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TÍTULO DO TRABALHO:

PRODELTA DEPOSITS OF THE UPPER APTIAN MACEIÓ FORMATION, ALAGOAS BASIN, BRAZIL: HETEROGENEITIES ANALYSES FOR RESERVOIR QUALITY

AUTORES:

Dayanne Fonseca Dantas, Nayara Rodrigues da Silva Souza, Tallys Celso Mineiro, Claus Fallgatter, Mário Ferreira de Lima Filho

INSTITUIÇÃO:

Universidade Federal de Pernambuco

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Abstract

During the late Aptian, the Alagoas Basin developed as a rift system. Such rifts have variable size and morphology, and depositional conditions lead to facies segregation and differentiation. The late Aptian interval of the Alagoas Basin is in part represented by the Maceió Formation. The main outcrop in the area (Morro do Camaragibe) consists of a prodelta deposit, largely influenced by gravity-driven flows, later affected by post-depositional processes, generating reservoir heterogeneities in a range of scales. Prodelta architectural elements were identified: delta front deposits, proximal lobes and lobe off-axis to fringe settings. The succession exposed along the outcrop represents a southwestward progradation trend, resulting in two thick, sand-rich delta front deposits. These delta front advances represent phases of greater sediment input and are associated with discharge fluctuations on long-lived flows with waning and waxing pulses attributed to flood-driven hyperpycnal underflows (sustained currents or fluvially-fed turbidites). For heterogeneities investigation, field data were acquired, including facies description and distribution, paleocurrent measurements, and detail sedimentological logs at a scale of 1:20 couplet with gamma-ray profiles. Facies distributions and reservoir predictions are linked to soft sediment deformations, showing contemporaneous faults, sand injections and sand and mud mixing at different scales, which partially affect reservoir quality. The identified facies fit into a shallower water context than previously suggested in the literature. Mud content is laterally and vertically variable along the studied interval, displaying higher concentrations in the lower half of the exposed succession, but overall showing a cleaning-upward trend in the upper half, resulting in an apparent improvement in reservoir quality in terms of primary porosity and permeability.

Keywords: rift basin, delta front deposits, flood-driven turbidites, soft sediment deformation, facies distribution

Introduction

The Alagoas Basin, located in the northeastern portion of Brazil, along the coast of the state of Alagoas (Fig. 1), is a marginal basin, formed after the Gondwana break-up. Its structural framework is in part characterized by an elongated, asymmetrical rift, formed by a series of half-grabens inclined towards the southeast (Ojeda & Fugita, 1974). Along with the Sergipe Basin, it is one of the eastern Brazilian marginal basins that show the most complete stratigraphic record, comprising five supersequences: Paleozoic, Pre-Rift, Rift, Post-Rift, and Drift. Part of the deposition in the Alagoas Basin during the Upper Aptian favored pulses of gravitational sediment flows in various forms. The Poção Formation consist of clast-supported conglomerates with basement-affinity blocks and pebbles from the Itaporanga, Joaquim Gomes, and Jundaí Intrusive Suites. The Maceió Formation (which is the focus of this work) records the end of the rift phase and comprises two main depositional elements: axial fan deltas that migrated and transported sediments along the basin's axis, showing aeolian reworking, and prodelta deposits (a turbidite succession exposed in the Morro do Camaragibe outcrop).

