Geoheritage (2021) 13: 98
https://doi.org/10.1007/s12371-021-00631-2

ORIGINAL ARTICLE

Geo-Mining Heritages of the Mariana Anticline Region, Southeast of Quadrilátero Ferrífero-MG, Brazil: Qualitative and Quantitative Assessment of Chico Rei and Passagem Mines

José Adilson Dias Cavalcanti[1] · Marilda Santana da Silva[2] · Carlos Schobbenhaus[3] · Hernani de Mota Lima[4]

Received: 11 May 2021 / Accepted: 3 November 2021 / Published online: 16 November 2021

Abstract
The main gold deposit discoveries in Minas Gerais during the colonial period occurred in the Mariana Anticline region, southeast of the Quadrilátero Ferrífero. Since then, it has been the target of gold extraction and exhaustively studied, which has given the region great significance. This paper describes and makes a quantitative assessment of Chico Rei and Passagem geo-mining heritages. These geo-mining sites show the important geological processes of the earth's crust during the Paleoproterozoic and Neoproterozoic, and the gold mining history, through its methods and techniques used in two distinct historical periods. Gold deposits occur along the main mineralized zone on the stratigraphic levels of the Caraça and Itabira groups. In the Chico Rei Mine, gold mineralization occurs mainly as quartz-sulfide veins hosted in the itabirites of Cauê Formation. Its operation marks the colonial period, where slave labor was used to mine gold with rudimentary techniques and also when geological knowledge was not satisfactory. In the Passagem Mine, gold mineralization is stratiform tourmalinites and quartz-tourmaline-sulfide veins hosted in Batatal Formation. The Passagem Mine, created in 1819, represents the imperial period, marked by the opening of the Brazilian ports, bringing geological knowledge and new techniques for decadent gold production, through its greatest exponent in the region, the Baron of Eschwege. The quantitative evaluation of the Chico Rei and Passagem mines using the GEOSSIT platform shows us that the two geosites have international scientific relevance, national relevance for educational and tourist use, and low risk of degradation.

Keywords Geosite · Gold deposits · Touristic mine · Minas Gerais

Introduction

Our planet has a complex geological history of 4.5 billion years, with various periods of agglutination and dispersion of continents, and opening and closing oceans imply change, forming important concentrations of metals and energy resources (Hazen 2010). Many regions around the world have mining activity-related history, such as the Rammelsberg Mine in Germany, the coal mines in Wales, the Wieliczka salt mine in Poland, Spain's La Union Mine, the Gambatesa Mine in Italy, and the Lousal Mine in Portugal (Sanmiquel 2018). In Brazil, the Quadrilátero Ferrífero region is an example of how mining activity has brought great benefits and development to society. From the colonial period to present day, the Quadrilátero Ferrífero region remains the largest producer of iron and gold in Brazil. In 2014, Minas Gerais was responsible for 46.6% (71,129 kg of Au) of gold production in Brazil (DNPM 2015). Therefore, there is an intimate relationship between geological and mining sites with historical, artistic, cultural, and religious heritages in this territory.

The concepts of geological and mining heritages, when analyzed together, lead us to the understanding that important elements of geodiversity can be exposed due to mineral extraction activity resulting in the exposure of significant geological features that otherwise would not be available to human access, such as open-pit and underground mines

✉ José Adilson Dias Cavalcanti
jose.adilson@cprm.gov.br

1 Geological Survey of Brazil, Belo Horizonte, Minas Gerais, Brazil

2 Department of History, Federal University of Ceará, Fortaleza, Ceará, Brazil

3 Geological Survey of Brazil, Brasília, Federal District, Brazil

4 School of Mines, Federal University of Ouro Preto, Ouro Preto, Minas Gerais, Brazil

(Castro 2018). Geodiversity comprises the nonliving aspects of our planet, encompassing not only the testimonies from a geological past (minerals, rocks, and fossils), but also the natural processes that modify landscapes giving rise to new testimonies (Brilha 2005). The term geo-mining heritage relates to the tangible and intangible elements of mining to the mineral and rock elements that have been exploited in the past, combining earth and humanity history (Mata-Perelló et al. 2018).

Society interacts with geology through direct exploitation of mineral resources by reshaping the landscape through industrial or agricultural activity and development of materials, and in some cases (e.g., by quarrying, mining, and cutting new roads), these activities reveal important geological information of scientific, educational, or cultural value (Brilha 2005). The understanding of geological and mining heritages encompasses scientific values in the various fields of knowledge of geology (mineralogy, petrology, stratigraphy, structural geology, tectonics, metallogeny, geomorphology, and hydrogeology) and contemplates mineral deposits, mineral and thermal waters, underground and open-pit mines as exploration structures, and the landscapes that result from these activities (Martinez 2019).

Geological heritage is understood as the natural occurrences of elements of geodiversity, geosites, which have exceptional scientific value, i.e., minerals, rocks, fossils, soils, or geoforms have their own characteristics that allow us to recognize the geological history of our planet (Brilha 2018). Mining heritage is an important part in the use and exploitation of geodiversity for the benefit of society, adding value to natural resources and development, being the basis of the formation of several historic cities, many now being also relevant in various thematic parks, world heritage sites, geosites, and geoparks around the world (Martinez, 2020).

Ouro Preto and Mariana are the most important touristic cities in the region and were declared National Historic Patrimony status by the National Institute for Historic and Artistic Heritage (IPHAN) in 1938 and 1945, respectively. Ouro Preto was also declared a World Cultural Heritage Site by UNESCO in 1980. Besides the historical, architectural, and landscape tourism, the region has an immense tourism appeal for its geological and mining heritages. The region is also where the Ouro Preto School of Mines was installed in 1876, with the objective of preparing engineers to explore the mines and transform their metals through metallurgy. In present time, the School of Mines building, located in the historical center of Ouro Preto, has been transformed into a complex of science and technical museums, which includes the Museum of Mineralogy.

The main geological and mining heritages that have been used for scientific research, educational, and tourism in this region are as follows: Chico Rei, Queimada Hill, and Veloso mines in Ouro Preto; Santo Antônio Hill and Passagem Mine, in Passagem de Mariana village; and Santana Hill in Mariana (Sobreira et al. 2014; Barbosa et al. 2018). Chico Rei and Passagem mines are the best known geo-mining heritages.

Geological Setting

The Quadrilátero Ferrífero is the historical and important mineral province of Brazil, located in the southern portion of the São Francisco craton. It represents the basement of the craton which is mainly composed of granito-gneissic terrains (TTG's complex), greenstone belt (Rio das Velhas Supergroup), and Paleoproterozoic metasedimentary sequences (Minas and Estrada Real Supergroups) (Fig. 1). The region has been affected by various tectonic events since the Archean to Cretaceous, giving rise to various mineral deposits, such as iron, gold, and imperial topaz (Fig. 2).

The Mariana Anticline is a rare antiformal structure that occurs in the southeast of the Quadrilátero Ferrífero, connected to the south with the Dom Bosco Syncline and to the northeast with the Cambotas-Fundão Fault System (Fig. 3). In the central portion, there are rocks of the Rio das Velhas Supergroup, and in the flanks of the Caraça and Itabira groups, there are rocks of the Minas Supergroup. In physiographic terms, the Mariana Anticline is represented by Ouro Preto mountain ridge (south flank), Antônio Pereira mountain ridge and Santana Hill (northeast flank), and Santo Antônio Hill in Passagem de Mariana district (hinge zone). Structurally, it represents an open fold closing south east and opening north west, the southern flank has east west alignment, and the northeastern flank has north west-south east direction (Nalini Jr. et al. 1992).

The Minas Supergroup was interpreted as a metasedimentary sequence deposited in a rift environment that evolved to a passive margin (Dopico et al. 2017). Its lithologies encompass thick layers of quartzites, shales, phyllites, dolomites, banded iron formations, graywackes, and metavolcanic rocks. At the base, the Caraça group is composed of metaconglomerates, alluvial metarenites, and marine metapelites, grouped in Moeda and Batatal formations. Isotopic studies in the metaconglomerates and auriferous quartzites of the Moeda Formation (U–Pb in zircon and xenotime) indicated a maximum age of deposition of 2.62 Ga (Koglin et al. 2014). The Itabira group is a sequence composed of banded iron formations, carbonate shales, ferruginous marbles, and rare intercalations of intermediate to mafic volcanic rocks (Cauê Formation) and an essentially carbonate sequence (Gandarela Formation) aged 2.42 Ga (Babinsky et al. 1995). Separated by an erosional discordance, the Piracicaba group is composed of metaconglomerates and ferruginous quartzites, which graded to metapelites and carbonaceous shales,

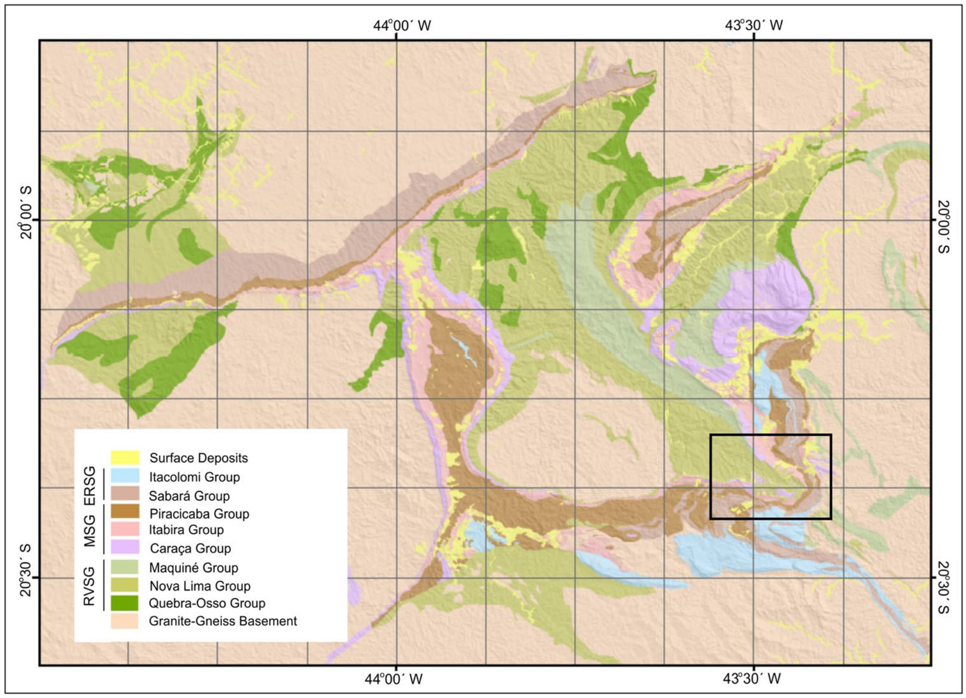


Fig. 1 Simplified geological map of the Quadrilátero Ferrífero with the location of the study area (adapted from Endo et al. 2019). RVSG Rio das Velhas Supergroup, SGM Minas Supergroup, SGER Estrada Real Supergroup; black rectangle—study area

representing the Cercadinho, Fecho do Funil, Taboões, and Barreiro formations. 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 et al. 1996).

Another unit that outcrops in the region and is not involved with auriferous mineralization is the Estrada Real Supergroup formed by Sabará and Itacolomi groups (Endo et al. 2019). The Sabará group is composed of phyllites, quartzites, metagraywackes, and metavolcanic rocks, interpreted as synorogenic turbiditic sequence (*flysch type deposits*), with a maximum sedimentation age of 2125 ± 4 Ma (U–Pb in zircon, Machado et al. 1992). The Itacolomi group is composed of quartzite, polymictic metaconglomerates, which contain clasts of banded iron formations, probably derived from the Cauê Formation. Datings on detrital zircons indicate minimum sedimentation ages of 2059 Ma (Pb/Pb in zircon, LA-ICPMS; Machado et al. 1996) and 2058 Ma (Alkmim et al. 2014). The intrusive rocks (post-Minas) are pegmatites that occur in the basement. These rocks were dated by Noce (1995) and indicated ages around 2.06 Ga. The presence of different generations of mafic dikes is common in the Quadrilátero Ferrífero, with one of them showing an age of 1714 Ga (Silva et al. 1995, *in* Alkmim & Marshak 1998). Recently, Cabral et al. (2020) identified, at the ancient Veloso Mine, an intrusive body in the banded iron formations of the Cauê Formation, dated to 565 Ma, interpreted as the product of anatectically reworked Palaeoproterozoic and Archaean felsic rocks.

