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EXPLORING HYDROCARBON RESERVOIRS ANALOGUES IN ANCIENT FLUVIAL SYSTEMS

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Abstract

Understanding subsurface reservoir characteristics is critical for the Oil & Gas industry to optimize field exploration and development. However, a significant "resolution gap" exists between large-scale seismic data and localized well logs, making it difficult to perform the detailed depositional facies analysis necessary to construct representative models. This project addresses this challenge by utilizing the Lower Devonian Furnas Formation in the Paraná Basin as a high-fidelity outcrop analogue for subsurface siliciclastic fluvial reservoirs. The main idea is to develop a high-resolution, quantitative 3D depositional model of sand-dominated fluvial bars to provide a conceptual frameworks required for subsurface reservoir characterization. The research will implement a multi-scale field and digital workflow, beginning with centimeter-scale stratigraphic measurements and a systematic lithofacies analysis to define the hydrodynamic processes governing the deposition. A hierarchical classification of bounding surfaces will be utilized to differentiate between different macroforms, while digital outcrop modeling via photomosaics will quantify the 3D geometry and stacking patterns of sandstone bodies. Expected results include a genetic model of fluvial bar evolution, the reconstruction of paleohydraulic transport dynamics, and the extraction of "hard" geostatistical parameters, such as width-to-thickness (W:T) ratios. Ultimately, this research will provide a predictive framework to reduce geological uncertainty in the exploration of understudied siliciclastic reservoirs.

Keywords: Sedimentology; Reservoir Analogues; Fluvial System; Braided Bars

Introduction

In Oil & Gas industry, to make decisions related to exploration and development of fields it is necessary to fully comprehension the subsurface reservoir characteristics. To understand the subsurface reservoirs, it's important to describe your dimension and geometry, analyze the conceptual relationships between reservoirs, and record the spatial relationships of facies inside of reservoirs (Howell, Martinius, y Good 2014). When this information is grouped as a 3D computer representation is called “geological reservoir model”. A geological model tries to represent the relationship between different depositional elements, geological structures, rock properties, and heterogeneities distribution (Cannon 2018). The main data used to construct the geological model is obtained from different sources (e.g. seismic, well log). Seismic data provides relevant information on large scales such as surfaces and faults used to define reservoir zones. Well log data defines some sub-seismic data as fractures, and petrophysical properties (porosity, permeability, fluid saturation, etc.) used to define the heterogeneity of reservoir in small scale.

Integrating seismic, sub-seismic, and small-scale features to analyze reservoirs is a big challenge (Pringle et al., 2006). Several works have used varied methodologies to integrate data at different scales (e.g. Aghli et al., 2019; Vásconez Garcia et al., 2024; Zhao et al., 2024; Zhou et al., 2023). However, using these data (seismic and well logs) is difficult to perform a detailed analysis of depositional facies. In hydrocarbon reservoirs, depositional facies are important because they perform a fundamental control in petrophysics properties of rock.

In the last year, the hydrocarbon industry in Brazil has been develop based on the pre-Salt carbonate reservoirs. Initially, the genesis and distribution of carbonate facies were unknown. Nevertheless, the use of carbonate outcrops helps to understand basic principles related to facies deposition and control factors of hydrocarbon distribution.

Currently, the pre-salt reservoir answer for 78% of total Brazilian production. Onshore and offshore post-salt reservoirs are responsible for remaining 22% (Loureiro, 2024) Perspectives for Brazilian Offshore). This information is demonstrating new exploration opportunities in siliciclastic reservoirs, especially in understudied reservoirs.

In Brazil, siliciclastic hydrocarbon reservoirs are in both onshore and offshore basin (e.g. Jequitinhonha, Recôncavo, and Portiguar), whose main depositional environmental are fluvial – deltaic, fluvial – turbiditic, lacustrine. Although the knowledge about these siliciclastic reservoirs is enough to continue with development of fields, nowadays is important to improve the studies of fluvial systems to extend and discover opportunities to explore new stratigraphic hydrocarbon reservoirs.

To establish a solid understanding of fluvial reservoirs, this project proposes the use of outcrops of Furnas Formation in the Parana Basin as an analogue to subsurface reservoirs. The use of outcrop analogues is a fundamental practice in the construction of geological models because they provide critical data that cannot be obtained through traditional subsurface methods. The use of Furnas formation outcrops as analogue will allow in the future to bridge a significant resolution gap related to facies deposition that seismic and well log data cannot achieve.

State of Art: Fluvial Bars

Fluvial bars, along with channels, constitute the primary sedimentary record of fluvial systems (Bridge, 2007). These macroforms are composed mainly of sand and gravel, with dimensions relative to the scale of the channel; specifically, their height is generally comparable to the bankfull depth of the adjacent channel (Bridge 2007; Sambrook Smith et al. 2006).

Bars are traditionally classified based on their position within the channel:

Braid Bars: Situated in the central portion of the channel, these are characteristics of braided systems. They are identified by frontal accretion surfaces with maximum dip angles of 60° relative to the direction of dune migration (Bridge 2007; Miall 2006).

