SEDIMENTOLOGICAL AND STRATIGRAPHIC ANALYSIS OF THE LAGOA FEIA FORMATION, RIFT PHASE OF CAMPOS BASIN, OFFSHORE BRAZIL

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ABSTRACT The Campos Basin is located offshore the State of Rio de Janeiro along the Southeast Brazilian Continental Margin. It comprises an approximate area of 100,00 km² up to 3,400 m isobath. The Lagoa Feia Formation comprises mainly the rift phase sediments of the basin. Intense tectonic activity generated normal faulting with a preferential northeastern direction and great vertical displacement. Large basalt flows, with ages varying between 120 Ma and 130 Ma, represent the onset of the rift system forming the basement upon which Lagoa Feia formation sediments were deposited. The lack of marine fossils indicates non-marine depositional environments for this formation. The formation can be subdivided into four depositional sequences: Basal Clastic Sequence, Talc-Stevensitic Sequence, Coquinas Sequence, and Clastic-Evaporitic Sequence. Sediments of the three basal sequences are indicative of typical lacustrine environments. The presence of talc and stevensite clay-minerals, and the diagenetic assemblage of the Coquinas Sequence suggest that this lake had alkaline brackish to saline waters. Alluvial fans and their associated facies developed on the western border and adjacent to other highs of the basin. Sand flat and mud flat facies compose the marginal portions of the lake, while in deeper waters hydrocarbon generating shales were deposited. The Coquinas Sequence represents an expressive amount of pelecypod calcirudites, and calcarenites deposits, which now are important hydrocarbon reservoirs. An important and regionally widespread erosional unconformity separates the Coquinas Sequence of the overlying Clastic-Evaporitic Sequence, which is characterized by shallow water sedimentation defined through stromatolitic and nodular limestones associated with extensive deposition of alluvial fans. The top of the Lagoa Feia Formation is marked by a thick evaporitic layer deposited under hot arid to semi-arid climate and relatively stable tectonic conditions, connected with the ocean at the south.

RESUMO ANÁLISE SEDIMENTOLÓGICA E ESTRATIGRÁFICA DA FORMAÇÃO LAGOA FEIA ESTÁGIO RIFTE DA BACIA DE CAMPOS LITORAL DO BRASIL. A Bacia de Campos está situada ao longo do litoral do Estado do Rio de Janeiro, Brasil, ocupando uma área de aproximadamente 100.000 km² até a cota batimétrica de 3.400 m. A Formação Lagoa Feia engloba os sedimentos depositados durante o estágio rifte. A intensa atividade tectônica desta fase provocou falhamentos de direção preferencial NE e de grandes rejeitos verticais. Expressivos derrames de rochas basálticas, com idades entre 120 e 130 Ma, marcam os estágios iniciais da fase rifte, formando o substrato sobre o qual se depositaram os sedimentos da Formação Lagoa Feia. A ausência de fósseis marinhos indica um ambiente de deposição não-marinho para a formação. Esta formação foi subdividida em quatro seqüências deposicionais: Seqüência Clástica Basal, Seqüência Talcó-Estevensítica, Seqüência das Coquinas e Seqüência Clasto-Evaporítica. Os sedimentos das três seqüências basais são caracteristicamente de ambiente lacustre. A presença dos argilo-minerais talco e estevensita, e de minerais diagenéticos na Seqüência das Coquinas indicam para esse lago águas salobras e alcalinas. Leques aluviais e fácies associadas desenvolveram-se na borda oeste da bacia. Fácies tipo *sand flat* e *mud-flat* compõem as porções marginais do lago enquanto nas partes mais profundas depositaram-se folhelhos, posteriormente geradores de hidrocarbonetos. A Seqüência das Coquinas engloba expressiva deposição carbonática, composta principalmente por calcirruditos e calcarenitos bioclásticos a pelecípodes, gastrópodes, que são importantes reservatórios de hidrocarbonetos. Separada da Seqüência das Coquinas por uma importante discordância regional, a Seqüência Clasto-Evaporítica se caracteriza por uma sedimentação em ambiente de água muito rasa sob clima quente, árido a semi-árido, definida por extensa deposição de leques aluviais e calcários estromatolíticos. O topo da formação é marcado por um significativo pacote de evaporitos depositado em condições tectônicas relativamente estáveis, sob clima quente, árido/semi-árido e em ambiente lagunar, provavelmente ligado com águas oceânicas meridionais.

