Multiscale Characterization of Analogue Outcrops Integrating Reservoir Properties and Geologic Processes*

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Abstract

Studies using outcrop analogues has been practiced over the last few years. These kinds of studies help to solve important questions that in the subsurface are not totally possible. In the Sergipe-Alagoas Basin, in northeast of Brazil, the carbonate and hybrid potential reservoir intervals from Riachuelo Formation provide great outcrops for studies of carbonate analogs in comparison to all Atlantic basins of Brazil. Deposits from shallow carbonate environments from the Carapeba Quarry were characterized using a multiscale reservoirs characterization approach with different tools.

Rappel practice was applied to detail lithology description of 19 vertical log profiles complemented with gamma ray logging of the detailed intervals. Five were correlated in a stratigraphic sections and 130 thin sections were described using microfacies methodology to characterize microscale heterogeneities of pore system. Laser scanner and Ground Penetrating Radar (GPR) were utilized in strategic positions, aiming to understand the depositional architecture and internal geometry of the sets. According to their compositional and textural characteristics, 12 different microfacies were recognized and grouped into 6 main facies: dolostone, grainstone, hybrid, dolomitized packstone, dolomitized wackestone, and shale, which were used in a 3D geological model. A petrophysical database of 49 samples associated to petrographic data were analyzed in order to introduce permeability and porosity data of each facies in the 3D model.

The highest values of porosity are in the hybrid lithologies, followed by dolomitized packstones. Dolostones were less porous. Hybrid samples, with porosity values between 12.23 to 18.197%, the permeability ranges from 0.0383 to 1.63 mD, while in dolostone samples, porosity is between 6.528 to 14.101%, the permeability varies from 0.0029 to 1.77 mD. Diagenetic features identified are micritization, dolomitization and dissolution. The facies characterized in Carapeba Quarry correspond to the usual carbonate complexities founded in this important type of reservoir, with good porosity values identified, but with poor connectivity between pores as evidenced by low permeability. However, at

greater depths and with a different burial history, these rocks can be different when fractured or dissolved. Next steps will consider the extension of 3D outcrop modeling to regional context, at the oil field scale, considering stratigraphic correlation at the distribution of different lithologies.

Introduction

Studies of outcrops are important to understanding multiscale heterogeneity aspects and relate them with analogue intervals to the subsurface. This study aims to characterize through a multiscale approach an outcrop from the Riachuelo Formation in the Carapeba Quarry that presents shallow marine carbonate deposits related to the beginning of drift phase of the Albian Sergipe-Alagoas Basin in northeast Brazil.

The main objective of these studies is creation of a 3D model of the outcrop section, based on a multiscale characterization of the deposits, in order to understand the permo-porosity heterogeneities and behavior of the carbonate facies. To attain these objectives, some procedures were developed: (1) Description of lithofaciologic profiles; (2) Description of thin sections in order to understand the textural and porosity heterogeneities; (3) Integration of lithostratigraphic correlation section to understand the lateral and vertical facies and understand the depositional model, important to understanding the facies variability and consequently the original permo-porosity distribution. The conceptual geologic model is important when developing the 3D virtual model, so it is indispensable to have it completely understood. Literature gives us support to better build the model.

Geological Setting

The Sergipe-Alagoas Basin is located in northeastern Brazil and extends for 35,000 km² in the coastal region of the Sergipe and Alagoas states. Its geologic evolution is related to the opening of South Atlantic Ocean and separation of the Africa and America continents.

It presents an elongated shape in a northeast-southwest direction with an extension of 350 km with an average width of 35 km onshore (Lana, 1985). The onshore area is 13,000 km², and the offshore area 20,000 km² to the 2,000 m bathymetric quota (Falcone, 2006) (Figure 1). This basin presents the most complete record in outcrops of the South Atlantic (Milani and Araújo, 2003), from the opening phase to the drift phase. The Sergipe-Alagoas Basin provides great outcrops for the studies of carbonate analogues to compare with other analogue intervals in another marginal Atlantic basin in Brazil. The studied intervals represent the beginning of the drift phase and include Albian deposits of the Riachuelo Formation, developed during three stages of sea level change: lowstand system tract (Sequence I), transgressive system tract (Sequence II), and highstand system tract (Sequence III) (Mendes, 1994). Its maximum thickness in the subsurface is about 2800 m.

This Riachuelo Formation is lithostratigraphically composed of three members, the Angico, Maruim and Taquari, respectively composed by sandstones and conglomerates with rare bioclast compounds; oolitic/oncolitic bioclastic banks, beyond algalic bioconstructions developed in some parts of a carbonate ramp with low influx of siliciclastic sediments (from Angico Member), resulting in bioclastic grainstones, wackestones and packstones; and finally by calcilutite and shale of deep marine environment and/or more internal lagoon.

The outcrop described in this work is in the Carapeba Quarry, located about 25 km from Aracaju's Center (coordinates: UTM: X- 701365; Y-8809149, 24L zone), Laranjeiras City, capital of Sergipe State. In general, the quarry exposes bioclastic calcarenites, with oolites and oncolites in several levels, interbedded with dolomitized marls and dolostones.

Material and Methods

This work was realized using analogue outcrops using Multiscale Reservoir Characterization (CAMURES). The objectives of this methodology are to integrate the macro scale database with micro scale petrographic and petrophysic properties (Figure 2 and Figure 5).

The macroscale characterization includes lithology descriptions of 5 vertical log profiles in 15 m high rock wall with 100 m of extension. In the Carapeba Quarry, the description of the profile was complemented with gamma ray logging and integrated with Laser Scanner methodology. The stratigraphic correlation section, along with lithofaciologic description and petrographic data from 130 thin sections described using microfacies methodology are used to characterize microscale heterogeneities of the pore system and its main framework features. This approach was essential to identify the stratigraphic cycles. The geometric patterns and lateral continuity of facies were mapped with Laser scanner and GPR. After the thin sections characterization it was possible to define 12 different microfacies, based on textural characteristics. Then they were grouped in 6 main facies (dolostone, grainstone, hybrid, dolomitized packstone, dolomitized wackstone and shale) aiming to generate 3D models. Petrophysical analysis were realized in 49 samples of specific intervals to represent the maximum heterogeneities of each facies. The petrophysical results associated with petrography data were compared to introduce the permeability and porosity data of each facies in the 3D model. These data were conditioned to respective represented facies when modeled in the software RMS.

Facies Analysis

The Carapeba Quarry exposes bioclastic calcarenites, including oolites and oncolites in several levels, interbeded with dolomitized marls and dolostones. The microfacies approach was applied to characterize specific facies use to modeling. The Figure 3 shows the main microfacies identified with the Riachuelo Formation in the Carapeba Quarry. The sedimentologic environment was recognized as a lagoon where oncolitic and peloidal wackestones and packstones sometimes dolomitized, marls and mudstones actually completely dolomitized, and fine sandstones containing vegetal fragments and fine dolomitized matrix. This lagoon environment was directly connected with the external margin of the platform, with presence of grainstones with peloid grain sand and intraclasts of red algae.

