

PS Using Analogue Hypogene Karst Systems to Understand the Pre-Salt Carbonate Reservoirs Offshore Brazil*

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Abstract

It became dogmatic that carbonate reservoirs affected by karst processes were subjected to subaerial exposure. However, there is a growing recognition that hypogene karstification, formed under deep-seated, confined conditions by rising fluid flow, can generate macro and mega (meter-scale) porosity. Although this kind of karst process has the potential to create extensive caves, it could also form features below seismic resolution, thus justifying the use of analogue studies. We investigated the major cave system in South America to unravel the geometry and origin of the hypogene system and use it as a predictive tool to understand the poro-permeability properties of pre-salt carbonate reservoirs offshore Brazil. The caves were developed in Neoproterozoic carbonates of the Salitre Formation in the São Francisco Craton, NE Brazil. We mapped both sedimentary facies and deformation patterns in the caves. In addition, we described in detail the carbonate and siliclastic facies in thin section and carried out a petrophysical analysis that included X-ray microtomography and the determination of porosity, permeability, and grain density. We identified five lithostratigraphic units, from bottom to top: (1) grainstone with cross-bedding stratification, (2) fine grainstone with chert nodules, (3) microbial carbonate, (4) interbedded fine siliciclastics and marls, (5) crystalline carbonate that interfingers with chert layers. Field and laboratory data indicate that units 4 and 5 formed a kind of seal for fluid flow, below which flow occurred laterally causing dissolution of units 1, 2, and 3. These five units are identified throughout the Salitre Formation, which makes the stratigraphic control predictable. In addition, the hypogene karst system occurs immediately in the gently folded hanging wall block of a thrust fault, which served as conduit for deep-seated fluids. Dissolution mainly enlarged subvertical fractures developed mostly along the anticline hinges. These hinges follow the general trend of regional deformation, which is also predictable. This study highlights the importance of determination of the origin of karst systems for understanding highly heterogeneous fractured and karstified carbonate reservoirs.