INTRODUCTION The Campos Basin, the most important Brazilian hydrocarbon province, is located offshore the State of Rio de Janeiro along the Southeastern Brazilian Continental Margin.

The Neocomian Lagoa Feia Formation comprises sedimentary rocks deposited mainly during the rift phase. This sedimentary package corresponds to the lake and gulf sequences defined by Asmus & Baisch (1983). This formation overlies basic volcanic rocks (120-130 Ma) and its upper limit is gradational with "Middle" Cretaceous strata.

A total of 458 exploratory wells, drilled in the Campos Basin, only 85 wells penetrated the entire rift section and reached either the basalt or crystalline basement. Most of these wells are located in the Badejo, Pampo, and Linguado oil fields area.

The stratigraphic and sedimentological aspects of the Lagoa Feia Formation have been studied by Schaller (1973), Castro *et al.* (1981), Schaller *et al.* (1981), Baumgarten *et al.*

(1983), Bertani & Carozzi (1984), and Carvalho *et al.* (1984). This paper emphasizes the synchronism between the component lithofacies of the Lagoa Feia Formation. Four depositional sequences as defined by Mitchum Jr. *et al.* (1977), were mapped through seismic stratigraphic analysis.

Depositional sequence interpretation allowed the understanding of the stratigraphy, the tectonics, and paleo-environmental conditions which have been active during Late Neocomian and Aptian times.

GENERALIZED STRUCTURAL FRAMEWORK The Campos Basin is a typical passive margin basin. Its tectonic evolution is very similar to other basins located along the Brazilian eastern coast.

The origin of the basin is related to the breakup of the Gondwanaland due to stress tensions during Early Cretaceous. A northeast trending rift valley system developed a series of horsts and half-grabens. A SW/NE oriented

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Figure 1 - Location map including the main oil fields of Campos Basin

principal fault system (synthetic and antithetic faults) shows vertical displacement varying from few to a maximum of 2,500 m. A less expressive fault system oriented in a ESE/NNW direction is also observed.

The most important mapped tectonic features (Fig. 2) are:

- An expressive fault with NNE direction (Campos Fault), which marks the western limit of occurrence of the Lagoa Feia Formation.
- The Badejo Regional High, the most prominent horst of the basin. Is is flanked to the west by the São João da Barra Low and to the east by the Corvina-Parati Low. Large amounts of lacustrine sediments were deposited within these lows (Fig. 3). The Badejo Regional High plunges to the north. Other less expressive structural highs and lows were also mapped.

Figure 2 - Structural map of Lower Cretaceous Basalts displaying the rift framework of Campos Basin

Seismic mapping of deep horizons of Campos Basin allowed the recognition of a notable parallelism between the main structural lineaments within the basin and lineaments of the onshore pre-Cambrian shield area (Dias *et al.* 1987).

The Neocomian tectonic activity of the rift phase was intermittent and its upper limit coincides with the pre-Alagoas (local stage) unconformity.

Few cases of fault reactivation are observed during the Late Cretaceous and Tertiary times.

Figure 3 - Isopach map of Lagoa Feia Formation (except evaporitic layers)

DEPOSITIONAL SEQUENCES The Lagoa Feia Formation can be subdivided into four depositional sequences by using well log correlations, and seismic stratigraphic analysis supported by biostratigraphic data.

