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STRUCTURAL CONTROL ON CONDUIT FORMATION: CASE STUDY OF TWO CARBONATIC CAVES NEAR TO BRASÍLIA – DF

CONTROLE ESTRUTURAL NA FORMAÇÃO DE CONDUTOS: ESTUDO DE CASO DE DUAS CAVERNAS CARBONÁTICAS PRÓXIMAS A BRASÍLIA - DF

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Abstract

There are numerous examples of the importance of tectonic structures on the development of caves and karst. The Morro da Pedreira region in central Brazil has been a field-school area for the GREGEO speleogroup. The main objective of this study is to characterize the type of tectonic structures that controls the conduits of two caves located in the Morro da Pedreira hill: Primeira Delas and Maracanãnzinho. Structures such as bedding planes, fractures and folds were classified and measured. All data were processed by *Stereonet* and *WinTensor* softwares. It was possible to observe that joints govern the conduit directions, with the bedding planes playing a minor role. Two families of joints were observed and assumed to represent flexural joints parallel to axial planes and tension joints orthogonal to the folds axis.

Keywords: structural geology; cave; joint; speleogenesis; Morro da Pedreira.

Resumo

Existem inúmeros exemplos da importância de estruturas tectônicas para o desenvolvimento de cavernas e carste. A região do Morro da Pedreira, na porção central do Brasil, tem sido utilizada como campo-escola pelo espeleogrupo GREGEO. O principal objetivo deste trabalho é caracterizar qual tipo de estrutura tectônica controla os condutos de duas cavernas inseridas nesse morro: Primeira Delas e Maracanãnzinho. Estruturas como acamamento sedimentar, fraturas e dobras foram identificadas e medidas. Todos os dados foram processados pelos programas Stereonet e WinTensor. Nessas cavernas observou-se que as juntas são os principais controles das direções dos condutos, enquanto o acamamento apresenta papel secundário. Duas famílias de juntas foram observadas e possivelmente representam juntas flexurais paralelas aos planos axiais e juntas de tensão ortogonais aos eixos de dobras.

Palavras-Chave: *geologia estrutural; caverna; junta; espeleogênese; Morro da Pedreira.*

1. INTRODUCTION

For decades, the way that carbonate rocks behave under different physical-chemical conditions has been an important theme of discussion. Processes regarding the rheology of these rocks and its interaction with fluids have proved to be of great importance for the comprehension of karst development and deformation behavior.

The evolution of the knowledge on karst geology shows that the tectonic structures are essential in the control of percolation and dissolution for caves development (KLIMICHOUK; FORD, 2000). Palmer, (1991) suggests that dissolution of proto-conduits occur preferentially on bedding planes and fractures, while primary porosity shows a minor influence. Others authors (KIM; SANDERSON, 2010; BAUER et al., 2016) emphasized that lithological changes combined with tectonic structures control the fluid migration in the carbonate systems. For instance, Watkins et al., (2015), after hydrochemical and structural modelling of Torridon Group, NW of Scotland, proposed that in a fold-thrust system, high strain zones as forelimbs and fold hinges present higher density of fractures oriented parallel to these zones. Similarly, Ennes-Silva et al., (2016) correlate a preferential development of the giant hypogenic caves Toca da Barriguda and Toca da Boa Vista with N-S hinge zones in the Neoproterozoic carbonates from NE Brazil.

The hydrological behavior of fault zones in carbonates may present complexes patterns as highlighted by BAUER et al., (2016). With respect to the fluid migration, faults can act as conduits, barriers, or both (CAINE et al.,1996). This will depend on the host-rock composition, deformational mechanisms, fault zone architecture and alteration of the fault zones (dissolution).

Observational analysis of speleothem alignment was carried out in two limestone caves in South Korea by kim & Sanderson, (2010). Their investigation consisted of measure the size and distribution of stalactites developed along fault systems of the ceiling of caves. In this case, the damage zone associated with strike-slip faults generated links to the planes that formed dilatational or contractional jogs, depending on the curvature of the planes. The higher amount and volume of stalactites were observed on the dilatational jogs. On the contrary, the lower amount and volume of stalactites were observed on contractional jogs. The notable importance of interaction or overlap between structures is also demonstrated by Ennes-Silva et al., (2016). These authors show that the intersection planes in the re-folded layered carbonates have driven the migration of tectonic fluids to the low-pressure hinge zones, making possible the prior dissolution of proto-conduits during deformation.

