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THE INFLUENCE OF HYPOGENE AND EPIGENE SPELEOGENESIS IN THE EVOLUTION OF THE VAZANTE KARST MINAS GERAIS STATE, BRAZIL

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ABSTRACT

The advanced state of karstification in the metadolomites of the Neoproterozoic Vazante Group has resulted in several geotechnical and hydrogeological problems in an underground zinc mine located in the city of Vazante, state of Minas Gerais, central Brazil, that have prompted detailed hydrogeological studies. The continuity of karstification at depths below the regional base level suggests that hypogenic karstification, driven by migration of fluids from below due to hydrostatic pressure or other sources of energy may be a major player in the area. In this work several tools were used to understand the mechanisms of karstification in the area, focusing on the relationship between karstification and the location of ore bodies.

The influence of both epigene and hypogene processes appears in the Vazante karstic evolution and has a relationship with the cave size. The study demonstrates that the size of voids decreases with depth. The largest cavities (greater than 15 meters) occur above the regional base level. This region is represented by the vadose zone, where epigenic karst processes predominate. Below this elevation, up to 250 meters in depth, a combination of epigene and hypogene processes occurs and the diameter of voids tends to decrease, being usually less than 10 meters. Below 250 meters, the phenomena of karstification are strictly hypogenic and the diameter of voids is limited to less than 5 meters.

INTRODUCTION

The city of Vazante lies in the northwest region of the state of Minas Gerais (Figure 1),in an area of tropical continental climate characterized by rainy summers and dry winters. The average annual temperature is 21.6 °C and average annual rainfall is about 1470 mm, of which 90% is concentrated between the months of October and March.

The region is an interesting example because it allows a comprehensive direct access to the karstic system in several situations, both in the contemporary vadose zone via dozens of dry caves and below the vadose zone via underground tunnels developed for zinc ore extraction. The Vazante mine exploits the largest Brazilian zinc deposit, with a production of 380 thousand tons/year of zinc concentrate. The zinc mineralization (willemite and hemimorphyte) is located in a shear zone oriented in a northeast direction that cuts across a sequence of carbonate and pellitic rocks belonging to the Neo-Proterozoic Vazante Group. The Vazante underground mine probably ranks among the most complex in the world regarding its hydrogeology and associated geotechnical problems. This complexity arises primarily due to the fact that its galleries are developed in carbonates with a high degree of karstification.

Significant voids intercepted by the underground mine at depths of up to 250 meters below the regional base level determined by the Santa Catarina River are not consistent with "classic" epigenic karstification models, which imply dissolution driven by meteoric water recharged on the surface. A borehole survey to explore deeper levels of mineralization reported voids at depths of up to 600 meters below the regional base level. These data motivated the investigation of the problem from the perspective of models that consider the migration of ascending fluids unrelated to precipitation and the movement of surface and subsurface water.

GEOLOGY, GEOMORPHOLOGY AND HYDROGEOLOGY

The local geology comprises four distinct units:

- Morro do Calcario Formation: metadolomites, metadolarenites, stromatolitic metadolomites and breccias.

• Poço Verde Formation: Green to purple slates and marls with layers of pink dolomite.

• Serra do Garrote Formation: carbonaceous phyllites and quartz phyllites.

The Geologic Map (Figure 1) shows the location and geometric setting of these formations, all dipping NW.

Geomorphologically, the region can be described as an elongated depression with nearly 60 km of flat relief on the metadolomites surrounded by hilly relief on the metapelites, phyllites and metamarbles. The focus of this study is an area covered by an extensive colluvial and alluvial overburden whose thickness varies from a few meters to more than a hundred meters, making recognition and assessment of the karstic processes difficult. This overburden masks a well-developed karstic surface where big pinnacles are common and ruiniform relief has been identified by drilling.

For the mining operation to be able to extract willemite ore, it is essential that the operations occur in an already drained environment. Therefore, dewatering is an integral part of the mining operations. Water table drawdown is achieved by intercepting hydraulically conductive geological structures through galleries, allowing the water to drain to a pumping station located at the base of the mine at a depth of 300 meters, and then having it pumped to the surface. Water level drawdown in the rocks of the Morro do Calcário and Poço Verde Formations is influenced by the existence of nine hydrogeological systems. From a hydrogeological point of view, the ore body is an aquitard slowing the underground flow, in spite of the fact that it is located in a fault zone, as observed by Frasa (1990) who described it as an impermeable seal. The schematic cross-section (Figure 2) shows the spatial relationship between these systems and the resulting heterogeneity of the aquifers systems.

