Breakdown mechanisms in iron caves. An example from Brazil

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Abstract: An iron cave in the vicinity of a mine in Carajás, Brazil, was selected to be mined within an assisted elimination project, planned to control all mine advancement operations towards the cave along with a strict speleological physical monitoring. It allowed, in a pioneering way, the recording of events in the cave from the first signs of damage until to the total collapse of the cave. The project lasted four years and it was possible to identify and describe four breakdown mechanisms in iron caves: Fragment downfall, Block downfall, Controlling structure reactivation, and Open discontinuity movement. The mechanisms occurred independently or together, and not necessarily in a chronological order. This work details and discusses the mechanisms and their relationships with the geostructural and geomechanical features of the cave to assist stability assessment studies.

Keywords: iron cave, assisted elimination of cave, cave breakdown mechanism, speleological study, Carajás

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INTRODUCTION

General considerations

The protection of speleological heritage in Brazil was foreseen in regulations proclaimed before the Federal Constitution of 1988 which declared caves to be Federal Government property and later confirmed by Resolution IBAMA 887/1990 (Brasil, 1990a), and Federal Decree 99,556/1990, (Brasil, 1990b).

Due to the intense growth of mining activity since 2008, leveraged by the growing demand for minerals in the international market, the legislation has become more restrictive. Resolution CONAMA 347/2004 (MMA, 2004) and Federal Decree 6.640/2008 (Brasil, 2008) which, among other requirements, established a protection buffer zone of 250 m around each cave that must be preserved until specific technical studies have determined the area of buffer zone required to protect the cave, and thus enable a license to be granted to operate without damaging the caves.

In the long-term, the need for studies has led to damaging economic and social consequences for the mining companies with increased mining costs and significant reductions in the area available for mining (Auler, 2015). On the other hand, it has forced the mining companies to increase their efforts in research and development to address the speleological issues in their production units, mainly in iron mining, since iron caves are more abundant in richer zones of the ore (Calux, 2011).

Explosive blasting in mine sites is one of the greatest risks for cave collapse, therefore, geostuctural studies and geomechanical quality modelling play a fundamental role in determining the correct size of the buffer zone around the caves and thus compliance with the legislation.

Compared with the vast body of literature about caves in carbonate terrains, where the process of genesis is mineral dissolution, the scientific literature on caves hosted in ferruginous rocks is quite limited. Some ideas about structural instability from carbonate caves however can be transferred to iron caves for instance Santo (2017), evaluated the susceptibility of collapse of a carbonate cave in southern Italy, and said that the problem of ceiling collapse is complex, affected by the random variability of the mechanical properties of the rock “in-situ” and presence of cracks and fractures in the massif. In addition, he explained that over the years, several stability analysis systems

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have been developed to estimate the degree of cave safety, and because of its simplicity, empirical methods are widely used. Goodings & Abdulla (2002) studied the collapse conditions of 49 caves based on the thicknesses between the ceiling and the ground-surface while Fraldi and Guarracino (2009), proposed a solution to predict collapse in natural caves, considering plasticity theory, with the aid of the calculation of variations and assuming that the form of collapsing rock mass is given by a Euler equation, which may be associated with the principle of maximum plastic dissipation.

Several studies of caves in iron terrains have been carried out in Brazil, and the number of publications has been increasing in recent years. Technological innovations in geomechanical, geotechnical and structural studies applied to iron caves have been published by Noce (2016) who proposed the geotechnical zoning of caves, and Brandi (2018) who developed a Geotechnical Index for Caves (GIC), providing a classification of massif quality specific for speleological science, ranking the susceptibility of structural instability of the cave spans. Araújo (2015), Araújo et al. (2016 a, b) used 3D laser topography to improve geomechanical cave classification while Valentim et al. (2016) and Dutra et al. (2017) developed geomechanical models of caves, and Brandi et al. (2015), showed the results of geotechnical instrument monitoring in the caves, using a technique borrowed from underground mining.