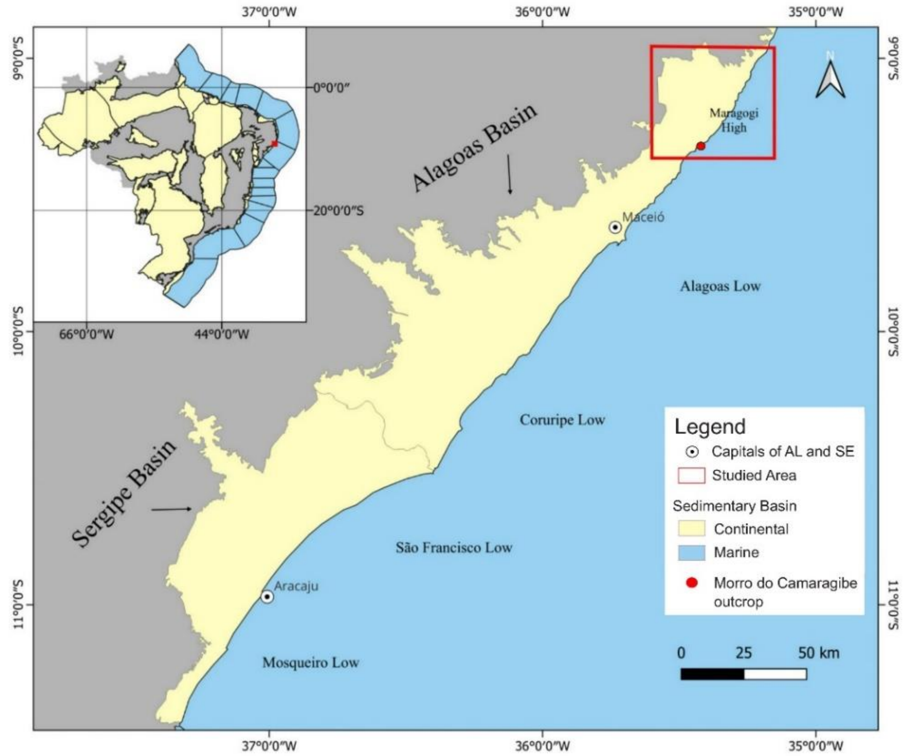

Figure 1: Location map of the studied area.

Previous studies suggest that the Morro do Camaragibe outcrop is formed by turbidite lobes with few channel fill deposits (Arienti, 2006; D'Ávila et al., 2008). Its deposition is linked to climate changes, with significant input of siliciclastic sediments during wet periods, favoring delta advances, and reduced sediment input during drier climates, resulting in the deposition of calcilutites, evaporites, and shales with high levels of amorphous organic matter, obtaining 12.4% in the Porto Calvo, 20.0% in the Japaratinga and 36.0% in the Barreiras do Boqueirão outcrops (Dantas et al., 2023).

Comparing subsurface data with outcrop analogues is usual in both exploration and production activities. This method is based on the premise that deposits formed under similar geological conditions share architectural characteristics that influence fluid flow and reservoir conditions. Since most of production fields are located in subsurface, where available data is sparse or of low resolution, using outcrop analogs benefits a complete observation of sedimentary bodies in various dimensions. The Morro do Camaragibe outcrop is the focus of this research due to its well-exposed deposits, a 1 km long, dip-oriented section. This area shows deposits associated with episodic sedimentation events, mostly consisting of gravitational subaqueous flows, forming a prodelta succession typically attributed to turbidity currents in the literature (Arienti, 2006; D'Ávila et al., 2008). This outcrop exhibits a variety of facies characteristics similar to those found in the subsurface of Brazil's most important productive basins.

Methodology

The data acquisition includes detailed descriptions of sedimentary facies and photographic images, as well as descriptions of the vertical and lateral continuity of individual sandstone beds. In total, approximately 40 meters of detailed sections were measured. Six sections (MC-1 to MC-6) with varying thicknesses (from 434 cm to 1056 cm) were described on a detailed scale of 1:20. Each sedimentary log is couplet with a gamma-ray profile obtained from CPS (counts per second) measurements taken every 10 cm. A dip-oriented correlation panel along approximately 400 m was created to illustrate the extent and geometry of individual sandstone beds and the vertical and lateral distribution of facies. Sediment transport trends were obtained through paleocurrent measurements. This compilation of data result in a schematic 3D block diagram of the depositional model.

