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Characterization of Bandeira Sedimentary Basin on Serra do Tamanduá, Northeastern Region of Quadrilátero Ferrífero, Minas Gerais, Brazil

Ana Paula de Campos Daher[1]*, Gabriel Jubé Uhlein[2], Júlia Mattioli[3,4]

Abstract
The Quadrilátero Ferrífero (QF) is a globally known region for its world-class metallic deposits. Although its Precambrian units have been vastly studied since the 1960s due to economic importance, the Cenozoic geological record represents an upcoming subject of interest. The occurrence of Cenozoic sedimentary deposits has been noticed since the end of the 19th century, but most of them are not yet fully characterized. This paper brings a complete description, mapping, 3D modeling, and simulations of the sedimentary deposit named Bandeira Basin, Serra do Tamanduá, QF. Based on field data, such as mapping and drill core database analysis, three drill cores were selected for further investigation and detailed description. The Bandeira Basin can be characterized and subdivided into three units: Unit A: found only in the southeast area and shows exclusively sediments from the Nova Lima Group; Unit B: intermediate unit that occurs in central and southeast areas, with Rio das Velhas Supergroup as a possible source of the sedimentary material; and Unit C: occurs at the top, and it is essentially colluvial deposits from Minas Supergroup units. The contacts between units are abrupt or erosive, recording successive deposition stages. The basin is thicker on its central and southwest ends and thinner on the east and north, where part of the basement outcrops. Cenozoic tectonic events were probably active in this area, controlling the sedimentary processes, with the NW-SE and NE-SW lineaments reactivated, triggering sediment deposition and migration to the deepest spot of the basin. These sediments were 3D modeled in Leapfrog Geo, the visualization of any given region of interest, in the modeled scale. This methodology allowed an assertive characterization of sedimentary filling and could be applied to other basins. This comprehension is important because these sediments are used indirectly or directly in civil projects.

KEYWORDS: Cenozoic; Colluvial deposits; Gandarela Syncline; neotectonics.

INTRODUCTION

Quadrilátero Ferrífero (QF) is a major interest region due to the world-class deposits of metallic ores, such as gold and iron, located in Minas Gerais State, southeastern Brazil. Due to its importance, extensive research on mineralized rocks and Precambrian host rocks has been performed, providing information on lithostratigraphic, structural, and ore-forming relationships (Dorr 1969, Lobato *et al.* 2005, Farina *et al.* 2016).

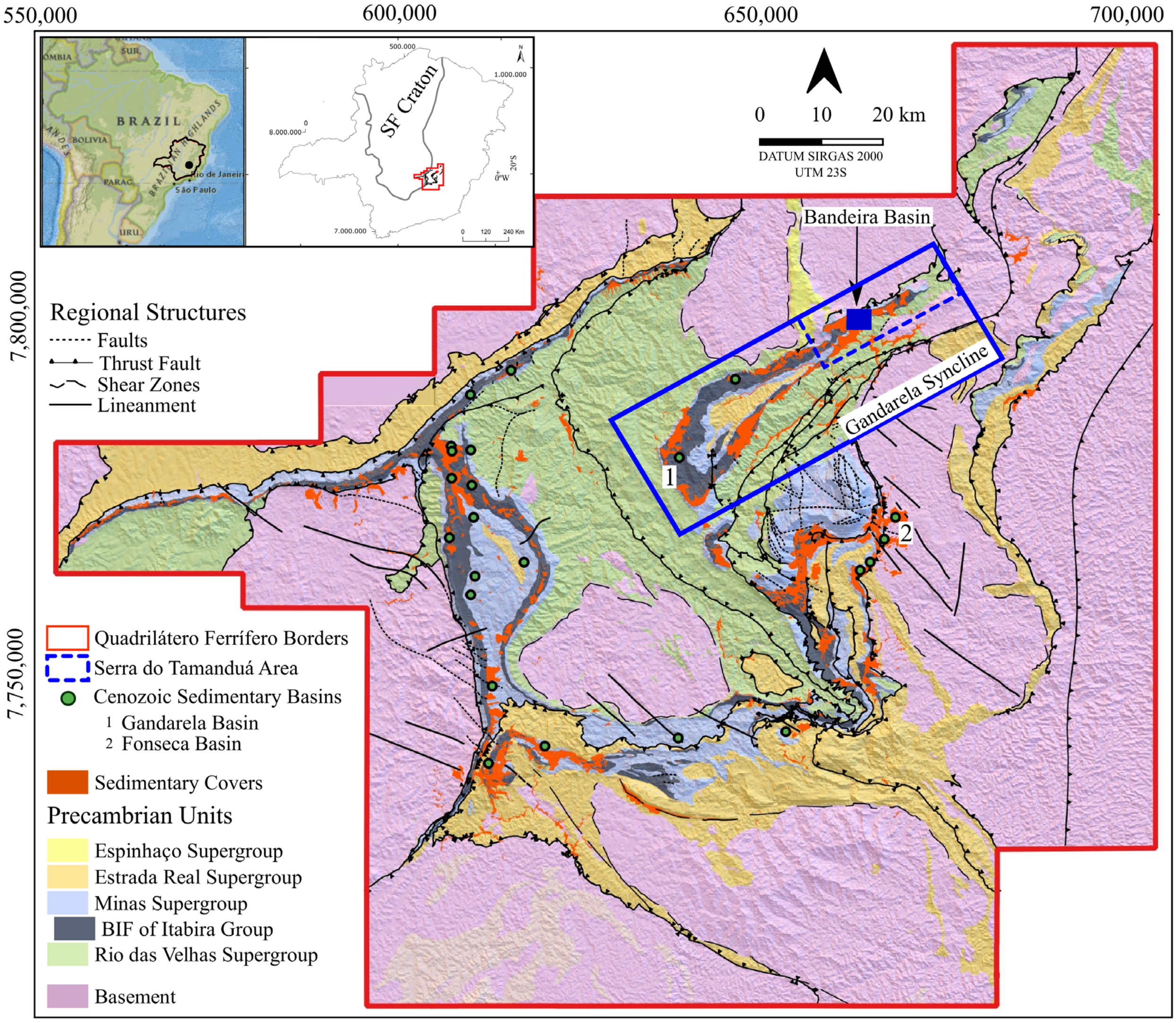
Although the main focus since the late 1960s has been on the ore-forming rocks, Cenozoic sedimentary basins also occurred in the region (Castro and Varajão 2020, Varajão *et al.* 2020) but have not been fully characterized, and with some exemption (*e.g.*, Gandarela and Fonseca Basins; Maizatto 2001), the Cenozoic basins are usually simply described as lateritic soils or lateritic covers. These units are important not only to determine the pedogenetic, morphologic, and erosive comprehension of Cenozoic processes but also to constrain the characteristics of these sediments, because roads, civil constructions, and mining infrastructure are often built over these sediments or using them as material source. Therefore, understanding these materials and their characteristics brings scientific, but also practical benefits.

This paper aims to synthesize the main studies on the Cenozoic deposits of the QF and to bring a detailed and complete description of sedimentary facies, and their contacts, thickness, and 3D arrangement from Bandeira Basin, which is located at Serra do Tamanduá, the northeastern portion of Gandarela Syncline, QF.

GEOLOGICAL BACKGROUND

The QF is a 12,000 km^2 region, on the southeast portion of the São Francisco Craton (Fig. 1; Alkmim 2004, Endo *et al.* 2020). Its name is referred to one of the most significant iron occurrences in the world. It has been studied since the 1960s and has become one of the most detailed studied regions in Brazil. The scientific research began with a partnership between the United States Geologic Survey and Departamento Nacional da Produção Mineral. The result of this partnership was a paper

[1]Universidade Federal de Minas Gerais, Programa de Pós-Graduação em Geologia – Belo Horizonte (MG), Brazil. E-mail: anap.daher@gmail.com
[2]Universidade Federal de Minas Gerais, Instituto de Geociências, Departamento de Geologia – Belo Horizonte (MG), Brazil. E-mail: guhlein@ufmg.br
[3]Université du Québec à Montréal, Earth and Atmospheric Sciences Department – Montreal (QC), Canadá. E-mail: julia.mattioli8@gmail.com
[4]GEOTOP – Montreal (QC), Canadá.
*Corresponding author



SF: São Francisco Craton.

Source: modified from Endo *et al.* (2019, 2020).

Figure 1. Geological map of the main units in Quadrilátero Ferrífero, Minas Gerais, Brazil.

that brings a synthesis of the unique and complex lithostructural settings of QF (Dorr 1969).

The basement consists of granite and gneissic rocks, mainly Archean, ranging to Paleoproterozoic, forming a nucleus all over the QF (Farina *et al.* 2015). Overlaying, in tectonic contact these rocks, the Rio das Velhas Supergroup is an Archean greenstone belt that consists of metasedimentary and metavolcanic rocks and hosts the main gold deposits in the region (Baltazar and Zuchetti 2007, Baltazar and Lobato 2020).