This paper describes the breakdown mechanisms caused by regular mining processes in iron cave N4E_0026, adapting the concept of “cave breakdown” of White (2012) and Osborne (2002). In general, the simplest type of collapse is caused by gravitational tension in fragmented ceiling blocks (White & White, 1969) reviving the work of Davies (1951). Cave breakdown mechanisms were studied during an assisted elimination project on a cave at the N4EN Mine in Carajás, with controlled mining advances and continuous monitoring, where all the progressive occurrences of physical damage to this cave were followed, from the beginning of fragmentation until the cave’s elimination from structural instability and collapse (irreversible impact). Iron ore mine N4EN, operated by Vale S.A., is used as a large laboratory, where technologies are applied to speleological studies, to increase the technical-scientific knowledge, in the search for solutions of a sustainable mining within the legal requirements for the preservation of speleological heritage.

The authors consider that by studying the progressive effects of breakdown mechanisms in an iron cave in a working mine site, they will be contributing to: (i) improving mine planning for cave conservation, (ii) the improvement of explosive blasting methods to minimize impacts on caves and resource sterilization, (iii) to stimulate seismographic waves mitigation techniques, (iv) to increase the volume of scarce scientific literature specific to iron caves, and (v) to the improve safety of researchers who need to spend long periods of study in caves near mining sites.

Irreversible impact on a cave
Brazilian environmental legislation is one of the most rigorous regarding damage to the environment, with the term “Environmental Impact” defined in Resolution CONAMA 01/1986, (Brasil, 1986). Specific legislation for the preservation of natural underground caves; Resolution CONAMA 347/2004 (MMA, 2004), and Federal Decree 6,640/2008 (Brasil, 2008), among others, establish another term: “Irreversible Impact”, which occurs when environmental factors or parameters of a cave are affected and do not return to their original condition, within a foreseeable period, after human activity has occurred.

In practice, the authors consider that an irreversible impact on a cave occurs when access by the entrances and/or passageways is blocked by collapse or burial, as in the term “terminal breakdown” of White (2012). This concept is also extended in case of a total collapse of the cave or any of its spans, and if there is some visible serious structural instability inside the cave indicating imminent collapse.

Assisted elimination projects on caves
In a small number of instances, if off-sets or other compensation is provided, Brazilian cave legislation allows for cave elimination to occur. These cases provide a unique opportunity for speleological studies in active mining sites. Our project, called the “Assisted Elimination Project”, is one of these, its’ schematic flow is shown in Fig. 1.

Fig. 1. Schematic flow of an assisted elimination project on a natural cave in a mining site.

STUDY AREA LOCATION AND STUDY CAVE
The Carajás region is located in the southeast of State of Pará where there are a set of flat-top hills with steep slopes (plateaus) with an average altitude of 650 m. Shallow caves are developed at the plateau edges as a result of weathering processes. The N4EN Mine is the study area where the Cave N4E_0026 is located (Fig. 2).
Regional geology

The strata in the study area belong to the Grão-Pará Group / Itacaiúnas Supergroup and are located in the Carajás Mineral Province (PMC), in the extreme southeast of the Amazonian Craton (Almeida et al., 1981), north of the South-American Platform (Cordani & Sato, 1999).

The Grão-Pará Group is subdivided into three formations: the basal Parauapebas Formation, the middle Carajás Formation and the upper Igarapé Cigarra Formation (Macambira, 2003).

The Carajás Formation, the main formation in the study area is in contact with the underlying Parauapebas Formation and shows intercalations between the mafic volcanic rocks and the banded iron formation (BIF) (Gibbs & Wirth, 1990). Significant volumes of basic rock occur in the iron rocks, standing out as dykes and other intrusive bodies. BIF is predominant in this formation and occurs as meso and micro banded jaspilite, forming bands of jasper (chert impregnated by microcrystalline hematite) and iron oxides deposited at 2,751 ± 4 Ma (Krymsky et al., 2002).

