3D Modeling of Carbonate Reservoir Analogue Outcrops Using CAMURES Methodology, Sergipe-Alagoas Basin (SEAL), Northeastern Brazil*

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Abstract

The use of a database from analogues outcrops of hydrocarbon reservoirs has been a common procedure to define predictive and geological models, integrating different scales to reduce uncertainty in production and exploration of reservoirs. The CAMURES Methodology for Multiscale Reservoir Characterization focuses the vertical and lateral variability of reservoir heterogeneities in order to the structure 3D geological model, aiming at spatial characterization of diagenetic faciological heterogeneities. CAMURES is developed on outcrops data acquisition with descriptions of facies, associated to logs, 3D digital images (Laser Scanner-Lidar) and sampling collected from interest zones, to perform petrographic and petrophysical analysis. This multiscale approach aims to apply different scales of characterization in analogue outcrops related to intervals of the same stratigraphy unit in the same basin and in similar reservoirs from another Brazilian coastal basins. For implementation of this methodology, three quarries were selected representing deposits of calcarenite (Mata de São José - Riachuelo Formation), calcilutite (Sá - Cotinguiba Formation) and coquina (Intercement - Morro do Chaves Formation), of SEAL Basin.

In order to create geological models, procedures of workflow management were performed, covering confection of lithologic logs, gamma ray logs, imaging with laser scanner, petrographic and petrophysical characterization of samples. The modeling was separated by zones, conditioned to well data containing facies information, layers orientation, as well as average geometry of facies bodies 3D interpreted from point cloud (laser scanner) and field data. Petrophysical modeling was conditioned to facies modeling and compared with the model analyzed at microscale. With stratigraphic markers, tracked points cloud and directions and inclinations of layers, the surfaces of a 3D modeling block were created allowing full geometry visualization of outcrop stratigraphic surfaces. Zones of best porosity were attributed to grainstone facies (Mata de São José) with average of 21.005% and 20.73%; mud/wackestones microfacies (Sá) with average of 23.42 to 34.15%; and calcarenite (Intercement) with average of 3.37 to 27.96%. The integration of multiscale 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. All 3D geological models were generated in powerful modeling software using benefits of workflow management mentioned above.

Introduction

The potential studies of "Analogues Outcrops Reservoir" are developed in order to reduce uncertainties related to the depositional and diagenetic models, which will be the basis for the construction of 3D petrophysical properties models in a multiscale model of the permo-porous system and the consequent process of "Fluid Flow Simulation" of reservoirs. Outcrop analogue studies permit development at different scales of characterization and provide understanding of the carbonate reservoir heterogeneities.

This article aims to present the application of the CAMURES Methodology (Multiscale Reservoir Characterization) to build 3D outcrop models using integration of data derived from a macro and microscale approach in the Sergipe-Alagoas Basin of northeastern Brazil. Modeling of calcarenite (Mata de São José - Riachuelo Formation), calcilutite (Sá - Cotinguiba Formation) and coquina (Intercement - Morro do Chaves Formation) outcrops were based on an integrated dataset consisting of (1) LaserScan image acquisition - derived 3D image covering the select areas (Intercement, Mata de São José, and Sá quarries), (2) fieldwork data - stratigraphic logs description with vertical and lateral sampling, (3) petrographic analysis of thin sections, and (4) petrophysical analysis (porosity and permeability).

Geologic Context

The Sergipe-Alagoas Basin is situated in northeastern Brazil, representing the main Mesozoic record exposition along the Brazilian continental margin (Figure 1). Tectonic-sedimentary evolution of the basin can be summarized in five stages, as follows (Campos Neto et al., 2007): Sineclisis, pre-rift, rift, post-rift, and drift. The studied outcrops include rift (Morro do Chaves Formation), and drift (Riachuelo and Cotinguiba formations).

The Morro do Chaves Formation is composed of limestones coquinoids and shale layers. The depositional model is related to a lacustrine to restrict marine in a rift context, where alluvial fans terrigenous sediments interact with the lacustrine carbonate sedimentation. This formation consists of coquinoids composed of bivalve mollusks (calcirrudites) which constitute the main carbonate lithology outcropping section of the Intercement Quarry.

The deposition of the Riachuelo Formation is related to the drift stage resulting in their hybrid facies. The Riachuelo Formation was deposited in a mixed carbonate environment, which consists of three members: Angico, Taquari and Maruim. The Angico Member is composed of conglomerates, sandstones, shales and some carbonates. The Taquari Member consists of interbedded shales and lime mudstones deposited in structural lows. The Maruim Member consists predominantly of carbonate facies of shallow water composed of oncolites, oolites, bioclasts, peloids and locally red algae patch reef. The Cotinguiba Formation consists of two members, the Sapucari and Aracaju. The Sapucari Member is composed of laminated and non-laminated lime mudstones. The Aracaju Member consists of laminated, organic-rich calcareous shales interbedded with lime mudstone.

CAMURES Perspective

Framing consistent and robust geological models depends on a precise characterization of properties distribution, based on a multiscale approach (Multiscale Reservoir Characterization). Analysis from the physical heterogeneity based on the architectural stratigraphy, lithofacies geometry and textural attributes contributes to the recognition of depositional “traps”, the same heterogeneities affect the delineation of the flow paths for fluid percolation during the diagenetic processes. In carbonate reservoirs this is observed when the flow path has a direct relationship to the texture and composition responsible for the initial poro-perm conditions.

The main input for the multiscale investigation are 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. Outcrop studies on the other hand permit a better understanding of the spatial relationship and the heterogeneities behavior. The CAMURES Methodology (Multiscale Reservoir Characterization) application focus on vertical and lateral variability of reservoir heterogeneities in order to develop a structural 3D geological model, aiming at spatial characterization of diagenetic faciological heterogeneities.

CAMURES is developed on outcrops data acquisition with description of facies, associated to logs, 3D digital image (Laser Scanner - Lidar) and sampling collected from zones of interest, to perform petrographic and petrophysical analysis (Figure 2). This multiscale approach aims to apply different scales of characterization in analogue outcrops related to subsurface intervals of the same stratigraphic unit in the same basin and in similar reservoirs from another Brazilian coastal basins. In a reservoir potentiality analysis the main point of interest is the pore space. Microscopic analysis must characterize the different types of porosity present in the lithofaciological intervals, observing how they interact at the other scales (mega, macro and mesoscales).

The field work is mainly based on the description electric logging of facies associated with vertical gamma rays logs in the outcrop, acquisition of 3D outcrop digital data, sample collection for petrographic and petrophysical intervals of interest, defined by the level of heterogeneity observed in the field. In addition to these approaches, ground penetration radar (GPR) data can also be collected and added into the 3D model after processing. The lithofaciologic logs analysis is based in studies such as Garcia and Eastwood (1981), and M.E. Tucker (2003) which focus on the methodology of outcrop description, and Koehrer et al. (2010) with direct application to carbonate outcrops. The set of attributes related to the development of all the methodology procedures for the Multiscale Reservoir Characterization is synthesized in Figure 3.

