

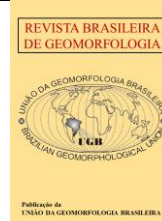


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Research Article

Sedimentology and chronology of unconsolidated alluvial fans of the Quadrilátero Ferrífero (Central Brazil): implications for landscape dynamics in the Late Quaternary

Sedimentologia e cronologia de leques aluviais inconsolidados do Quadrilátero Ferrífero (Brasil Central): implicações para dinâmica da paisagem no Quaternário Tardio

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Abstract: This paper identifies and discusses the paleoenvironmental characteristics of the Quadrilátero Ferrífero based on studies of unconsolidated alluvial fans and the chronological organization of their respective sedimentary facies. These alluvial fans were submitted to stratigraphic survey and dating by Optically Stimulated Luminescence (OSL) and, subsequently, their ages and faciological characteristics were compared with the paleoclimatic and paleotectonic data available for the region. The description and interpretation of the sedimentary facies evidenced a lack of aggradational processes, which are inactive. About 40% of the identified facies are plastic (Gmm) and pseudoplastic (Gcm) debris flows interspersed with occasional channel-filling facies (Gt), hyper-concentrated (Sm), and mud (Fm) flows. The unconsolidated alluvial fans of the Quadrilátero Ferrífero had their genesis throughout the Pleistocene, mainly in a dry climate, with vegetation retraction and sedimentary filling of river valleys. Climatic oscillations to establish a humid environment increased the flow of drainage courses and, consequently, erosion of the deposits. However, it was cenozoic tectonics that acted most strongly in the dismantling of the fans through strong fluvial incision in the Holocene, caused by uplifts of the Brazilian continental shelf.

Keywords: Optically stimulated luminescence; Fácies Profiles; Paleogeography; Paleoclimate, Cenozoic Tectonics.

Resumo: Este artigo identifica e discute as características paleoambientais do Quadrilátero Ferrífero com base em estudos de leques aluviais inconsolidados e organização cronológica de suas respectivas fácies sedimentares. Tais depósitos foram alvo de levantamento estratigráfico e datação por luminescência opticamente estimulada (LOE) e, posteriormente, tiveram suas idades e características faciológicas cotejadas aos dados paleoclimáticos e paleotectônicos disponíveis para região. A descrição e interpretação das fácies sedimentares evidenciaram ausência de processos agradacionais, estando os mesmos inativos. Cerca de 40% das fácies encontradas são de fluxos de detritos plásticos (Gmm) e pseudoplásticos (Gcm) intercaladas a eventuais fácies de preenchimento de canal (Gt), fluxos hiperconcentrados (Sm) e de lama (Fm). Os leques aluviais inconsolidados tiveram sua

gênese ao longo do Pleistoceno, na maioria das vezes em clima seco, com retração da vegetação e preenchimento sedimentar dos vales fluviais. Oscilações climáticas para estabelecimento de clima úmido ocasionaram no aumento da vazão dos cursos de drenagem e, conseqüentemente, erosão dos depósitos. Porém, foi a tectônica cenozoica que atuou mais fortemente no desmantelamento dos leques por meio da forte incisão fluvial no Holoceno, provocada por soerguimentos da plataforma continental brasileira.

Palavras-chave: Luminescência Opticamente Estimulada; Perfis de fácies; Paleogeografia; Paleoclima; Tectônica Cenozoica.

1. Introduction

Alluvial fans are semi-conical deposits of poorly selected detrital material accumulated in valleys installed on the periphery of higher regions. The weathered sediments in their feeder basins are transported by a confined channel that acquires lateral mobility, expanding in all directions, forming a 180° arc (Blair & McPherson, 1994; Bahrami, 2013; Vetra & Clark, 2018). Bahrami (2013) stated that their genesis and evolution are controlled by interacting tectonic and climatic factors, while the lithological and morphometric characteristics of the source area cannot be ignored. For McPherson *et al.* (1987), the climate rarely interferes with the characteristics of a fan, which is conditioned mainly to tectonic, lithological, geomorphological, and morphometric issues of the basin where it is located.

According to Owen *et al.* (2014), because these features are susceptible to environmental changes, alluvial fans can contain important regional records of the tectonic, climatic, and hydrological dynamics. Although important, these deposits, especially those partially constituted by colluviums, are underestimated in studies of depositional environments due to their high susceptibility to erosive processes and lack of criteria for their recognition since colluvial deposits are not included in traditional facies models (Nemec & Kazanci, 1999; Lopes *et al.*, 2020).

Blair & McPherson (1994) concluded that the alluvial fans are not part of the dynamics of the intertwined fluvial system. These authors assert that, although widespread, this concept is adopted without accounting for the different sedimentation events and hydraulic characteristics of the two environments, accounting only for the morphological aspects. Additionally, the idea that the evolution processes of a hydrographic basin and alluvial fan are the same is also premature since they respond differently to periods of tectonic and climatic instability. Assine (2003) highlights that, in tectonic studies, the existence of alluvial fans does not confirm synsedimentary movement since deposits are not necessarily associated with active fault scarps. Despite this, according to Anstey (1965) and Blair & McPherson (1994), its preservation potential is low when not developed in an environment of resurgent tectonics, thus justifying the lack of works of this nature.

The natural water scarcity in the arid and semi-arid regions of the world contributes to the maintenance of these features at the foot of the escarpments, added and/or eroded only by intense and sporadic rains. The preserved morphological, hydraulic and sedimentary characteristics facilitate the acquisition of data used in several works around the globe (e.g., Nemec & Kazanci, 1999; Turner & Makhoulouf, 2002; Oguchi & Oguchi, 2004; Makhoulouf *et al.*, 2010; Owen *et al.*, 2014). In regions with a humid climate, however, higher water availability favors pedogenetic and erosive processes that de-characterize the surface of the fans. The fieldwork and data collection are hampered by the dismantling of deposits and the high vegetation density (e.g., Darby *et al.*, 1990; Evans, 1991; Neves *et al.*, 2005; Saito, 2005; Lopes *et al.* 2020).

In several regions of Brazil, tectonic work identified deposits of alluvial fans in the filling of Cenozoic grabens, as in the case of the das Mortes (Saadi, 1991), Aiuruoca (Santos, 1999) and Sapucaí (Ferreira, 2001) rivers, in Minas Gerais, and Rezende (Gontijo, 1999; Lima & Melo, 1994), in Rio de Janeiro. Mello (1992) studied the sedimentary facies, depositional architecture and morphostratigraphic relationships of a system of Holocene alluvial fans in the middle of the Paraíba do Sul River, between São Paulo and Rio de Janeiro (Manso Alloformation). Neves *et al.* (2005) described pre-Quaternary Cenozoic fans at the base of fault scarps in the Japi ridge in São Paulo. In Espírito Santo, Lana *et al.* (2016) studied kilometric alluvial fans dominated by gravity flow.

However, few works in the Quadrilátero Ferrífero focus on alluvial fans. Despite this, Dorr (1969) described a geomorphology of high ridges, high plateaus, deep canyons, and wide valleys that give rise to this feature. Furthermore, Varajão (1991) concluded that the regional landscape evolution was conditioned by extensional faults and epigenetic uplifts that were more intense in the Neogene and Quaternary. Although the tremendous altimetric amplitude and the resurgent tectonics may have contributed to the development of regional fans, these same

variables, added to the humid climate, allowed for the consumption of the deposits generated, considering the high rates of fluvial incision, vegetation density, and the installed erosion and advanced pedogenetic processes (Lopes *et al.*, 2020). Additionally, Barros (2012) also considers the possibility that regional alluvial deposits have been buried by colluvium or dismantled due to anthropic activities. These characteristics differentiate these fans from others around the world.

In this region, some research was based on understanding the evolution of terraces and river plains, having peripherally described alluvial fans uncharacterized by erosive and pedogenetic processes in the basins of the rivers Piracicaba (Rossi, 2008), Paraopeba and Serra Azul stream (Marques, 1997; Moreira, 1997; Barros, 2015). In the literature, Barbosa (1980), while working with sediments at the foot of Ouro Branco ridge and Sobreira (2001) with cover deposits in the Carmo stream, refer to this deposit as talus. Detailed studies on the subject are reported only in the regions of Chapada da Canga (Castro, 2017) and in the basins of the Casa Branca and Piedade streams (Lopes, 2017; Lopes *et al.* 2019; Lopes *et al.* 2020; Lopes *et al.* 2021; Lopes *et al.* 2022).