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Introduction

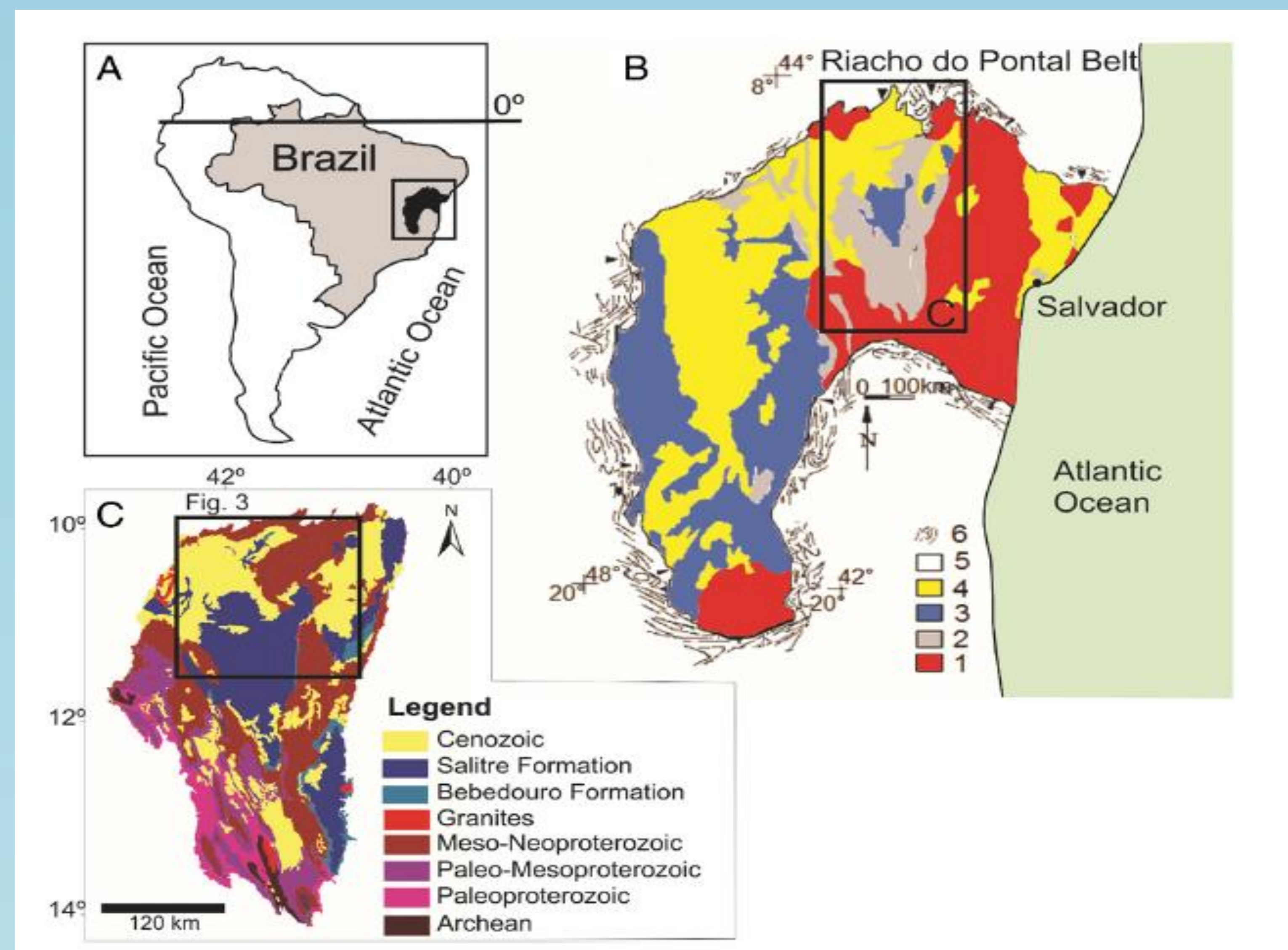
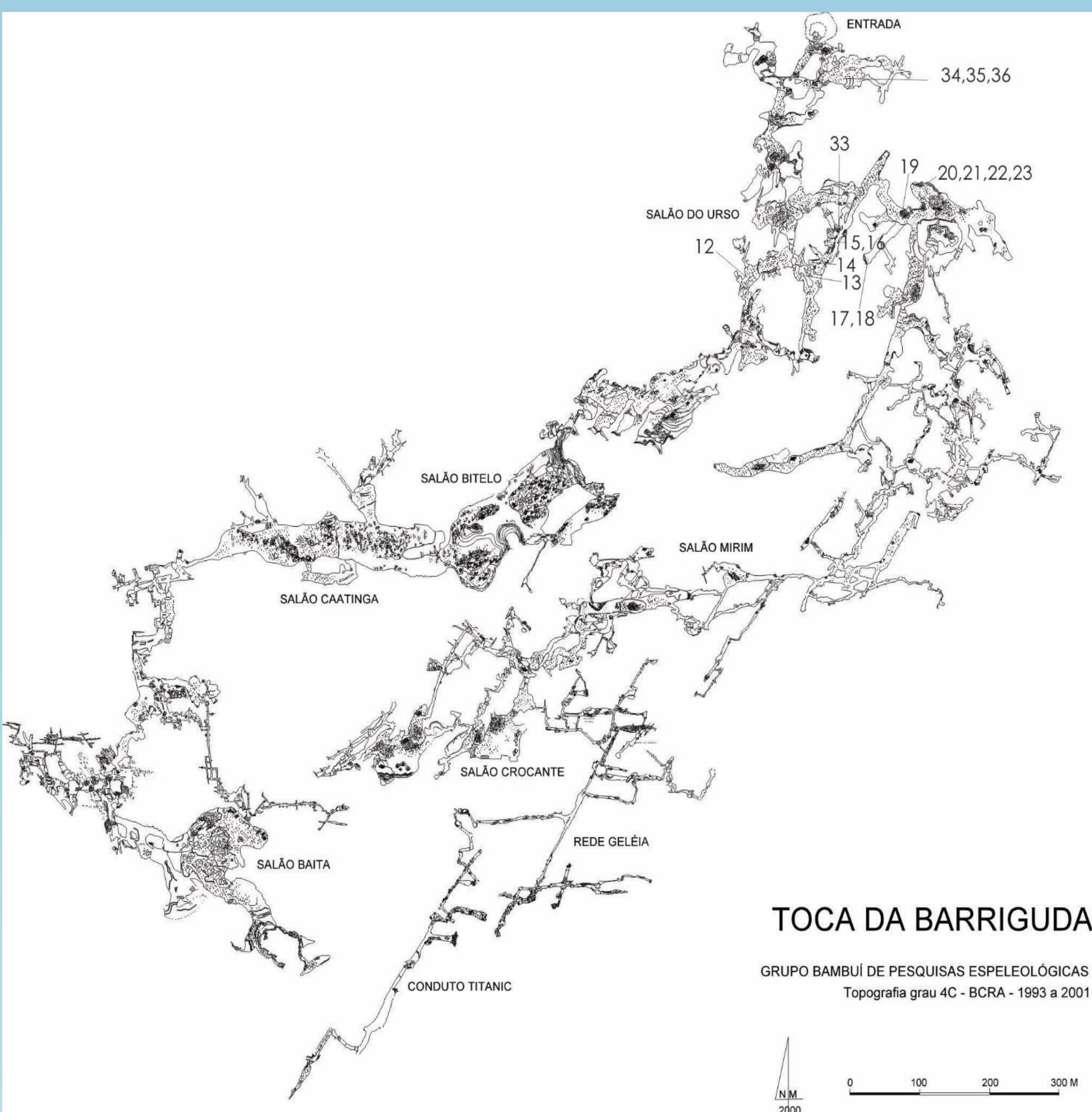
It became dogmatic that carbonate reservoirs affected by karst processes were subjected to subaerial exposure. However, there is a growing recognition that hypogene karstification, formed under deep seated, confined conditions by rising fluid flow, can generate macro and mega (meter-scale) porosity. Although this kind of karst process has the potential to create extensive caves, it could also form features below seismic resolution, thus justifying the use of analogue studies.