Results and Discussion

The succession exposed at the Morro do Camaragibe outcrop is dominated by thin beds, with two intervals of anomalously thick and amalgamated sandstone beds that are easily recognizable and mappable in the area. This study focuses on the lower sand-dominated interval (Fig. 2), which represents the first advance of the delta front recorded in the outcrop. The whole outcrop consists of a gentle anticline, probably produced by salt diapirism in subsurface (Souza-Lima et al., 2021), thus oldest strata are exposed in the central portion and the younger beds at the northern and southern ends.

Figure 2: The studied interval exposed in the central part of the Morro do Camaragibe outcrop.

The lower sandy interval is up to 10 meters thick and is primarily composed of tabular and amalgamated sandstone beds. Individual beds consist of medium to very coarse-grained, moderately-to-poorly sorted sandstones, eventually containing scattered granules and often exhibiting soft sediment deformation structures. These beds are amalgamated or interbedded with very fine-grained sandstones and siltstones. Sandstone beds are generally massive, followed by one or more interval of fine-to very fine-grained sandstone beds with abundant load casts and flame structures. These beds are organized in a thinning upward succession. Small to medium-sized cross-beddings and large intra-bed scours (Fig.

3A) are also present. Some beds exhibit occasional intervals of inverse and/or normal grading, with alternation of plane-bedded and ripple cross laminated bedforms (Fig. 3B). Ball and pillow structures are common (Fig. 3C).

Individual sandstone beds show abundant and dispersed rafts of sedimentary clast, mainly composed of siltstones interbedded with very fine-grained sandstones, some of which have preserved their primary sedimentary structures. These beds also show small to large-size mudstone clasts (Fig. 3D), often with a contorted and deformed aspect that are clearly mixing into the matrix. The shearing and disaggregation of these clasts formed mud streaks within the matrix that decrease in abundance away from the clasts, leading to an increase mud content into the matrix (Sobiesiak et al., 2016). Also, an interval of intraformational conglomerate is emplaced within the succession (Fig. 4). Paleocurrent readings indicate transport towards the southwest, with slight deviations towards the southeast.

