss, making then possible the diffusion and flux of the oil found in the rock and elsewhere. Together this cracking process, retrometamorphism and hydrothermal mineral alteration could have provoked change in the porous system of the rock.

6. Discussion

The term “basement rocks” generates a variety of definitions, although most petroleum geologists consider basement as any metamorphic or igneous rock which is unconformably overlain by a sedimentary sequence (Petford and McCaffrey, 2003; Koning, 2003). Oil and gas may have migrated into older porous metamorphic or igneous rocks, thereby forming a basement reservoir. Landes et al. (1960) stated that “the only major difference between basement rock and the overlying sedimentary rock oil deposits is

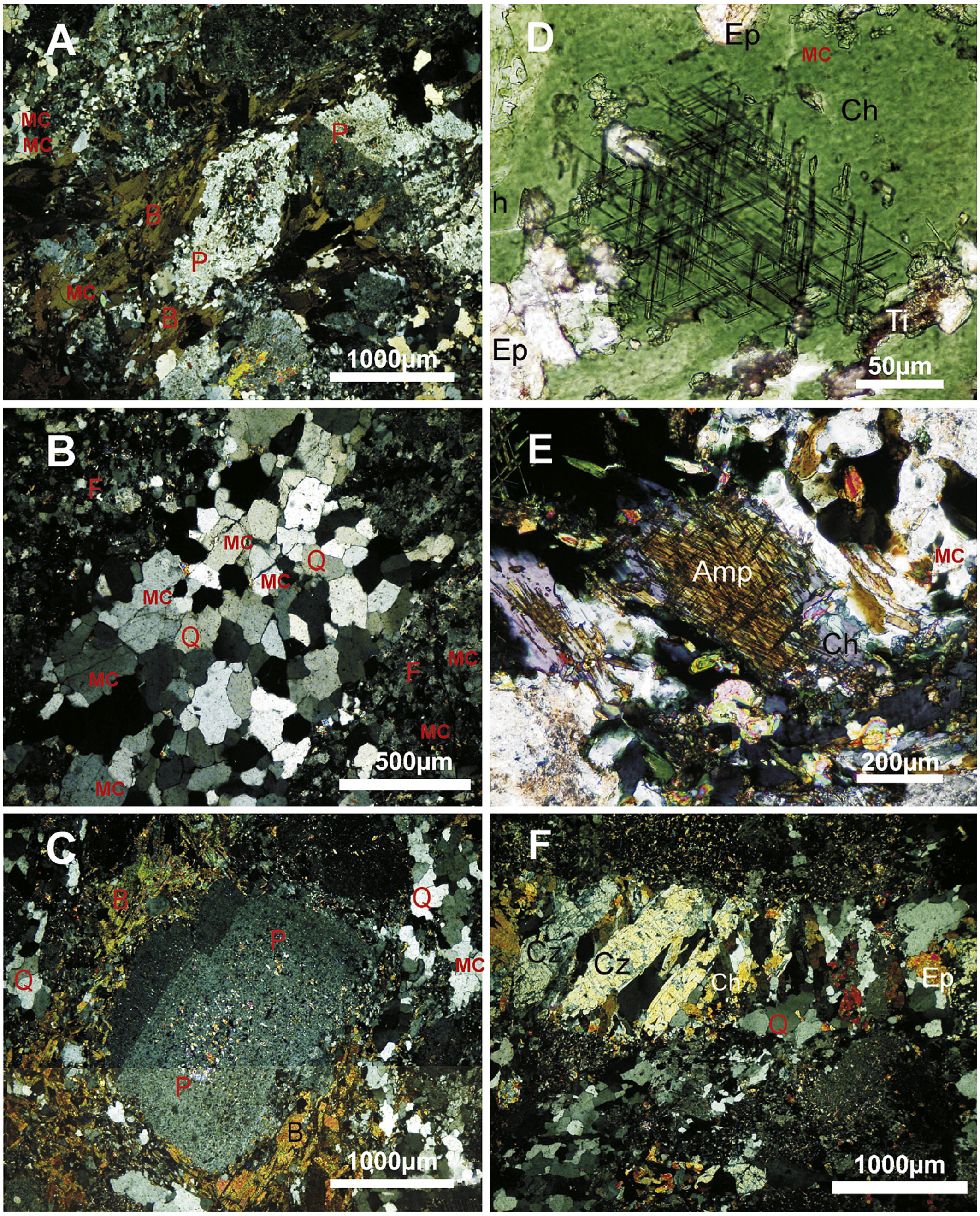

Fig. 5. (A) Lepidoblastic texture of the gneiss characterized by the orientation of crystals of biotite and chlorite. Note that the foliation is conspicuously deviated by large grains of altered felsdspar. (B) Granoblastic texture of the gneiss in an area dominated by quartz and feldspar; a quartz polycrystalline aggregate is enveloped by a matrix formed mainly by feldspar. Note a set of microcraks (MC) that enhance the permoporous system (C) Crystal of altered subhedral plagioclase with deformation feature defined by a recrystallized core and a mantle of new grains, more visible at upper and right limit of the crystal. (D) Detail of a crystal of green chlorite showing relict cleavage of amphibole. Note the association with epidote and titanite. (E) Relict of amphibole replaced by chlorite with purple interference color. (F) Fracture in the gneiss filled by epidote, quartz, clinozoisite and chlorite. Observe that the minerals into the vein tend to be parallel to the rock foliation. Amp: Amphibole; B: Biotite; Ch: Chlorite; Cz: Clinozoisite; Ep: Epidote; F: Feldspar; P: Plagioclase; Ti: Titanite; Q: quartz; MC: microcracks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that in the former case the original oil-yielding formation (source rock) cannot underlie the reservoir".