Local geology

Cave N4E_0026 is located in the lateritic zone. Gonçalves et al. (2016) described three types of weathering horizons in the Carajás plateaus, sometimes associated with the underlying parent rock: A top horizon of lateritic crust, showing detrital portions cemented by iron oxyhydroxides, whose dominant lithotype is detrital lateritic crust (DLC); a middle transition horizon consisting of iron oxyhydroxides and, locally showing low density zones associated with the occurrence of caves, which the dominant lithotype is the lateritic iron formation (LIF), and a bottom saprolite horizon, which can be clayey if it develops on volcanic rocks or of hematitic iron, if it is developed from the jaspilites (Fig. 3).

In the lateritic horizons the major structures strike N-S, NE-SW and NW-SE (Fig. 4).

<table>
<thead>
<tr>
<th>Weathering Profile</th>
<th>Thickness (m)</th>
<th>Summary Description and Dominant Lithotype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateritic Crust</td>
<td>0 to 15</td>
<td>Angular to sub-rounded clasts, poorly selected (cm to m), and matrix/silt-sandy cement of hardened iron oxide/hydroxide, Dominant lithotype: Detrital Lateritic Crust</td>
</tr>
<tr>
<td>Transition Horizon</td>
<td>0 to 20</td>
<td>Bands of intercalated iron oxide/hydroxide, generally porous to cavernous textures. In general, fractured and with intense weathering, Dominant lithotype: Lateritic Iron Formation</td>
</tr>
<tr>
<td>Saprolite</td>
<td>&gt; 20</td>
<td>Material with a high degree of weathering, with presence of relics of the dominant ferrigenous matrix rock (Jaspilite), Dominant lithotype - Friable Hematite</td>
</tr>
</tbody>
</table>

Fig. 3. Brief description of the three typical weathering horizons of Carajás plateaus (modified of Gonçalves et al., 2016).

Fig. 4. Local geology and main structures of the study area.
CAVE N4E_0026

Cave location and morphology

Cave N4E_0026 is one of a group of monitored caves, selected as being representative of the caves in the plateaus of Carajás. The cave is located in upper slope in an irregular rocky escarpment, perpendicular to the main slope of the hillside (Fig. 5).

The cave has four entrances. Entrances 1 and 2 are arched with a height between 1.5 to 3.0 m, allowing access to the central region of the cave, whereas Entrances 3 and 4 are smaller with irregular ceilings, about 1.5 m high, allowing access to the southern sector of the cave. Its dimensions are considered to be slightly larger than the regional average with a map length (concept according to Chabert, 1981) of 162 m, area of 556 m² and volume of 923 m³. Figure 6 shows the floor plan of the cave, its entrances and the morphology of the main spans with their cross sections.

Fig. 5. Location of Cave N4E_0026. The orange spot indicates the cave field.

Fig. 6. Topographic floor plan of Cave N4E_0026, its entrances and the morphology of the main spans with their cross sections (Photos 1-4).

Geostructural map

Cave N4E_0026 is developed in lateritic iron formation (LIF) and detrital lateritic crust (DLC). The LIF shows a higher degree of weathering and geomechanical resistance however small more weathered portions with lesser resistance occur, mainly in the most distal portion to the north of the cave. The weathering and resistance of the DLC shows greater variation due to the heterogeneity of this lithotype.

Banding in the LIF strikes WSW-ENE and dips vertically. Both lithologies are intersected by sub-vertical fractures NNW-SSE and ENE-WSW, in
addition to sub-horizontal fractures. The fractures exhibit irregular and rough surfaces and extend for decimeters to meters. These structures are aligned with the main directions of regional structures in the area (Fig. 7).

**Geomechanical map**

According to Jordá-Bordehore (2016), it is easier to and more efficient to use graphical-empirical approaches and geomechanical classifications to evaluate the stability of a cave. He emphasized that the better the quality of a massif, the better the stability will be. One of the most widely used international classifications of rock quality is the RMR index (Rock Mass Rating) proposed by Bieniawski (1989). This is employed in Figure 8, which shows the geomechanical map of the Cave N4E_0026 (Araújo, 2016).

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Fig. 7. Geostructural map of Cave N4E_0026. A = Lateritic iron formation; B = Detrital lateritic crust; C = Sub-vertical fracture NNW-SSE; and D = Sub-vertical fracture NW-SE.