In this perspective, we analyzed the structures that appear to control two carbonatic caves near to Brasília (central Brazil). This study was based on the assumption that, on both regional and local scales, faulting formation in low-porosity massive carbonates is primordial to the karst development. Therefore, a field trip was realized to collect structural data and check if these structures are in agreement with the conduct directions. The main idea is to find evidence of the type of structures that mostly controls the cave passages.

2. METHODOLOGY

Structural measurements were acquired using two geological compass (*Brunton* type) and another digital (smartphone) with *FieldMoveClino* application. It was differentiated sedimentary bedding planes (S_0), joints, faults, veins, as well as fold, axial plane and fold axis.

The obtained data were plotted on a grid by *Stereonet* software, version 10.2.8 (CARDOZO; ALLMENDINGER, 2013; ALLMENDINGER et al. 2013). We used equal-area grid (Schmidt net) because they present no statistical bias when a large number of data is plotted. All data were plotted in the lower hemisphere, since it is assumed that all structural elements are defined to be inclined below the horizontal reference surface. On every plot, the north pole is the upper point where all lines of longitude converge (the south pole is the lower convergence point). The countour plots of data density were calculated based on the poles of the planes. The statistic method used was the 1% area contours, where the counting circle is automatically constrained to be 1% of the total net area.

The optimized Right Dihedron method was applied utilizing the software *WinTensor* (DELVAUX; SPERNER, 2003), with the objective to deduce the local stress fields σ1, σ2 e σ3.

3. RESULTS

Study site: Location and geological characteristics

The speleological occurrence of the Morro da Pedreira was decreted a Natural Monument of Federal District – Brazil by the decree num. 31758 (DISTRITO FEDERAL, 2010). It is located in the central Brazil region, approximately 30 kilometers to the north of Brasília (Figure 1).

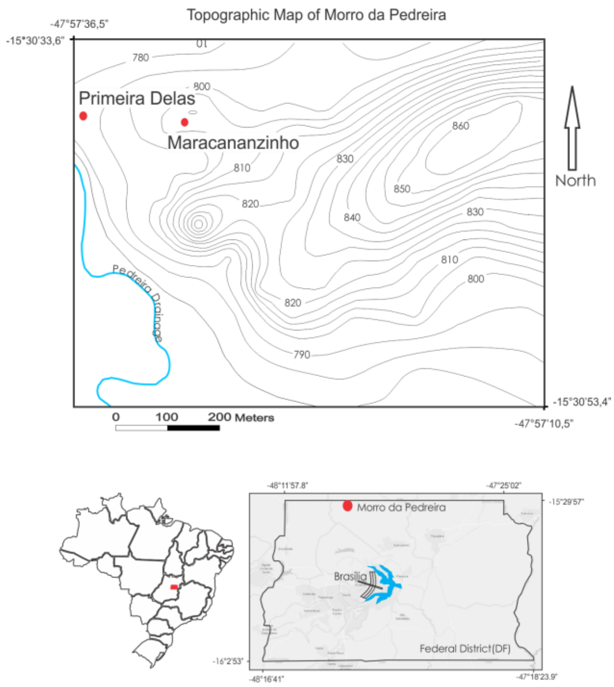

Figure 1: Location Map. Bottom: Brazil and its political division. The square highlighted in red represents the Distrito Federal (DF). Detail on the bottom right shows the DF limits and its capital, Brasília, also capital of the Country (airplane shape). To the north of Brasília, the red dot shows the study site, the Morro da Pedreira region. Top: Topographic map of the Morro da Pedreira Hill. The

two caves analyzed on this study are marked with red dots (Primeira Delas Cave and Maracanãnzinho Cave).

Several caves are known in this region, although this study was focused only in two caves: Primeira Delas Cave and Maracanãnzinho Cave. These caves are close to each other and are located in the lower topographic level of the hill, around 780 – 800 m of elevation. They were used in this study due to their proximity and easy access.