Lagoon

The lagoon was dominated by a low to moderate energy environment. It has different facies with several sedimentary constituents that reflect the variability of the energy and the terrigenous part of the system. The main constituents recognized were peloids, equinoidea and bivalves, as well as solenoporacea red algae *Marinella* and cyanobacteria *Girvanella*, with a provenance of adjacent material from the external margin. This facies was intensively bioturbated. Wackestone and oncolitic and peloidal packstones/floatstones are the main microfacies identified, sometimes dolomitized, beyond marls, mudstones completely dolomitized, fine sandstones with carbonate cementation and vegetal remains, provenance from the temporary siliciclastic part of the lagoon, as the part of distal deltaic fans in a low energy system. Shoreface sediments often dolomitized and are associated with this deposit and made for coarse sandstones with great bioclastic material (essentially bivalves). "Coquinoide" deposits made mainly of oostrea bivalve and gastropods (*Peruviella dolium*) are outstanding deposits.

Inner Ramp

A restricted environment is represented by low to moderate energy, generally with well-sorted facies, sometimes moderately-sorted with green and red algae coarse grains. Oolitic grainstones and micritized oolitic grainstones are the microfacies that characterize this environment. The main bioclastic elements present are mollusks, *Dasycladacean* green algae, *Marinella* and *Pycnoporidium* solenoporacea red algae, beyond agglutinated benthonic foraminifer and miliolids. Figure 4 show the conceptual geologic model for Riachuelo Formation.

Diagenesis

Dolomitization is the most relevant process that occurred at Carapeba Quarry (Figure 6). In general, the size of dolomite crystals is a function of the numbers of nucleation sites and the growth rate. Based on this principle, it is believed that the finest dolomite occurred replacing the finest precursors carbonates, like mudstones and the wackestones matrix, with some peloidal and bioclastic content.

The heterogeneity in the dolomitization process for the partially dolomitized calcarenites is associated with bioturbation and consequently to permeability difference due to the biogenic structure. The presence of bioturbation promoted the preferential circulation of dolomitizing fluids, leading to complete dolomitization of these rocks, while not in bioturbated zones the dolomite is restrict to some dispersed planar euhedral crystals. In the latter, the dolomitization is selective, possibly associated with the composition of dolomitized grains, implicating that the mineralogy of the micritic cover or grains have been of calcite with high magnesium content, as approached by Buchbinder and Friedman (1970).

The considered dolomitization model operant in the described intervals assign the meteoric fluids participation that infiltrate by a meteoric fluids fringe that invaded the carbonate zone on lagoon and carbonate bars (Figure 4), mixing with the marine fluids fringe, leading to propitious conditions to dolomitization (Mixing water model - Dorag Model). The mixing water model is easily maintained by the evidence of marine regression during the deposition of the Maruim Member, as pointed out by Mendes (1994), associated with Milankovitch Cycles. Data presented by Diaz et al. (2009) demonstrate that the oxygen isotopes signature indicates the influence of meteoric water in the dolomitizing fluid and that the carbon isotope signature diagnoses that the cement, precursor of the dolomitized matrix, was deposited in a marine environment. Nevertheless, there is progression of dolomitization during mesodiagenesis, because there are developing of rhombs of dolomite over other smaller dolomite crystals.

Both micritic calcite and dolomite dissolution processes occur associated with meteoric fluids percolation, infiltrated in deposits by their exposition (telodiagenesis). As a result of this process there is generation of a secondary position. Other diagenetic features are bioturbation, micritization, cementation, neomorphism and dissolution.

Petrophysical Analysis

49 samples were analyzed aiming to obtain poro-perm values and these petrophysical data were integrated to facies characteristics. The facies analysis was applied to definite the first step of the 3D modeling. The highest values of porosity were identified with hybrid lithofacies, followed by dolomitized packstones and the less porous were dolostones. On hybrid samples, porosity values vary from 12.23 to 18.197% (average 15.773%), and permeability varies from 0.0383 to 1.63 mD (average 0.3683 mD). Partially dolomitized packstones porosity varies from 10.285 to 19.762 (average 14.25%), and permeability varies from 0.112 to 1.15 mD (average 0.47055 mD). In dolostones, porosity ranges from 6.528 to 14.101% (average 10.008%) and permeability varies from 0.0029 to 1.77 mD (average 0.23572 mD). Partially dolomitized packstones is the facies that has the best relation between porosity and permeability, probably because the moldic porosity was associated with dissolution of dolomite cement, (intergrain and in fracture), and microporosity. The high values of porosity presented by facies are related to the microporosity, because in thin sections the rocks present low macroporosity occurrence, furthermore, the pores are disconnected, and there is no significant grain/matrix/cement dissolution, which results in low permeability values.

3D Modeling

Definition of Zones for 3D Modeling

Stratigraphic analysis was realized focusing on multiple characteristics of these rocks. One of those observations was the fossiliferous content, summarized in Figure 3, obtained after the detailed description of 76 thin sections. The fossiliferous assemblage in carbonate rocks are essential when analyzing the sea level variations, since a single fossil can give us evidence of a different environment of sedimentation, internal or external lagoon, ooidal banks, corals, etc.

The Carapeba Quarry succession exposed in general a progradation of the ooidal banks system over a lagoon. This situation is evidenced by the presence of shallow ooidal bank sediments (with associated red and green algal bioclasts) occurring on the top of the succession that overlies dolomitized marls from the lagoon. Examining high frequency stratigraphy on the profiles of the front wall, it is possible to identify four shallowing-upward cycles (LCR in Portuguese) of fifth order (Figure 7). The outcrop presented seven cycles from the base to the top.

In short, these four surfaces are the boundary of each zone for realizing the modeling, consequently, each facie modeling is condition to its occurrence in each zone. Base and top of a zone define an interval of time where the facies inside have the same geological time, sharing the same diagenetic process (Figure 8).

Facies Modeling

The distribution of five facies on the geologic grid was based on stratigraphic correlation, vertical and horizontal geometric distributions and at points cloud of laser scanner, gamma ray profile, and petrographic data. Based on these data, the “Facies Modelling: Belt” tool of RMS was used to create a stochastic model to represent the transitional geologic environments in systems including progradation and retrogradation.