KARSTIC FEATURES

Shallow Karstification

Field work was directed towards studying caves and voids, with detailed analysis of the underground morphological features. The Instituto do Carste (Brazilian Karst Research Institute) promoted an exchange of information with the Ukrainian Institute of Speleology and Karstology that facilitated scientific analysis of some major Brazilians caves which potentially displayed hypogene characteristics. Four caves in the region of Vazante were visited, all displaying morphological features generated by hypogene karstification processes, such as feeders, rising wall channels, rising chains of ceiling cupolas and cupolas (Figure 3).

Two caves (Lapa Nova and Lapa Nova II) are related to the mineralized body (aquitard) and are located in the upper footwall aquifer. These caves are very close to each other although their conduits do not have any lateral physical connection at present. Both caves display a 3D maze pattern (Figure 6). The distal northwestern portion of the caves is located approximately 100 m from the mineralized (willemite) zone and in this sector it is possible to observe a large feeder connected with a master passage, which shows morphological characteristics indicative of the genesis by ascending flow, including associated rising wall channels, ceiling half-tubes, and domes. The flow at this level is from northwest to southeast,in the direction of the Santa Catarina River, the present regional base level.

Deep Karstification

A statistical analysis of approximately 300,000 meters of boreholes has been performed in order to obtain data about the depth control of karstification. With respect to the relationship

