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Superposed folding and associated fracturing influence hypogene karst development in Neoproterozoic carbonates, São Francisco Craton, Brazil

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ABSTRACT

Porosity and permeability along fractured zones in carbonates could be significantly enhanced by ascending fluid flow, resulting in hypogene karst development. This work presents a detailed structural analysis of the longest cave system in South America to investigate the relationship between patterns of karst conduits and regional deformation. Our study area encompasses the Toca da Boa Vista (TBV) and Toca da Barriguda (TBR) caves, which are ca. 107 km and 34 km long, respectively. This cave system occurs in Neoproterozoic carbonates of the Salitre Formation in the northern part of the São Francisco Craton, Brazil. The fold belts that are around and at the craton edges were deformed in a compressive setting during the Brasiliano orogeny between 750 and 540 Ma. Based on the integrated analysis of the folds and brittle deformation in the caves and in outcrops of the surrounding region, we show the following: (1) The caves occur in a tectonic transpressive corridor along a regional thrust belt; (2) major cave passages, at the middle storey of the system, considering both length and frequency, developed laterally along mainly (a) NE–SW to E–W and (b) N to S oriented anticline hinges; (3) conduits were formed by dissolutional enlargement of subvertical joints, which present a high concentration along anticline hinges due to folding of competent grainstone layers; (4) the first folding event F1 was previously documented in the region and corresponds with NW–SE- to N–S-trending compression, whereas the second event F2, documented for the first time in the present study, is related to E–W compression; and (5) both folding events occurred during the Brasiliano orogeny. We conclude that fluid flow and related dissolution pathways have a close relationship with regional deformation events, thus enhancing our ability to predict karst patterns in layered carbonates.

1. Introduction

Fracture control of fluid flow has long been recognized as an important process in hydrogeology ore and petroleum geology (e.g., Agar and Geiger, 2014; Faybishenko et al., 2005; Long at al., 1996). The last two decades have seen an increase in studies of fluid flow related to hypogene karst, which is associated with upward flow in soluble rocks (Klimchouk, 2007; Klimchouk et al., 2009).

Karst features show a close relationship with tectonic structures. Fractures and folds have been identified as important features influencing fluid migration and karst development in carbonates units (White, 1988; Aydin, 2000; Klimchouk and Ford, 2000; Andre and Rajaram, 2005; Billi, 2005; Ford and Williams, 2007; Palmer, 2007; Sauro et al., 2013; Shanov and Kostov, 2015).

Despite advances in the understanding of structural controls on karst conduits, several problems are still unresolved. Although published predictive models of the origin of cave systems exist, the limited number of field-based investigations makes it difficult to assess fluid circulation and development of karst (Billi et al., 2007). First, a structural analysis at the scale of the karst system is lacking in many studies. Such studies of large caves, especially of hypogene origin, are scarce. Second, it is still a matter of debate as to why some tectonic structures are more vulnerable to karst development than other structures. Third, the correlation of karst patterns with regional deformation has not been addressed previously. Fourth, in the case of hydrocarbon reservoir studies and despite the use of some quantitative assessment and statistical descriptions, detailed and subseismic analysis of the deformation–karstification relationship is still lacking. Fifth, most

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studies investigate karst of epigenetic origin, i.e., formed in shallow, unconfined geologic settings due to direct recharge from the surface (Sauro et al., 2013). Structural studies of karst of hypogene origin are still limited.

In the present contribution, we focus on the geometry and orientation of cave passages and their relationship with regional deformation events to understand how hypogene karstification occurs in folded carbonates. Our study area encompasses a giant karst system composed of two caves: Toca da Boa Vista (TBV, 107 km of cave passages) and Toca da Barriguda (TBR, 34 km of cave passages) in the Neoproterozoic Salitre Formation located at the northern part of the São Francisco Craton, Brazil (Fig. 1). The hypogenic nature of these caves has been recently demonstrated (Auler and Smart, 2003; Klimchouk et al., 2016). By gathering field structural data on the TBV and TBR caves, we show that the pattern of these hypogene caves is influenced by a previously established pattern of superposed folding and that tectonic and field-based studies should be used in the prediction of fluid pathways and karstification in carbonate units. These results could be used as input data for modeling of reservoirs and aquifers and could enhance our ability to predict the karstification of carbonates by ascending fluids.

2 . Previous studies on tectonic control of karst systems

Early studies of karst systems recognized fractures as the major control of fluid flows in carbonate rocks (Swinnerton, 1932; Sweeting, 1950). This control was confirmed latter by many studies (e.g., Ford and Ewers, 1978; White, 1988; Palmer, 1975, 1991, 2007; Ryder, 1975; Brook and Ford, 1978). Ford (1971) proposed a model of cave evolution based on the guidance of flow by the spatial density of fractures within an aquifer. Lowe and Gunn (1997) recognized that some carbonate facies and bedding planes, favorable to karstification due to physical, lithological or chemical characteristics ("inception horizons"), support the development of proto-conduits and further guide conduit development. One of the early statistics about the structural guidance of cave development concluded that 57% of the cave passages occur on favorable bedding planes and 42% are controlled by the fractures, whereas only 1% were formed due to the primary carbonate porosity (Palmer, 1991). Klimchouk and Ford (2000) provided a summary of the general controls that geologic structure, including fractures, imposes on cave development.