Fig. 8. Geomechanical map of Cave N4E_0026. A) Class II – Good rock; B) Class III – Fair rock; C) Class IV – Poor rock.
METHODS

The most important processes used in this project were controlled mining followed by detailed speleological and geotechnical studies of the cave taken before mining and after every mining advance.

The Carajás iron mines are open pit mines with benches 15 m high, with some pits reaching a depth of 500 m. The controlled mining advances began 250 m from the cave because Brazilian environmental legislation requires a protective buffer zone of 250 m around caves. Progressive advances by increments of 50 m were used in order to better control the mining process.

The exact distances between the blast and the cave and the time between each 50 m advancement towards the cave, varied greatly because the mine is large and was under regular operation deepening the pit during the research period. It can be said however that each 50m section of advancement took approximately one year between February 2014 and March 2018. The blasting used explosive charge limits and seismic wave mitigation techniques.

Speleological studies were performed 3 months before mining began to define the environmental parameters of the cave in an untouched condition. It is important to note that the Carajás region has well defined rainy (January to May) and dry seasons (August to October) so the beginning of the mining advance in February 2014, allowed the speleological studies to record information during both seasons. These studies all used non-invasive methods to preserve the original physical conditions of the cave including; geostuctural mapping (using visual survey without hammer), geomechanical mapping (using a qualitative parameters approach and quantitative collection of superficial hardness data by strength testing the walls and ceilings employing a Schmidt Sclerometer) and photographic mapping and monitoring. Seismic monitoring also began before operations started to record background effects.

All records were stored in a database before and throughout the project. After the start of mining operations, it was essential that monitoring occurred immediately after each blast until the irreversible impact of the cave.

OBSERVATION AND DISCUSSION

Assisted elimination project on Cave N4E_0026

The project began in February 2014 along with the cave monitoring program, that followed the sequence of physical damage the cave experienced until its collapse and irreversible impact in March 2018. Figure 9 shows an aerial view of the project and the location of the cave on two occasions.

Iron cave breakdown mechanisms

On viewing the progress of physical damage until the final collapse of the study cave and taking advantage of the geostuctural-geomechanical mapping experience on this ferriferous karstic environment near mining sites, four distinct breakdown mechanisms were observed and studied: (i) Fragment downfall, (ii) Block downfall, (iii) Controlling structure reactivation and (iv) Open discontinuity movement (Fig. 10). These four mechanisms can occur individually or associated with others and not in any particular chronological order. This is similar to the classification scheme for rock fragments in karst caves of White (2012), which describes 3 types of fragments: block, slab and chip, which differ in shape and size. The same concept can be used for iron caves, as the Fragment downfall mechanism that produces fragments ranging from friable sandy-clay material to irregular chunks of centimetric dimensions and flat shards when derived from lateritic iron formation, and irregular sub-angular to sub-rounded fragments when derived from detrital lateritic crust.

Fragment downfall mechanism

This mechanism is strongly linked with weathering processes promoted by water in primary and/or secondary discontinuities, or by extended exposure of host rock to high relative humidity and temperature variations inside the cave. The relative humidity is constant at 100% for the vast majority of caves although the shallower the ceiling thickness, the higher these variations. The floors, walls, and ceilings generally have a “patina” of a very common speleothem called “crust” which indicate a long period of exposure.
The geomechanical quality of the rocks inside the cave (about 1.5 m deep into the wall) is almost always less than the quality of the rock in the massif, due to this exposure to humidity that leads to weathering and/or dissolution.

The fragment downfall mechanism usually restricted to small-scale portions of clayey material, hydrated or not, promotes less resistance due to a lack of cohesion. It does clayey material that is preferentially located on cave ceilings and secondarily, on cave walls and “footers”, usually coinciding with the contact between detrital lateritic crust (which usually “supports” the ceiling) and lateritic iron formation (Fig. 10A). The fragment downfall mechanism not produce blocks but fragments, chunks and shards.