The objective of this work is to investigate the paleoenvironmental factors responsible for the formation of alluvial fans based on the sedimentological and geochronological characterization of their facies. The lack of holistic studies regarding these important features justifies its development. The integrated analysis of the sedimentary facies and their respective absolute ages allowed us to establish an integrated information picture, contributing to new interpretations about the morpho-sedimentary evolution of the region. Also, due to their peculiar hydraulic and sedimentary dynamics, the investigation of alluvial fans must be segregated from studies of river terraces and talus deposits to improve data quality and expand the horizon of interpretations.

2. Study Site

The Quadrilátero Ferrífero comprises an area of 7,000 km² in the southern portion of the São Francisco Craton (Almeida, 1977). The area's geological configuration consists mainly of granite-gneissic and migmatite rock complexes surrounded by Archean and Proterozoic megastructures, of which we highlight the Gandarela, Dom Bosco, and Moeda Synclines, the Curral Homocline, the Mariana Anticline, and the Caraça Massif (Fig 1). More details on the regional complex lithological and structural history can be found in Castro *et al.* (2020).

The studied alluvial fans developed from a set of mountain ranges belonging to such megastructures, spatially organized in Figure 1, where several authors identified records of tectonic movements throughout the Cenozoic (e.g., Saadi, 1991; Moreira, 1997; Sant'anna *et al.*, 1997; Lipski, 2002; Barros & Magalhaes Júnior, 2020). In addition to tectonic work, Salgado *et al.* (2006), Salgado *et al.* (2007), Salgado *et al.* (2008), and Peifer *et al.* (2021) investigated rock denudation and erosion rates and demonstrated differential erosion.

The tectonic dataset, associated with denudation and erosion data, confirms that the dynamics of the source areas of the studied alluvial fans are controlled by both differential erosion and neotectonics. Such dynamics added to anthropic interventions may have imprinted expressive changes in these areas since the genesis of the deposits.

The high topographic amplitude is one of the most outstanding features of the region's relief. Above 1200 m, the highest areas correspond to mountain crests supported by Itabirites and Quartzites covered by rocky vegetation. Contrasting with the high areas are the Granite-gneiss and migmatitic complexes, limited to 1040 m in height, with rounded top hills, convex slopes, and embedded fluvial channels. In addition to the gallery forests around the river channels, this area is home to dense vegetation of the seasonal semideciduous type, typical of the transition between the Savana (Cerrado) and the Atlantic Forest (Machado, 2018).

The Quadrilátero Ferrífero hydrographic network is divided into three large and important basins. The Paraopeba and Velhas river basins dominate in the west and central areas, respectively (Fig. 1). These rivers run south-north, cross epigenetic gorges of Funil and Sabará, flowing into the São Francisco River in northern Minas Gerais. The eastern portion has fluvial segments of the upper course of the Doce River, represented by the rivers Conceição, Piracicaba, Gualaxo do Norte, and Gualaxo do Sul.

The regional climate is humid tropical, with 1325 mm annual average rainfall (driest in August and wettest in December) and 21.3°C annual average temperature (18°C minimum in June and 27.3°C maximum in January) (Reboita *et al.* 2015). Furthermore, floristic records found in sedimentary layers of lakes in southeastern Brazil provided more complete discussions about the regional paleoclimate. Most of these records converged to expressive climatic fluctuations in the last 50 ka (Behling, 1995; Ledru *et al.*, 1996; Behling & Lichte, 1997; Parizzi *et al.*, 1998; Behling, 2003; Rodrigues-Filho *et al.*, 2002; Ledru *et al.*, 2009; Enters *et al.*, 2010; Seixas *et al.*, 2015).

The five deposits of alluvial fans studied were identified in the flattened river valleys and peripheral to the high areas (Fig. 1).

1. Alluvial fan of Itacolomi ridge is located at the base of the Itacolomi ridge, in the Southeast portion of the Quadrilátero Ferrífero (Fig. 1), on metavolcanic rocks, schists, chlorite schists, phyllites and quartzites of the Sabará Group (Minas Supergroup) (Baltazar et al. 2005). The maximum height of the current source area regarding the sediments is about 330m, with quartzites, conglomerate lenses, and phyllites from the Itacolomi Group outcropping, for the most part. Subordinately, there are graphite schist, micaschists, and phyllites from the Barreiro Formation of the Piracicaba Group (Minas Supergroup) (Baltazar et al. 2005). This rather anthropized inactive fan exhibits better-preserved fragments on the western side. The sediments are truncated by the plains of the Seminario Stream and the Carmo River, tributaries of the Doce River. Sobreira (2001) concluded that this entire region comprises a large fan-shaped talus deposit that can reach 10 m thick.

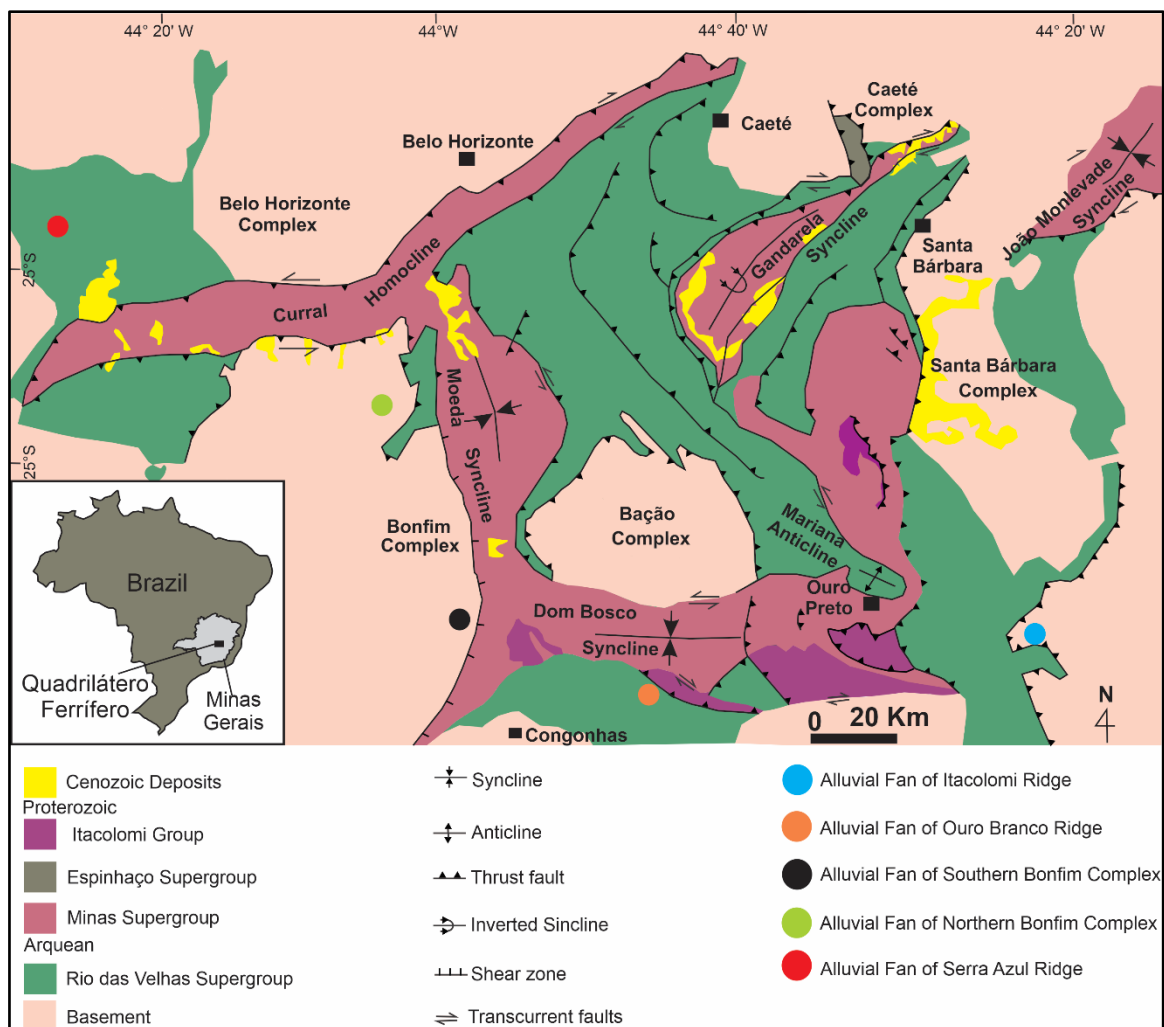


Figure 1. Geological map showing the Quadrilátero Ferrífero, the spatial distribution of the studied alluvial fans, and their respective source areas.

2. Alluvial fan of the Ouro Branco ridge in the southern portion of the Quadrilátero Ferrífero (Figure 1) is deposited on the schists and phyllites of the Nova Lima Group (Rio das Velhas Supergroup). This fan is inactive, and its sediments are added to other adjacent ones, forming a large alluvial-colluvial complex of about 15 km². Ouro Branco ridge, the current source area is approximately 500 m high, composed of undivided quartzites and phyllites of the Itacolomi Group (Baltazar et al. 2005). According to Barbosa (1980), this deposition was caused by the tectonic reactivation of the Ouro Branco ridge, the source area.

