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Research Paper

Geoconservation of geological and mining heritage related to banded iron formation of Itabira Group, Quadrilátero Ferrífero, Minas Gerais, Brazil: A challenging issue

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ABSTRACT

The Quadrilátero Ferrífero is a mineral-rich region covering about 7,000 km^2 in Central-Southern Brazil. It is known for its extensive gold and iron ore reserves, and for its historical cities. Many geological and mining sites related to gold mining and iron ore mining are in protected areas, and have been studied for preservation and use in educational and tourism projects, but at the same time, the region has suffered many pressures from mining companies and its preservation is in a constant state of alert. Recently, geoconservation studies have emphasised the value of geological and mining heritage, its importance for understanding the history of territorial occupation, as well as the geological evolution of our planet. For example, the Cauê Peak is the type-locality of the Cauê Formation, where six new minerals (arsenopalladinite, atheneite, isomertieite, palladseite, jacutingaite and palladinite) were identified in the Au—Pd deposits which were listed by the International Mineralogical Association (IMA), and where the systemic iron mining activities began with the creation of the first mining company, the Brazilian Hematite Syndicate, in 1909. Since the 19th century, many of these geosites have been the target of research and educational field trips in the training of geologists and mining engineers at the Ouro Preto School of Mines and Federal University of Minas Gerais. These geosites can be used to explain the geological history in the Archaean-Paleoproterozoic boundary of the Quadrilátero Ferrífero (QF), the depositional environment of banded iron formations of the Cauê Formation, and also through the Transamazonian (2.1-1.94 Ga) and Brazilian (650-450 Ma) orogenies responsible for development of Au—Pd and iron deposits. When observing the Cauê Peak, the Itabira Peak and the Curral Mountain, the different stages in the evolution of the anthropic landscape can be observed. The Cauê Peak has been transformed into an open pit mine, the Itabira Peak is surrounded from all sides by mining activities and the Curral Mountain undergoes processes for authorization of mining activities in an area that should be preserved.

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1. Introduction

Geoconservation has a very broad scope, which not only involves taking into account geological aspects, but also other environmental sciences, legislation, spatial planning, and even economics and sociology (Urquí, Martinéz, & Valsero, 2007). According to these authors, the conservation of natural environments should be understood as a set of measures and actions aimed at maintaining or recovering the natural value of a particular site or natural element. Geoheritage sites can occur on different scales, from small rock outcrops to huge landscapes formed by rocks and soil that must be identified and documented accurately (Crofts et al., 2020).

Abiotic diversity is fundamental for biodiversity and for the development of human societies, for without it there would be a very limited number of living species, and possibly no humans (Gray, 2004). The term geoconservation refers specifically to geological elements - abiotic -such as geological heritage, geosites and geodiversity. Geoconservation involves the protection from damage of internationally and nationally significant geosites, their physical management, and their enhancement for scientific and educational uses (ProGEO, 2011). Geoconservation also aims to preserve cultural, scientific and landscape features among others, which may be related to geological heritage or elements of geodiversity.

The main geoconservation strategies must involve inventory, quantification, classification, conservation, enhancement, dissemination and monitoring (Brilha, 2005). Subsequently, it is necessary to carry out their promotion, i.e., making them accessible for educational and/or touristic use (Garcia, Mansur, Nascimento, & Pereira, 2020; Higa & Garcia, 2021). There is no specific legislation for geological heritage protection in Brazil, only for fossils and caves. At the state level, there are some states that have legislation applied to geodiversity and with important initiatives, such as the Geological Monuments project of the State of São Paulo, Geological Paths of Rio de Janeiro, the Geological and Paleontological Sites project of Paraná, the Geological Paths project of Bahia, and the Geological Monuments project of Rio Grande do Norte (Araújo, Silva, & Aquino, 2021). The State of Minas Gerais does not have any specific legislation for geological heritage, but there is conservation of natural monuments which are defined as integral conservation units with the objective of preservering unique natural sites of great scenic beauty (IEF, 2022). Several geosites studied are located in environmental preservation areas, such as environmental preservation areas (APAs); private natural heritage reserves (RPPNs); national, state and municipal parks, and protected as natural monuments by the State Institute of Historical and Cultural Heritage of Minas Gerais (IEPHA). Despite the existence of several types of preservation areas, the Quadrilátero Ferrífero (QF) urgently needs political action that promotes geoconservation of its geosites, since their conservation also means preserving the history and culture of its people.

The banded iron formations (BIFs) of the Cauê Formation have been mined since the begining of the 18th century for gold, and later, from the 20th century, for iron ore. The Quadrilátero Ferrífero is responsible for approximately 70% of the Brazilian and approximately 10% of the world's iron ore production (Amorim & Alkmim, 2011). In addition to mineral reserves, BIFs also constitute aquifers that supply most of the cities located in this region. It is located in the central region of Minas Gerais, which was the main occupation axis of the territory during the colonial period and where today the cities of Ouro Preto, Mariana, Congonhas, Sabará, Caeté, Santa Bárbara, Barão de Cocais, and Catas Altas are located. These cities maintain traces of human occupation, of the gold mining activities that took place during the 18th century, and of the iron mining activities occurring since the beginning of the 19th century.

The geological and mining heritage in the region have been targets of research since the 19th century and have also contributed, for more than a century, to the educational field trips of students in the Geology and Mining Engineering courses at the Ouro Preto School of Mines and the Federal University of Minas Gerais. The geosites discussed here occur at the Archean-Paleoproterozoic boundary and are related to the deposition of the banded iron formations (~2.52 Ga) and with the Transamazonian (2.1–1.94Ga) and Brasiliano orogenies (650 - 450 Ma) from which the gold and iron deposits originated.

2. Methodology

This study is part of the project Geological Heritage of Brazil, Inventory of the Minas Gerais State. The inventory has 110 geosites distributed in the various geological domains of the state, of which 33 geosites are located in the Quadrilátero Ferrífero. In this study, eight geosites that are in Paleoproterozoic banded iron formations of the Cauê Formation, Itabira Group are discussed. These geosites are Cauê Peak, Itabira Peak, Curral Mountain, Piedade Mountain, Rola Moça Mountain, Gongo Soco Mine, Santo Antônio Hill, Santana Hill, and Chico Rei Mine.

The first part of the present research was revision of the literature about banded iron formations, mineralizations of Au—Pd and Fe, and the history of gold and iron mining in the Quadrilátero Ferrífero. Subsequently, an inventory was made of the geosites related to the iron formations of the Itabira Group and of the gold and iron mines (in operation, stopped and exhausted) in the vicinity of the inventoried geosites.

Geological heritage constitutes the register of notable features of geodiversity, represented by geological sites of exceptional value, the geological memory of the country. These sites are key locations for the understanding of the origin and evolution of the Earth and the evolution of life since its formation, which is why they need to be preserved (Brilha, 2016). The characterisation and assessment was carried out the application of the GEOSSIT platform of the Geological Survey of Brazil, using a method proposed by Brilha (2016). Subsequently, a survey of the preservation areas where the geosites were located was carried out in order to analyse the current situation of these areas in relation to their geoconservation. The conservation units had their regulation defined through Law No. 9.985 of 2000, which created the National System of Preservation Units (SNUC). The SNUC has 12 categories of conservation units which can be of full protection, or sustainable use (Couto & Figueiredo, 2019). In the full protection group, there are the following categories: national park, natural monument, ecological station, biological reserve and wildlife refuge. In the sustainable use group, there are the following categories: environmental protection area, area of relevant ecological interest, national forest, extractive reserve, wildlife reserve, sustainable development reserve, and private reserve of natural heritage. The agencies responsible for these areas are, at national level, the Chico Mendes Institute of Biodiversity Conservation (ICMBio); at state level, Minas Gerais the State Forest Institute (IEF); and at municipal level, the local municipalities.

The purpose of national parks is to preserve natural ecosystems of great ecological relevance and scenic beauty, allowing for scientific research and the development of environmental education and interpretation activities, recreation in contact with nature, and environmental tourism (ICMBio, 2022). The basic objectives of the state parks are to preserve natural ecosystems of great ecological relevance and scenic beauty; to facilitate scientific research and the development of environmental education and interpretation activities; for recreation in contact with nature; and ecological tourism. State parks belong to the category of fully protected conservation units and are under public ownership (IEF). The municipal parks contribute to the preservation of flora, fauna and water resources, as well as to allow the population to have close contact with green areas, thus ensuring good environmental quality of the cities. An environmental preservation area (APA) corresponds to an extensive natural area, with a certain level of human occupation, which guarantees the protection and conservation of biotic, abiotic, aesthetic, or cultural attributes that are important for the quality of life of the population (IEF, 2022). The state special protection areas (APEE) are the areas defined and demarcated by the Minas Gerais State Government for the protection and conservation of springs (IEF, 2022). The natural monuments belong to the group of full-protection conservation units, and the basic goal is to preserve rare, unique natural sites or sites of great scenic beauty, and can be made up of public and private areas (IEF, 2022). Private natural heritage reserves (RPPNs) are conservation units of private domain in perpetuity, with the objective of conserving biodiversity, without expropriation or alteration of the rights of use of the property. They can be created in rural and urban areas without minimum size for their establishment (ICMBio, 2022).

3. Mining history

Mining in Brazil is closely related to the process of territorial occupation. Gold production in Minas Gerais began in the last decades of the 17th century, when hundreds of alluvial deposits were discovered around Ouro Preto, Mariana, Sabará and

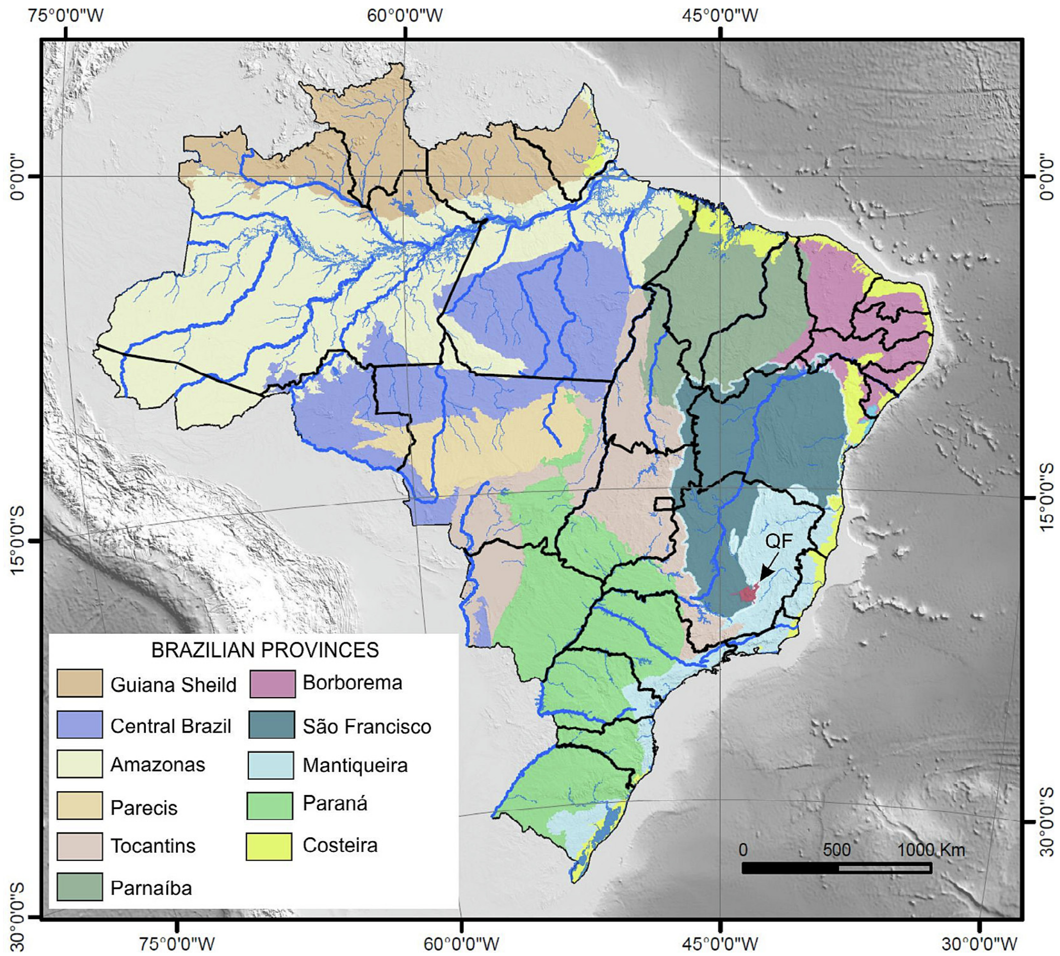

Fig. 1. Map of structural provinces of Brazil and the location of the Quadrilátero Ferrífero domain (QF) (adapted from Almeida et al., 1981).

Caeté (Souza & Reis, 2015). Alluvial gold and quartz vein deposits were found in a free state and their mining was carried out in the open, using tray structures and a catas system. In this historical period, underground mining was rarely used and all processes were very rudimentary.

The extraction of gold occurred in the river beds, on the slopes of the mountains and within the massifs (by opening open-pit mines), and more rarely through underground mines (Sobreira, 2014). The gold in alluvium, paleo-alluvium, and in the more superficial layers was depleted over time, causing the decline of mining in Minas Gerais. The lack of advanced mining techniques in this period was described by several European naturalists that visited the region's mines as the main cause of this decline. It was only during the Brazilian Empire, when foreign companies were allowed to mine for gold and other metals, those more advanced mining techniques were implemented in the underground mines, creating a new lease of life for gold mining in Minas Gerais.

In the 19th century, the gold mines of Passagem de Mariana, Gongo Soco and Morro Velho were under the command of British mining companies. At the beginning of this century, gold production was in full decline. Only with the arrival of the British was there a transfer of technology, incorporating new methods of mining and treatment of the gold ore, causing a new rush in gold mining in the State of Minas Gerais.