**Block downfall mechanism**

This mechanism involves the movement of blocks along discontinuities due to changes in the rock stress. The topographic location of iron caves, generally on rocky cliffs near the top of hills, also facilitates the displacement of blocks near entrances by gravitational loads. This occurs due to the intersection of long and widening discontinuities, which release blocks of rock material by loss of friction. Thus, the shape of the block is determined by the number, size, and orientation of the discontinuities. The poor resistance of the massif in this case is due to the presence of a high number of fractures or other types of discontinuity, even if the constituent rock material is little altered (Fig. 10B).

As with the observations of White (2012), the block downfall mechanism produces much coarse material, like blocks or slabs of tens of centimeters to metrical dimensions (up to 10 m in length), with forms usually in straighter slabs when derived from the lateritic iron formation banding or irregular, sub-angular or sub-rounded, when derived from detrital lateritic crust.

**Controlling structure reactivation mechanism**

This mechanism may occur when cave halls and/or conduits (passages) are developed parallel to and/or following the directions of regional scale structures. These structures are mapped in the cave as discontinuity planes that may be fractures, faults, joints, lithological contacts and/or contacts between lithologies of different geomechanical qualities.

The intersections of these discontinuities generally produce large blocks of tens of meters (usually over 10 m in length), which may become unstable when vibrations produced by nearby operations, such as explosive blasting from mining sites occur.

In the case of intense vibrations, friction loss can induce instability leading to the collapse of large blocks / slabs, mostly from cave ceilings. This mechanism can occur anywhere in the cave, but it is more frequent at cave entrances that often have open discontinuities parallel to the free face of the slope and perpendicular to the cave conduits (Fig. 10C).

Still, adapted to the rock fragments classification of White 2012, it can be affirmed that this mechanism produces more coarse material, like large blocks or slabs of metrical dimensions (above 10 m in length), with slab form straighter when derived from lateritic iron formation banding or irregular, when derived from detrital lateritic crust.

**Open discontinuity movement mechanism**

Open discontinuities are common near the top edge of the ferruginous massifs that host the iron caves. These discontinuities occur as elongated small steps / depressions parallel to the plateau edges on the surface and also inside the caves, particularly near the entrances. These are relief joints and/or tension cracks, non-tectonic structures, and generally, not very penetrative. They are more common in detrital lateritic crust with sub-vertical dips but can also be observed in sub-horizontally dipping crust (Fig. 10D).

Open discontinuities are closely linked to tropical climatic conditions and the laterization processes, marked by intense rains and high temperatures. The progressive opening or closing of these discontinuities occurs by daily and seasonal variations in temperature.
and humidity on the rigid surface of the detrital lateritic crust, together with the lack of support of the entrances due to the headward erosion (suspended ceilings).

This mechanism is linked to the genesis of the caves and to the geomorphological aspects of landscape modeling, with deepening of the valleys and regression of the reliefs. The detrital lateritic crust has a reptile behavior, that from a nearby explosive blasting, the produced seismic waves vibration can spread along the surface until reaching the free face of the rocky massif with the amplitude tending to be maximum, being able to favor the movement of these discontinuities.

**Occurrences of breakdown mechanisms in Cave N4E_0026**

Figure 11 shows the five dates and locations where physical damage occurred in Cave N4E_0026 during the project. For each occurrence, the locations of physical damage (and their mechanisms) were plotted on the geostructural and geomechanical maps (RMR index of Bieniawisk, (1989)). It should be noted that the distance (horizontal straight-line length between the nearest blasting line and the cave), played an important role in this process, with the collapse of the cave and its irreversible impact only occurred very close at 32 m. The relations of explosive charges, blasting depths and techniques, and seismographic registers, will not be discussed in this work.

**Occurrence 1**

Two locations with physical damage were identified as due to during mining operations at a 111 m distance (Fig. 11A). At the first location, the block downfall mechanism was observed in the Central Hall at the ceiling-wall between entrances 2 and 3, with a single fallen block with dimensions of approximately 0.90 x 0.40 x 0.30 m. The lithological domain is of the transition horizon, in the lateritic iron formation lithotype, very weathered, in accordance with the RMR geotechnical classification, which indicates poor rock. The banding at this location is prominent sub-vertical intersecting the sub-horizontal fractures, which contributes to the discretization (well-defined and prone to fail) of blocks (Fig. 12).