Database Framework

Modeling of calcarenite (Mata de São José - Riachuelo Formation), calcilutite (Sá - Cotinguiba Formation) and coquina (Intercement - Morro do Chaves Formation) carbonate facies reservoir types were based on an integrated dataset consisting of (1) LaserScan image acquisition-derived 3D image covering the select areas (Intercement, São José, and Sá quarries), (2) fieldwork data - stratigraphic logs description with vertical and lateral sampling, (3) petrographic analysis of thin sections, and (4) petrophysical analysis (porosity and permeability).

The use of LIDAR Systems (Light Detection and Ranging) for petroleum reservoir modeling has become popular in the last few years and several studies have been published discussing techniques and applications of this technology. The possibility of attribute extraction from digital data that represent with fidelity the morphology and external geometry of bodies has helped the geoscientific community on interpretations of these deposits. The contribution comes not only from the quantity of information that can be extracted from the LIDAR approach, but mainly on the possibility of integration with other types of data, such as GPR and electric logs. For Hodgetts (2013), LIDAR Systems are particularly appropriate for studies of analogue outcrops in the petroleum industry, since the scale of acquisition is similar to a hydrocarbon reservoirs, covering heterogeneities from a few centimeters to tens of kilometers.

In order to create geological models, procedures of workflow management were performed, covering confection of lithological logs, gamma ray logs, imaging with laser scanner, petrographic and petrophysical characterization of samples. Figure 4 shows the workflow developed in the RMS software (ROXAR) indicating the types of input data and building the foundations for the generation of 3D geological model.

Discussion

Petrographic and Petrophysical Setting

In the microscale analysis, the microfacies technique was applied to the main quarries where the CAMURES methodology was developed in order to characterize in detail the studied sections and the set of heterogeneities was characterized to be represented in the 3D geological model rock intervals. To these microfacies are assigned their diagenetic relations, depositional environment and porosity and permeability data acquired through petrophysical analysis. Some of the microfacies defined for this study are represented in the Figure 5.

This microfacies technique is based on the study of textural and paleoecological properties and allows the establishment of an ideal sequence of microfacies that statistically represents environmental change steps and its sedimentary evolution in time and space with the ultimate goal of building sections, paleoenvironmental maps and models that allow defining the extent and the nature of carbonate reservoirs.

The understanding of these carbonate reservoirs and their quality is related to porosity and permeability properties, which are essentially controlled by depositional structures, textural and compositional aspects of the rock, diagenetic processes and products (volume, intensity distribution), and types of porosity and its distribution. In this case, the reservoir characterization process from petrophysical data analysis enables the understanding of perm/poro properties in these kind of rocks.

Outcrop Distribution and Geometry (LIDAR Acquisition)

With this approach the Terrestrial Laser Scanner was used for acquiring outcrop LIDAR data. The principle of acquisition with the Laser Scanner has its basis in the emission of a laser which consequently will receive a reflection from the object hit by it. That will create a 3D virtual image of the outcrop enabling us to model solid surfaces with accuracy and precision. Point clouds can be georeferenced, and attributes such as layer thicknesses, geometry of bodies, area calculations, reflectance profiles associated with different lithologies, lithologic boundaries, among others, can be extracted. Outcrops from Riachuelo, Cotinguiba and the Morro do Chaves formations were imaged, being part of a complete multiscale characterization. Figure 6 shows the point clouds acquired on quarries Mata de São José (Riachuelo Formation), Sá

(Cotinguiba Formation) and Intercement (Morro do Chaves Formation). Once data was acquired, a processing workflow was applied to each points cloud, using the Cyclone software. The Figure 7 illustrate the complete processing.

At each quarry the processing workflow for points cloud was applied, however it is important to note that each individual outcrop has specific features that need to be considered during processing. In the Mata de São José Quarry the most evident feature was the tabular geometry of the layers whereby it is possible to measure thickness of each layer and then map cyclicity variation from deposition. In the Sá Quarry, an important aspect was the presence of organic matter at basal layers, bringing differences on reflectance, and allowing the mapping of the surface that represents a permeability barrier found on the outcrop. Another representative approach was the correlation of these reflectance logs with Gamma Ray (GR) logs. When separated, the different tracks of the GR log (elements K, U and Th) showed different numbers of occurrence for high values (peaks). When observed specifically, U element presented major peaks on basal layers, confirming the presence of organic matter and enabling correlation of this high frequency of peaks with low values observed on the reflectance log, at exact same region. This allows us to create reflectance logs at the main front of the quarry and use them in 3D modeling, by setting different zones with different values for permeability (zone with organic matter and zone without it). Besides that, all the structural framework in the Sá Quarry could be mapped and measured for using in structural modeling with the 3D modeling software. At the Intercement Quarry the most important aspect was the identification of shale layers between coquinas stratum through geometry and reflection analysis which allowed lateral continuity measurement and surfaces exporting. For each outcrop these specific features can be correlated with other kinds of data. After processing, points cloud and measured attributes are exported into modeling software's for application on 3D analogue reservoir modeling.

Reservoir Modeling

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

For generation of the 3D models it is important to characterize the lithologies as their depositional and diagenetic settings (grain arrangement, selection, roundness, grains relationship/cement matrix amount). The microfacies were grouped by lithologies, as shown the Table 1. The depositional environment of Mata de São José outcrop is transitional with carbonates and siliciclastic depositions (mixed sedimentation); the facies were deposited in internal and external lagoons on a shallow to deep carbonate platform. The facies percentage is shown in Table 2. The São José outcrop modeling is presented in Figure 8.

The Sá outcrop facies were defined based on microfacies analysis of samples collected. The facies found were mud/wackestone (CM2) with planktonic foraminifer, and wackestone (CM6) with echinoids and micro-detritus. The porosity ranged from 23.42 to 34.15% (mean 27.57%) and 0.0001 to 0.48mD permeability (mean 0.13mD). The best porosity values was of mud/wackestones microfacies (CM2). This is due to the strong presence of microporosity present in these rocks. The lenses of microfacies CM6 has satisfactory porosity values, ranging between 26 and 28% (Figure 9).

In general, the permeability values the model presented are low. The microfacies CM6 presented relative higher values to their lithological type (wackestone with echinoids) composed by bioclastic constituents arranged more favorable for fluid percolation. The CM2 microfacies has low permeability due to lack of connection between pores.

In the Intercement Quarry, 3D modeling of five facies was defined according to core samples and analysis. The structural model presents the integration between the fault model and the stratigraphic surfaces. The porosity ranges from 3.37 to 27.96%. At the Quarry Intercement there were fifteen lithologic zones separated by 16 limit surfaces, including 8 levels of shales and 7 coquinoids intervals (Figure 10).