Basement rocks are important oil and gas reservoirs in many areas of the world, including reservoirs such as fractured or weathered granites, quartzites or metamorphics. Schutter (2003) presented the distribution of hydrocarbons occurrences in and around igneous rocks, showing them to be global in extent, occurring in over 100 countries worldwide. Accordingly Koning (2000, 2003) and Schutter (2003) oil is produced from basement rocks in a number of countries including China, Vietnam, former USSR (West Siberia), Ukraine, Indonesia, Libya, Algeria, Morocco, Egypt, USA, Brazil and Venezuela.

Although basement oil fields are typically very complex reservoirs with multiple lithologies, possibly two or more fracture systems and multiple oil-water or gas-water contacts (Koning, 2003), as verified by Petford and McCaffrey (2003) commercial oil deposits in basement rocks are not geological accidents, but are oil accumulations which obey all the rules of oil sourcing, migration and entrapment.

As demonstrated by McCaffrey et al. (2003) fractures are ubiquitous in crystalline rocks and control the strength and the fluid

Table 1
Modal composition (vol%) of the basement tonalitic gneiss.

	S201	S202	S203	S204	S205	S206	S28	S07	S09	S10	S11	S12
Quartz	31.2	27.8	37.4	39.1	33.8	27.0	39.2	28.8	25.8	42.8	42.6	42.4
Plagioclase	49.4	42.6	35.6	44.2	39.5	45.0	43.3	35.6	50.6	43.2	44.1	51.6
Biotite	2.8	5.8	1.0	2.6	2.6	3.6	0.8	28.4	3.4	2.6	0.8	0.4
Chlorite	12.4	13.0	4.8	11.2	17.4	17.8	8.6	3.8	17.2	4.4	5.6	1.0
Opaque	1.4	1.6	1.6	0.8	tr	0.6	0.2	0.8	tr	0.8	1.0	0.4
Epidote	1.6	6.5	17.0	1.2	5.2	5.6	5.6	0.8	1.6	2.6	3.4	2.4
Sericite	0.8	2.0	2.2	0.6	1.5	0.6	1.8	1.8	1.2	3.6	2.0	1.8
Titanite	0.4	0.5	tr	0.3	tr	0.4	0.3	–	tr	tr	0.5	tr
Clinozoisite	tr	0.2	0.4	–	tr	–	tr	tr	0.2	–	tr	tr
Zircon	tr	tr	tr	tr	–	tr	tr	–	–	tr	–	tr
Allanite	tr	tr	tr	tr	tr	–	0.2	–	–	tr	tr	–
Apatite	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Q	38.7	39.5	51.2	47.0	46.1	37.5	47.5	44.7	33.8	49.8	49.1	44.7
A	0	0	0	0	0	0	0	0	0	0	0	0
P	61.3	60.5	48.8	53.0	53.9	62.5	52.5	55.3	66.2	50.2	50.9	55.3

tr = trace.

transport. Reservoir basement rocks in Venezuela, California, Kansas, and Morocco are fractured metamorphic and igneous rocks, and trapping can be either anticlinal or due to varying permeability. These basement rock accumulations occur where the basement is at a higher elevation than the surrounding flanking sediments and the sedimentary veneer overlying the basement rock may or may not contain oil accumulations (Landes et al., 1960).

