PS Multiscale Characterization of Coquinas Reservoirs in Analogues Outcrops, Sergipe Alagoas (Brazil) and Lusitanian (Portugal) Basins*

Antônio Jorge Vasconcellos Garcia[1], Gustavo Gonçalves Garcia[1], Márcio Vinicius Santana Dantas[1], Samuel Alécio Tavares Figueiredo[1], Karen Ariadne Leite Santos[1], Izaura Oliveira Carvalho[1], Daniela Dantas de Menezes Ribeiro[1], and Larissa Lima da Rocha[1]

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[1]PROGEOLOGIA/NUPEG, Federal University of Sergipe, Aracaju, Sergipe, Brazil (garciageo@hotmail.com)

Abstract

The coquinas reservoirs have been widely studied because they constitute important intervals in oil production with accumulation model controlled by stratigraphic, structural and diagenetic factors in complex carbonates systems. The objective of this study was to develop a robust analysis of multi-scale properties related to the permo-porous system in analogues outcrops of coquina reservoirs, attempting to the comprehension of associated diagenetic processes evolution. This approach aims for the integration of different tools in 3D modeling and permo-porous reservoir characterization, which in this study focus on outcrops of two coastal basins with coquinas intervals, the Sergipe-Alagoas and Lusitanian Basins. The methodology applied in deposits of Morro do Chaves (Intercement Quarry, Alagoas State, Brazil) and Corálico do Amaral formations, in the Lusitanian Basin (outcrop in Salgado Beach, São Martinho do Porto, Portugal), included the description and systematic sampling of lithotypes, Gamma Ray logging, 3D digital imaging (Laser Scanner-Lidar), petrographic characterization, petrophysical analysis of samples, and biostratigraphic and paleoenvironmental context of related geological models. The integrated analysis of these attributes was supported by the high-resolution sequence stratigraphic principles. In Intercement Quarry, were described 12 depositional cycles characterized into five facies (Calcirrudite, Calcarenite, Calcilutite, Shale, Sandstone), in which little thick shales, but with large lateral continuity, were used as markers surfaces between the coquinas for 3D modeling. These conclusions were based on compositional and geometrical characteristics obtained from six geological logs described, and depositional architecture described and captured in the field by Laser Scanner. The 3D geological models were generated in the RMS software, and made possible the representation of compositional heterogeneities responsible for the permo-porous properties heterogeneities distribution, conditioned to diagenetic aspects and fluid flow control. Data acquisition in formation Corálico do Amaral is in progress and by the end of these studies will serve as a comparison of analogues Pre-salt models.

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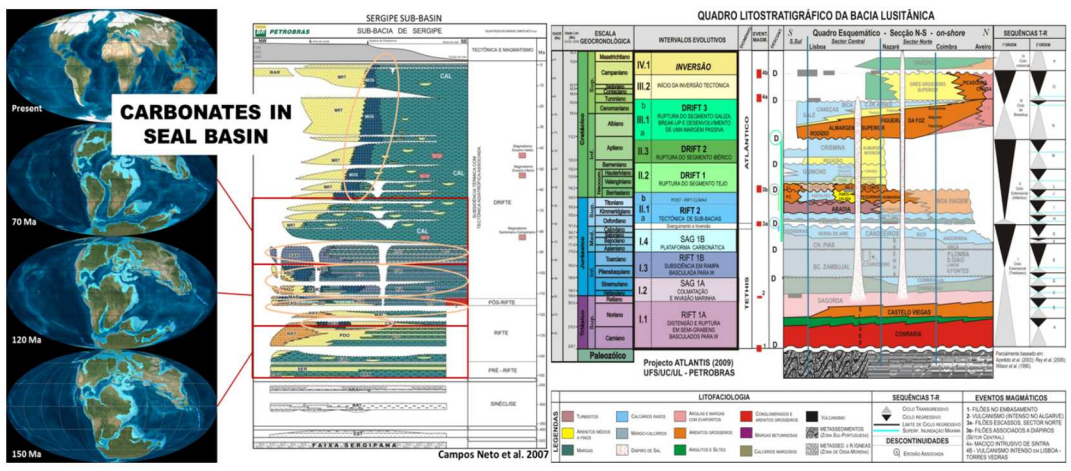
INTRODUCTION

The CAMURES Methodology is applied to build 3D outcrop models developed by the integration of data derived from macro, meso and micro-scale studies of bioclasticcalcirudites, "coquinas", Morro do Chaves Formation, and "coquinas" limestone, Corálico do Amaral Formation, from outcrops in Sergipe-Alagoas Basin (SEALB), Brazil, and Lusitanian Basin (LB), Portugal, respectively.

The Sergipe-Alagoas basin is situated in the Northeast of Brazil, representing the main Mesozoic record exposure along the Brazilian continental margin. Tectonic-sedimentary evolution of the basin can be summarized in 5 stages as follows: Sineclisis; Pre-rift; Rift; Post-Rift; Drift. The studied outcrops include Rift (Morro do Chaves Formation) and Drift (Riachuelo and Cotinguiba Formations).

Lusitanian Basin is located at Iberian Margin in the North Atlantic whose oceanic spreading began in lower Cretaceous. However, the origin of this basin whose basal sediments dating from Upper Triassic is linked to a much older geodynamic context, started by the paleozoic continental collisions, sustained with the whole evolution of western Tethys and finished by the opening of North Atlantic.

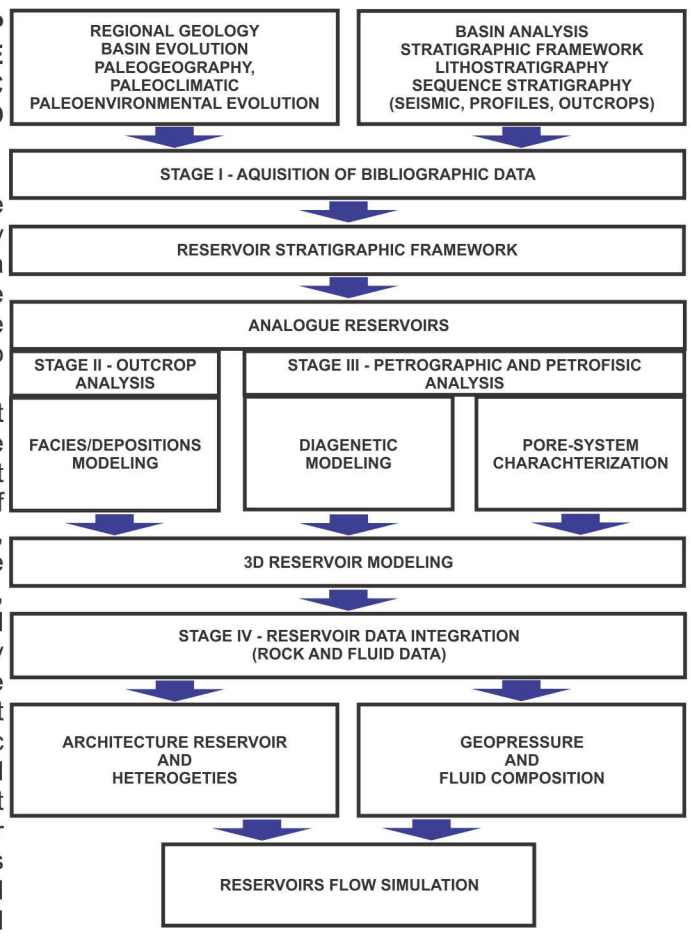


Stratigraphic chart of each basin. Left side, paleogeographic evolution of continents; in the middle, Sergipe-Alagoas basin chart; and in the right, Lusitanian basin chart.