Iron ore mining activities in the Quadrilátero Ferrífero were very limited during the 18th century. Iron ore was only used in small forges to produce tools to be used in gold mining. These forges were mostly built by slaves that brought crucible technology

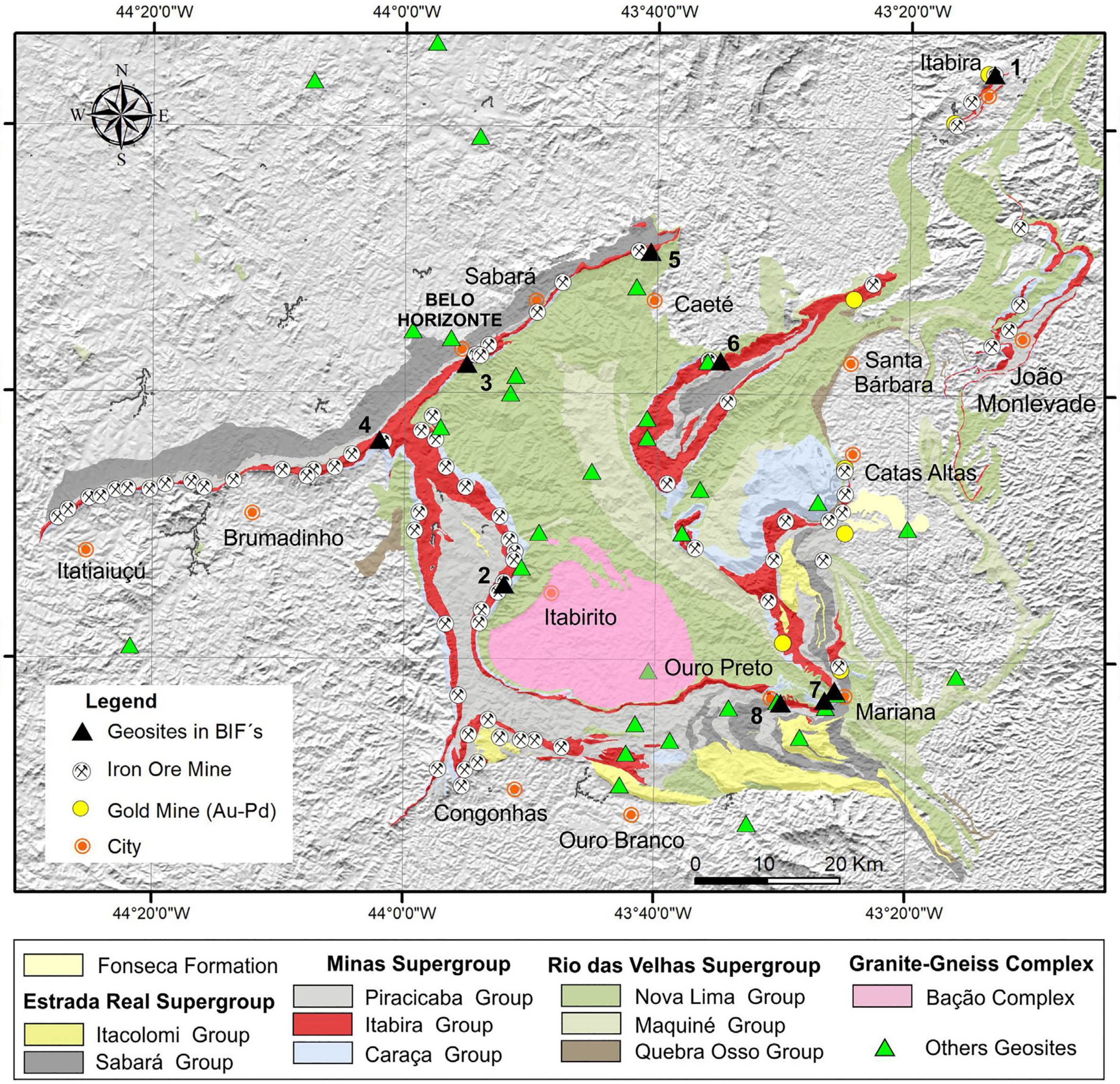

Fig. 2. Simplified geological map of Quadrilátero Ferrífero with location of main geosites and historical cities, geological and mining heritages related to banded iron formations studied. (1) Cauê Peak. (2) Itabira Peak. (3) Curral Mountain Park. (4) Rola Moça Mountain. (5) Mountain of Piedade. (6) Gongo Soco. (7) Santo Antônio and Santana hills. (8) Chico Rei Mine. Map based on Pinto and Silva (2014) and Endo et al. (2019).

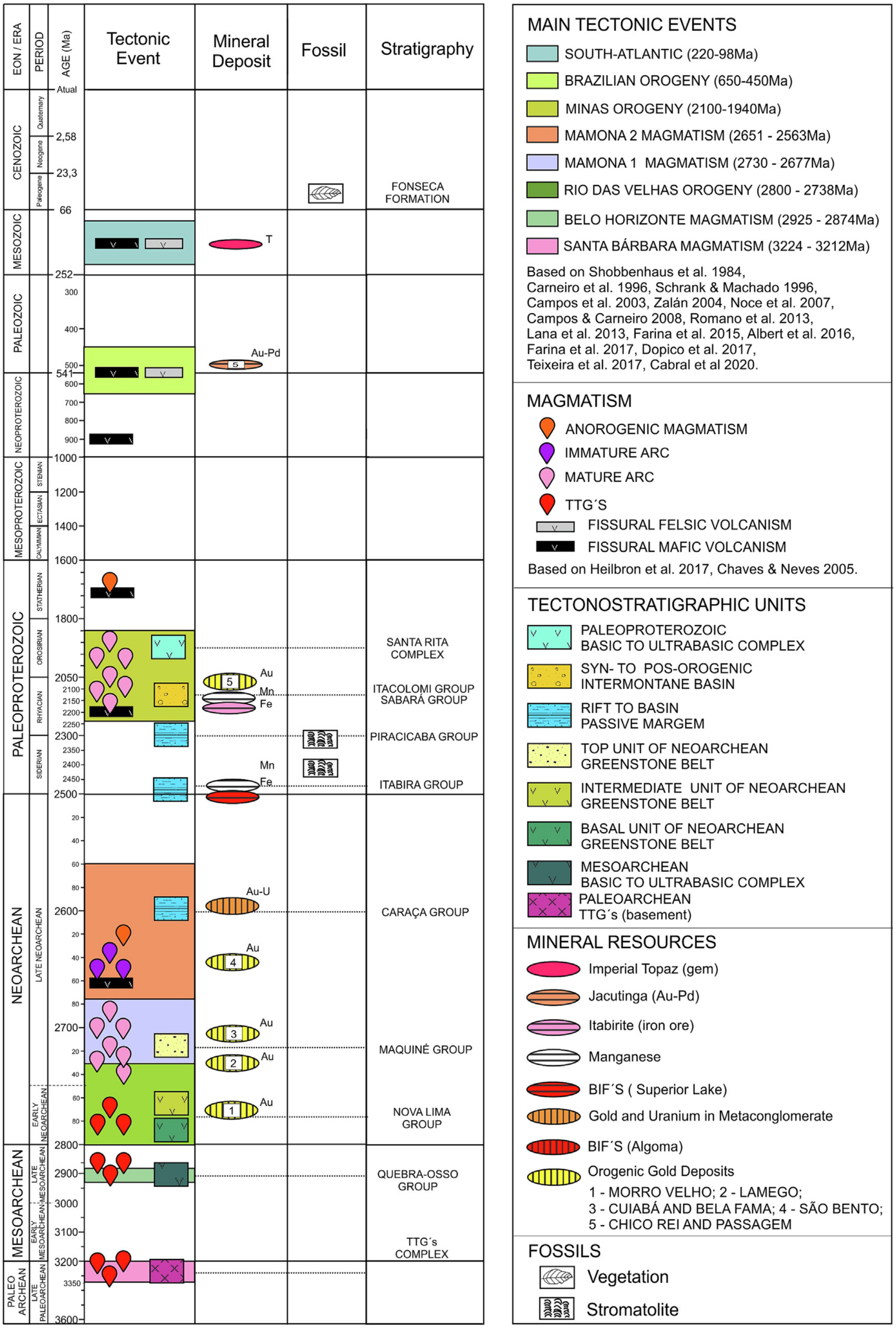

Fig. 3. Chart with the main stratigraphic and tectonostratigraphic units, tectonic events, mineral resource and fossils of the Quadrilátero Ferrífero (compiled from Cavalcanti, Silva, Schobbenhaus, & Lima, 2021).

Fig. 4. (a) Cauê Peak in 1910. (b) Cauê Peak in the first years of ore extraction between 1942 and 1945 (photos compiled from Vale 2012).

from Africa. According to Gonsalves (1932), almost all the iron used in construction in this period was imported and its production was prohibited in Brazil. Only with the arrival of D. João VI was the implementation of iron factories allowed. The first iron factory was built in Sorocaba, State of São Paulo, in 1801. Only in 1808, through a royal charter, was a company to be allowed to extract iron ore in Minas Gerais, and so, in 1809, the Gaspar Soares Iron Factory, in Minas Gerais, was set up. In 1811, the Baron of Eschwege arrived in Minas Gerais aiming to produce iron industrially in the region of Congonhas do Campo. It was then that the "patriotic factory" was created, which in 1812 produced the first iron bar with the aid of a hydraulic horn. Later, the direct iron production process was brought from Europe by Mr. Monlevade, who built the São Miguel de Piracicaba Factory, in 1825. With the graduation of the first mining engineers, from Escola de Minas de Ouro Preto, there was a great increase in studies in the metallurgy area in Brazil. In 1888, the Esperança factory was founded in Itabira do Campo (today Itabirito), at the foot of Itabirito Peak.

In the 1910's the steel industry came into favour because of the studies carried out by the students and professors of the School of Mines, which confirmed the existence of enormous reserves of high quality iron ore in Brazil—around 10 billion tons.

Fig. 5. Google Earth satellite image from Cauê Peak today. The open pit is being filled with tailings.
Source: Google Earth in 2022.

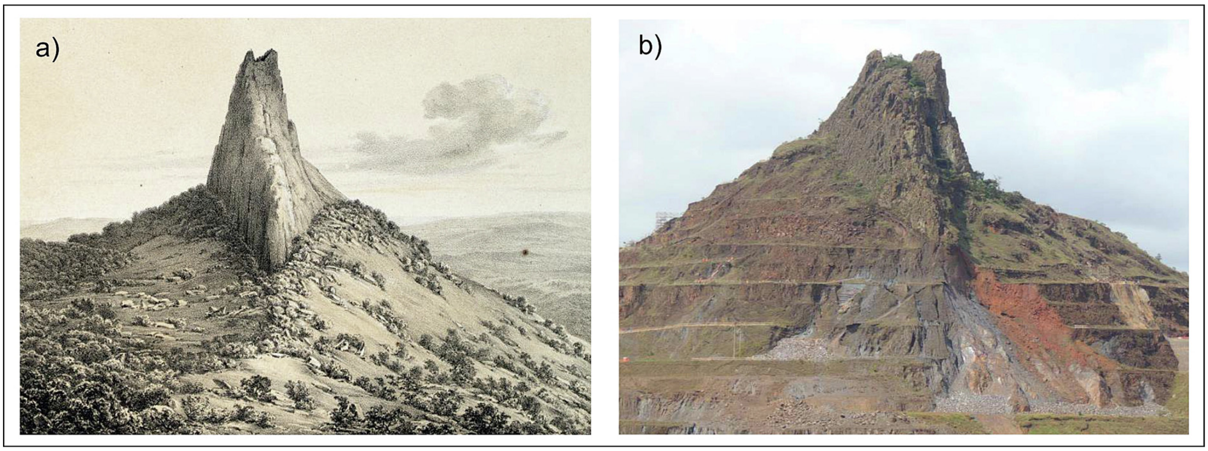

Fig. 6. Images of Itabira Peak. (a) Itabira Peak, according to Martius (1906). (b) The peak today surrounded by the Pico Mine benches (compiled from Rosière et al., 2009).

These studies were disclosed at a congress in Stockholm, organised by large steel companies from Europe and the United States. With this, the Federal Government started encouraging the domestic production of iron and steel by encouraging Brazilian or foreign companies and individuals wishing to set up steel undertakings in Brazil. And so began the iron rush in Minas Gerais in the Quadrilátero Ferrífero region, with the founding of the Brazilian Hematite Syndicate based in London, which later became the Itabira Iron Ore Company (Vale, 2012).

In the 1940s, the Rio Doce Valley Company (CVRD) and the Nacional Steel Company (CSN) were created in order to supply the international market due to the demand for iron during World War II. Then, between the years 1946 and 1964, an agreement was signed between the United States Geological Service (USGS) and the National Department of Mineral Research (DNPM), when 42 geological maps were mapped at the scale 1:25,000 and the integration resulted in the geological map of the Quadrilátero Ferrífero, by Dorr (1969), at a scale of 1:150,000 (Zapparoli et al., 2019).

4. Geology and metallogeny

The Quadrilátero Ferrífero is located in the southernmost part of the São Francisco craton and is interpreted as a portion of the crust stabilised since the early Phanerozoic, and in the Archaean was part of a larger block called the Paramirim craton (Almeida,

Fig. 7. Google Earth satellite image from Pico Mine and Itabira Peak today.
Source: Google Earth in 2022.

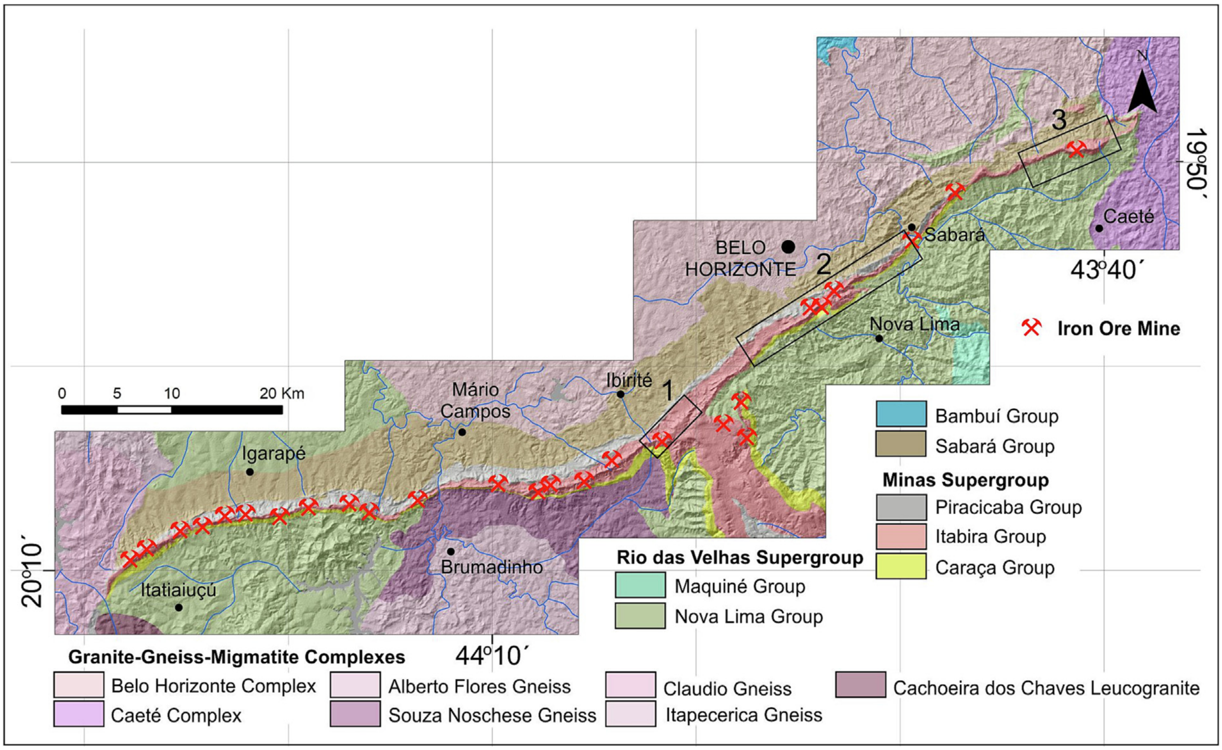

Fig. 8. Simplified geological map of the Curral Mountain Ridge with the location of the iron ore mines and the main geosites. (1) Rola Moça Mountain. (2) Curral Mountain. (3) Piedade Mountain. Map based on Pinto and Silva (2014).