Local Brazilian Chronostratigraphic Units, firstly defined at Sergipe-Alagoas (Schaller 1969) and Recôncavo-Tucano (Viana *et al.* 1971) basins, have been used in the chronostratigraphic characterization of the Lagoa Feia Formation. In an ascending order, the local stages identified at Campos Basin are: Aratu, Buracica, Jiquiá, and Alagoas subdivided mainly through ostracode assemblages. In geochronological time they range from Late Neocomian to Aptian. Seismic mapping was useful to identify sequence boundaries in areas where electrical log identification of stratigraphic markers is not reliable. Depositional sequences boundaries correspond to unconformities or stratigraphic markers as originally defined by Baumgarten (1985) in Badejo, Pampo and Linguado oil fields area.

The depositional sequences defined in Campos Basin are: Basal Clastic Sequence, Talc-Stevensitic Sequence, Coquinas Sequence, and the younger one, the Clastic-Evaporitic Sequence.

Figure 4 – Typical log of Lagoa Feia Formation showing the four depositional sequences

Basal Clastic Sequence The Basal Clastic Sequence comprises the oldest sediments (Aratu and Buracica local stages) deposited in the Campos Basin. These sediments rest directly on basic volcanic rocks extruded during the Early Cretaceous.

The upper boundary of this basal sequence corresponds to an electrical log marker (LF-20) which is best identified at the Badejo, Pampo, and Linguado area.

Talc-Stevensitic Sequence The overlying Talc-Stevensitic Sequence was deposited during Late Buracica and Early Jiquia ages. The upper boundary is defined by the LF-35 stratigraphic marker. Seismically this marker corresponds to a strong, regional reflector at the base of the Coquinas layers.

Coquinas Sequence The Coquinas Sequence is the most important sequence of the Lagoa Feia Formation because it embraces both, its reservoirs and the principal source rocks of the Campos Basin. The Coquinas Sequence was deposited during the Late Jiquia age and is separated from the overlying depositional sequence by a regional unconformity, called the "pre-Alagoas" unconformity. This unconformity is seismically mapped throughout the basin and represents a regional erosional surface which leveled the relief formed in the early phases of rifting.

Clastic-Evaporitic Sequence The Clastic-Evaporitic Sequence comprises a terrigenous basal portion deposited over the "pre-Alagoas" unconformity overlain by a thick evaporitic layer. The base of the evaporites corresponds to a very clear seismic reflector mapped throughout the basin. The top of the evaporites is taken as the upper boundary of the Lagoa Feia Formation. Chronostratigraphically the Clastic-Evaporitic Depositional Sequence corresponds to the Alagoas local stage.

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS The Lagoa Feia Formation is characterized by a complexity of lithologic types.

Paleoenvironmental reconstruction was made using isopach and facies maps. Facies maps were based on cores and well cutting descriptions due to the absence of Lagoa Feia Formation outcrops. These maps were constructed for each of the previously defined depositional sequences. The lack of marine fossils suggests non-marine depositional environments for this formation.

Basal Clastic Sequence The Basal Clastic Sequence was subdivided into two units to permit a better depositional environment interpretation: the essentially conglomeratic lower part superimposed by a terrigenous-carbonate upper part.

The lower section has been reached only by few wells and comprises an alluvial fan system (Fig. 5A). The conglomerates are composed mainly of basaltic fragments, quartz, and feldspar grains, intensely cemented by calcite. These conglomerates change to cross-stratified sandstones and distally to brown mudstones frequently presenting desiccation cracks (Plate 1 – A, B).

The upper part of the Basal Clastic Sequence also comprises alluvial fan, marginal and distal lacustrine facies. The marginal lacustrine facies is composed of bioclastic calcarenites, calcilutites with features of local subaerial exposition (Plate 1 – C), and siltstones composed of talc peloids associated with stevensite peloids. The distal lacustrine facies is represented by marls, calcilutites, and dark shales.

Talc-Stevensitic Sequence The Talc-Stevensitic Sequence is characterized by a marginal lacustrine facies (Fig. 5C) that comprises siltstones and sandstones composed of talc and stevensite peloids generally dolomitized and silicified. Ostracod shells can also be present (Plate 1 – D). Talc peloids always present concentric structures, frequently with ostracod shell nuclei.