THE ANALOG OUTCROP APPROACH AND THE CONTROLS ON THE GENETIC PROCESSES RELATED TO RESERVOIR PROPERTIES

The studies of Analogue Outcrops applied to Exploratory Geological Modeling requires a rigorous recognition of the potential "Analogue Type" before the multi-scale integration to modeling process.

The concept of "Perfect Analogue" results in the definition of the best representative of each type of subsurface reservoir, considering not only the lithological, depositional, diagenetic and structural affinities, but also the geometry and depositional architecture related to the different sedimentary basin and tectonic evolution, including burial history. Tectonic activity, uplift and tilting will be responsible for differentiation in the lithofacies distribution, especially in mixed and carbonate depositional systems.



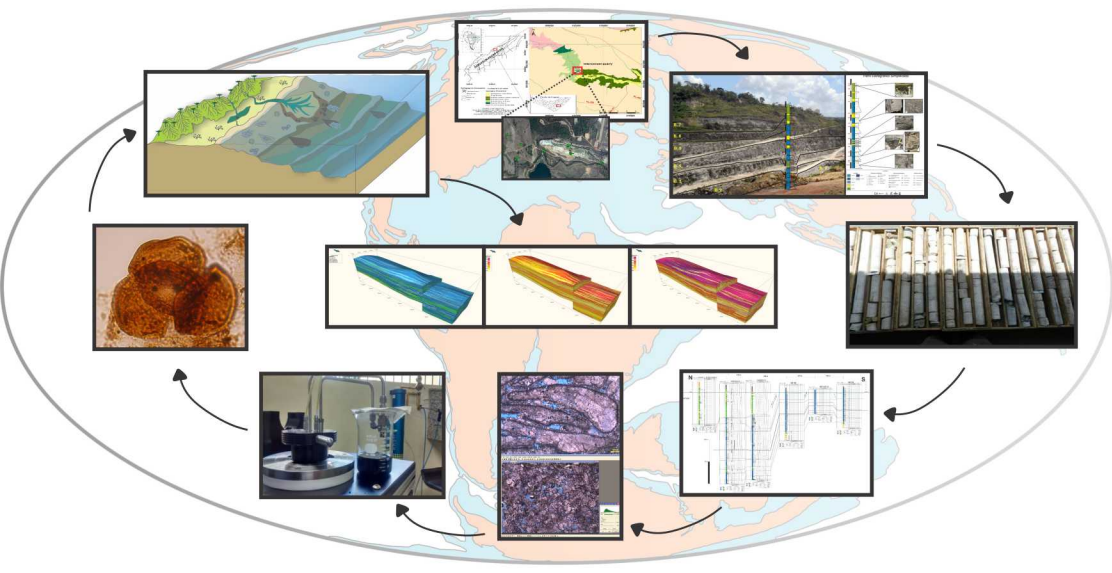
Workflow of CAMURES methodology with conception of perfect analogue.

CAMURES METHODOLOGY

The main input for the multiscale investigation of petroleum system analysis came from subsurface and surface data. From the subsurface perspective, the data provides punctual information about the heterogeneity observed and can be either direct or indirect including core, well logs and seismic data. Outcrops studies on the other hand permit a better understanding of the spatial relationship of the heterogeneities behaviour. The CAMURES Methodology (Multi-scale Reservoir Characterization) application focus on vertical and lateral variability of reservoir properties in order to 3D Geologic Modeling, aiming to spatial characterization of diagenetic and faciological heterogeneities

CAMURES is developed on outcrops data acquisition with description of facies, associated to GR-logs, GPR data, 3D digital image (Laser Scanner-Lidar) and sampling collected from interest zones, to perform petrographic and petrophysic analysis. This multiscale approach aims to apply different scales of characterization in analogue outcrops related to buried intervals of the same stratigraphy unit in the same basin or in similar reservoir from another Brazilian coastal basin. The pore space distribution is the main point of interest in a potential reservoir analysis. Microscopic analysis must characterize the different type of porosity present in the lithofaciologic intervals, under similar or differents diagenetic processes, observing how they interact in the multi-scale approach (mega, macro, meso and micro-scales).

Integration of micropaleontologic data with architectural stratigraphy analysis, lithofacies geometry and textural attributes contributes to the recognition of depositional particularities important to understanding the stratigraphic and paleogeographic distribution of source rocks and reservoir intervals.

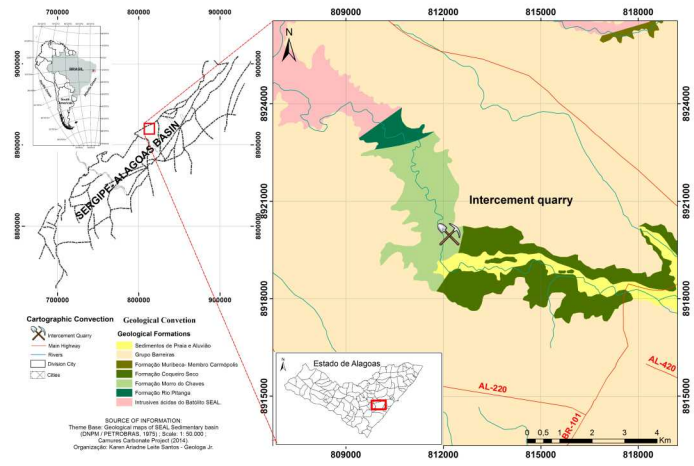


CAMURES Methodology.

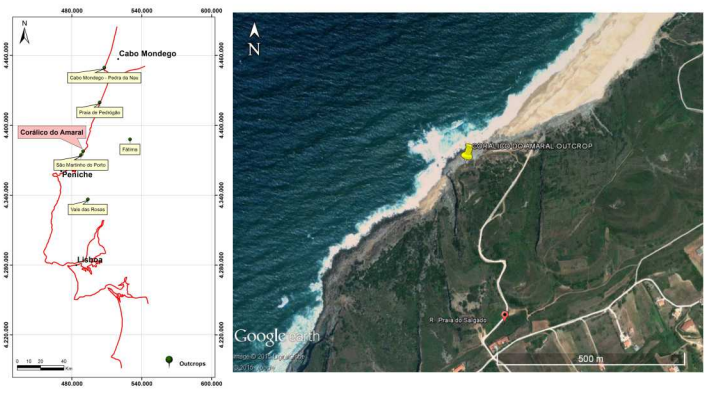
GIGA-MEGA SCALE – REGIONAL DATA BASE

Morro do Chaves Formation was deposited during rift stage of the evolution of the Sergipe-Alagoas Basin. The best exposure in outcrops are in the area of Intercement quarry, and the sediments are distributed as the following map. The spatial distribution of the lithologies are very important according to CAMURES methodology, because it help to understand the pathways of diagenetic processes.

The image below shows the location of the Coralico do Amaral outcrop at the Lusitanian Basin, at the Salgado Beach.