Walters (1953) described oil production from fractured Precambrian basement rocks in central Kansas, U.S.A. He observed that the wells known to be producing from basement are on the summits of buried Precambrian hills. Porosity consists of a reticulated fracture system. Oil migrated locally into the fractures in the Precambrian rocks from the overlying rocks or from the flanks of each hill. Walters (1953) considered that where encountered structurally (or topographically) high, the fractured basement rocks are worthy of careful consideration as a potential commercial oil reservoir. P'An (1982) also recognized that basement reservoirs always occur on highs or uplifts within the basin, and have been subjected to long periods of weathering and erosion. The younger sediments (presumably source beds) directly overlie basement, providing opportunity for entrapment of oil in the basement rock.

One important basement producer is the La Paz-Mara oil fields. Oil occurs in intensely fractured pre-Cretaceous igneous (granites) and metamorphic rocks in the northwest Maracaibo Basin, Venezuela. The accumulations are believed to have a common origin in the Cretaceous limestones of La Luna and Cogollo Formations. As observed by Smith (1956) migration into the basement may have taken place as a result of hydrostatic pressure gradients established by dilatancy accompanying fracturing. According Landes et al. (1960) initial production of Mara Oil Field was about 2700 bbl/day but one well produced 17,000 bbl/day.

The characterization of the fractures pattern and their resulting apertures is of particular importance in crystalline reservoirs, as flow occurs mainly in fractures. This aspect is crucial in igneous and metamorphic rocks, since fractures in these rocks are generally the most important pathways for fluid migrations. Although this generally accepted hypothesis of "up-slope" theory of oil migration in basement reservoirs, McNaughton (1953) presented an alternative proposition in which "fracturing of competent basement rocks involves dilatancy which in turn reduces hydrostatic pressures in focal areas of deformation. Pressure gradients are thereby established between the potential basement reservoir rocks and the overlying source and carrier beds containing oil, gas, and water. Thus a tendency to "suck in" fluids into the basement rocks is established".

Areshev et al. (1992) described an oil- and gas fields from the continental shelf of Southern Vietnam, in which the main pay-zone is in the basement, composed of granites and granodiorites. The granites have undergone severe alteration as a result of tectonic, hydrothermal and surface weathering processes, that allowed cavernous fracture porosity in deep basement zones, and to "porous cavernous" fracturing at more shallow levels.

In Brazil, the most important oil reservoir in basement is that of the Carmópolis Field, state of Sergipe. There the reservoirs are fractured Precambrian schists and phylites that are cut by quartz veins of SW-NE direction (Milani and Medeiros de Araújo, 2003). The authors stress the heterogeneous characteristic of the permoporous system which was developed by fractures, microfractures and dissolution features observed in the quartz veins.

Considering the geological framework of the Sousa Basin, the sediments overlie tonalitic gneiss basement that undergone severe changes in its mineralogy due to retrometamorphic and alteration phenomena's. Besides, expressive fracturing of the rock is noteworthy, what can be related to the normal fault system that uplifts this basement. These modifications possibly caused disturbs in physical parameters of the gneiss like as porosity and permeability, similar to that pointed by Arashev et al. (1992) in Southern Vietnam. The formation of secondary porosity should be related mainly to the development of cracks and microcracks, maybe enhanced by the rearrangement of the minerals from retrometamorphic and alteration processes (see the development of cracks and microcracks in Figs. 4 and 5). The formation of a permoporous system in granitic rocks is treated by Psyrillos et al. (2003) possibly as resulting from the relationship between fluid flow, tectonics and hydrotermal alteration. They considered that the alteration process of the fractured granite gave rise to a porous quartz-kaolin rock matrix. In Sousa Basin basement, the secondary porosity and permeability of the rock could be markedly related to fracturing but the fabric of chlorite and biotite, defining a lepidoblastic texture (Fig. 5A), should have improved this parameter, in order to make easy the migration of the alteration fluid, and, at last extension, the above mentioned oil.