The two caves are hosted in limestone of the so called PC unit (pelitic-carbonated unit) of the Paranoá group. Stratigraphically it represents the topmost unit of this group, and was formally termed as Córrego do Barreiro Formation by Campos et al., (2013). According to the authors, this formation is mainly composed of silty metapelites (85% of the whole succession), although carbonatic rocks occurs as lenses interdigitated with the pelitic facies. The carbonatic rocks are mainly dark grey limestones (mudstones, grainstones, packstones, floatstones). Locally also occurs stromatolites. This carbonatic lenses display hundreds of meters thick, and may reach more than 1 kilometer long. Calcareous breccia are observed, sometimes silicified, close to the boards of the lenses or in lower topographic zones, probably associated to the base of the carbonatic cycles (CAMPOS et al., 2013).

Such carbonate lenses were deposited during the Mesoproterozoic and no longer show primary porosity. Macroscopically, the rock consists of dark gray microcrystalline layered metalimestones, with an interbedding of muddy material (Figure 2 - A).

Sedimentary structures are preserved such as wave ripples, stromatolites, algal flats and parallel lamination. The rock reacts intensively to hydrochloridric acid attack, suggesting that calcite is the main mineral. In spite of the lack of primary porosity, secondary porosity is well developed by tectonic processes, as expected for a carbonate in a fold and thrust belt.

The bedding plane is wavy and shows some small-scale folds. Inside both caves is possible to observe metric folds (Figure 2 - B). A plenty of fractures crosscut the host rock. Some of them are filled with calcite (veins) (Figure 2 - C). Those veins are composed of calcite crystals, which may reach a few millimeters long in the longest growth axis. It is also possible to observe pores in the central part of the vein (indicated by the yellow arrow in Figure 2 – D), as well as the termination of the crystals in a suture zone in the center of the vein. The closing of the vein in the center shows that it grew from both sidewalls simultaneously. This is evidence for syntaxial veins with two fronts that grow inwards from the wall rock (STREKEISEN, 2019).

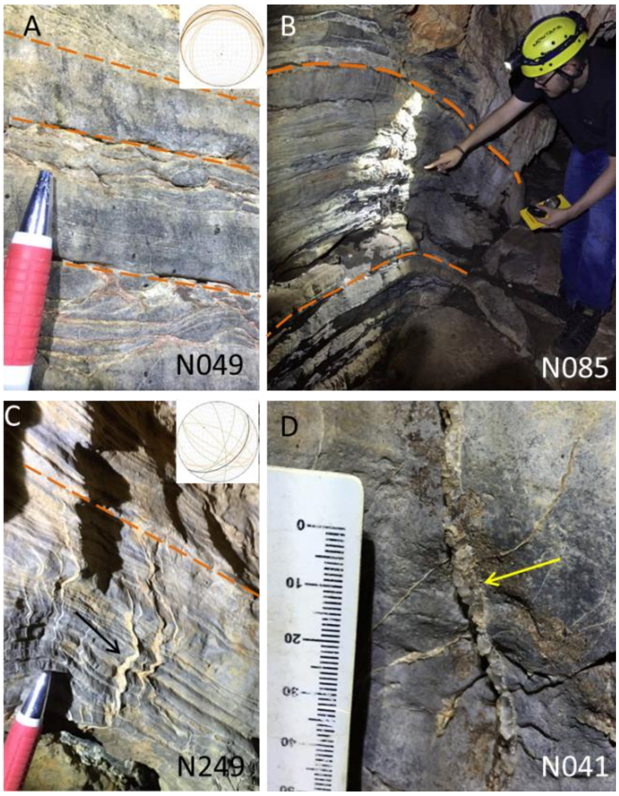

Figure 2: Overview of the two caves visited. The azimuth on the bottom right corner of each picture is the direction that faces the photograph. Orange dashed line = bedding plane. A) Bedding plane in the entrance outcrop of the Primeira Delas Cave. The stereogram on the top right show the S_0 planes dipping towards north. B) Fold inside Maracanãnzinho Cave. C) Details of the veins (indicated by the black arrow). The stereogram on the right top show the vein planes for both caves, with mean dip direction to SE. D) Detail of the syntaxial vein.

The Primeira Delas (PD) and Maracanãnzinho (Mz) caves show prominent reticular and geometrical shapes as observed in the maps prepared by the GREGEO speleogroup (Figure 3).