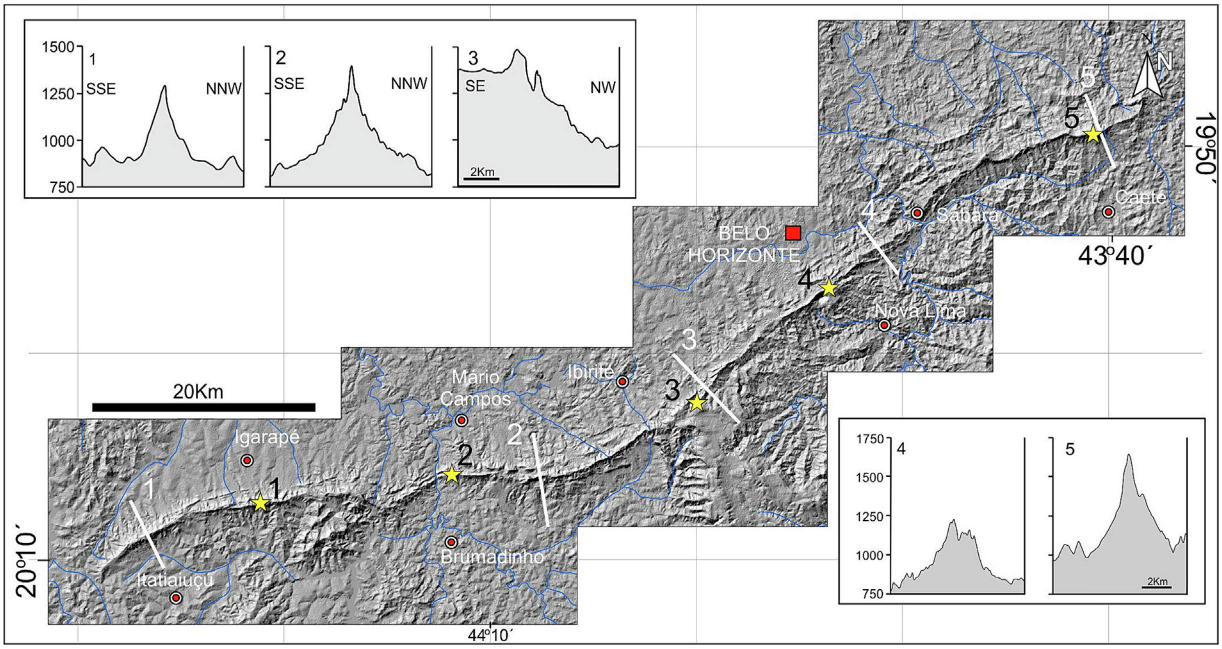

Fig. 9. Digital Terrain Model of Curral Mountain Ridge with the location of the topographic profiles and the main peaks. Profiles: (1) Itatiaiuçú Mountain (or Azul Mountain); (2) Três Irmãos Mountain; (3) Rola Moça Mountain; (4) Curral Mountain; (5) Piedade Mountain. Peaks and mountains: (1) Itatiaiuçú Peak (1,435 m); (2) Três Irmãos Peak (1,422 m); (3) Rola Moça Peak (1,506 m); (4) Belo Horizonte Peak (1,388 m); (5) Piedade Mountain (1,654 m).

Fig. 10. Photographs from some points of Curral Mountain Ridge. (a) Partial view of the Curral Mountain Ridge from Rajagabaglia Avenue, Belo Horizonte. (b) View from the viewpoint of the Curral Mountain Municipal Park. (c) View to the east from the viewpoint of the Curral Mountain Municipal Park, Belo Horizonte. (d) Entrance to Mangabeiras Park. (e) Outcrop of itabirite in Mangabeiras Park. (f) Parcial view of Pedra Grande Natural Monument and the trail that leads to the top of the rock (Cortesy of Alisson Amorim). (g) Cave entrance in itabirite of the Pedra Grande Natural Monument (Cortesy of Frederico Moreira).

Hasui, Brito Neves, & Fuck, 1981; Heilbron, Cordani, & Alkmim, 2017) (Figs. 1 and 2). The Archaean crust consists of granite-gneiss complexes and the Rio das Velhas greenstone belt, and is overlain by two Paleoproterozoic meta-volcano-sedimentary sequences of the Minas and Estrada Real supergroups (Alkmim & Marshak, 1998; Dorr, 1969; Endo et al., 2019).

The Minas Supergroup was interpreted as a rift sequence, which subsequently evolved into a passive margin basin (Dopico, Lana, Moreira, Cassino, & Alkmim, 2017). Its lithotypes encompass thick layers of quartzites, phyllites, iron formations, dolomites, greywacke and metavolcanic rocks (Dorr, 1969). At the base, the Caraça Group is composed of meta conglomerates and metarenites grouped in the Moeda formation, and metapelites grouped in the Batatal formation. Isotopic studies in the Moeda Formation (U—Pb in zircon and xenotime) indicated maximum age of deposition at 2.62 Ga (Koglin et al., 2014). The Itabira Group is a sequence composed of Lake Superior-type banded iron formations, carbonatic shales and ferruginous marbles grouped in the Cauê Formation and another essentially carbonatic sequence referred to as the Gandarela Formation with an age of 2.42 Ga (Babinsky, Chemale, & Van Schumus, 1995). Separated by an erosional discordance at the top, the Piracicaba Group is composed of meta conglomerates and ferruginous quartzites, which graduate to carbonaceous metapelites and shales at the top. U—Pb ages in detrital zircons of the Piracicaba Group indicate similar patterns to the Caraça Group, with ages between 3353 and 2275 Ma (Machado, Schrank, Noce, & Gauthier, 1996), indicating gneiss terrains as a common source of the sediments (Figs. 2 and 3).

4.1. Banded iron formations

Banded iron formations are the main source of iron ore and are particularly important for the understanding of the evolution of the atmosphere, chemical composition of the oceans, and the emergence of life on our planet (Spier, Oliveira, Sial, & Rios, 2007). The iron formations of the Minas Supergroup in the Quadrilátero Ferrífero are concentrated in the Cauê Formation (Dorr II, 1958) of the Itabira Group (Harder & Chamberlin, 1915) which has its type localities at Cauê Peak (Itabira city) and Itabirito Peak (Itabirito city). The Cauê Formation is a classic Paleoproterozoic BIF deposited in a rift environment that evolved to a continental shelf, being classified as a “Lake Superior” by Gross (1980). Several geological processes acted on these rocks modifying the original characteristics of the sediments, resulting in a metamorphosed and oxidised BIF (Spier, 2005). The Cauê Formation is composed of lenses and layers of sericite phyllite, dolomite phyllite, and marble, which occur intercalated with the banded iron formations that can reach thicknesses between 250 and 300 m. Felsic and pyroclastic volcanic rocks occur in smaller proportions, with thicknesses of a few metres up to 70 m.

4.2. Au—Pd deposits

The Au—Pd deposits are known in the region by the name “Jacutinga”, which is an indigenous name commonly used to describe a type of pulverulent itabirite rich in manganese (Ladeira, 1988). The ore bodies are thin concordant lenses that occur in

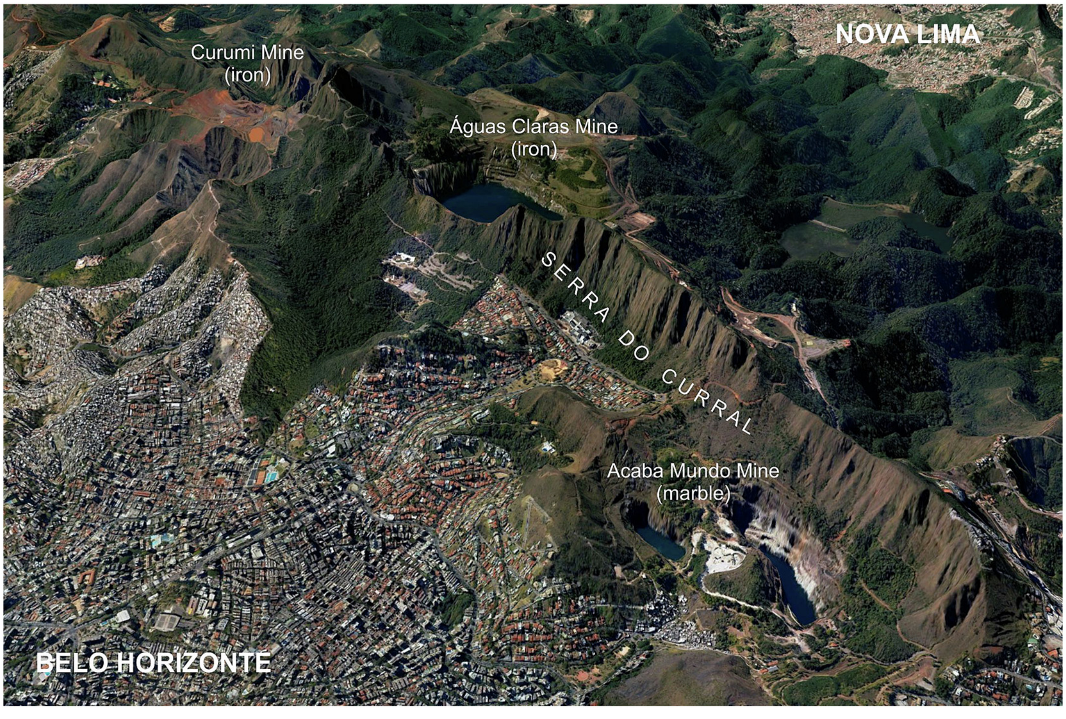

Fig. 11. Google Earth satellite image of the Serra do Curral in Belo Horizonte where the mines that operated in the region can be seen. *Source*: Google Earth in 2022.

Fig. 12. (a) View of the plateau at the top of the Rola Moça Mountain. (b) Extension of the mountain in direction to Belo Horizonte. (c) Explicative panel of the local geology. (d) Detail of the hematite pebbles of the detrital-lateritic cover of the plateau.

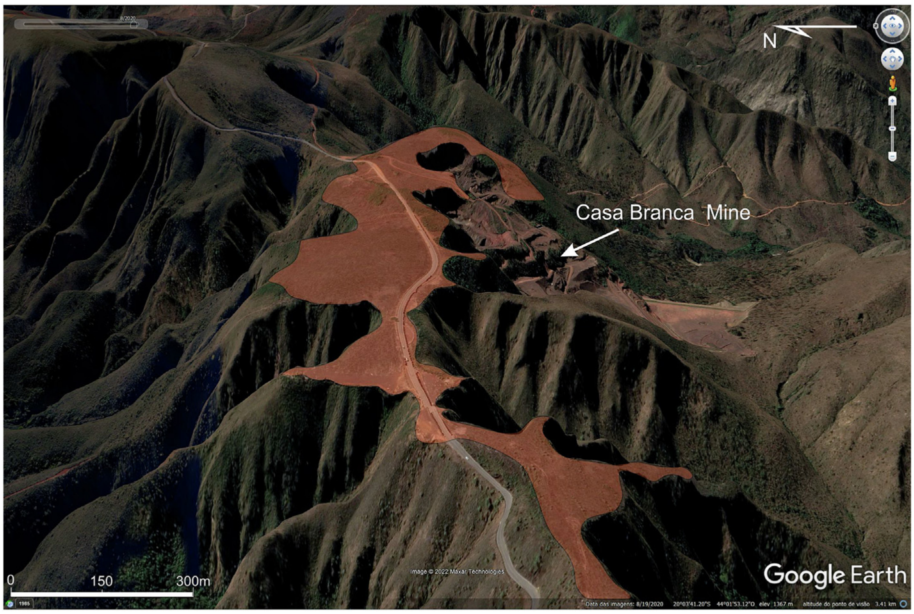

Fig. 13. Google Earth satellite image from the main plateau of Rola Moça Mountain shows abandoned iron mine. *Source*: Google Earth (2022).

