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Hypogenic origin, geologic controls and functional organization of a giant cave system in Precambrian carbonates, Brazil

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ABSTRACT

This study is focused on speleogenesis of the Toca da Boa Vista (TBV) and Toca da Barriguda (TBR), the longest caves in South America occurring in the Neoproterozoic Salitre Formation in the São Francisco Craton, NE Brazil. We employ a multidisciplinary approach integrating detailed speleomorphogenetic, lithostratigraphic and geological structure studies in order to reveal the origin of the caves, their functional organization and geologic controls on their development. The caves developed in deep-seated confined conditions by rising flow. The overall fields of passages of TBV and TBR caves represent a speleogenetically exploited large NE–SW-trending fracture corridor associated with a major thrust. This corridor vertically extends across the Salitre Formation allowing the rise of deep fluids. In the overall ascending flow system, the formation of the cave pattern was controlled by a system of sub-parallel anticlines and troughs with NNE–SSW dominant orientation, and by vertical and lateral heterogeneities in fracture distribution. Three cave-stratigraphic stories reflect the actual hydrostratigraphy during the main phase of speleogenesis. Cavities at different stories are distinct in morphology and functioning. The gross tree-dimensional pattern of the system is effectively organized to conduct rising flow in deep-seated confined conditions. Cavities in the lower story developed as recharge components to the system. A laterally extensive conduit network in the middle story formed because the vertical flow from numerous recharge points has been redirected laterally along the highly conductive unit, occurring below the major seal — a scarcely fractured unit. Rift-like and shaft-like conduits in the upper story developed along fracture-controlled outflow paths, breaching the integrity of the major seal, and served as outlets for the cave system. The cave system represents a series of vertically organized, functionally largely independent clusters of cavities developed within individual ascending flow cells. Lateral integration of clusters occurred due to hydrodynamic interaction between the flow cells in course of speleogenetic evolution and change of boundary conditions. The main speleogenetic phase, during which the gross cave pattern has been established and the caves acquired most of their volume, was likely related to rise of deep fluids at about 520 Ma or associated with rifting and the Pangea break-up in Triassic–Cretaceous. This study highlights the importance of speleogenetic studies for interpreting porosity and permeability features in carbonate reservoirs.

1. Introduction

Historically, karst studies were mainly concerned with shallow, hydrogeologically unconfined settings where karstification is related to direct recharge from the overlying surface (i.e., epigene karst). For a long time, the possibility of deep-seated karst development (hypogene karst) was deemed to be low to nonexistent within the dominant "geomorphological" paradigm of karst. Solution porosity features found in deep burial environments have commonly been interpreted as paleo-(epigenic) karst, i.e. karst that had commenced in exposed settings but later buried under younger strata.

The last decade has witnessed an expansion in the recognition of importance of hypogene karst (speleogenesis) that develops by upwelling flow, without direct genetic relationship to the surface. Previously regarded as an aberrant phenomenon of local significance, hypogene karst is now increasingly recognized as one of the fundamental categories of karst of wide global occurrence and importance (Klimchouk, 2007, 2009, 2012). At the same time, it has become clear that speleogenesis, and resultant patterns and functioning of void–conduit

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systems, differ fundamentally between hydrogeologically confined deep-seated, hypogene settings and surface-related epigene settings. Thus, the identification of the cave origin (type of speleogenesis) is of paramount importance for many practical fields concerned with post-depositional heterogeneities and fluid flow in soluble rocks. This is particularly true for carbonate reservoir characterization as they host around 60% of the world's oil and 40% of the world's gas (Montaron, 2008), including many super-giant and highly productive fields. Meanwhile, prospecting and exploitation of such reservoirs presents many difficult challenges stemming from poor understanding of the properties of karst void–conduit systems. Being the result of fluid circulation in a given geological media comprising soluble rocks, solutional void–conduit systems contain a wealth of information about fluid history and geological (geodynamic, hydrogeological, geomorphological, etc.) evolution of an area. When evolved, such systems exert a dominant control over subsurface fluid flow. Detailed studies of large accessible cave systems are indispensable for improving our understanding of speleogenetic processes and, therefore, of resultant porosity and permeability in carbonate reservoirs. Such cave systems can serve as analogs of karst reservoirs.

With current advances in studying hypogenic speleogenesis, the origin of caves in many regions is being re-interpreted (e.g. Klimchouk and Ford, 2009; Stafford et al., 2009). The diversity of hypogene cave patterns is now recognized as the result of complex interplay of geological conditions and cave-forming processes, varying in space and time (Klimchouk, 2007; Audra et al., 2009b). However, geologic controls over fluid flow and speleogenesis in hypogene settings are not yet sufficiently understood.