The first visited cave (Primeira Delas) shows a reticular (network) shape, where the conduits are developed in two main directions: NW-SE and NE-SW. Larger halls form in the intersection points of these two main directions, and resemble to have a triangular shape. The map of Maracanãnzinho is not completed yet. The mapped portion shows conduits developing mostly in the NW-SE direction. The first larger hall shows an enlargement to NE direction that may relate to a fracture system, although this NE-SW direction is not evident in other mapped conduits. The roof of the Maracanãnzinho first hall is represented by dipping of the bedding plane. Also, is interesting to note the vertical development of the conduits, clearly shown on the cross sections of PD cave. Those sections developed mostly vertically, closing towards the roof, suggest the passages are product of dissolution and enlargement of diaclases.

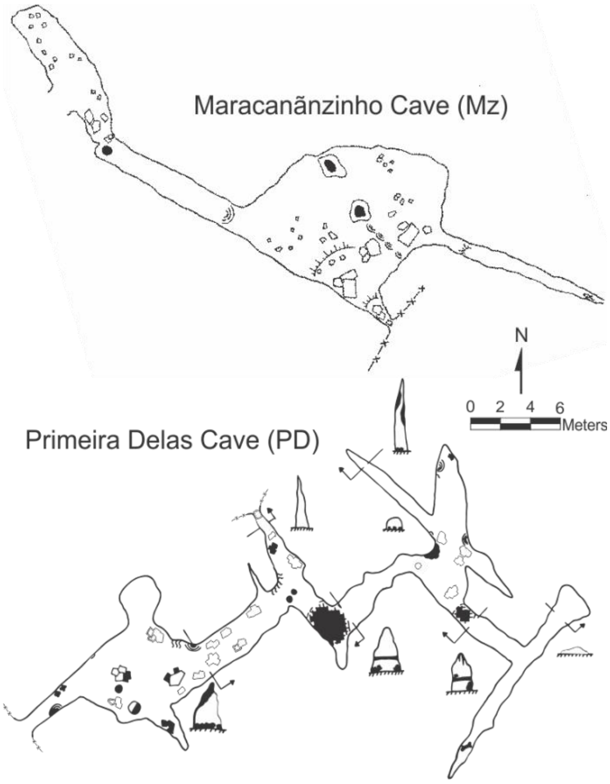

Figure 3: Topographic map of the studied caves, produced by GREGEO Speleogroup. A) Map of Primeira Delas Cave (GREGEO). B) Map of Maracanãnzinho Cave – incomplete.

Structural Data

Table 1 summarizes the quantity and type of structure measured as well as the caves dimensions. The mean bedding plane for the PD Cave is 003°/18° and for the Mz Cave is 354°/16°. Both caves displayed a plenty of fractures, including some "dry" joints and some joints filled by calcite (veins), as well as a few diagnosed faults (with small rake) and folds.

Table 1: Rock Structural Data – number of measurements of each type of structure (this study). Cave Speleometry – Horizontal length and depth of caves (Pereira et al. 2009).

	Rock Structural Data						Cave Speleometry	
Caves	S_0	Joint	Vein	Fault	Axial Plane	Fold Axis	Length	Depth
Primeira Delas	52	16	19	2	1	1	87	4
Maracananzinho	43	15	13	2	1	1	46	3

Most of the fractures observed does not show evidence of movement, and were classified as joints. In the PD Cave two families of joints were measured, in the NE-SW direction (dip to SE) and a second family with WNW- ESE direction (dip to SW). Both families of joints show a mean dip angle around 60°-70° degrees. On the other hand, the Mz Cave revealed one single family of joints in the NE-SW direction, with dip angle around 70°-80° degrees to SE.

Two faults were measured at the PD Cave. Each fault plane show a different direction, but both presented high dip angles (032°/81°; 130°/71°). The fault 130°/70° is a normal fault while the 032°/81° is a reverse fault. Due to the high angle of the reverse fault plane, we suppose that it might be a product of reactivation of a previous normal fault or joint with the evolution of deformation.

Discussions

The low primary porosity of the metalimestones of the Morro da Pedreira cave system resulted in a preferentially dissolution of planar structures. In the two caves analyzed, the low angle dip of the strata show minor influence in the dissolution of the conduits, leaving only fractures as the preferential flow path of dissolution fluids. Even with a minor influence of the bedding plane in conduits distribution, they act as inception horizons in both caves (Figure 4), shaping the format of the walls due the differential dissolution over the different rock types, as demonstrated by Filipponi et al., (2010).