Conclusions

The studies of analogue outcrops applied to Exploratory Geological Models requires a rigorous recognition of the "Analogue Type Potential" before starting the multiscale integration to modeling process. The concept of "Perfect Analogue" results in the definition of the best analogue representative to each type of subsurface reservoir, considering not only the lithologic, depositional, diagenetic and structural affinities, but also the type of reservoir, considering geometry, and depositional architecture related to the different sedimentary basin types.

The basin context play an important role in the extension of the Analogue Model along the studied deposits, taking into account evolutionary peculiarities from sectors of the depositional area. Factors such as tectonic activity, and uplift and tilting will be responsible for differential dip in layers and differentiation in lithofacies distribution, especially in mixed and carbonate depositional systems.

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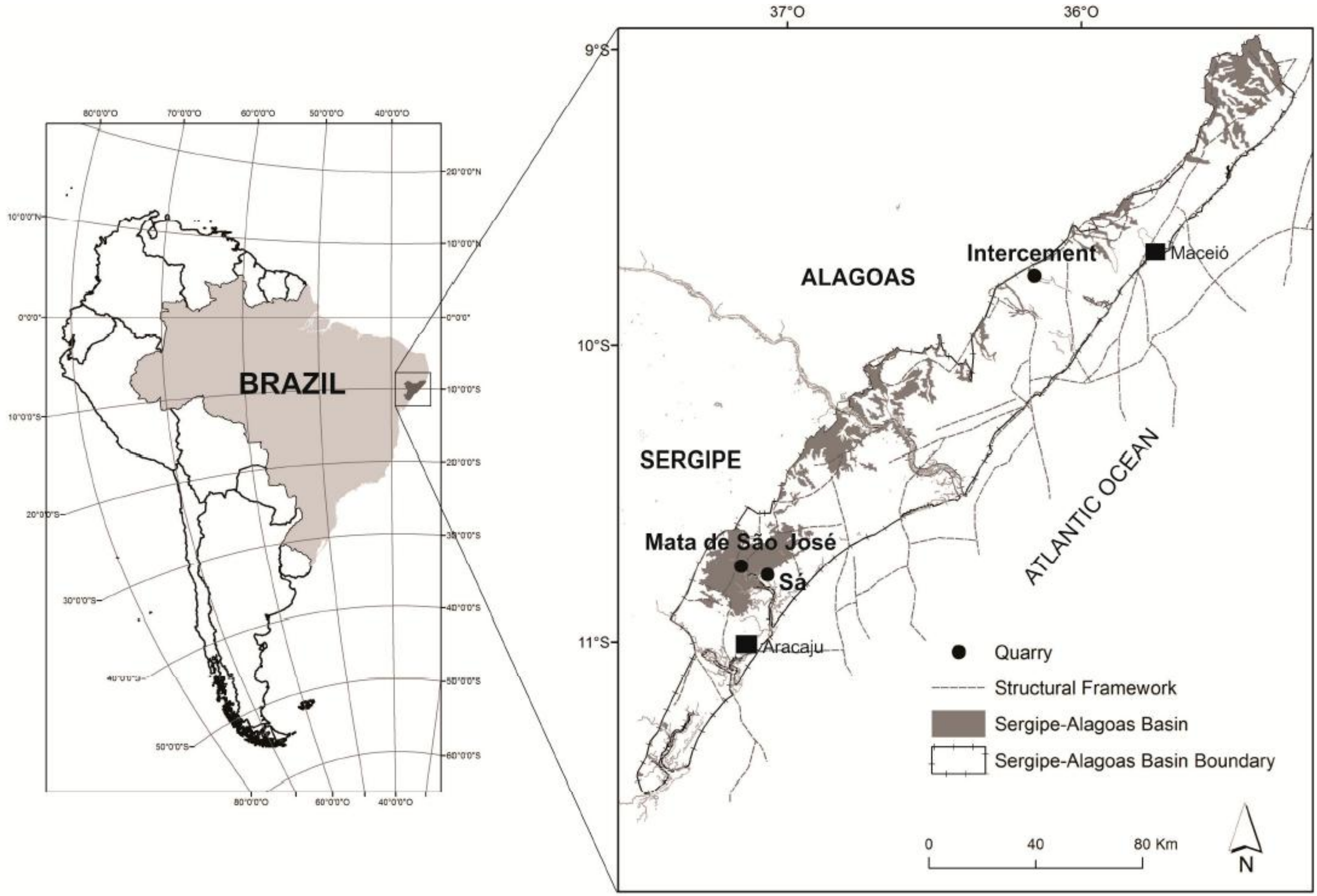

Figure 1. Simplified map of the Sergipe-Alagoas Basin, with location of the study area Mata de São José, Sá e Intercement outcrops. Structural framework modified of Lana (1990).