Methodology

The Chico Rei and Passagem geo-mining sites in question are part of the project "Inventory of the Geological Heritage of Brazil," developed by the Geological Survey of Brazil. The project uses the GEOSSIT application to undertake the qualitative and quantitative assessment of the geosites surveyed in the project. GEOSSIT was structured according to the methodologies proposed by Brilha (2005) and Garcia-Cortés and Urquí (2009). The current version uses the quantitative assessment criteria, presented in tables of scientific value, potential educational and tourism use, and degradation risk according to the methodology and concepts published by Brilha (2015). The goal of quantitative evaluation is to decrease the subjectivity associated with evaluation procedures, especially when the inventory involves dozens or hundreds of sites, because at some point, it will be necessary to decide at which geosites the resources should be used (Brilha 2018). The application is available on the website of the Geological Survey of Brazil at the following address: https://www.cprm.gov.br/geossit.

The methodological proposal for inventory of the geological heritage of Brazil is based essentially on scientific criteria, but other criteria are also considered, such as the potential for educational and tourist/cultural use. The geological sites of relevant value, due to their unique characteristics or representativeness related to one or several disciplines of geology, have an interest that provides them with a scientific value, which allows them to be used to recognize, study, and disclose/communicate issues related to the origin, evolution,

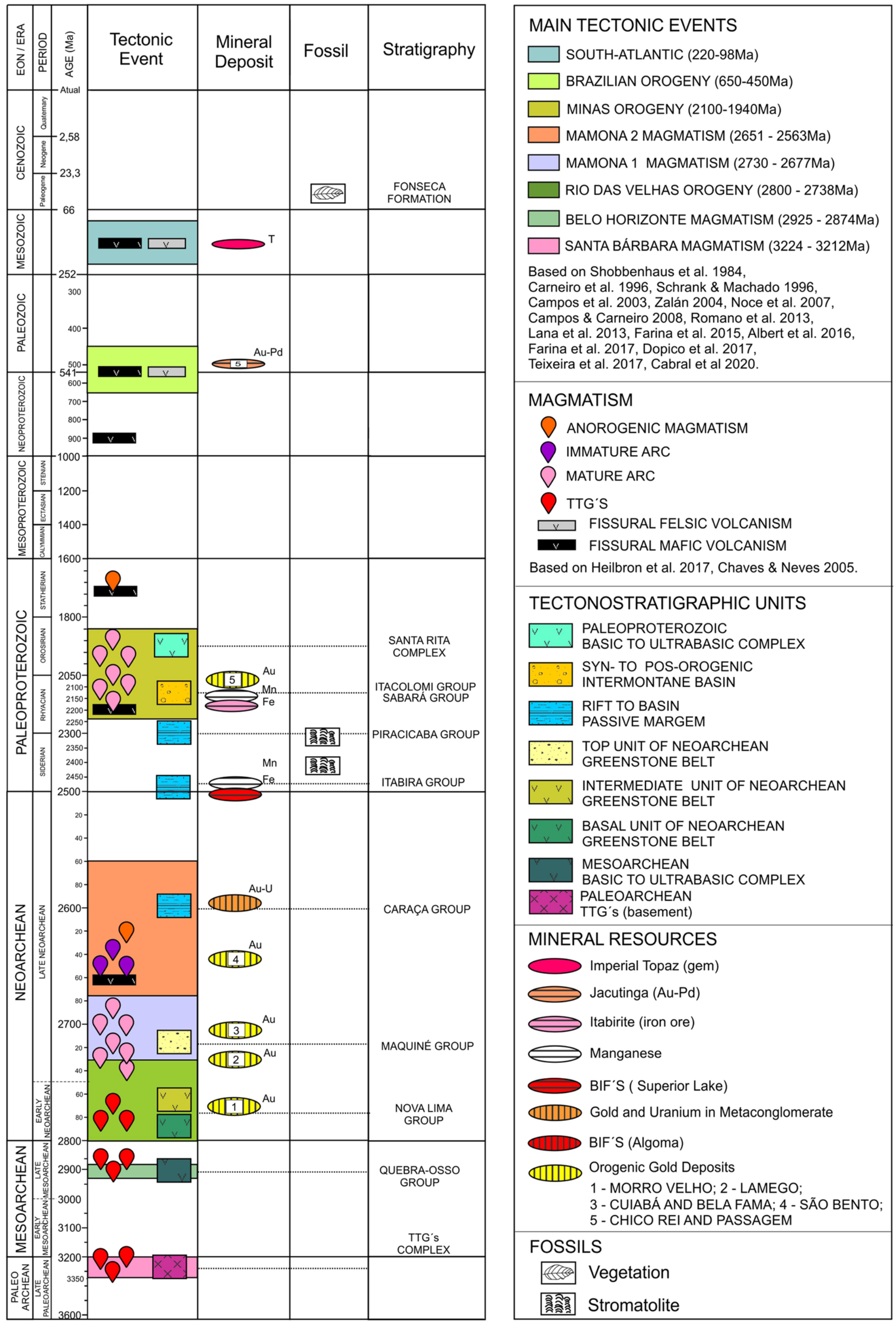


Fig. 2 Chart with the main stratigraphic and tectonostratigraphic units, tectonic events, mineral resources, and fossils of the Quadrilátero Ferrífero province

and composition of the Earth, processes that have shaped it, the climates, and landscapes of the past and present, as well as the origin and evolution of life, which is why they need to be conserved. In addition to scientific value, a geological site may have potential educational and/or potential tourism/cultural use (Schobbenhaus 2019).

According to the project's methodology, geosites with scientific value are sites in a study area that best represent a particular geological material or process, with characteristics of a type locality, that are in the best possible state of conservation, and with significant scientific publications. Sites with potential for educational/didactic use have geological features that can be easily understood by students, have relatively easy and quick access, are near populations with infrastructure and logistics, and have good observation conditions, which is essential for the education of students and teachers at all levels of education. Sites with

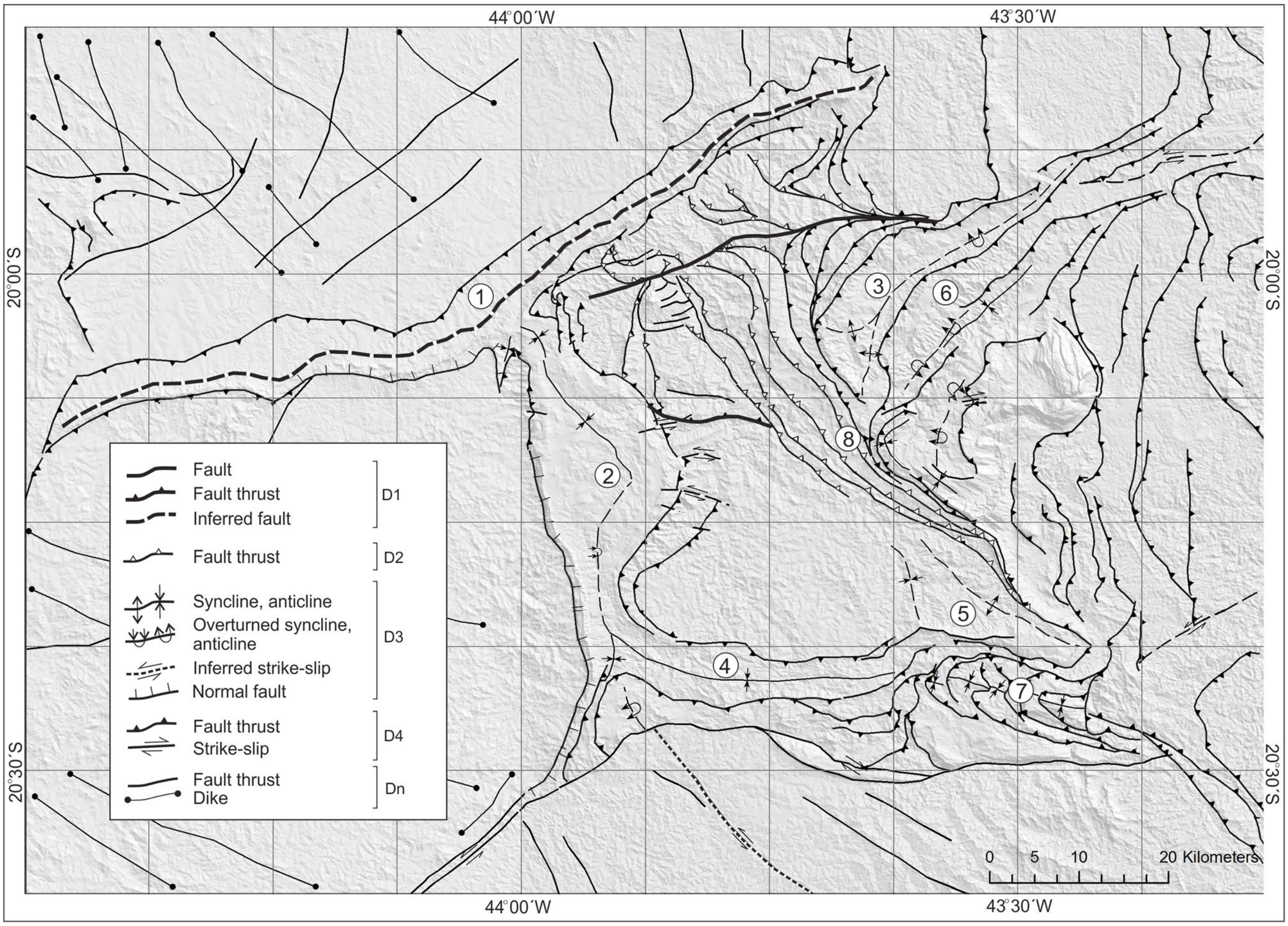


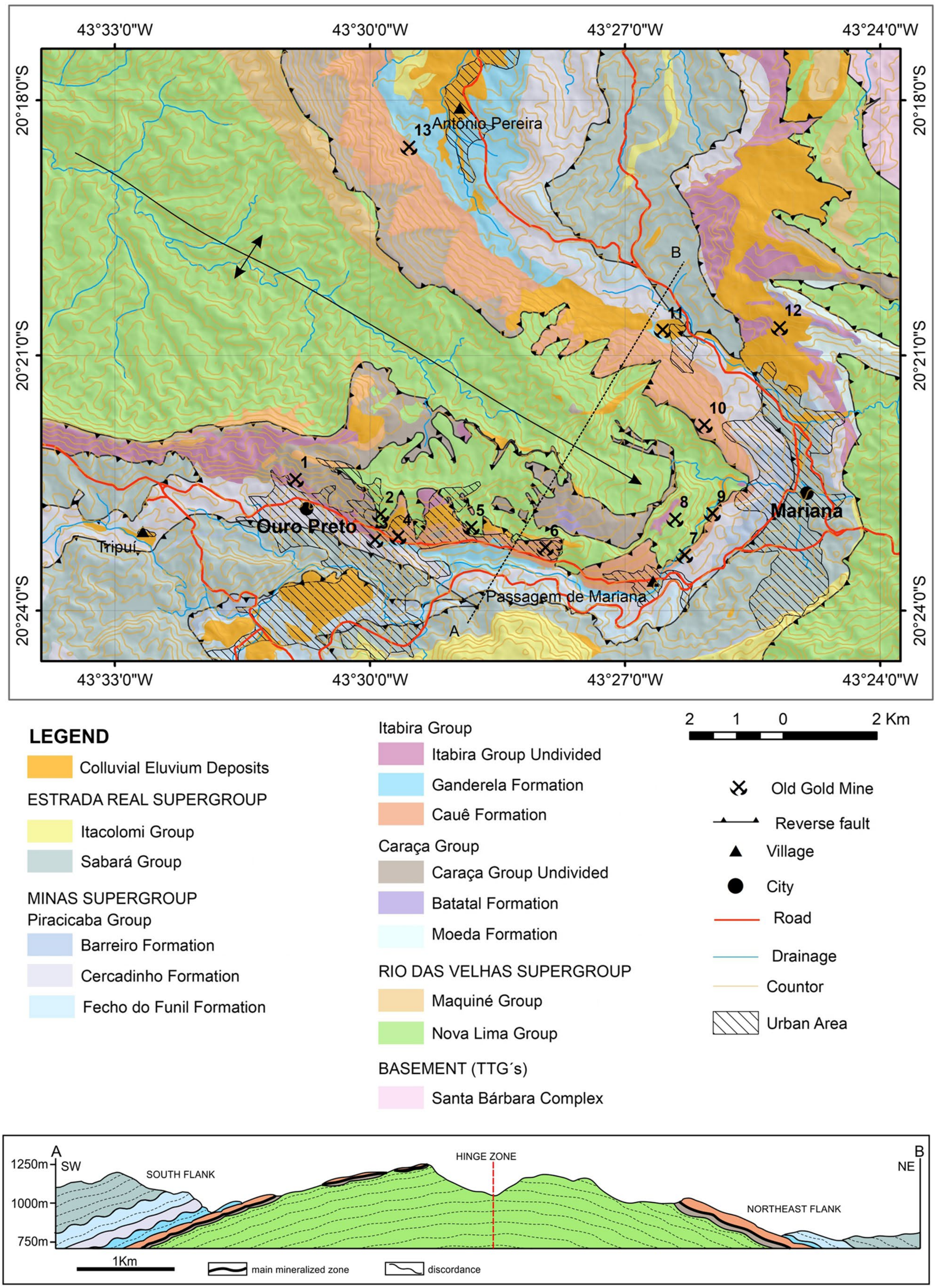
Fig. 3 Simplified structural map of the Quadrilátero Ferrífero showing the main megastructure and deformational events. 1—Curral Homocline, 2—Moeda Syncline, 3—Gandarela Syncline, 4—Dom Bosco Syncline, 5—Mariana Anticline, 6—Conceição Syncline, 7—Nappe Itacolomi, and 8—Cambotas-Fundão Thrust Fault System (after Chemale Jr. et al. 1994; Baltazar and Zucchetti 2007; Cavalcanti et al. 2016)

potential for tourism/recreational/cultural use are those that take into account their exceptional natural beauty, potential for recreational activities, coexistence of other natural values whose geological characteristics can be easily observed and understood by laypeople, and easy access and proximity to populations with infrastructure and logistics. It is important to promote geology to the laypeople, which can contribute to the sustainable development of local populations. Another important point is the evaluation of the risk of degradation of the site, combined with its scientific value and potential educational/didactic and/or tourism/recreational/cultural use, which is very important in the evaluation of the site and is directly related to the implementation of a management plan for geoconservation of the site.