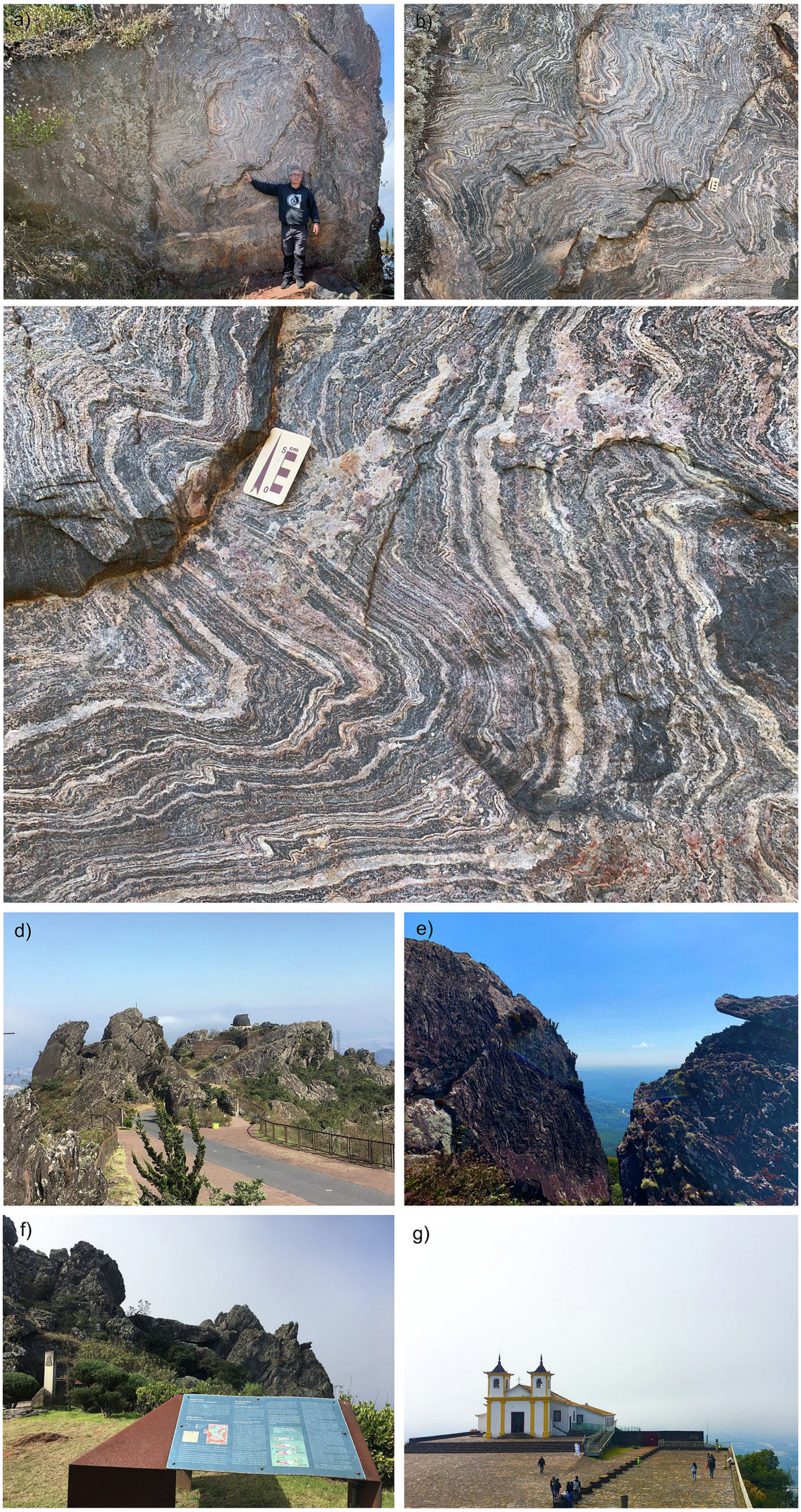

Fig. 14. Photographs of Piedade Mountain. (a) Outcrop of folded itabirite. (b) and (c) Details of the folded itabirite. (d) Partial view with the Federal University of Minas Gerais (UFMG) observatory in the background. (e) Itabirites outcrops and horizon view. (f) Dashboard about geology. (g) Sanctuary Church of Our Lady of Piety.

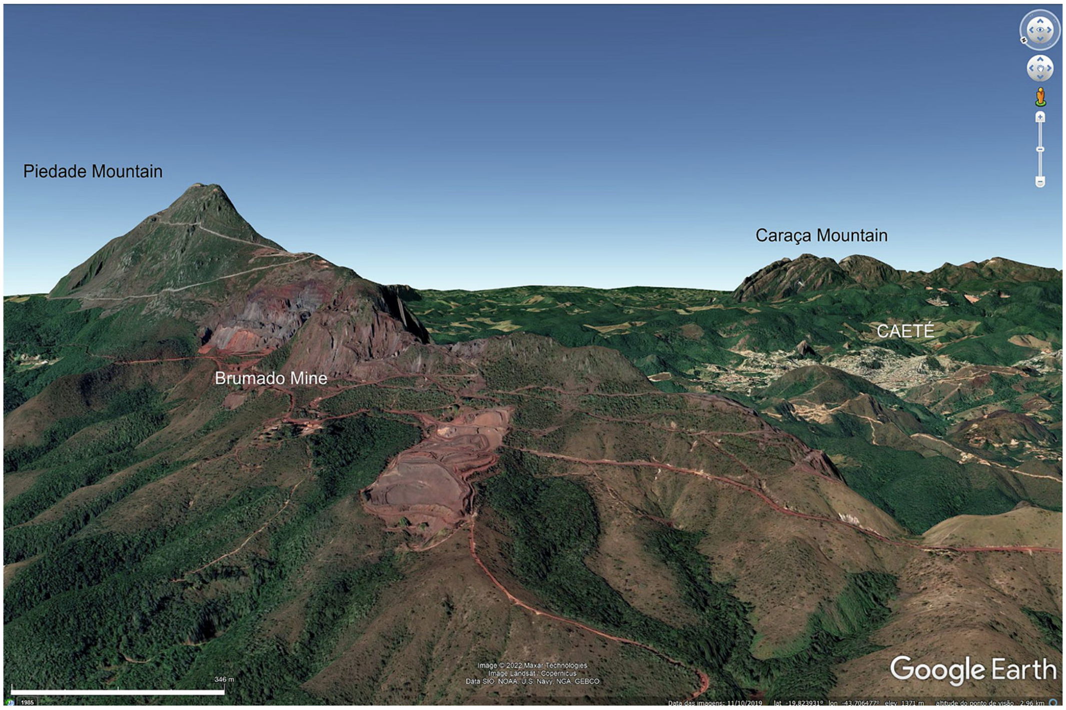

Fig. 15. Google Earth satellite image of the Piedade Mountain with the iron mine that operated in the region. *Source*: Google Earth in 2022.

Fig. 16. (a) Shaft No.10 of rectangular shape and depth of 8.5 m. (b) Shaft No.13 of circular shape with 17 m depth. (c) Arched gallery. (d) Stone arch. Photos compiled from IEPHA-MG (1998).

the itabirites of the Cauê Formation and are located in the eastern and northeastern portions of the Quadrilátero Ferrífero (Fig. 2). The main mines that have extracted Jacutinga are Cauê, Conceição, Gongo Soco, Pitangui, Cata Preta, Maquiné, Antônio Pereira, and Brucutú. These mines appear to be unique cases of Au—Pd deposits in oxide facies of Lake Superior Paleoproterozoic banded iron formations in the world (Olivo et al., 1995).

Jacutinga was described by Henwood (1871) and Hussak (1904) in the Gongo Soco and Maquiné mines as Au-Pd-rich specular hematite veinlets and contains manganese, talc and kaolinite (Cabral, Zeh, Galbiatti, & Lehmann, 2015; Galbiatti, Fonseca, Pereira, & Polônia, 2007). The Cauê Peak is located in the Itabira mountain range, where gold was initially mined in the rivers and streams that coincided with the axis of the Cauê syncline (Rosière, Spier, Rios, & Suckau, 2008). Olivo et al. (1995) considered that the genesis of the mineralisation is related to the Transamazon event in 1.83 Ga, where the ore bodies are parallel to the foliation and the stretching lineation. Galbiatti et al. (2007) considered that the ore bodies are conditioned by fractures associated with transcurrent faults correlated to the Brasiliano event. Thus, the fractures, as well as their intersections, would be the structural controls of the mineralisation and also responsible for the geometry of the ore bodies.

Mineralisation is restricted to soft iron ore and occurs between siliceous itabirite and compact hematite. Cabral (1996) considered the deposit to be of hydrothermal origin composed of two characteristic mineral assemblages: specular hematite-talco-caulinite and goethite-pyrolusite. According to this author, the Gongo Soco Au—Pd deposit was considered proximal, where the source of the gold would be the banded iron formation itself and that gold and palladium transport occurred under oxidising and acidic conditions. Cabral et al. (2015) performed dating on monazite grains from Jacutinga sampled at Conceição Mine, located in Itabira, Minas Gerais (MG) and obtained an age of 495.6 ± 2.2 Ma. This age of Au—Pd mineralisation was correlated to a hydrothermal event, on a regional scale, which occurred in the late Brasiliano stages.

4.3. High grade iron ore deposits

High-grade iron ore from the Quadrilátero Ferrífero (typically >64% Fe) is mined to produce pellets. Vale estimates reserves of 600 million metric tons (Mt) and inferred resources of 2100 Mt. outside mined areas. Low grade ore, on the other hand, has reserves of 6,000 Mt to 8,000 Mt. and inferred resources of 25,000 Mt. (Rosière et al., 2008).

The origin of the iron ores of the Quadrilátero Ferrífero has been widely discussed in the literature. It was initially interpreted as a product of metasedimentary substitution, of hydrothermal alteration (Guild, 1957), of supergene enrichment (Dorr, 1965) or by the combination of hypogene and supergene fluids that propitiated the concentration of Fe by remobilization (Dorr II, 1958). Rosière and Rios (2004), based on textural and fluid inclusion studies, adopted the hydrothermal model to explain the formation of stratabound, tabular and high grade schistose ore bodies. According to Rosière et al. (2008), the largest high-grade ore deposits are of hydrothermal origin, but had an overlay of supergene alteration. The ore is related to two progressive events of the Transamazonian orogenesis (2,250 Ma and 1,900 Ma). The first event occurred between 2,255 Ma and 2,059 Ma, causing the

Fig. 17. Google Earth satellite image of Gongo Soco iron mine and geosite.
Source: Google Earth in 2022.

Fig. 18. Photographs of Santo Antônio and Santana hills. (a) and b) Ruins of the 18th century occupation. (c) Dams to accumulate water for washing the gold ore. (d) Access shaft to the ore body. (e) Access gallery to the ore body. (f) Detail of auriferous quartz vein with sulphide. (g) Ore washing area. (h) Ore tailings area sculptured in the rock.

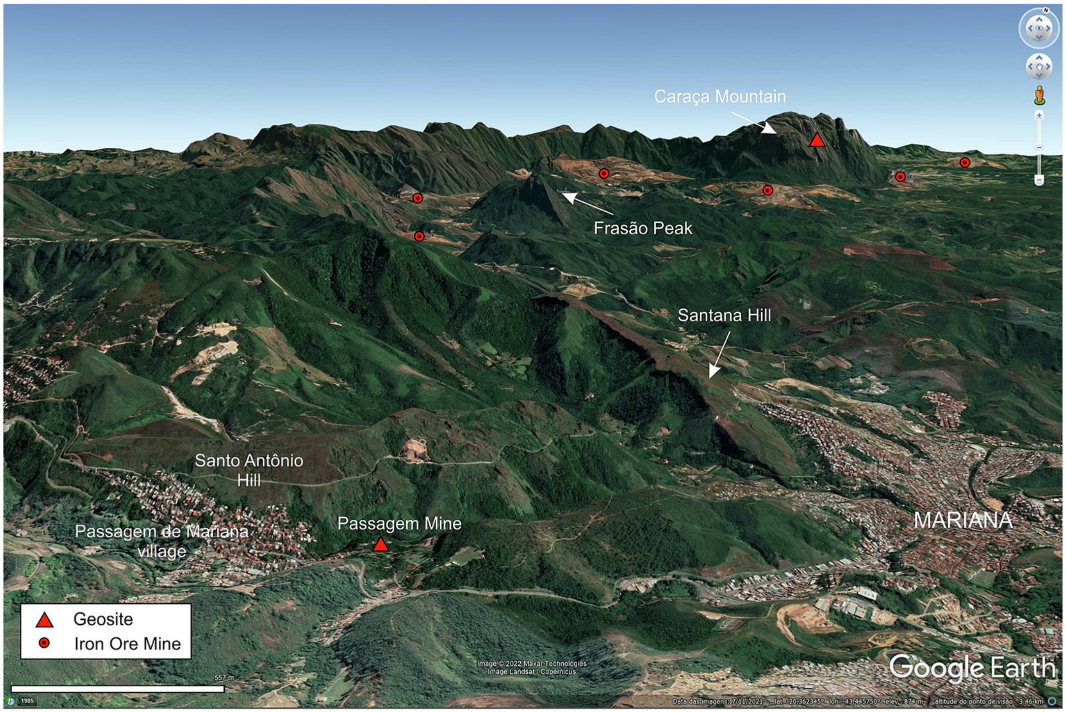

Fig. 19. Google Earth satellite image showing the Santo Antônio and Santana hills in Mariana, and iron ore mines and geosites. *Source*: Google Earth in 2022.

Fig. 20. Photographs of Chico Rei Mine. (a) Mine entrance. (b) Main gallery with a bridge over the flooded lower level. (c) View of the main gallery to a direct the exit. (d) Secondary gallery giving access to the main hall.

inversion of the Minas Basin, and generating the synclinal troughs. During the Brasiliano event (~600 Ma), faults and reverse shear zones were generated in the eastern domain of the Quadrilátero Ferrífero, which were important for the formation and structural control of iron ore deposits restricted to this region.

5. Results

The Quadrilátero Ferrífero stands out for the richness of geodiversity elements, especially regarding the geological and mining sites. The region was the target of intense gold mining activity during and after the colonial period, and iron mining activities from the mid-20th century and into the 21st century which caused profound changes in its landscape (geoforms). These are scars that keep record of both open-pit and underground mining activities. But at the same time, it exposes geological elements that would not be visible if the mining activities had not existed, adding value to the geological sites.

5.1. Geological and mining heritages

5.1.1. Cauê Peak

The Cauê Peak is located in the Itabira Syncline and also the type locality of the Cauê Formation (of the Itabira Group) (Figs. 4 and 5). The Cauê Formation (Itabirite Cauê) was described by Dorr II (1958) at Cauê Peak, as a formation mainly composed of itabirites - a metamorphic rock composed of the intercalation of thin layers of quartz and hematite - locally appearing narrow layers and lenses of dolomitic and amphibolitic itabirite, and more rarely, phyllite and quartzite.

Iron ore mining in the Cauê Peak region began in 1909 with the foundation of the first mining company, the Brazilian Hematite Syndicate, which was succeeded by the Itabira Iron Ore Company. In 1941, Getúlio Vargas, president of Brazil, signed Decree-Law No. 4352 which created Vale do Rio Doce Company (CVRD), a mixed economy company, with an administrative Center in Itabira. In the early 1950s, the Brazilian government took definitive control of the CVRD operational system, making it the largest exporter of iron ore in Brazil. In 1997, the company was privatised and today it is considered one of the largest mining companies in the world. With the exhaustion of the deposits in the last decade of the twentieth century, the mine pit began to be used for

Fig. 21. Ores from Chico Rei Mine. (a) Tourmalinite with quartz veins. (b) Massive vein of quartz-arsenopyrite. (c) Banded vein of arsenopyrite, embedded in quartzite. (d) Pyrite fragments from massive veins of quartz-pyrite-chalcopyrite. Photographs compiled from Cavalcanti (1999).

the disposal of waste rock and tailings (Galbiatti et al., 2007). The iron ore mining activity lasted throughout almost the entire 20th century (1909–2003).