7. Conclusions

The Sousa Basin presents oil accumulation in crystalline rocks from the basement. The tonalitic gneiss of Borborema Province shows clear evidences of strong transformations due to the activity of metamorphic/hydrothermal fluids as well as brittle structures. The irregular porosity and permeability developed in the gneissic basement was possibly induced by a combination of fracturing with mineralogical and textural modifications during retrometamorphic and post-metamorphic (hydrothermal alteration phenomena) events. Expressive fracturing of the rock allowed an important pathway for fluid migration, allowing its exhsudation. The importance of the fractures analysis, as secondary porosity, highlights the relevance of the detailed petrographic study of the basement of Sousa Basin.

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References

Almeida, F.F., Hasui, Y., Brito Neves, B.B., Fuck, R.A., 1981. Brazilian structural provinces: an introduction. Earth Sciences Review 17, 1–29.

Almeida, F.F.M., Hasui, Y., 1984. In: Paulo, São (Ed.), O Pré-cambriano Do Brasil. Edgard Blücher, São Paulo.

ANP (Agência Nacional do Petróleo). Brazil Round 9, 2008. Rio Do Peixe Basin. Nona Rodada de Licitações. Cid Queiroz Fontes. Bid Area Department.

Areshev, G., Le Dong, T., San, N.T., Shnip, O.A., 1992. Reservoirs in fractured basement on the continental shelf of Southern Vietnam. Journal of Petroleum Geology 15, 451–464. http://dx.doi.org/10.1111/j.1747-5457.1992.tb01045.x.

Brito Neves, B.B., Santos, E.J., Van Schmus, W.R., 2000. Tectonic history of the Borborema Province. In: Cordani, U., Milani, E.J., Thomas Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America. In-Fólio Produção Editorial, Rio de Janeiro, pp. 151–182.

Carvalho, I.S., 1989. Icnocenoses continentais: bacias de Sousa, Uiraúna-Brejo das Freiras e Mangabeira. MSc thesis. Universidade Federal do Rio de Janeiro, Rio de Janeiro, pp. 1–167. [Unpublished].

Carvalho, I.S., 1993. DSc thesis. Os conchostráceos fósseis da bacias interiores do Nordeste do Brasil, vol. 1. Universidade Federal do Rio de Janeiro, Rio de Janeiro, pp. 1–319. [Unpublished].

Carvalho, I.S., 2000. Geological environments of dinosaur footprints in the intracratonic basins of northeast Brazil during the Early Cretaceous opening of the South Atlantic. Cretaceous Research 21, 255–267.

Carvalho, I.S., 2004. Dinosaur footprints from northeastern Brazil: Taphonomy and Environmental Setting. Ichnos 11, 311–321.

Carvalho, I.S., Leonardi, G., 1992. Geologia das bacias de Pombal, Sousa, Uiraúna-Brejo das Freiras e Vertentes (Nordeste do Brasil). Anais da Academia Brasileira de Ciências 64, 231–252.

Castro, D.L., Castelo Branco, R.M.G., 1999. Caracterização da arquitetura interna das bacias do Vale do Cariri (NE do Brasil) com base em modelagem gravimétrica 3-D. Brazilian Journal of Geophysics 17 (2,3), 129–144.

Castro, D.L., Oliveira, D.C., Castelo Branco, R.M.G., 2007. On the tectonics of the Neocomian Rio do Peixe Rift Basin, NE Brasil: Lessons from gravity, magnetics, and radiometric data. Journal of South American Earth Sciences 24, 184–202.

Córdoba, V.C., Antunes, A.F., Jardim de Sá, E.F., Silva, A.N., Sousa, D.C., Lins, F.A.P.L., 2008. Análise estratigráfica e estrutural da Bacia do Rio do Peixe, Nordeste do Brasil: integração a partir do levantamento sísmico pioneiro 0295_RIO_DO_PEIXE_2D. Boletim de Geociências da Petrobras 16, 53–68.

Da Rosa, A.A.S., Garcia, A.J.V., 2000. Palaeobiogeographic aspects of northeast Brazilian basins during the Berriasian before the break up of Gondwana. Cretaceous Research 21, 221–239.

Ebert, H., 1970. The Precambrian geology of the Borborema belt (state of Paraíba and Rio Grande do Norte, northeastern Brazil) and the origin of its mineral resources. Geologische Rundschau 59, 1299–1326.