Based on this methodology, the identification of the geosite goes through the recognition of its representativeness, integrity, rarity, and also of scientific knowledge. The definition considers the in situ and ex situ occurrences (museum collections) as geological heritage. By this evaluation method, a site of geological interest is considered a geosite of national relevance when its scientific value is equal or higher than 200 and of international relevance when this value is higher than 300. Sites of geological interest that have a scientific value less than 200 are important resources for education and tourism. These, when found in situ, are called "geodiversity sites" or, when found ex situ, are simply referred to as "geodiversity features." These occurrences are considered to be of national interest when the potential educational and tourism use has a value equal to or greater than 200. Values less than 200 characterize "geodiversity sites" of regional or local importance with interest in the area of a geopark or similar contexts.

Historical Aspects of Ancient Gold Mining in the Mariana Anticline

Gold mining was the most absorbing economic activity of the Minas Gerais Captaincy during the first seventy years of the eighteenth century. In the last decade of the seventeenth


43°33'0"W
43°30'0"W
43°27'0"W
43°24'0"W
20°18'0"S
20°21'0"S
20°24'0"S
Antônio Pereira
Ouro Preto
Tripuí
Mariana
Passagem de Mariana
A
B
1
2
3
4
5
6
7
8
9
10
11
12
13
LEGEND
Colluvial Eluvium Deposits
ESTRADA REAL SUPERGROUP
Itacolomi Group
Sabará Group
MINAS SUPERGROUP
Piracicaba Group
Barreiro Formation
Cercadinho Formation
Fecho do Funil Formation
Itabira Group
Itabira Group Undivided
Ganderela Formation
Cauê Formation
Caraça Group
Caraça Group Undivided
Batatal Formation
Moeda Formation
RIO DAS VELHAS SUPERGROUP
Maquiné Group
Nova Lima Group
BASEMENT (TTG´s)
Santa Bárbara Complex
2 1 0 2 Km
Old Gold Mine
Reverse fault
Village
City
Road
Drainage
Countor
Urban Area
1250m
1000m
750m
SW
SOUTH FLANK
HINGE ZONE
NE
NORTHEAST FLANK
1Km
main mineralized zone
discordance

◂**Fig. 4** Geological map of the Mariana Anticline with the location of the main ancient gold mines and geological profile with the main mineralized zone (adapted from Vial et al. 2007; Cavalcanti et al. 2016). (1) Veloso Mine, (2) Two Bocas Mine, (3) Chico Rei Mine, (4) Jeje Mine, (5) Bom Jesus das Flores Mine, (6) Taquaral Mine, (7) Passagem Mine, (8) Santo Antônio Hill Mine, (9) Mata Cavalo Mine, (10) Santana Hill Mine, (11) Rocinha Mine, (12) Maquiné Mine, and (13) Antônio Pereira mines

century, hundreds of alluvial gold deposits began to be discovered in the streams and creeks of Ouro Preto, Mariana, Sabará, and Caeté, causing the first great gold rush in the history of Brazil (Oliveira 1977). The cities of Mariana and Ouro Preto were responsible for more than 50% of the gold production of the Quadrilátero Ferrífero, about 350 tons of gold (Oliveira 1977; Lanari 1977). Actually, the gold rush in Brazil between 1700 and 1770 was equivalent to the whole production of the rest of the new world, from its discovery up until 1850. The gold production in the cicle represented half of the world production during the XVI, XVII, and XVIII centuries (Castro et al. 2011).

In Ouro Preto and Mariana, the first group of deposits was discovered in Antônio Dias, Padre Farias, Bento Rodrigues, Carmo Creek, Bueno Creek, and Pedras River. New deposits were later discovered in Inficionado, Furquim, São Caetano, Ouro Branco, São Bartolomeu, Itabira do Campo, Antônio Pereira, Camargos, Catas Altas da Noruega, São Sebastião, and others. The second group of deposits was discovered in 1700, along the Velhas River, which is composed of the mines of Sabará, Congonhas, Raposos, Rio Acima, and others. Finally, the third group of deposits of Caeté is composed by the mines of Cuiabá, Morro Vermelho, Ribeirão Comprido, and others (Lanari 1977).

Several geo-mining sites related to both open-pit and underground gold mining are present along the Mariana Anticline. The open-pit mines generated an anthropogenic geomorphology, as they removed large volumes of soil, almost completely modifying the local landscape. On the south flank of the anticline, in the Ouro Preto mountain ridge, six mining areas were delimited (Veloso, Lages-Palácio Velho or Encardadeira, Queimada Hill, Saragoça, Tassara and Moreira, and Taquaral) where open-pit mines, channels for conducting water to the mining fronts, ore reservoirs (mundéus), and several galleries excavated in search for auriferous veins were identified (Cavalcanti et al. 1997). On the northeast flank of the anticline, in the Antônio Pereira mountain ridge, Rocinha, Santana, Maquiné, and Antônio Pereira mines were identified. In the hinge zone of the anticline, in Passagem de Mariana village, the Passagem, Mata Cavalo, and Santo Antônio Hill mines were identified (Fig. 4).

Gold mining in the region occurred both in the riverbed and on the slopes of the mountains and within the massifs (through open-pit mines) and more rarely through underground mines (Sobreira 2014). The gold in the alluvium, paleoaluvium (*grupiaras*), and in the more superficial layers was exhausted over time, causing the decline of mining in Minas Gerais. Several European travelers (Conde de Suzannet, Francis de La Porte Castelnau, Hugh Weddel, and Richard Burton) who visited the mining region pointed out that the lack of the use of mining techniques was the main cause of the decline of gold extraction in the region (Souza 2009). Rugendas produced a famous painting showing the washing of gold ore at the foot of the Serra do Itacolomi, Ouro Preto (Figs. 5 and 6).

Only during the imperial period in Brazil, when foreign companies were allowed to explore for gold and other metals, were more advanced underground mining techniques implemented, creating a new heyday for gold mining in Minas Gerais. The Passagem Mine, along with the Morro Velho and Gongo Soco mines, is the best example of underground mine that used the underground mining techniques brought by engineers trained at the best European mining schools in the nineteenth century, such as the École des Mines de Paris, Royal Mining School of Freyberg, and Cornwall School of Mines (Souza 2014). This new age of gold mining in Minas Gerais occurred with the use of new techniques for mining underground and for processing the ores, as well as the use of gunpowder, mercury amalgamation, and the widespread use of hydraulic power in drainage, ventilation, transport (with wagons and buckets), and ore grinding operations (Souza and Reis 2015).

Metallogenetic Studies in the Mariana Anticline

The first systematic metallogenesis studies occurred mainly in the nineteenth century (Eschwege 1833, Gorceix 1876, Ferrand 1894; Derby 1899). Currently, several studies have been carried out in the region of the Mariana Anticline (Fleischer and Routhier 1973, Heineck et al. 1986, Vial 1987, Fleischer & Vial 1991, Schrank and Machado 1996a, 1996b, Kwitko et al. 1998, Oliveira 1998, Cavalcanti 1999, Cavalcanti and Schrank 1999, Chauvet et al. 2001, Cavalcanti 2003, Kwitko and Oliveira 2004, Cavalcanti and Xavier 2006, Vial et al. 2007, Garda et al. 2009, Cabral and Zeh 2015, Trumbull et al. 2019).

The geology of gold in the Mariana Anticline region was described in detail by Paul Ferrand in his book "L'Or à Minas Geraes, Bresil" (1894). Ferrand pointed out that the main mineralized level was located in the contact zone between two rock sequences, today known as the Minas and Rio das Velhas Supergroups, along the entire Ouro Preto mountain ridge and in the Passagem de Mariana region, for more than 15 km in length, where there are more than 350 galleries (Lacourt 1937a). In some places,

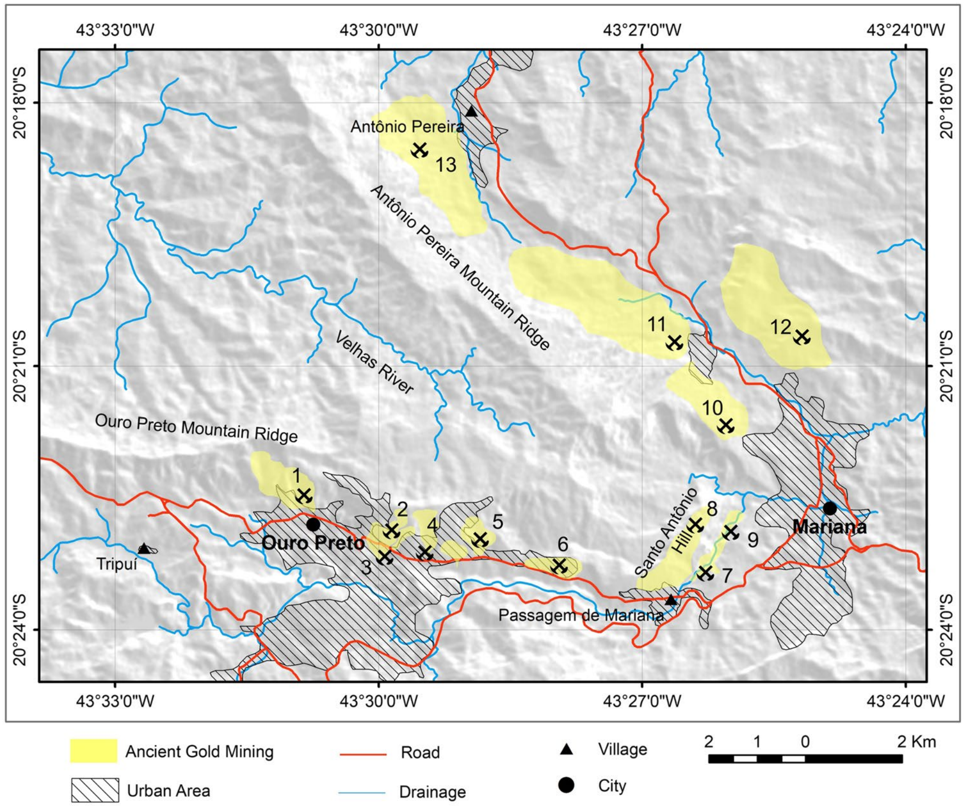


Fig. 5 Map showing the location of ancient gold mining areas along the Mariana Anticline. The names of the mines are the same as in Fig. 4. Background image Alos Palsar, ASF *Alaska Satellite Facility*, available at https://www. alaska. edu

the layers of carbonaceous phyllites and itabirites were entirely excavated (as in Santo Antônio Hill in Passagem de Mariana) until they reached the mineralized zones (open-pit mining). According to Ferrand (1894), the first mineralized level is located at the lower contact of the Moeda formation with shales of the Nova Lima group, where the mineralizing solutions spread out in the rock stratification planes, silicifying and mineralizing the quartzite, giving rise to mineralized layers with abundant arsenopyrite, which can reach thicknesses of a few centimeters to 5 m. The second mineralized level is represented by discordant and concordant veins embedded in the quartzite, composed of quartz, arsenopyrite, and gold, with thicknesses varying from 2 to 5 m and heights from 10 to 30 m. The third deposit occurs at the contact with the Moeda Formation and Batatal Formation (mainly carbonaceous phyllite), where the mineralization is a bed of auriferous quartz with thicknesses varying from centimeters to decimeters and more rarely from 1 to 3 m. In the transition from the Batatal to Cauê formations, a layer of quartz with altered pyrite and free gold is almost constant, with thicknesses of decimeters to centimeters and often forming auriferous buckets. Finally, irregular veins and lenses of quartz are embedded in the Cauê Formation. Eschwege (1833) described the mines of Veloso and Lages where the mineralization occurs in layers of gold-bearing quartz and tourmalinites (Table 1).