In this region, in the gold washing concentrates, six new minerals associated with Au—Pd mineralisation, known as “jacutinga”, were discovered in the Cauê Formation. These minerals (arsenopalladinite, atheneite, isomertieite, palladseite, palladinite and jacutingaite) make up the International Mineralogical Association (IMA) list. Other rare minerals have also been identified in this context, such as, porpezite, mertieite II, temagamite, stibiopalladinite, and oxygen-containing Pt-Pd-Au-Cu-Fe-Mn composite groups, known as black gold (Atencio, 2020).

5.1.2. Itabira Peak

Itabira Peak (today called Itabirito Peak) served as a geographical landmark for the Bandeirantes, pioneers of Minas Gerais in the 17th and 18th centuries, and today presents itself, due to its physical and geological characteristics, as a symbol-witness of the mineral wealth of the region (Figs. 6 and 7). The protected area of Itabirito Peak was established as a natural monument by Article 84 of the Acts of Transitional Dispositions of the Constitution of the State of Minas Gerais of 1989. It is a topographic ledge composed of compact iron ore, consisting of iron oxides (hematite and magnetite), with an approximately lenticular shape and vertical attitude, standing 80 m above the current landscape. The ore body, of hydrothermal origin, was formed during the Transamazonian tectonic event of the Paleoproterozoic age and is part of the Cauê Formation of the Itabira Group (Rosière, Renger, Piuzana, & Spier, 2009).

The Itabira Group type locality is described by Harder and Chamberlin (1915):

> *… The Itabira iron formation takes its name from Itabira Peak, near the town of Itabira do Campo, a rather striking mountain of splendid specular Hematite which forms a conspicuous landmark visible for many miles around. Though varying greatly in character, the Itabira formation is generally hard and resistant and much more durable than the softer schists which lie immediately above and below it. The result is that wherever the iron formation now appears at the surface in inclined beds, it stands up in prominent ridges or as a chain of “iron hills”…* (p. 359).

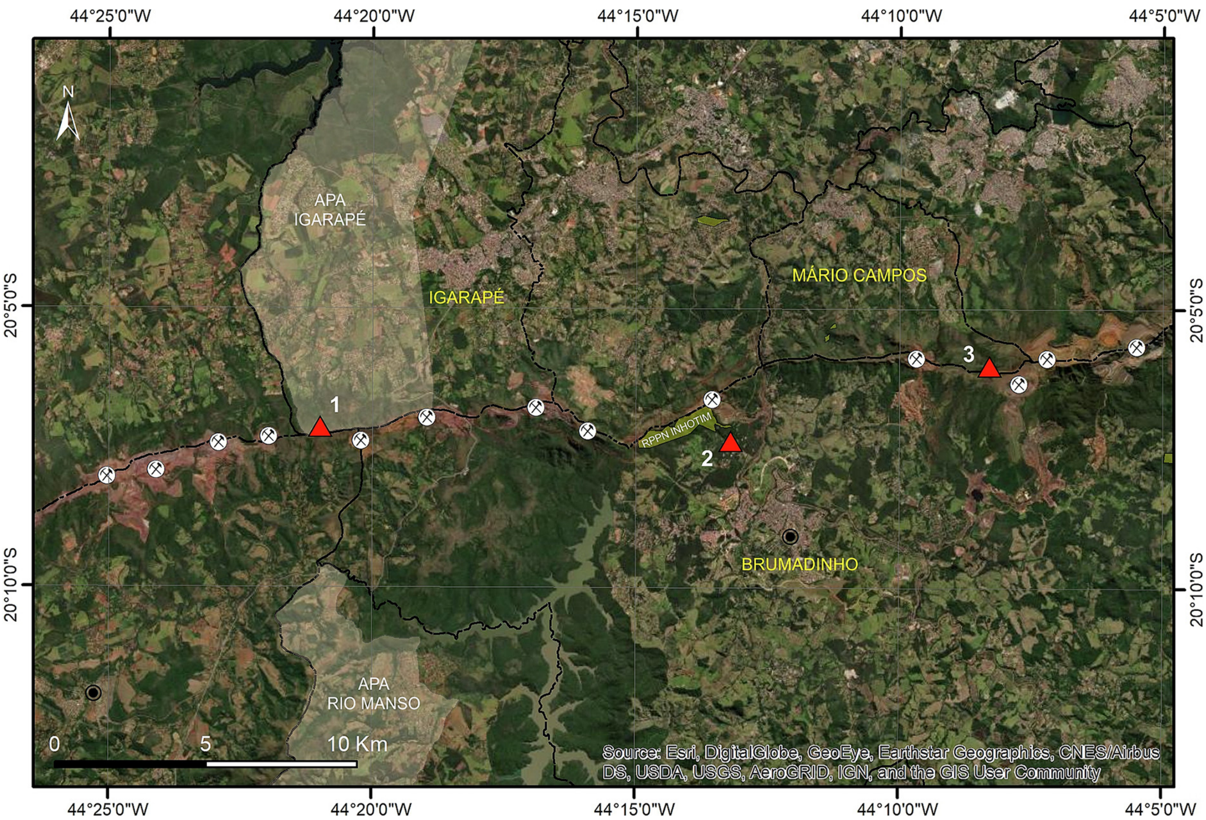

Fig. 22. Curral Mountain Ridge Western sector. Satellite image with the location of the iron ore mines in the alignment of the mountain, the peaks of Pedra Grande and Três Irmãos, the Inhotim Contemporary Art Museum and conservation areas. Red triangles: (1) Pedra Grande Peak; (2) Inhotin Contemporary Art Museum; (3) Três irmãos Peak. Image from ArcGis Basemap.

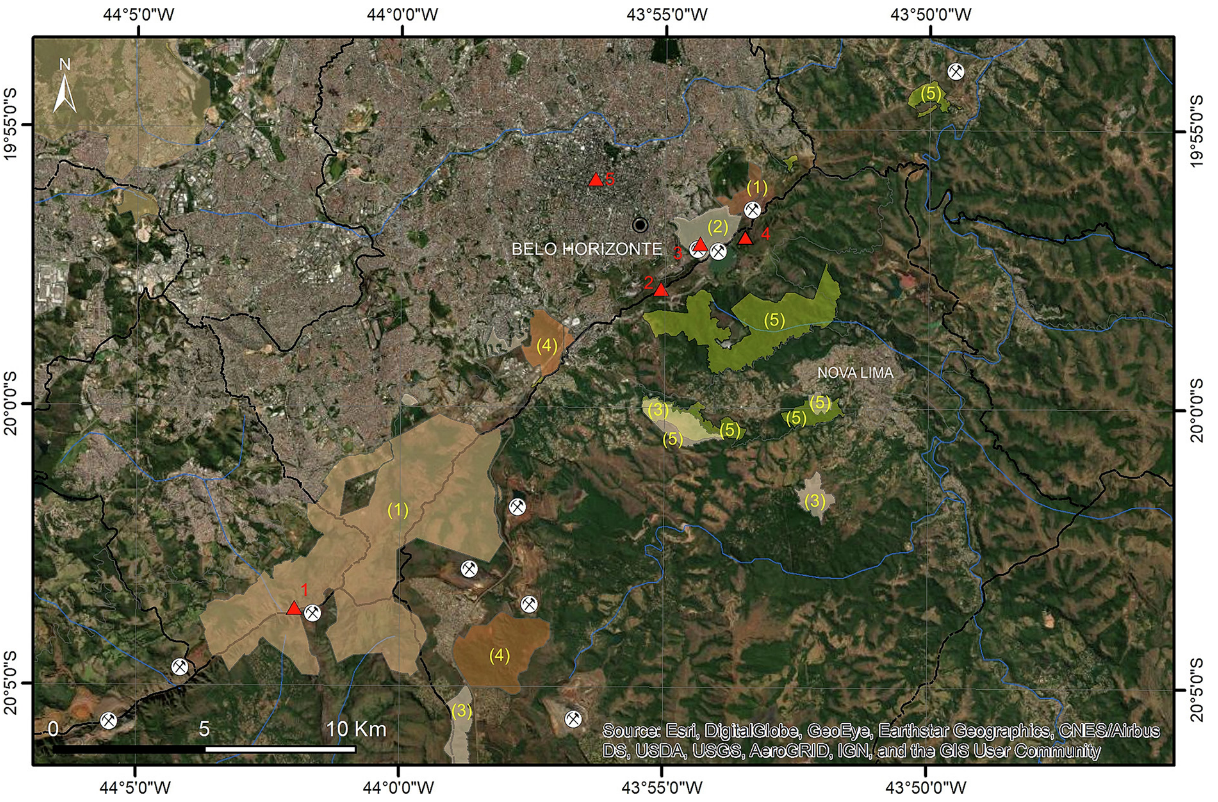

Fig. 23. Curral Mountain Ridge central sector. Red triangles: (1) Rola Moça Mountain State Park. (2) Curral Mountain Park. (3) Mangabeiras Park. (4) Belo Horizonte Peak. (5) Mines and Metal Museum. Colour areas: (1) State park. (2) Municipal park. (3) Natural monument. (4) Ecological station. (5) Private natural heritage reserve (RPPN). Image from ArcGis basemap.

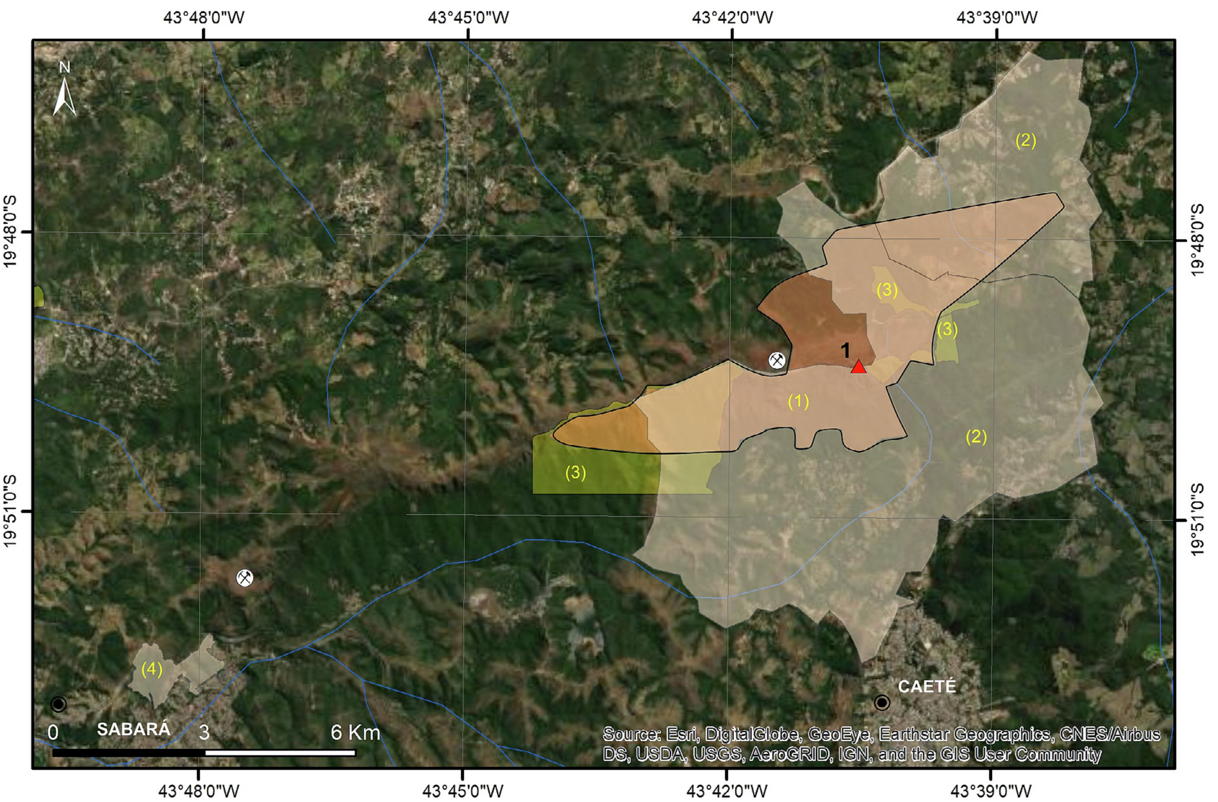

Fig. 24. Curral Mountain Ridge east sector. Piedade Mountain and the Our Lady of Piedade Sanctuary are located. Red triangle: (1) Piedade Mountain. Colour areas: (1) Natural monument. (2) Environmental preservation area (APA). (3) Private natural heritage reserve (RPPN). (4) Municipal park. Image from ArcGis basemap.

5.1.3. Curral Mountain homocline

The Curral Mountain homocline is an extensive “hogback” of approximately 100 km in length, formed from the remainder of an inverted synclinal fold of the Minas Supergroup rocks over the granitic rocks of the Belo Horizonte region, known as the Belo Horizonte Peripheral Depression (Medina, Dantas, & Saad, 2005). According to these authors, the lithostructural control of the mountain range is marked by the stratigraphic positioning of the iron formations and quartzite at the top, where the layers have high-angle dips (Fig. 8). Along the mountain range there are countless iron ore mines and geosites, but at the same time, it can be considered a great underground water reservoir that occurs mainly in the itabirites of the Cauê Formation, responsible for supplying part of the cities of the Belo Horizonte metropolitan region.

The Curral Mountain receives several denominations along its structure (Figs. 8, 9 and 10): (a) Azul Mountain located in the extreme southwest up to Pedra Grande Peak; (b) Itatiaia Mountain between Pedra Grande Peak and Garganta da Conquistinha; (d) Farofas Mountain, between Conquistinha Canyon and Paraopeba Canyon, which is also known as Fecho do Funil; (e) Três Irmãos Mountain, between Fecho do Funil and Três Irmãos Peak; (f) the Rola Moça Mountain between the Três Irmãos Peak and the region where the mountain range is cut by the BR-040 Highway; (g) Curral Mountain in Belo Horizonte and Nova Lima, a stretch between the BR-040 highway and Belo Horizonte Peak; (h) Taquaril Mountain located between Belo Horizonte Peak and Rio das Velhas Valley; and (i) the Piedade Mountain, between the Rio das Velhas Valley and the northeast end of the mountain range (Amorin, 2021) (See Fig. 10)

Curral Mountain of Belo Horizonte corresponds to the central stretch of the homonymous homoclinal structure that extends from the Belvedere neighbourhood (Belo Horizonte) to Sabará City. The mountain was protected at the federal level by the National Historic and Artistic Heritage Institute (IPHAN) in 1961 and at the municipal level in 1991. Mangabeira Municipal Park is an area that was rehabilitated where a ferrobel iron ore mine operated in the 1960s and 1970s. Access to the top of the mountain can be made through the trails of the Curral Mountain Municipal Park, popularly known as Paredão Park. In the southwest of the mountain is the Acaba Mundo mine, in the central portion is the Águas Claras mine and to the northeast is the Curimi mine (Fig. 11).