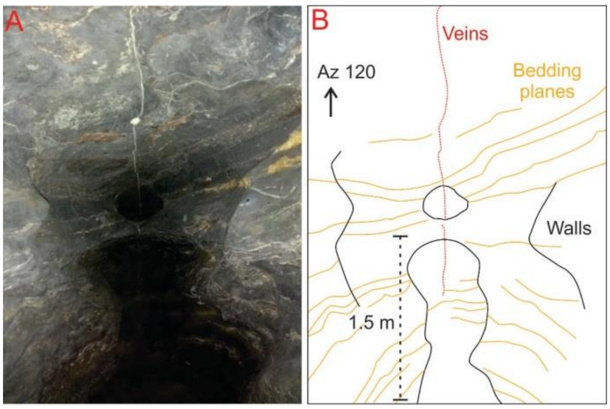

Figure 4: Cross section of Primeira Delas cave. A) Image of the 120° azimuth conduit of the PD Cave, parallel to the vein on the ceiling. B) Sketch showing the format of the conduit controlled by bedding planes, resulting in a small bridge.

With regard to the deformation of S_0, the poles of bedding planes show a concentration in the SE quadrant with high plunge (Figure 5). This suggests the predominance of bedding planes dipping gently towards NW. For the same projections, it is possible to identify two main guirdles of distribution of poles. For the PD Cave one guirdle shows a distribution along NE-SW direction and another in the E-W direction (Figure 5A). In the case of the Mz Cave the guirdles are distributed along N-S and NW-SE directions (fig, 5B). As a pattern of guirdles normally indicates folding, these two orthogonal variability of the attitudes directions for both caves suggests that bedding planes are deformed by two different folding phases.

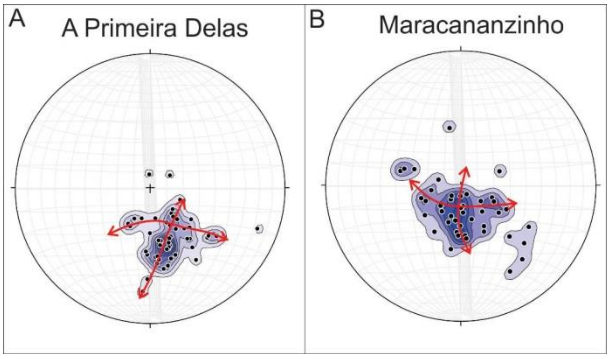

Figure 5: Bedding planes represented as poles for Primeira Delas (A) and Maracanãnzinho (B) caves. Red arrows indicate the orientation of the guirdles representing folds.

The measures along the caves showed that the conduits development is directly related to the dissolution of joints and faults, with no S_0 control. The majority of the joints are filled with white calcite (not speleothem), which indicates that they were filled and formed during the tectonic event, instead of lithostatic decompression or cooling.

Aligned stalactites, flowstones and coralloids along the fractures on the ceiling were formed by re-precipitation of carbonates from vadose water that migrated in the fractures. This is an indicator that dissolution oriented by these fractures still occurs in the present-day.

The Figure 6 - A and C correspond to the attitudes of the bedding planes (small circles), as well as joints and veins (rose diagrams). One family of joint (NE-SW) is parallel to the distribution of veins, pointing that these two structures can be grouped as the same family. Field observations indicate that parts of these veins are parallel to the local axial plane of folds, permitting us to assume that they were formed during the folding as NE-SW flexural joints.

Other family of joints and veins showed main distribution in the NW-SE direction. If we assume that this family of joints was formed coevally to the flexural joints, is possible to infer that they are tension joints fractured parallel to the greater stress tensor (σ_1) and opened perpendicular to the lower stress tensor (σ_3). However, the re-folding phase discussed above could generate joints and veins according to the newer stress field, skewing the previous interpretation. Caution must be taken when analyzing the chronological order of fracturing whilst sorting the relative timing of fracturing may be a challenge.