As the auriferous mineralizations of the Mariana Anticline region are found in Mariana and Ouro Preto and in Passagem de Mariana village (Mariana) and Antônio Pereira village (Ouro Preto), this was denominated in the “Ouro Preto-Mariana Auriferous District” (Chauvet et al. 1994). To better understand the spatial distribution of the auriferous occurrences in the region, descriptions will be made separately in the domains of Ouro Preto mountain ridge, Passagem de Mariana, and Antônio Pereira mountain ridge.

Mining activity records in the Ouro Preto mountain ridge are clear and include open-pit and underground mines, channels for water conduction, dams (*mundéus*), areas of waste, and artifacts that were used in the process of metal extraction (Cavalcanti et al. 1997). Through the identification of these sites, eight gold mining areas were characterized along the ridges (Fig. 5). These mining sites were described by Eschwege (1833) as Coronel Veloso, Lages-Antônio Dias, Queimada Hill, Saragoça, São João Hill, Tassara and Moreira, Sumaré, and Taquaral mining. Cavalcanti (1999) studied the region of Lages-Antônio Dias, near the center of Ouro Preto, where Palácio Velho (or Encardideira) is located, and reported that the mineralization is hosted in the sequence of rocks of the Caraça and Itabira groups and is formed by quartz-tourmaline-sulfide veins and tourmalinite. The Caraça group is composed of sericite quartzite and carbonaceous phyllites that are cut by quartz-tourmaline-arsenopyrite veins. The Itabira group is represented by banded

Fig. 6 Washing gold ore in a valley near to the Itacolomi mountain range in Ouro Preto, Minas Gerais (Rugendas 1835), from the National Library (Rio de Janeiro), available at http://objdigital.bn.br/acervo_digital/div_iconografia

iron formations of carbonate, sulfide, and oxide facies that are cut by quartz-tourmaline-pyrite veins; it also contains stratiform tourmalinite bodies rich in arsenopyrite.

In Passagem de Mariana village, open-pit mining, called Santo Antônio Hill, was developed in the itabirite layer. At Passagem Mine, the mining was overlying the itabirite, developed in a thick tourmalinite layer with abundant gold and even visible to the naked eye (Eschwege 1833). According to Fleischer and Routhier (1973), gold deposits in Passagem Mine are associated with quartz-tourmaline-arsenopyrite veins, quartz-carbonate-tourmaline-arsenopyrite veins, and stratiform tourmalinite with variable thickness (up to 5 m), forming a continuous layer, situated between the quartzite, carbonaceous shales, and banded iron formation. Mata Cavalo Mine is located in lateral continuity with the Passagem Mine, and the main mineralization was described by Heineck et al. (1986) as hydrothermalite situated between the level of the Moeda Formation and the itabirites at the base of Cauê Formation.

In Antônio Pereira mountain ridge, the ore bodies are basically quartz-tourmaline-arsenopyrite veins (Kwitko and Oliveira 2014). In the Santana Mine, the mineralization is positioned in the contact between the quartzite of the Moeda Formation and the itabirites of the Cauê Formation and is composed of quartz-tourmaline-arsenopyrite veins, which is part of a similar context of the Passagem Mine (Souza and Menezes 1996). The Maquiné Mine is located 2 km east of the Santana Mine, outside the context of the Mariana Anticline, and the ore is jacutinga with free gold in flakes and nuggets (Lacourt 1937b). In Antônio Pereira village,

Table 1 Main ancient gold deposits of Mariana Anticline (modified from Ferrand (1894))

Type deposit	Deposit	Municipality	Propriety	Composition	Host rocks
Quartz-pyrite gold vein	Santana Hill	Mariana	D. Pedro Gold Mining Company Limited	Quartz, tourmaline, arsenopyrite, marcasite, calcite, and visible gold	Phyllite, schist, itabirite
	Passagem	Mariana	Ouro Preto Gold Mines of Brazil Ltda	Quartz, tourmaline, arsenopyrite, pyrite, marcasite, dolomite, siderite, stibinite, moscovite, chlorite, and gold	Dolomite, tourmalinite, schist, quartzite
Quartz gold vein	Antônio Pereira	Ouro Preto	Paula Castro	White quartz, arsenopyrite limonitized, clay, and sand mass (Bugre)	Itabirite, dolomite
	Saragoça	Ouro Preto	Multiple owners	Quartz with arsenopyrite and scorodite	Quartzitic schist
	Veloso	Ouro Preto		Quartz	Banded iron formation
	Chico Rei	Ouro Preto		Quartz, limonite, pyrite, arsenopyrite	Banded iron formation, toumalinite
Auriferous itabirite	Maquiné	Mariana	D. Pedro Gold Mining Company Limited	Jacutinga (free gold)	Banded iron formation, sacaroid quartz vein

the mineralization is an ore called "Bugre" and auriferous veins (Kwitko et al. 1998). Bugre is a friable clay-sandy mass, embedded in dolomite and itabirite intercalations, where gold is associated with limonitized arsenopyrite. The veins are composed of dolomite, quartz, and arsenopyrite, in addition to chlorite, fluorite, pyrite, pyrrhotite, calcite, and tourmaline.

Geo-Mining Heritages in the Mariana Anticline

The Mariana Anticline region stands out for the richness of geodiversity elements, especially regarding the collection of geological and mining sites (Sobreira et al. 2014). The region was the target of intense mining activity during and after the colonial period, which caused profound changes in its landscape (geoforms). These are scars that keep record, mainly of the gold mining activities both open-pit and underground. However, at the same time, geological elements have been exposed that would not be visible if the mining activities had not existed, adding value to the geological sites.

Along the antiform structure dozens of geological and mining sites have been mapped. In the south flank, in the Ouro Preto mountain ridge domain, five ancient underground mines are being used as tourist facilities: Chico Rei, Du Veloso, Jêje, Felipe dos Santos, and Santa Rita mines (Queiroz et al. 2014; Barbosa et al. 2018). According to these authors, all mines use signs along the galleries, they are illuminated, and visitors wear helmets and flashlights. The main activity performed in the mines is a guided tour along the galleries where visitors learn about the gold mining history, mining techniques, and geology and gold deposits. Some mines have recreational facilities, a snack bar, restaurant, museum, and gift store. Another key area in this sector is Queimada Hill, an important site where the Archeological Park of Queimada Hill is currently being established. The site contains ruins of buildings, shelters excavated in the rock, underground gold mines and vent pipes, dams (*mundéus*) which are constructions made for washing gold, small dams, segments of water catchment channels, and hydraulic systems with channels used to transport water and gold mud (Ferreira 2011).

On the northeast flank are Santana Hill and the Antônio Pereira mountain ridge. The main site is Santana Hill, where Vila do Gogo is located. The site was declared a heritage site by municipal law in 2008, as a landscape and archeological site. This site has ruins of open-pit gold mining structures, walls of stone, underground mines, shafts, and a set of dams (*mundéus*) staggered in the valleys and used to retain mud rich in gold resulting from the washed terrain (Araujo 2010, Sobreira et al. 2014).

In the hinge zone are the Santo Antônio Hill, Passagem, and Mata Cavalo mines. Santo Antonio Hill is located in the western part of Mariana, close to the border of Ouro Preto, north of Passagem Village. The area is currently used for adventure tourism by private companies. It is a very expressive site from the point of view of mining activity and history because of the quantity of ruins in the region. In relation to the ruins regarding the mining activity, there are traces of open-pit mining, dams (*mundéus*), water reservoirs, aqueducts, canoes, galleries, shafts, waste piles, and stone walls (Prefeitura Municipal de Mariana, 2008). This complex has great potential for the installation of an archeological park because it is a preserved area and there was no urban occupation by the local community.

Two examples of the use of geological and mining sites as tourist, educational, and scientific research facilities are the Chico Rei and Passagem mines (Fig. 7). These two mines exhibit different styles of gold mineralization and also different mining techniques. The mineralization at Chico Rei Mine is mainly associated with quartz veins embedded in the banded iron formation (itabirite) of the Cauê Formation of the Itabira group. The gold mineralization at Passagem Mine is associated with levels of tourmalinites and quartz-carbonate-sulfide veins hosted in the carbonaceous phyllites of the Batatal formation of the Caraça group. Chico Rei Mine is a totally rudimentary mining activity, with work carried out using slave labor, which generated tortuous and very tight drifts. The galleries were excavated along the veins, often opening chambers in places where there were pockets of veins rich in gold. Passagem Mine, however, highlights the use of the technique. The ore body was reached by a decline following the ore dip and exploited by the room.

Chico Rei Mine

Chico Rei Mine is on a property that was known as Encardadeira Farm which belonged to Major Augusto and was sold in 1740 to the slave Galanga, baptized as Francisco (Fig. 8). He became known as Chico Rei, since he was king of his tribe in the Congo (Zaire), a person respected and admired by many white people. He used the gold extracted from the mine to free his subordinates. With the discovery of access to the old mine in the 1940s, the family of the current owner named it "Chico Rei Mine" in honor of the black African, a legendary leader and symbol of freedom in Minas Gerais (Martinez 2019).

Location

The mine is located in the Antônio Dias neighborhood, within the historic center of Ouro Preto, Minas Gerais. It can be accessed through narrow streets via the address, 108 Dom Silvério Street. It is possible to get there on foot from Tiradentes Square, by going down the slope of Claudio Manoel Street, taking a left onto Bernardo Vasconcelos Street until the church of Antônio Dias and then taking a left onto Dom Silvério Street, and after the bridge on the right is the mine of Chico Rei.

Mine Geology

Chico Rei Mine represents, in metallogenetic terms, a rare example of gold mineralization hosted in Paleoproterozoic banded iron formations of the Minas Basin, in the Quadrilátero Ferrífero. Inside the mine quartz-arsenopyrite and quartz-pyrite mineralized veins are present, as well as barren quartz veins and thin layers of tourmalinite. The gold mineralization was interpreted as an orogenic gold deposit. In the mine, there are also outcrops of the carbonaceous phyllite of the Batatal Formation and the quartzite of the Moeda Formation. Tectonic structures formed by the Brasiliano event can also be seen. In the mineralized zone, the carbonaceous phyllites are folded and crenulated, so that the main foliation is not controlled. Within the sequence of banded iron formations, there are differentiated layers of weathered banded shales (clay) of brownish color, siliceous, and amphibolitic itabirites (Fig. 8).

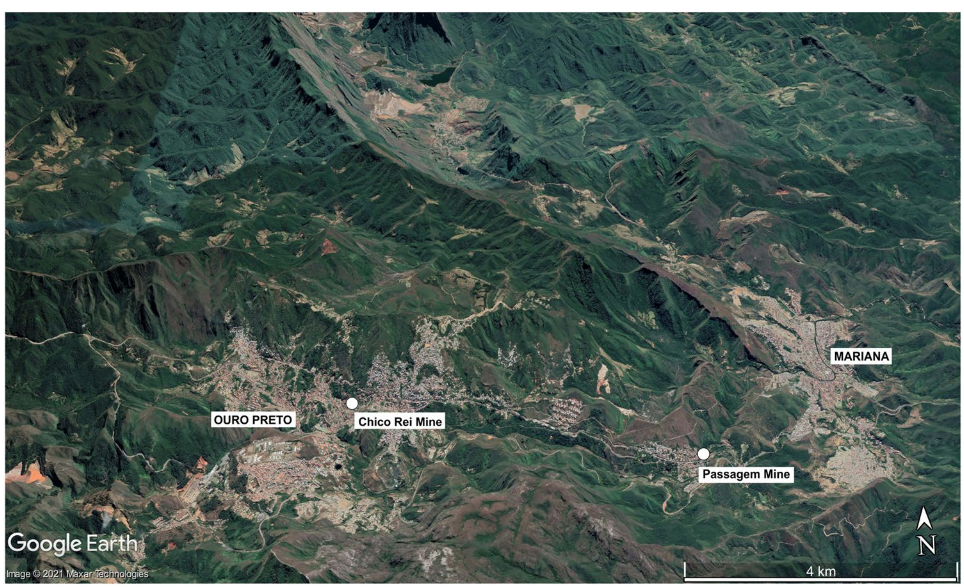


Fig. 7 Satellite image of Mariana Anticline with the location of Chico Rei and Passagem mines (from Google Earth Pro, access in April 2021)