3. Alluvial fan of the Southern Bonfim Complex is located at the base of Moeda ridge, in the southwest region of the Quadrilátero Ferrífero, on top of the gneiss-migmatite granites of the Bonfim Complex (Figure 1). Tributaries of the right bank of the Paraopeba River greatly dissect this inactive fan. The current source area of the sediments, in Moeda ridge, is 500 m above the current valley of the Boa Esperança stream. This area has a wide variety of lithotypes of Minas Supergroup, such as laterites and ferruginous debris; quartzites from the Moeda Formation and the Itacolomi Group; phyllites from the Batatal Formation and, for the most part, itabirites from the Cauê Formation (Baltazar et al. 2005).

4. Alluvial fan of the Northern Bonfim Complex is also located at the base of Moeda ridge, in the northwest portion of the Quadrilátero Ferrífero, on the gneiss-migmatite granites of the Bonfim Complex (figure 1). The Piedade stream truncates such sediments; this fan's current source area, is about 510m high and, according to the geological base of Baltazar et al. (2005), consists of quartzites from the Moeda Formation (Minas Supergroup), phyllites from the Batatal Formation (Caraça Group – Minas Supergroup), schists and phyllites (Nova Lima Group - Minas Supergroup) and itabirites from the Cauê Formation (Itabira Group - Minas Supergroup). Lopes et al. (2020) studied this fan using facies and paleocurrent analysis, sedimentary provenance (U/Pb), and Optically Stimulated Luminescence (OSL) dating (12 ka) and concluded that these raised deposits in the middle of the landscape were preserved by the fault zones in the vicinity. They would have enhanced the erosive character of the drainages and, consequently, accelerated the deepening of the valleys.

5. Alluvial fan of Azul ridge sits on the migmatitic granite-gneiss basement of the Belo Horizonte Complex in the northwest portion of the Quadrilátero Ferrífero. This inactive fan is dissected by tributaries of the left bank of the Serra Azul stream, which, in turn, flows into the Paraopeba River. Moreira (1997) and Barros (2015) studied six river levels in the Serra Azul stream basin, of which level 4 belonged to the Serra Azul fan and dated it 41ka.

3. Materials and Methods

In fieldwork, the proximal, middle, and distal portions of the alluvial fans identified by photointerpretation were subjected to a detailed survey of stratigraphic profiles based on the criteria established by Compton (1962; 1965) and Tucker (2014). In addition to the hand magnifying glass (10x) and the granulometric chart, measuring tape and Jacob's rod were used for eventual stacking in laterally discontinuous profiles.

The main characteristics of the sedimentary facies observed were: 1) thickness; 2) granulometry; 3) degree of grain roundness; 4) selection; 5) presence of matrix; 6) collar; 7) downstream granulometric reduction patterns; 8) type of contact between the facies along the vertical succession; 9) clast imbrication; 10) petrographic composition of sediments, and 11) sediment structure. The codes assigned to the described and interpreted facies, with adaptations when necessary, were proposed by Miall (1978). Grain size analyses followed the granulometric scale of Wentworth (1922).

Furthermore, the depositional ages of the facies analyzed in this study were organized chronologically to interpret the different paleoenvironmental contexts of the Quadrilátero Ferrífero. Laboratory parameters related to annual and equivalent dose rates were discussed by Lopes et.al (2020) and Lopes et al. (2023). These authors dated by OSL facies of the alluvial fans studied following the SAR-Single Aliquot Regeneration protocol (Murray & Wintler, 2000; Wintler & Murray, 2006). Specifically, 15 aliquots were used to determine 15 different equivalent dose rates for each sample and these measurements were, subsequently, treated using the central age model.

Kenworthy *et al.* (2014) reported that the OSL is significantly limited to conventional sampling techniques, yielding adequate age estimates only for thick sedimentary layers (>60 cm) of sand and other fine grains. Therefore, dating sediments such as gravel deposits from alluvial fans that lack such characteristics is an enormous challenge. Due to the impossibility of collecting samples of cuttings in tubes, these authors mentioned excavating the deposits and collecting them on light-proof canvas at night. Their ages were determined using reduced aliquots, thus demonstrating that heterogeneous deposits, modally constituted by granules, pebbles, Cobbles or boulders, can also be successfully dated.

Like Kenworthy *et al.* (2014), Lopes et. al. (2020) and Lopes et.al. (2023) were anchored in the dating of facies with superior modal granulometric composition. These challenging characteristics required sampling methods or objects that go beyond the traditional. Thus, using metallic tubes attached to the sampler and the lever for removing these tubes from the deposits was of great importance during the fieldwork. More details about the sampled equipment and the quality of the ages can be found in Lopes et. al. (2023).

The others procedures adopted by Lopes et al. (2020) and Lopes et al. (2023) for sampling, analysis and obtaining ages are described below.

The samples were collected in 40 cm long metallic tubes with a 4 cm diameter, always avoiding contact with sunlight. A surface strip of the deposit was vertically scraped to exclude sediments exposed to sunlight, bioturbation, and pedogenetic horizons. The sediments were sampled from a homogeneous area as often as possible, avoiding contact between facies, to facilitate the dose rate estimation as the radius of influence of gamma radiation from natural radionuclides is approximately 30 cm (Guedes et al., 2013). Additionally, whenever possible, efforts were made to insert the tubes in facies with fine granulometry, mainly in sandy lenses trapped between the gravel, preferably facies in the distal regions, which may reduce the probability of collecting sediments with partial bleaching.

The sites, profiles, and respective facies for sampling were strategically chosen to avoid mistakes that could underestimate or overestimate the ages, according to Stokes (1999), Murray & Olley (2002), Maia et al. (2011), and Guedes et al. (2013).

Facies with a marked presence of opaque, neoformed minerals and with advanced pedogenetic processes that may have leached or precipitated minerals with radioactive elements over the time of burial were also avoided. According to Guedes et al. (2013), the leaching of these elements after burial can underestimate the annual dose rates leading to overestimated deposition ages. Otherwise, the precipitation of new radioactive elements would overestimate the annual dose rates, resulting in underestimated deposition ages.

Jain et al. (2004) stated that not exposing the material to sunlight for at least 16 hours before burial would imply partial bleaching of the grains, which could overestimate the ages. In this sense, because they cover greater distances and, therefore, are exposed to sunlight for longer, we sought to sample (whenever possible) the sediments from the most distal zones of the alluvial fans.

Table 1. Experimental procedures applied to dating the samples (SAR- 15 aliquots).

1. Preheat 220°C for 10s to eliminate unstable electrons and shallow traps.
2. Optically Stimulated Luminescence (OSL) measurement (stimulation for 40s at 125°C).
3. Test dose irradiation to correct sensitivity.
4. Preheating 200°C for 10s.
5. OSL measurement (stimulation for 40s at 125°C).
6. Irradiation with light.

In the laboratory, under low-intensity red light, the sediments from the central part of the metal tubes were removed, dried and sieved. After dosimetric separation, grains between 88-180µm were treated with H₂O₂ (20%), HCl (10%) and HF (20%) for quartz segregation and removal of organic matter, CaCO₃, feldspar and the outer layer of quartz affected by alpha radiation. The experimental procedures used to obtain the equivalent dose are shown in Table 1. Such procedures were performed in the TL/OSL Automated System, Model 1100 series Daybreak Nuclear Instruments Inc. (Guérrin et al. 2011). The data referring to the rates of Thorium, Uranium and Potassium were generated by γ spectroscopy method, measurements were made on the NaI-Tl detector, models 802-2 and 727, Canberra Industries Inc. Cosmic radiation was calculated following Prescott & Hutton (1994), for which the latitude, longitude, elevation, collection depth and density data of each sample were provided to the laboratory.

4. Results

All fans studied are inactive and mostly in an advanced state of dissection by both natural processes and anthropic activities. These factors led Anstey (1965) to classify the range of current humid regions of the globe as "short-lived deposits". They are often confused with other sedimentary features and, according to Saito & Oguchi (2005), become unknown. When inserted in the geo-morphogenesis of their respective regions, they are described as mere sterile piles of eroded and vegetated gravel.