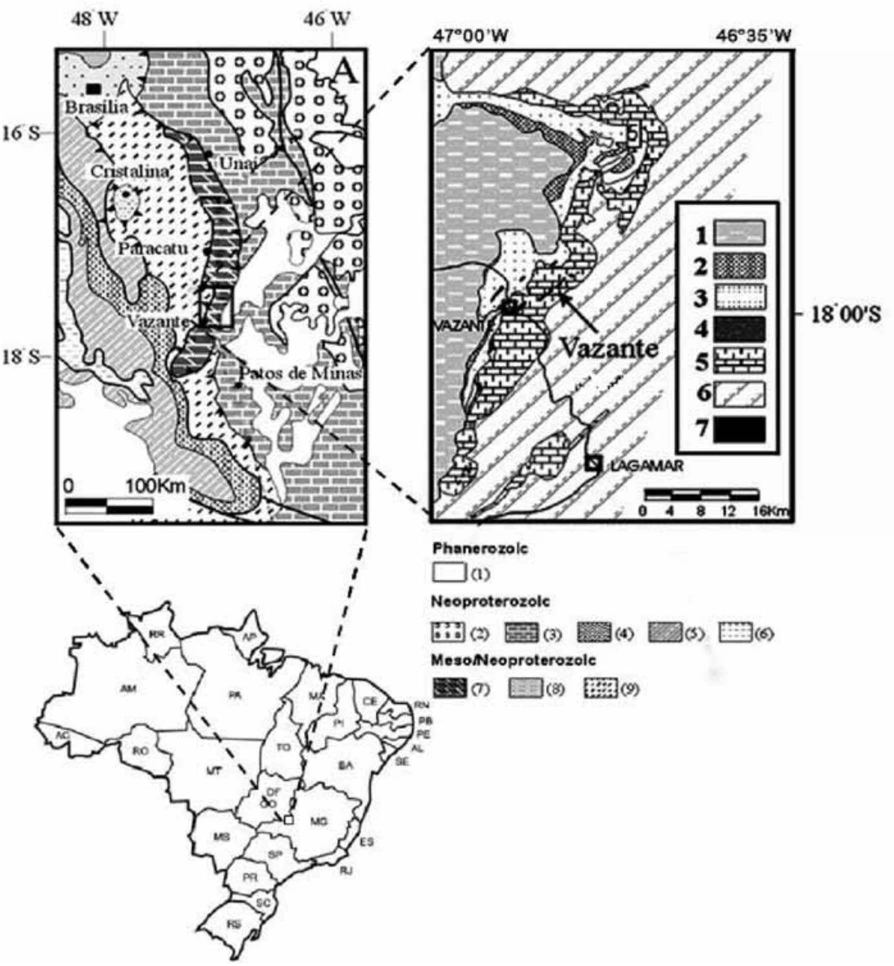
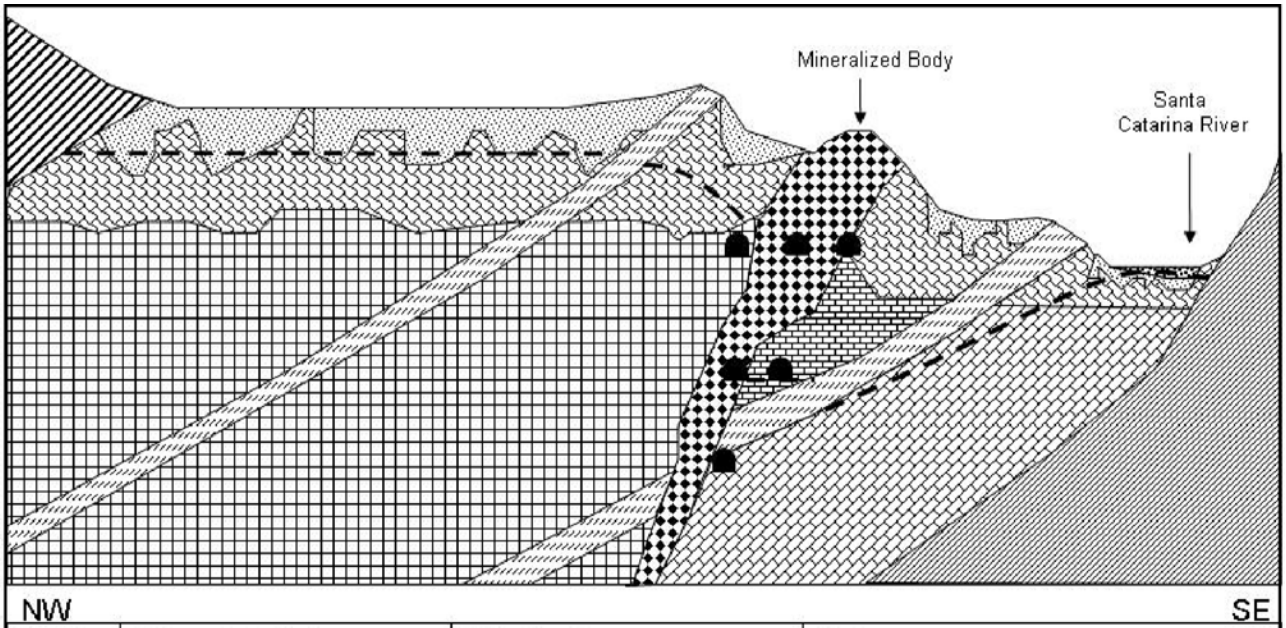


Figure 1. Location and simplified geological context. Modified from Dardenne, 2000. (1) Paracatu Formation (carbon phyllite with quartzite); (2) Serra do Landim Formation (chlorite phyllite); (3) Serra da Lapa Formation (marlstones, quartzites and dolomites); (4) Serra do Velosinho member (carbonaceous marlstones and shales); (5) Morro do Calcário Formation (stromatolitic bioherms, breccias, metadolomites with algal lamination and marstones); (6) Serra do Garrote Formation (carbonaceous slates and marlstones); (7) Pb.



Legend	Hydrogeologic System	Hydrogeologic properties	Litology
	Serra do Garrote Formation	Aquiclude	Phyllite
	Lapa Formation	Aquiclude	Marlstone
	Black phyllite	Aquitard	Black phyllite
	Hangwall	Karstic/Fissured	Pink metadolomite
	Upper Footwall	Karstic/Fissured	Gray metadolomite with intecalation of marlstone.
	Lower Footwall	Karstic/Fissured	Gray marl metadolomite
	Breccia	Fissured Aquitard	Mineralized and breccied pink metadolomite.
	Epikarst	Karstic	Karstic surface metadolomite
	Alluvium	Intergranular Aquifer	Silt and sand
	Colluvium	Aquiclude	Mudstone and siltstone
	Water Level	Tunnel	

Figure 2. Schematic cross-section illustrating the hydrogeologic systems.

between the presence of voids and the lithological types, the borehole data show that 53% of the voids occur in association with hydrothermal breccias (vicinity of the mineralized body-aquitard), 30% in pink metadolomite (hangwall) and 7% associated with gray metadolomite (upper footwall). The analysis also demonstrates that the size of voids decreases with depth (Figure 4). Down to a depth of approximately 150 meters (to an elevation of 600 m above sea level), voids with diameters greater than 15 meters are not uncommon. Up to 300 meters from surface (elevation 450 m), the diameter of voids tend to decrease, being usually less than 10 meters. Below 450 m, the diameter of voids is restricted to less than 5 meters.