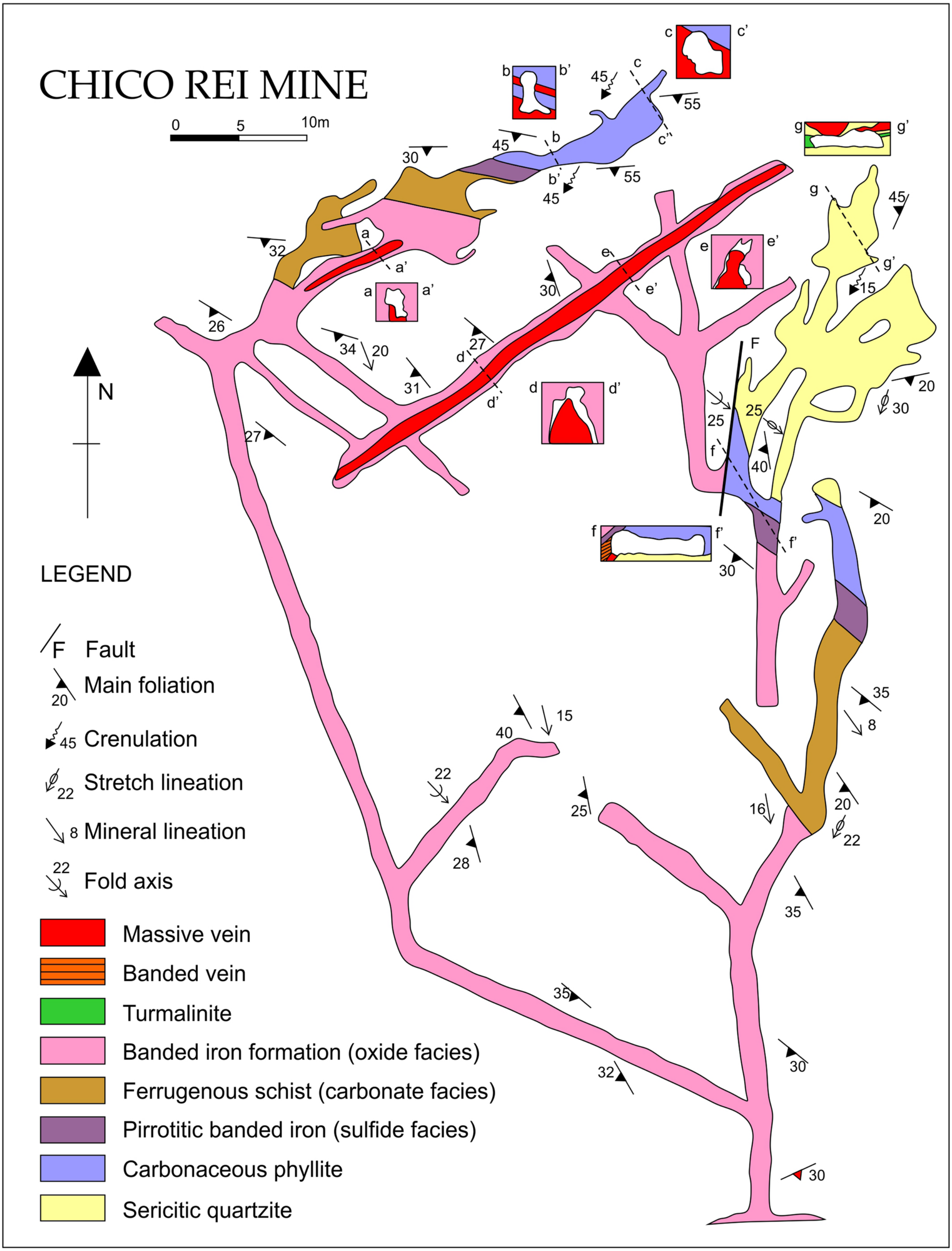


Fig. 8 Geological map of the Chico Rei Mine showing mineralized areas and main lithology and structures

Gold is mainly associated with quartz-sulfide veins (arsenopyrite and pyrite), secondarily with tourmalinites, and it is also disseminated in the host rocks (banded iron formations). The veins have a 230°/subvertical direction with a south west drop and represent tension veins perpendicular to the mineral lineation described in the mine (146°/subhorizontal). The quartz-arsenopyrite banded vein is associated with conjugate hydraulic fracturing in a shear zone with normal motion to south east.

Tourmalinite is intensely brecciated and occurs in the contact between Moeda Formation and Batatal Formation. The ore horizon is formed by tourmaline blocks immersed in a quartz mass forming a stratabound body. The tourmalinites are not cohesive and have a grain size of medium to fine sand (Fig. 9a). A large amount of quartz veins without preferential orientations cut through the tourmalinites.

The quartz-arsenopyrite veins embedded in the tens of meters are intensely fractured carbonaceous phyllites with 240°/subvertical direction. They are composed of quartz and massive portions of arsenopyrite (Fig. 9b, c). Microscopically, the massive portions of arsenopyrite (99%) have quartz, tourmaline, and white mica as accessories. The arsenopyrite is euhedral to subhedral without preferential orientation. Quartz is anhedral and fills the voids between grains.

The quartz-pyrite veins are more than 50 m in length, 1 to 5 m wide, are aligned at a direction of 240° with a south west dip, and are highly fractured. The plunge is to the south west, and the gallery follows the top of the vein. The mined ore was the material surrounding the vein. This material is fully weathered, and only in rare spots in the sample are parts of it fresh, composed essentially of pyrite (Fig. 9d). Microscopically, the pyrite turned out to be rich in chalcopyrite inclusions and had fractures filled by goethite.

Mining Methods

Chico Rei Mine is an example of underground mining from the colonial period, carried out by slave labor in an extremely rudimentary manner. The mine is formed by a set of intersecting drifts that seem to chase the gold veins. The gold extracted was free gold that can be seen with the naked eye, as the ancient geologists would say. Pointers and sledgehammers were used, and when necessary, homemade gunpowder was used for detonation. The ore was loaded onto *carumbés* and wheelbarrows. Outside, there is a stream which was possibly used to wash the gold using *canoes* and wooden *gamelas* (or *bateias*) (Fig. 10).

Chico Rei Mine exhibits significant extension with numerous intersecting and overlapping drifts, most of which are almost impossible to access due to cave-ins and flooding. The sectors studied consist of four main drifts with predominantly ogive-shaped and more rarely quadrangular sections with heights less than 1.80 m and widths less than 1.50 m. One chamber mapped in the mine has a circular shape which is approximately 7 m in diameter. The drifts were always small sections, poorly lit, making the work difficult and causing damage to the health of the slaves who worked in them. The lack of geological knowledge at this time also made the work very difficult (Hermani 2002).

Fig. 9 **a** Quartz vein in tourmalinite in carbonaceous phyllite, **b** massive vein of quartz-arsenopyrite in banded iron formation, **c** massive vein of arsenopyrite in quartzite, and **d** pyrite fragments from massive quartz-pyrite veins

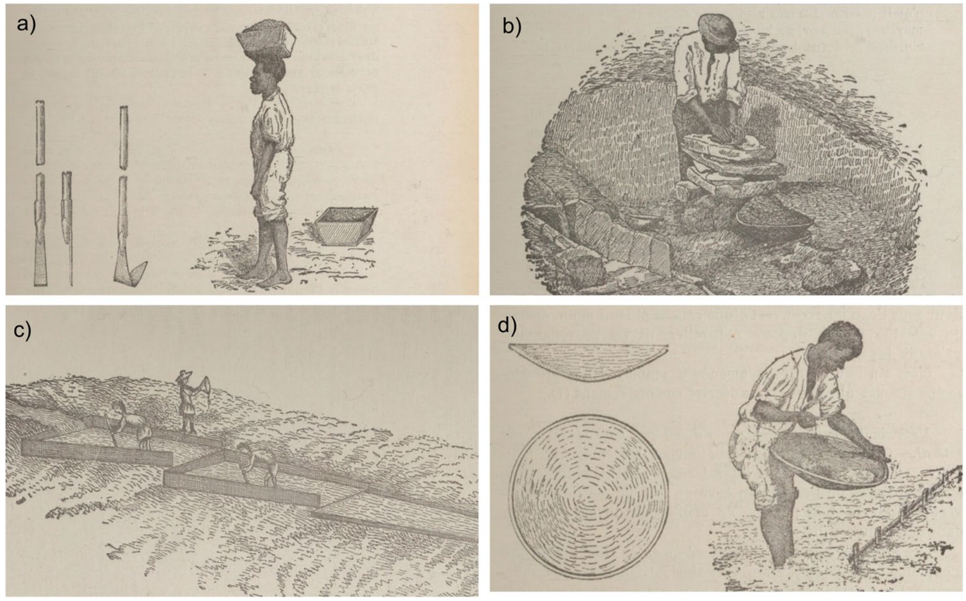


Fig. 10 Methods and techniques used by slaves in the region. **a** Tools (chisels and amocrafe) used in gold mines and black man carrying ore in *carumbé*, **b** black man crushing gold ore, **c** canoe service to concentrate the ore, and **d** *bateias* and their use for prospectors (*faiscadores*) to remove the gold for concentrated ore in *canoes*, compiled from Ferrand (1894)

Tourist, Cultural, and Educational Aspects

Chico Rei Mine was the first underground gold mine open to tourism in Ouro Preto. The mine is located in Dona Marizinha's residence. After being discovered, it began to be used as a tourist facility, in the 1980s (Fig. 11). It has an intense flow of Brazilian and foreign tourists. This is facilitated by the local tourist guides who include the mine as part of the tourist routes around the historic center of Ouro Preto. It is a natural laboratory to learn about the history of mining in the colonial period, the geology of the Quadrilátero Ferrífero, and about gold mineralization, specifically in the rocks of the Minas Supergroup.

The cultural activity related to the Chico Rei Mine is the *Congada*, a religious festival that honors *Our Lady of the Rosário*, known as the saint of the blacks. Chico Rei, according to local traditions, is recognized as an African king who was enslaved in Ouro Preto (ancient *Villa Rica*) who managed to buy his freedom and be crowned again as king, giving rise to *Congado*. The research conducted by Santos (2019) was based on the myth of Chico Rei in the Reign of Our Lady of the Rosário and Our Lady Efigênia from *Alto da Cruz* of Ouro Preto and also on the presence of its history in the Ouro Preto schools, built through several historical productions.

Passagem Mine

Passagem Mine is one of the largest underground mines currently open to tourism in Brazil and also the first mining enterprise of the imperial period, which persisted for almost 200 years, going through several periods of Brazilian history. It is used by tourists, students of all levels, in scientific studies conducted by researchers from several universities, and by divers that explore the flooded underground levels.

Location

The mine is located in Passagem de Mariana village, in the municipality of Mariana. It can be accessed via Highway BR-040 leaving from Belo Horizonte in the direction of Ouro Preto towards Rio de Janeiro, for about 30 km and then taking the BR-356 (Inconfidentes Highway) towards Ouro Preto. When you arrive in Ouro Preto, you continue in the direction of Mariana for another 8 km and arrive at Passagem de Mariana village. After crossing the bridge, continue for another 500 m, until a roundabout and take a left, and the mine entrance is approximately 100 m from the roundabout.

Historical Aspects

Passagem Mine is the oldest mechanized gold mine in Minas Gerais and also the most important in the auriferous district of Ouro Preto-Mariana, with its production estimated at 60 tons of gold (Vial 1988). Souza (2009) in his doctoral thesis, described the history of Passagem Mine in detail (Fig. 12). According to this author, gold mining in Passagem de Mariana village began in the early eighteenth century, in the Carmo Creek and then on the slopes of the hill (Santo Antônio Hill), through the drilling of shafts until reaching the ore body.

With the change in policy of mineral extraction in Brazil from 1817 onwards, the imperial government authorized the formation of mining companies. It was during this

Fig. 11 **a** View of the mine entrance; **b** view from outside into the main gallery, where it is possible to see the flooded lower level; **c** view from inside into the main gallery; **d** view of the gallery giving access to the main chamber; **e** visitor reception area; and **f** attached restaurant in the basement of Mariazinha's residence

period that Baron Eschwege bought Passagem Mine and then founded the "Mineralogical Society of Passagem," in 1819, becoming the first mining company in Brazil. In 1859, the Baron of Eschwege sold the company to the Englishman Thomas Bowden, who resold it in 1863 to Thomas Treloar, representative of the "Anglo-Brazilian Gold Company Limited." This company then acquired the land of three adjacent properties: Fundão, Mata Cavalo, and Paredão mines (Souza 2009). In 1880, it became controlled by a French company that created "The Ouro Preto Gold Mines of Brazil Limited," which operated until 1927. Later, it was sold to the Ferreira Guimarães Group, formed by bankers and industrialists from Minas Gerais, who founded the "Companhia Mina da Passagem Sociedade Anônima," which operated until 1954, with about 70 km of galleries (Souza 2009). Since then, there have been several attempts to reopen it, but Passagem Mine has never operated again.