Examples of the modern structural studies of karst usually associate a substantial proportion of structural datasets with karst cavities and conduits (Billi et al., 2007). More recent studies based on field data have indicated that joints and fault damage zones act as pathways for fluid flow and karst conduit development (Galdenzi and Menichetti, 1995; Tîrlă and Vijulie, 2003; Billi, 2005; Billi et al., 2007; Audra et al., 2007; Sauro et al., 2013).

Several studies concluded that cave passages formed on bedding planes could still be associated with tectonic guidance. This occurs because cave passages tend to form at the intersection of bedding planes and fractures, rather than on the bedding planes alone (Jaskolla and Volk, 1986; Smart and Christopher, 1989; Gillieson, 1996; Tognini and Bini, 2001; Osborne, 2001; Orndorff and Harlow, 2002; Waltham et al., 2005; Lánczos et al., 2013; Lačný, 2013).

Numerical models have also been developed to predict how fluid circulation along fractures generates karst conduit systems (Gabrovsek and Dreybrodt, 2001; Romanov et al., 2003; Andre and Rajaram, 2005;

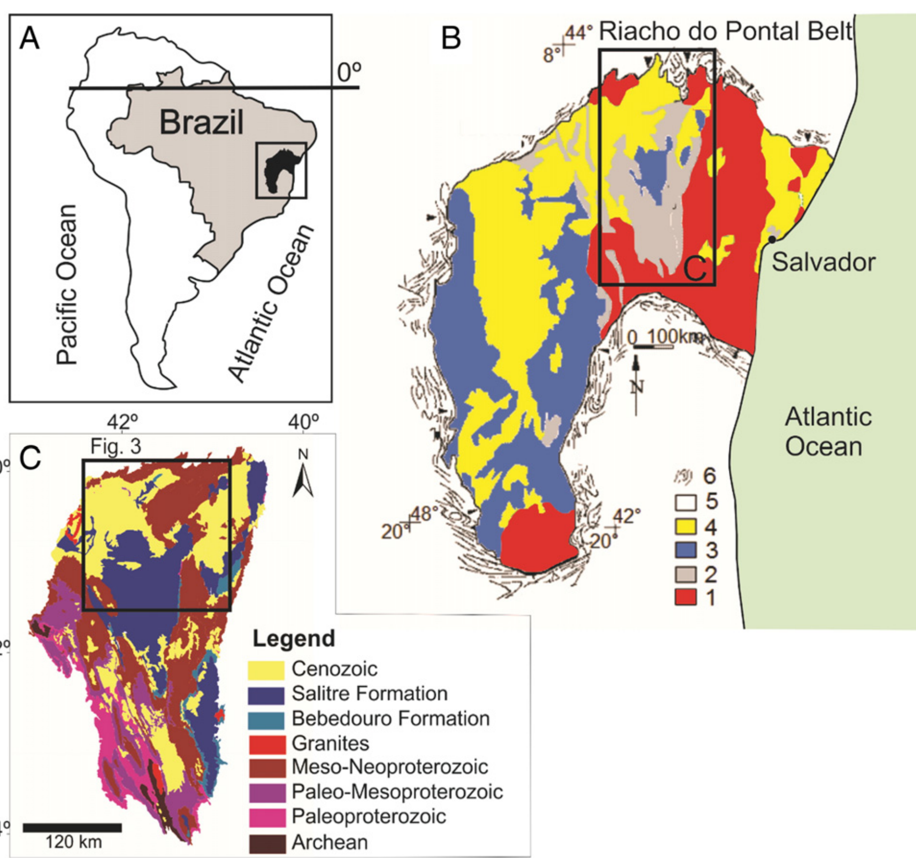

Fig. 1. (A) The South American continent and location of the São Francisco Craton in black; (B) Main lithostratigraphic units of the São Francisco Craton and surrounding folding belts (modified from Alkimim et al., 1993). Key: 1—Archean–Proterozoic basement, 2—Mesoproterozoic sedimentary rocks of the Espinhaço Supergroup, 3—Neoproterozoic rocks of the São Francisco Supergroup, 4—Phanerozoic sedimentary covers, 5—Neoproterozoic Folding belts, 6—Structural lineaments; (C) Detail map of the sedimentary units in the northern part of the Craton, with location of the Salitre Formation and study area (modified from Bizzi et al., 2003).