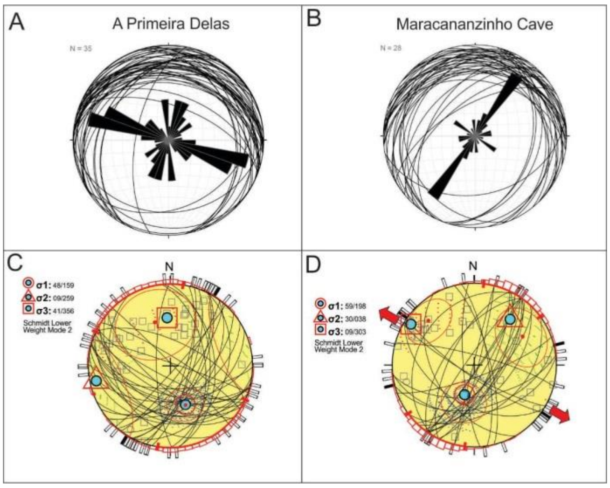

Figure 6: Stereogram with bedding plane directions plotted in small circles together with rose diagrams of joints and fractures, as well as *WinTensor* analysis of Primeira Delas Cave (A-C) and Maracanãnzinho Cave (B-D).

The Right Dihedron analysis for the measures of joints and veins in the PD cave did not result in any reliable positioning of σ_1, σ_2 and σ_3 stress tensors due to the occurrence of these structures in two distinct directions NE-SW and NW-SE (Figure 6 - B). Nonetheless, if we assume that the majority of these fractures are tension joints (Figure 6 - C), the preferential NE-SW fractures measured in the Mz Cave indicates that σ_3=09°/303°. This interpretation is in agreement with the model of the folds and veins observed for the cave, and represented schematically in figure 7.

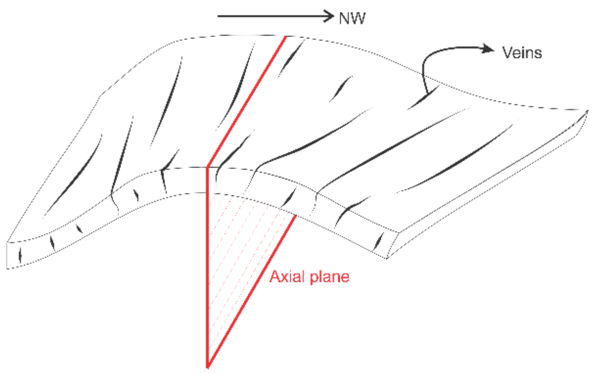

Figure 7: Model representing folds observed in the Maracanãnzinho Cave. Veins are sub-parallel to axial plane, indicating that they are flexural joints filled by calcite.

It should be pointed out that the distribution pattern of fractures and veins represented in the rose diagrams may be biased. It is necessary to crosscut the structure to observe and measure the plane/line. If the conduit was developed in a fracture zone, the cave is probably parallel to this structure, and in this case won't be possible to measure the fractures. This may result in fewer measurements taken in the directions parallel to the main conduits.

4. CONCLUSIONS

Tectonic structures are important in the process of cave formation. The two caves analyzed in this study also proved to have a major tectonic structural control. The main goal of this study was to define the type of structures that mostly controls the cave passages. Therefore, were measured bedding planes, in general with E-W direction dipping towards north, as well as two families of joints, one with NE-SW direction (dip to SE) and the other with NW- SE direction (dip to SW).

The bedding plane shows a pattern of two guirdles orthogonal to each other, suggesting that the bedding planes were deformed by two distinct folding phases. In both caves, the low dip angle of bedding strata had minor influence in the dissolution of conduits, although they have a role in defining the shape of the ceiling and of the cave walls.

The preferential dissolution flow seems to be controlled by fractures, mainly joints. There are two main directions of joints. Some are parallel to the calcite veins, assumed to be NE-SW flexural joints. The other family (NW-SE) was inferred to be tension joints opened perpendicular to the lower stress tensor σ3, considering that both families of joints were formed coevally. We highlight that caution must be taken regarding the chronology – synchronicity of the fracture structures.

Due to the presence of these two distinct fracture directions, it was not possible to reliable positioning the tensors σ_1, σ_2 and σ_3 in the Primeira Delas Cave. On the other hand, the Right Dihedron analysis in the Maracanãnzinho Cave indicated a σ_3 = 09°/303°, in agreement with the folds and veins model for the cave.

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