The Minas Supergroup consists of metasedimentary rocks from Siderian, which recover the greenstone belt. Its base consists of siliciclastic units (Caraça Group — Dorr 1969; Nunes 2016), with quartzites and micaceous phyllites. The intermediate layers (Itabira Group — Dorr 1969) consist mainly of metasedimentary chemical units (dolomitic bodies and ferruginous chert) and schists. Itabira Group hosts almost all the iron deposits of QF. The top of the Minas Supergroup is mainly dominated by siliciclastic units (Dorr 1969, Dutra 2017), intercalated with ferruginous quartzite, carbonaceous and sericite phyllites, micaceous schists, and metabreccias (Piracicaba Group). These are classically interpreted as marine platform environments to marine slopes (Dorr 1969).

The Estrada Real Supergroup (Endo *et al.* 2020) are Riacian rocks deposited in restricted basins. It is subdivided into Sabará Group (Almeida *et al.* 2005) and Itacolomi Group (Machado *et al.* 1996).

Cenozoic deposits as lateritic and sedimentary covers occur spread in QF, on top of Archean and Proterozoic units. Those were identified with a wide variety of thicknesses and heterogeneous sedimentary records.

The QF has a complex evolution, with multistage sedimentation and deformation processes. The pre-Cambrian geological units and structural records are well documented, as well as the evolution processes that occurred during Archean and Proterozoic (Farina *et al.* 2016). However, the Cenozoic sedimentary records, its characteristics, and genesis processes are not yet fully understood. The detailed studies were performed relying on good outcrops and, in some cases, drill hole data.

Previous studies focused on Gandarela and Fonseca Basin suggested that the early stages of sedimentary units are lacustrine and fluvial records, and the upper units are the result of debris flow, found to be Eocene to Oligocene in age, based on palynological data (Maizatto 2001). Lipski's (2002) findings show the close relationship between the reactivation of pre-Cambrian basement structures to the now-formed basins, presenting active neotectonics activity in QF.

Serra do Tamanduá (Fig. 1) consists mainly of the Rio das Velhas Supergroup and the Minas Supergroup lithologies, covered by lateritic deposits spread along the ridge (Lobato *et al.* 2005, Endo *et al.* 2019). The focus of this paper is Bandeira Basin, one of these basins along the Serra do Tamanduá.

STATE OF THE ART: CENOZOIC SEDIMENTARY BASINS IN QUADRILÁTERO FERRÍFERO

Dorr (1969) described these recent sedimentary covers as mudstone, laterite, and canga, and their genesis processes. In this paper, the Fonseca Basin was briefly described as a sedimentary basin, as previously described by Gorceix (1894 *apud* Dorr 1969).

The aspects discussed are mostly related to mudstone, often described as a massive clayey material, non-plastic, and associated with the filling of ancient morphological features such as valleys. They are more commonly spotted in the western portion of the QF, on the Moeda e Dom Bosco synclines.

This author discusses some possibilities for the origin of these units. Dorr (1969) highlights that these covers do not have transitional contact with the underlying saprolite material and are not intercepted by younger intrusive rocks, which demonstrates that they are the youngest units in this area. Although some outcrops of the lateritic covers present deformational structures such as joints, few or no sedimentary structures are seen.

Dorr (1969) emphasizes that horizons with yellow, white, and red colors are the result of iron oxide leaching. In conclusion, the author lists the following possible explanation, although indicates it clearly as an open question:

- Weathering product of dolomite (Guild 1957 *apud* Dorr 1969);
- Laterization of siliceous ferruginous dolomite (Pomerene 1964 *apud* Dorr 1969);
- Reworked ocherous itabirite (Gair 1962 *apud* Dorr 1969);
- Windblown volcanic ash filling Cenozoic valleys (Dorr 1969).

Dorr (1969) also distinguishes *in situ* materials, such as duricrusts, mostly known as canga and laterite. The paper indicates that laterite is a non-cemented material that forms as a result of debris, talus, and ferruginous soil of iron formation, while the canga-cemented material is rich in iron oxides and hydroxides. There are three recognized types of canga:

- Normal: composed of lithic fragments, such as hematite, itabirite, quartzite, and phyllite, cemented by iron and aluminum oxide and hydroxide;
- Chemical: poor in lithic fragments but rich in limonite;
- Rich: composed of hematite fragments cemented by limonite.

Most recent papers (*e.g.,* Spier *et al.* 2018) treat canga as a rock-like material, because its cemented matrix, usually with ferruginous oxides and hydroxides, makes it as resistant as rock material. The occurrence of canga is usually described in surface exposures, but there are some occurrences in the subsurface as well, as in the Águas Claras Mine, in the northern part of the QF.

This kind of setting is described by Spier *et al.* (2018), which shows a canga layering over itabirites, with both *in situ* and normal canga. Overlying this normal canga, it is described as a brick-red material, which is a red massive sedimentary clay, with dozens of meters of thickness. This material is covered again by another normal canga layer. These authors investigated the age of these reference units, discovering that the upper layer is 26 Ma and the lower layer is 41 Ma, which is a very important result that indicates a complex history of deposition, pedogenetic, and tectonic Cenozoic events.

Papers published since the 1990s described sedimentary basins individually. Using different approaches, they often aim to explain the genesis processes of the geological setting, *e.g.,* Morro do Caxambu deposit (Santos and Varajão 2004), Gongo Soco Formation (Saadi *et al.* 1992), and other examples (Lipski 2002). The most complete studies consist in the characterization of Fonseca and Gandarela's Basin, both located at the eastern portion of QF (Fig. 1). The sedimentary occurrences units range from Paleogene to Neogene (Lobato *et al.* 2005).

The Fonseca Basin is a 32 km^2 area with sediments as thick as 35 m, over a granite-gneissic basement. It is completely described from outcropping sediments, with the most outstanding palynological as well as macrofauna records. It consists of two units: Fonseca Formation is mainly fluvial unit at the base, and the upper unit is Chapada de Canga Formation, formed by alluvial fan ferruginous cemented conglomerates (Maizatto 2001, Castro and Varajão 2020).

The Gandarela Basin consists of a 9 km^2 in area, at least 125 m in thickness characterized by 15 drill hole core descriptions. Seven sedimentary facies with the most complete palynological record of the southeastern continental Brazilian basins were described, and two facies association: the first, lacustrine, partially covered by the second, a debris flow controlled. Its basal contact is not intercepted by the drill hole described, but it is most likely units of the Minas Supergroup (Maizatto 2001, Castro and Varajão 2020).

Castro and Varajão (2020) present one of the most recent papers to address the age of these sediments and establish an age hierarchy among the known recent deposits. The authors suggest that the previously generic terrigenous deposits can be detailed from the sedimentary facies' perspective.

The lack of details for these occurrences can be explained by the shortage of outcrops. Also, the outcrops alone do not always show the accurate dimension of the deposit, which having drill hole information can be very enlightening.

The approach adopted by Castro and Varajão (2020), Varajão *et al.* (2020), and previously by Santos e Varajão (2004) is based on the macro and micro characteristics of the sediments. The more recent work shows five main facies that do not necessarily occur in all the recent deposits and are discontinuous both laterally and vertically. The facies are as follows:

- Fragmentary facies (F): immature sediments in a clayey matrix, reddish brown to dark red, composed of angular to subrounded lithic fragments of phyllite, quartzite, hematite, and itabirite, that range from millimeters to decimeters in diameter;
- Nodular facies (N): massive sediments in a silt clay red matrix, and rich in yellow, white, red, and pink stains, lithic fragments, and nodules. Commonly, these are associated with other sedimentary facies such as fragmentary and quartz sand clay facies;
- Quartz sand clay (AQA): the sediments are in a variety of colors such as red to white, with a clayey to silty matrix. It has a high percentage of quartz, white mica, heavy minerals, and lithic fragments;
- Massive clay (AM): massive, rich in fine to coarse-grained quartz and ferruginous millimetric nodules;
- Conglomerate (C): sediments are composed of lithic fragments of phyllite, ferruginous quartzite, and vein quartz, subangled to subrounded, in a clay sandy matrix, that generally occurs overlying other sedimentary facies, suggesting paleochannel records.

These Cenozoic sedimentary units are closely related to graben and horst structures, caused by late tectonics in South American passive margin (Varajão *et al.* 2020). These authors resume the perspective presented in Lipski (2002) and show further details of five selected sedimentary deposits in Moeda Syncline.

The Cenozoic strain state in South America is mainly responsible for generating or reactivating structures of the basement, triggering sedimentary processes (Lipski 2002). Therefore, graben-like features caused sediments to be concentrated in basins. Those unconsolidated sediments were later deformed by brittle processes. Small-scale faults and fracturing surfaces are formed due to compressional and extensional punctual strain. The sedimentary features described by Lipski (2002), focusing on structural analysis, show the close relationship between the reactivation of pre-Cambrian basement structures to the now-formed basins.