The morphology of the cavities can be described as elongated features, with predominantly vertical development, mainly controlled by structures trending northwest and by the banding of the rock. It is common to observe features of rising flow morphologic suite as defined by Klimchouk (2007). Among them the more frequent are cupolas, vertical tubes, rising wall channels, rising chain of cupolas, and outlets,.

GENESIS OF KARSTIFICATION

IPT (2004) correlated groundwater routes and karstification depth in the area with the model of groundwater circulation in karst aquifers proposed by Worthington (1991) that considers the flow depth to be a function of catchment length, dip and strike; it postulates a maximum depth of 170 m (425 m elevation) for the area. However, field data and boreholes show the development of voids below this elevation.

The dissolutional morphological features observed in the caves and in the underground mine show that they are generated thorough karstification by rising flow. In all studied caves, the morphology of conduits indicates genesis by ascending flow but, when a resistant layer is reached, the conduit development follows the dip direction (from NW to SE) until the confining bed is breached and conduits continue at a new upper level. This characteristic is evident in the Lapa Nova Cave, where the master passages have developed preferentially in layers of gray dolomite. The layer that divides the two levels of the cave is a massive pink dolomite with high resistance to flow.

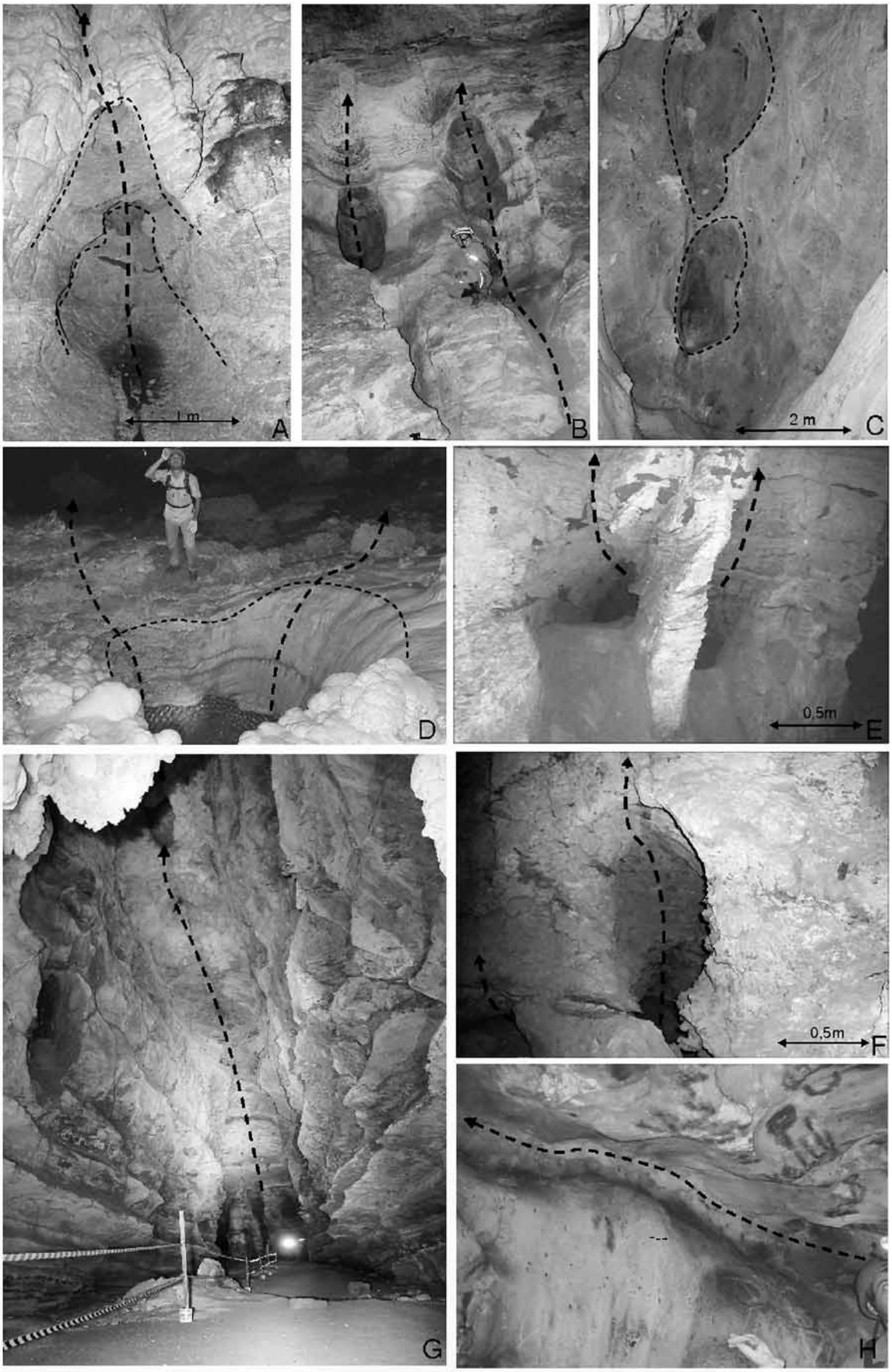


Figure 3. Examples of morphological features generated by hypogene speleogenesis as identified in Vazante caves: A = rising chains of ceiling cupolas; B = side feeder with rising wall channels. C = cupola viewed from below; D = feeder; E, F = side feeders; G = outlet with connecting ceiling channel; H = ceiling channel in epigenic speleothem.

In both Lapa Nova and Lapa Nova II caves, located near the mineralization, the main feeders are situated in the portion nearest to the mineralized body, as can be seen in Figure 6. At least nine caves in the Vazante region display this behaviour, which suggests that their genesis has been influenced by willemite mineralization. According Klimchouk (2007) the condition of confinement is an essential element for development of hypogene speleogenesis, and the mineralized body meets this requirement. At greater depth (elevation 100 m), when the mineralized body disappears, there is connection between the hangingwall and upper footwall aquifers. The difference in hydraulic properties between the two permits groundwater flow from the hangingwall to the upper footwall through the breccia pores, dissolving them and forming the voids currently observed in the underground mine. Figure 7 show a schematic cross-section illustrating this model.

The activity of epigenic karst processes is also observed in the region. All visited caves are presently in the vadose zone, and display characteristics of later epigenic overprinting such as recent sediment filling and surface water invasion.

The influence of epigene and hypogene processes is also illustrated in schematic cross-section in Figure 7. The largest cavities occur above the regional base level, in the vadose zone where epigenic karst processes predominate. However, we have to bear in mind that at least some of these cavities are likely to be hypogenic in origin, relict with regard to the current vadose conditions. Below this elevation, down to 250 meters in depth, a combination of epigene and hypogene processes occurs, previously analysed by IPT (2004) with the groundwater circulation model of Worthington (1991). This region corresponds to the epikarst described by Frasa (1991) as a weathered mantle. Below the elevation