Rola Moça State Park was created in 1994. In the park area there are six springs that are responsible for the water supply of part of the metropolitan region of Belo Horizonte. At the top of the mountain, outcrops of ferruginous laterites of Cenozoic, popularly known as “canga” and itabirites of the Cauê Formation appear (Figs. 12 and 13). The term “canga” was first used by von Eschwege (1833), for a conglomerate of ironstone composed of angular, rarely rounded fragments of specularite schist and magnetic hematite with a ferruginous cement of red or yellow and brown limonite. Canga may form in situ and/or be transported and

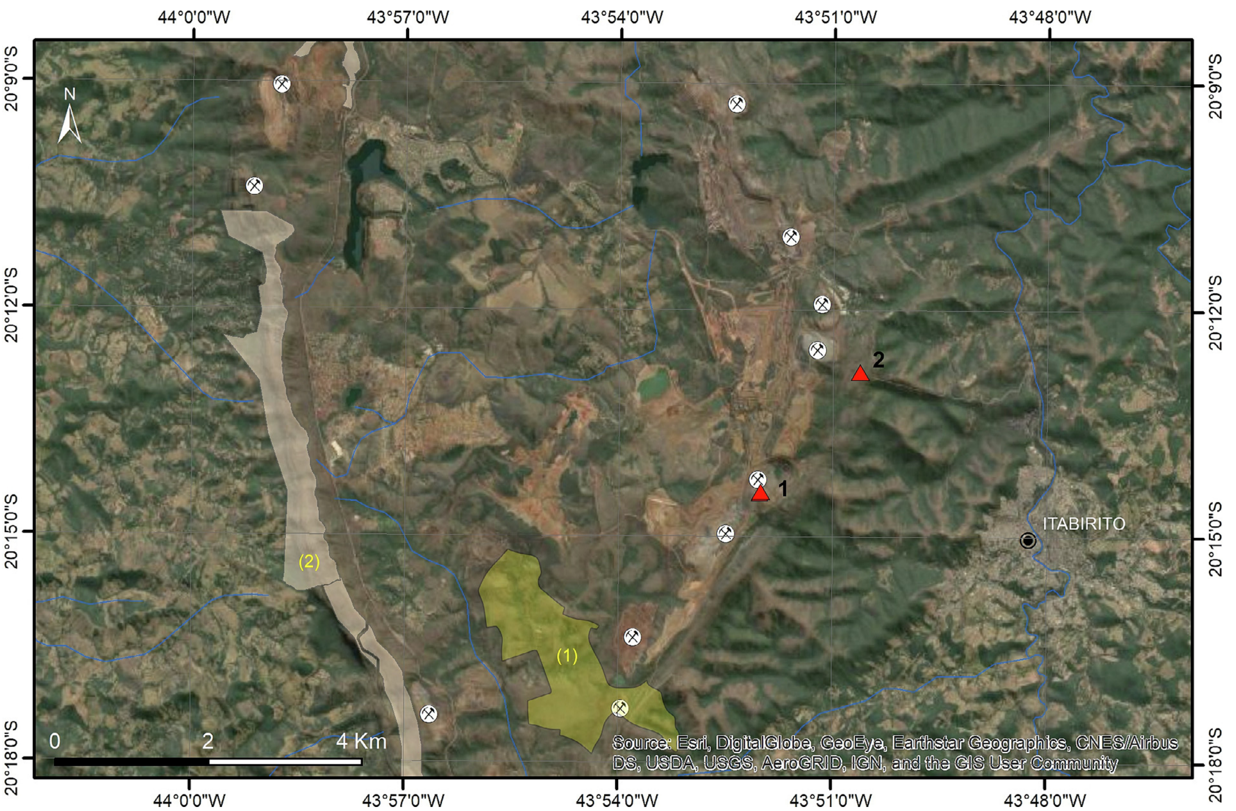

Fig. 25. Moeda Mountain, with the location of the environmental protection areas and the geosites. Red triangles: (1) Itabirito Peak. (2) Cata Branca Mine. Colour areas: (1) Ecological station. (2) Natural monument. Image from ArcGis basemap.

deposited. In situ canga occurs on weathered itabirites and can reach up to 30 m in thickness, but more commonly, thickness ranges between 1 m and 5 m. The transported canga is formed from the cementation by Fe oxides and oxides-hydroxides, as well as eroded material from the hills, and may form extensive coverings. In mineralogical terms, canga has a complex mineralogy essentially formed by oxides and oxyhydroxides of Fe. The mineral phases identified were goethite, magnetite, martite, hydrothermal hematite (specularite) and supergene hematite, reliquary and supergene quartz, and gibbsite (more rarely). Dating by the (U—Th)/He method by Monteiro (2011) indicated ages between 43.75 ± 8.75 Ma and 0.37 ± 0.07 Ma. These results showed that canga are younger than the saprolites and come from repeated phases of dissolution and reprecipitation of the Fe oxyhydroxides that are responsible for their rejuvenation near the surface (Fig. 13).

In Piedade Mountain, mainly itabirites of the Cauê Formation with large outcrops that show the intercalations of iron-rich layers and silica-rich layers are found, as well as beautiful ductile structures such as folds in various styles, shear zones and faults. It is also possible to study the relief of the region, as it allows the observation of large areas of the Quadrilátero Ferrífero (Figs. 14 and 15). Piedade Mountain was declared a natural monument by the State of Minas Gerais in 1989, but only in 2006 was the protected area approved. At the beginning of the 19th century, its scientific and landscape recognition was based on reports by naturalists, such as Auguste de Saint-Hilaire, J. B. von Spix and C. F. P. von Martius (who climbed the mountains in 1818) and Baron Eschwege. The latter published, in 1832, his contributions on the geology of Brazil which includes a topographic map enclosing the Sabará River Valley and the first geological description of Piedade Mountain (Ruchkys, Renger, Noce, & Machado, 2009). This mountain is one of the best places to observe and study the iron formations of the Quadrilátero Ferrífero.

5.1.4. Gongo Soco

The Gongo Soco ruins are the remains of the ancient Gongo Soco Gold Mine and Farm which were acquired by the Imperial Brazilian Mining Association (Gomes, 2011). The ruins were declared to be natural heritage by the State Institute for Historical and Artistic Heritage (IEPHA) in 1995. The geosite is currently of scientific, educational and touristic interest. During the period when the mine was administered by the Imperial Brazilian Mining Association (1826–1856), it became one of the most important

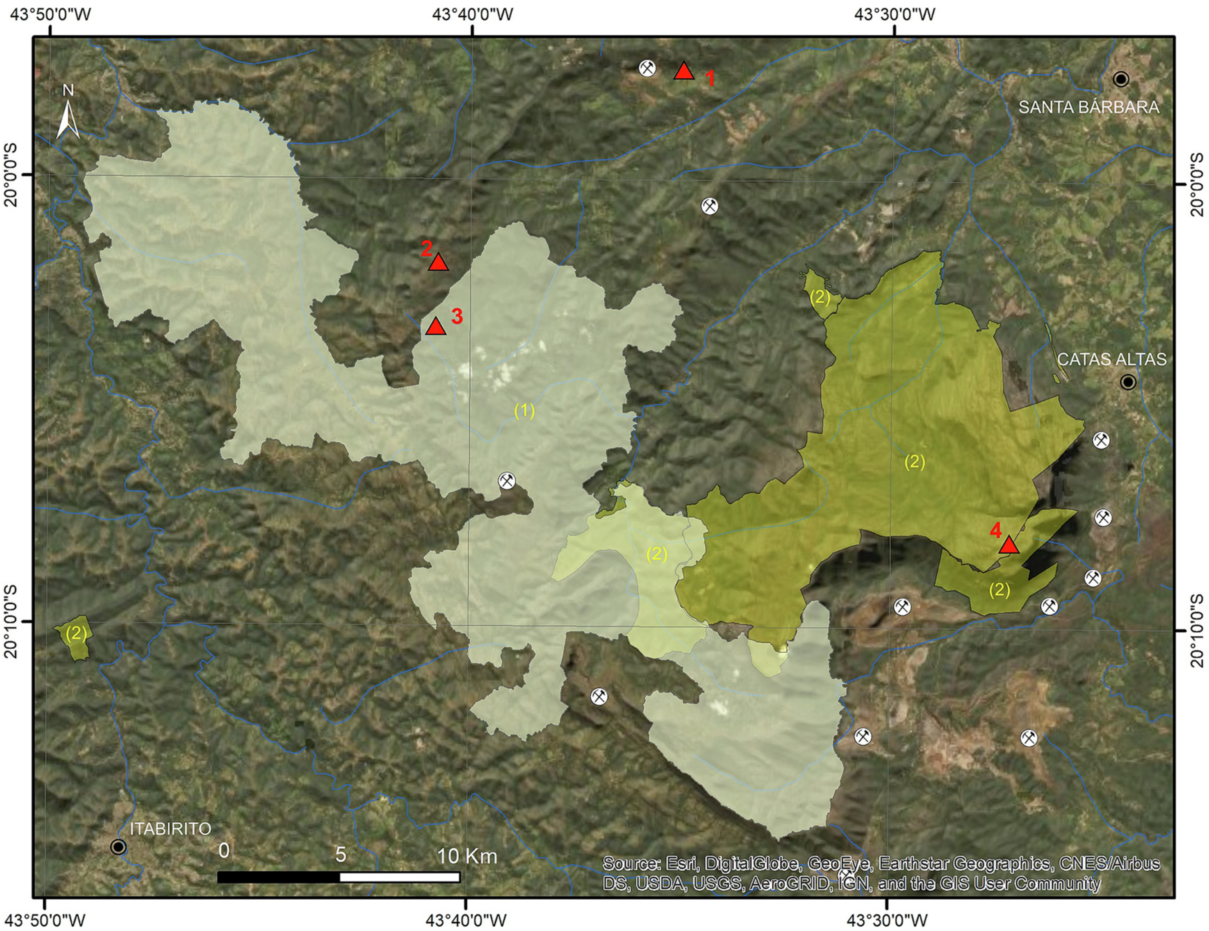

Fig. 26. Cambotas-Fundão fault system with the location of the preservation areas and the geosites. Red trinagles: (1) Gongo Soco. (2) Paleoburrow Gandarela. (3) Gandarela Basin. (4) Caraça Mountain and Centenário Cave. Colour areas: (1) National park. (2) Private natural heritage reserve (RPPN). Image from ArcGis basemap.

gold mines in Minas Gerais (Cabral, 1996). In this period, it reached a depth of 140 m and had an estimated production of 12,887 kg of gold (Fig. 16).

The Gongo Soco Mine is located in an important Au—Pd hydrothermal deposit typology in the Paleoproterozoic banded iron formations of the Cauê Formation, known as jacutinga, of Cambrian age (496 Ma). It is also the type locality of the mineral palladinite, which is listed by the International Mineralogical Association (IMA) as a questionable mineral. The name of the mineral is in allusion to the type of gold mineralisation with which the mineral is associated, jacutinga.

Throughout the second half of the 20th century, the Gongo Soco Mine started producing iron ore and had as a by-product, the gold extracted from the jacutinga (Fig. 17). Iron ore production in Gongo Soco in the period between 2007 and 2014 was 51.7 million tons, considered to be a large mining enterprise (Neto, 2008). The mine is located in the central-northern region of the Quadrilátero Ferrífero, in the context of the Gandarela Synclinal. The sinclinal surroundings are formed by shales of the Nova Lima group of the Rio das Velhas greenstone belt and the syncline is composed of rocks of the Caraça, Itabira and Piracicaba groups of the Minas Supergroup, and Sabará Group of the Estrada Real Supergroup.

5.1.5. Santo Antônio Hill and Santana Hill

Santo Antônio Hill and Santana Hill are important geomining sites, located in the Mariana Anticline, southeast region of the Quadrilátero Ferrífero (Fig. 18). The municipal government of Mariana has carried out an archaeological inventory of the two sites, but they have not yet been declared preservation areas. In these sites, it is possible to identify the techniques used in gold mining in the XVIII century, besides the geological context in which the auriferous mineralisation and the mineralisation itself are inserted (Fig. 19). The ore bodies are quartz-tourmaline-gold veins hosted in a layer composed of sericite and carbonaceous phyllites of the Batatal Formation, located between the quartzites of the Moeda Formation (lapa) and the itabirites of the Cauê Formation (cape). Besides the mining structures (dams, wells, water conduction channels, pylons, canoes and tailing piles), there are substantial ruins of two old mining villages built in the 18th century, using canga blocks as structural elements.

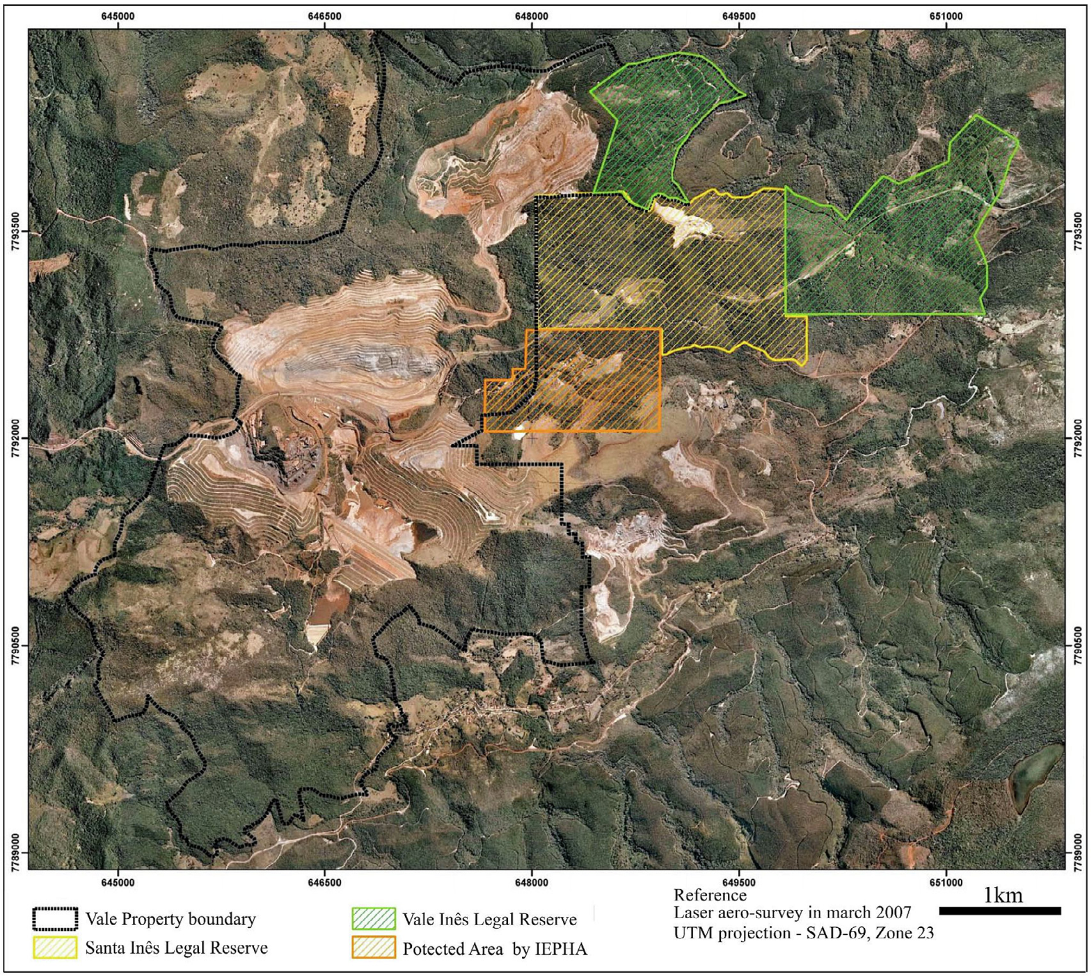

Fig. 27. Satellite image with location of Gongo Soco Iron Mine and the protect area established by State Institute for Historical and Artistic Heritage (IEPHA-MG), compiled by Neto (2008).