Study Area/Methods

We investigated the major cave system in South America to unravel the geometry and origin of the hypogene system and use it as a predictive tool to understand the porosity-permeability properties of pre-salt carbonate reservoirs offshore Brazil.

The caves were developed in Neoproterozoic carbonates of the Salitre Formation in the São Francisco Craton, northeastern Brazil.

We mapped both sedimentary facies and fracture systems in the caves. In addition, we described in detail the carbonate and siliciclastic facies in thin section and carried out a petrophysical analysis that included X-ray microtomography and the determination of porosity, permeability and grain density.



TOCA DA BOA VISTA

CAMPO FORMOSO - BAHIA - BRASIL

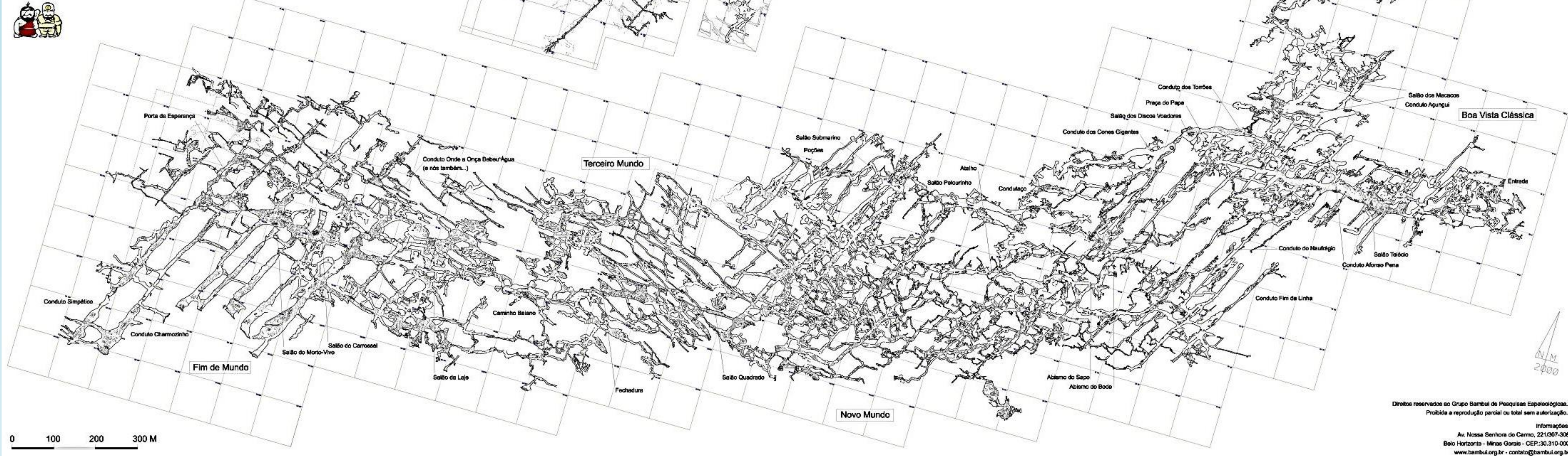
Projeção horizontal: 106.940 m Desnível: -96 m

Localização: (UTM 24L)

x=296.105 y=8.876.288

Topografia grau 4C - BCRA - 1987 a 2011

GRUPO BAMBUÍ DE PESQUISAS ESPELEOLÓGICAS



Geometry of Toca da Boa Vista and Toca da Barriguda cave system (Map kindly provided by the Bambuí Group of Speleological Research).