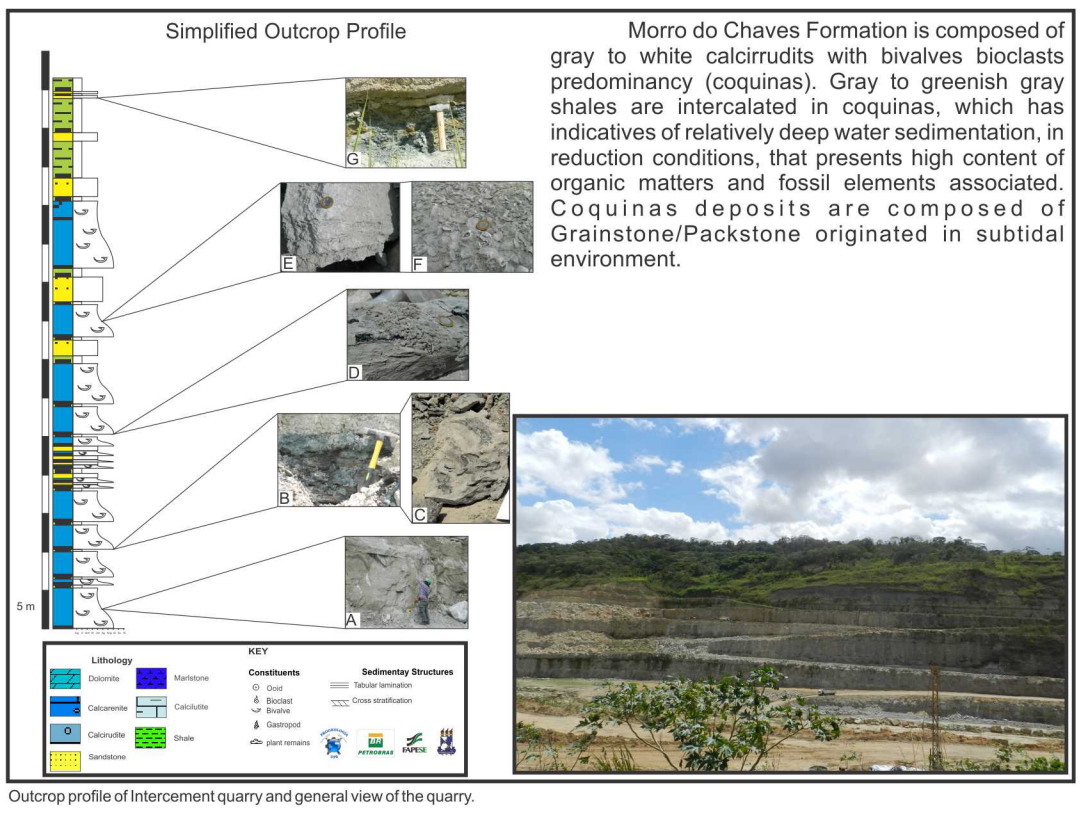


Simplified map of Sergipe-Alagoas Basin overlaid by the structural framework. On the right side, detailed tectonic-stratigraphic map of the studied area.



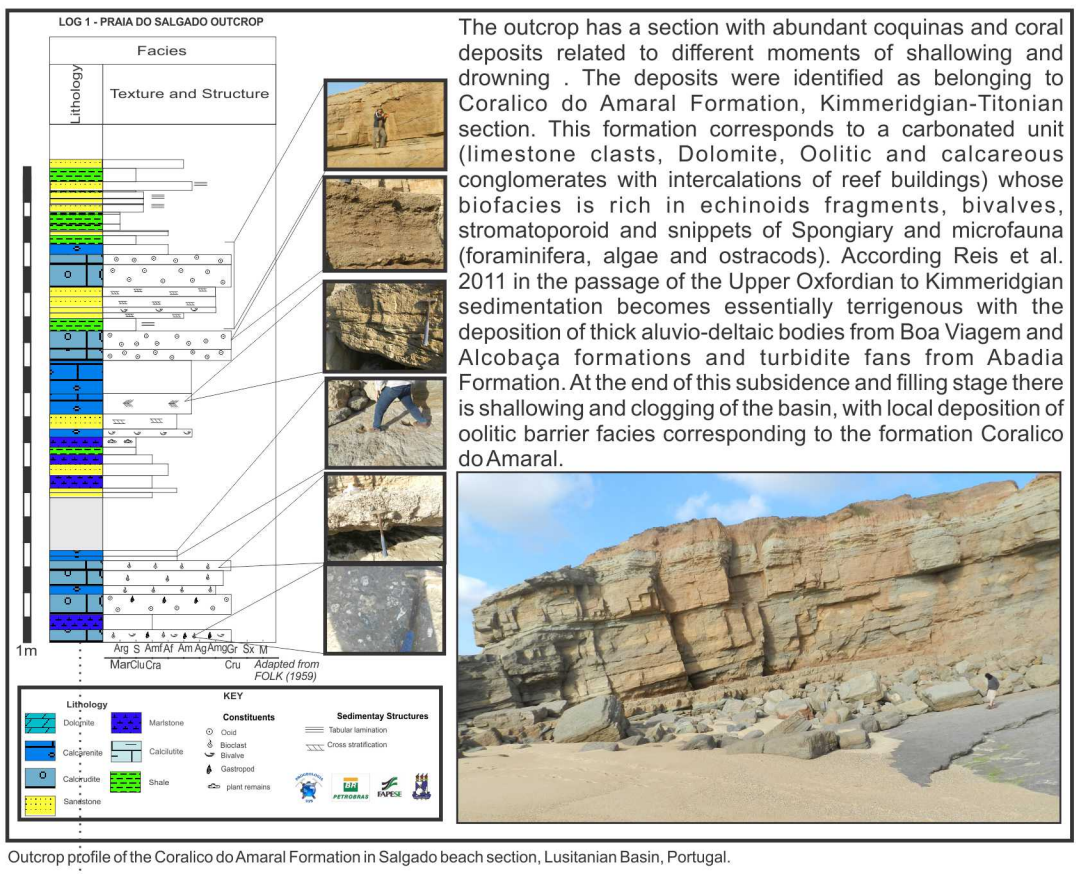
Location map of Salgado Beach outcrop. On the right side, aerial image from Google Earth.

STRATIGRAPHIC CONTEXT



Morro do Chaves Formation is composed of gray to white calcirrudits with bivalves bioclasts predominancy (coquinas). Gray to greenish gray shales are intercalated in coquinas, which has indicatives of relatively deep water sedimentation, in reduction conditions, that presents high content of organic matters and fossil elements associated. Coquinas deposits are composed of Grainstone/Packstone originated in subtidal environment.

Outcrop profile of Intercement quarry and general view of the quarry.



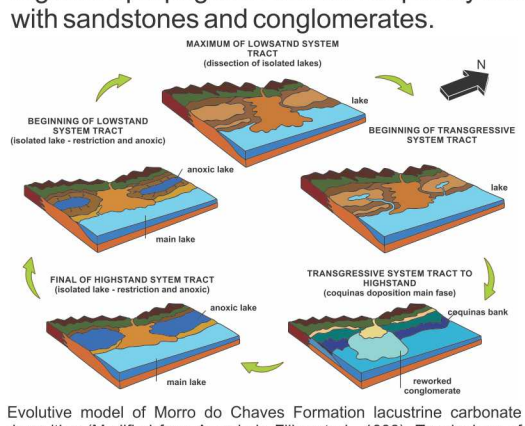
The outcrop has a section with abundant coquinas and coral deposits related to different moments of shallowing and drowning . The deposits were identified as belonging to Coralico do Amaral Formation, Kimmeridgian-Titonian section. This formation corresponds to a carbonated unit (limestone clasts, Dolomite, Oolitic and calcareous conglomerates with intercalations of reef buildings) whose biofacies is rich in echinoids fragments, bivalves, stromatoporoid and snippets of Spongiary and microfauna (foraminifera, algae and ostracods). According Reis et al. 2011 in the passage of the Upper Oxfordian to Kimmeridgian sedimentation becomes essentially terrigenous with the deposition of thick aluvio-deltaic bodies from Boa Viagem and Alcobaça formations and turbidite fans from Abadia Formation. At the end of this subsidence and filling stage there is shallowing and clogging of the basin, with local deposition of oolitic barrier facies corresponding to the formation Coralico do Amaral.

