STRATIGRAPHIC ASPECTS AND FACIES DESCRIPTION OF MIRANDIBA BASIN, NORTHEAST, BRASIL

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ABSTRACT

Mirandiba Basin, located in the central portion of the State of Pernambuco, represents one of the Northeast Brazilian intracontinental rift basins. Considering the lack of geological studies in this area, this research aims to document and describe the main sedimentological and faciological aspects observed in Mirandiba Basin. The methodology involved the observation of Google Earth's images, and the analysis of the Digital Elevation Model (DEM), derived from SRTM (Shuttle Radar Topography Mission), in order to provide a better view of the area and to promote the selection of the best outcrops. Four sedimentary formations were identified in this study. The Tacaratu Formation (Siluro-Devonian) represents the oldest and most abundant sediments of the basin and it is essentially composed of sandstone dominated facies. As main characteristics, the basin shows the presence of deformation bands, mainly at its border, and the common presence of conglomeratic levels, as well. The Inajá Formation, located stratigraphically above Tacaratu Formation, is marked by sandstone facies (composed of reddish sandstones, eventually containing small limonite nodules) and by a siltstone facies. The Aliança Formation consists of two facies: (i) red to brown shales, representing the most abundant facies and (ii) calciferous siltstone (which contains ostracods), usually interbedded between layers of the anterior facies. The Sergi Formation, which presents the smallest extent, is dominated by the presence of sandstone facies; however, conglomeratic and siltstone facies are also observed. Four facies associations (S1, S2, S3 and F1) were described to characterize two main depositional systems in Mirandiba Basin. Associations S1, S2 and S3 characterize a typical fluvial braided system associated to the Tacaratu, Inajá and Sergi formations, whereas F1 association describes a lacustrine environment in the Aliança Formation.

Keywords: Mirandiba Basin, Northeast Brazilian Intracontinental Rift Basins, stratigraphy, facies association, Digital Elevation Model.

RESUMO

A Bacia Mirandiba, localizada na porção central do estado de Pernambuco, representa uma das bacias interiores do Nordeste. Considerando a falta de estudos em geologia nesta área, esta pesquisa tem como objetivo documentar e descrever os principais aspectos sedimentológicos e faciológicos observados na Bacia de Mirandiba. A metodologia envolveu além da observação de imagens do Google Earth, a análise do Modelo Digital de Elevação (DEM), derivado do SRTM (*Shuttle Radar Topography Mission*), ambas com intuito de proporcionar uma melhor visualização da área e seleção dos melhores afloramentos. Quatro formações sedimentares foram identificadas neste estudo. A

Formação Tacaratu (Siluro-Devoniano) representa os sedimentos mais abundantes e antigos da bacia e é composta por fácies essencialmente arenosas. Como características principais estão a presença de bandas de deformação principalmente na borda da bacia, além da comum presença de níveis conglomeráticos. A Formação Inajá, localizada estratigraficamente acima da Formação Tacaratu, é marcada por fácies arenosas (compostas por arenitos vermelhos contendo, por vezes, nódulos limoníticos) e por uma fácies siltítica. A Formação Aliança é composta por duas fácies: (i) folhelhos vermelhos a marrons, representando a fácies mais abundante e (ii) arenitos calcíferos, geralmente intercalados entre camadas da fácies anterior. A Formação Sergi, a qual apresenta a menor extensão, é predominantemente marcada por presença de fácies arenosa, no entanto, também são observadas fácies conglomerática e siltosa. Quatro associações de fácies (S1, S2, S3 and F1) foram descritas para caracterizar os dois principais sistemas deposicionais da Bacia Mirandiba. A associação de fácies S1, S2 e S3 caracterizam um sistema fluvial entrelaçado associado as formações Tacaratu, Inajá e Sergi, enquanto a associação F1 descreve um sistema deposicional lacustre caracterizado na Formação Aliança.

Palavras-chave: Bacia Mirandiba, Bacias interiores do Nordeste, estratigrafia, associação de fácies, Modelo Digital de Elevação.