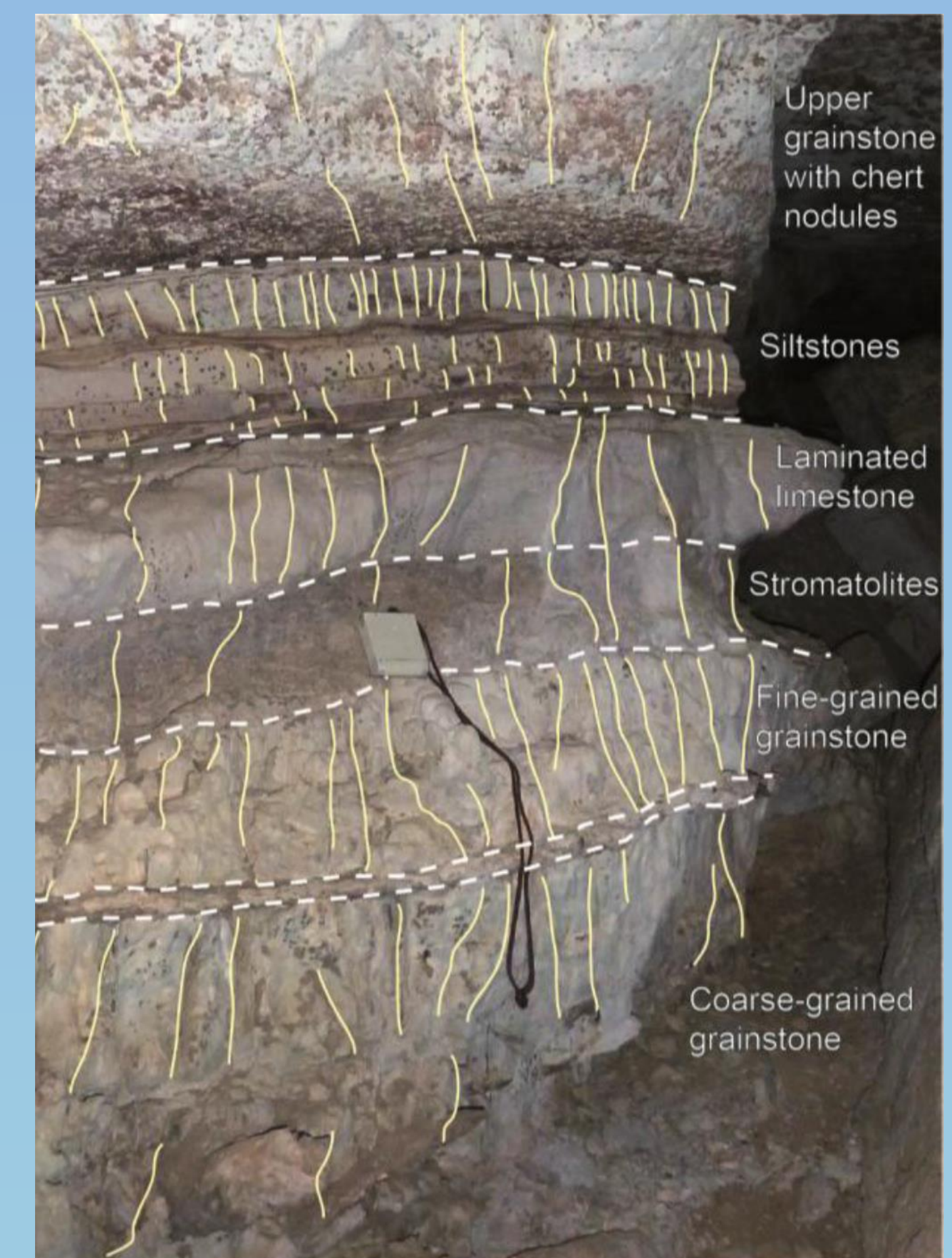
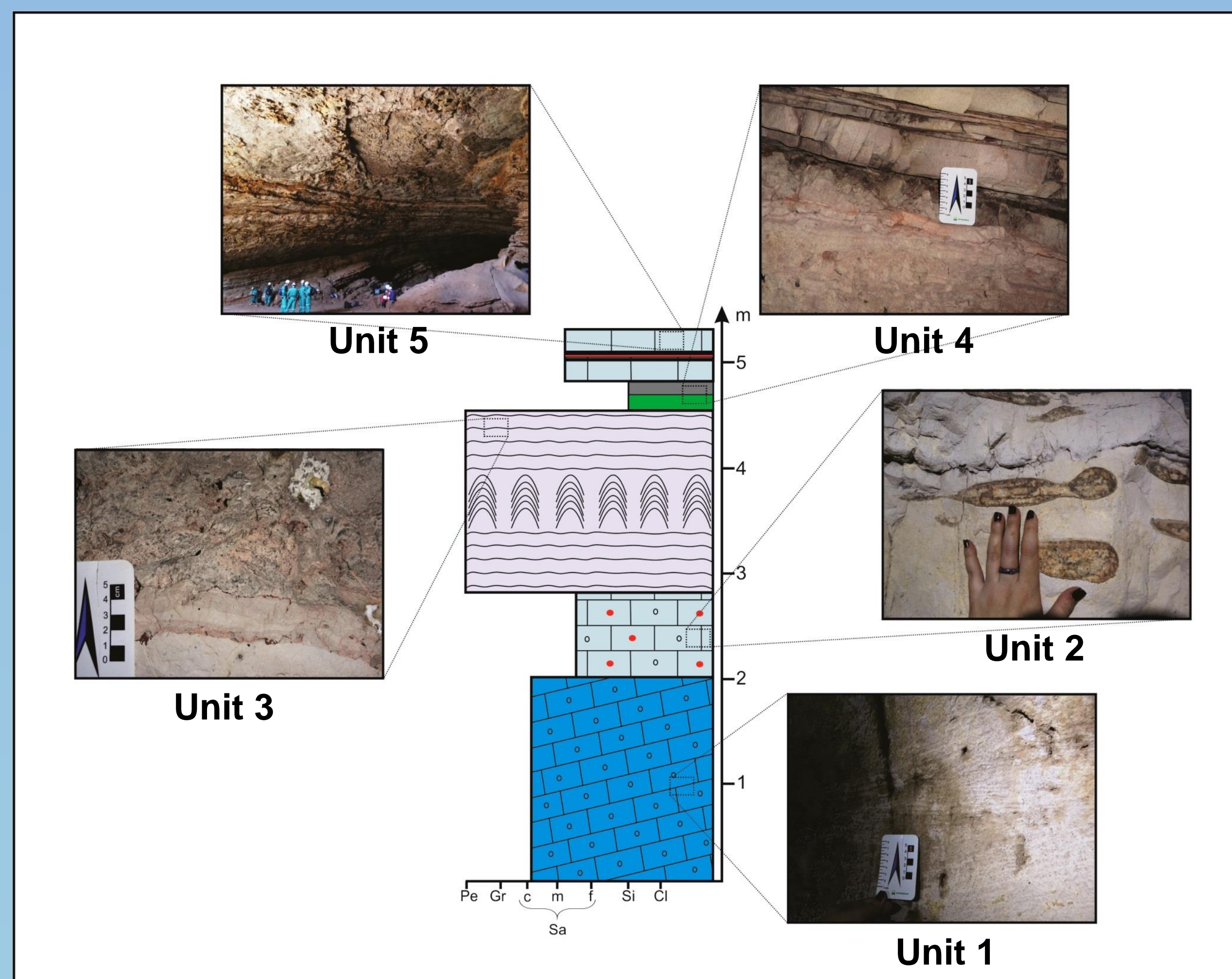
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Results