The origin of the peloids is controversial. Bertani & Carozzi (1984) interpret the talc peloids as kerolitic ooids which are normally associated with hyaloclastites composed of volcanic glasses, and hyalotuffs, usually altered to trioctahedral smectites. All these microfacies would have been therefore originated from volcanic activity.

However, Rehim *et al.* (1986) interpret the peloids as the product of the chemical precipitation from lacustrine, brackish alkali water rich in Si and Mg. The stevensite (magnesian trioctahedral smectite) peloids are formed by chemical precipitation, while the talc peloids are originated through the diagenetic alteration of chemically precipitated magnesian silica gel.

A distal lacustrine facies also occurs besides alluvial fan facies, similar to those previously described. This facies is essentially composed of dark shales.

Coquinas Sequence The principal characteristic of the Coquinas Sequence is the expressive amount of limestone deposition throughout the basin (Fig. 6A).

Several facies can be recognized in the carbonate section (Carvalho *et al.* 1984): calcilutites; peloidal, oolitic or bioclastic calcarenites; calcirudites composed of pelecypods (reworked of bioaccumulated deposits) and locally of gastropods with or without calcarenite matrix; and *in situ* pelecypod bioaccumulated limestones which are normally associated with contemporaneous depositional highs (Plate 2 – A, B).

The coquinas are locally pure calcite but sometimes contain abundant talc and stevensite peloids. These rocks are generally cemented by calcite, chert or dolomite. High energy, matrix free calcirudites, and calcarenites are the best reservoir

Figure 5 – Facies maps of Lagoa Feia depositional sequences showing the depositional environments: A. facies map of Basal Clastic Sequence (Lower Part); B. facies map of Basal Clastic Sequence (upper part); C. facies map of Talc-Stevensitic Sequence

A **B** **C** **D**

Plate 1 – Main lithofacies of Lagoa Feia Formation: **A.** conglomerate composed of basalt fragments with gravitational cement (arrow); **B.** stratified sandstones and brown mudstones representing distal facies of alluvial fans; **C.** calcilutite with intense silicification (S); **D.** shelly sandstone composed of talc peloids

rocks of the Lagoa Feia Formation. The coquinas are one of the producing reservoir rocks of the Badejo, Linguado and Pampo fields in the south of the basin.

In the sindepositional lows of the basin, marls and shales rich in organic matter have been found. These shales are responsible for the principal hydrocarbon generation of the Campos Basin.

The occurrence of alluvial fan deposits in this sequence is more significant than in the older ones. This fact denotes an

important tectonic activity during the deposition of the Coquinas Sequence.

Clastic-Evaporitic Sequence The Coquinas Sequence is unconformably overlain by the Clastic-Evaporitic Sequence. The lower part of this sequence comprises a terrigenous and carbonate deposition whereas the upper part is essentially evaporitic.

The lower portion (Fig. 6B) is marked by intense

A **B** **C** **D**

Plate 2 – Main lithofacies of Lagoa Feia Formation: A. pelecipod bioaccumulated with silt to clay matrix; **B.** coquina (pelecipod calcirudite) with detrital matrix, reworking of lithofacies A; **C.** carbonate crusts with Chert (C) forming “tepee” structure; **D.** nodular limestones intercalated with stromatolites

progradation of the alluvial fan facies. The main constituents are basalt fragments. However, there is a gradual increase of fragments of metamorphic and igneous rocks northward in the basin. The mudflat becomes extensive and consists dominantly of reddish-brown mudstones with frequent subaerial exposition features.

While clastic deposition was dominant at the border of the basin, synchronous deposition occurred in its distal portions.

These carbonate facies (Plate 2 – C, D) comprise diagenetic nodular limestones and laminated-limestones, probably algal in origin (stromatolites).