INTRODUCTION

The evolution of northeast Brazilian intracontinental rift basins, including their tectonic, structural and sedimentary aspects, have been addressed in several studies since the 1970's (e.g. Ponte, 1971; Conceição *et al.*, 1988; Matos, 1992; Matos, 1999). These studies treated those basins in a regional matter and did not discuss properly their individualities, except for the Araripe Basin. Probably, this could be due to their size and variety of stratigraphic record. Basins as Mirandiba, Betânia, and São José do Belmonte cover regions of 140 km², 280 km² (Aguiar *et al.*, 2010) and 750 km² (Costa *et al.*, 2006), respectively. On the other hand, the Araripe Basin comprises an area of 9.000 km².

In order to minimize this issue, a geological mapping was performed through the limits of Mirandiba Basin. It involved the description of its main sedimentological and stratigraphic aspects. Thus, the aims of this paper are: (1) to document a set of sedimentary formations recognized on the field, and (2) to describe the principal

sedimentological facies observed in these formations.

GEOLOGICAL SETTING

Mirandiba Basin represents one of the Brazilian intracontinental rift basins. It is located in the Central Domain of Borborema Province and it is placed, specifically, in Alto Pajeú Terrain, which is limited by the lineaments Patos to the north and Pernambuco to the south (Fig. 1) (Medeiros, 2004). The basement rocks are represented by Precambrian metamorphic (gneiss, migmatite, schist, quartzite) and igneous rocks (granite and syenite) (Silva Jr., 1997). The main regional structures are E-W and NE-SW transcurrent shear zones. These megashears have their genesis related to the evolution of the Brasiliano-Pan-African Orogeny (0.6 - 0.58 Ga) (Vauchez *et al.*, 1995). According to Matos (1999), this complex network of regional shear zones controls the crustal heterogeneities around the Central domain. It only discussed about early-rift and post-rift stage.

In general, when discussing about the evolution intracontinental rift basins of Brazil, Mattos (1992) suggests three

different stages known as Sin-rift I, II and III based on structural style, rift dynamics, and stratigraphic variations

The first one occurred in the Late Jurassic and records the initial phase of the rifting process marked by a crustal extensional deformation with deposition of clastic sediments in a wide and shallow basin. The second occurred in early Cretaceous (Neocomian age) and is characterized by the presence of faulted strata (syndepositional conditions) deposited in the intracontinental rift basins. The final stage known as Sin-rift III (Barremian age) represents the climax stage of the rifting process. Then, the extensional process started to be focused along the South Atlantic continental margin

In a similar way to other intracontinental basins of the Northeast of Brazil, the development of Mirandiba Basin comprises two main evolutionary phases (Leite *et al.*, 2000; Silva Jr., 1997). The first one consists of a thermal subsidence (synclisis) during Paleozoic. The other is related to a rifting phase, which consists of a sequence of tectonic events related to the fragmentation of Gondwana Palecontinent and further South Atlantic Ocean opening, during Neojurassic and Cretaceous (Matos, 1992; Matos, 1999).

The Mirandiba Basin records two tectonosequences. The first sequence, termed as Beta sequence, represents the

earliest depositional cycle reported in Brazilian intracratonic basins. It corresponds to a complete transgressive-regressive cycle occurred during the Silurian-Devonian period with a depositional system being formed by continental and shallow marine environments (Soares *et al.*, 1978; Ponte and Ponte Filho, 1996; Rocha & Leite, 1999). The second one is termed pre-rift sequence representing the precursor stage of the rifting process. Some authors argue that it represents the early stage of the rifting process. For these authors the lithosphere was already stretching, however, faults and other main structures were still not generated at this point (Matos, 1999). Furthermore, it comprises an exclusive continental depositional cycle formed by Jurassic lacustrine and fluvial-eolian deposits (Rocha & Leite., 1999; Ponte & Ponte Filho., 1996).