Point Bars: Located on the inner margins of channel bends, these are the diagnostic features of meandering systems. They are characterized by lateral accretion surfaces that typically occur at a 90° angle to the primary flow direction (Bridge 2007; Miall 2006).

The internal complexity of bars allows for a hierarchical distinction between simple and complex forms:

Unit Bars: These are simple, elongated forms migrating in the direction of flow. They typically exhibit metric to decimetric thickness and are characterized by intermediate-scale cross-stratification. These unit bars often show a longitudinal grain-size fining from the "head" (upstream) to the "tail" (downstream) (Cant y Walker 1978; Hey, Bathurst, y Thorne 1982).

Compound Bars: Formed by the amalgamation of multiple unit bars through successive episodes of erosion and deposition, these features reach much larger dimensions—spanning hundreds of meters to kilometers in length. Their internal organization is highly complex, reflecting the continuous migration and overprinting of constituent unit bars (Bridge 2007; Cant y Walker 1978; Hey et al. 1982).

A fluvial bar is divided into distinct morphological zones that dictate its petrophysical properties:

Bar Head: The upstream portion where the coarsest sediments are deposited due to high-energy conditions; this zone often provides the most reliable paleocurrent data (Arche y Miralles 2010; Bluck 1979).

Bar Tail: The downstream portion characterized by finer grain sizes (Bluck 1979).

Platform and Supra-platform: The platform remains stable within the channel, while the supra-platform is subject to water-level fluctuations, often resulting in distinct lithological changes and the development of high-velocity plane-parallel lamination at the top (Bluck 1979).

The formation of a bar initiates when a loss of stream power leads to the deposition of the coarsest sediment fraction, creating a bed obstacle that eventually emerges as a stable form (Leopold y Wolman 1957). In sand-dominated systems, such as those described in the Furnas Formation, bar growth occurs primarily through lateral and downstream accretion. During low-flow stages, bars undergo topographical modification, including the incision of "chute" channels that cut through topographically low areas between unit bars, adding further architectural complexity to the reservoir body (Bridge 2007; Leopold y Wolman 1957).

Geological Setting

The Paraná Basin is characterized by six major lithostratigraphic units, or supersequences, which record the basin's history from the Caradocian to the Senonian (Milani, 1997).

i) Rio Ivaí Supersequence (Caradocian – Llandoverian): This includes the oldest rocks in the basin, representing the first Phanerozoic sedimentation cycle. It consists of basal conglomerates and sandstones that transition into matrix-supported conglomerates and fossiliferous argillites (Milani, 1997).

ii) Paraná Supersequence (Lochkovian – Frasnian): Seated on a discordance above the Rio Ivaí, this unit records a complete transgressive-regressive cycle. It begins with the continental to transitional sandstones of the Furnas Formation, which are covered by the marine pelites of the Ponta Grossa Formation. It is bounded at the top by the "pre-Itararé" unconformity, representing a gap of approximately 55 million years (Milani, 1997).

iii) Gondwana I Supersequence (Westphalian – Scythian): Formed after the peak of glacial conditions during the deglaciation phase. It includes the Itararé and Guatá Groups, followed by a regressive section (Passa Dois Group) and the progressive continentalization represented by the Rio do Rasto Formation (Milani, 1997).

iv) Gondwana II Supersequence (Neoanisian – Eonorian): Characterized by short-duration, restricted fluvial and lacustrine deposits (Milani, 1997).

v) Gondwana III Supersequence (Neojurassic – Berriasian): Dominated by the vast eolian sandstones of the Botucatu Formation. During the Triassic, this was followed by extensive volcanic activity, where lavas were injected across the entire basin, covering the Botucatu desert (Milani, 1997).

vi) Bauru Supersequence (Senonian): Limited to the north-central portion of the basin, it consists of alluvial-fluvial and eolian deposits (Milani, 1997).

The Furnas Formation is a Lower Devonian sedimentary unit that occupies an extensive area within the Paraná Basin. Lithologically, it is composed of a succession of white, medium-to-coarse-grained quartz sandstones that are kaolinitic and display various types of cross-stratification (Milani, 1997; Sedorko et al., 2013).

Furnas Formation exhibits distinct vertical variability:

i) Basal Section: Characterized by frequent conglomeratic lenses up to 1 meter thick.

ii) Intermediate Section: Dominated by medium-grained sandstones intercalated with thin siltstone levels, occasionally showing "herringbone" cross-stratification.

iii) Upper Section: Composed primarily of medium to coarse sandstones, though fine-grained layers with Hummocky cross-stratification are also present.

While historical interpretations suggested mixed environments ranging from fluvio-deltaic to shallow marine, recent studies of its sedimentary architecture and lithofacies strongly support an origin within a large braided fluvial system. This system is dominated by sand-rich channel bars that constitute the primary architectural elements of the formation.