This study is focused on speleogenesis of the cave system consisting of the Toca da Boa Vista (TBV) and Toca da Barriguda (TBR) caves. These caves, occurring in the Neoproterozoic carbonates of the Salitre Formation (Una Group) in the São Francisco Craton, Brazil (Fig. 1), are the longest in South America and among the longest in the Southern Hemisphere, with mapped conduit lengths of ca. 107 and ca. 34 km respectively. Early studies of the caves (Auler, 1999; Auler and Smart, 2003) recognized their hypogene character but proposed a model of shallow speleogenesis in a laterally flowing aquifer. Here we present a multidisciplinary approach integrating detailed speleomorphogenetic studies and studies of lithostratigraphy and geological structure (fracturing and folding), which allowed us (1) to demonstrate the origin of the caves by deep ascending flow under confined conditions, (2) unravel the functional organization of the cave system, and (3) constrain geological controls over the cave development.

2. The study area

TBV and TBR are located close to the village of Laje dos Negros in the municipality of Campo Formoso (Bahia State), in the northeastern Brazil (Fig. 1). The study area is in the northern part of the São Francisco Craton (Fig. 2) that has been preserved from the Brasiliano orogeny at

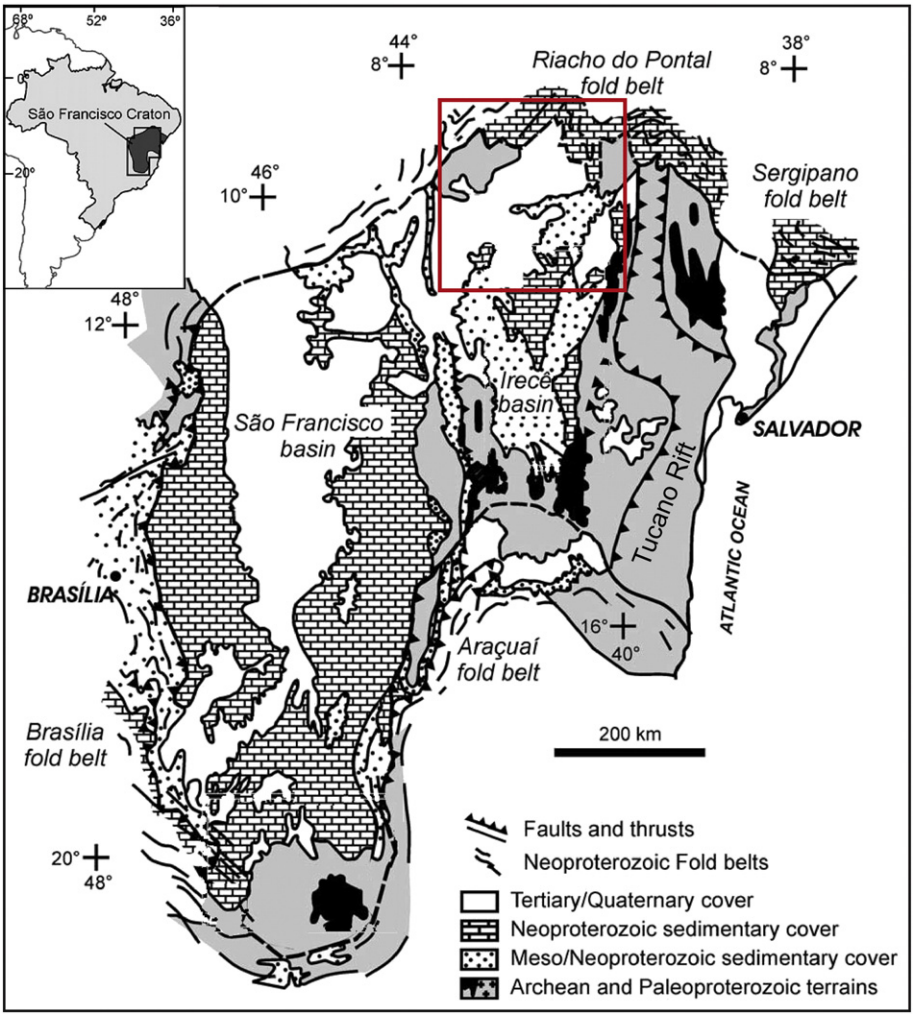

Fig. 1. Geological map of the São Francisco Craton showing Neoproterozoic basins, surrounding fold belts, and the study area (red square cf. Fig. 2A). From Santos et al. (2000), as modified by Trindade et al. (2004).