Due to similarities, in terms of lithostratigraphic record, and spatial proximity, some authors (e.g. Braun, 1966; Aguiar, *et al.*, 2010; Brasilino *et al.*, 2014) correlated Mirandiba Basin stratigraphic formations to those present in Jatobá Basin. Following these assumptions, as well as the fact that Mirandiba Basin does not have its own stratigraphic chart, we also used Jatobá Basin lithostratigraphic terminology to assign different formations in Mirandiba Basin.

Figure 1: Simplified geological map showing the Northeast Brazilian intracontinental rift basins. The study area, Mirandiba Basin, is highlighted in the red square (modified from Ponte, 1991).

MATERIAL AND METHODS

The analysis of Mirandiba Basin sedimentary and faciological characteristics was grounded by a 1:50.000 scale geological mapping, in which approximately 80 outcrops were studied during three fieldwork stages. DEM (Digital Elevation Model) images (30 m resolution) derived from SRTM (Shuttle Radar Topography Mission) – provided by the Brazilian Geomorphometric Data Bank (TOPODATA), were used in order to achieve a regional topographic visualization (Fig. 2). In addition, Google Earth images were used to identify the best land exposures.

Facies analysis presented here was based on the classification scheme of Miall (1996).

RESULTS

Four different sedimentary formations were identified in this study: Tacaratu, Inajá, Aliança, and Sergi (Fig. 3). The first two are Paleozoic. Tacaratu Formation date from the Silurian/Devonian period (Barbosa, 1964), while Inajá Formation, from the Devonian period (Barreto, 1968; Pereira *et al.*, 2012). The younger formations (Aliança and Sergi) are Mesozoic and date from Upper Jurassic (Leite *et al.*, 2000, Silva *et al.*, 2017).

Figure 2: DEM image displaying the topographic variation in the study area. The dashed region represents Mirandiba Basin contour.

Figure 3: Simplified geologic map of Mirandiba Basin superimposed over the DEM image (directionally filtered in the 135Az orientation).

Tacaratu Formation

The Tacaratu Formation represents Mirandiba Basin wider formation, covering an area of approximately 100 km². Its outcrops generally present 0.3 to 1.5 meters in height, but some residual inselbergs reaching up to 7 meters are observed (Fig. 4A).

The formation is composed by fine- to very coarse-grained (predominantly coarse), pale yellow to white sandstones showing, locally, conglomeratic levels (Fig. 4B), and pebbles spread in its matrix. The mineralogy is represented essentially by quartz (~ 80 - 90%), but feldspar and mica crystals (e.g. muscovite) are usually identified (Fig. 4C). Overall, these sandstones are moderately sorted, structureless, highly consolidated and show subrounded grains. However, those characteristics may vary among the different facies recognized.

The sandstone layers show cross and horizontal stratification (Fig. 4D) and inverse grading, but most are structureless. The strata show tabular geometry, dipping at low to moderate angles (10° - 40°) to NW and NE. Deformation bands are typically observed close to the margin of the basin.

A nonconformity was identified in SW part of the basin. It is defined by the contact of Tacaratu Formation and the gneissic-migmatitic Serra Talhada Complex (Fig. 4E).

FACIES DESCRIPTIONS

Three different facies were recognized in Tacaratu Formation studied outcrops. All of them are sandstone dominated.

Sm: Massive sandstone

This facies is composed of fine- to very coarse-grained sandstone. The grains are moderately sorted and subrounded. Occurrences in which the grain size vary from coarse to very coarse is common to observe a considerable amount of feldspar (up to 20 %) and muscovite (~2 %). In some cases, this sandstone has a pebbly admixture. The sets' thickness varies from 0.28 to 1.3 m.

Sh: Horizontally stratified sandstone

This facies consists of horizontally stratified, medium- to coarse-grained sandstone, with rounded to subrounded grains. The set's thickness reaches up to 80 cm.

Sp: Cross-stratified sandstone

This facies is represented by medium- to coarse-grained, cross-stratified sandstone. Pebbles, usually of size varying from 0.5 – 5 cm, are commonly present in the base of sets (pebble lag), or between cross-strata (Figure 5). The sets' thickness varies from 0.2 to 2 m.