Mine Geology

Passagem Mine is also a rare example of auriferous mineralization hosted in Paleoproterozoic rocks of the Quadrilátero Ferrífero in Minas Supergroup, where one of the main ore bodies is a stratiform tourmalinite. Besides tourmalinites, the mineralization is composed of quartz-carbonate-sulfide and quartz-sulfide veins. The most accepted deposit classification is an orogenic gold-quartz-tourmaline vein type deposit, where the main ore is veins composed of white quartz (60% of the volume), carbonate (ankerite), tourmaline, sericite, and sulfides (Vial et al. 2007). The main sulfide is arsenopyrite that is almost always accompanied by pyrite and pyrrhotite and in smaller proportions chalcopyrite, galena, lollingite, bertierite, and maldonite. The most common types of hydrothermal alteration are silicification, sulfidation, and tourmalinization and to a lesser extent sericitization and carbonation. The mineralized zone is confined to a

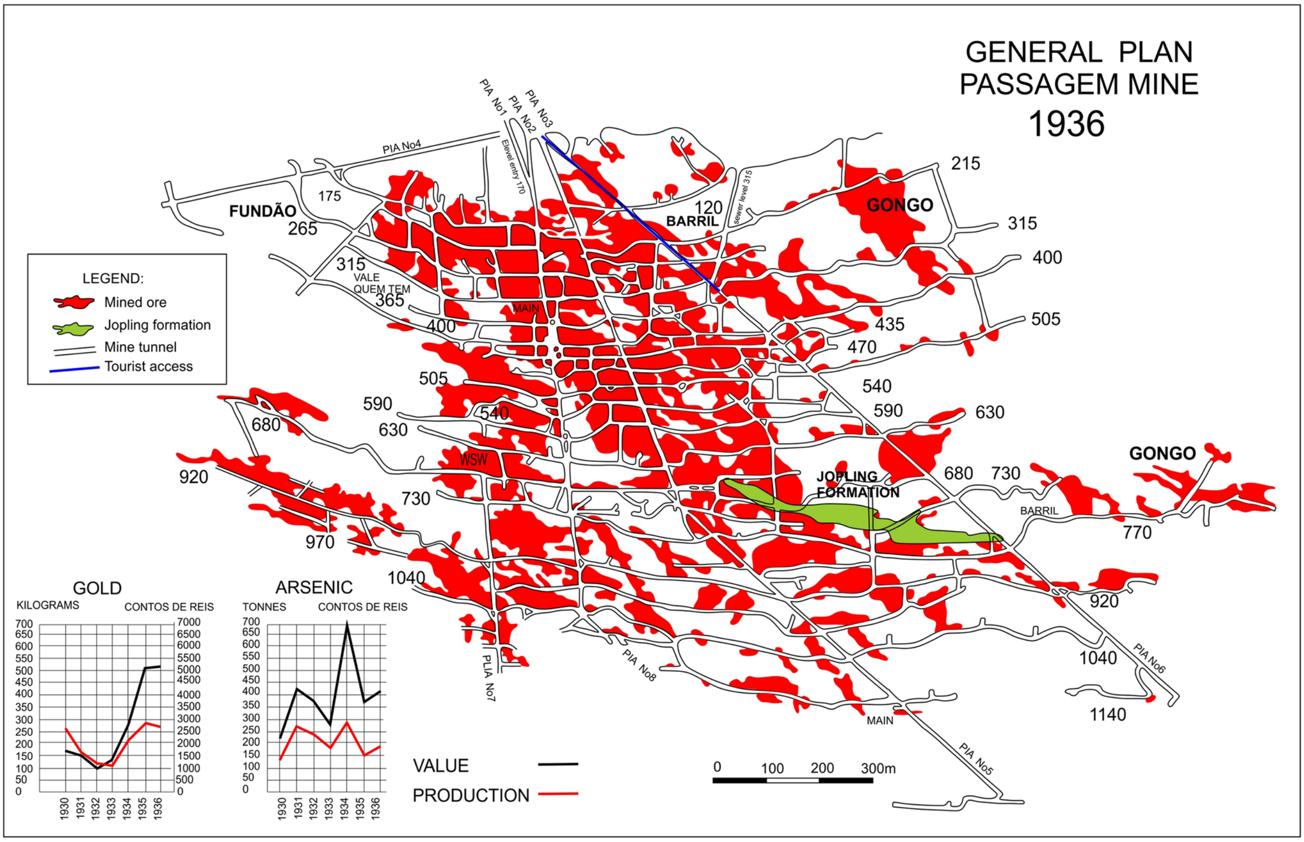


Fig. 12 Map of Passagem Mine with the location of the ore bodies mined until 1936 (compiled and modified from Campos (1938))

tabular zone, described by Chauvet et al. (1994) as the main mineralized contact. According to these authors, the ores are mainly veins of quartz-tourmaline-arsenopyrite, quartz-carbonate-tourmaline-arsenopyrite, and stratiform tourmalinite. The stratiform tourmalinite occurs in thicknesses ranging from a few centimeters to 3 m, as well as in the form of breccias in the mineralized veins.

Fleischer and Routhier (1973) and Ladeira (1991) considered that mineralization occurs at the level of the Batatal Formation. This level is dominated by carbonaceous phyllite with biotite, ferruginous dolomite, and metachert. These authors assumed that the itabirite of the Cauê Formation is the hanging wall of the mineralization, and the quartzite of the Moeda Formation is the footwall, with the stratiform tourmalinite being the main ore, with contents that can reach up to 200 g/ton. The mineralization settings may represent an imbricated complex of rocks, i.e., sericite quartzite, silver-gray phyllite, the graphitic sericite phyllite, the carbonate rock, and the quartz-carbonate-biotite schist (Vial 1988). This author considers that occurrences of rocks belonging to the Batatal and Moeda formations are rare, and that the main ores are quartz-tourmaline-sulfide veins and amphibole-pyrrhotite schist.

Cavalcanti (2003) described the lithological successions in the geological profiles at levels 120, 175, and 265. In each profile, the lithological successions are different, but the mineralization consists of quartz-tourmaline-sulfide veins, quartz-carbonate-tourmaline-sulfide veins, and stratiform tourmalinite.

At level 120, the banded iron formation is the hanging wall and the sericite-quartz schist, the footwall. Between these units, an imbricated complex of lithologies occurs where the stratiform tourmalinite is found (Fig. 13a). This imbricate complex is formed by the following sequence, described from top to bottom: carbonaceous biotite schist, carbonate rock containing levels of tourmalinite, and the stratiform tourmalinite. The banded iron formation contains, at the top, a very weathered sulfide metachert level (Fig. 13b). The carbonate rock shows asymmetric boudinage and interstratal shear features. The main ores are quartz-carbonate-tourmaline-sulfide veins (arsenopyrite) and sulfide-bearing tourmalinite.

At level 175, the lithological sequence, from bottom to top, is the following: sericite-quartz schist with staurolite, stratiform tourmalinite, carbonate rock with tourmalinite levels, and biotite-carbonaceous schist. All this sequence is cut by quartz-tourmaline-sulfide veins and

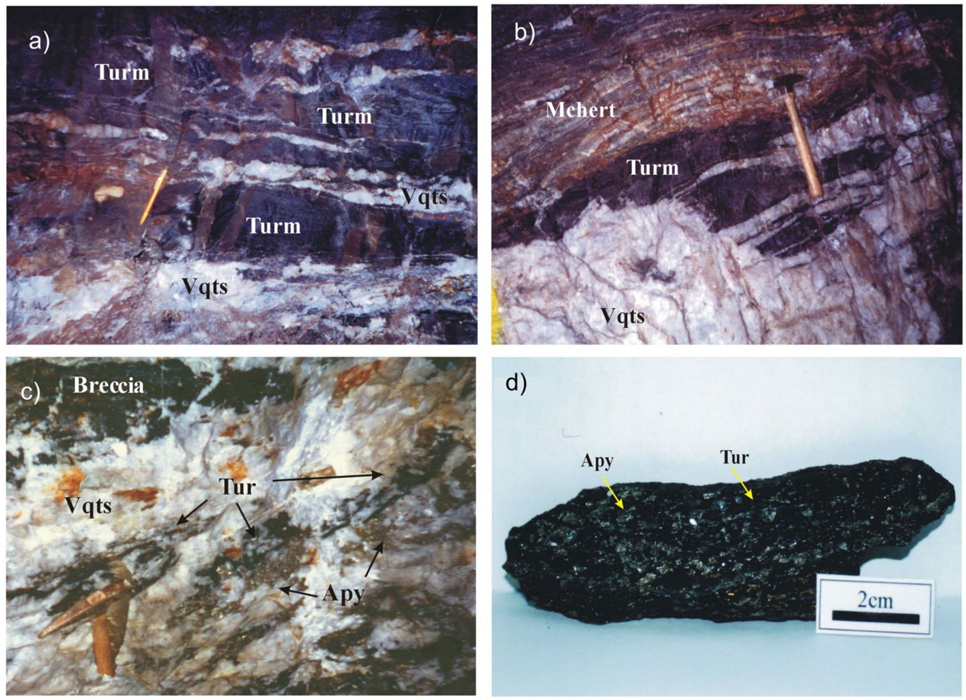


Fig. 13 Main mineralized zone at the Passagem Mine. **a** Quartz-tourmaline-arsenopyrite vein (Vqts) and tourmalinite (Turm); **b** Quartz-tourmaline-arsenopyrite vein with tourmalinite breccia and metachert (Mchert) on top; **c** mineralized vein with high concentrations of arsenopyrite (Apy), tourmaline (Tur), and tourmalinite breccia; and **d** arsenopyrite-rich tourmalinite fragment

quartz-carbonate-tourmaline-sulfide veins. The quartz-carbonate-arsenopyrite-tourmaline veins occur mainly parallel to the main foliation of host rocks and are intercepted by the quartz-turmaline-arsenopyrite veins. Near the ore bodies, the sericite-quartz schist, the footwall of the mineralization is silicified, tourmalinized, and sulfidized. Breccias of tourmalinite and carbonate rocks occur in the quartz-tourmaline-sulfide veins (Fig. 13c). The presence of centimeter levels of the carbonate rock is common, often showing boudinage and rupture when they are associated with the quartz-carbonate-tourmaline-sulfide veins.

At level 265, the lithological sequence from bottom to top is as follows: sericite-quartz schist (with biotite, staurolite, chloritoid, and garnet), tourmalinite, carbonate rock, and biotite schist with tourmaline and kyanite. The top of the sericite-quartz schist is tourmalinized, and the carbonate rock has centimeter levels of tourmalinite. The tourmalinite layer is approximately 3 m thick and highly sulfidized (Fig. 13d). In the carbonate rock, the veins parallel to the main foliation are composed of quartz and carbonate and fine tourmaline layers.

At the site called "Sindicato," the western portion of the mine, the lithological sequence is formed by sericite-quartz schist (at the base) and itabirite (at the top). The ores are quartz-tourmaline-sulfide veins that are embedded in both the sericite-quartz schist and the itabirite. In this zone, it is common for itabirite breccias to be immersed in the mineralized veins. The halos of hydrothermal alteration with tourmalinization, sulfidation, and silicification show deformation features associated with the vein in the sericite-quartz schist.

Mining Methods

The mining method used in Passagem Mine was described by Ferrand (1894) in his book "L'Or a Minas Geraes, Brésil" and by Maia (1948) in his free teaching thesis "Considerações Sobre a Prática de Lavra em Passagem, MG," held at the Ouro Preto School of Mines and described here through the article published by Miranda and Curi (2017). The "room and pillar" method, accessing the ore bodies through declines, in turn, enables access to different rooms at different levels in the mine (Fig. 12). The main access was made through declines (called Pia) with a slope of around 19° and a length of 1032 m. From the declines, the ore bodies were accessed through drifts that determined the levels of the mines (e.g., level 350). The main drifts have 15-inch gauge rails and approximately 10 kg per meter, over which the ore was transported by trolleys pushed by the miners. The ore was mined by starting at each level, and transversal drifts were opened following the plunge of the ore body, leaving pillars (approximately 3 m in diameter) for ceiling support. According to Miranda and Curi (2017), the ore extracted from the stopes was transported on each level to a loading point for hoisting via declines to the surface.

Ore Processing

The annual reports issued by the "Ouro Preto Gold Mines" company, from 1899 to 1904, highlight the improvements in ore processing techniques adopted by Passagem Mine during this period. According to Souza (2009), the ore processing plant in Passagem Mine had three mills, two of which were Brazilian mills, one with 24 hands of wooden pestles and another with 32, and a Californian one with 40 iron hands (Fig. 14a). This set of mills produced about 100 to 120 tons per day of grinded ore.