METHODS

For the description of Bandeira Basin, it was used a multistage method, with bibliographic research, field mapping, and *in situ* investigation. The macro characteristics of the sediments are presented with a synthesis of the field observations, showing the map and the main features of key samples.

This investigation was initiated with an extensive bibliographic study, using local and regional maps such as Lobato *et al.* (2005; 1:50,000) and Endo *et al.* (2019, 1:150,000), highlighting differences and similarities in the contacts and description of the sediments. It was used as a base for a field survey made to check the units that outcrop in the study area, which resulted in a local detailed field map.

A total of 320 m of drill holes were described, and they are identified as MAD-FSE0001, MAD-FSE0002, and MAD-FSE0003. The profile of these drill holes is shown later in this article. The drill hole samples set the pattern to lithofacies references and codes that are used from this point on.

A database of 35 drill holes, in a total of 4250 m of core samples, was provided and analyzed, in addition to the three drill holes described. All data were carefully checked in the way that it was possible to use this information afterward in the tridimensional software. The database was uneven, due to multiple drill hole surveys and descriptions of samples through time. It identified the need to have a unified assignment for all the drill hole descriptions, so this work also adapted the descriptions given so that they would match all databases available.

In synthesis, it was used a database of 38 drill holes, in total. Three of these were described in detail by the authors, while the rest had their descriptions given by the mining company and had their data compiled and treated using the three detailed drill holes as reference.

The following steps have been performed:
- Assign classification to each described interval;
- Reclassification of selected intervals to bring compatibility to all the databases;
- Comparison between the database and drill hole photos;
- Final validation and creation of the database in the format of importing to the tridimensional modeling.

The sedimentary facies classification was done with a modified classification from Castro and Varajão (2020). Considering the three cores described, an individual profile of each drill hole was drawn, so the material found could be grouped on sedimentary facies, using nomenclature based on Miall (1978) and illustrated, showing a correlation in depth and lateral placement. The names of the facies are explained in their descriptions. For those drill holes, samples for petrographic analysis were selected and described under an optic microscope.

All the drill hole data were used to build the tridimensional model with the Leapfrog Geo 2022.1 software, with the mapping results and structural information. To model the basement of the basin, besides the drill hole database, surface and regional mapping provided the necessary information. The format of the basin was modeled considering the following:
- The drill hole information provides unique and punctual information, that, when accessed from the tridimensional point of view, can enlighten significant lateral and vertical distribution of the units;
- Although difficult to track on drill hole samples, the contact relations of the sediments can be modeled from the features that could be described and considering basic sedimentary principles;

The basin geometry can be inferred using information first of the sediments described, but also considering the concept of accommodation space for these sediments. This reference comes from other sedimentary deposits known in QF.

RESULTS

The Bandeira Basin is a sedimentary deposit found in northeastern Serra do Tamanduá (Fig. 1). Its sediments lie over Archean (outcropping in part of the study area) and Proterozoic weathered rock. The sediments of the Bandeira Basin occur over a large area in the Serra do Tamanduá, outcropping in railway and road cuts and as crusts on the floor. It is composed of multiple clayey to sandy sediments, many of which are interbedded with gravel-rich sediments. The simplified geological map, as well as the location of the drill holes, is displayed in Fig. 2.

BANDEIRA BASIN

The sediments outcropping is shown in Fig. 2, as well as part of its basement. The characteristics of every material will be described in stratigraphic order, and illustrated with hand size and microscopic samples in Figs. 3–7.

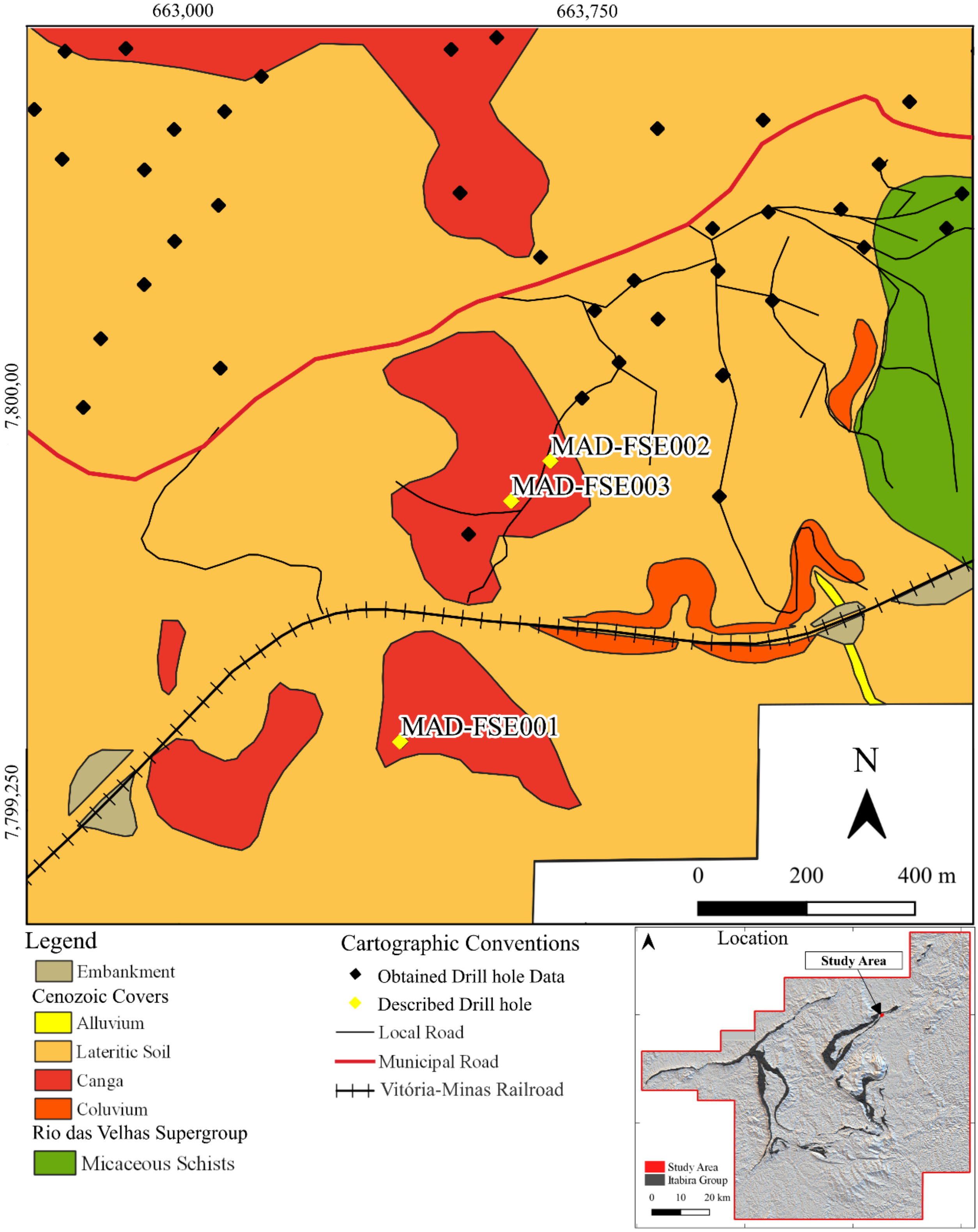


Figure 2. Simplified geological map of the Bandeira basin area highlighting the drill hole database.

Figure 3. (A) White clay, massive; (B) clay with white and ochre massive portions and quartz pebble in small proportion; (C) material with manganiferous vein; (D) pink clay; (E) rounded pebble and cobble conglomerate, of mica schist and lateritic material.

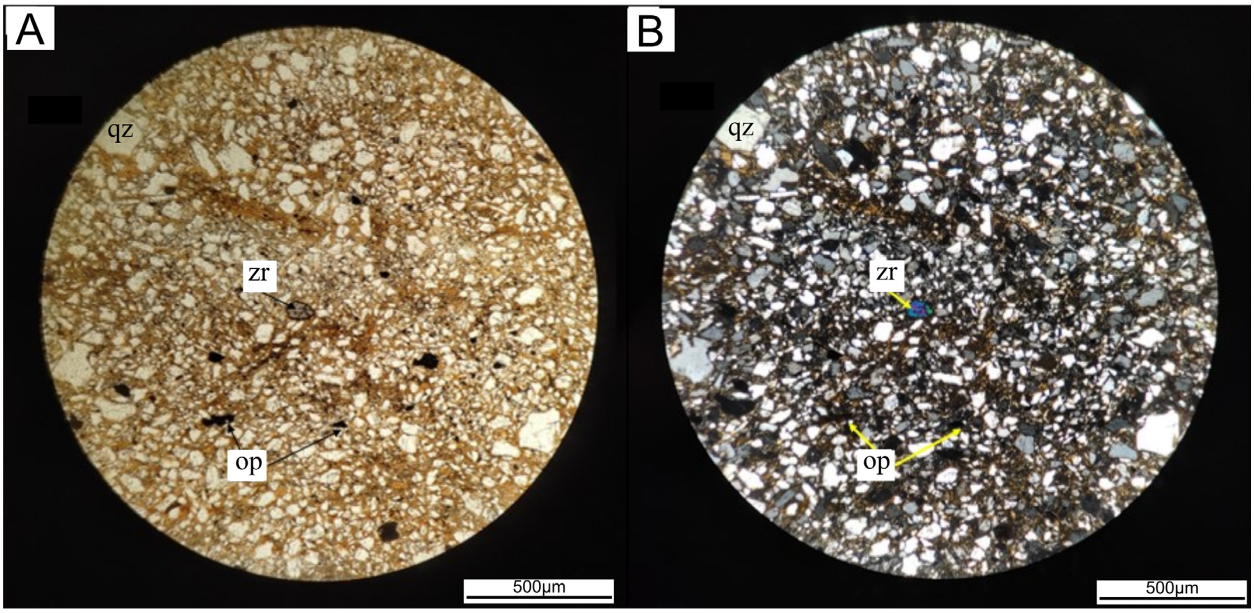


Figure 4. Microphotography of thin section, 10× magnification, of the immature sandy quartzose sediments from MAD-FSE003 (71 m), rich in angular quartz grain (qz), some opaque minerals (op) and rare zircon (zr) (A) under plane-polarized light and (B) under crossed-polarized light.