We identified five lithostratigraphic units, from bottom to top: (1) grainstone with cross-bedding stratification, (2) fine grainstone with chert nodules, (3) microbial carbonate, (4) interbedded fine siliciclastics and marls, (5) crystalline carbonate that interfingers with chert layers. Field and laboratory data indicate that units 4 and 5 formed a seal for fluid flow, below which flow occurred laterally causing dissolution of units 1, 2, and 3. These five units are identified throughout the Salitre Formation, which makes the stratigraphic control predictable.

In Toca da Boa Vista and Toca da Barriguda is possible to recognize morphology features which are aligned to main direction structures developed and quantify them. Main directions for conduits are NNE-SSW and E-W, which coincides to directions of joints, faults and folding directions.

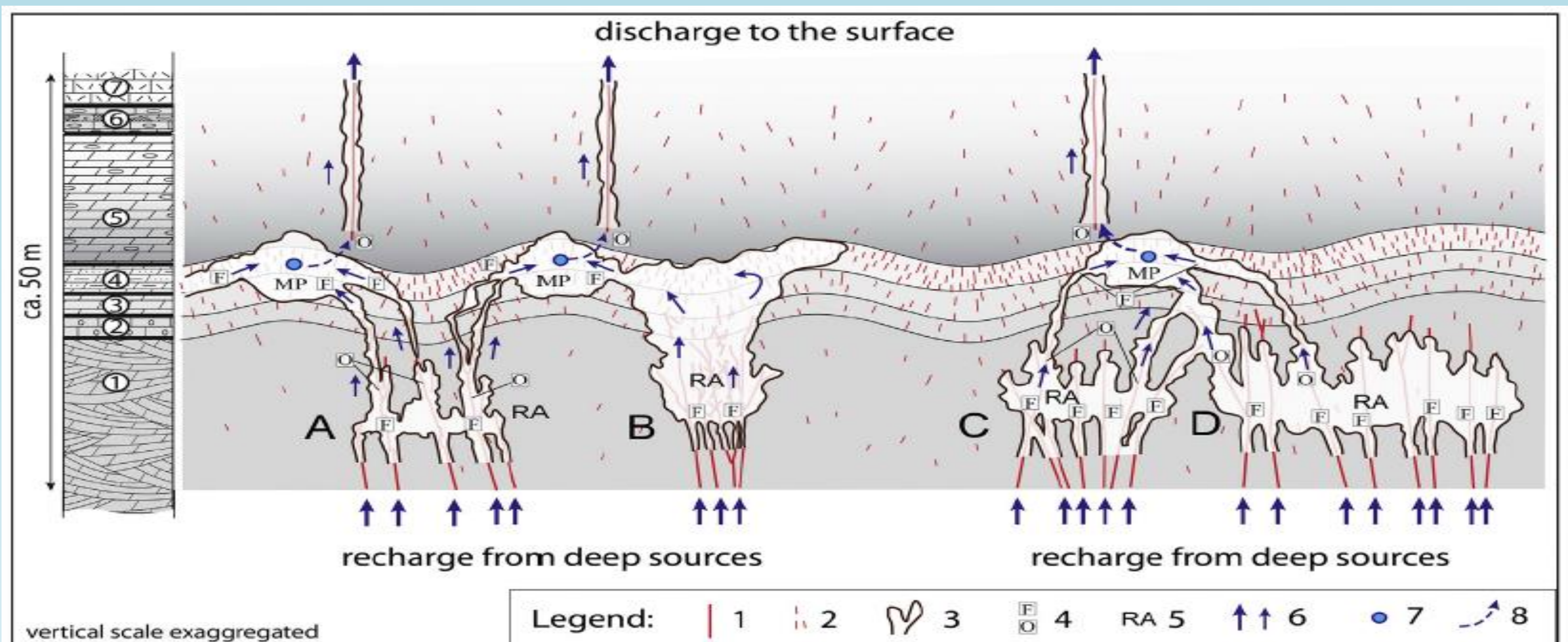
Three cave-stratigraphic stories identified: The lower cave-stratigraphic storey developed as a recharge component of the system, which formed along fracture corridors that served as feeders for the ascending flow. The middle cave stratigraphic storey comprises mainly sub-horizontal cave passages developed along highly conductive carbonate layers, which are capped by a seal that prevented fluid flow to ascend directly to the upper part of the karst system. The upper cave-stratigraphic storey comprises outlets formed along fractures. This last storey represent fracture zones, which allowed outflow paths through the seal..



Lithostratigraphic units and features as they occur in the caves. (Cazarin, 2015) Distribution of fractures in the cave system.



Morphology of Toca da Boa Vista and Toca da Barriguda karst system. A e B are feeders (NNE-SSW direction) ; C and D Are rift-like passages (NNE-SSW direction); E is an outlet developed in the intersection of N-S and E-W fractures; F is cupolas developed along E-W fracture, and, G is a cupola (Ennes-Silva et al., 2015).



Details of the vertical structure and functional organization of the cave system (conceptual model). (Klimchouk et al., 2016)

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The model of karst system considered facies distribution and structural geology.