Table 1: Facies recognized at Tacaratu Formation in Mirandiba Basin, following the approach of Miall (1977) and Miall (1996).

Facies	Structures	Interpretation
Sm	Structureless (massive)	Bioturbated sand, or deposition by suspension fallout.
Sh	Horizontal stratification	Streams high speed flat bed.
Sp	Cross-stratification	Unidirectional migration of subaqueous two-dimensional dunes.

Figure 4: (A) Overview of a residual inselberg (approximately 7 m high) observed in Tacaratu Formation. (B) Coarse-grained sandstone showing conglomeratic level, indicated by dashed line, and deformation bands (see arrow). (C) Overview of medium-grained, pale yellow sandstone. In detail, the collected sample showing muscovite crystals. (D) Outcrop of Tacaratu Formation showing massive (on the base) and cross-stratified (on the top) layers. (E) Nonconformity defined by the contact between Tacaratu Formation sandstone and Serra Talhada Complex gneiss (198Az/26°/108Az).

Figure 5: Stratigraphic column of Tacaratu Formation outcrop showing a fining upwards grain size trend. The bottom layer is a coarse-grained sandstone containing pebbles between different cross-strata. Its contact with the following layer is marked by pebble lag (~1 cm thick). The subsequent layers (in upward direction) show (i) cross-stratification, (ii) massive texture (with some pebbly admixture), and (iii) cross-stratification.

Inajá Formation

The outcrops of Inajá Formation are located in the eastern portion of the basin, stratigraphically above the Tacaratu Formation and cover an area of approximately 9 km². The formation is observed in the highest parts of the basin (reaching up to 590 m of elevation) and shows a plateau morphology (Fig. 6A).

Inajá Formation is composed by reddish, fine- to coarse-grained, highly consolidated sandstone (predominantly fine-grained) and yellow to cream-colored siltstone. The sandstone grains are moderately sorted and vary from rounded to sub-angular. In situ spheroidal limonitic nodules (1 – 15 cm) occur dispersed in the sandstone. Locally, iron concretions with 80 cm to 1 m diameter were observed (Fig. 6B).

The sandstone layers are tabular and, in some occurrences, show shallow dip angle (~ 15°) to NW or NE. The main sedimentary structures identified in Inajá Formation were horizontal stratification, cross-stratification (Fig. 6C) and ripple marks (Fig. 6D).

FACIES DESCRIPTIONS

Sm: Massive Sandstone

Fine-grained, well-sorted sandstone, with subrounded to rounded grains. Locally show spheroidal limonitic nodules disperse randomly in

the matrix. In some occurrences, the content of muscovite and feldspar is up to 10%.

Sh: Horizontally stratified sandstone

Medium- to coarse-grained sandstone, moderately sorted, with subrounded grains. Present horizontal stratification.

Sp: Cross-stratified sandstone

Fine- to coarse-grained sandstone, moderately sorted, showing subrounded grains. Locally, show, as Sm facies, limonitic nodules disperse in the matrix. Individual beds reach up to 35 cm (Fig. 6C).

Sr: Rippled sandstone

This facies consists of fine-grained sandstone, showing ripple marks (Fig. 6D).

Fsm: Massive siltstone

Only one occurrence of this facies was observed in the field. The layer exposed is about two meters thick and is stratigraphically underneath by sandstone layers (specifically facies Sm and Sp). The contact between this facies and the Facies Sr is abrupt, marking an unconformity. The facies is composed of yellow to cream-colored siltstone lacking sedimentary structures (Fig. 6E).

Table 2: Facies recognized at Inajá Formation in Mirandiba Basin following the approach of Miall (1977) and Miall (1996).

Facies	Structures	Interpretation
Sm	Structureless (massive)	Bioturbated sand, or deposition by suspension fallout.
Sh	Horizontal stratification	Streams high speed flat bed.
Sp	Cross-stratification	Unidirectional migration of subaqueous two-dimensional dunes.
Sr	Ripple marks	Ripples (lower flow regime).
Fm	Structureless (massive)	Suspension load fall-out of mud bioturbated.