The final stage of deposition of Lagoa Feia Formation is essentially chemical in character. The presence of saline mineral assemblages permit the individualization of some evaporitic facies (Fig. 6C). From the proximal area towards the east, the following lithofacies can be recognized:

Figure 6 – Facies map of Lagoa Feia depositional sequences showing the depositional environments: A. facies map of Coquinas Sequence; B. facies map of Clastic-Evaporitic Sequence (Lower Terrigenous Part); C. facies map of Clastic-Evaporitic Sequence (Upper Evaporitic Part)

anhydrite, halite + anhydrite, halite + anhydrite + soluble salt minerals (carnallite/sylvinite). Limestones locally occur associated with more proximal facies.

DEPOSITIONAL SEQUENCES AND GEOLOGIC EVOLUTION The oldest sediments of the Campos Basin belonging to the Lagoa Feia Formation rest directly on basalts (120-130 Ma) extruded during the early phases of the South America/Africa breakup.

The lack of typical marine organisms suggests that these sediments were deposited within continental environments, mainly under lacustrine conditions.

Sedimentation starts in Aratu times (Late Neocomian) with deposition of the Basal Clastic Sequence. This sequence was confined to the most prominent structural lows probably forming isolated lakes (Fig. 7A). The subaerial terrigenous environment represented by alluvial fans had been restricted to areas adjacent of structural highs resulting from active faulting.

From the first stages of rifting until the Jiquiá age the subaqueous lacustrine deposition extended and progressively covered the intrabasinal highs (Fig. 7B). However, the most prominent highs were only covered during the Alagoas time.

Sedimentation diagenetic minerals like gypsum, anhydrite, and Mg-calcite as well as the presence of thick and ornamented ostracode shells were used by Bertani & Carozzi (1984) suggest a saline and alkaline lake for the depositional environment of Lagoa Feia Formation. Similar conclusion was

obtained by Rehim *et al.* (1986) when they attributed chemical precipitation of Mg-silicic gel (subsequently altered to talc) and stevensite from a lake water with salinity varying from 3,500 to 35,000 ppm and pH 8/9. This water body would also be rich in Mg and Si elements.

Organic matter analysis from Lagoa Feia Formation shales (Dias *et al.* in press) showed isotopic ratios ($^{13}\text{C}/^{12}\text{C}$) tending to be less negative from the Basal Clastic Sequence towards the Coquinas Sequence. This fact could indicate a progressive increase in the salinity of the lacustrine water. These lakes are supposed to be eutrophics based on hot paleoclimate indications and mainly on the expressive accumulation and preservation of organic matter.

At the border of the basin, and adjacent to intrabasinal active highs, a subaerial terrigenous environment (alluvial fans) persisted during the sedimentation of all depositional sequences. Important tectonic activity can be inferred from the expressive occurrence of alluvial fans during Upper Jiquiá local stage.

After the deposition of the Coquinas Sequence, a regional erosional surface leveled the relief formed during the early stages of continental rifting. This regional unconformity – “pre-Alagoas” unconformity – marks the end of the rift-phase of the Campos Basin.

The overlying Clastic-Evaporitic Sequence is considered as the transitional stage between typical continental depositional environments of the rift phase and the typical marine sedimentation of “Middle” Cretaceous.

Figure 7 – Block diagrams displaying physiographic evolution of the basin during the Eocretaceous: A. Aratu stage, showing isolated lakes; B. Jiquiá stage, showing the distribution of coquinas and oil shales in a broad lake; C. Alagoas stage, showing the lagoonal model during evaporite deposition.

The expressive development of alluvial fans characterizes the lower part of the Clastic-Evaporitic Sequence. However, terrigenous sedimentation was contemporaneous to a carbonate deposition, mainly composed of stromatolitic and nodular limestones. These diagenetic nodules are indicative of subaerial exposure. Therefore, these limestones probably were deposited under very shallow subaqueous environment.

Finally, a thick evaporitic layer was deposited from a saline water body, under hot arid to semi-arid climatic conditions. The depositional environment was probably lagoonal (Fig. 7C) linked with meridional ocean waters. They represent the development of an extensive evaporitic basin that formed between Africa and South America just prior to the formation of the South Atlantic Ocean.

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Todo cientista poderia (deveria) considerar-se um terminólogo em sua especialidade.

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