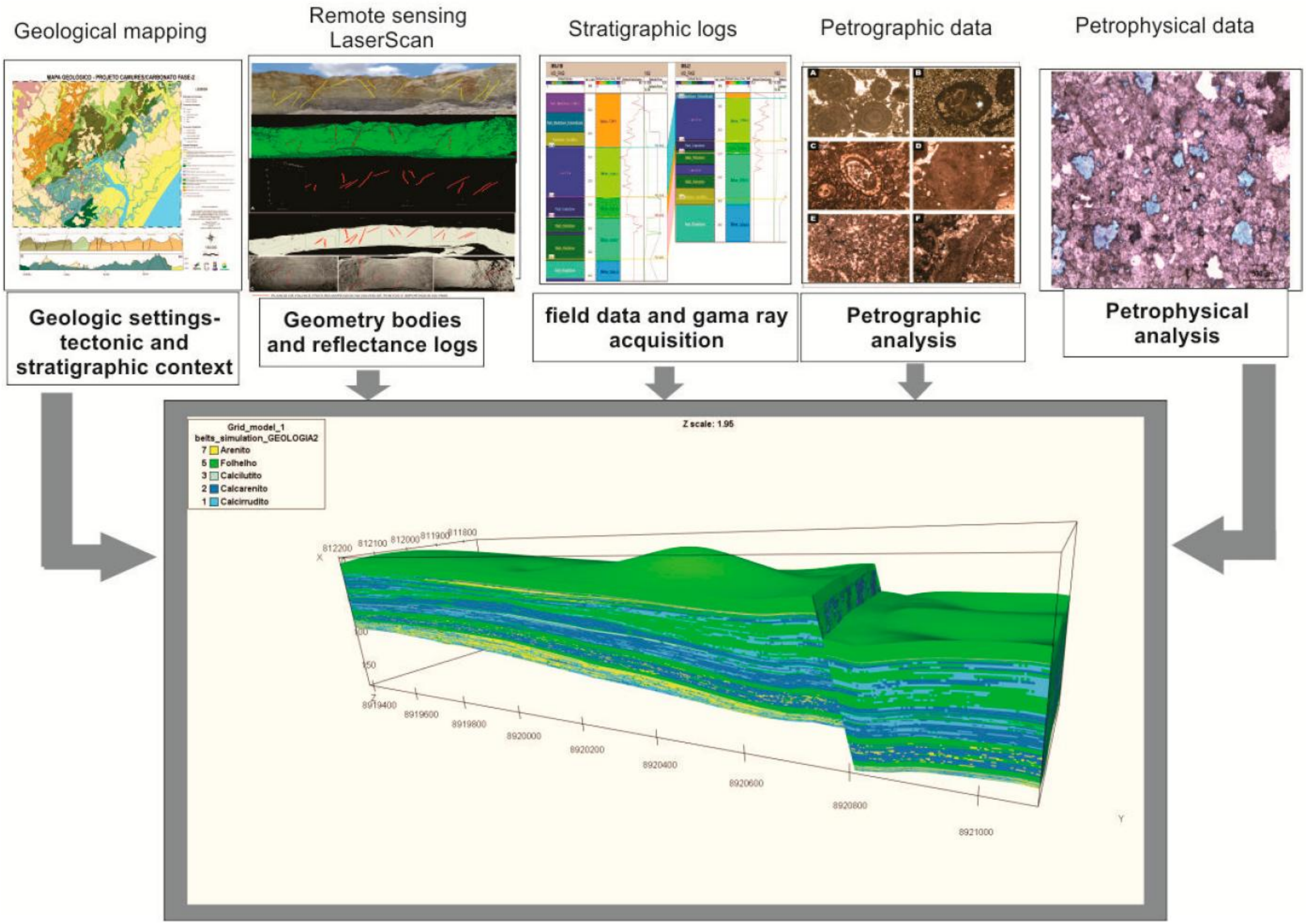

Figure 2. Outline of the Multiscale Characterization Methodology, indicating the main procedures used in this study (photos are of the different study outcrops).

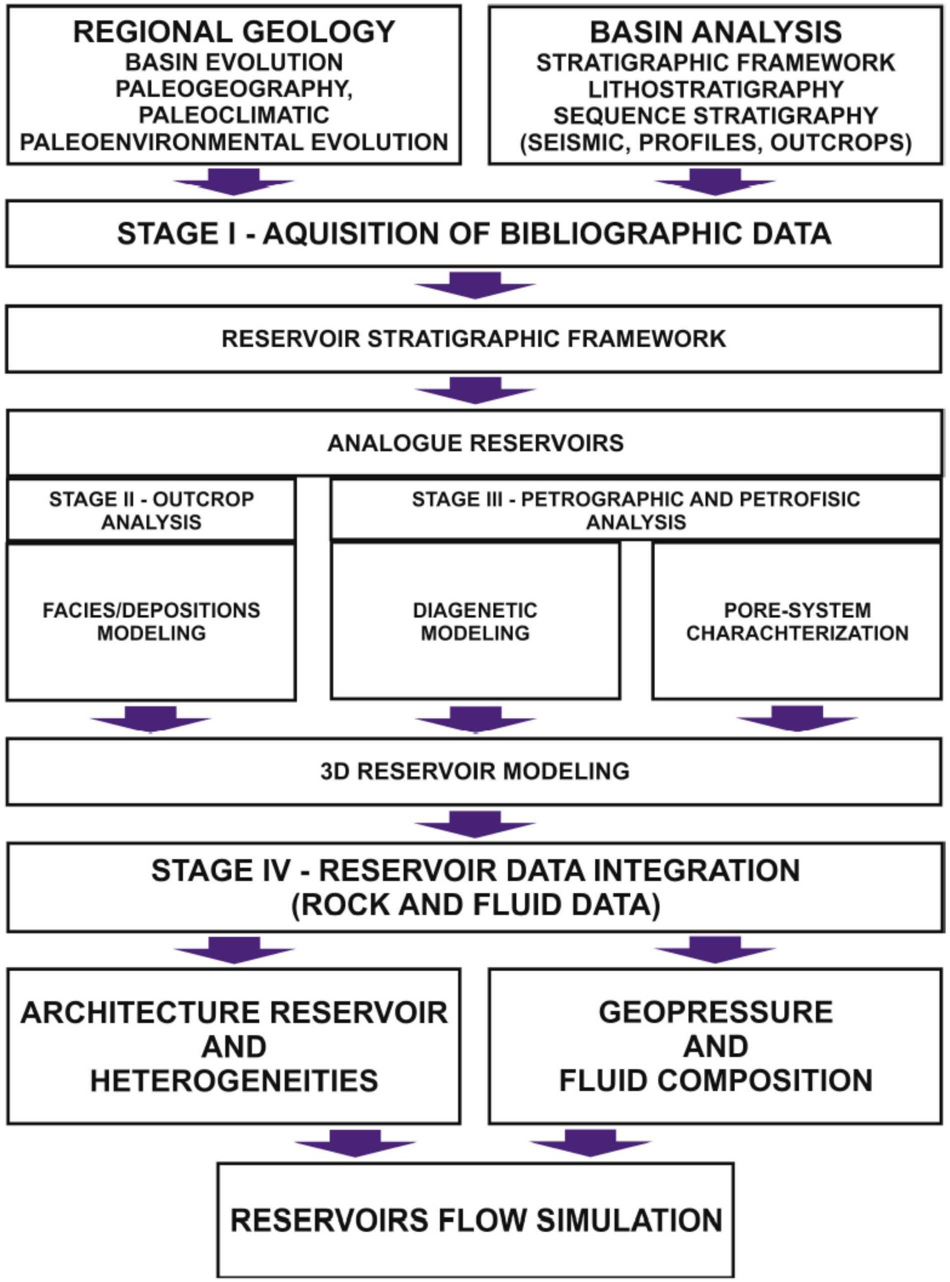

Figure 3. Flowchart of the CAMURES methodology application.