To adjust the mesh, in other words to fit the profiles fields with the facies distributions in the software, the tool "Well log Editor/Calculator" was used. This is very necessary due to the fact we have to honor all the field interpretation and the geologic settings studied. Spherical variogram and Kriging method were applied to better develop the facies inside the zones. After applying these tools it was possible to verify that the facies variation in a 2D cross section through the profiles was similar to the correlation interpreted with geology. In the generated 3D model it is possible to see the agradational pattern of the lithological succession, that exhibit the stabilization of the carbonate system, repeating the lithologies through the section. Facies have good lateral continuity in this scale. The 3D modeling of this work was realized in RMS, software from Roxar.

Petrophysical Modeling

The distribution of permo-poro parameters was conditioned to the facies model, where every value of petrophysical data was attributed in the respective cell and extrapolated to the neighbors with the same characteristics. As said before, the interpolation of data was done for each zone. Simulation algorithm available in RMS was applied to modeled petrophysical data (Figure 9).

The sequence from the best to the worst facies is Hybrid rock (15.77%), Packstone (14.25%), Wackestone (13.84%), Grainstone (11.81%) and Dolostone (10%). And for permeability it is Packstone (0.436 mD), Hybrid (0.368 mD), Grainstone (0.261 mD), Dolostone (0.235 mD), and Wackestone (0.192 mD). It is seen that all facies present great values of porosity, but their permeability is too low. This is due to microporosity, detected and described in thin sections. Usually, they are not connected, and indeed this impacts heavily on permeability and consequently on low fluid flow.

Conclusions

This study focused on the variability of the carbonate lithologies in a 3D model. The application of the CAMURES approach was important to support the prediction of facies behavior which were controlled by the depositional environment, interpreted as shallow lagoon influenced by inner margin sediments. Facies heterogeneity inside each modeled zone was expected since previous interpretations as shallow water carbonate environment. In carbonates, lateral facies variations even at the worked scale are intense. The knowledge of the conceptual depositional model was very important to understanding the interaction among the five modeled facies. The dolomitization identified in the section was controlled by smooth variations of the sea level, resulting in mixing waters at groundwater level.

Acknowledgments

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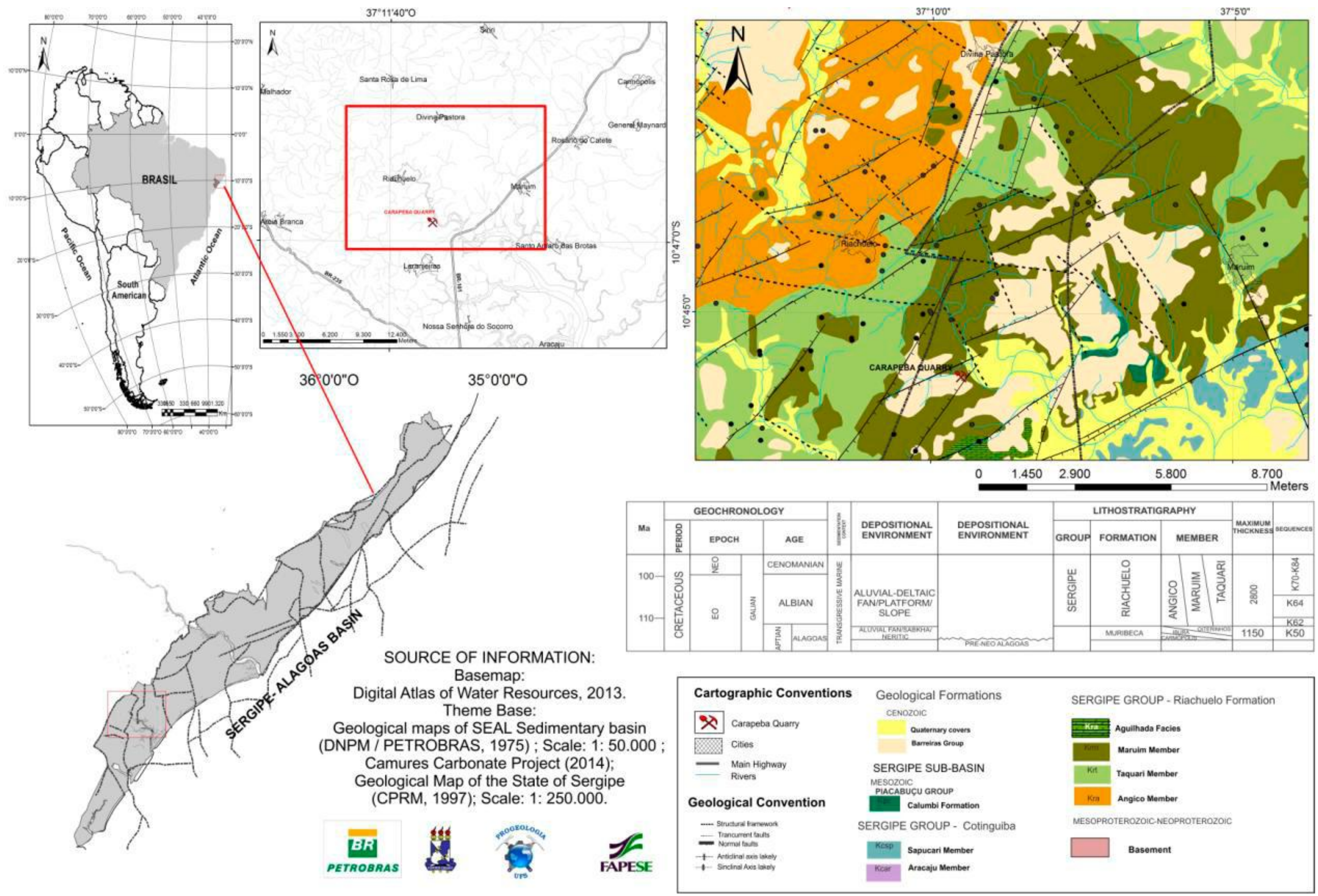


Figure 1. Sergipe-Alagoas Basin location map, detailed geologic map with Carapeba Quarry location and simplified stratigraphic chart.