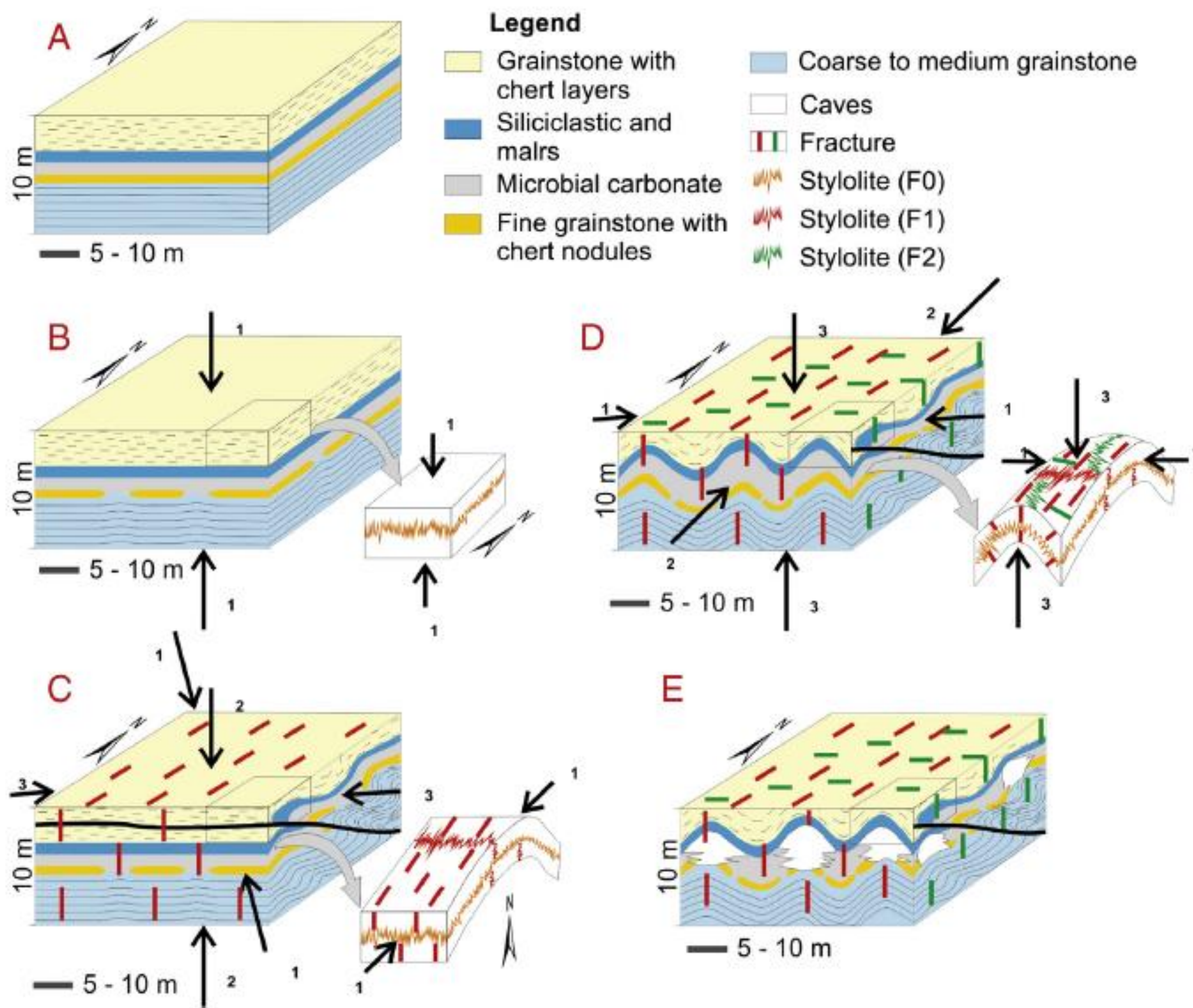
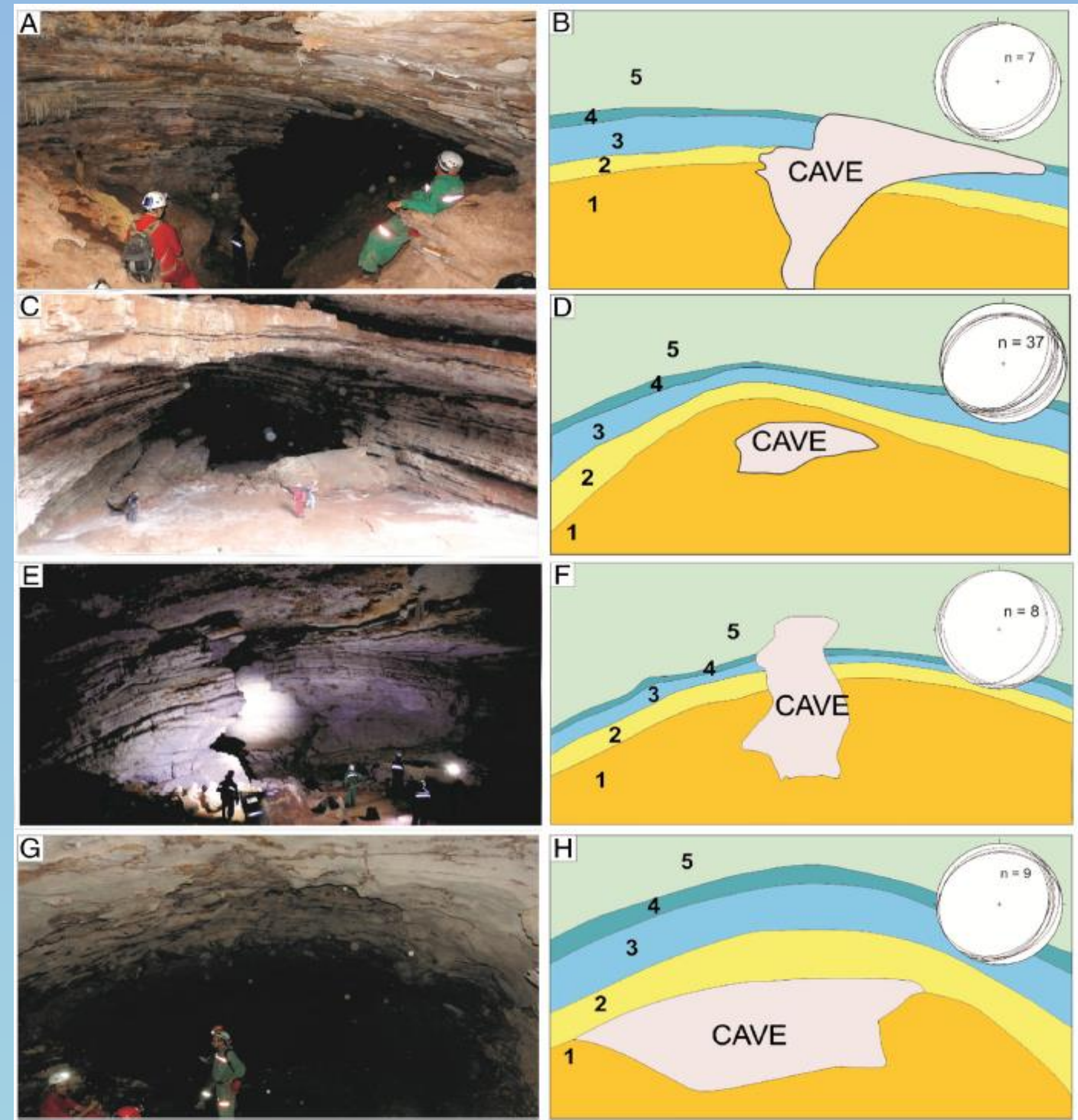
The hypogene karst system occurs immediately in the gently folded hangingwall block of a thrust fault, which served as conduit for deep-seated fluids.