The surface of the hills is entirely covered by canga, which is a rock resulting from the weathering of banded iron formations belonging to the Cauê Formation (Varajão et al., 2009).

5.1.6. Chico Rei Mine

The Chico Rei Mine, located in the urban area of Ouro Preto city, is one of the rare underground mines open to tourism that bears witness to the mining activity that took place during the colonial period in Minas Gerais (Fig. 20). It is where the techniques used in gold extraction can be seen, as well as evidence of the hydrothermal activities involved in the process of auriferous mineralisation in the banded iron formations of the Cauê Formation. Throughout the mine galleries, besides observing the mineralisation process in the rocks and their structures, one can see large veins of quartz-arsenopyrite and veins of quartz-pyrite-chalcopyrite (Fig. 21). It is a rare example of gold mineralisation in quartz-sulphide veins hosted in itabirites of the Cauê Formation. Gold mineralisation is mainly associated with quartz-sulphide veins (arsenopyrite, pyrite and chalcopyrite) and secondarily with tourmalinites. The quartz-arsenopyrite banded vein is associated with conjugate hydraulic fracturing in a shear zone with normal movement to the southeast.

5.2. Environmental protection area

Some geological and mining sites are within areas of permanent preservation and also in areas of tourist use, and even so they are under pressure with the advance of mining activity (Table 1). The main example is in the Curral Mountain, in the sectors where the Piedade Mountain, Rola Moça Mountain, Três Irmãos Peak, Pedra Grande Natural Monument and Curral Mountain in Belo Horizonte. These are considered preservation areas, and are being fought over in the courts for the release of mining activities, which may, if carried out, cause serious damage to biodiversity and geodiversity. The western sector of the Curral Mountain

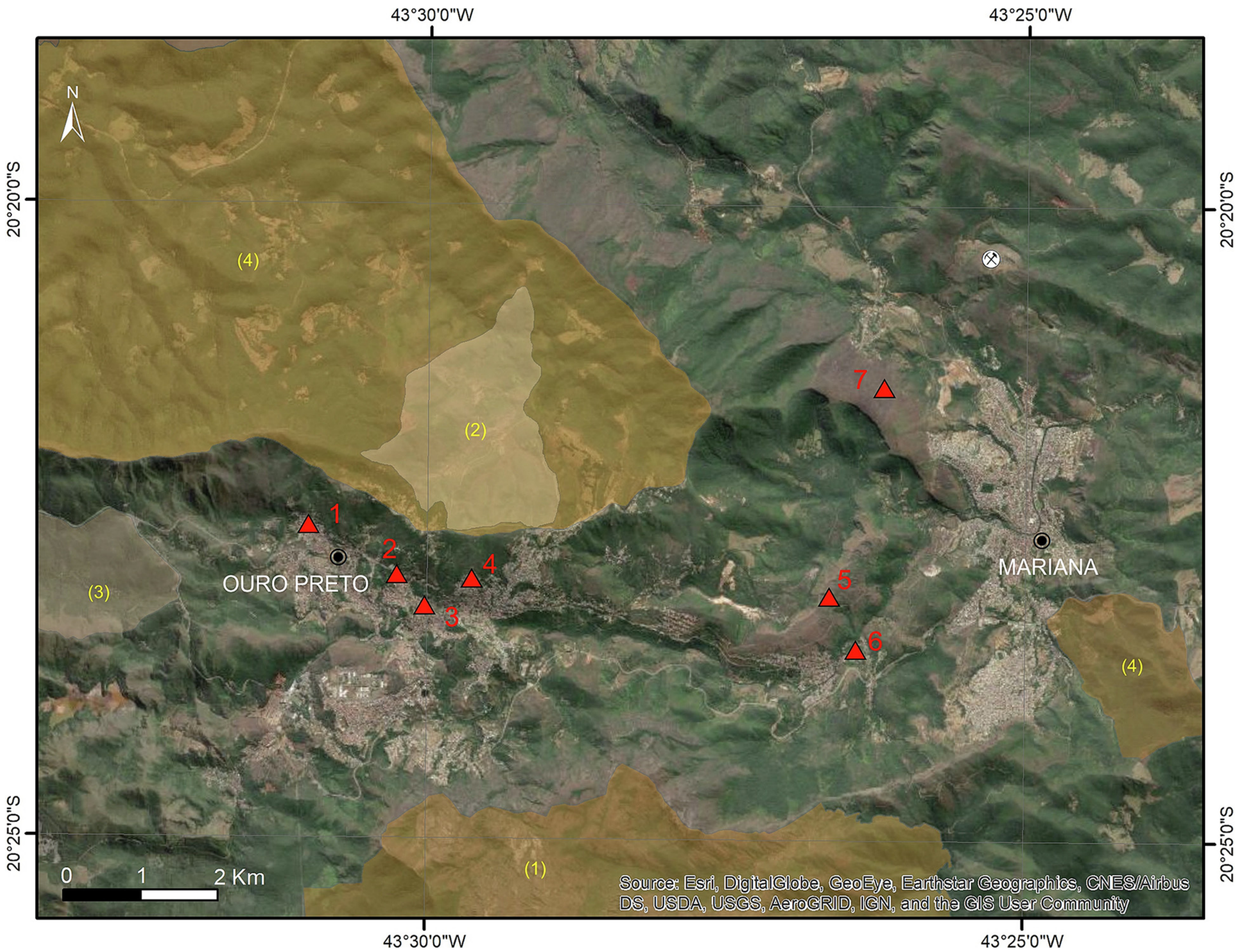

Fig. 28. Satellite image showing the location of the main geosites along the Mariana Anticline and convervation areas. Red triangles: (1) Du Veloso Mine. (2) School of Mines Mineralogy Museum. (3) Chico Rei Mine. (4) Queimada Hill. (5) Santo Antônio Hill. (6) Passagem Mine. (7) Santana Hill. Colour areas: (1) State park. (2) Municipal park. (3) Ecological station; (4) Environmental preservation area (APA). Image from ArcGis basemap.

is where a large number of iron ore mines are concentrated (13 mines), which are already mining the top of the mountain, near the Pedra Grande Natural Monument (in Igarapé) and the Três Irmãos Peak (in Mário Campos) (Fig. 22). In this sector, there is the Inhotim RPPN, which houses the open-air Museum of Contemporary Art of the same name. The central sector is where the Rola Moça Mountain State Park, Mangabeiras Municipal Park, Curral Mountain Municipal Park, Belo Horizonte Peak, and Baleia State Park; and the Minas Tênis Clube, Portal Sul, and Albert Scharle RPPNs are located, which also survive amidst pressure for

Table 1
Conservation units in the Quadrilátero Ferrífero.

Order	Conservation unit	Typology	Area (ha)	Level
1	Parque Nacional da Serra do Gandarela	National park	31,260	Federal
2	APA Estadual Cachoeira das Andorinhas	Environmental preservation area (APA)	18,700	State
3	APA Estadual Seminário Menor de Mariana	Environmental preservation area (APA)	285	State
4	APA Estadual Sul - Região Metropolitana de Belo Horizonte	Environmental preservation area (APA)	164,365	State
5	Estação Ecológica Estadual de Aredes	Ecological station	1,281	State
6	Estação Ecológica Estadual de Fechos	Ecological station	602	State
7	Estação Ecológica Estadual do Cercadinho	Ecological station	224	State
8	Estação Ecológica Estadual do Tripuí	Ecological station	392	State
9	Floresta Estadual do Uaimii	State forest	4,398	State
10	Monumento Natural Estadual da Serra da Moeda	Natural monument	2,372	State
11	Monumento Natural Estadual da Serra da Piedade	Natural monument	1,947	State
12	Monumento Natural Estadual de Itatiaia	Natural monument	3,216	State
13	Monumento Natural Estadual do Pico do Itabirito	Natural monument	6	State
14	Parque Estadual da Baleia	State park	102	State
15	Parque Estadual da Serra do Rola Moça	State park	3,941	State
16	Parque Estadual do Itacolomi	State park	7,000	State
17	Parque Estadual Serra do Ouro Branco	State park	7,520	State
18	APA Municipal Aguas da Serra da Piedade	Environmental preservation area (APA)	4,570	Municipal
19	APA Municipal Descoberto	Environmental preservation area (APA)	1,419	Municipal
20	APA Municipal Igarapé	Environmental preservation area (APA)	823	Municipal
21	APA Municipal Rio Manso	Environmental preservation area (APA)	7	Municipal
22	Monumento Natural Municipal Mãe D'Agua	Natural monument	797	Municipal
23	Monumento Natural Municipal Morro do Elefante	Natural monument	43	Municipal
24	Monumento Natural Municipal Morro do Pires	Natural monument	110	Municipal
25	Monumento Natural Municipal Serra da Calçada	Natural monument	585	Municipal
26	Monumento Natural Municipal Serra do Souza	Natural monument	199	Municipal
27	Parque Municipal Aggeo Pio Sobrinho	Municipal park	27	Municipal
28	Parque Municipal Cachoeira das Andorinhas	Municipal park	18	Municipal
29	Parque Municipal Florestal Chacara do Lessa	Municipal park	113	Municipal
30	Parque Municipal Mangabeiras	Municipal park	236	Municipal
31	Parque Municipal Mata das Borboletas	Municipal park	3	Municipal
32	Parque Municipal Roberto Burle Marx	Municipal park	18	Municipal
33	Reserva Biologica Municipal Campos Rupestres de Moeda Norte	Biological reserve	84	Municipal
34	Reserva Biologica Municipal Campos Rupestres de Moeda Sul	Biological reserve	755	Municipal
35	Quebra Ossos	Private natural heritage reserve (RPPN)	7	Private
36	Fazenda Capivary	Private natural heritage reserve (RPPN)	1,984	Private
37	Horto Alegria	Private natural heritage reserve (RPPN)	1,064	Private
38	Corrego do Sitio I	Private natural heritage reserve (RPPN)	180	Private
39	Quebra Ossos II	Private natural heritage reserve (RPPN)	23	Private
40	Santuario da Serra do Caraça	Private natural heritage reserve (RPPN)	10,187	Private
41	AngloGold Ashanti-Cuiaba	Private natural heritage reserve (RPPN)	726	Private
42	Reserva Monsenhor Domingos Evangelista	Private natural heritage reserve (RPPN)	59	Private
43	Reserva da Serra da Piedade	Private natural heritage reserve (RPPN)	71	Private
44	Portal Sul	Private natural heritage reserve (RPPN)	5	Private
45	Minas Tênis Clube	Private natural heritage reserve (RPPN)	14	Private
46	Mata Samuel de Paula	Private natural heritage reserve (RPPN)	147	Private
47	Vale dos Cristais	Private natural heritage reserve (RPPN)	248	Private
48	Albert Scharle	Private natural heritage reserve (RPPN)	83	Private
49	Macaubas	Private natural heritage reserve (RPPN)	104	Private
50	Mata do Jambreiro	Private natural heritage reserve (RPPN)	180	Private
51	Grota da Serra 03	Private natural heritage reserve (RPPN)	3	Private
52	Grota da Serra 01	Private natural heritage reserve (RPPN)	2	Private
53	Riacho Fundo I e II	Private natural heritage reserve (RPPN)	21	Private
54	Sítio Grimpas	Private natural heritage reserve (RPPN)	20	Private
55	Inhotim	Private natural heritage reserve (RPPN)	145	Private
56	Andaime	Private natural heritage reserve (RPPN)	175	Private
57	Vale Verde	Private natural heritage reserve (RPPN)	26	Private
58	Fazenda João Pereira / Poço Fundo	Private natural heritage reserve (RPPN)	427	Private
59	Mata São Jose	Private natural heritage reserve (RPPN)	552	Private
60	Itabiruçu	Private natural heritage reserve (RPPN)	221	Private

the opening of new iron ore mines (Fig. 23). The western sector of Curral Mountain is the most preserved, with only two iron ore mines (Córrego do Meio and Brumado), and is where Piedade Mountain is situated. In this sector, there are the following preservation areas: Piedade Mountain State Natural Monument, Águas da Serra da Piedade Municipality APA, Descoberto Municipality APA, Florest Chacara do Lessa Municipality APA, and the RPPNs of Piedade Mountain, Monsenhor Domingos Evangelista and Anglo Gold Ashanti-Cuiabá (Fig. 24).

In the Moeda syncline, the mines are concentrated, mainly, on the eastern flank where Itabira Peak, the ancient Cata Branca Gold Mine, the State Ecological Station of Aredes, South and North Rupestrian Grasslands of the Moeda Biological Reserve, Mãe D'Água Natural Monument, and Calçada Mountain Natural Monument. Itabirito Peak stands out among the Pico, São Francisco, Galinheiros, Fernandinho I and Fernandinho II mines, leaving only the peak (Fig. 25).

The Cambotas-Fundão Fault System is another sector of the Quadrilátero Ferrífero that concentrates a great amount of iron ore mines (12 mines). In this domain, there is the Caraça Mountain, where Centenário Cave, the Caraça Santuary, and the Caraça old school are located; and in the Gandarela syncline are the Gongo Soco Mine, the paleoburrow and Gandarela basin (Fig. 26). It is also where the Gandarela Mountain National Park, Caraça Mountain RPPN, Alegria Forest Garden RPPN and the protected area of Gongo Soco are located (Figs. 26 and 27).