Outcrop profile of the Coralico do Amaral Formation in Salgado beach section, Lusitanian Basin, Portugal.

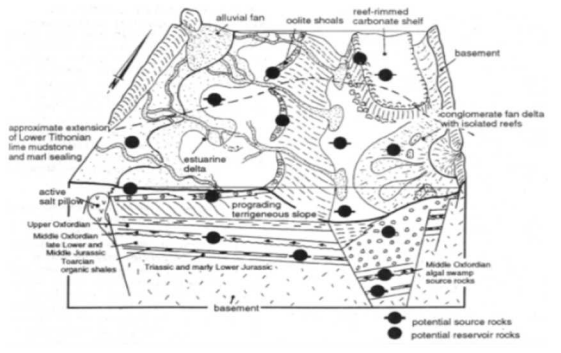
PALEOENVIRONMENTAL APPROACH

Depositional context of Morro do Chaves Formation is related to a mixed of carbonate-siliciclastic sedimentation formed by coquinas carbonates associated with terrigenous deposits (shales and sandstones) from Coqueiro Seco Formation.

The assumed model for this formation is originated from lacustrine sedimentation in rift context, where coalescents terrigenous aluvial fans progrades and interacts with lacustrine sedimentation. The advance and retreat of the lacustrine border, influenced by tectonism or climate changes, often permited the drowning of the terrigenous deposits, favoring the organism propagation and consequently the deposition of carbonate lithofacies, intercalated with sandstones and conglomerates.



Evolutive model of Morro do Chaves Formation lacustrine carbonate deposition (Modified from Azambuja Filho et al., 1998). Terminology of marine systems tracts adapted to lacustrine environment.



Depositional Systems at Arruda Sub-Basin at the Coralico do Amaral depositional time (According to Leinfelder, 1994).

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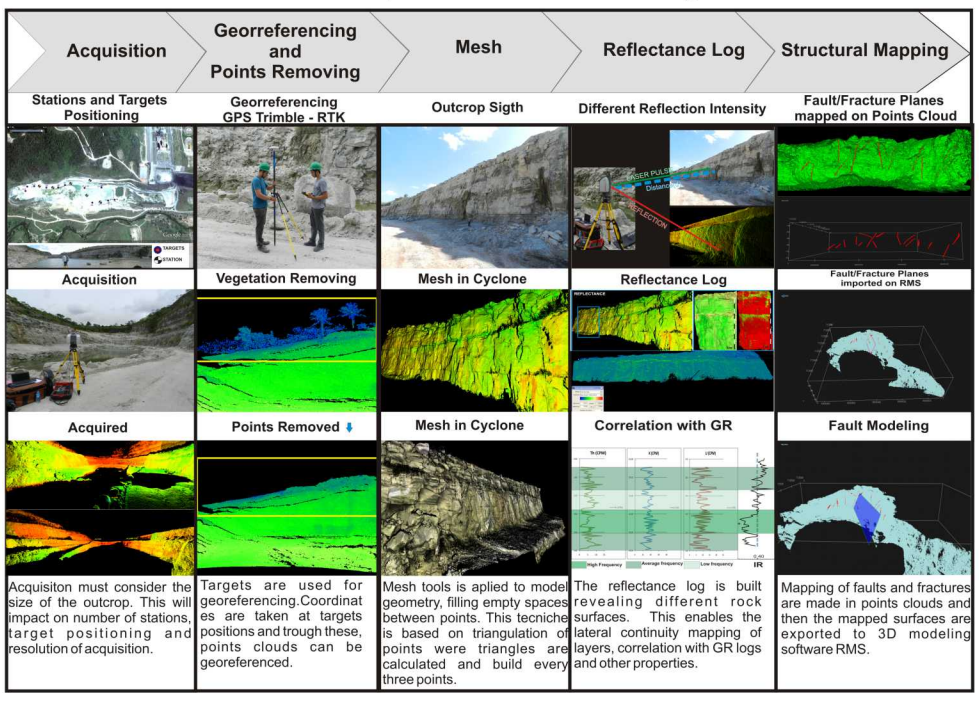
MACRO-MESO ESCALE – OUTCROPS DATA BASE

The outcrops studies permited the integration of properties extracted from digital data that represent with fidelity the morphology and external geometry of bodies and possibility of integration with others dataset, like GPR and electric logs.

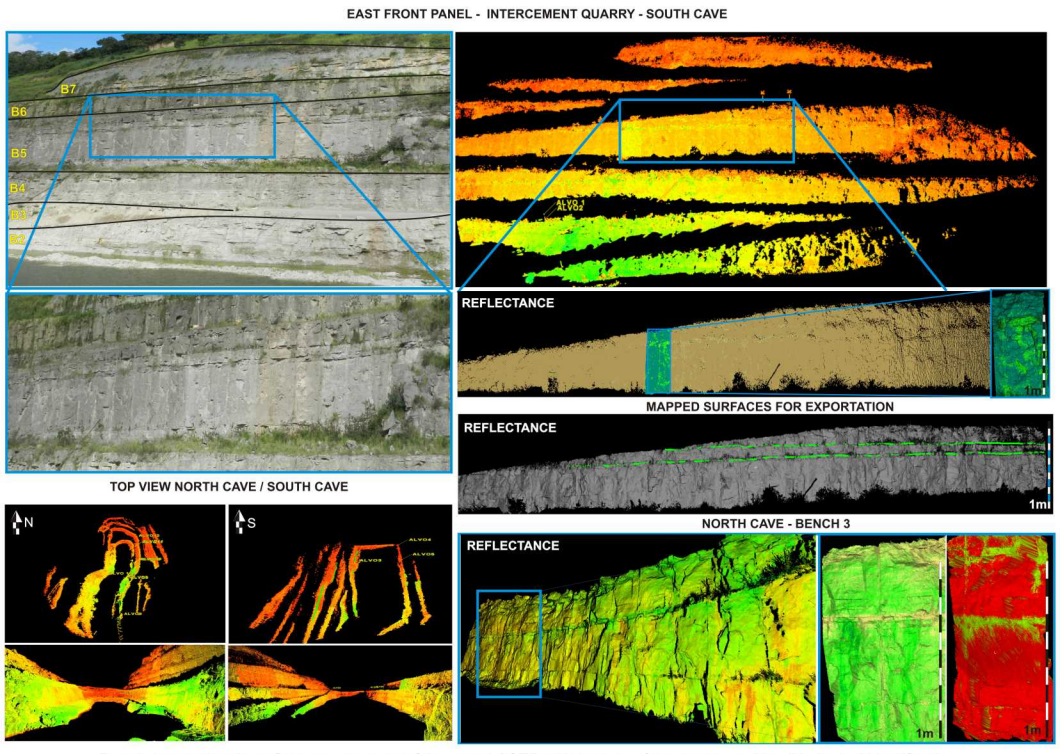
Laser Scanner Acquisition and Processing Workflow



MULTISCALE CHARACTERIZATION (LASER SCANNER AND 3D MODELING)

The layers of shale and calcirudites that were identified in the "points cloud" have thicknesses of 50cm to 1m, to the shales, and thicknesses of 2 to 5m, on average, to the calcirudites, which may reach 10m thick in some specific portions. In lateral extension of measures, both rock types have extension through all south and north pit, totaling 700m of lateral extension on display in mining.