4.1. Sedimentary profiles and OSL ages

The facies from three sedimentary profiles were characterized in the alluvial fan of the Itacolomi ridge (Fig. 2). The first, in the proximal zone, was described 236m above the do Carmo River. With similar facies' characteristics, the middle zone profile was analyzed in a road cut, positioned 78m above the same river. This thick deposit did not allow us to establish the type of contact with the basement. The sediments of the proximal and middle zones comprise the massive Gmm facies. The granulometry is predominantly subangular quartz and quartzite cobble (subordinate schist and phyllite) immersed in a sandy-muddy matrix. The age of sediment deposition in the middle zone was estimated at 20.1 ± 1.6 ka (Lopes et. al. 2023, Table 2).

Performed on the Seminario Stream wall, 14m above do Carmo River, the distal zone profile consists of Gmm and Gt facies. The sediments of the Gmm facies are massive and have modally rounded cobble of quartz and quartzite (subordinate schist and phyllite) supported by a sandy-muddy matrix. The Gt facies are superimposed on the previously described facies, and supported by rounded and stratified quartz and quartzite pebbles.

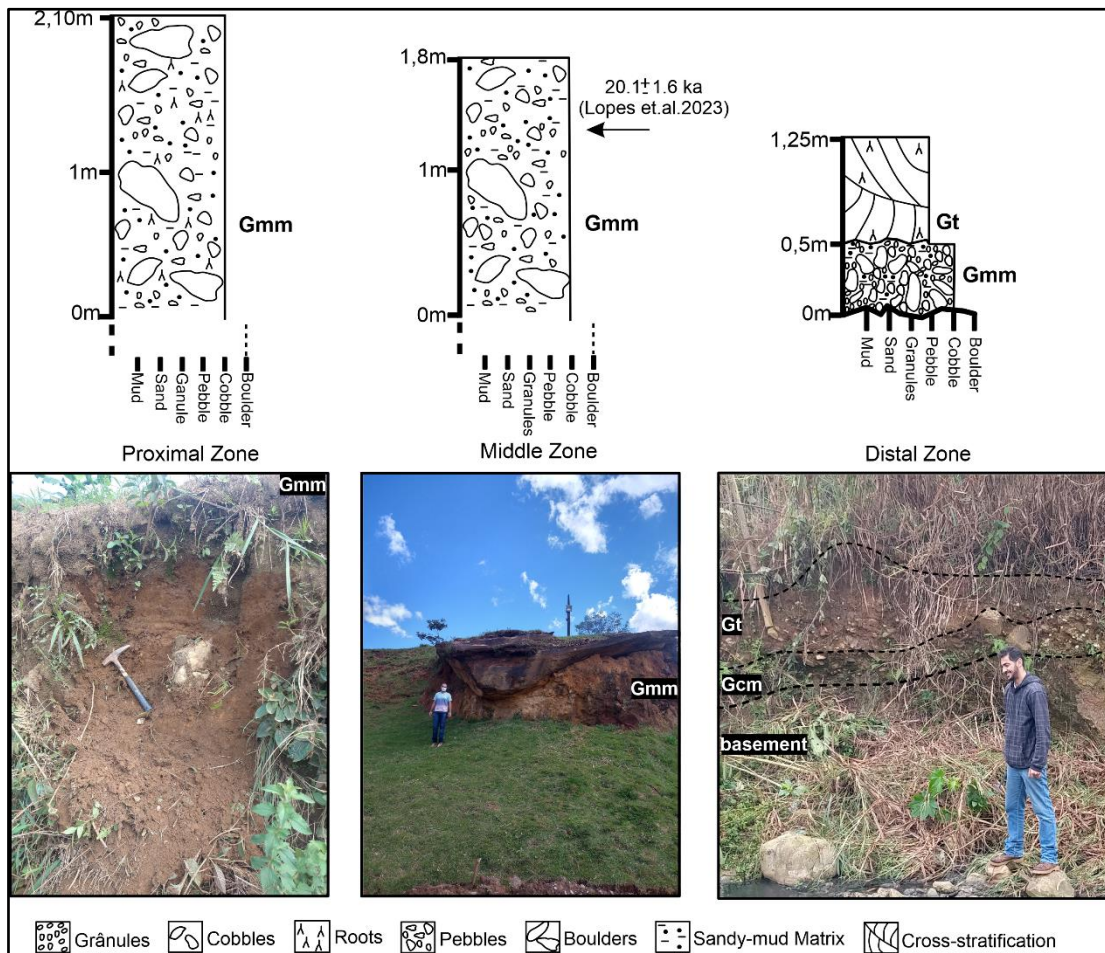


Figure 2. Sedimentary profiles of the proximal, middle and distal zones of the alluvial fan in Itacolomi ridge.

Two sedimentary profiles were surveyed in the alluvial fan of Ouro Branco ridge (Fig. 3). Given the great thickness and compaction of the sediments, the proximal zone profile was limited to the depth of an ephemeral channel, making it impossible to analyze the deeper facies or their contact with the schists and undivided phyllites of the basement. This same profile is positioned 160m above the current base level, the Soledad dam, while the facies succession comprises the Gcm, Gt and Sm facies.

The massive Gcm facies consists mainly of subangular quartz and quartzite pebbles surrounded by a sandy matrix, and the sedimentation age is estimated at 13.3 ± 0.8 ka (Lopes et.al. 2023, table 2). The Gt facies sediments are superimposed, supported by subangular stratified quartzite and quartz pebbles. The remainder of the profile

exhibits massive Sm facies whose quartz and quartzite sand grains are well selected, with a deposition age estimated at 9.7 ± 0.7 ka (Lopes et.al. 2023, table 2).

Positioned 5m above the Soledad dam, the distal zone profile of the Ouro Branco ridge fan comprises the Gmm facies, characterized by granules and rounded quartz and quartzite pebbles supported by a sandy-muddy matrix, deposited in 33.2 ± 0.4 ka (Lopes et.al. 2023, table 2).

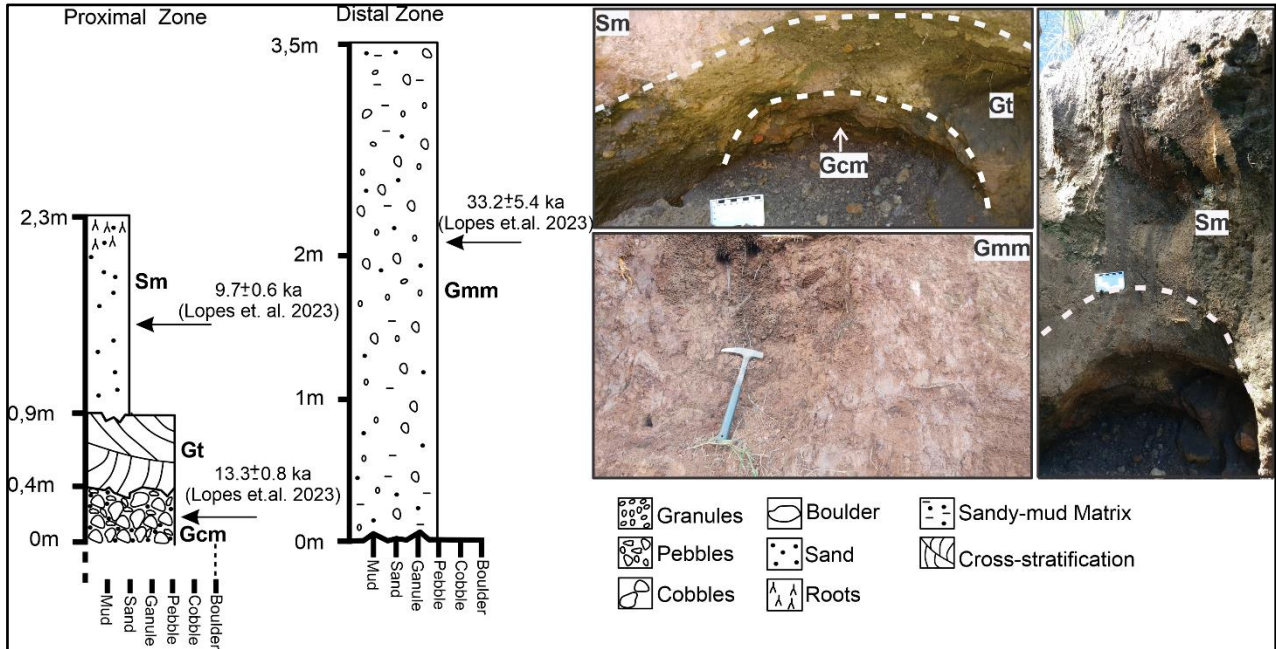


Figure 3. Sedimentary profiles of the proximal and distal zones of the alluvial fan in Ouro Branco ridge.

Three sedimentary profiles were surveyed in the Southern Bonfim Complex fan (Fig. 4). The proximal zone profile studied in a road cut, 340m above the Paraopeba River, consists of the massive Gcm facies, with mostly angular pebbles of quartz, quartzite and phyllite. The middle zone profile, conducted in a road cut, 142m above the Paraopeba River, consists of Gcm and Gt facies.