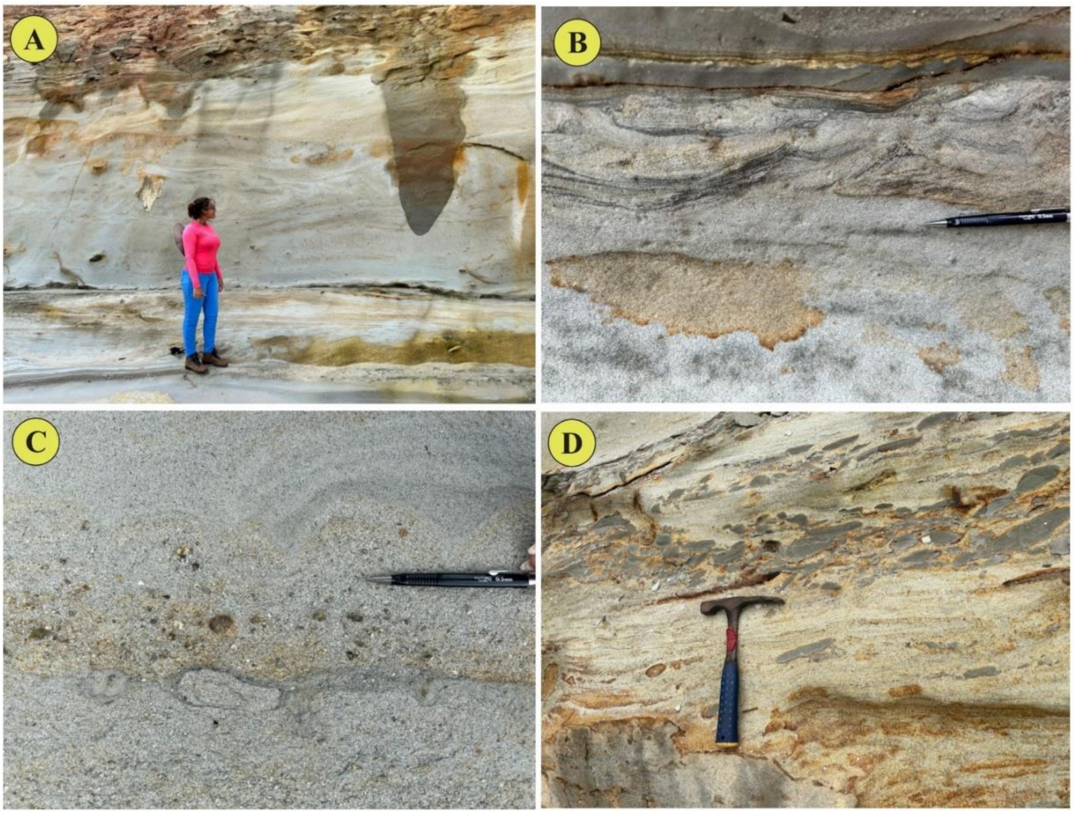

Figure 3: A) Intra-bed scours within a medium to coarse-grained sandstone bed; B) ripple cross laminated sandstone bed; C) Small-scale ball and pillow structure; D) deformed and contorted mudstone clasts.

The studied interval shows Soft Sediment Deformation Structures (SSDS), such as penecontemporaneous faults, balls and pillows, small-scale sand injections and various degrees of sand and mud mixing, which in turn affect primary porosity and permeability (Silveira et al., 2023). This occurrence causes heterogeneities within the deposits, impacting reservoir predictions. The gamma-ray readings indicate values ranging from 250 to 350 CPS, with peaks exceeding 400 and 500 CPS (Fig. 4). The sandstone beds in the northern end of the study interval are slightly cleaner compared to its southern end. Individual gamma-ray logs also show a cleaning-upward trend (Fig. 4). High gamma-ray signatures are consistent with a mud-rich matrix, likely induced by the disaggregation of mudstone clasts, which is not homogeneous throughout the studied interval. The relatively high values suggest locally “dirty” and mud-rich intervals, resulting in low permeability and primary porosity. The fluctuating of CPS values in the sandstones point to a heterogeneous matrix and likely indicate variations in mud content. Low gamma-ray readings are compatible with "clean" sandstones that have a low percentage of mud.