Some of these surfaces could also be mapped according to the variation in intensity of reflection when compared to adjacent calcirudites. The intensity of reflection is first checked visually in the point cloud and then quantified in Cyclone allowing the identification of shales with better exposure. The intensity of reflection for shales showed averaged 26%, and calcirudites had 28%. The difference is due to the coloring of dark shale when compared to adjacent limestone which is lighter and whitish. When image filters were applied, the difference became more evident, mainly on intermediate portion of the east wall in south pit.



Panels integrating the reflectance property of the scan LASER with images of the quarry, making lithological identification.

OUTCROPS CHARACTERIZATION

The carbonate facies of Morro do Chaves Formation represent shallow water depositional conditions, under subtidal situation, where were deposited essentially calcirudits mainly consisting of bioclasts of bivalves ("coquinas"), from white to gray, showing finegrain upward, with calcarenite on top in most packages. The interstratification of these lithologies with fossiliferous shales, gray and green-gray, indicates conditions of relatively deeper water in distal situations to terrigenous contributions.

The "coquinas" deposits are arranged in continuous layers showing lenticular geometry, ranging from 0.2 m to 12.0 m thickness. The coarser intervals tend to present primary porosity filled by coarse calcite cement. The bioclasts have sizes between 0.5 cm and 5.0 cm lithologies and their deposits can be classified according Dunham (1962) as Grainstone / Packstone.

Interstratified with "coquinas" layers occured greenish shales, ranging from millimeter thicknesses up packages of approximately 6.0 m thick. May occur as lenses or intraclasts of shales in calcirrudits intervals. They have woody plant fossils fragments and large number of fossil fish fragments with dimensions up to 40.0 cm. Pyrite nodules with 8.0 cm in maximum diameter represent a reducing environment during eodiagenetic context. It is also observed fossiliferous ostracods levels, visible in hand specimens. Hummockys cross structures in calcirrudites can also be observed suggesting storms during the deposition of some "coquinas" intervals.

Toward the top of the outcrop is observed the reduction of the thickness of the layers of calcirrudit and relative increase in shale thicknesses. It is also observed an increased presence of siliciclastic materials represented by sandstones of medium to coarse interspersed in "coquinas" deposits, featuring a mixed sedimentation. The sandstones have plane-parallel bedding at the bottom, starting to cross stratification on top.

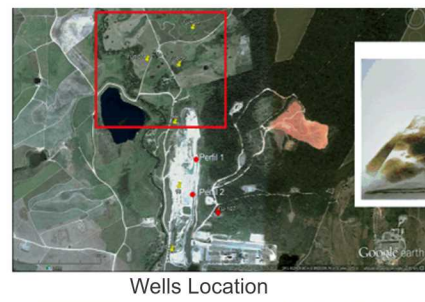
General description and interpretation of the sets in Intercement Quarry.

Salgado beach outcrop has a length of approximately 1 km along the coast with good exposure and good lateral continuity of the layers.

In its stratigraphic column the outcrop brings a record of alternating shallowing and drowning events. At its base limestone with abundant bioclasts of gastropods, oolites, oncolites and coral fragments were found. Further up at the middle portion of the profile, calcarenite and oncolytic calcirudites with shells and plant remains were found, sometimes interspersed with medium to fine sandstones with cross stratification, and shales that sometimes present coal fragments. In some calcarenite it was observed the presence of "herringbone" stratification. Next layers in direction to top of the profile, the system becomes predominantly terrigenous with medium to thick sandstone layers with planar stratification, interspersed with shales rich in plant remains.

Throughout the outcrop rolled blocks with abundant gastropods and shells of different sizes (reaching 3 to 9 cm in diameter) were found. These blocks were collapsed from upper layers of the profile described above, probably resulting from the erosion of shale layers below them.

CORE DESCRIPTION AND SAMPLING FOR PETROGRAPHIC AND PETROPHYSIC ANALYSIS



Wells Location

Oil Extraction

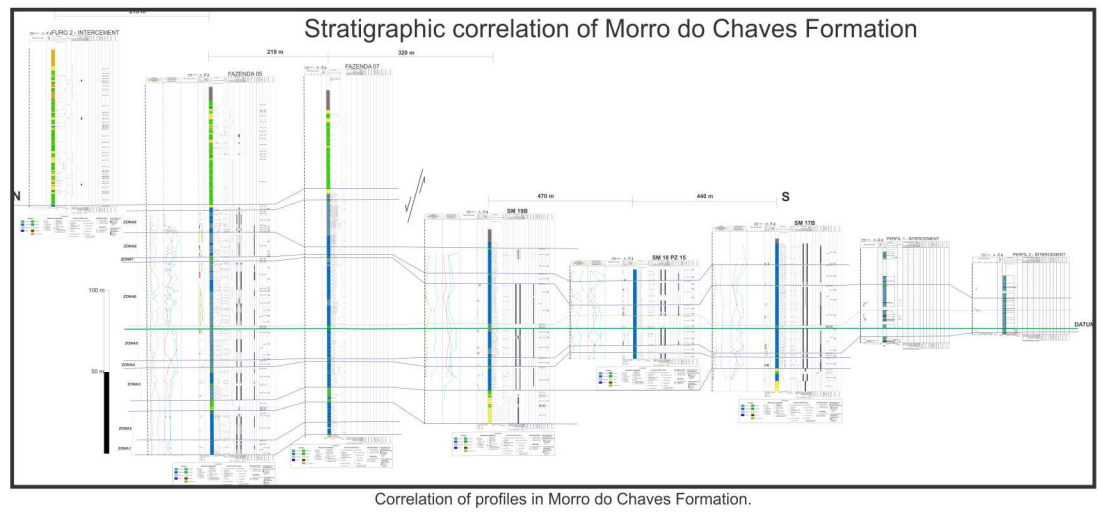
Cores

Plug with Organic Matter

Plug

Petrophysic Analysis

Stratigraphic correlation of Morro do Chaves Formation



Correlation of profiles in Morro do Chaves Formation.

PETROGRAPHIC CHARACTERIZATION

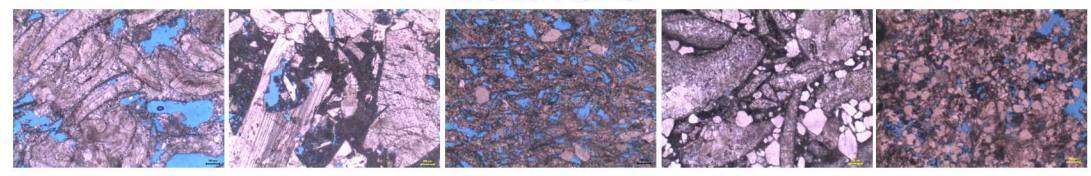
Morro do Chaves Formation presents low diversity of fossil content, being ostracodes and bivalves mollusks fragments the main important components. Siliciclastics are also important, like clay intraclasts, feldspar, mica and metaquartzites. They all represents a bioclastic carbonatic sedimentation in relatively calm waters with continuous influency of siliciclastic aport from continent, associated with erosive reworking of the ground.