The massive Gcm facies are filled over the basement rocks and supported mainly by subangular pebbles of quartz, quartzite, phyllite and itabirite. At the profile top is the Gt facies exhibiting subangular pebbles up to 0.01m irregularly stratified, composed of quartz, quartzite, itabirite and phyllite. The distal zone profile surveyed at 83m above the Paraopeba River has Gmm and Gcm facies. The massive Gmm facies is composed mainly of subrounded pebbles of quartz, quartzite, phyllite and itabirite immersed in a sandy-muddy matrix. The remainder of the profile shows the massive Gcm facies with rounded pebbles. OSL dating estimated a deposition age of 64.4 ± 3.5 ka (Lopes et.al. 2023, table 2).

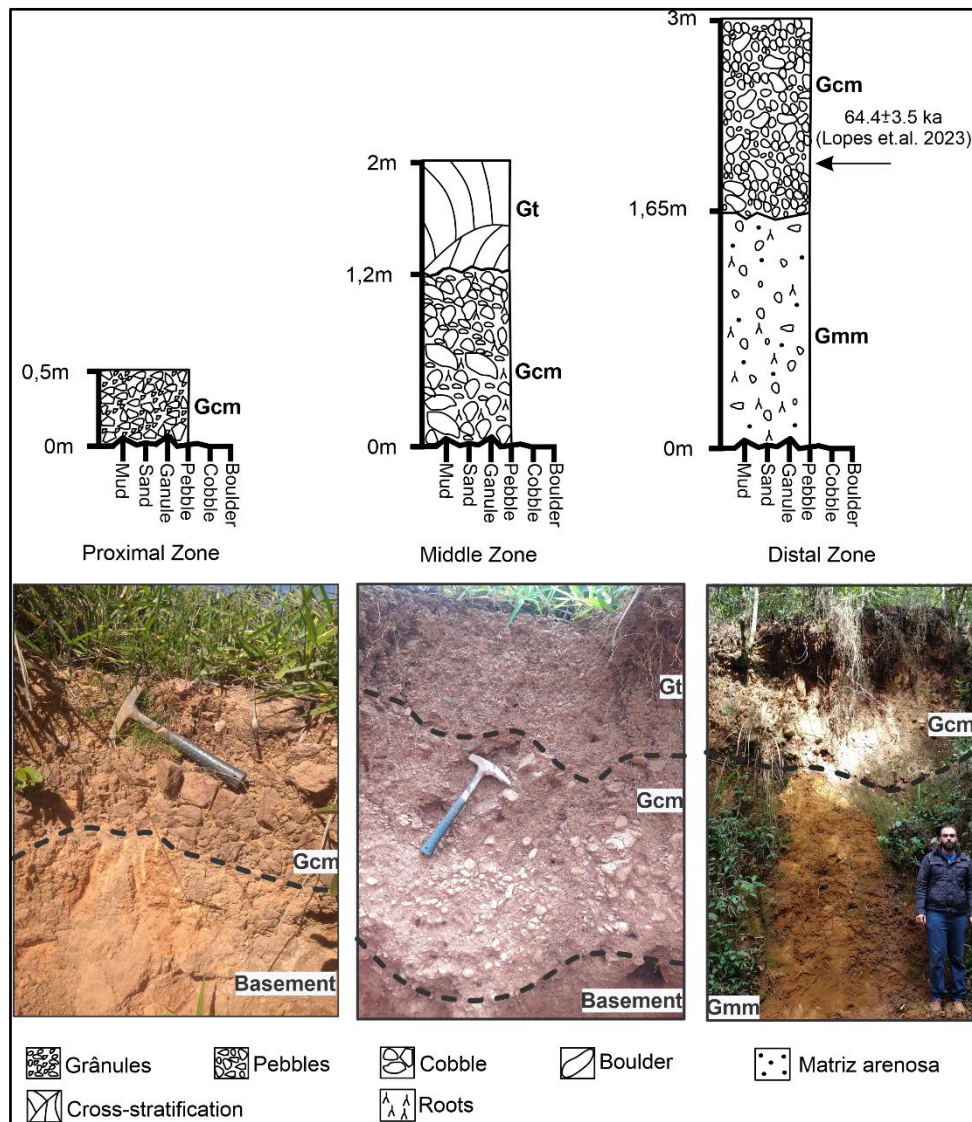


Figure 4. Sedimentary profiles of the proximal, middle and distal zones of the alluvial fan in Southern Bonfim Complex.

Three sedimentary profiles were surveyed in the alluvial fan of the Northern Bonfim Complex (Fig. 5). The proximal zone profile, located 93m above the Paraopeba River, is divided by the Gt and Gmm facies. The Gt facies has sub-rounded and stratified pebbles, arranged on the slope in the river channel. Lopes et al. (2020) established a sedimentary provenance from the higher areas of the Moeda rigde, with the metasediments of the Moeda and Cauê Formations as the main and secondary sources, respectively, and age of 12.1 ± 0.6 ka. The remainder of the profile has Gmm facies, consisting mainly of rounded quartz, quartzite and itabirite pebbles supported by a sandy-muddy matrix and scattered roots.

The facies profile of the middle fan zone was described in a road cut at 73m above the Paraopeba River, divided by the massive Gcm and Gmm facies. The Gcm facies is modally supported by subrounded quartzite and quartz pebbles whereas Gmm consists mainly of subrounded quartzite and quartz cobble immersed in a sandy matrix.

The facies profile of the distal zone is divided into the massive Gcm and Gmm facies and determined in a road cut at 54m above the Paraopeba River. The Gcm facies, with an estimated deposition age of 9.3 ± 0.6 ka (Lopes et al. 2023, table 2), is superimposed in erosive contact with the rocks of the Bonfim Complex, consisting modally of rounded pebbles of quartzite, quartz and itabirite. On top is the Gmm, with rounded pebbles of quartzite, quartz and itabirite supported by a sandy-muddy matrix.