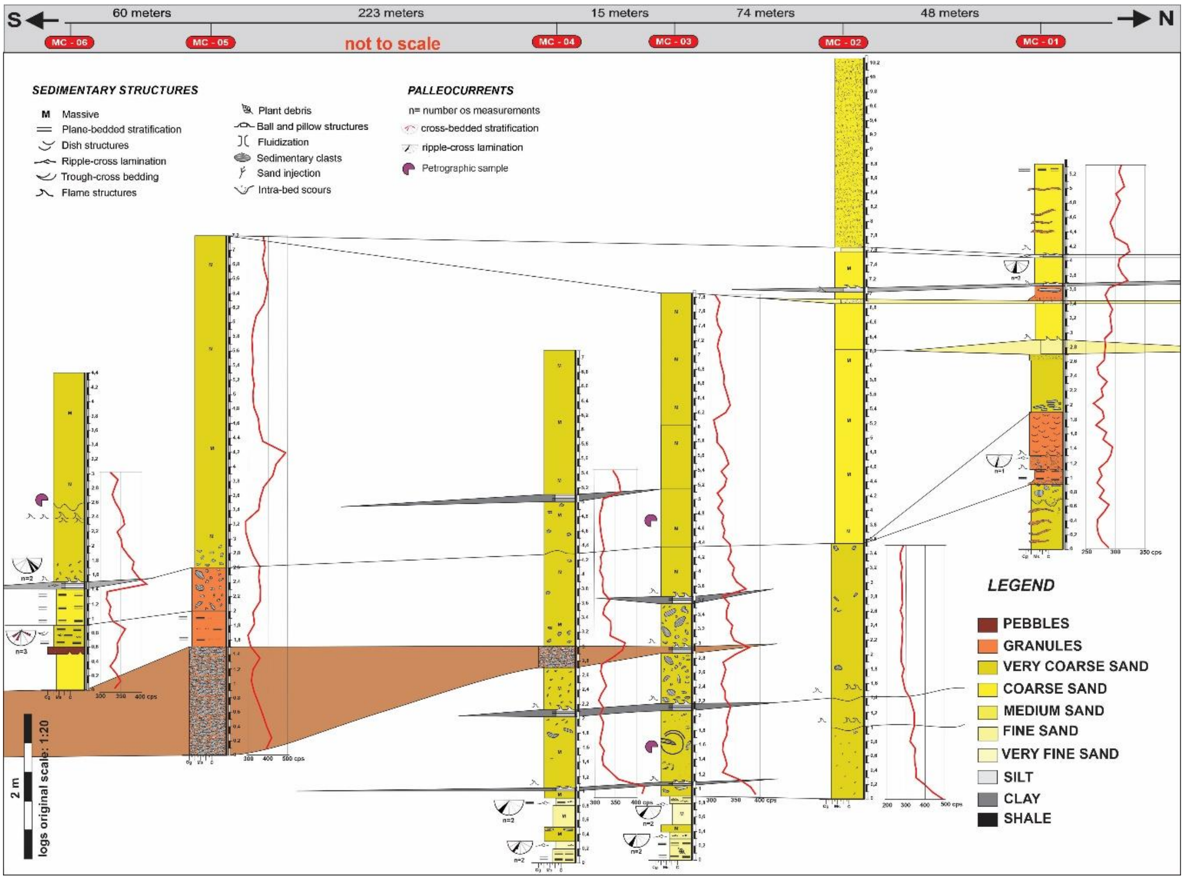

Figure 4: Dip-oriented panel correlation of sedimentary logs coupled with gamma ray profiles.

The deposits are related to tractive and dense flows, showing a wide variation of facies. As such, the following architectural elements of the prodelta setting were identified: delta front deposits, proximal lobes (comprising gradational cycles comparable to Bouma Sequences; Mutti et al. 1996), intermediate lobes (representing the transition from high-density to low-density sand-rich currents), and distal to fringe settings (consisting of low-density sand-rich currents).

Deposition at the Morro do Camaragibe outcrop occurred in a relatively shallower context than previously suggested in the literature. The two thick, sand-rich intervals represent phases of greater sediment discharge and are ascribed to delta front advances, probably a result from high sedimentation rates associated with a rapid delta progradation during wet periods (Arienti, 2006; D'Ávila et al., 2008). Subtle grain size changes, intra-bed incisions, and vertical alternation of bedforms (planar-bedding and ripple cross lamination) within the same layer suggest repeated waxing and waning pulses of the flow during the same depositional event. These evidences point to a direct connection with river floods and gravity flows, thus deposition from discharge fluctuations on long-lived flows with acceleration and deceleration pulses attributed to flood-driven hyperpycnal turbidity flows (sustained currents of Kneller and Branney, 1995; Zavala et al., 2011; or waxing-to-waning depletive flows of Kneller, 1995; Kneller and Buckee, 2000). Intra-bed scours associated with erosion and levels with residual gravels, may record the peak velocity reached by the hyperpycnal flow (Mulder et al., 2003; Mutti et al., 2003).

According to Postma (1990), delta systems in rift settings exhibit distinct parasequence stacking patterns, depending on the stage of rift development. This pattern is primarily governed by two variables: the subsidence rate and sediment supply. During periods of high subsidence rate, due to lateral fault connection and increased vertical fault displacement, a retrogradational stacking pattern develops. On the other hand, when subsidence ceases or decreases, a progradational pattern is established until the basin is fully filled. Thus, the fan delta systems of the Maceió Formation during late Aptian were dominated by braided distributaries that discharged their load into a relative shallow lake with an axial sediment supply source, as shown in Figure 5.