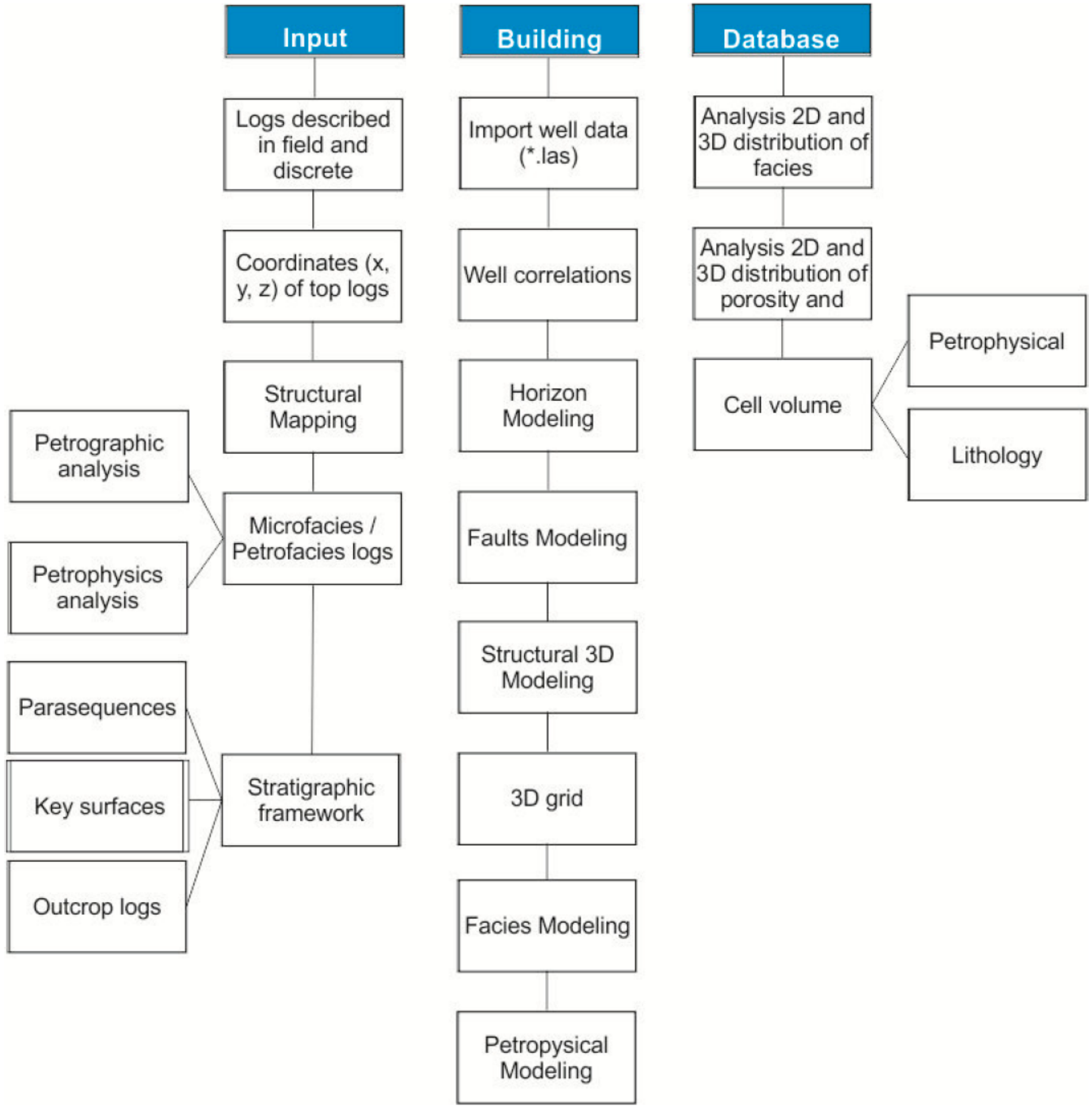

Figure 4. Workflow of the three phases (input, building, and database) developed to create the 3D geomodel using RMS software.

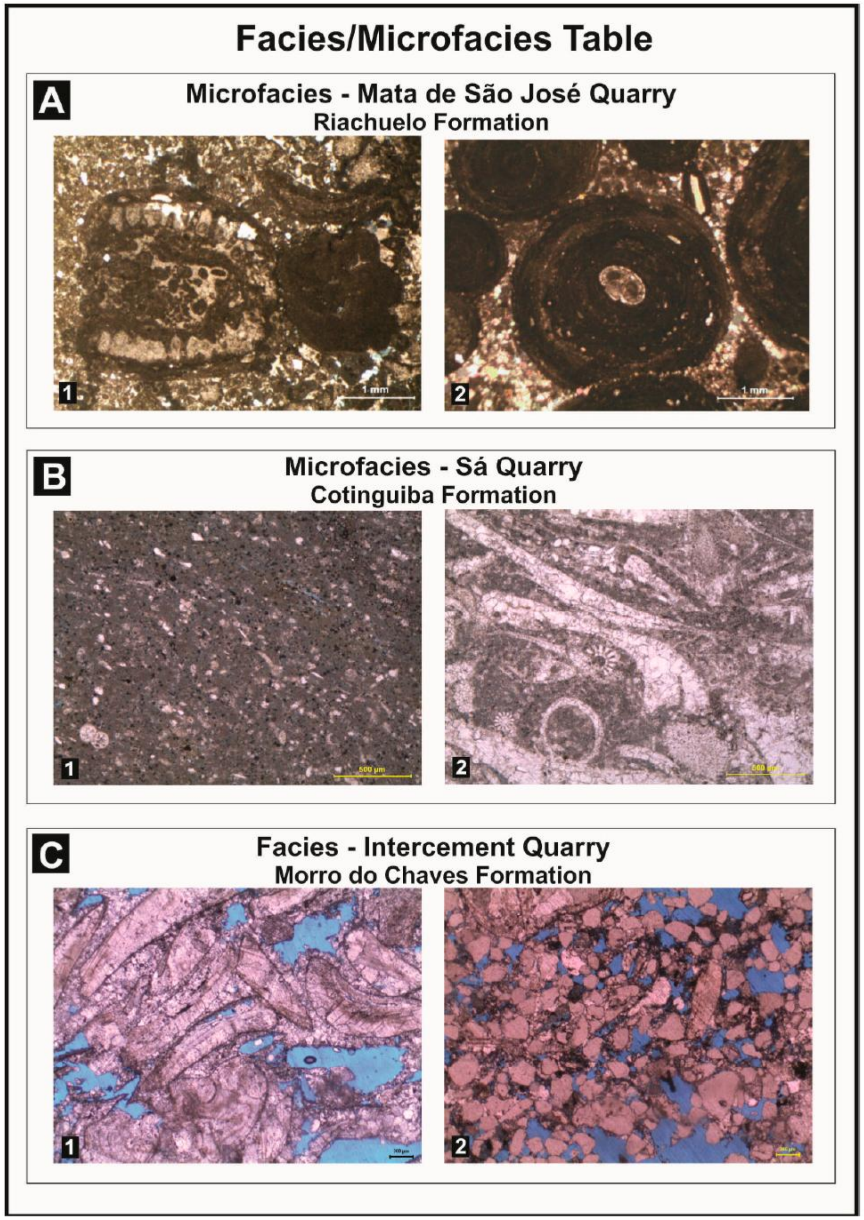

Figure 5. Facies/Microfacies photomicrographs of (A) Mata de São José Quarry: 1. Peloidal packstone with red and green algae, sometimes partially dolomitized; 2. Oncolytic Packstone, sometimes partially dolomitized. (B) Sá Quarry: 1. Mud to Wackestone with planktonic foraminifera; 2. Packstone with mollusks and echinoids. (C) Intercement Quarry: 1. Thick calcarenite; 2. Sandstone.