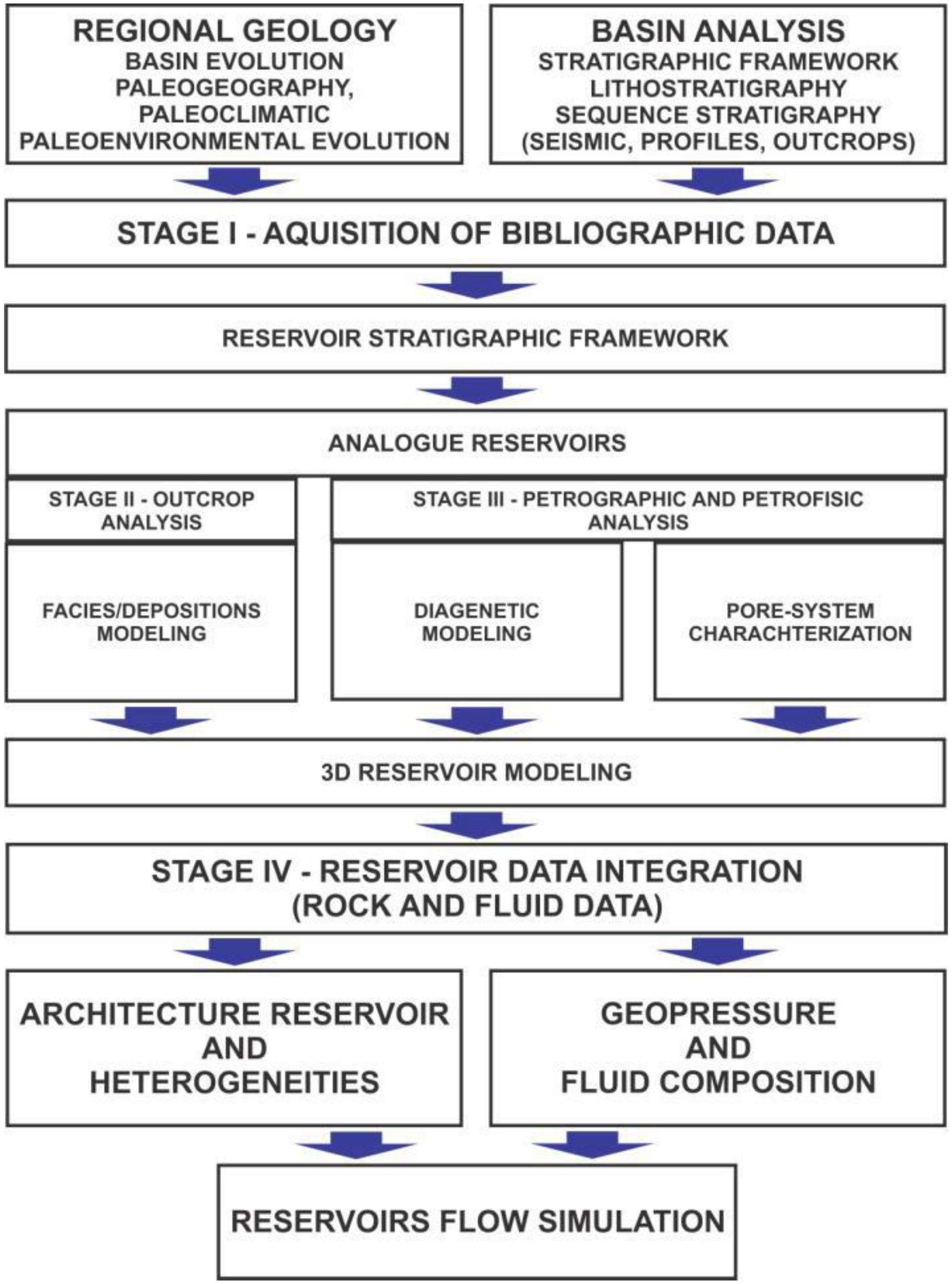
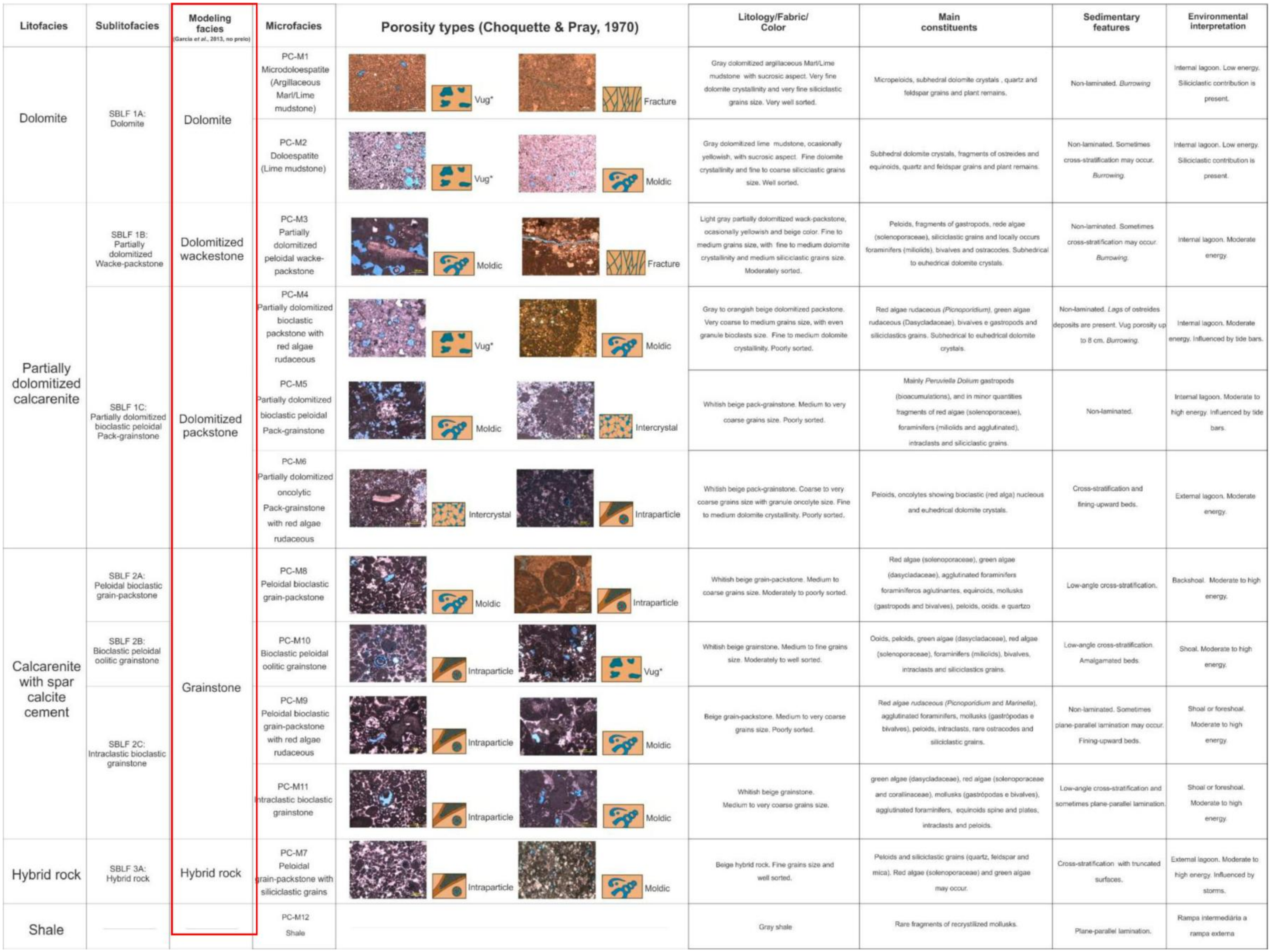


Figure 2. Workflow of the studies realized in this article from the microscale to the macroscale.