Mica Phyllite and Quartz Mica Phyllite

In the study area, it is identified altered mica phyllite (red, purple to light yellow saprolite), with no or few schistosities that are parallel to steeply dipping. It has white mica, chlorite, and quartz that vary its content. They are identified as phyllite from the Nova Lima Group, outcropping only in the northeastern portion of the area. Its contact with the Minas Supergroup does not outcrop, although it can be seen as an abrupt contact in some drill hole samples.

Gravel with rounded clasts

Sediments similar to conglomerate were found in the drill hole MAD-FSE0001, and it is clast supported. The lithic fragments are green, yellow, and black, showing high sphericity and rounded to angular shape. It was not observed clast orientation. Its matrix is sandy-silty with clay, with fine- to medium-grained sand (Fig. 3E) Quartz fragments are present in the matrix. The clasts are surrounded by a ferruginous cortex. At the base, it shows a sharp contact with mica phyllite saprolite, while toward the top, the matrix proportion increases progressively turning into a diamict-like sediment.

Organic mud

Organic mud occurs around 75 m in depth. It is composed of black clayey sediment with kaolinite spheres. The top and bottom contact is abrupt. It may have a role as a stratigraphic

Figure 5. (A) Sand clayey matrix, with pebbles of canga and laterite; (B) CGSLith massive clayey matrix, with quartzose and lithic fragments; (C) CGSLim massive colluvium with clay to silty matrix, pebble-sized grain surrounded by goethite and some hematite silt widespread; (D) colluvium with planar bedding, with massive and laminated strata, rich in manganese, hematite, and quartz sand-sized grain and a few lithic fragments.

marker, with the potential to pollen and microfossil content, which further investigation in the thin section shall reveal.

Gravel with angular clasts

Only in drill hole MAD-FSE0001 gravel deposit with about 7 m thick lies over the organic soil and under a horizon of white sediment. It is composed of a clayey matrix with boulders, cobbles, and gravels of sericite phyllite, quartz sericite schist, and quartz vein fragments, white to beige. The clasts are mostly angular to subangular, and some smaller are rounded. These fragments within these deposits show similarities with the weathered mica phyllite (belonging probably to the Rio das Velhas Supergroup) described in the northeastern part of the studied area (Fig. 2).

Clayey and sandy quartzose sediments

These units are heterogeneous interbedded massive clay (Cm) and quartzose sand (Sq) sediments, in which might occur quartzose gravel (Gq). These sediments do not outcrop in the area, but they are described in all three of the drill holes sampled. In the drill hole database provided, they are often simply described as siltstone, with no further details. They have a maximum thickness of 36 m and are thicker on the west and south portions of the study area.

For the most part, it is white, clayey, light, and rich in kaolinite, as shown in Fig. 3A. The claystone is always massive, white to yellow or yellow with white nodules. Locally, nodules are pink and red, as shown in Fig. 3B. In these parts, one might find some gravel or coarse quartzose sand content in sparse points. The grains are high in sphericity, angular to rounded, and immersed in a clayey matrix with few mica grains.

In some depths, the drill hole intercepts layers of massive, light pink, lilac, and purple clayey sediments with white nodules (Fig. 3C). It overlies the rich organic layers at the bottom of this sequence and was only seen in MAD-FSE0001 with 1 m in thickness.

There are several portions in which sandy sediments are found. These are usually 10 cm to a few meters thick, usually white, massive, and quartzose. Locally, a few lithic fragments of ferruginous quartzite and quartz vein may be present. These sandy sediments present some levels with a kaolinite matrix with fine-grained quartz and sparse pebbles of quartzite. This sediment can contain some kaolinitic clay, with medium to coarse grains and some laminae rich in manganese oxide. In the thin section (Fig. 4), these sandy sediments show up to 35% of the clayey matrix, with much of the grains being angular in shape, with magnetite, zircon, and hematite as accessory minerals.

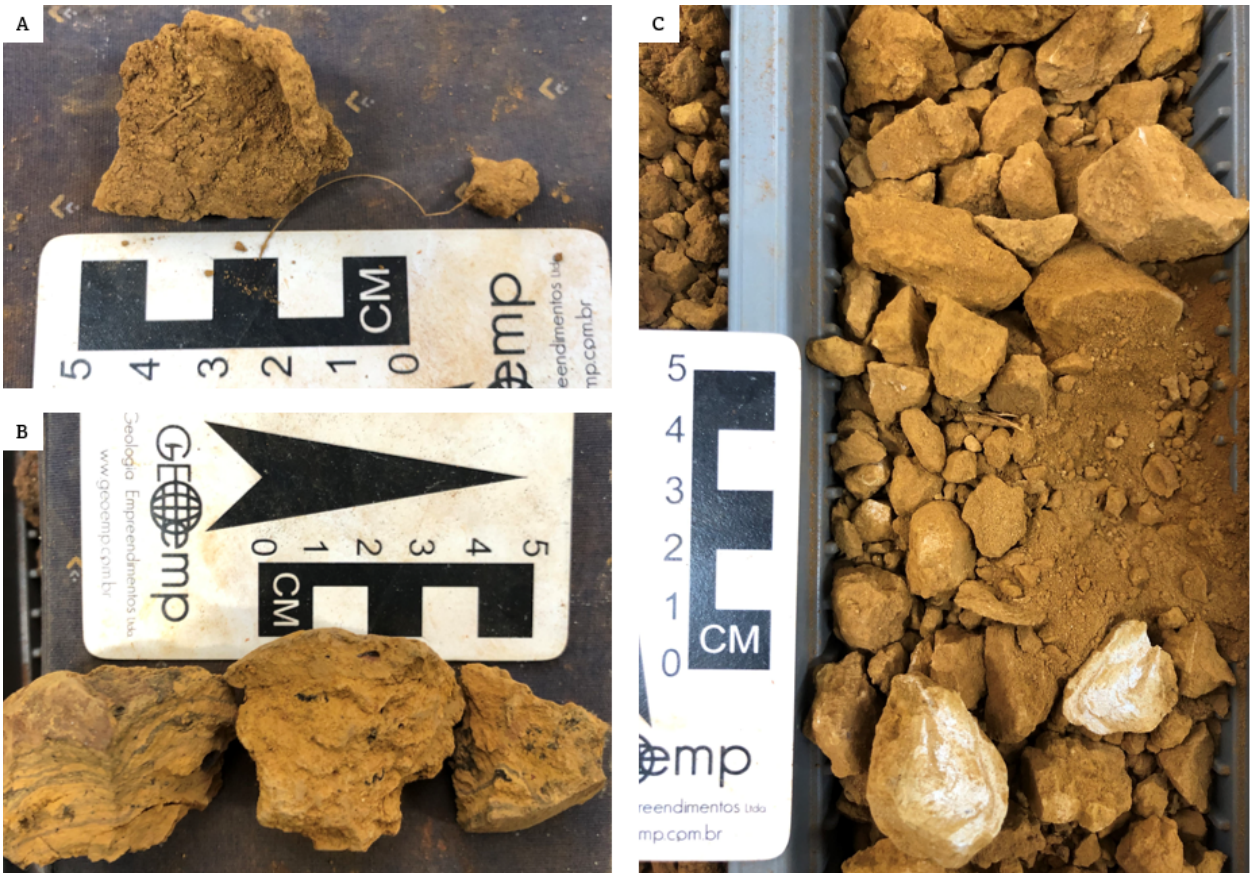


Figure 6. (A) Material rich in thin roots and organic remains; (B) Ochre material with pebble-sized manganiferous nodules; (C) material rich in kaolinitic portions in and with thin roots.