The Mariana Anticlinal has a high concentration of geological and mining sites and it is also where there is a greater concentration of preservation areas, but that are not in the domain of the sites that occur in the BIF's: Tripuí Ecological Station that is the type locality of the tripuhyite mineral; Seminário Maior State APA, Mariana Itacolomi Peak; Itacolomi State Park, locality of the type locality of the Itacolomi Group; Cachoeira das Andorinhas State APA, and the Cachoeira das Andorinhas Municipal Park, are already in the domain of the Rio das Velhas greenstone belt (Fig. 28). Here, three archaeological mining sites (Morro da Queimada, Morro Santo Antônio, and Morro Santana) are also in the process of being declared heritage sites.

6. Discussion

A descriptive and quantitative evaluation of eight geosites that are situated in the banded iron formations of the Itabira Group was carried out (Table 1 and 2, Fig. 29). The geosites of Itabira Peak and Piedade Mountain were previously written about by the Commission of Geological and Paleobiological Sites by Rosière et al. (2009) and Ruchkys et al. (2009), respectively. The main interests of the geosites are related to metallogenesis (gold and iron), stratigraphy (type-section), sedimentology (paleoenvironmental), geomorphology and mineralogy (minerals from the IMA list), structural geology, mining, and the environment, denoting the diverse aspect of the scientific knowledge of the Quadrilátero Ferrífero and the possibilities of use by the local community (Table 2)

The relevance was analysed in relation to scientific importance, educational, and geotouristic use. The GEOSSIT platform allows a classification in three levels: international, national, and regional/local. The geosites of Cauê Peak, Itabira Peak, Gongo Soco, and Chico Rei Mine were classified as being of international relevance. Curral Mountain, Santo Antônio Hill, Santana Hill, and Piedade Mountain were classified as being of national relevance. Regarding educational and tourist use, Curral Mountain, Rola Moça Mountain, Santo Antônio Hill, Santana Hill, Chico Rei Mine, and Piedade Mountain are visited by schools and universities from various regions of Brazil, as well as by Brazilian and foreign tourists in the Ouro Preto region. The geosites of Cauê and Itabira peaks are restricted to scientific use, as they are within mining areas.

In relation to the degradation risk, most geosites present high and medium values. This is due to the context where the geosites are located, a region where the main activity is mining, and in a state that still does not have a specific legislation for the protection of the geological heritage. Although many of these areas have been formally protected or are even located within protected areas, for example, due to their biodiversity or historical value, they are still under threat today.

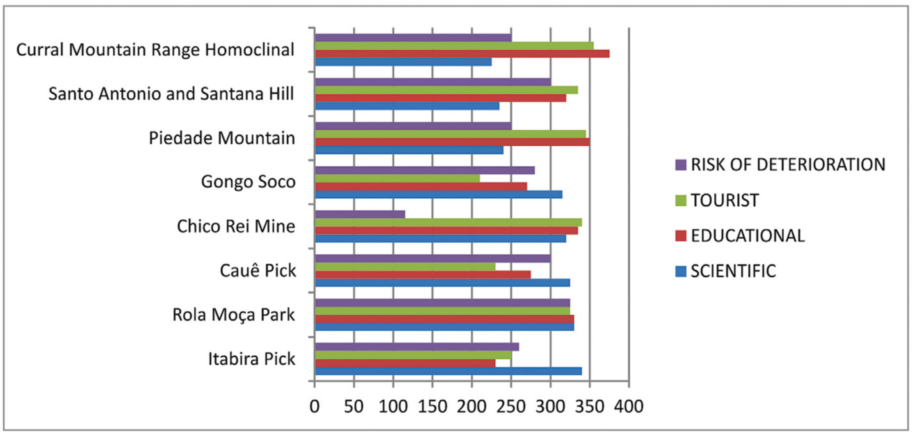

Fig. 29. Diagram with the scientific, educational, touristic relevance and degradation risk of the geosites analysed in the GEOSSIT platform.

Table 2
Main geosites in the banded iron formations of the Itabira Group. Description was compiled from GEOSSIT.

Order	Geosite	Description	Interest		Value			Risk of deterioration
			Main	Secondary	Scientific	Educational	Tourist	
G1	Cauê Peak	The type locality of the Cauê Formation, a sequence rich in iron formations, responsible for all iron ore production in the Iron Quadrangle. It is the site where five new minerals associated with Au—Pd mineralisation, known as "Jacutinga", were discovered. These minerals (arsenopaladinite, atheneite, isomertite, paladseite and jacutingaite) are listed by the International Mineralogical Association (IMA)	Mineralogy	Stratigraphy	325	275	230	300
G2	Itabira Peak	An important geological, historical, and economic reference in Minas Gerais state. In the 17th and 18th centuries, it served as a geographical landmark for the bandeirantes, the pioneers of Gerais. Today its importance lies in its metallogenetic and geological characteristics as a symbol-witness of the mineral wealth of the region	Stratigraphy	Metalogeny	340	230	250	260
G3	Curral Mountain Homoclinal	With >100 km in length, is a hogback relief generated on an inverted homoclinal structure by the Brasiliano tectonic event between 650 Ma and 500 Ma. It has several sites of geological interest and several important protection areas in the historical, cultural, religious, environmental and scientific context	Structural	Paleoenvironment	225	375	355	250
G4	Gongo Soco Mine	The Gongo Soco gold occurs in an important Au—Pd hydrothermal deposit hosted in the Paleoproterozoic banded iron formations of the Cauê Formation, known as Jacutinga, of Cambrian age (496 Ma)	Mineralogy	Geomining	315	270	210	280
G5	Santo Antonio and Santana Hill	An important geomining heritage located in the Mariana Anticline, specifically in Passagem village, near of Passagem Mine, southeast region of the Quadrilátero Ferrífero. In this geosite, it is possible to learn about the techniques used in gold mining in the 18th century, as well as the geological context of auriferous mineralisation and gold mineralisation in the Paleoproterozoic	Geomining	Metalogeny	235	320	335	300
G6	Chico Rei Mine	Rare underground mines open to tourism that testifies to the mining activity that occurred during the colonial period in Minas Gerais. The techniques used to extract gold can be observed, as well as evidence of the hydrothermal activities involved in the gold mineralisation process in the Paleoproterozoic banded iron formations of the Minas Supergroup	Metalogeny	Geomining	320	335	340	115
G7	Rola Moça Mountain	The Serra do Rola Moça is shaped by a Cenozoic ferruginous cover known as "Canga", which resulted from the weathering of the Paleoproterozoic banded iron formations, in paleoenvironmental conditions very different from the present times. The canga plateaus represent sparse testimonies of an ancient erosion surface dating back to the Upper Cretaceous/Paleogene interval	Geomorphology	Paleoenvironmental	330	330	325	325
G8	Piedade Mountain	Piedade Mountain has beautiful outcrops of itabirite from the Cauê Formation that indicate important changes in the	Paleoenvironmental	Sedimentology	240	350	345	250

(continued on next page)

Table 2 *(continued)*

Order	Geosite	Description	Interest		Value			Risk of deterioration
			Main	Secondary	Scientific	Educational	Tourist	
		composition of the Earth's atmosphere in the early Proterozoic and deformation structures related to the tectonic events that gave rise to the structural framework of the Iron Quadrangle. It is an important geological site that reflects the geo-ecological evolution of the Earth in the Archean-Paleoproterozoic limit and also a guide-mark of the first pioneers who arrived in the region around 1,673, fascinated by the Sabarabuçu indigenous legend, which attributed the existence of silver in the glittering mountain range, stimulating several expeditions in search of the precious metal						

Once recognized, the geosite needs to be protected and the community and public authorities should work to ensure its conservation (Quesada-Román et al., 2022). Many geosites are located next to protected areas and gain local, national, and international prominence. This is the case of the Quadrilátero Ferrífero, which has become highlighted not only for its mineral reserves, but also for the environmental disasters and challenges that lie ahead in relation to the preservation of natural areas and their geosites. After the two major disasters that occurred in the Fundão and Feijão dams and the constant alarms related to the tailing dams of the Casa de Pedra Mine in the region of Congonhas and the Gongo Soco Mine in Barão de Cocais, we do not know what to expect. We have many geoconservation problems and we also have actions that have been working well in general. Of the various geosites presented here, almost all have problems when it comes to geoconservation. The best preserved geosite is the Chico Rei Mine, which in the last three decades has been used for geotourism and historical and cultural tourism in Ouro Preto. All the others are being affected in some way. Cauê Peak, in Itabira, was completely destroyed, being transformed into an open-pit mine. Itabira Peak, in Itabirito, is isolated within a mine area, with its surrounding landscape completely anthropized. The Curral (in Belo Horizonte), Piedade (in Caeté) and Rola Moça (Brumadinho) mountains have already been targets for iron ore mining in the past, but currently, with the rising price of iron ore, they have been under constant threat of reopening of mining enterprises. The geomining archaeological site of the Gongo Soco Mine is under threat of dam failure. The geomining and archaeological sites of the Santo Antônio and Santana hills, in Mariana, are in a state of total neglect, which may be the gateway to their destruction, either by occupation as urban space or by mining activity.

When analysing from another point of view, outside the context of the iron formations, we see that the Quadrilátero Ferrífero is much more than that. It is known for its geology and its gold and iron deposits, but also for its historical cities, its natural areas full of waterfalls, mountains and peaks, and also for its biodiversity and geodiversity. The great diversity of landscapes and a history rich in cultural, religious and artistic elements make the Quadrilátero Ferrífero an international tourist destination (Fig. 30). The historic cities of Ouro Preto and Mariana are home to important works of art of the Mineiro Baroque, represented mainly by the sculptures of Antônio Francisco Lisboa (Aleijadinho) and the paintings of Manoel da Costa Athaide. Many of Aleijadinho's sculptures were made in padra-sabão (steatite) and the most important set of works “The 12 Prophets” can be seen on the churchyard stairs of the Sanctuary of Bom Jesus de Matozinhos, in Congonhas, and also in several churches throughout the Quadrilátero Ferrífero. Part of the gold exploited during the colonial period can be seen in the interiors of the churches, as for example in Pilar Church in Ouro Preto, one of the richest in gold in Brazil. The old underground gold mines of Passagem de Mariana and Chico Rei are also well known. Other important geosites are Caraça Mountain (Catas Altas and Santa Bárbara) and Itacolomi Peak (Ouro Preto-Mariana). Caraça Mountain is a multi-use tourist resort focused on environmental preservation, education, culture, religion, and science. It has an architectural complex formed by a neogothic church, an old school building, an inn, several waterfalls, and trails that give access to the top of the mountain with an altitude of 2,072 m. Itacolomi Peak State Park is another natural area of great importance for environmental preservation and water sources. It is the type locality of the Itacolomi Group and a historical reference of the mining region during the colonial period, used by travellers of the Estrada Real.

The Estrada Real was created at the end of the 17th century because of the rapidly growing gold extraction in the Quadrilátero Ferrífero region. The route was opened connecting the port city of Paraty, in the state of Rio de Janeiro, to the region of Ouro Preto (ancient Villa Rica) in Minas Gerais. This route became known as the “Caminho Velho”. Later, in order to improve control of the gold production, facilitating the flow and shortening the travel time from about two months to 25 days or 15 days on horseback to the mining region of Vila Rica, the “Caminho Novo” was opened, departing from the city of Rio de Janeiro (Calaes & Ferreira, 2009).

Fig. 30. Ouro Preto City, ancient Villa Rica. (a) Pilar Church. (b) Interior of Pilar Church, with the altars covered in gold. (c) Casa dos Contos, ancient gold smelting house of Villa Rica. (d) Side view of the school of mines, with the Itacolomi Peak in the background. (e) In the foreground is the Town Hall and Church of Our lady of Carmo and in the background is Itacolomi Peak. (f) Soapstone handcraft fair and São Francisco church in the background.

7. Conclusion

Outcrop areas of the banded iron formations of the Cauê Formation in the Quadrilátero Ferrífero concentrate a great variety of geological, mining, and biodiversity sites belonging to the Serra do Espinhaço Biosphere Reserve which was recognized by UNESCO in 2005. Biosphere reserves stimulate the sustainable use of natural resources by contributing to the generation and dissemination of technical, scientific, cultural, and traditional knowledge, i.e., they provide sustainable development, conditions, and opportunities for a harmonious interaction between human beings and the territory they occupy (Gomes, 2011).

But, at the same time, it shows that with the large number of conservation areas and heritage sites protected by state and municipal agencies, most of the geosites are under pressure or threat from mining activities in the region. Despite the amount of environmental preservation areas and springs, it is clear that geosites suffer great pressure from mining companies. An alternative to reduce this pressure would be the elaboration of a project to evaluate the mineral reserves of the Quadrilátero Ferrífero and the priority areas for the preservation of geodiversity, biodiversity, and springs. It is time to establish a greater balance between the parties.

The geosites studied have had their areas protected since 1961 (Curral Mountain), 1989 (Itabirito Peak), 1994 (Rola Moça Mountain), 1995 (Gongo Soco Mine), and 2006 (Piedade Mountain). The geosites, Santo Antônio Hill, Santana Hill, and Chico Rei Mine, have not yet been officially protected.

There is an urgent need for law-making and public politics focusing on the geoconservation of the geological heritage of the State of Minas Gerais, especially in the mining areas and those of great historical and tourist value, such as in the Quadrilátero Ferrífero, which is one of the most important mineral provinces of Brazil. Besides the geosites presented here, the Quadrilátero Ferrífero has a great diversity of geosites that occur in other important geological units, such as (i) the quartzite and the Au—U mineralisation in the conglomerates of the base of Caraça Group; (ii) the stromatolitic marbles, caves and the paleoburrow of the Gandarela Formation; (iii) stromatolites of the Piracicaba Group; (iv) Archean volcanism and the gold mineralisation of the Rio das Velhas Supergroup; (v) and the fossiliferous Cretaceous of Fonseca Basin fossils. There is a need for urgent protective actions of the geosites that have not yet been protected, and also the revision of the limits of the protected areas, observing geodiversity, biodiversity, and the historic, cultural and religious elements in an integrated way.

Ethical statement

This contribution is original and unpublished. The manuscript is not under evaluation for publication by another journal. The text does not fall into the situations described in Plagiarism Policy.

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CRediT authorship contribution statement

José Adilson Dias Cavalcanti: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Marilda Santana da Silva:** Investigation, Writing – review & editing. **Carlos Schobbenhaus:** Funding acquisition, Methodology, Project administration, Supervision, Resources. **Daniel Atencio:** Writing – review & editing. **Hernani de Mota Lima:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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