Litofacies	Sublitofacies	Modeling facies (Garcia et al., 2013, no prelo)	Microfacies	Porosity types (Choquette & Pray, 1970)	Litology/Fabric/ Color	Main constituents	Sedimentary features	Environmental interpretation
Dolomite	SBLF 1A: Dolomite	Dolomite	PC-M1 Microdoloespatite (Argillaceous Marl/Lime mudstone)	Vug*; Fracture	Gray dolomitized argillaceous Marl/Lime mudstone with sucrosic aspect. Very fine dolomite crystallinity and very fine siliciclastic grains size. Very well sorted.	Micropeloids, subhedral dolomite crystals , quartz and feldspar grains and plant remains.	Non-laminated. *Burrowing*	Internal lagoon. Low energy. Siliciclastic contribution is present.
			PC-M2 Doloespatite (Lime mudstone)	Vug*; Moldic	Gray dolomitized lime mudstone, ocasionally yellowish, with sucrosic aspect. Fine dolomite crystallinity and fine to coarse siliciastic grains size. Well sorted.	Subhedral dolomite crystals, fragments of ostreides and equinoids, quartz and feldspar grains and plant remains.	Non-laminated. Sometimes cross-stratification may occur. *Burrowing.*	Internal lagoon. Low energy. Siliciclastic contribution is present.
Partially dolomitized calcarenite	SBLF 1B: Partially dolomitized Wacke-packstone	Dolomitized wackestone	PC-M3 Partially dolomitized peloidal wacke-packstone	Moldic; Fracture	Light gray partially dolomitized wack-packstone, ocasionally yellowish and beige color. Fine to medium grains size, with fine to medium dolomite crystallinity and medium siliciclastic grains size. Moderately sorted.	Peloids, fragments of gastropods, rede algae (solenoporaceae), siliciclastic grains and locally occurs foraminifers (miliolids), bivalves and ostracodes. Subhedrical to euhedrical dolomite crystals.	Non-laminated. Sometimes cross-stratification may occur. *Burrowing.*	Internal lagoon. Moderate energy.
	SBLF 1C: Partially dolomitized bioclastic peloidal Pack-grainstone	Dolomitized packstone	PC-M4 Partially dolomitized bioclastic packstone with red algae rudaceous	Vug*; Moldic	Gray to orangish beige dolomitized packstone. Very coarse to medium grains size, with even granule bioclasts size. Fine to medium dolomite crystallinity. Poorly sorted.	Red algae rudaceous *(Picnoporidium)*, green algae rudaceous (Dasycladaceae), bivalves e gastropods and siliciclastics grains. Subhedrical to euhedrical dolomite crystals.	Non-laminated. *Lags* of ostreides deposits are present. Vug porosity up to 8 cm. *Burrowing.*	Internal lagoon. Moderate energy. Influenced by tide bars.
			PC-M5 Partially dolomitized bioclastic peloidal Pack-grainstone	Moldic; Intercrystal	Whitish beige pack-grainstone. Medium to very coarse grains size. Poorly sorted.	Mainly *Peruviella Dolium* gastropods (bioacumulations), and in minor quantities fragments of red algae (solenoporaceae), foraminifers (miliolids and agglutinated), intraclasts and siliciclastic grains.	Non-laminated.	Internal lagoon. Moderate to high energy. Influenced by tide bars.
			PC-M6 Partially dolomitized oncolytic Pack-grainstone with red algae rudaceous	Intercrystal; Intraparticle	Whitish beige pack-grainstone. Coarse to very coarse grains size with granule oncolyte size. Fine to medium dolomite crystallinity. Poorly sorted.	Peloids, oncolytes showing bioclastic (red alga) nucleous and euhedrical dolomite crystals.	Cross-stratification and fining-upward beds.	External lagoon. Moderate energy.
Calcarenite with spar calcite cement	SBLF 2A: Peloidal bioclastic grain-packstone	Grainstone	PC-M8 Peloidal bioclastic grain-packstone	Moldic; Intraparticle	Whitish beige grain-packstone. Medium to coarse grains size. Moderately to poorly sorted.	Red algae (solenoporaceae), green algae (dasycladaceae), agglutinated foraminifers foraminiferos aglutinantes, equinoids, mollusks (gastropods and bivalves), peloids, ooids. e quartzo	Low-angle cross-stratification.	Backshoal. Moderate to high energy.
	SBLF 2B: Bioclastic peloidal oolitic grainstone		PC-M10 Bioclastic peloidal oolitic grainstone	Intraparticle; Vug*	Whitish beige grainstone. Medium to fine grains size. Moderately to well sorted.	Ooids, peloids, green algae (dasycladaceae), red algae (solenoporaceae), foraminifers (miliolids), bivalves, intraclasts and siliciclastics grains.	Low-angle cross-stratification. Amalgamated beds.	Shoal. Moderate to high energy.
	SBLF 2C: Intraclastic bioclastic grainstone		PC-M9 Peloidal bioclastic grain-packstone with red algae rudaceous	Intraparticle; Moldic	Beige grain-packstone. Medium to very coarse grains size. Poorly sorted.	Red *algae rudaceous (Picnoporidium* and *Marinella)*, agglutinated foraminifers, mollusks (gastrópodas e bivalves), peloids, intraclasts, rare ostracodes and siliciclastic grains.	Non-laminated. Sometimes plane-parallel lamination may occur. Fining-upward beds.	Shoal or foreshoal. Moderate to high energy.
			PC-M11 Intraclastic bioclastic grainstone	Intraparticle; Moldic	Whitish beige grainstone. Medium to very coarse grains size.	green algae (dasycladaceae), red algae (solenoporaceae and corallinaceae), mollusks (gastrópodas e bivalves), agglutinated foraminifers, equinoids spine and plates, intraclasts and peloids.	Low-angle cross-stratification and sometimes plane-parallel lamination.	Shoal or foreshoal. Moderate to high energy.
Hybrid rock	SBLF 3A: Hybrid rock	Hybrid rock	PC-M7 Peloidal grain-packstone with siliciclastic grains	Intraparticle; Moldic	Beige hybrid rock. Fine grains size and well sorted.	Peloids and siliciclastic grains (quartz, feldspar and mica). Red algae (solenoporaceae) and green algae may occur.	Cross-stratification with truncated surfaces.	External lagoon. Moderate to high energy. Influenced by storms.
Shale			PC-M12 Shale		Gray shale	Rare fragments of recrystilized mollusks.	Plane-parallel lamination.	Rampa intermediária a rampa externa

Figure 3. Table of facies/microfacies from Carapeba Quarry defined to 3D modeling (inside the red box).