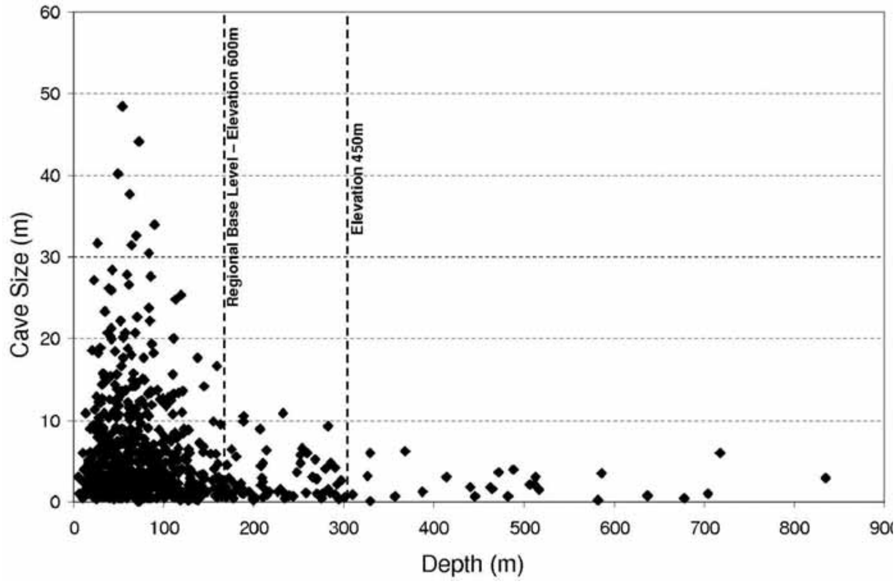


Figure 4. Relationship between size and depth of occurrence of cavities.

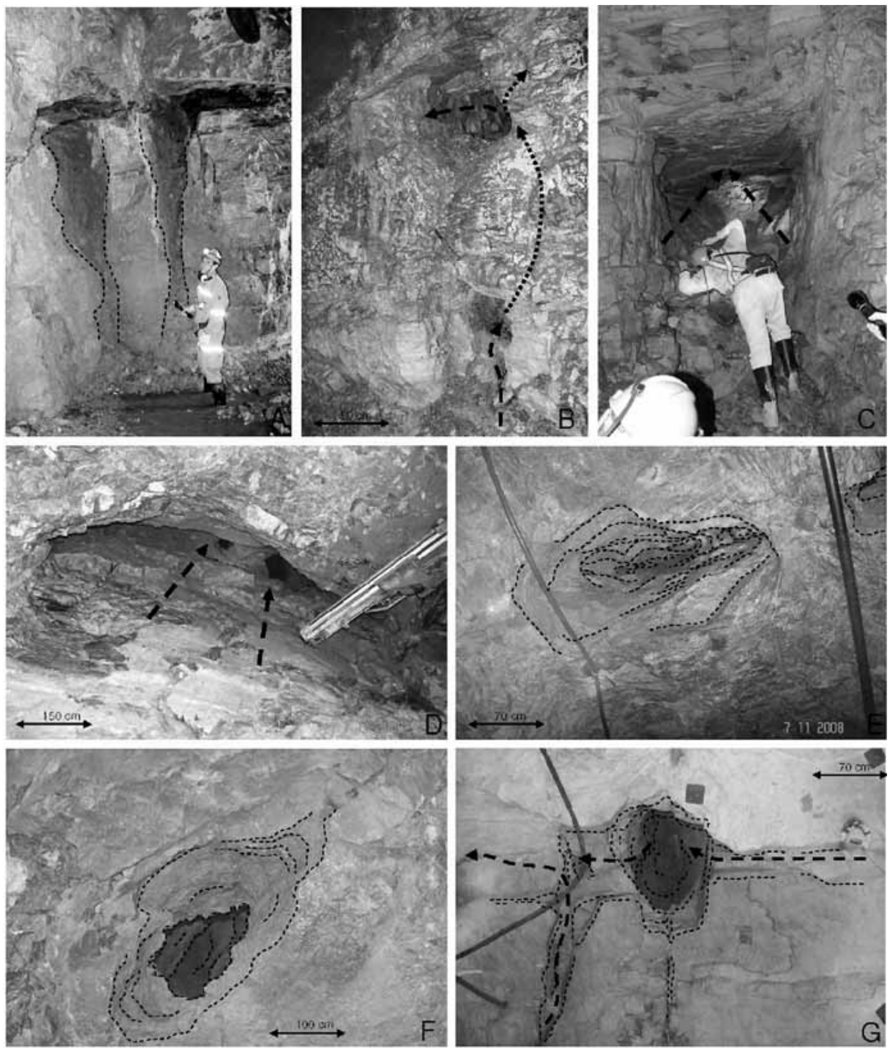


Figure 5. Examples of morphological features generated by hypogene speleogenesis as identified in Vazante underground mine: A = vertical tubes; B = vertical passage formed by ascending flow. When a resistant layer is reached (phyllite in this case) the conduit develops following the dip direction; C = outlet; D = outlets viewed from below; E, F = outlets in cupolas and domepits; G = cupola and rising wall channels viewed from below.