Figure 6: (A) Overview of plateau morphology exhibited by Inajá Formation rocks. (B) Outcrop showing 1 meter diameter iron concretion. (C) Bed approximately 35 cm thick, showing planar cross-stratification (Sp facies). (D) Ripple mark in fine-grained sandstone (Sc facies). (E) Abrupt contact between facies Fsm and Sm, which is easily noticed by differences in color and lithology: yellow to cream-colored siltstone and reddish sandstone, respectively.

Aliança Formation

Aliança Formation consists of a discontinuous series of outcrops, located in the midwest part of Mirandiba Basin, covering an area of approximately 6 km². Two types of lithologies are recognized in its extension: 1 – red to brown shale, characterizing the most abundant sort of rock in this formation; and interbedded with the former, discontinuous thin layers of 2 – calciferous sandstone (Fig. 7A, B). As reported by Silva *et al.* (2017), the calciferous sandstone contains non-marine ostracods, which are attributed to the genus *Theriosynoecum* (Fig. 8) and *Alicenula* (Fig. 9).

4.3.1 Facies Descriptions

Fm: massive mudstone and siltstone (shale)

Red to brown mudstone and shale (non-fossiliferous layer) (Fig. 7B).

Fsm: massive siltstone

Well sorted, fine-grained calciferous siltstone, showing green to gray colors (Fig. 7B). Ostracod shells constitute the grains, essentially (Fig. 7C).

Figure 7: (A) Overview of Aliança Formation outcrop. Black arrows indicate fragments of calciferous sandstone (in gray color) (Sm facies), dispersed in brown shale (Fsm facies). (B) Detail showing the contact between a discontinuous thin layer of calciferous sandstone (Sm) interbedded in reddish shale (Fm).

Figure 8: *Theriosynoecum*. (A): ♀ Right lateral view. (B) ♀ Right lateral view. (C) ♀ Dorsal view. (D) ♂ Left lateral view. (E) ♂ Left lateral view. (F) ♂ Dorsal view. (G) ♀ Dorsal view. (H) Internal view. (F) Internal view. Scale: 0,1 mm.

Figure 9: *Alicenula*. (A) Left lateral view. (B) Right lateral view. (C) Dorsal view. Scale: 0,1 mm.

Sergi Formation

Sergi Formation is located at the north portion of Mirandiba Basin (Fig. 10A). Its outcrops cover an area of 4 km². This formation consists of fine- to

medium- sandstone, predominating over coarse- and very coarse-grained sandstone. Siltstone layers are observed locally. The sandstone is, in general, moderately sorted, with rounded to subrounded grains and shows pale yellow to white colors.

The sedimentary structures observed are cross and horizontal stratification. Between different sets is common to observe angular pebbles and rocks fragments.

These rocks are, essentially, composed of quartz and, in smaller proportions, mica and lithic fragments. Five different facies were recognized in Sergi Formation studied outcrops. Sandstone dominated facies are the most common, followed by conglomerate and siltstone dominated.

FACIES DESCRIPTIONS

Gm: Massive conglomerate

This facies consists of a matrix-supported conglomerate, containing pebbles of quartz and lithic fragments, which sizes vary from 5 to 15 cm. The matrix is mainly composed of poorly sorted, coarse-grained sandstone (Fig. 10B and 10C).

Sm: Massive sandstone

Fine- to coarse-grained sandstone, well sorted, with subrounded grains (Fig.

10B, E and Fig. 11). Showing, locally, lithic fragments (e.g. gneiss fragments).

Sh: Horizontally stratified sandstone

Fine- to medium-grained sandstone, well sorted, with subrounded grains. The thickness of the beds vary from 15 cm to 25 cm (Fig. 10B, D and Fig. 11).

Sp: Cross-stratified sandstone

Fine- to very coarse-grained, moderate to well-sorted sandstone. The grains are subrounded and bed geometry is tabular. The most common sedimentary structure is planar cross-bedding.