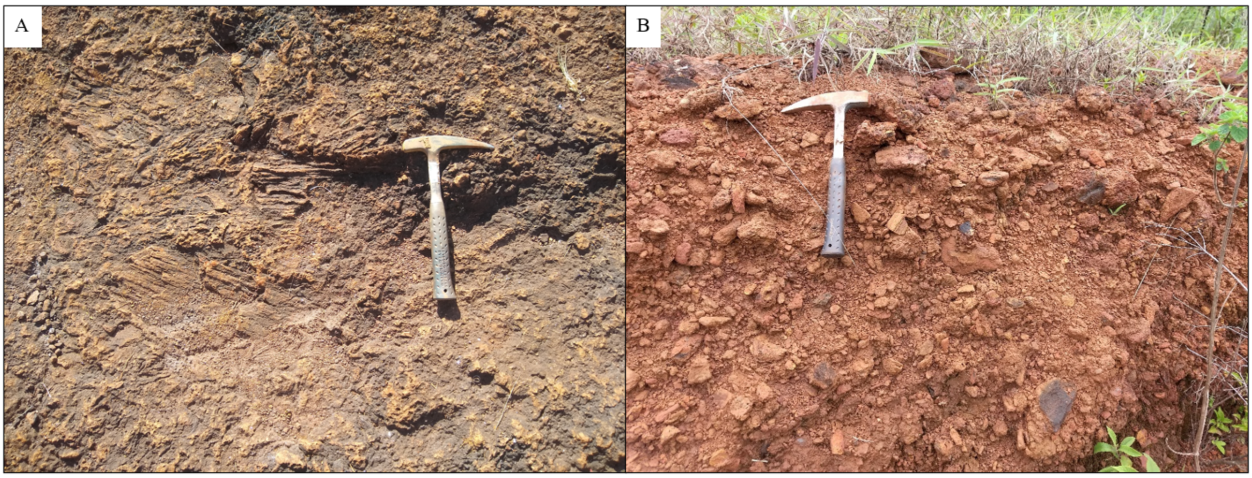


Figure 7. Canga occurrences outcropping as crusts on the floor. (A) Poor in matrix or (B) rich in matrix.

There are some remarkable portions of white to beige clayey sediment rich in manganese oxides. The manganese oxides can be both nodules and filling extensive fractures, millimetric thick, with no structural pattern, although they may often occur parallel to the drill hole axis, as shown in Fig. 3D. These manganese-rich sediments are identified mostly on the bottom of the clayey and sandy sediments, sometimes being a challenge on how to distinguish it from the underlying weathered bedrock. These manganese oxides are more clearly and regularly aligned in millimetric features in a matrix that is rich in iron oxide and hydroxide.

Clay to gravel sediments

This is the most common unit of Bandeira Basin, outcropping in the study area. It can reach 37 m in thickness. It outcrops aside the Vitória-Mina's railroad tracks as a dark brown material with pebble and cobble-sized clasts of itabirite, hematite, and canga immersed in a sandy to clayey matrix. It overlies both the Archean units and the Minas Supergroup, with erosive contact. These sediments form a complex and heterogeneous unit. Its identified facies are as follows:

- Cgshem: Massive, dark brown sediment, with a clay (C) matrix in which there are fine sand (s) to sparse pebble-sized (g) clasts of quartz and hematite (hem). The clasts have low sphericity, and some coarse-sized specular iron oxide grain occurs, as shown in Fig. 5A;
- Cgslith: Sediment rich in clayey to sandy matrix, often red. The clasts are pebble and sparse cobble-sized, with high sphericity, of mica phyllite (gray or silver), itabirite

(mostly with low sphericity), hematite, and milky quartz to crystalline quartz vein (Fig. 5B);
- Cslam: Sediment with interbedded levels of laminated clayey to sandy (s) and clayey (C) massive material. The layers that present parallel bedding structures, as in Fig. 5D, have laminae (lam) of black, sandy, and silty hematite and quartzose grains, laminae of red clayey with high plasticity, and yellow and gray quartzose and micaceous sand. Some of these layers present erosive contact with the other layers;
- Csglim: Yellow to brown material, in which matrix is clay (C) silty to clayey sand, with some massive sandy (s) layers composed of specularite and magnetite (Fig. 5C), with moderate plasticity. This material contains granule to pebble-sized (g) clasts of quartz and lithic fragments, some of them surrounded in goethite or limonite (lim). There are few fragments bigger than 5 cm. Most of the clasts are rounded to subangular, with high sphericity.

Residual soil

It is found in some specific depths a yellow to ocher clayey material (Figs. 6B and 6C) that has a transitional contact to the clay to gravel sediments layers in the bottom and an erosive contact to the material often overlying it. For this contact with the sediments, the soil originates from the sediments themselves. These layers are up to 5 m in thickness and occur in all three drill holes, near 15 m (MAD-FSE003), 22 m (MAD-FSE001), and 35 m (MAD-FSE002). It is clayey, with sparse fine- to medium-grained sand content, with cobbles and some black manganese nodules. These nodules increase in content toward the top, as well as some thin roots and wood small fragments (Fig. 6A).

Canga

The canga is a clast-rich, rock-like ferruginous material (Fig. 7A), with few or no ferruginous matrix. The fragments are usually between 0.5 and 15 cm in diameter, angular to subangular, with a low degree of sphericity, often surrounded by a botryoidal goethite concentric layer. In some outcrops, canga can have (Fig. 7B) some matrix content, with up to 10 cm clasts of itabirite and canga or limonitic material. The matrix is dark brown, sand clayey, with fine to coarse-grained quartzose sand.

Lateritic soil

This soil-like material is red to reddish brown and overlies mostly of the sedimentary units. It is sand clayey to sand silty clayey, and rich in pebble to cobble-sized hematite, canga, and limonitic material matrix supported. Roots and wood-like fragments occur, mainly in the shallow levels. It has transitional contact increasing cementation downward to canga or increasing the pebble content to clay silt sandy sediments.

STRATIGRAPHIC UNITS OF BANDEIRA BASIN

Based on the spatial associations in the drill holes, this paper proposes the categorization of Unit A, Unit B, and Unit C, as shown in Fig. 8. The units may be synthesized as follows:

- Unit A: It consists of gravel and diamict-like sediments, including sandy materials and black organic sediments. It is the bottom-most interval and occurs only in the MAD-FSE001 drill hole core in the southwest;
- Unit B: It comprehends the facies with clay and sandy sediments interbedded with gravels. Transport reworking is low as seen by the angular fragments. This unit is found only in-depth, with variable thickness in the three drill holes described and in other drill holes, from the database, located in the central to the western portion of the area;
- Unit C: It reunites facies with clay, silt, and sandy sediments, which correspond to a colluvionar material affected by pedogenesis in different moments. There is some transport reworking, as shown by the rounded fragments. It is widely spread and is the most extensive in-depth unit, which can be found in every drill hole core.

DISCUSSION

Processes interpreted for the Bandeira Basin facies

The mapping data, as well as the drilling information, show that the basement of the Bandeira Basin consists of weathered rocks of the Minas and Rio das Velhas supergroups, in the depositional setting presented as shown in Fig. 9. The sediments are located at Serra do Tamanduá, NE-SW oriented, and at the easternmost part of the Gandarela Syncline. The slope decreases from north to south of the ridge. The sedimentary basin is located on the southern side of the ridge, suggesting that the area may have experienced material gravity reworking from the north on its natural slopes.

Drill hole information indicates that the sediment layers are thicker where they are on top of the Rio das Velhas Supergroup than when they are overlying the Minas Supergroup. The oldest sediments are grouped in this paper under the name of Unit A, with conglomeratic, sandy, and clayey sediments that were only noticed on the southwest portion of the Bandeira Basin, which is around 75 m in depth in MAD-FSE001. These sediments have fragments of chlorite schist and quartz, which are consistent with a provenance from the weathered rocks of Rio das Velhas Supergroup (Nova Lima Group). The fragments are often rounded and have high sphericity, suggesting a reworking process by sedimentary transport, possibly with the influence of water. The proportion of fragments decreases upward in gradational contacts, punctually erosive, especially where the sediments are richer in fragments.