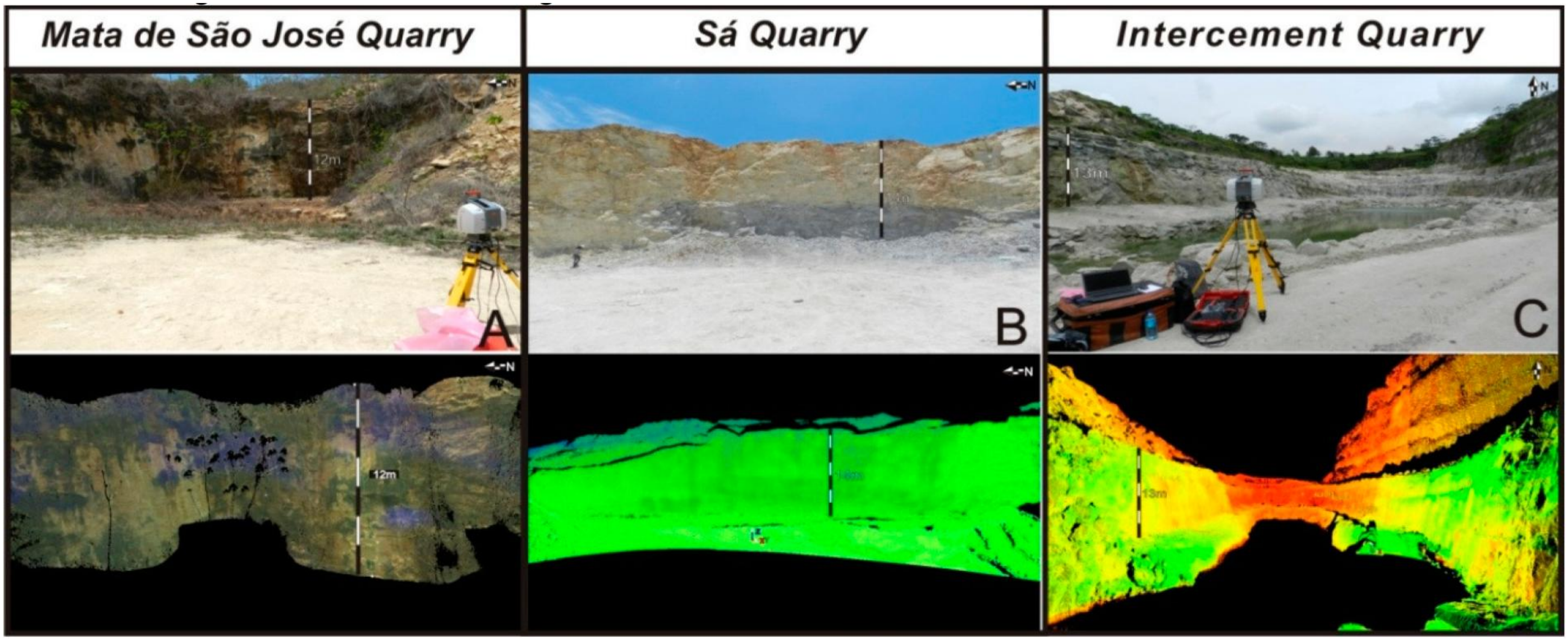

Figure 6. Points Clouds Acquisition of: (A) Mata de São José Quarry - Riachuelo Formation, (B) Sá quarry - Cotinguiba Formation, and (C) Intercement Quarry - Morro do Chaves Formation.

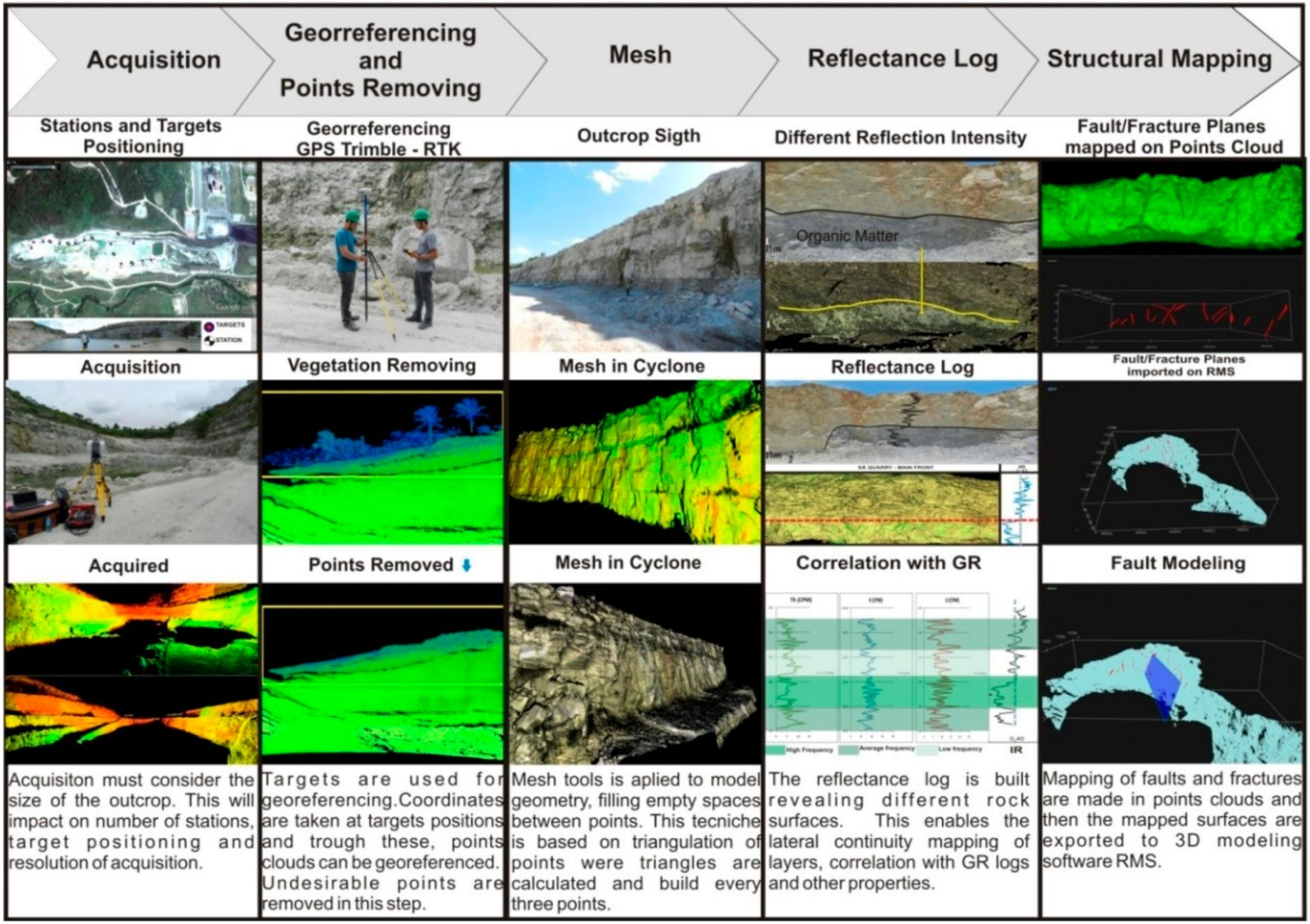

Figure 7. Points Cloud Processing Workflow. Steps: Georeferencing, removing points, meshing, reflectance logging, and structural mapping.