Objectives

i) Principal Objective

The primary objective of this research is to develop a high-resolution, quantitative 3D depositional model of sand-dominated fluvial bars within the Furnas Formation (Paraná Basin). By utilizing these outcrops as a strategic reservoir analogue, the project seeks to bridge the critical "resolution gap" providing the geostatistical and conceptual framework necessary to optimize the characterization of subsurface siliciclastic reservoirs.

ii) Specific Objectives

To achieve this primary goal, the following specific objectives will be addressed:

- Facies Analyses: Conduct a detailed description and genetic interpretation of the lithofacies in the Furnas Formation to define the hydrodynamic processes and sediment deposition mechanisms that govern initial reservoir quality.
- Paleohydraulic Reconstruction: Reconstruct the spatial-temporal evolution of the fluvial system by analyzing high-density paleocurrent data and grain-size distribution patterns.
- Hierarchical Architectural Modeling: Identify and differentiate architectural elements through the hierarchical classification of bounding surfaces (erosional

and non-erosional), enabling the quantification of the 3D geometry and connectivity of depositional bodies.

- Bar-Scale Characterization: Perform an analysis of the "fluvial bar" architectural element to generate a predictive genetic model that accounts for the internal heterogeneities, facies relationships, and potential fluid-flow direction common in braided systems.

Methodology

The research will utilize a multi-scale field and digital workflow to characterize the sedimentary architecture of the Furnas Formation and reconstruct the evolution of its fluvial bar systems.

a) Facies Analysis

Field Data Acquisition: Detailed stratigraphic sections will be measured at centimeter-scale resolution. The study will prioritize high-quality vertical and horizontal exposures, such as those in the Canyon do Guartelá, to ensure continuity of data.

Lithofacies Description: Sedimentary units will be defined based on physical attributes, including lithology, grain size, sorting, geometry, and primary structures (e.g., cross-stratification scales and types).

b) Hierarchical Architectural Characterization

Bounding Surface Classification: A five-fold hierarchical classification of bounding surfaces (1st to 5th order) will be implemented to differentiate depositional units.

1st and 2nd Order: Representing individual laminae (foresets) and reactivation surfaces within sets.

3rd and 4th Order: Defining limits of sets within cosets and bounding specific mesoforms or sub-elements (e.g., unit bars).

5th Order: Major surfaces defining individual macroforms or bar-scale units.

Digital Outcrop Modeling: High-resolution digital photomosaics and 2D architectural sketches will be developed using graphic software to trace surface continuity and quantify the 3D geometry and stacking patterns of sandstone bodies.

c) Paleohydraulic and Morphodynamic Reconstruction

Paleocurrent Analysis: Directional data will be collected from foresets, ripple marks, and scour axes. This data will be processed using specialized software to reconstruct sand drift trends and flow dynamics.

Bar Modeling: The project will identify specific architectural sub-elements, to reconstruct the internal evolution of sand-dominated bars. This analysis will determine if bar growth was driven by lateral or downstream accretion processes.

d) Reservoir Analogue Integration

Quantitative Parameter Extraction: Field data will be synthesized to extract "hard" geostatistical parameters, such as width-to-thickness (W:T) ratios and geobody connectivity.

Analogue Modeling: The integration of architectural elements and hierarchical surfaces will result in a sheet-braided depositional model. This model will serve as a predictive framework to bridge the "resolution gap" in subsurface reservoir characterization.

Expected results

Genetic Lithofacies Identification: The research will result in a systematic classification and genetic interpretation of the lithofacies within the Furnas Formation. This includes distinguishing between primary depositional characteristics, such as traction-current deposits (cross-stratified sandstones) and those resulting from rapid depositional events.

Reconstruction of Transport Dynamics: By synthesizing high-density paleocurrent data with grain-size distribution, the project will produce a reconstruction of the spatial-temporal evolution of the fluvial system, identifying the energy levels and flow regimes that governed sediment distribution.

Bounding Surface Hierarchy: A primary output will be a hierarchical classification of bounding surfaces. This classification will differentiate between small-scale laminae and major surfaces defining the boundaries of macroform units, such as fluvial bars.

Geobody Geometry and Stacking: The project will quantify the three-dimensional geometry and spatial relationship (vertical stacking and lateral continuity) of the sandstone bodies. This results in a deterministic understanding of how these bodies are distributed within the stratigraphic framework.

Internal Morphodynamics: The research will produce a predictive genetic model of bar evolution, reconstructing the internal organization of Unit Bars (BU) and their transition into larger complexes.

Paleoenvironmental Validation: The synthesized data will provide robust evidence to validate the interpretation of the Furnas Formation as a massive braided fluvial system, contributing to the broader stratigraphic knowledge of the Paraná Basin.

Workplan

ACTIVITIES	FIRST QUARTER	SECOND QUARTER	THIRD QUARTER	FOURTH QUARTER
Literature review	X	X	X	X
Field work		X		
Data Compilation		X		
Data Interpretation			X	
Writing manuscript			X	X
Publish manuscrip				X

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