This sedimentary record could be interpreted as a first pulse of basin filling, rich in coarse material, with its source area probably near the depositional site. These sediments were only found in one drill core, and it may implicate a local process, where the basin just started to form. The fragments themselves might have been formed after reworking of weathered outcropping material, as they often show a layer of ferruginous cortex outside the fragments. The weathered mica phyllites of Rio das Velhas Supergroup were eroded, transported, and then deposited in an incipiently formed Bandeira Basin. Although

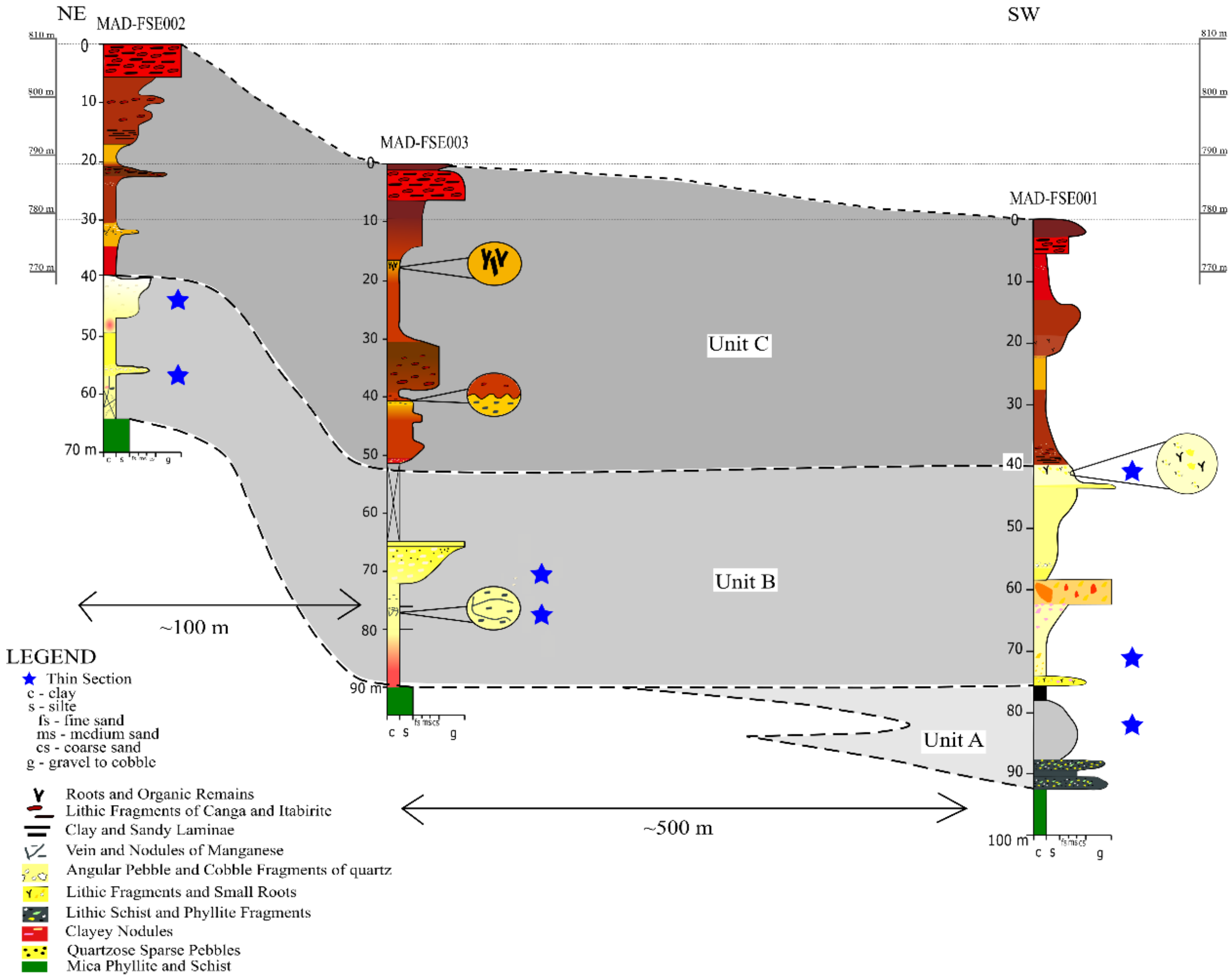


Figure 8. Drill hole profile description for MAD-FSE001, MAD-FSE002, and MAD-FSE003. Drill hole profiles are with individualized intervals, some remarkable features, and their correlations. The colors used are as similar as possible to the real core sample.

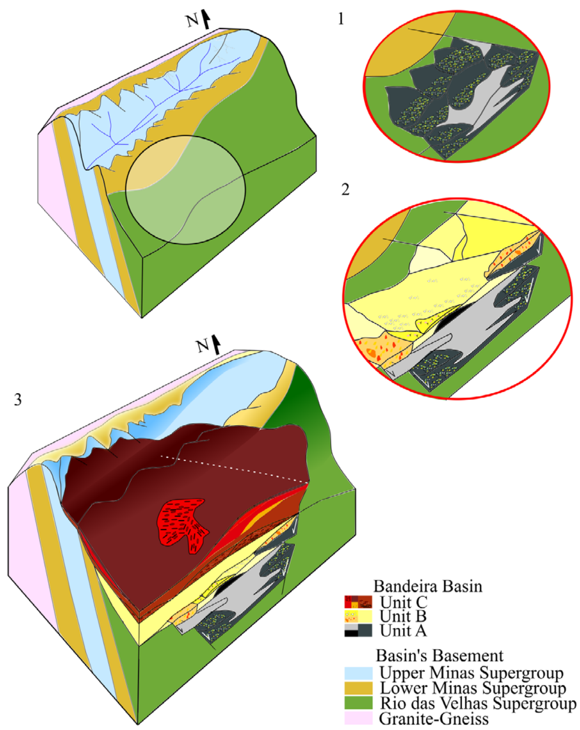


Figure 9. Geological arrangements in a 3D representative model.

the process that triggered the sedimentation is not yet clear, especially considering this one drill hole, it is interpreted as a fan delta debris, with fluvial influence (Fig. 9 1).

The upper limit of facies association A is marked by an organic-rich layer with 1.35 m thick of black clayey material. This represents a shift in the sedimentation process and perhaps the involvement of a water body, such as a lake.

Unit A is overlain by interbedded clayey and sandy sediments, which are found throughout the southern and central areas of the Bandeira Basin. The contact between the black organic material from Unit A and the base of Unit B is abrupt. This might mean a lack of stratigraphic record, suggesting that the organic-rich material could be thicker and that the process and environment responsible for the deposition of such sediment might have lasted more than its actual thickness suggests.

Unit B occurs from depths around 35–75 m. These sediments are mostly massive, kaolinite-rich, light in density, and greasy to the touch, where the argillaceous sediments are predominant. The contact relation is difficult to classify on the drill hole samples, but the interleaving is frequently locally erosive. Identifying sparse coarse sand grains, granules, and pebbles with high sphericity and angularity is frequent in clayey sediments. The sediments might have been transported by cohesive (muddy-rich) debris flow, as exemplified in Fig. 9 2. In some parts, this unit can be classified as diamict-like sediments, due to the increase in size and quantity of clasts. The occurrence of manganese veins and nodules can be associated with the groundwater level and oxidation processes during subaerial exposure.

In the southern portion of the area, also in the drill hole MAD-FSE001, besides those sediments, a talus-like material is found in the middle of the clayey and sandy sediments, or as named Unit B, different from all the described facies. This suggests an episodic deposition of non-cohesive (granular or clay-poor) flow. The boulders are sericite phyllite consistent with the one found outcropping in the study area, around the Vitória-Minas' railroad. This indicates that the basement of the basin, the weathered rocks of the Nova Lima Group, is the source area of these sediments. The high content of kaolinite endorses this interpretation.

The other drill holes described, along with the database provided by the mining company, do not show any evidence of this kind of material. Unit B often shows interbedded conglomeratic sediments with massive clayey and sandy ones. However, it does not show any talus-like sediments except in the MAD-FSE001 drill hole. The talus-like occurrence, as shown in Fig. 9, is noteworthy not only because it shows a different sedimentation process, but it can also represent a topographic break near the point surveyed. This might suggest the simultaneous influence of tectonic processes influencing sedimentation. It is not clear which unity in Rio das Velhas Supergroup could provide the amount of quartz content found in these sediments.

The upper layer of sediments is Unit C and outcrops all over the study area (Fig. 9 3). These sediments are thicker in the central and southwestern portions of the area, ranging from 9 to 35 m thick (average of 20 m). The basal contact is abrupt, with successive layers of colluvial sediments and some erosive contact. The sediments have fragments with different angularity, sphericity, and composition, as once described, that indicates a different source area when compared to Unit B. Unlike Units B and A, this unit is richer in sedimentary structures, such as massive sediments intercalated with bedded and laminated ones. Once the lithic fragments are mostly itabirite, ferruginous quartzite, and canga, it is most likely that the source area for these sediments is the Minas Supergroup, probably the Itabira and Piracicaba groups.

The sediments are poorly sorted and show a diversity of clast lithotypes in most of the described layers, suggesting low-sorting capacity deposition processes and multiple source areas. This unit is interpreted as formed by colluvionar processes along the southern slopes of the Serra do Tamanduá.

The clear layering structures in these sediments, with evidence of erosive contacts between some of them, might indicate that at least part of the sediments experienced a longer transport and perhaps an underwater deposition. These sediments might represent the distal part of the flow since they represent a non-cohesive mass flow.Another distinct feature identified in Unit C is the presence of ochre horizons, which are rich in manganese nodules, wood fragments, and small roots. These horizons are at a maximum of 5 m thick and have basal gradational contact and upper abrupt contact. They have been interpreted as residual soils of the colluvium, indicating that these sediments have been exposed to pedogenetic processes, with phreatic influence.