At the second location the fragment downfall mechanism was observed in Blocks Hall, where a cluster of centimetric irregular chunks to flat shards have fallen from an area of the ceiling, approximately 0.50 x 0.25 m in lateritic banded iron formation, close to the contact with detrital lateritic crust. Clayey portions and some humidity, indicating low cohesion occur at this locality despite the RMR geomechanical classification identifying good quality rock at this locality (Fig. 13).

![](image)

Fig. 11. Occurrences of physical damages and their mechanisms observed in the Cave N4E_0026 during the assisted elimination project. For each occurrence, the locations of the damaged locations were plotted on geostructural and geomechanical maps. Note the relation of the distance between the mining blast and the cave.
Occurrence 2

The open discontinuity movement mechanism was identified in the Central Hall at the ceiling near the pillar at the Entrance 2, with a 0.6 m opening movement of a sub-horizontal fracture, when the mining operations were at 230 m distance (Fig. 11B).

This location is in a very weathered lateritic iron formation with a clayey matrix with a prominent millimeter to centimeter wide sub-vertical banding, intersecting the sub-horizontal fractures. The massif was classified as good quality rock by the geomechanical mapping (RMR) (Fig. 14).

Fig. 12. Block downfall mechanism in action at the ceiling-wall in Cave N4E_0026 observed in Occurrence 1.

Fig. 14. Open discontinuity movement mechanism in action in the the sub-horizontal ceiling fractures in Cave N4E_0026 observed in Occurrence 2.

Occurrence 3

Two locations with physical damage were identified during mining operations at distance of 48 m (Fig. 11C).

At the first location the block downfall mechanism was observed at the top of the pillar at Entrance 2, in Central Hall where a single block approximately 1.30 x 0.50 x 0.20 m had fallen. The host rock there is transition horizon, in weathered, low-resistant lateritic iron formation, despite the RMR indicating good quality geomechanical conditions at this site. The host rock there is intersected by sub-horizontal and sub-vertical fractures (Fig. 15).

The second location where fragment downfall mechanism occurred was in the ceiling near the pillar of Entrance 2 in the Central Hall, where a cluster of irregular chunks approximately 0.90 x 0.50 m had fallen from part of the ceiling. The host rock there is lateritic iron formation, close to the contact with detrital lateritic crust. At this locality the rock contains clayey portions and some humidity is present, indicating low cohesion. The RMR geomechanical classification for this site indicated good quality rock (Fig. 16).

Fig. 13. Fragment downfall mechanism in action at the ceiling in Cave N4E_0026 observed in Occurrence 1.

Fig. 15. Block downfall mechanism in action at the pillar of the entrance 2 in Cave N4E_0026 observed in Occurrence 3.3

Occurrence 4

Nine locations with physical damage were identified as a result of mining operations at a distance of 67 m (Fig. 11D).

This occurrence identified seven locations with fragment downfall mechanisms and two with block downfall mechanisms. The collapses in the seven locations were likely caused by processes already described, occurring in more weathered, humid and less resistant materials, regardless of the host rock at the site, either lateritic iron formation or detrital lateritic crust. The two locations with the block downfall mechanism behave very similar to those already described, with the potential to produce centimeter to meter sized fragments at the intersection between sub-vertical and sub-horizontal fractures and/or bandings. There was not a good correspondence with geomechanical classification and the extent and type of damage. Only one physical damage occurred in a location where the host rock was considered to be of poor quality.
Occurrence 5 (Irreversible Impact)

Five locations with physical damage were identified as a result of mining operations at a distance of 32 m. (Fig. 11E). The amount of physical damage may have been greater, as for safety reasons the cave was not inspected inside once collapse and obstruction occurred at Entrance 2, resulting in a classic irreversible impact, in accordance with the “terminal breakdown” concept of White (2012).