Françolin, J.B.L., Cobbold, P.R., 1994. Cretaceous Rio do Peixe basin (NE Brazil) and its significance for the opening of the Atlantic. Journal of Structural Geology 16 (5), 647–661.

Fortier, D.C., Schultz, C.L., 2009. A new Neosuchian Crocodylomorph (Crocodyliformes, Mesoeucrocodylia) from the Early Cretaceous of north-east Brazil. Palaeontology 52, 991–1007.

Garcia, A.J.V., Wilbert, A., 1994. Palaeogeography evolution of Mesozoic pre-rift sequences in coastal and interior basins of northeastern Brazil. In: Embry, A.F., Beauchamp, B., Glass, D.J. (Eds.), 1994. Pangea: Global Environments and Resources, vol. 17. Canadian Society of Petroleum Geology, Memoir, pp. 123–130.

Koning, T., 2000. Oil production from basement reservoirs – examples from Indonesia, USA and Venezuela. World Petroleum Congress 16. June 11–15, 2000, Calgary, Canada. Conference Paper. Document ID 30146.

Koning, T., 2003. Oil production from basement reservoirs – examples from Indonesia, USA and Venezuela. In: Petford, N., McCaffrey, K. (Eds.), Hydrocarbons in Crystalline Rocks, Geological Society of London, Special Publications, vol. 214, pp. 83–92.

Landes, K.K., Amoruso, J.J., Charlesworth Jr., L.J., Heany, F., Lesperance, P.J., 1960. Petroleum resources in basement rocks. AAPG Bulletin 44, 1682–1691.

Leonardi, G., 1989. Inventory and statistics of the South American dinosaurian ichnofauna and its paleobiological interpretation. In: Gillette, D.D., Lockley, M.G. (Eds.), Dinosaur Tracks and Traces. Cambridge University Press, Cambridge, pp. 165–178.

Lima, M.R., 1983. Paleoclimatic reconstruction of the Brazilian Cretaceous based on palynology data. Revista Brasileira de Geociências 13, 223–228.

Lima, M.R., Coelho, M.P.C.A., 1987. Estudo palinológico da sondagem estratigráfica de Lagoa do Forno, Bacia do Rio do Peixe, Cretáceo do Nordeste do Brasil. Boletim do Instituto de Geociências–USP. Série Científica 18, 67–83.

Lima Filho, M.F., 1991. Evolução tectono-sedimentar da Bacia do Rio do Peixe-PB. MSc thesis. Universidade Federal de Pernambuco, Pernambuco, pp. 1–99. [Unpublished].

Mabesoone, J.M., 1972. Sedimentos do Grupo Rio do Peixe (Paraíba). Congresso Brasileiro de Geologia 26, 1. Sociedade Brasileira de Geologia, Belém, 236.

Mabesoone, J.M., 1994. Sedimentary Basins of Northeast Brazil. In: Geology Department, Special Publication 2. Federal University Pernambuco, pp. 1–308.

Mabesoone, J.M., Campanha, V.A., 1973/1974. Caracterização estratigráfica dos grupos Rio do Peixe e Iguatu. Estudos Sedimentológicos 3/4, 21–41.

Mabesoone, J.M., Lima, P.J., Ferreira, E.M.D., 1979. Depósitos de cones aluviais antigos, ilustrados pelas formações Quixoá e Antenor Navarro (Nordeste do Brasil). In: *Simpósio de Geologia do Nordeste*, 9, Anais, Recife, Sociedade Brasileira de Geologia/Núcleo Nordeste, Boletim 7, pp. 225–235.

Machado Jr., D.L., Dehira, L.K., Carneiro, C.D.R., Almeida, F.F.M., 1990. Reconstruções paleoambientais do Juro-Cretáceo no Nordeste Oriental Brasileiro. Revista Brasileira de Geociências 19, 470–485.

Matos, R.M.D., 1992. The Northeast Brazilian rift system. Tectonics 11, 766–791.

McCaffrey, K.J.W., Sleight, J.M., Pugliese, S., Holdsworth, R.E., 2003. Insights from Attribute Analysis Fracture Formation and Evolution in Crystalline Rocks. In: Geological Society, London, Special Publications, vol. 214, pp. 109–124. http://dx.doi.org/10.1144/GSL.SP.2003.214.01.07.

McNaughton, D.A., 1953. Dilatancy in migration and accumulation of oil in metamorphic rocks. AAPG Bulletin 37, 217–231.