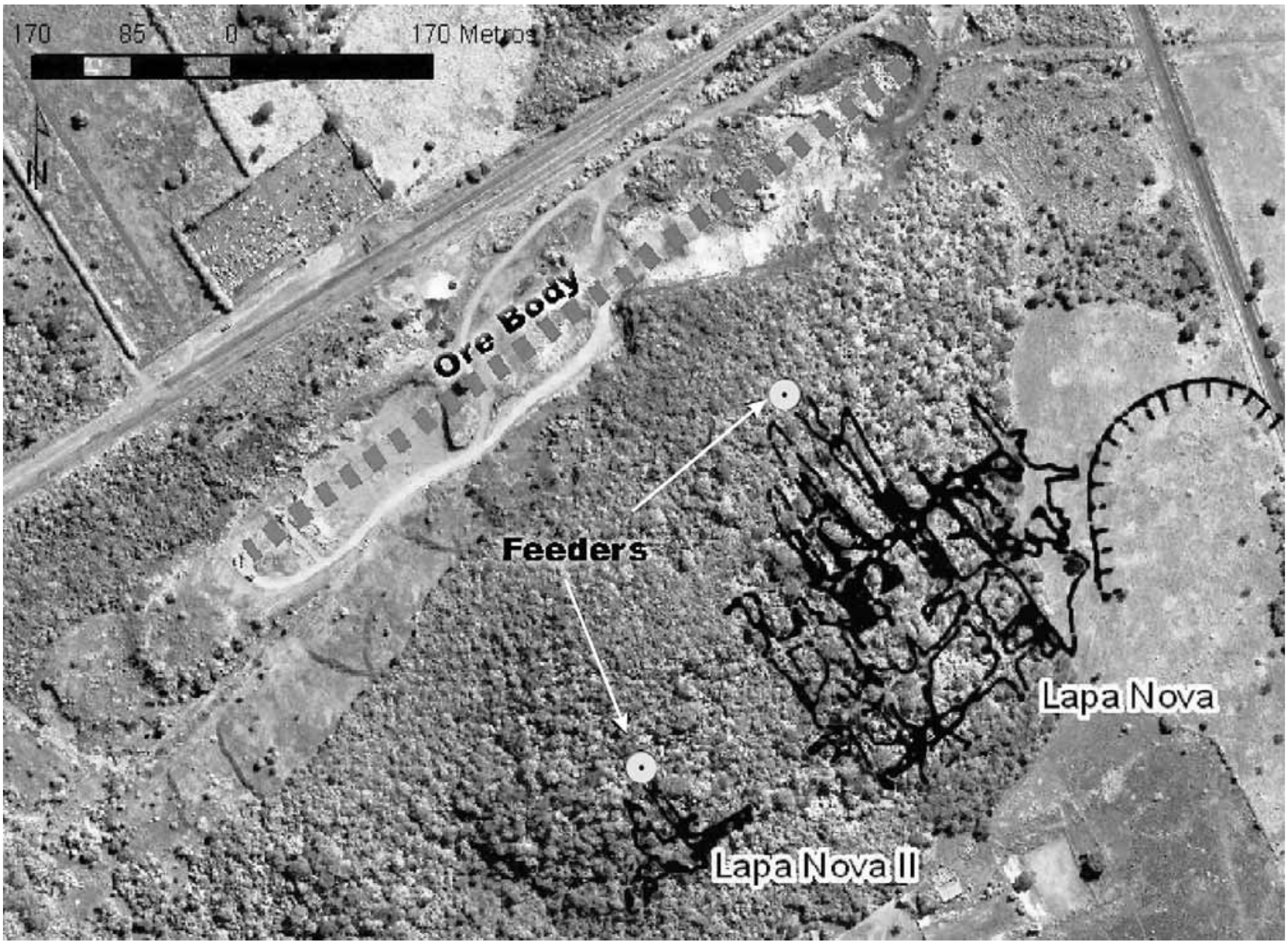


Figure 6. Spatial relationship between the caves (Lapa Nova and Lapa Nova II) and the ore body. The light-grey spots locate the main feeders.