These characteristics lead to generation of different textural types of its deposits, from calcarenites and calcirrudites free from matrix and cemented by spatic calcite, until calcirrudites rich in clay matrix or micritic, resulting of depositional erosive processes with mix of components. Taphonomic studies are being carried out in order to characterize the relations between depositional processes and the defined carbonate microfacies.

Petrophysical characteristics varies too much. The main types of porosity observed in grainstone/rudstone rocks are moldic, vugular, interparticle and intraparticle, with average porosity of 15%.

The micro-scales studies of the Coralico do Amaral Formation are in progress.

MICROFACIES



F 17 - 16: Grainstone/Rudstone bioclastic with bilvalve.

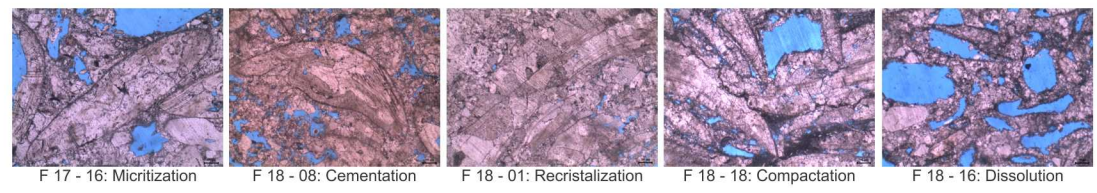
F 17 - 06: Packstone/Rudstone bioclastic of bivalves molluscs. Shells broken and angular.

F 17 - 21: Grainstone of bivalve molluscs.

F 19 - 18: Pack-Grainstone/ Rudstone bioclástico of bivalves with terrigenous.

F 05 - 46: Sandstone with carbonate cimentation.

DIAGENETIC ASPECTS



F 17 - 16: Micritization

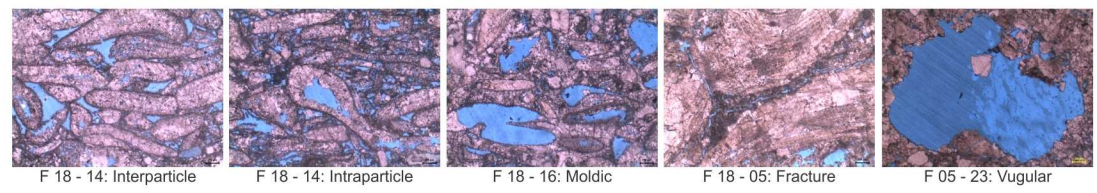
F 18 - 08: Cementation

F 18 - 01: Recristalization

F 18 - 18: Compactation

F 18 - 16: Dissolution

POROSITY TYPES



F 18 - 14: Interparticle

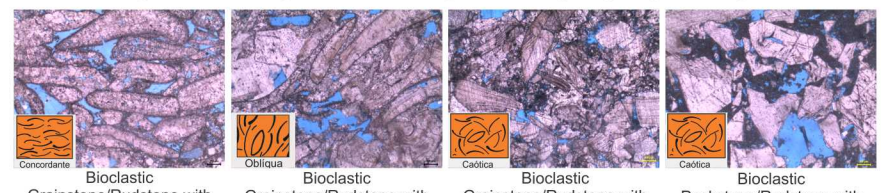
F 18 - 14: Intraparticle

F 18 - 16: Moldic

F 18 - 05: Fracture

F 05 - 23: Vugular

ORIENTATION AND PRESERVATION OF SHELLS



Bioclastic Grainstone/Rudstone with disjointed molluscs whole shells, recrystallized and rounded with concordant guidance.

Bioclastic Grainstone/Rudstone with disjointed and broken molluscs whole shells, recrystallized, rounded with oblique orientation.

Bioclastic Grainstone/Rudstone with disjointed and broken molluscs shells, recrystallized, rounded and angular distributed chaotically.

Bioclastic Packstone/Rudstone with broken molluscs shells, recrystallized, angular distributed chaotically.

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MICROFACIES ASPECTS OF DIFFERENT STRATIGRAPHYC ZONES

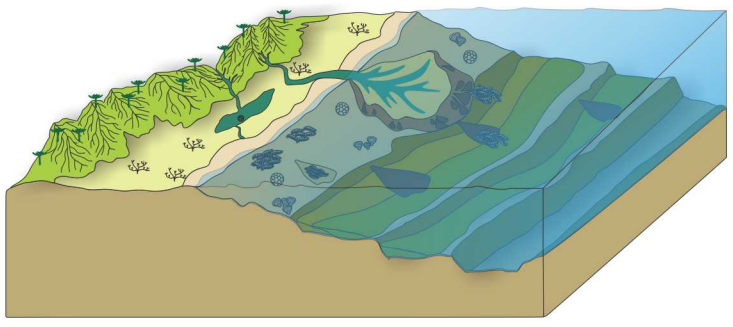
	General description	Macroscopic aspects	Microscopic aspects	Graphic
ZONE 5 - MCH	It has a moderate grains content (53,79% average). Its framework is frequently open, sometimes normal and locally tight. Cement content is not the most significant between zones (15,33%). It has high total porosity, ranging from 12,06% a 20,61% (average 18,8%). This zone has the best reservoirs conditions between all studied because its biggest macroporosity, 8,24%. Intergranular pore type is frequently found, and considered the best for permeability values.	F17b-9 Very coarsed white calcarenite. F19b-9 Coarse grained white calcarenite.	F17b-9 Bioclastic bivalves mollusks Grainstone/Rudstone. High dissolution. F19b-9 Bioclastic bivalves mollusks Grainstone/Rudstone.	ZONE 5 / MICROPOROSIDADE X MACROPOSIDADE / ZONE 5 - GRÃOS X POROSIDADE / ZONE 5 - MATRIZ MICRÍTICA X POROSIDADE / ZONE 5 - MATRIZ CALCARENÍTICA X POROSIDADE / ZONE 5 - CIMENTO X POROSIDADE
ZONE 8 - MCH	It has great content of grains (58,49%), open to normal package, sometimes locally tight. One of the less cemented zone (13,85%). It has 9,45% of total matrix, being almost everything of micritic matrix (9,27%). Its total porosity ranges from 9,91 a 27,96% (average 18,02%), being the second biggest value of porosity between zones, with frequent intergranular porosity and present moldic. Because of this characteristics we can conclude that this zone has high reservoir potential, given your high porosity, low cementation and good lateral continuity.	F18-16 Calcarenito grosso. Com porosidade móldica. F5-26 Calcarenito grosso cinza esverdeado com intraclastos.	F18-16 Grainstone/Rudstone bioclástico de moluscos biválvios. Com porosidade móldica. F5-26 Grainstone/Rudstone bioclástico de moluscos biválvios com siliciclásticos.	ZONE 8 / MICROPOROSIDADE X MACROPOSIDADE / ZONE 8 - GRAINS X POROSITY / ZONE 8 - MATRIZ MICRITIC X POROSITY / ZONE 8 - CALCARENITE MATRIX X POROSITY / ZONE 8 - CEMENT X POROSITY

Best reservoir zones for oil prospection, according to studied proprieties

DEPOSITIONAL MODEL

The carbonate facies of Morro do Chaves Formation characterizad shallow water conditions, in infratidal environment with calcirudaceous deposit consisting mainly by bioclasts of bivalves ("coquinhas"), showing finingupword granulometry (sandstone) and white to gray colors, eat calcarenites on top in most packages. The interlayred of these lithologies with gray and green-gray shales, containing fossils of fish and other organic elements, indicates conditions of relatively deeper water in the distal situations terrigenous contributions, which come to dominate reducing conditions favoring a high organic content in some intervals.