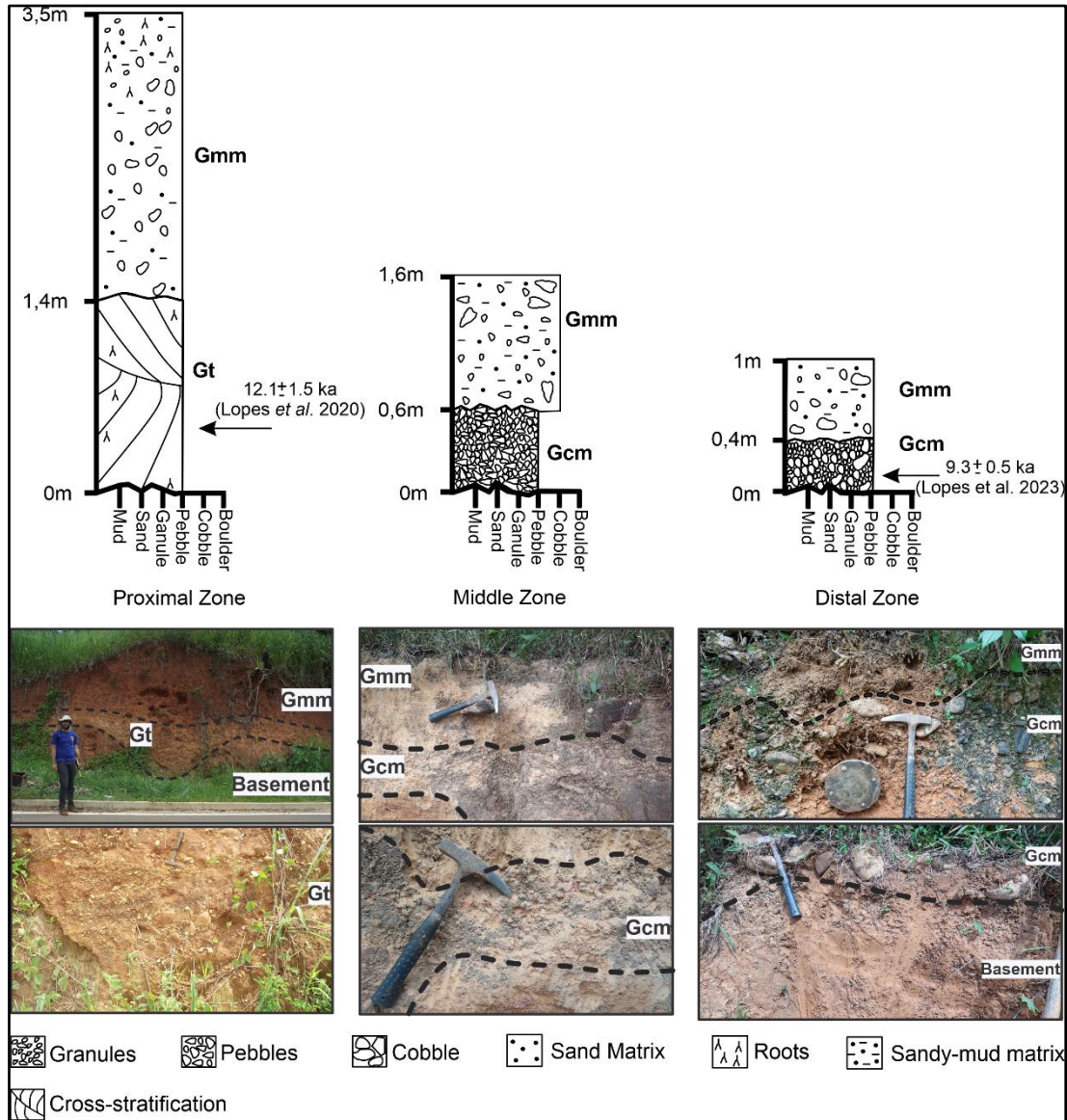


Figure 5. Sedimentary profiles of the proximal, middle and distal zones of the alluvial fan of the Northern Bonfim Complex.

Two sedimentary profiles were surveyed in the alluvial fan of Azul ridge (Fig. 6). The profile of the proximal zone is 158m above the Paraopeba riverbed, divided into Gcm, Gt and Gmm facies. The massive Gcm facies consists of well-rounded quartz and quartzite pebbles with an estimated sedimentation age of 56.3 ± 6.7 ka (Lopes et al. 2023, table 2). The Gt facies consists of irregularly stratified quartzite and quartzite subrounded pebbles, with an estimated deposition age of 20.9 ± 1.5 ka (Lopes et al. 2023, table 2). At the top of the profile, the Gmm facies consists mainly of subrounded quartzite and quartz pebbles supported by a sandy matrix.

The distal profile is positioned 67m above the Paraopeba River and consists of the massive Gcm, Gmm and Fm facies, from base to top. The Gcm facies is mainly supported by well-rounded pebbles of quartzite, quartz and, subordinately itabirite. The Gmm facies is composed of well-rounded granules of quartzite, quartz and itabirite supported by a sandy matrix, dated at 40.6 ka by Barros (2015). At the top of the profile, there is the muddy Fm facies.

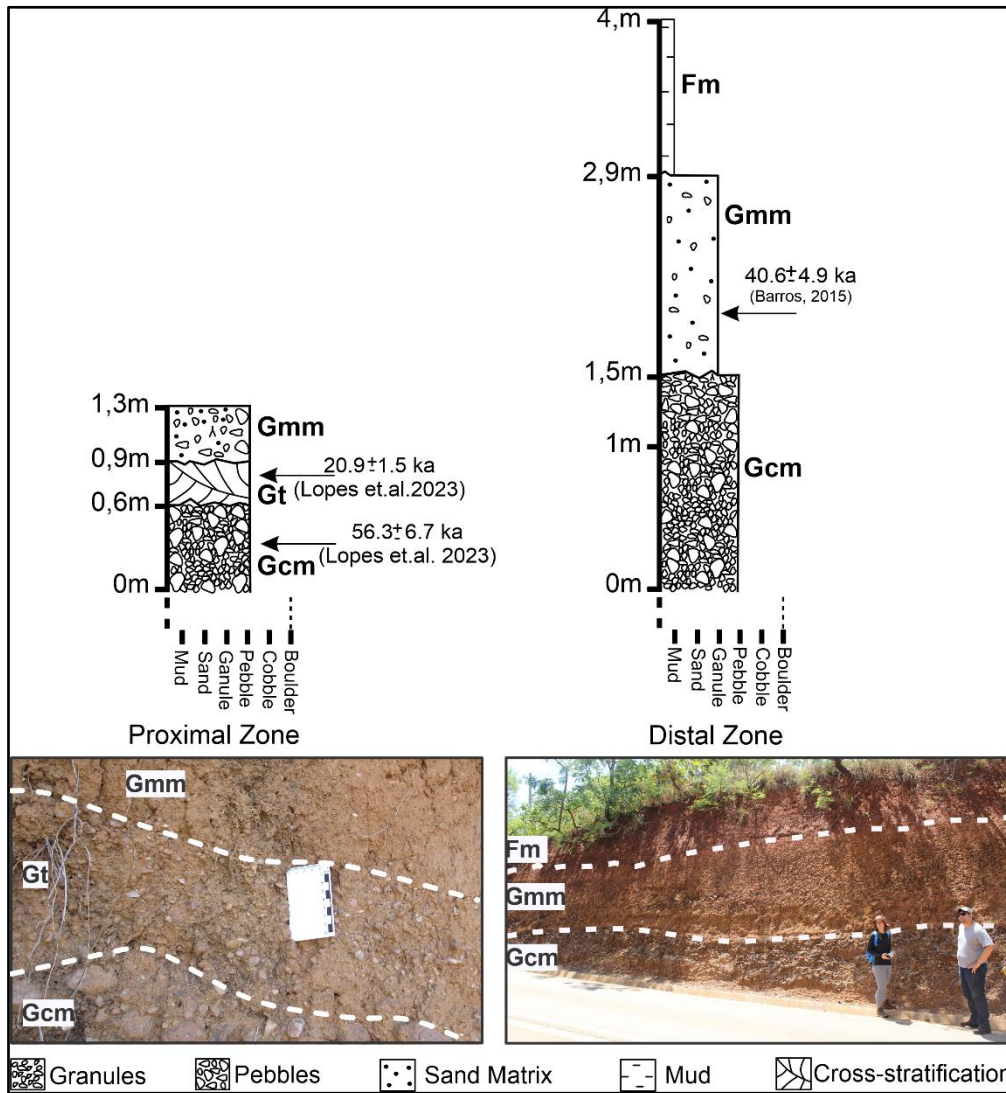


Figure 6. Sedimentary profiles of the proximal and distal zones of the alluvial fan in Azul ridge.

Table 2. Alluvial fans, dated facies, annual dose rate, equivalent dose rate, deposition ages and water content.

Alluvial fans	Facies	Annual Dose Rate ($\mu\text{Gy}/\text{year}$)	Equivalent Dose (Gy)	Age (ka)	Water content (%)
Itacolomi ridge	Gmm	1.8040 ± 100	$36,9 \pm 2,2$	20 ± 1.6	$5,7 \pm 0,6$
Ouro Branco ridge	Sm	2.420 ± 110	$23,5 \pm 1,3$	9.7 ± 0.6	$6,4 \pm 0,6$
	Gcm	3.300 ± 120	$44,0 \pm 2,1$	13.3 ± 0.8	$7,9 \pm 0,8$
	Gmm	960 ± 140	$32,0 \pm 2,0$	33.2 ± 5.4	$12,4 \pm 1,2$
Southern Bonfim Complex	Gcm	4.500 ± 150	$290,8 \pm 13,1$	64.4 ± 3.5	$7,1 \pm 0,7$
Northern Bonfim Complex	Gcm	3.700 ± 120	$34,4 \pm 1,8$	9.3 ± 0.5	$10,5 \pm 1,0$
Azul ridge	Gt	1.590 ± 90	$33,3 \pm 1,5$	20.9 ± 1.5	$4,3 \pm 0,4$
	Gcm	780 ± 80	$43,7 \pm 2,1$	56.3 ± 6.7	$0,8 \pm 0,1$

5. Discussion

5.1. Sedimentary facies and paleoclimate

The figure 7 contains the spatial distribution of the studied alluvial fans of Quadrilátero Ferrífero, age of facies and their respective paleoclimates. These data are related to the evolution phases of the regional relief from the perspective of river terraces (table 3), proposed by Barros & Magalhães Júnior (2020).