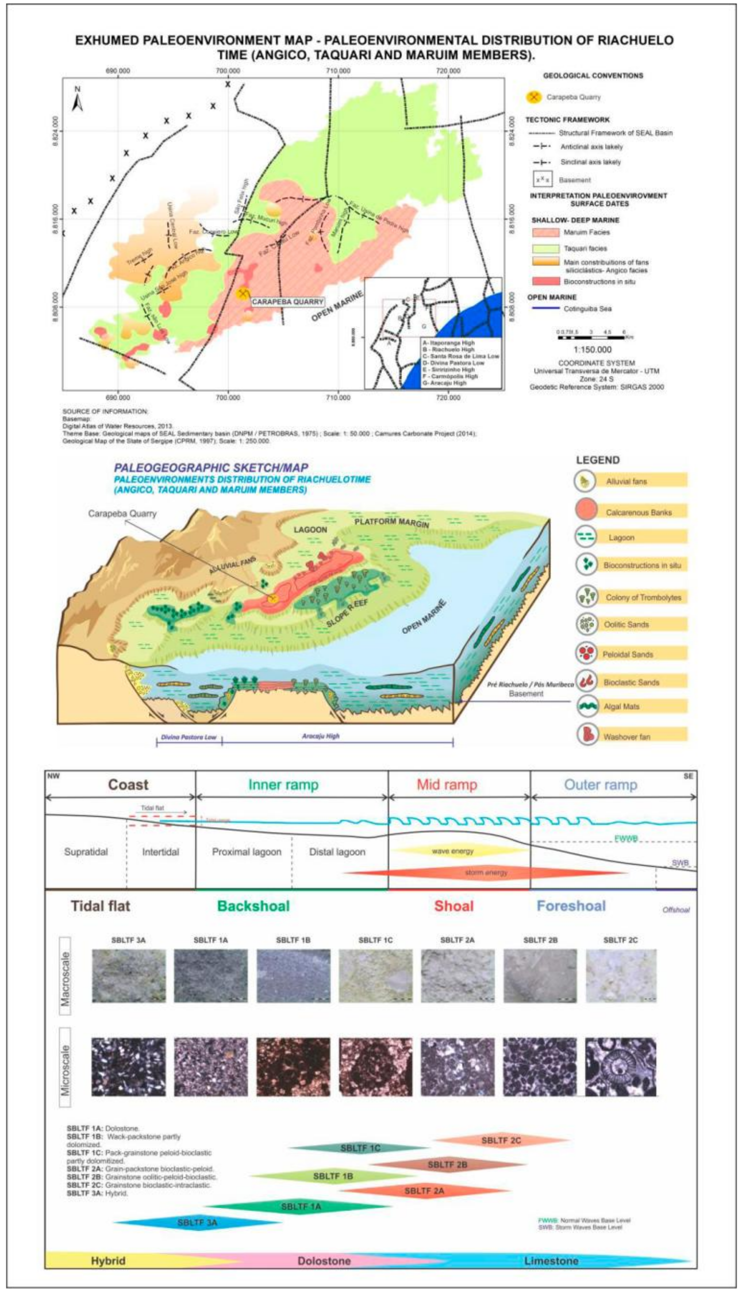


Figure 4. Integration among mapping, regional geologic model and Carapeba geologic model.

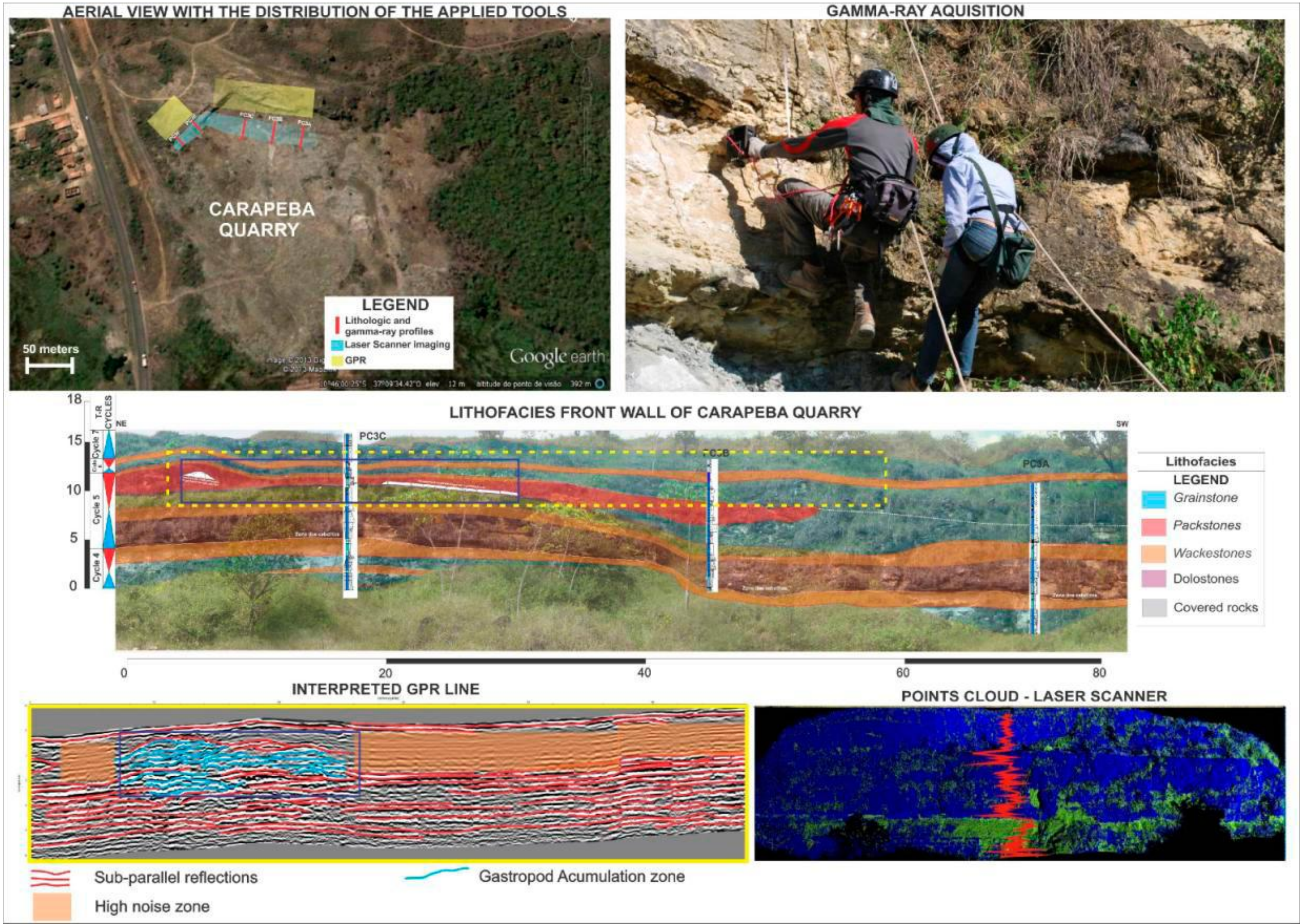


Figure 5. Methodology applied in this work: GPR, gamma-ray and log profile, and stratigraphic correlation.