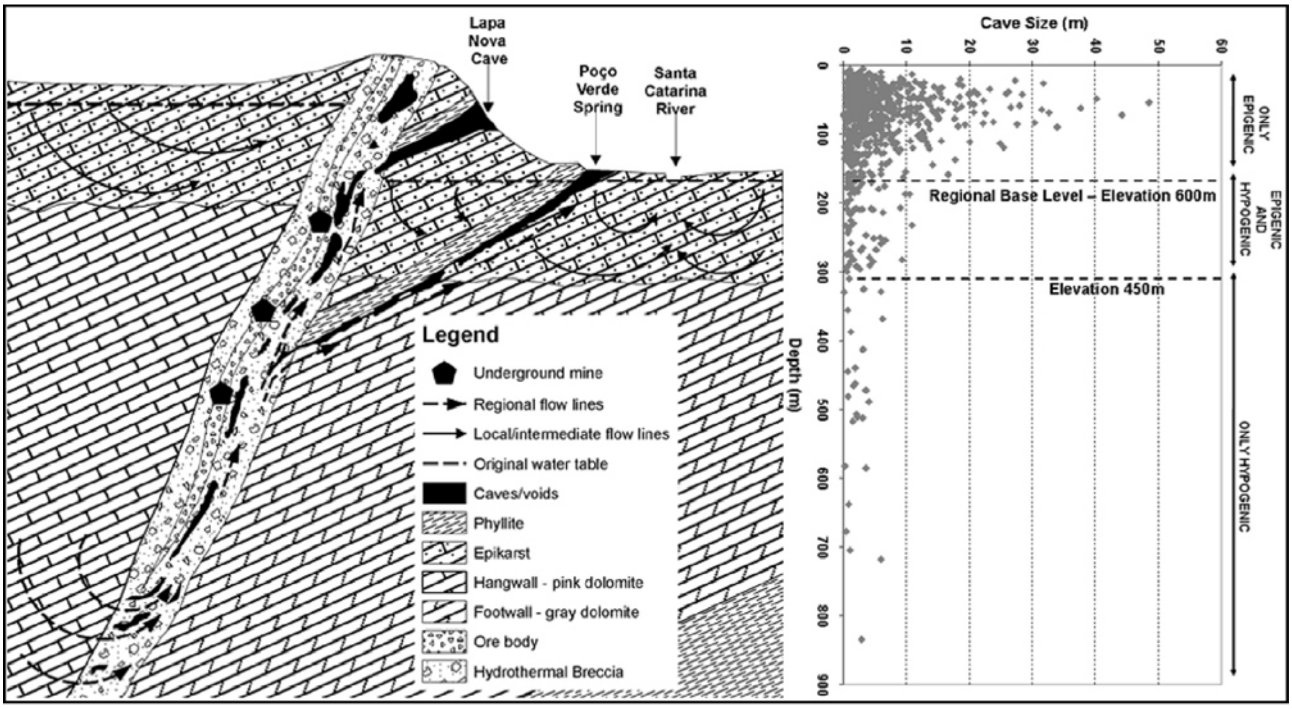


Figure 7. Model for the Vazante karstic system. The graph on the right side relates size versus depth of occurrence of cavities.

Table 1
Summary of the three depth regions influenced by different flow systems.

Elevation	Speleogenic model (contemporary processes)	Flow type	Void size	Example of endokarstic features
From surface to elevation of 600 m (vadose zone)	Only epigenic, overprinted onto relict hypogenic cavities	Descending flow fed by precipitation	> 15 m	Lapa Nova Cave
From elevation of 600 m to elevation of 450 m	Epigenic and hypogenic	Phreatic (local ground water system) interacting with deep ascending flow.	Between 15 m and 10 m	Poço Verde Spring
Below 450 m elevation	Only hypogenic	Ascending flow	< 5 m	Voids intercepted by underground mine.

450 meters, the phenomena of karstification are strictly hypogenic.

At greater depths (below 450 m) hypogene processes alone are responsible for the generation of voids. Following surface denudation, these voids will tend to become shallower in relation to the surface. At elevations around 450 meters (still 250 meters below the regional base level), hypogene features become subject to phreatic (local ground water system) processes. In this phase both hypogene and epigene phenomena coexist, which tends to accelerate the development of caves due to mixing with more aggressive meteoric water. The karst springs, Poço Verde, Poço das Piranhas e Sucuri, are features associated with this system. After reaching the vadose zone, the caves will be subject only to epigenic overprint. Table 1 summarizes the information presented.

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