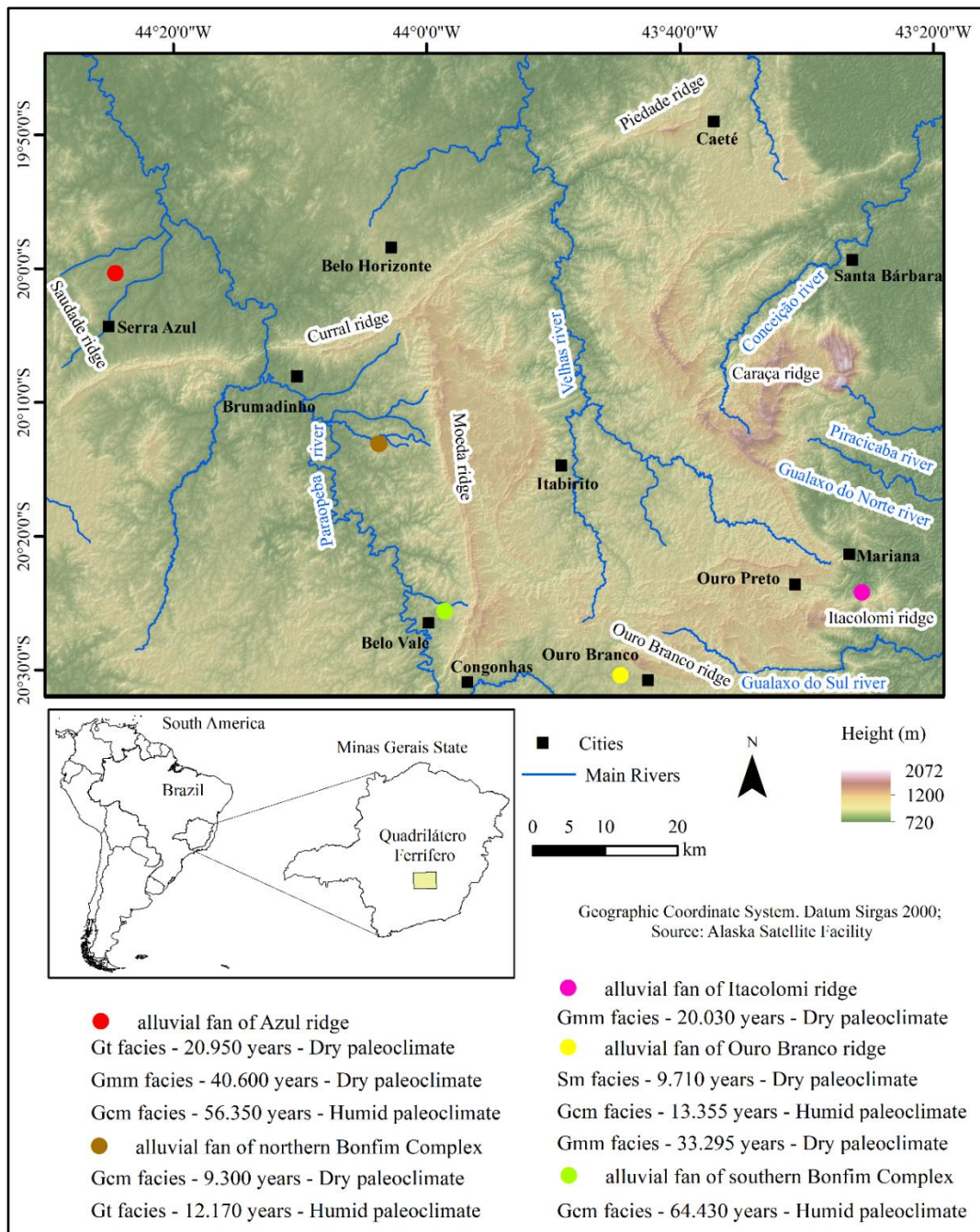


Figure 7. Spatial distribution of the studied alluvial fans, age of facies and paleoclimate.

Table 3. Organization of dated facies and association with the evolution phases of the Quadrilátero Ferrífero's relief proposed by Barros & Magalhães Júnior (2020).

Alluvial fan	Facies	Relief evolution phase
Northern Bonfim Complex	Gcm	River sedimentation phase 5
Ouro Branco ridge	Sm	River sedimentation phase 5
Northern Bonfim Complex	Gt	River incision between sedimentation stages 4 and 5
Ouro Branco ridge	Gcm	River incision between sedimentation stages 4 and 5
Itacolomi ridge	Gmm	River sedimentation phase 4
Azul ridge	Gt	River sedimentation phase 4
Ouro Branco ridge	Gmm	River sedimentation phase 3
Azul ridge	Gmm	River sedimentation phase 2
Azul ridge	Gcm	River sedimentation phase 1
Southern Bonfim Complex	Gcm	River sedimentation phase 1

5.1.1. Northern Bonfim Complex Fan

The Gt facies, limited to the proximal region (Fig. 5), refers to the filling of a confined channel and dated at 12.1 ka by Lopes et al. (2020). According to the data of Barros & Magalhães Júnior (2020), its deposition occurred during a period of incision in the drainage network associated not only with tectonic movements but also with the establishment of a humid climate (Ledru, 1993; Behling, 1997), whose increase in fluvial energy enabled the generalized notching of the thalweg (Thomas, 2008; Barros & Magalhães Júnior, 2020).

The Gcm facies observed in the middle and distal zones (Fig.5) of the fan yielded a deposition age of 9.3 ka, a period marked by the beginning of a dry climate (Behling, 1995; Parizzi et al. 1998 and Enters et al. 2010). According to Bigarella et al. (1994) and Ab'Sáber (2003), physical processes were predominant in sculpting the landscapes in this drier climate. The mechanical disintegration of rocks added to surface erosion and soil removal during torrential rains promoted the flattening of landscapes in an erosion dynamic on the slopes and sediment filling of the base levels. Furthermore, Barros et al. (2016) concluded that the drier and/or colder periods lead to vegetation retraction, favoring erosion and mass movements that filled the valleys of the Quadrilátero Ferrífero.

5.1.2. Ouro Branco ridge Fan

The Gmm facies in the distal zone was detailed and dated 33.2 ka. Regarding the paleoclimatic framework, the major inference of dry paleoclimate is highlighted and listed in the literature by Behling (1997), Behling & Lichte (1997), and Ledru et al. (2009). This facies is generated by a flow of plastic behavior, low viscosity and high cohesion, caused by a torrential rain that transported the sediments. Such findings corroborate the idea of erosion of slopes and sediment-clogged river valleys in dry weather periods (Bigarella et al., 1994; Ab'Sáber, 2003; Barros et al., 2016).

In the Gcm facies, the sediments were filled during a wet period, 13.3 ka (Ledru, 1993; Behling, 1997; Cruz Júnior, 2003) and regionally marked by the incision of the drainage network (Barros & Magalhães Júnior, 2020). Nemeč & Postma (1995) associated debris flows with (semi) arid climates and aqueous flows with humid climates. In this sense, the sedimentary characteristics of the pseudoplastic debris flow facies (Gcm) would be inconsistent with the humid paleoclimate, established by most of the authors cited in the previous paragraph. Blair & McPherson (1995) harshly criticized Nemeč & Postma (1995) and stated that the relationship between climate and facies is a widespread misconception in studies on alluvial fans. According to Blair & McPherson (1994), although non-cohesive debris flows move mainly by gravity, they are not always free of fluids.

The Gt facies, positioned between the Gcm (13.3 ka) and Sm (9.7 ka) facies, has not been dated. Despite this, dating the overlying and underlying facies allowed the inference of a humid paleoclimatic regime during its clogging (Ledru, 1993; Araújo et al., 2005; Seixas et al., 2015), whose facies characteristics converge to a continuous paleo flow, confined and with enough energy to select and stratify the pebbles.

The Sm facies from the Holocene had a sedimentation age estimated at 9.7 ka. Regarding the paleoclimate, the data available from Parizzi et al. (1998) and Araújo et al. (2005) for the region are divergent. Given this, it is noteworthy that the grain flow facies in alluvial fans are typically found and described in environments marked by aridity (Lowe, 1976; Lowe, 1982; Turner & Makhoul, 2002).

5.1.3. Itacolomi ridge Fan

The first aggradational event occurred at the end of the Pleistocene, in 20.1 ka when the Gmm facies sediments were transported to the do Carmo River plain. In this same basin, Costa (2007) dated 18.1 ka the river terrace sediments corresponding to the L3 level of Barros & Magalhães Júnior (2020).

The comparison of paleoclimatic data compiled from the southeastern region of Brazil with the deposition age of the Gmm facies of the same fan allows us to infer a dry and cold paleoclimate (Ledru et al., 2009; Behling & Lichte, 1997), typical of the Last Maximum Glacial (Van Der Hammen & Hooghiemstra, 2000). The plastic character, low viscosity and high cohesion of the Gmm facies corroborate the interpretation that torrential rain was responsible for carrying the sediments accumulated in the source area to the fluvial valley of the current do Carmo River.

The Gt facies of this fan is restricted to the distal portions. It is believed that after the Gmm facies filled up the valley, the removal of unconsolidated sediments from the fluvial channel, controlled by the energy variation of the flow, selected and stratified the pebbles from the Gmm facies. In other words, this facies is related to the secondary processes on the surface of the fan (Blair & McPherson, 1995).