Field data integrated with micropaleontological and petrographic studies support the conclusion that calcirudaceous deposits (coquinas) were generated in subaqueous environment where cyclic supply of terrigenous siliciclastic sediments (sandstones and conglomerates from Coqueiro Seco Formation), controlled by tectonic activities and / or climate variations, make shallow the water body and permitting the deposition of bioclastic carbonate sediments (bivalves) of the Morro do Chaves Formation. This bioclastic materials , more or less reworked by fluvial correntes ou waves influences, was accumulated in calcarenosas and calcirudaceas lenses, showing chaotic or organized shell distribution and parallel or cross-stratification structures, interlayered with shale and marl, deposited at relatively deeper water positions of the lacustrine environment under anoxic conditions.



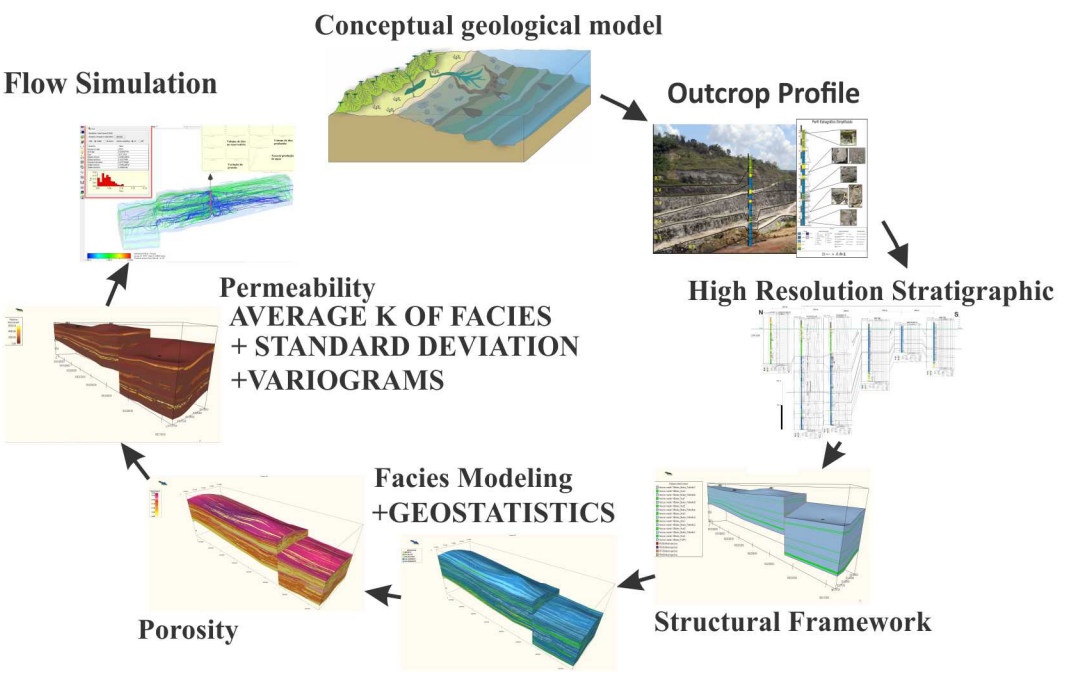
Depositional model to carbonate deposits of Morro do Chaves Formation.

The data integration about the the Morro do Chaves Formation permit recognized their deposition in a coastal area of a large a aquatic environment, like a lagoon. The esporopolínic association permit conclude that this lake / lagoon would be located on a herbaceous vegetated plain, with remote mountainous areas, where a large port arborea vegetation lived, under a general hot weather conditions and restrict water availability. The accessibility of the palinologic material to the depositional lacustrine environment was controlled by seasonal flash flood from the highlands during the rain periods and by air currents air.

Optical microscope analysis under fluorescent light allowed some progress on the issues of paleoenvironmental unit. In some sampled intervals was identified algalic vesicles, introducing to the system depositional a new element, the algae. These are possible ficomas of algae Prasinophyceae class, identified in two intervals located at the top of the stratigraphic section. The habitat of living species of Prasinophyceae class is predominantly marine, but there are also records in fresh or brackish water environments (Tappan, 1980). These elements can be found in proximal deposits, related to shallow lakes and fan deltas in marine environments. These data support the Arai (2009) hypothesis related to marine invasions come from the northeastern.

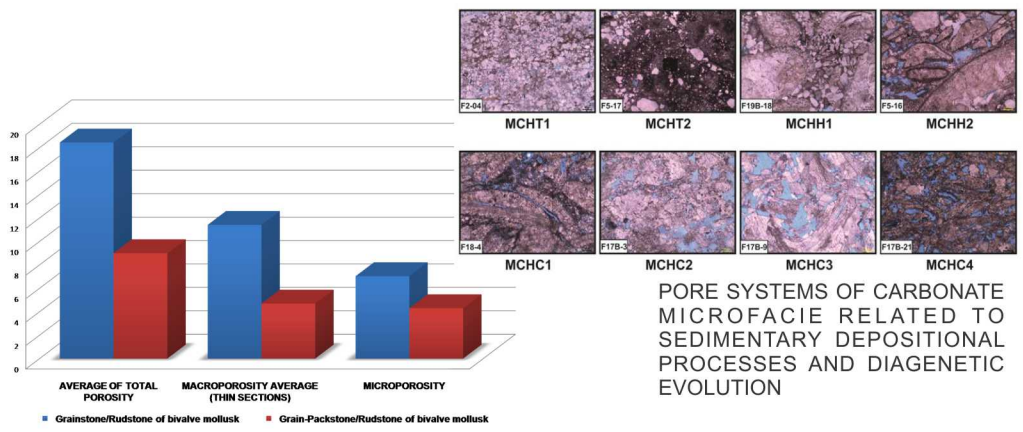
CAMURES METHODOLOGY APPLIED TO 3D GEOLOGICAL MODELING OF RESERVOIR PROPERTIES

For the implementation of this methodology, samples of the representative deposits of calcarenite, calcilutite and coquina of SEAL Basin were selected. In order to develop the geological models, petrophysical modeling was conditioned to facies modeling and compared with the model analyzed in micro-scale. The integration of multi-scale data in 3D geological modeling software allowed the recognition of heterogeneities responsible for controlling the fluids flow in reservoirs, as well as the compositional attributes of the studied outcrops analogues.



3D Facies Model, 3D Porosity Petrophysic Model, Porosity Petrographic Model and Porosity Petrographic/Petrophysic Model.