The concentration process included chloritization, which was used since 1890. That was later, in 1900, replaced by cyanidation, and in the same year, a Wilfley concentrator was acquired. Between the period of Eschwege to Burton, D. Pedro II, Courcy, Ferrand, and the last report of 1904, there was a technological revolution at Passagem Mine. In relation to the use of driving force, equipment, labor, and machinery, human traction was replaced by animal traction and the latter by hydraulic traction; chloride amalgamation was replaced by cyanidation. Underground, hand drilling was replaced by air compressed drilling, the ore was transported in carumbés by wagons (Fig. 14b), and electric light was installed (Souza 2009).

Tourist Destination

With the end of gold extraction in 1984, the Passagem Mine Company faced the challenge of giving the mine a new function in order to implement tourism activity. In 1999, part of the mine was adapted for tourism use, so that the general public could visit an underground mine and, at the same time, could learn about the history of gold mining in Minas Gerais and also about the geology and the mining methods used in the extraction of gold ore.

Currently, Passagem Mine is part of the touristic route in the region of Ouro Preto and Mariana and receives a large number of foreign and Brazilian tourists and students of all levels. The visitation area is composed of a decline where tourists descend in a *trolley* driven by a steel cable, which is the same as the one used when the mine was active (Fig. 15a, b). This decline gives access to the large stops with pillars containing mineralized veins and traces of the host rocks of the mineralization (Fig. 15c). In addition, it has a lake in shades of blue, which is currently used for diving activities in the natural cave environments (Fig. 15d).

Quantitative Assessment

For the quantitative assessment of the scientific value of geosites, seven criteria can be used (Brilha 2016). According to this author, the geosite has a maximum scientific value when it is the best representative occurrence for a certain geological feature or geological framework, with a rare well-known international reference with publications about it, and when it presents several well conserved geological features with scientific relevance that are easily available for future research.

Garcia et al. (2017) selected geosites of São Paulo State, in Brazil, which were assessed in order to quantify the scientific value and degradation risk. This assessment was made using the same principles and methods described in Brilha (2016). The scientific value was evaluated based on five criteria: representativeness (30%), scientific knowledge (15%), integrity (25%), geological diversity (10%), and rarity (20%). Those authors did not take into account the traditional classification that addresses the local, regional, national, or international relevance of geosites.

Brocx and Semenuik (2018), using the semiquantitative method of Brocx and Semeniuk (2007), developed "The Geoheritage Tool-kit," a globally comparative method developed to enable the systematic identification and categorization of regions, areas, geosites, or geological

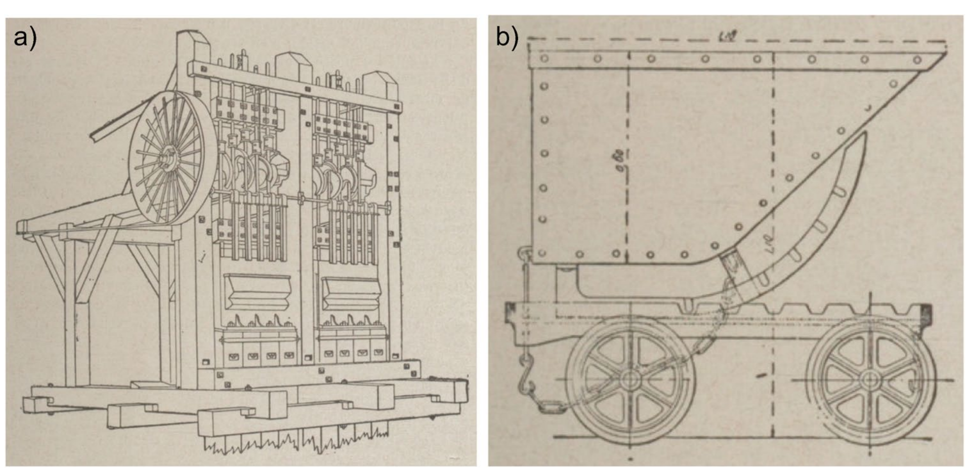


Fig. 14 Equipment of Passagem Mine, described by Ferrand (1894). **a** Californian mill (Sandycroft type) and **b** metal tilting trolley

Fig. 15 Tourist area of Passagem Mine. **a** Descent in *trolley* over rails; **b** final stretch of the descent on the inclined plane, at level 315; **c** detail of stops with pillars where it is possible to observe the rocks and parts of the ore body which remained as pillars; and **d** crystalline water lake that outcrops at level 315 of the mine (photos compiled from https://mariana.minasdapassagem.com.br, on 07/17/2020, with permission)

features of geoheritage significance at all scales (terrane, site, and microscale), allocate them to a conceptual category of geoheritage and scale of reference, and assess their level of significance. This method considers assessing the geoheritage significance and thus providing degrees of significance that can be ranked according to levels or degrees in four (4) levels of significance: international, national, state/regional, and local. Brocx and Semeniuk (2015) described the meaning of the criteria adopted for the levels of significance: (i) international—one of or a few or the best of a given feature globally; (ii) national—though globally relatively common, one of or a few or the best of a given feature nationally; (iii) state-wide/regional—though globally relatively common and occurring throughout a nation, one of or a few or the best of a given feature state-wide or regionally; and (iv) local—occurring commonly through the world, as well as nationally to regionally, but especially important to local communities.

In this paper, the quantitative assessment of the geo-mining heritages was conducted in the GEOSSIT platform of the Geological Survey of Brazil. GEOSSIT is intended to be used for the inventory, qualitative, and quantitative assessment of geosites and geodiversity sites. It was developed according to the methodologies proposed by Brilha (2005) and Garcia-Cortés and Urquí (2009). Currently, the application began to adopt the methodology and concepts of Brilha (2016), with adaptations that modified some quantitative assessment criteria presented in tables that validate the scientific value, the potential educational and tourist use, and also the degradation risk (Schobbenhaus & Berbert-Born 2021).

The scientific value considers representativeness, type locality, scientific knowledge, integrity, geological diversity, rarity, and limitations on use. In relation to its representativeness, the geological domain in which the geosites are located was taken into account. In this case, the Quadrilátero Ferrífero domain was considered the main mineral province of Minas Gerais. Based on the valuation using the GEOSSIT tables, the Chico Rei and Passagem mines were classified in relation to scientific value as geosites of international relevance, both with values of 320 (Tables 2 and 3).

In relation to the potential for educational and tourism use, GEOSSIT considers vulnerability, accessibility, limitations on use, safety, logistics, population density, association with other values, scenic beauty, singularity, observation conditions, didactic potential, geological diversity, potential for disclosure, economic level, and proximity to recreational areas. In terms of educational value, both the Chico Rei and Passagem mines were classified as national relevance reaching values of 335 and 375, respectively. In tourism use, the Chico Rei and Passagem mines were classified as national relevance with respective values of 340 and 375 (Tables 2 and 3).

In relation to degradation risk, GEOSSIT considers deterioration of geological elements, proximity to areas and/or activities with the potential to cause degradation, legal protection, accessibility, and population density. Chico Rei and Passagem mines were considered to be at low risk with respective values of 115 and 165 (Tables 2 and 3).

Table 2 Quantitative assessment of scientific value, educational and tourism use, and degradation risk of Chico Rei Mine

Scientific value				Potential for educational and tourism use					Degradation risk			
Class	Weight	Answer	Value	Class	P.E	P.T	Answer	Value	Class	Weight	Answer	Value
A1—representativeness	30	The place of interest is the best example, currently known, in the work area, to illustrate elements or processes, related to the thematic area in question (when applicable)	4	C1—vulnerability	10	10	Possibility of deterioration of secondary geological elements due to anthropic activity	3	B1—deterioration of geological elements	35	Possibility of deterioration of secondary geological elements	2
A2—type-locality	20	The place of interest is recognized, in the work area, as a secondary type-locality, being the source of a para stratotype, lithodemic unit, or a paratype	2	C2—accessibility	10	10	Place of interest without direct access by road, but located less than 1 km from a road accessible by vehicle	1	B2—proximity to areas/activities with the potential to cause degradation	20	Not applicable	0
A3—scientific knowledge	5	There are articles about the place of interest in books, international scientific journals, directly related to the thematic category in question (when applicable)	4	C3—limitations on use	5	5	The place of interest has no limitations for use by students and tourists	4	B3—legal protection	20	Place of interest located in an area with legal protection and with access control	1
A4—integrity	15	The main geological elements (related to the thematic category in question, when applicable) are very well preserved	4	C4—safety	10	10	Place of interest with security infrastructure (fences, stairs, handrails, etc.), mobile communications network and located less than 10 km from emergency services	4	B4—accessibility	15	Place of interest without direct access by road but located less than 1 km from a road accessible by vehicles	1
A5—geological diversity	5	The place of interest with 3 or 4 different types of geological aspects with scientific relevance	2	C5—logistics	5	5	There are restaurants and accommodation for groups of 50 people less than 15 km from the place of interest	4	B5—population density	10	Place of interest located in a municipality with less than 100 inhabitants per km^2	1

Table 2 (continued)

Scientific value				Potential for educational and tourism use					Degradation risk			
Class	Weight	Answer	Value	Class	P.E	P.T	Answer	Value	Class	Weight	Answer	Value
A6—rarity	15	There are, in the study area, 2–3 examples of similar sites (representing the thematic category in question, when applicable)	2	C6—population density	5	5	Place of interest located in a municipality with less than 100 inhabitants per km^2	1			**Risk of degradation**	**115**
A7—limitations on use	10	There are no limitations (need for authorization, physical barriers, etc.) to carry out sampling or fieldwork	4	C7—association with other values	5	5	There are several ecological and cultural values within 10 km of the place of interest	4				
		Scientific value	**320**	C8—scenic beauty	5	15	Place of interest commonly used in tourist campaigns in the country, showing geological aspects	4				
				C9—singularity	5	10	Occurrence of unique and rare aspects in the country	4				
				C10—observation conditions	10	5	Observation of all geological elements is done in good condition	4				
				C11—didactic potential	20	0	Occurrence of geological elements that are taught at all levels of education	4				
				C12—geological diversity	10	0	There are 3 or 4 types of geodiversity elements	3				
				C13—potential for disclosure	0	10	Occurrence of geological elements that are evident and perceptible to all types of public	4				

Table 2 (continued)

Scientific value				Potential for educational and tourism use					Degradation risk			
Class	Weight	Answer	Value	Class	P.E	P.T	Answer	Value	Class	Weight	Answer	Value
				C14—economic level	0	5	Place of interest located in a municipality with an HDI (Human Development Index) higher than that found in the state	3				
				C15—proximity to recreational areas	0	5	Place of interest located less than 5 km from a recreational area or with tourist attractions	4				
							Educational value	**335**				
							Tourist value	**340**				

PE educational potential, *PT* tourism potential

Conservation

The Quadrilátero Ferrífero region is inserted in the Biosphere Reserve of the Espinhaço Ridge, declared by UNESCO in 2005, and also in the Atlantic Forest Biosphere Reserve Area recognized by UNESCO in 1991, but this does not really protect the geo-mining heritage sites in Minas Gerais. Other areas of protection on a larger scale are as follows: Cachoeira das Andorinhas State APA (Environmental Protection Area), the Cachoeira das Andorinhas Municipality Park and the State Forest of Uaimii (north of Ouro Preto); State Ecological Station of Tripuí (west); State Park of Itacolomi (south); Minor Seminary State of Mariana APA (east); and the Ouro Preto/Mariana State APE (Special Protection Area), which includes the entire Mariana Anticline region.

These areas do not directly protect the geo-mining heritages in the Mariana Anticline. However, local governments are promoting the conservation of some areas (Fig. 16). The Municipality of Mariana has protected the archeological and landscape complex of Santo Antônio Hill in Passagem de Mariana village and Santana Hill (in Mariana), and the Municipality of Ouro Preto has protected Queimada Hill with the creation of the Archeological Park of Queimada Hill (in Ouro Preto).

The Chico Rei Mine is located on private property that makes the management of it, promoting its preservation, tourism, and educational use appropriate. The Passagem Mine is also located on private property of the Cia Minas da Passagem, and currently, the company that owns the tourist exploitation rights of the mine is Pincus Turismo Ltda.