If these soil-like horizons occur in depth, as described in Bandeira Basin section, it indicates that it was later buried by distinct debris flow. The material that buries these colluvium residual soils is richer in granule and pebble-sized clasts of hematite, itabirite, and lateritic materials in greater amounts than the sediments in depth. It is also clearly richer in sandy matrix, with quartz and Fe-oxide composition.

These last, most superficial layers are the subject of a recent, yet different, pedogenetic process that resulted in the cementation of the sediments, leading to the formation of canga. In some areas, these canga layers are overlaid by a lateritic soil material, which is different from the canga exactly because it is not yet cemented. The lateritic soil means the canga layers suffered weathering that broke the cemented matrix. The characteristics of canga and the lateritic soil are very similar, being the cementation grade the one distinctive factor. This probably means that the process that once resulted in the canga might be overturned by a process that weathers the canga and produces its chemical fragmentation.

The terrain morphology probably had a massive influence on the distribution of the sediments, as the thickness of the sediments in relation to the basin basement is clearly variable. The east and southeast parts of the Bandeira Basin are 2–10 times thinner than the central and northwestern portions of the basin. All the southern part of the study area's basement is composed of the Rio das Velhas Supergroup.

Comparison and basin correlation

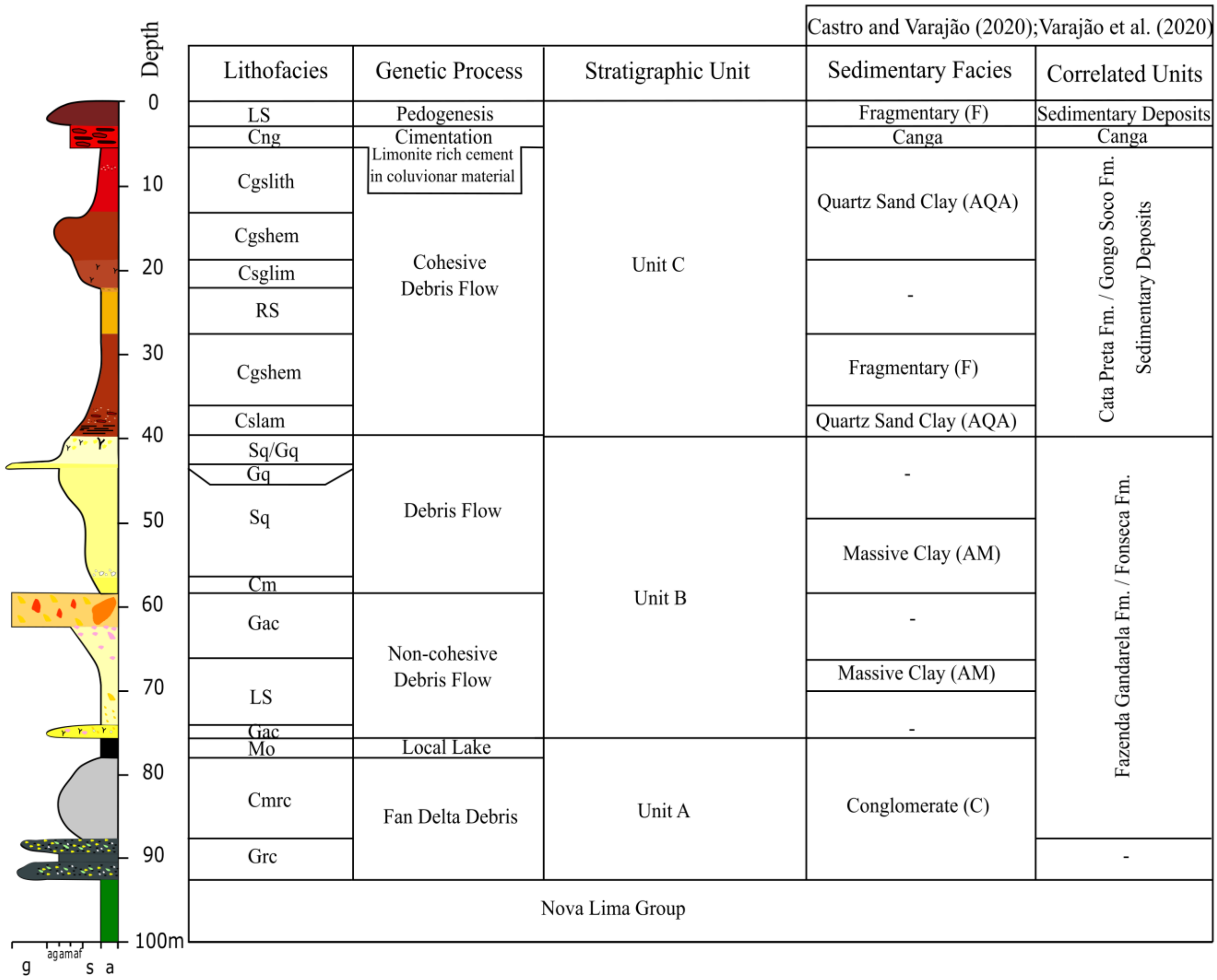
Multiple well-known papers have attempted to explain the origin of the recent sediments found in QF (Maizatto 2001, Spier *et al.* 2018, Varajão *et al.* 2020). For the allochthone units, the genesis is explained with depositional history and pedogenetic processes related to time and basin geometry complexities.

It is suggested for the Bandeira Basin a clear contribution of slope erosional and transport processes that reworked both the Rio das Velhas and Minas Supergroup in different times and spaces. The upper unit, here classified as Unit C, is probably the result of reworking of the Minas Supergroup. Below it, Units B and A (Fig. 8) forming clay, sandy, and gravel sediments possibly represent the reworking of the Archean units of the Nova Lima Group from Rio das Velhas Supergroup.

The changing in source areas, from base to top in the Bandeira Basin (i.e., from the Archean Nova Lima Group to the Paleoproterozoic Minas Supergroup), is probably a function of the evolving Bandeira Basin that slowly covered the Archean source areas with sediments due to its lateral expansion. Also, it might have some influence on neotectonics' movements that uplifted Paleoproterozoic rocks exposing them to a faster erosion rate.

The sedimentary model presented for the Gandarela and Fonseca basins (Castro and Varajão 2020, Varajão *et al.* 2020) is similar to the ones that occur in Bandeira Basin and can be correlated (Fig. 10).

In facies association A, the gravel facies from Bandeira Basin are very similar to the Conglomerate facies, as well as it correlates with channel fluvial sediments, present in Facies Association A of Fonseca Basin (Maizatto 2001). Part of the intervals described in facies association B is associated with the Massive Clay facies from Castro and Varajão (2020). The Fragmentary and Quartz Sand Clay facies from Castro and Varajão (2020) can be related to layers found in the facies association C (Fig. 10), as well as the canga layers.



Source: Castro and Varajão (2020) and Varajão *et al.* (2020).

Figure 10. Drill hole profile MAD-FSE001, indicating proposed lithofacies units and processes interpreted for the Bandeira Basin, as well as a comparison with the sedimentary facies and geological units.

The Bandeira Basin shows only one canga layer, which is different from the situation in Águas Claras Mine (Spier *et al.* 2018). Also, the Nodular Facies (Castro and Varajão 2020, Varajão *et al.* 2020) do not have an equivalent in Bandeira Basin. However, many of the layers here described do not have correlation nor similar descriptions in the literature up to now, thus enriching the collection of sedimentary facies and processes known for the Cenozoic basins in the QF.

Figure 10 shows the drill hole profile MAD-FSE001, its described lithofacies, and processes. It also shows the stratigraphic units proposed and the comparison with the literature.

GEOMETRY OF THE BANDEIRA BASIN

The difference in thickness along the Bandeira Basin is a distinct feature of the shape of the basin, as it might have a relation to how the neotectonics affected the QF and had an impact on both the sedimentation and accommodation process of the recent sediments.

It is possible to simulate the three-dimensional environment of the probable setting for the Bandeira Basin. Considering other examples in the literature (Lipski 2002, Varajão *et al.* 2020), these sedimentary basins tend to be formed by fault activity, where the blocks shift relative to others, whether along existing structures or forming new ones, generating space for sedimentation and progressive infilling of paleo relief along the slope where the sediments were transported. The Leapfrog Geo 2022.1 software was used to generate a model interpretation (Fig. 11).

The model that is consistent with the information analyzed was made considering the main role of fault-controlled basement displacement. Figure 11 shows this scenario that combines the idea of tectonic controlled erosion and deposition. This potential setting can be found in Bandeira Basin, especially if considering the great increase in thickness of the sediments in the central portion of the area. Varajão *et al.* (2020) showed that the space of accommodation can be associated with erosional processes, which are always associated with faulting systems. The fault-controlled basin was conceived considering the geomorphological lineaments mapped on a regional scale, from today's setting.