Mendonça Filho, J.G., Carvalho, I.S., Azevedo, D.A., 2006. Geochemical aspects of the oil from the Sousa Basin (Lower Cretaceous), Northeast Brazil: geological context. São Paulo, UNESP. Geociências 25, 91–98.

Medeiros, V.C., 2008. Geologia e Recursos Minerais da Folha Sousa SB.24-X-A, escala 1:250.000, Estados da Paraíba, Rio Grande do Norte e Ceará. Recife. CPRM – Serviço Geológico do Brasil.

Milani, E.J., Medeiros de Araújo, L., 2003. Recursos Minerais Energéticos: Petróleo. In: Bizzi, L.A., Schobbenhaus, C., Vidotti, R.M., Gonçalves, J.H. (Eds.), Geologia, Tectônica e Recursos Minerais do Brasil. CPRM, Brasília, pp. 553–564.

P'An, C.-H., 1982. Petroleum in basement rocks. AAPG Bulletin 66, 1597–1643.

Passchier, C., Trouw, R.A.J., 2005. Micro-tectonics, second ed. Springer-Verlag Berlin Heidelberg, Germany.

Petford, N., McCaffrey, K., 2003. Hydrocarbons in crystalline rocks: an introduction. In: Petford, N., McCaffrey, K. (Eds.), Hydrocarbons in Crystalline Rocks, Geological Society of London, Special Publications, vol. 214, pp. 1–5.

Petri, S., 1983. Brazilian Cretaceous paleoclimates: evidence from clay-minerals, sedimentary structures and palynomorphs. Revista Brasileira de Geociências 13, 215–222.

Ponte, F.C., 1992. Origem e evolução das pequenas bacias cretácicas do interior do Nordeste do Brasil. In: Simpósio sobre as Bacias Cretácicas Brasileiras, 2, Rio Claro (SP), Resumos expandidos, UNESP, pp. 55–58.

Psyrillos, A., Burley, S.D., Manning, D.A., Fallick, A., 2003. Coupled mineral-fluid evolution of a basin and high: kaolinization in the SW England granites in relation to the development of the Plymouth Basin. In: Geological Society, London, Special Publications, vol. 214, pp. 175–195.

Regali, M.S.P., 1990. Biocronoestratigrafia e paleoambiente do Eocretáceo das bacias do Araripe (CE) e Rio do Peixe (PB), NE-Brasil. In: Simpósio sobre a Bacia do Araripe e bacias interiores do nordeste, Crato, Atas 1, pp. 163–172.

Roesner, E.H., Lana, C.C., Hérissé, A.L., Melo, J.H.G., 2011. Bacia do Rio do Peixe (PB): novos resultados biocronoestratigráficos e paleoambientais. In: Carvalho, I.S., Srivastava, N.K., Strohschoen Jr., O., Lana, C.C. (Eds.), Paleontologia: Cenários de Vida. Editora Interciência, Rio de Janeiro, pp. 135–141.

Schutter, S.R., 2003. Occurrences of hydrocarbons in and around igneous rocks. In: Petford, N., Mccaffrey, K.J.W. (Eds.), 2003. Geological Society, London, Special Publications, vol. 214, pp. 35–68.

Smith, J.E., 1956. Basement reservoir of La Paz-Mara oil fields, western Venezuela. AAPG Bulletin 40, 380–385.

Trompette, R., Egydio-Silva, M., Tommasi, A., Vauchez, A., Uhlein, A., 1993. Amalgamação do Gondwana Ocidental no Panafricano-Brasiliano e o papel da geometria do Cráton do São Francisco na arquitetura da Faixa Ribeira. Revista Brasileira Geociências 23, 187–193.

Valença, L.M.M., Neumann, V.H., Mabesoone, J.M., 2003. An overview on Callovian-Cenomanian intracratonic basins of Northeast Brazil: Onshore stratigraphic record of the opening of the southern Atlantic. Geologica Acta 1, 261–275.

Van Schmus, W.R., Brito Neves, B.B., Harckspacher, P., Babinsky, M., 1995. U/BP and Sm/Nd geochronologic studies of the eastern Borborema province, northeastern Brazil: Initial conclusions. Journal of South American Earth Sciences 8, 267–288.

Walters, R.F., 1953. Oil production from fractured pre-Cambrian basement rocks in Central Kansas. AAPG Bulletin 37, 300–313.