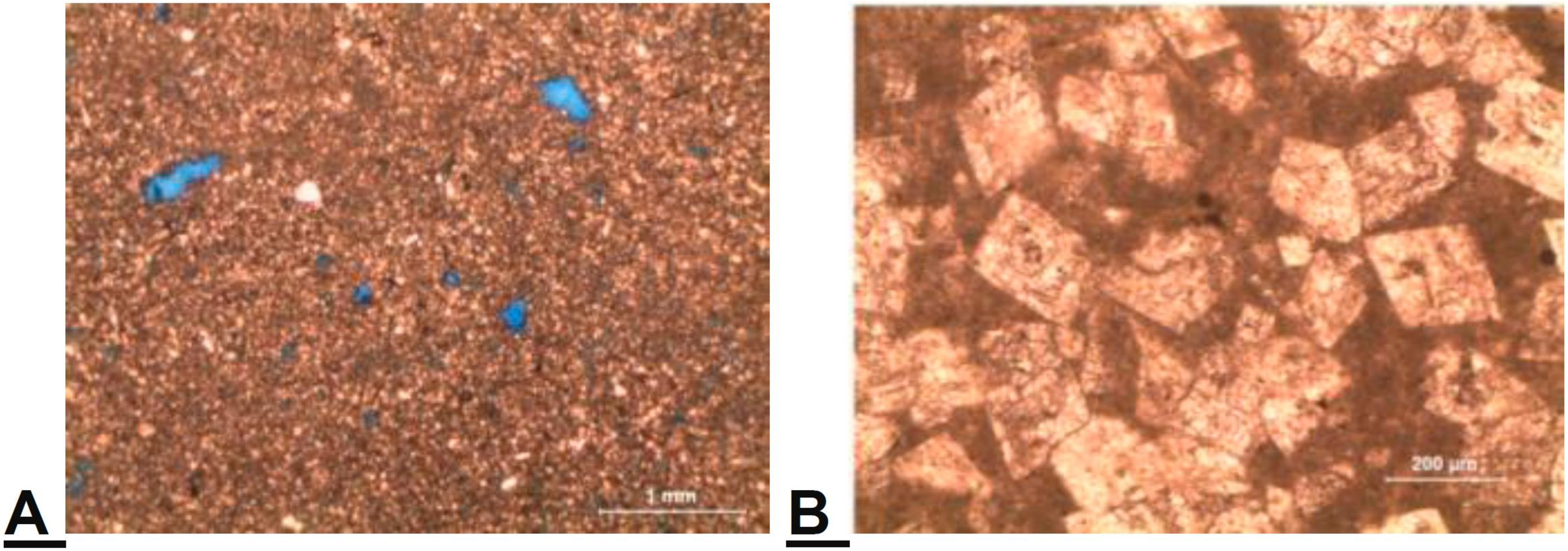


Figure 6. Examples of dolomitized facies identified at Carapeba Quarry. (A) Dolomitized mudstone; (B) Partly dolomitized peloidal Wacke-packstone.

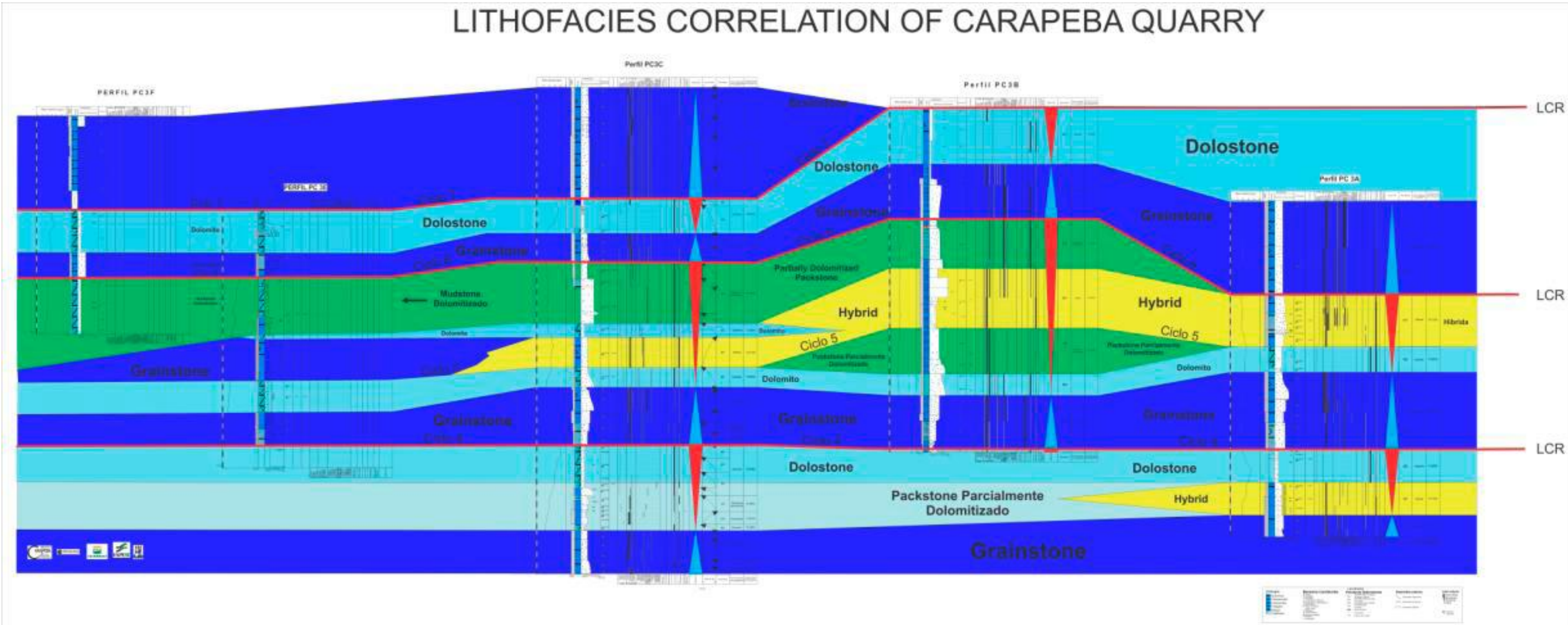


Figure 7. Outcrop profile correlation of the Carapeba Quarry.