According to Lipski (2002), the basement can provide direct information for the format of the basin. Hence, the model was drowned considering that the thicker portions of the sediments are aligned to the NW-SE orientation. In this scenario, most of Units B and A have the Rio das Velhas Supergroup as the basement and source area. This is consistent with the gravel and talus facies containing clasts of phyllites and schists only. The Rio das Velhas Supergroup is also a more probable source area for the argillaceous white massive clay found in these units. In fact, the main thickness of the sediments, represented by Units B and A, is

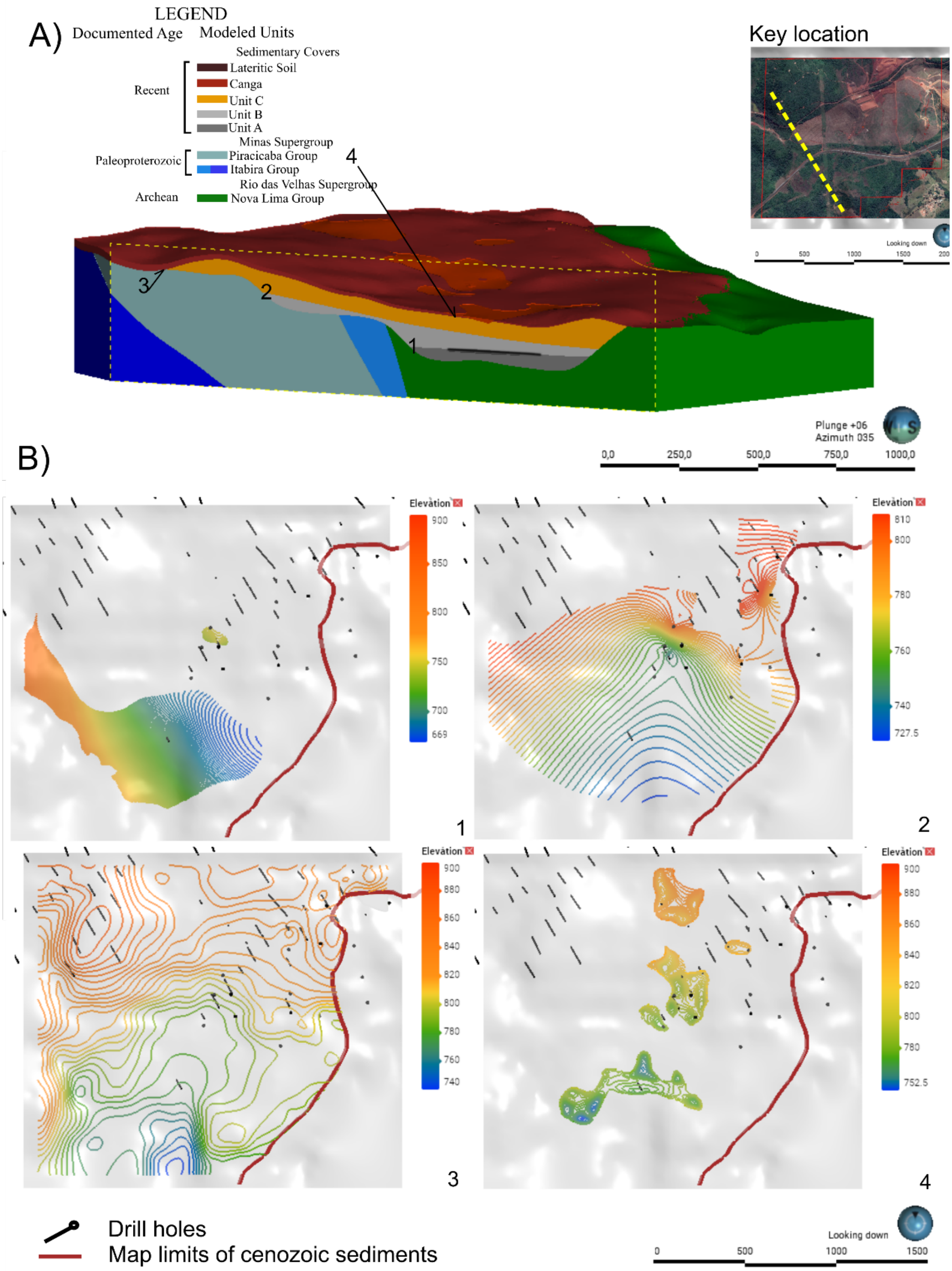


Figure 11. Modeled simulations of the Bandeira Basin. (A) Section of the geological model, considering the criteria and interpretation presented in this chapter; (B) contour map of the contact of the main sedimentary units identified in Bandeira Basin, presenting the contact between Units A and B in B1; contact between Units B and C in B2; contact of lateritic soil in B3 and contact of canga units in B4.

generated in the context of tectonically active landscapes. Both of those units correspond to the central and southwestern portions of the basin. The contours representative of the contact between Units B and A were modeled and are presented in Fig. 11 1.

Differently from Units B and A, Unit C (contact between Units B and C indicated in Fig. 11 2) can be related to the predominant erosional process, which has been acting on the Minas Supergroup as a source area. The facies that comprehend Unit C are widely spread and clearly more extensive than the other two units. There are some points where the thickness laterally varies suddenly, but those sediments are always occurring on the surface all over the area. That suggests that, even if the sediments suffered some tectonic influence, this is no longer the case, at least for the upper part of the sedimentary sequence.

The outcropping units, lateritic soil and canga, are outcropping in almost all the area of the basin. Both were modeled and are presented in Fig. 11 3 and 4, respectively. The lateritic soil is almost homogeneous in thickness, but the canga unit consists of local occurrences, with thin thickness.

Evolutionary model for Bandeira Basin

The Bandeira Basin has a complex sedimentation history. The ancient landscape consists of the units of Minas e Rio das Velhas Supergroup outcropping and forming the Serra do Tamanduá. Those consist of the basement, which suffered the effect of tectonic activity. This started a process of modification on the relief existing at the time, allowing the deposition of the oldest unit investigated, Unit A, only occurring in the southernmost part of the area. At this point, probably only the Rio das Velhas Supergroup was sourcing sediments, as shown by the composition of the fragments found. What started as a debris-predominant forming process has its upper layer dominated by lacustrine deposition, forming an organic-rich clayey layer.

The Bandeira Basin might have started as a local sedimentation, probably evolving into a wider area for a sedimentation area, represented by Unit B. The talus-like sediments and their interbedded feature with clay-rich material from Unit B both show that the source area was presumably the Rio das Velhas Supergroup and that the basement of the basin was still influenced by tectonic normal fault activity. At this point, it is not possible to know whether this activity was continuous or episodic, although its geological record tends to show that at least some episodic sedimentation occurred.

Given that normal faulting influenced sedimentation (mainly in Units A and B), it is likely that the main mechanism of subsidence is mechanical subsidence. Further basin analysis studies are needed to better enlighten his subject.

Unit C sets the start of the contribution of the Minas Supergroup as the source area for the basin. The material probably was transported by successive debris flow processes. It is likely that these flows could have been spaced in time, suffering some aerial exposure, due to the soil-like material found interbedded with colluvium in this unit. The presence of manganese nodules, clay nodules, and small roots and organic material endorses this hypothesis. The uppermost and outcropping lithotypes correspond to the canga and lateritic soil, which are the result of pedogenesis on the coluvionar material from Unit C previously deposited.

CONCLUSION

Although the focus on the QF was the host rock of the world-class iron and gold deposits, in recent years, the knowledge of the recent sedimentary deposits has evolved. The occurrence of sedimentary basins has been known since the late 19th century, but it lacks further studies.

In this context, this paper brings a characterization of the sedimentary deposit now named Bandeira Basin, found in Serra do Tamanduá. The description of the deposit was based on geological mapping, drill hole samples, as well as thin section, to comprehend the stratigraphic variation of the lithotypes, their distribution, and their relationship with the basement rocks. Some of the conclusions are as follows:

- The sedimentary deposits can be divided into at least three units of distinct lithotypes;
- These lithotypes are different in composition, granular sizes, and contact relation, resulting in the association of different sedimentary processes, morphology of the terrain, and, probably, tectonic processes;
- Drill hole data are essential to define and understand the vertical and lateral distribution of the Bandeira Basin units. With only the mapping data, most of the features and processes interpreted would not be possible;
- The units described can be correlated to other sedimentary basins of QF, although Bandeira Basin has a predominance of debris flow processes for the sediment's deposition, which does not occur in other basins analyzed.

The detailed characterization of these sediments was inspired by advances in scientific knowledge, but it is clearly relevant to other fields of study. The methods applied in this paper are mostly simple, low cost, and bring a relatively quick answer on the type of material found in the samples analyzed. It is important to constrain and characterize this material as it is used as material not only for building, *e.g.,* local roads, but also for civil infrastructures that are built over these materials. Therefore, the knowledge of the physical characteristics of the material will provide a better understanding of its behavior under different circumstances.

Bandeira Basin can be compared with other known sedimentary deposits in further studies in QF, providing a better understanding of local and regional recent sedimentary and tectonic processes.

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