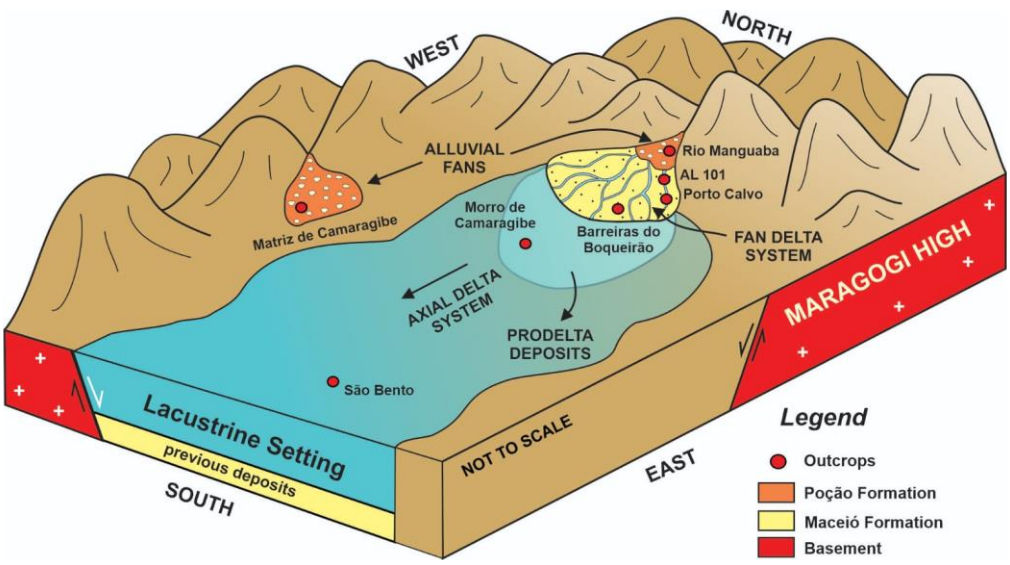

Figure 5: Simplified depositional model of the Maceió Formation during late Aptian showing the position of the prodelta deposits of the Morro do Camaragibe and other important outcrops of the area.

Conclusion

The succession exposed in the Morro do Camaragibe area shows a general progradation trend that culminate with at least two intercalated thick, sand-rich delta front deposits. In this scenario, the succession represents fluvially-fed hiperpycnal turbidites, where the generation of gravitational flows is associated with river discharges. The amount of plant remains, such as leaves and wood fragments within the sandstone beds, indicates that vegetation proliferated along riverbanks during low-energy periods and then eroded during higher-energy periods, accumulating in the delta front deposits. However, some beds within the studied interval show inverse to normal grading within the same bed, suggesting recurrent pulses of acceleration and deceleration of flow during the same event. This type of evidence points to a direct connection between river floods and gravitational flows, thus hyperpycnal flows. Hyperpycnal flows occur when sediment-laden river discharge is denser than the water in the receiving basin, which is more common in lakes, as is the case here.

Thus, the described facies are part of a shallower water context than previously suggested in the literature and are related to a prodelta system. Similar deposits are also recognizable during the rift phase of various Brazilian marginal basins. Our results will contribute to the understanding the origin and formation of these deposits and can be used to predict geometries and facies distribution as an analogue to aid seismic and well data. The depositional models produced will certainly impact any conceptual model that may be applicable in areas with similar conditions. Additionally, turbidites are one of the major contributors to the formation of hydrocarbon reservoirs, where their depositional architecture and the input of fluvially-fed turbidite systems are comparable to other hydrocarbon reservoirs in marginal basins.

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References

Arienti, L. M. 2006. Gravity flow deposits of the Maceio Formation-Alagoas Basin, NE of Brazil; Depositos de fluxos gravitacionais da Formacao Maceio-Bacia de Alagoas, NE do Brasil. *Boletim de Geociências da Petrobrás, 14.*

d'Avila, R.S.F., Arienti, L.M., Aragão, M.A.N.F., Vesely, F.F., Santos, S.F., Voelcker, H.E., Viana, A.R., Kowsmann, R.O., Moreira, J.L., Coura, A.P., Paim, P.S.G., Matos, R.S., Machado, L.C. R., 2008. Ambientes de Água Profunda. In: Silva, A.G., Aragão,M.A.N.F.,Magalhães, A.J. C. (Eds.), Ambientes de Sedimentação Siliciclástica do Brasil. Beca, São Paulo, pp. 246–300.