Of the five locations with physical damage, three were caused by block downfall mechanism and two by controlling structure reactivation.

The three locations with block downfall mechanism behaved similarly to those already described with block breakdown at entrances 1, 3, and 4, producing fallen rectangular blocks, up to 3 m in length, resulting from the intersection of planes of vertical fractures with sub-horizontal bands. Contrary to what was expected, the geotechnical features of all entrances were mapped with good or fair quality, but the close proximity of the blasting operations has to be considered.

There were two locations where controlling structure reactivation mechanisms were observed, the first, in the west sector of the cave, exactly above the Entrance 2 (see the left star in Fig. 11E), was responsible for the irreversible impact. It occurred in the plane of an extensive closed fracture oriented in an NNW-SSE direction, intercepting another extensive fracture oriented in an NE-SW direction defining a large block of metric dimensions approximately 12 x 20 and 5 m thick, with both fractures guiding the development of conduits and halls (Fig. 17).

The geomechanical model showed a boundary between rocks of two distinct rock quality classifications, with good quality in Entrance 2 and fair quality in Central Hall, almost delineating the block that collapsed. This raises the question as to whether geomechanical boundaries can be interpreted as being indicative of structural weaknesses (Fig. 18).

CONCLUSIONS

The induced movement in these fracture planes, due to the proximity of mining operations, led to a block friction loss and structural instability, with its collapse and obstruction of Entrance 2. Figure 19 shows images before and after the irreversible impact.

The second location with controlling structure reactivation mechanism was located in the east sector of the cave (see the right star in Figure 10E), it produced an opening displacement of approximately 30 cm in the preexisting NNW-SSE fracture on the ground at the boundary of the plateau, near entrance 4, in detrital lateritic crust host rock (Fig. 20).
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Fig. 18. Left: Cave N4E_0026 geomechanical map over a drone image. The orthogonal directions of the fractures of collapse delineates a block over Entrance 2, almost coincident with the “geomechanical boundary” between good and fair rock. Right: Collapse caused by the controlling structure reactivation mechanism leading to an irreversible impact of the cave.

Fig. 19. Entrance 2 of Cave N4E_0026 on two occasions. Left: Before the collapse, highlighting both directions of the fractures that defined a collapsed block over Entrance 2. Right: After the collapse, showing the obstruction of Entrance 2 leading to an irreversible impact of the cave.

Fig. 20. Preexisting NNW-SSE fracture at the plateau boundary near the Entrance 4 enlarged some 30 cm by the action of the controlling structure reactivation mechanism leading to an irreversible impact of the cave.

mechanisms occurred independently or associated, without necessarily happening in a chronological order.

As the mining front approached the cave sequentially from 250 to 50 m, there was an increase in physical damage, although restricted to small portions of the cave, due to the action of the more common mechanisms such as fragment and block downfall and open discontinuity movement. Only when the operations were about 30 m distant from the cave, it was possible to observe the friction loss by the action of the controlling structure reactivation mechanism, leading to the collapse of the cave, showing the significance of the variable distance in the process.

The knowledge of local and regional geology, together with the geostructural and geomechanical mapping of the cave, was essential for understanding iron cave breakdown mechanisms. It allowed to verify that the geomechanical classification used (RMR) was not accurate enough for stability assessment alone, considering that some of good rock classifications presented physical damage. Thus, other variables should be included to improve the assessment as for example, thickness and morphology of ceiling, span’s dimension and presence of water.

Still on the subject of geomechanics, there was a coincidence between the main fractures that formed the collapsed block which led to an irreversible impact of the cave, and the “geomechanical boundary” between two distinct rock qualities, raising the possibility that these “boundaries” could also serve as indicators of structural weaknesses.

Finally, the work pioneered and raised for discussion a little explored subject about iron cave breakdown in order to increase technical-scientific support for stability assessment studies and hope to contribute to the harmonious and sustainable coexistence between mining and the speleological heritage.

Fig. 20. Preexisting NNW-SSE fracture at the plateau boundary near the Entrance 4 enlarged some 30 cm by the action of the controlling structure reactivation mechanism.
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