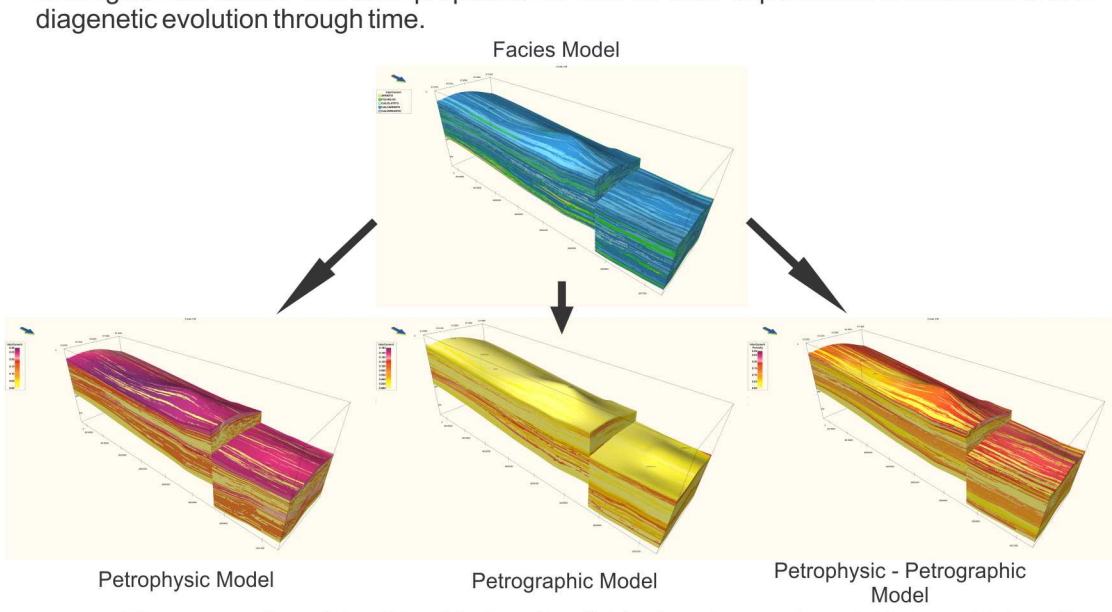
MACROPOROSITY (PETROGRAPHIC ANALYSIS) AND MICROPOROSITY RELATIONSHIP IN MORRO DO CHAVES MICROFACIES



PORE SYSTEMS OF CARBONATE MICROFACIE RELATED TO SEDIMENTARY DEPOSITIONAL PROCESSES AND DIAGENETIC EVOLUTION

3D MODELLING OF FACIES AND PORE SYSTEM OF COQUINA CALCRUDITE AND CALCARENITE

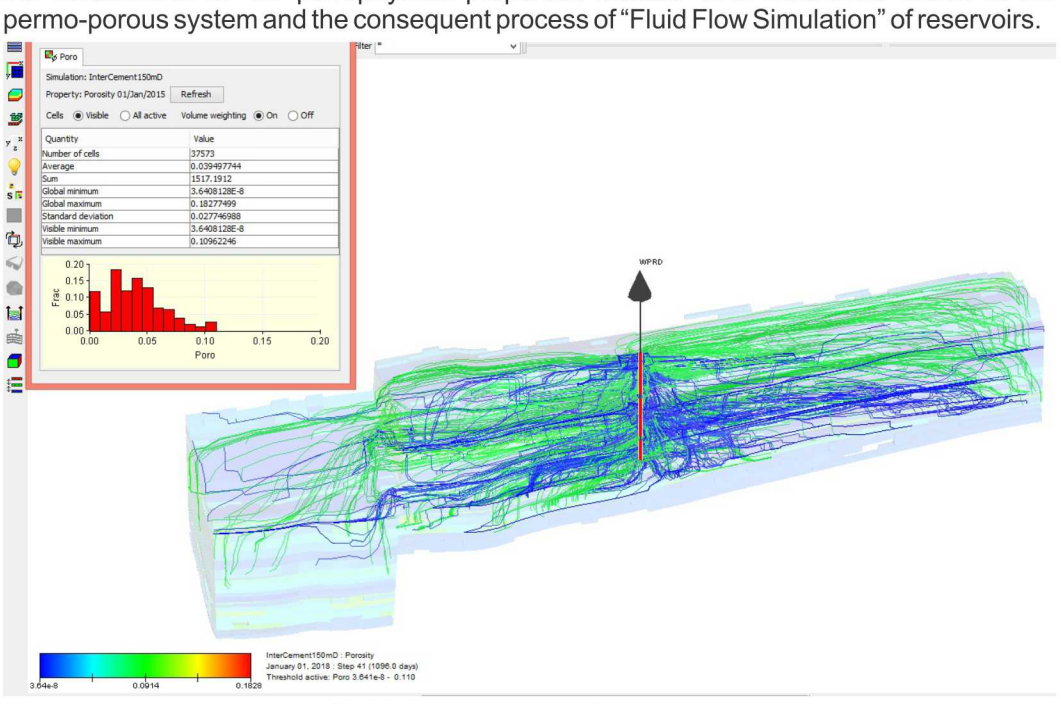
For the 3D model of the reservoir properties it is important to characterize the lithologies distribution and their properties as well as their depositional environments and diagenetic evolution through time.



The generation of the 3D grid aimed to divide the structural model into multiple cells with facies, porosity, permeability, among other data. The outcrop is modeled deterministically using multi-scale tools. In the extrapolation process are used 3D stochastic data using geostatistical information. Mixed stochastic deterministic was the used modeling approach.

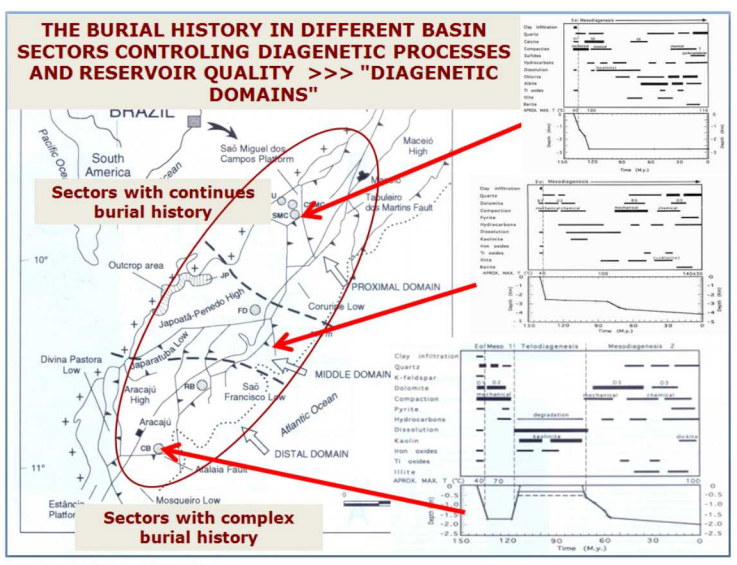
CAMURES WORKFLOW FROM 3D MODELING TO FLUID FLOW SIMULATION

The studies of "Analogues Outcrops Reservoir" are developed in order to reduce uncertainties relates to the "Depositional na Diagenetic Models", which will be the basis for the construction of "3D petrophysical properties Models" in a multi-scale model of the permo-porous system and the consequent process of "Fluid Flow Simulation" of reservoirs.



Simulation in 3D model of Morro do Chaves Formation.

NEXT APPLICATIONS OF THE CAMURES METHODOLOGY



Mapping of diagenetic processes and porosity evolution in siliciclastic and hybrid carbonate analogue reservoirs in sergipe-alagoas basin.

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