5.1.4. Azul ridge Fan

Moreira (1997) believed that it is unlikely that well-rounded pebbles were sourced in the Saudade ridge, very close to these deposits, and attributed the Gcm basal facies to a fluvial level of the homonymous stream. In other words, this fan genesis is associated with deposition by a drainage course, 56.3 ka, whose sediments were later buried by unconfined sedimentary flows. The deposition is correlated with a phase recognized as clogging of the oldest preserved terraces in the region, under humid climatic conditions (Barros & Magalhães Júnior 2020).

The Gt facies, dated at 20.9 ka, locally overlapping the Gcm in the proximal region, comprises a confined paleo flow record that was deposited in a dry and cold paleoclimatic context, also related to the Last Glacial Maximum (Ledru et al., 2009; Behling & Lichte, 1997; Behling, 1997; Barros et al. 2016; Barros & Magalhães Júnior, 2020).

In the distal region, Barros (2015) dated the Gmm facies at 40.6 ka. Barros & Magalhães Júnior (2020) agglutinated the aforementioned facies to phase 2 (~47ka) of the relief evolution of the Quadrilátero Ferrífero, in a dry climate (Behling & Lichte, 1997), where a probable torrential rain removed sediments from the source area to the fan surface.

5.1.5. Southern Bonfim Complex Fan

The Gcm facies was dated to 64.4 ka. This facies is observed in the proximal, middle and distal zones, whose maturity of sediments increases downstream. The paleoclimate data from Ledru et al. (2009) and Cruz Junior (2003) converge to a humid and hot climate in its deposition date.

5.2. Considerations on alluvial fans and Cenozoic tectonics

In recent years, important data about the tectonic movements of the Brazilian continental shelf have been published. Ross (2016), for example, concluded that it is marked by epigenetic uplifts in phases of greater or lesser intensity. Saadi (1993) brought light to an orogenic event in the Andes Cordillera, which occurred between the Lower and Middle Pleistocene and culminated in the generalized uplift of the Brazilian continental shelf.

This uplift reflected in the Quadrilátero Ferrífero between the end of the Pleistocene and the beginning of the Holocene, reactivating and moving faults in a crust portion characterized by significant crustal discontinuities and uplift axes (Ferreira Filho & Fonseca, 2001; Sarges, 2002; Modenesi-Gauttieri et al., 2002; Riccomini et al., 2004; Silva & Mello, 2011). Castro et al. (2020) concluded that this period corresponds to the most recent and compressive phase of the South Atlantic tectonic event that fractured, failed, and reactivated inherited crustal discontinuities and, more recently, contributed to the generation of terrigenous deposits, alluvium, eluvium, and colluvium.

Evidence of these movements marked the regional landscape with a strong river incision and exposure of terraces (Barros & Magalhães Júnior, 2020), sediment traps of a tectonic nature in the Conceição River (Barros & Magalhães Júnior, 2013), deformation and faulting of fluvial sediments of das Velhas, Maracujá and Paraopeba rivers (Saadi, 1993; Marques, 1997; Moreira, 1997) and, finally, uplifted and/or tilted blocks in the Paraopeba and Maracujá rivers (Magalhães Jr. & Saadi, 1993; Varajão et al., 2009; Lana & Castro, 2010).

Taking the sedimentation ages and the altimetric position of the terraces as a reference, Barros & Magalhães Júnior (2020) identified high values for the Holocene fluvial incision of the Quadrilatero Ferrífero. Lopes (2017) and Lopes et al. (2020) did the same in the Piedade and Casa Branca streams, upstream of Fecho do Funil, where drainage courses cut old sediments from alluvial fans. All these authors reported rates varying between 0.33 and 1.29 mm a⁻¹, considered from orogenic environments if compared to the Andean studies by Safran et al. (2005). Barros & Magalhães Júnior (2020) concluded that the high values of the fluvial incision are explained by the incision of the drainage network in unconsolidated sediments and saprolite.

Although the river incision values found by Lopes (2017) and Lopes et al. (2020) are consistent with the same magnitude obtained in alluvial terraces, believed to be infeasible to establish incision rates for environments with alluvial fans. Due to the sudden dynamics of sediment filling by concentrated flows, the top sediments may be associated with events that clogged the trough and, consequently, overflowed at the edges of the channels. Thus, it is impossible to define the altimetric position of the fluvial channel at the time of sediment deposition, which may overestimate or underestimate the fluvial incision rates.

Undoubtedly, the fluvial dissection acted more strongly on the sediments of the alluvial fans of the Southern and Northern Bonfim Complex, where the Paraopeba River and its tributaries drain. In this same basin, Barros & Magalhães Júnior (2020) found the highest incision rates in the Quadrilatero Ferrífero, between 2247 and 4494 mm/ka, and concluded that it settled on a tectonic block which underwent greater uplift during the Late Quaternary.

Thus, according to these authors, the pulse between the Middle and Upper Pleistocene generated tectonic activities of greater or lesser intensity in the last 100 ka years, sometimes leading to an incision in the drainage network. In other words, by controlling the dynamics of the Paraopeba River, tectonics influenced the sedimentation of the Bonfim Complex alluvial fans during uplifting episodes in the Curral ridge, which blocked the Fecho do Funil sediments upstream (Magalhães Jr. & Saadi, 1993) and, subsequently, in Holocene fluvial dissection. Lopes et al. (2020) proposed that the river network notched fault and fracture planes, leaving adjacent fragments preserved.

Another interesting observation regarding the tectonic block where the Paraopeba River basin drains is the fact that the Gcm facies of the fans of the Ouro Branco ridge and the northern Bonfim Complex were deposited in periods of fluvial incision. This river incision may reflect both the tectonic uplifts that naturally destabilize the slopes, leading to material sedimentation and the greater energy of the drainage courses due to more humid climates (Thomas, 2008; Barros & Magalhães Júnior, 2020).

In do Carmo River, Lopes (2017) based on the age (18ka) of a terrace obtained by Costa (2017), found an incision of 0.17 mm/ka while Barros & Magalhães Júnior (2020) reported values between 210 and 420 mm/ka in the same basin. These terraces are chrono correlated to the Gmm facies of the Itacolomi ridge fan. In this sense, the phases of greater incision of the do Carmo River also implied the fluvial dissection of its tributaries, contributing to the dismantling of the fan. The same occurred in the basins of the Serra Azul and Mateus Leme streams, where Barros & Magalhães Júnior (2020) found rates varying between 472 and 1061 mm/ka in phase 1, and 463 mm a⁻¹ in phase 4. These phases are chrono-correlated with the deposition of the Gcm and Gt facies of the Azul ridge fan.

It is noteworthy highlighting the relevant influence of the tectonic environment on the thickness of the alluvial fans facies. The Pleistocene fans described have less thick facies than the Chapada da Canga, of maximum Neo-Oligocene age (Maizato, 2001). Castro (2017) stated that the geological sections of the Chapada da Canga fan demonstrate that its generation was conditioned by taphogenic basin, which allowed for the accumulation and preservation of sediments in local grabens. On the contrary, the younger fans, mainly those of the Bonfim Complex, had their genesis and evolution linked to epigenetic tectonic dynamics. This difference in the facies thickness becomes even more discrepant when compared with the fans developed in large sedimentary basins whose regional subsidence allows a large sedimentary accumulation, such as the megafans of the Pantanal wetland basin, described by Assine (2003), Silva (2010), Kuerten (2010); Corradini (2011), Pupim (2014), among others.

6. Conclusions

- The sedimentary characterization demonstrated facies predominantly composed of debris flows in all regional fans whose lithological and mineralogical composition is conditioned by the geology of their respective source areas. The description and interpretation of the sedimentary facies contribute to the Cenozoic stratigraphy of the Quadrilátero Ferrífero.
- The ages of the sedimentary facies of the alluvial fans, even those acquired in debris flows, were considered reliable after extensive discussion of the determining factors for obtaining the annual equivalent dose rates, as evidenced by Lopes et al. (2023). Also, the ages are chronologically consistent with the geomorphological landscape where they are located and with the geomorphological literature available for the region.
- Paleoclimatic analysis of the facies deposition demonstrated, in most cases, consonance between facies characteristics and their respective paleoclimate. This analysis also complements the studies by Barros & Magalhães Júnior (2020), where the age of clogging of the sedimentary facies of alluvial fans is related to the evolution phases of the relief proposed from the traditional perspective of river terraces.
- Within the tectonic perspective, the main conclusion refers to the fluvial incision. Uplifts of the Brazilian shelf are reflected in the strong incision of the drainage network throughout the Pleistocene and Holocene. This river dissection occurred not only in the main drainage courses but also in the tributaries and, in addition to generating river terraces according to data by Barros & Magalhães Júnior (2020), it also dissected the alluvial fans.

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