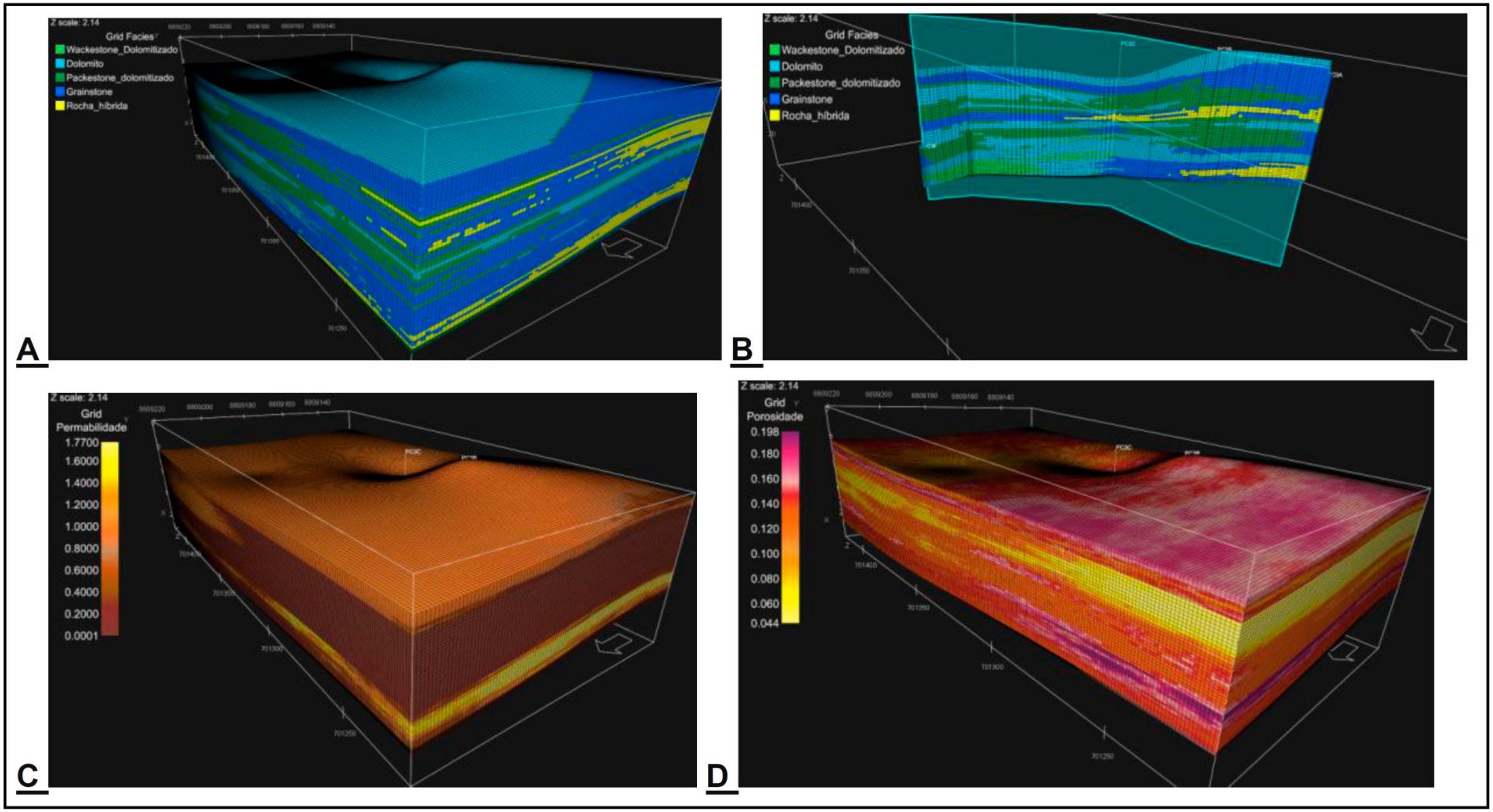


Figure 8. 3D geological models of the Carapeba Quarry. (A) Facies model; (B) Fence of 3D model; (C) Permeability distribution conditioned to facies model; (D) Porosity distribution conditioned to facies model.

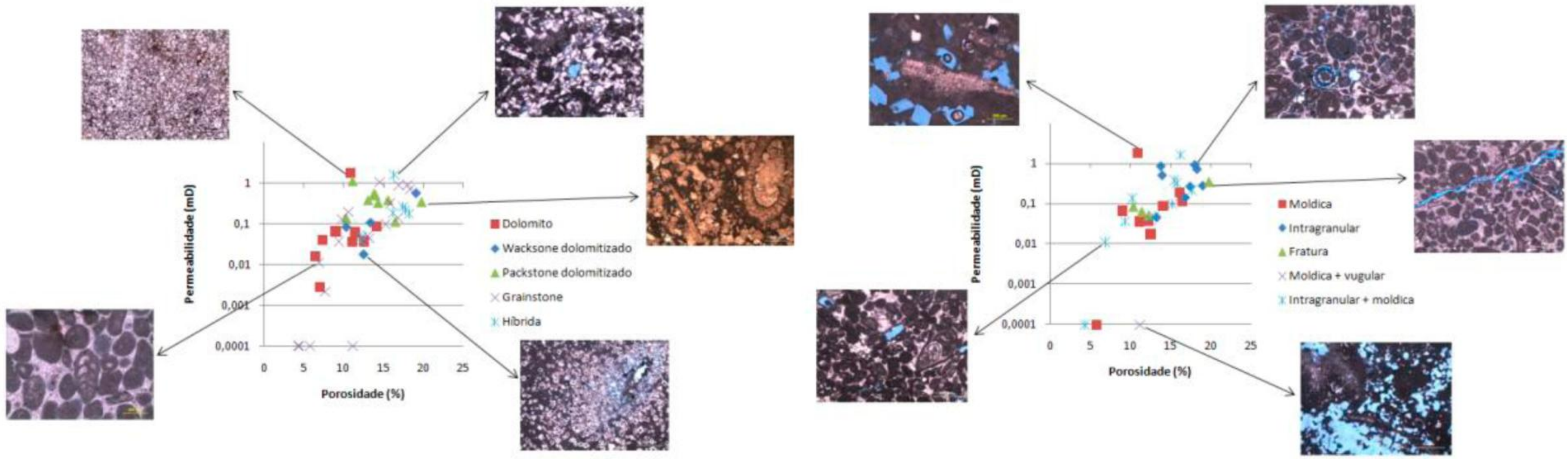


Figure 9. Porosity-permeability cross plots showing the inverse relation between properties.