Fl: Fine laminated siltstone

Fine laminated siltstone, whose beds are approximately 30 cm thick. They are commonly observed between sandstone dominated facies (Fig. 10F).

Table 3: Facies recognized at Sergi Formation in Mirandiba Basin following the approach of Miall (1977) and Miall (1996).

Facies	Structures	Interpretation
Gm	Structureless (massive)	Depositional load as bed sheets or lag channel floor.
Sm	Structureless (massive)	Bioturbated sand, or deposition by suspension fallout.
Sh	Horizontal stratification	Streams high speed flat bed.
Sp	Cross-stratification	Unidirectional migration of subaqueous two-dimensional dunes.
Fl	Fine lamination	Overbank or waning flood deposits.

Figure 10: Overview of Sergi Formation outcrop: at a road-cut approximately 30m wide and 6m high. (B) Lithofacies succession marked by massive sandstone on the base, followed by horizontally stratified sandstone and massive conglomerate. (C) Detail of matrix-supported massive conglomerate (Gm facies), comprising quartz and lithic fragment pebbles. (D) Detail of horizontally stratified sandstone (Sh facies). (E) Horizontally stratified sandstone layer (Sh facies) interbedded by layers of massive sandstone (Sm facies). (F) Contact between fine laminated siltstone and horizontally stratified siltstone.

Figure 11: Stratigraphic columns of Sergi Formation outcrops (correlate layers are named with similar letters). Both outcrops show a coarsening upward grain size trend. In (1) is possible to observe the sequence of Sh and Sm facies, represented by B and, C and D, respectively. In (2), is besides those facies, a basal layer “A” is also observed.

DISCUSSION AND CONCLUSIONS

Table 4 summarizes facies associations (S1, S2, F1 and S3) for the four formations described in Mirandiba Basin. The facies association S1 comprises the facies Sm, Sh and Sp. It represents part of an architectural element of a river channel with a tabular geometry showing a finning up succession typical of fluvial systems in the Tacaratu and Inajá formations. Composed of facies Sr and Fm, Facies association S2 is identified in some outcrops of Inajá Formation. It suggests a shallow marine platform depositional environment; however, this is not enough evidence to support this interpretation. F1 is described in Aliança Formation and it consists of Fm and Sm facies. This association represents a lacustrine environment rectified by biostratigraphic data (Ostracods). The facies association S3 is composed of facies Gm, Sm, Sh, Sp, and Fl. It is interpreted as a complete river channel

(CH) with overbank/flood deposits of a braided system.

The depositional environments in Mirandiba Basin are mostly continental, but shallow-marine sedimentation could be also interpreted in some outcrops associated with Inajá Formation. Tacaratu, Sergi, and Inajá formations were formed by typical fluvial braided systems, whereas Aliança Formation was generated by a lake deposit. Costa *et al.* (2007) argue that Aliança and Sergi's formations are also associated with fluvial and eolian systems, respectively in Jatobá Basin. However, in Mirandiba Basin, we did not find enough evidence to support this interpretation. Probably, it is due to the outcrops poor conservation, small size and shallow depth of the basin.

New researches about Mirandiba Basin are still necessary to improve the knowledge about its genesis, evolution and structural styles.

Table 4: Facies association and depositional environment interpreted in Mirandiba Basin.

Facies Association	Facies	Sedimentary structures	Formation	Depositional environment
S1	Sm	Structureless (massive)	Tacaratu/Inajá	Fluvial braided
	Sh	Horizontal stratification		
	Sp	Cross-stratification		
S2	Sr	Ripples marks	Inajá	Shallow marine platform?
	Fm	Structureless (massive)		
F1	Fm	Structureless (massive)	Aliança	Lacustrine
	Sm	Structureless (massive)		
S3	Gm	Structureless (massive)	Sergi	Fluvial braided
	Sm	Structureless (massive)		
	Sh	Horizontal stratification		
	Sp	Cross-stratification		
	Fl	Fine lamination		

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