The stratigraphy of the Salitre Formation is roughly the same across the region. One important question that may arise is why the TBV-TBR system occurs in a specific site of the Campo Formoso Basin. It follows that the TBV-TBR cave system occurs at the top of a regional NE-SW-striking thrust, which is trends roughly in the same direction of both caves.

Dissolution mainly enlarged subvertical fractures developed mostly along the anticline hinges. These hinges follow the general trend of regional deformation, which is also predictable.

Our data indicate several events of porosity evolution, such as subaerial exposure, folds and fractures, hydrothermal events (exotic minerals assemblage), sulfuric acid dissolution, dissolution at the water table, condensation corrosion, and faults and fractures reactivation. The major enhancement of secondary porosity was due to hypogene speleogenesis.

Structural evolution of the hypogene system (from Ennes-Silva et al., 2015).



Discussion/Conclusion

Karst processes are of primary importance for the generation of secondary porosity and permeability in carbonate reservoirs. Although the paleokarst concept was commonly implied previously to interpret karst porosity in deepseated reservoirs, there is a rapidly growing recognition of hypogene karstification that occur in mesogenetic environment and can create macro- and mega (meter-scale) porosity and conduit permeability. Field analogues studies in representative caves are crucial to better understand the system and enable using this knowledge in developing reservoir models in carbonates. The system of largest caves in South America, Toca da Boa Vista and Toca da Barriguda, developed in the Neoproterozoic carbonates of the Salitre Formation, is an field analogue of carbonate reservoirs affected by hypogenic karst processes.

This study highlights the importance of determining the origin of karst systems for understanding highly heterogeneous fractured and karstified carbonate reservoirs as the Pre-salt in offshore Brazil.

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