Dantas, D.F., Fallgatter, C., Pereira, R., Lima Filho, M.F., Souza, N.R.S. Análise de matéria orgânica total em folhelhos e argilitos da Formação Maceió, Bacia de Alagoas. In: 29º Simpósio de Geologia do Nordeste, 2023, Campina Grande. 29º Simpósio de Geologia do Nordeste, 2023. p. 290-290.

Kneller, B., 1995. Beyond the turbidite paradigm: physical models for deposition of turbidites and their implication for reservoir prediction. In: Hartley, A.J., Prosser, D.J. (Eds.), Characterization of Deep Marine Clastic Systems. Geol. Soc. Spec. Publ. 94, pp. 31–49.

Kneller, B.C., Branney, M.J., 1995. Sustained high-density turbidity currents and the deposition of thick massive sands. Sedimentology 42, 607–616.

Kneller, B.C., Buckee, C.M., 2000. The structure and fluid mechanics of turbidity currents; a review of some recent studies and their geological implications. Sedimentology 47, 62–94.

Mulder, T., Syvitski, J. P., Migeon, S., Faugères, J. C., & Savoye, B. (2003). Marine hyperpycnal flows: initiation, behavior and related deposits. A review. *Marine and Petroleum Geology, 20*(6-8), 861-882.

Mutti, E., Davoli, G., Tinterri, R., & Zavala, C. (1996). The importance of ancient fluvio-deltaic systems dominated by catastrophic flooding in tectonically active basins. *Memorie di Scienze Geologiche*, *48*, 233-291.

Mutti, E., Tinterri, R., Benevelli, G., di Biase, D., & Cavanna, G. (2003). Deltaic, mixed and turbidite sedimentation of ancient foreland basins. *Marine and Petroleum Geology*, *20*(6-8), 733-755.

Ojeda, H. A. O. & Fugita, A. M. 1974. Bacia de Sergipe/Alagoas: geologia regional e perspectivas petrolíferas. In: Cong. Bras.Geologia, 28, Porto Alegre. Anais... Porto Alegre, SBG, 1: 137- 158.

Postma, G. 1990. Depositional architecture and facies of river and fan deltas: a synthesis. *In:* Colella, A.; Prior, D.B. (Eds.), *Coarse- Grained Deltas*. IAS Special Publication, Blackwell, Oxford, v. 10, p. 13–27.

Silveira, D. M., Vesely, F. F., Fallgatter, C., Rodrigues, M. C. N. D. L., & de Castro, A. P. (2023). The Maracangalha injectite complex: An overlooked hydrocarbon play in the Lower Cretaceous Recôncavo Basin, NE Brazil. *Marine and Petroleum Geology*, *158*, 106529.

Sobiesiak, M., Kneller, B., Alsop, G.I. and Milana, J.P. 2016. Inclusion of substrate blocks within a mass transport deposit: A case study from Cerro Bola, Argentina. In: Submarine Mass Movements and their Consequences. Advance in Natural and Technological Hazards Research (Eds G. Lamarche and J. Mountjoy), pp. 487–496.

Souza-Lima, W., Pierini, C., Fischer, C. M., & Silva, B. O. (2021). Paleogeografia da seção cretácea neoaptiana do Nordeste da Bacia de Sergipe-Alagoas, Brasil: Cretaceous Late Aptian paleogeography from Northeastern Sergipe-Alagoas Basin, Brazil. *Geosciences= Geociências, 40*(2), 397-406.

Zavala, C., Arcuri, M., Di Meglio, M., Gamero, H., Contreras, C., 2011. A Genetic Facies Tract for the Analysis of Sustained Hyperpycnal Flow Deposits. 61. American Association of Petroleum Geologists, pp. 31–51.