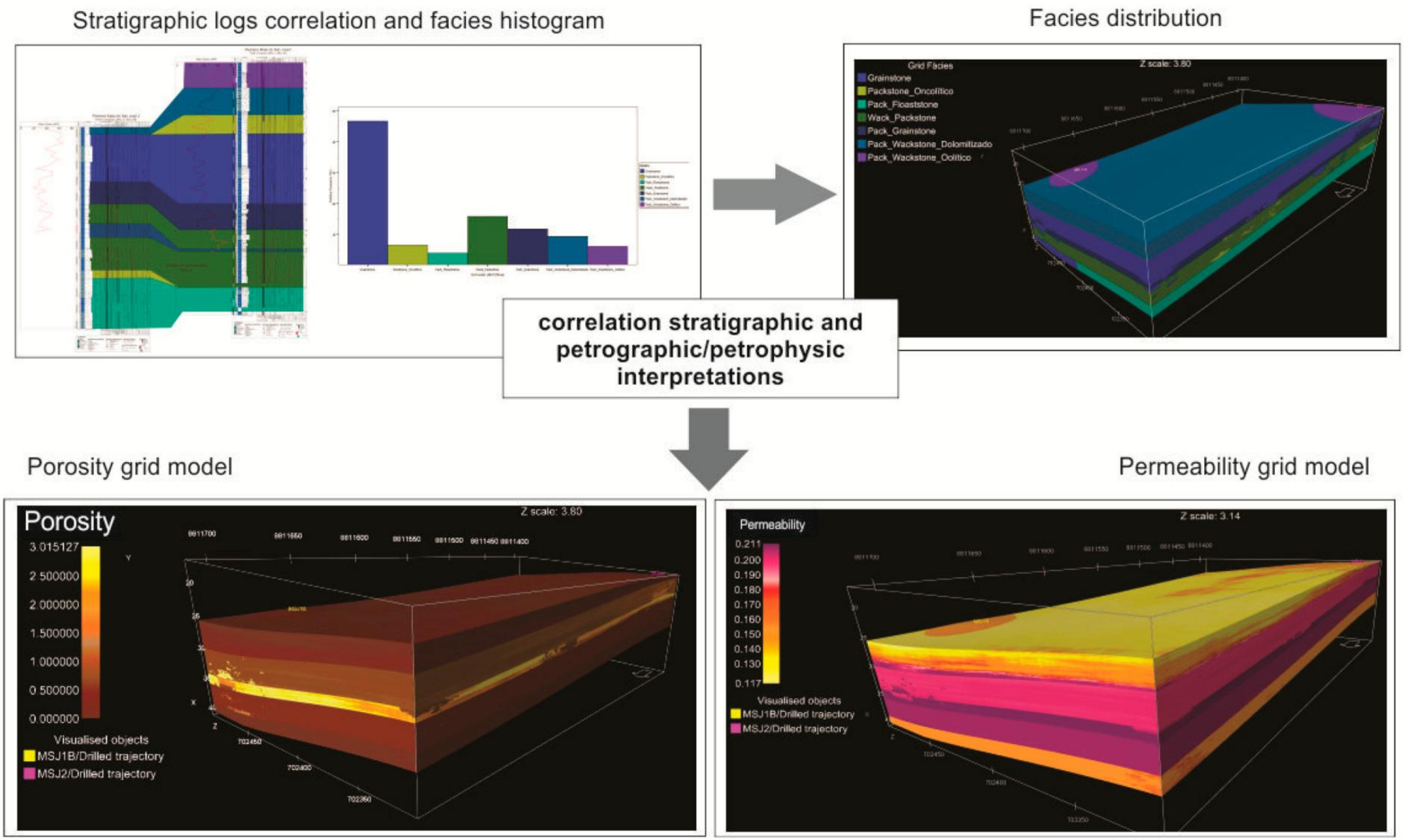

Figure 8. Workflow from data source to reservoir property modeling of Mata de São José quarry. Main data source are samples for poro-perm measurements and petrography, and stratigraphic logs based on field work acquisition.

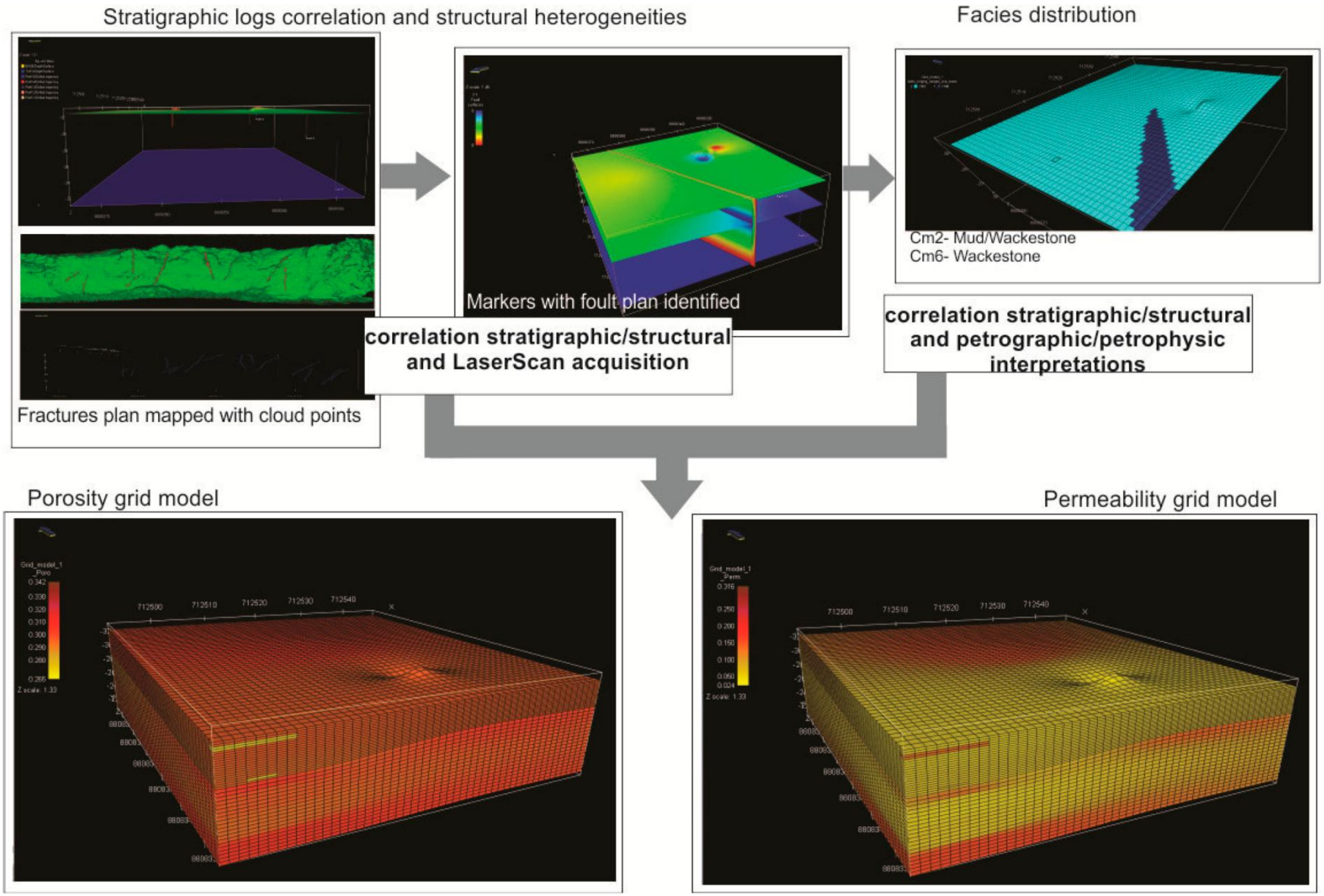

Figure 9. Workflow from data source to reservoir property modeling of Sá Quarry. Main data source are samples for poro-perm measurements and petrography, and stratigraphic logs based on field work acquisition. The geomodel model was created including the main stratigraphic heterogeneities and structural heterogeneities.

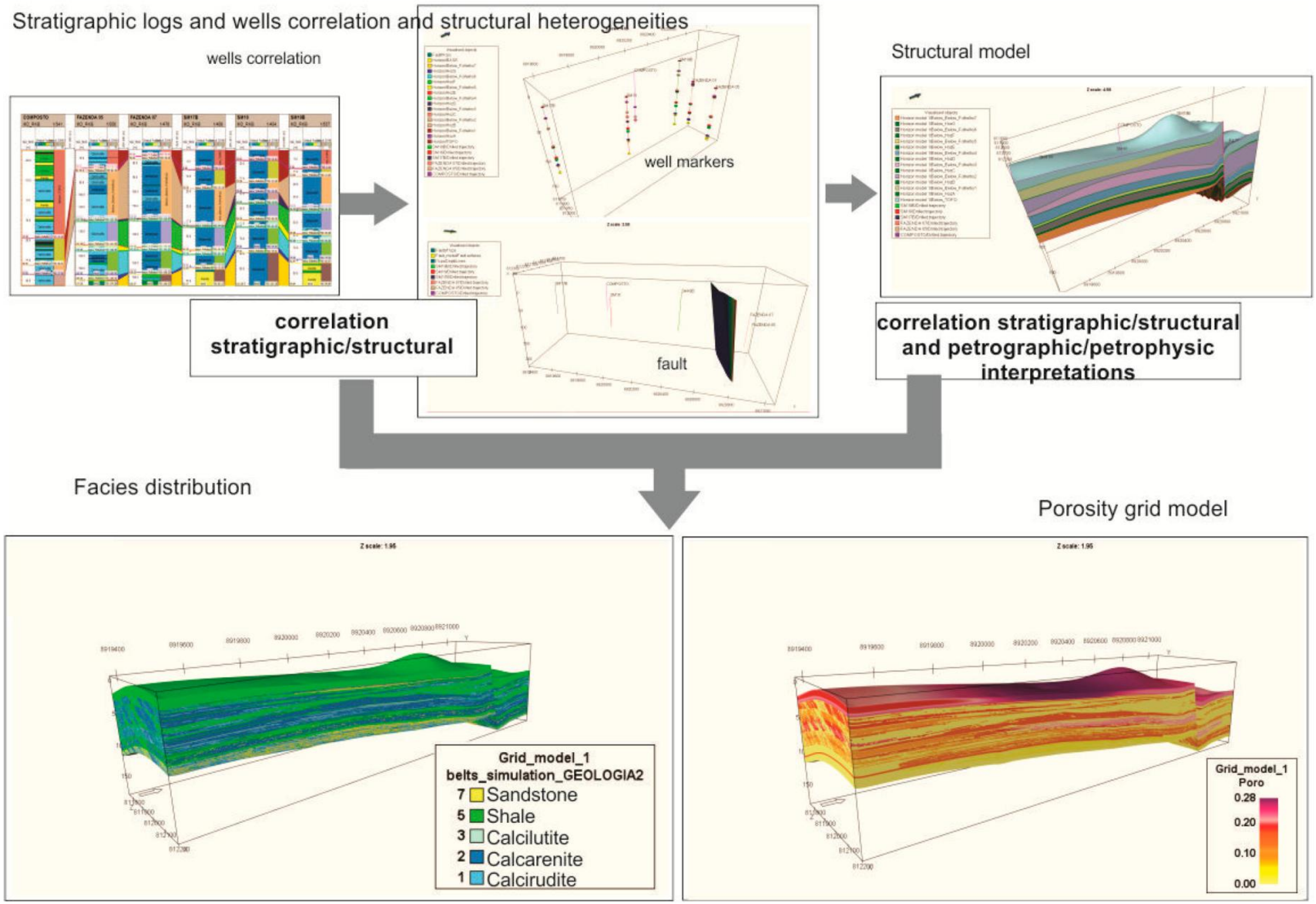

Figure 10. Workflow from data source to reservoir property modeling of Intercement Quarry. Main data source are samples for poro measurements, and stratigraphic logs based on field work acquisition and wells. The geomodel was created including the main stratigraphic heterogeneities and structural heterogeneities. This model is in process and the next steps will include poro-permeability grid models.

Outcrops	Amount	Lithologies
Mata de São José	7	Packstone/Floatstone, Packstone Oncolitic, Wack/Packstone, Pack/Grainstone, Grainstone, Pack/Wackstone Dolomitizado e Pack/Wackestone Oolitic.
Sá	2	Mud/Wackstone and Wackestone
Intercement	7	Calcirudite, Calcarenite, Calcilutite, Shale, Sandstone, Conglomerate, Conglomerate sandstone

Table 1. Microfacies used in 3D modeling outcrops.

Facies	Percentage(%)
Grainstone	46.6%
Wack/packstone	15.8%
Pack/grainstone	11.7%
Pack/wackstone dolomitizated	9.3%
Packstone oncolitic	6.5%
Pack/wackstone oolitic	6.1%
Pack/floatstone	3.9%

Table 2. Facies percentages in the São José outcrop.