Final Considerations

The development of this region is related to mineral and tourism industries. Mariana Anticline has been the target of many studies in several areas regarding the preservation of geological, mining, and archeological heritages. It is located in the area proposed for the Quadrilátero Ferrífero Geopark. Some areas have been protected (Queimada Hill, Santo Antônio Hill, and Santana Hill), and others are in the process of being protected by the municipalities of Mariana and Ouro Preto. For a long time, these areas were occupied by vulnerable populations that ended up mischaracterizing and even destroying part of the heritage, especially the archeological heritage related to the gold mining activities during the colonial period. Important actions have been conducted in the region, such as follows: listing undertaken by local governments, research

Table 3 Quantitative assessment of scientific value, educational and tourism use, and risk of degradation of Passagem Mine

Scientific value				Potential for educational and tourism use					Degradation risk			
Class	Weight	Class	Class	Class	Class	P.T	Answer	Value	Class	Weight	Answer	Value
A1—representativeness	30	The place of interest is the best example, currently known, in the work area, to illustrate elements or processes, related to the thematic area in question (when applicable)	4	C1—vulnerability	10	10	Possibility of deterioration of secondary geological elements due to anthropic activity	B1—deterioration of geological elements	35	Possibility of deterioration of secondary geological elements	1	B1—deterioration of geological elements
A2—type-locality	20	The place of interest is recognized, in the work area, as a secondary type-locality, being the source of a para stratotype, lithodemic unit, or a paratype	0	C2—accessibility	10	10	Place of interest without direct access by road, but located less than 1 km from a road accessible by vehicle	B2—proximity to areas/activities with the potential to cause degradation	20	Not applicable	0	B2—proximity to areas/activities with the potential to cause degradation
A3—scientific knowledge	5	There are articles about the place of interest in books, international scientific journals, directly related to the thematic category in question (when applicable)	4	C3—limitations on use	5	5	The place of interest has no limitations for use by students and tourists	B3—legal protection	20	Place of interest located in an area with legal protection and with access control	3	B3—legal protection

Table 3 (continued)

Scientific value				Potential for educational and tourism use					Degradation risk			
Class	Weight	Class	Class	Class	Class	P.T	Answer	Value	Class	Weight	Answer	Value
A4—integrity	15	The main geological elements (related to the thematic category in question, when applicable) are very well preserved	4	C4—safety	10	10	Place of interest with security infrastructure (fences, stairs, handrails, etc.), mobile communication network and located less than 10 km from emergency services	B4—accessibility	15	Place of interest without direct access by road but located less than 1 km from a road accessible by vehicles	4	B4—accessibility
A5—geological diversity	5	The place of interest with 3 or 4 different types of geological aspects with scientific relevance	4	C5—logistics	5	5	There are restaurants and accommodation for groups of 50 people less than 15 km from the place of interest	B5—population density	10	Place of interest located in a municipality with less than 100 inhabitants per km2	1	B5—population density
A6—rarity	15	There are, in the study area, 2–3 examples of similar sites (representing the thematic category in question, when applicable)	4	C6—population density	5	5	Place of interest located in a municipality with less than 100 inhabitants per km^2			Risk of degradation	**115**	
A7—limitations on use	10	There are no limitations (need for authorization, physical barriers, etc.) to carry out sampling or fieldwork	4	C7—association with other values	5	5	There are several ecological and cultural values within 10 km of the place of interest	4				
		Scientific value	**320**	C8—scenic beauty	5	15	Place of interest commonly used in tourist campaigns in the country, showing geological aspects	4				

Table 3 (continued)

Scientific value				Potential for educational and tourism use					Degradation risk			
Class	Weight	Class	Class	Class	Class	P.T	Answer	Value	Class	Weight	Answer	Value
				C9—singularity	5	10	Occurrence of unique and rare aspects in the country	4				
				C10—observation conditions	10	5	Observation of all geological elements is done in good condition	4				
				C11—didactic potential	20	0	Occurrence of geological elements that are taught at all levels of education	4				
				C12—geological diversity	10	0	There are 3 or 4 types of geodiversity elements	3				
				C13—potential for disclosure	0	10	Occurrence of geological elements that are evident and perceptible to all types of public	4				
				C14—economic level	0	5	Place of interest located in a municipality with an HDI (Human Development Index) higher than that found in the state	3				
				C15—proximity to recreational areas	0	5	Place of interest located less than 5 km from a recreational area or with tourist attractions	3				
							Educational value	**375**				
							Tourist value	**375**				

PE educational potential, *PT* tourism potential

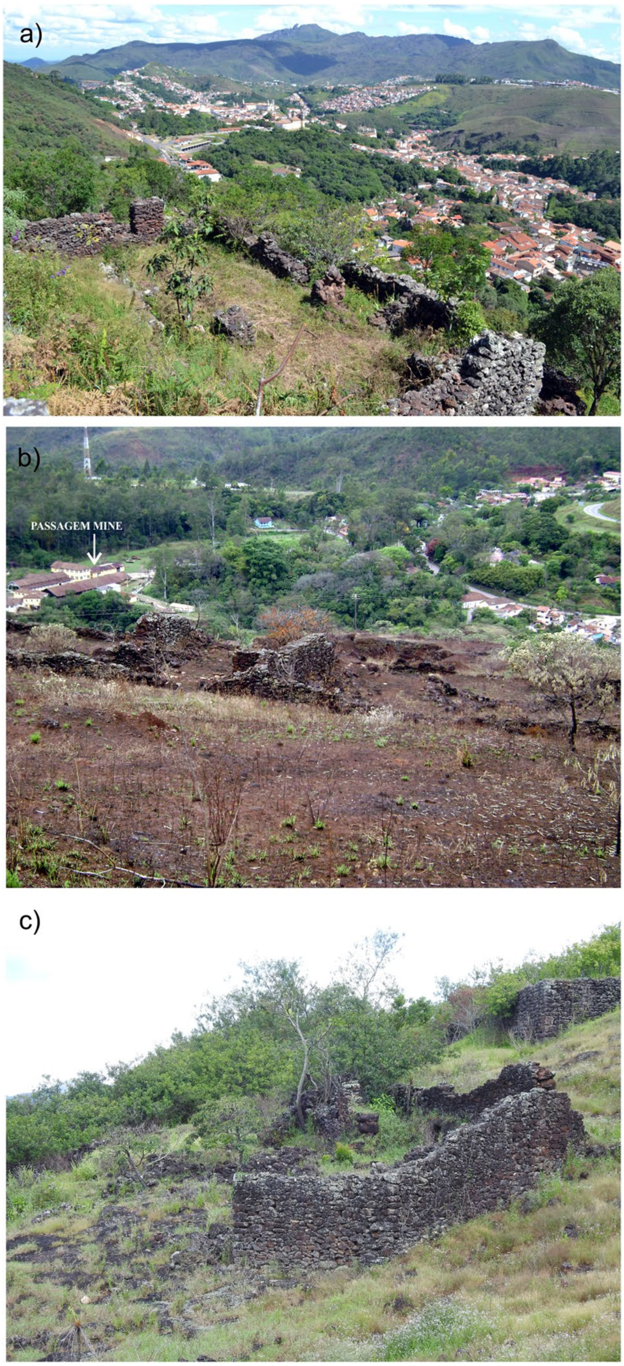


Fig. 16 View of the ruins of the eighteenth century mining villages. **a** Ouro Preto Mountain ridge, with a view of Itacolomi Peak in the background; **b** Santo Antônio Hill, with the Passagem Mine in the valley background; and **c** Santana Hill (photos by Paulo Simões)

projects aimed at surveying and characterizing the sites; educational activities involving local populations, public elementary and high schools, and also the university; and the development of tourist routes.

At Chico Rei Mine, it is possible to experience an important chapter in the geological history of the Quadrilátero Ferrífero, which involves the processes responsible for the auriferous mineralization associated with the metasedimentary sequences of the Minas Basin (Minas Supergroup) and also the history of gold mining in the colonial period. It is widely used as a tourist/educational/cultural facility. Students and professors from several universities develop research and extension projects in the region where the mine is located. The site has good infrastructure for visitors and offers a protective helmet and guide. In the external area, there is a dam with the water that comes out of the mine, where it is possible to experience the concentration of gold from the material from the mine using the *bateia*.

The Passagem Mine also shows us an important chapter in the geological history of the Quadrilátero Ferrífero, through the depositional environments of the Minas Supergroup and the mineralizing events that occurred in the region. The formation of the tourmalinite layers correlated to exhalations on the ocean floor. These rocks were later involved in the Minas orogeny (or Transamazonian event) that generated hydrothermal systems culminating in the formation of the gold deposits of Passagem. The mine has a great infrastructure to receive visitors and also has access to a museum and a restaurant.

The quantitative assessment using GEOSSIT has proved effective and is a public platform developed by the Geological Survey of Brazil, which uses the concepts and methodologies for inventorying and classifying geosites developed by Brilha (2005, 2016, and 2018) and Garcia-Cortés and Urquí (2009). This evaluation faithfully portrays the importance of these two sites, in a geological and mining context, and considers them to have geo-mining of international scientific relevance and of national educational and tourism relevance and to have a low risk of degradation.

In Ouro Preto and Mariana, other activities that rescue the cultural, social, and economic values related to the local geology are the extraction, lapidation, and production of jewelry using imperial topaz in the Rodrigo Silva and Antônio Pereira villages and the extraction and production of *pedra-sabão* (steatite) handicrafts in the Cachoeira do Brumado and Santa Rita de Ouro Preto villages.

Funding This research was supported by Geological Survey of Brazil, Ministry of Mines and Energy, Federal Government of Brazil.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Albert C, Farina F, Lana C, Stevens G, Storey C, Gerdes A, Dopico CM (2017) Archean crustal evolution in the Southern São Francisco craton, Brazil: constraints from U-Pb. Lu-Hf and O Isotope Analyses Lithos 266–267:64–86. https://doi.org/10.1016/j.lithos.2016.09.029

Alkmim FF, Lana C, Duque TRF (2014) Zircões detríticos do Grupo Itacolomi e o registro do soerguimento do cinturão Mineiro. 47th Congresso Brasileiro de Geologia, Salvador, Brasil. Annals CD-ROM

Alkmim FF, Marshak S (1998) Transamazonian orogeny in the Southern Sao Francisco craton region, Minas Gerais, Brazil: evidence for Paleoproterozoic collision and collapse in the Quadrilátero Ferrífero. Precambr Res 90(1):29–58. https://doi.org/10.1016/S0301-9268(98)00032-1

Araújo WM (2010) Plano de preservação das ruínas de edificações existentes no parque arqueológico do Morro Santana em Mariana-MG. Course Work. Federal Institute of Minas Gerais, Ouro Preto, 89p

Babinsky M, Chemale F, Van Schumus WR (1995) The Pb/Pb age of the Minas Supergroup carbonate rocks, Quadrilátero Ferrífero, Brazil. Precambr Res 72:235–245. https://doi.org/10.1016/0301-9268(94)00091-5

Baltazar OF, Zucchetti M (2007) Lithofacies associations and structural evolution of the Archean Rio das Velhas greenstone belt, Quadrilátero Ferrífero, Brazil: a review of the setting of gold deposits. Ore Geol Rev 32:471–499. https://doi.org/10.1016/j.oregeorev.2005.03.021

Barbosa VSB, Lima HM, Laudares S, Fonseca BM (2018) Mine Closure in Ouro Preto: the remnants of the 18th century gold rush and the tourism as an economic opportunity. REM 72:39–46. https://doi.org/10.1590/0370-44672018720131

Brilha JBR (2005) Patrimônio Geológico e Geoconservação: a conservação da natureza na sua vertente geológica. Ed. Palimage, Braga.

Brilha JBR (2016) Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: a review. Geoheritage 8(2):119–134. https://doi.org/10.1007/s12371-014-0139-3

Brilha JBR (2018) Geoheritage: inventories and evaluation. Chapter 4. In: Emmanuel Reynard and José Brilha, Geoheritage: assessment, protection and management pp. 69–85. https://doi.org/10.1016/C2015-0-04543-9

Brocx M, Semeniuk V (2007) Geoheritage and geoconservation, history, definition, scope and scale. J R Soc West Aust 90:53–87

Brocx M, Semeniuk V (2015) Using the Geoheritage Tool-Kit to identify inter-related geological features at various scales for designating geoparks: case studies from Western Australia. E. Errami et al. (Eds.), From geoheritage to geoparks, geoheritage, geoparks and geotourism, https://doi.org/10.1007/978-3-319-10708-0_17

Brocx M, Semeniuk V (2018) Introducing the geoheritage tool-kit: a globally-applicable comparative method to identify and/or assess the significance of geological features in geoparques. International Scientific Conference "Geoparks and Modern Society", Belogradchik, Bulgaria

Cabral AR, Zeh A (2015) Detrital zircon without detritus: a result of 496 Ma old fluid-rock interaction during the gold-lode formation of Passagem, Minas Gerais, Lithos, 212.

Cabral AR, Zeh A, Tupinambá M, Pimenta J (2020) First evidence for Neoproterozoic magmatism in the Quadrilátero Ferrífero of Minas Gerais, Brazil, and geotectonic implications. Journal of South American Earth Sciences, 104. https://doi.org/10.1016/j.jsames.2020.102844

Campos J, Carneiro M (2008) Neoarchean and Paleoproterozoic granitoids marginal to the Jeceaba-Bom Sucesso lineament (SE border of the southern São Francisco Craton): genesis and tectonic evolution. J S Am Earth Sci 26(4):463–484. https://doi.org/10.1016/j.jsames.2008.09.002

Campos JCS, Carneiro MA, Basei MAS (2003) U-Pb evidence for Late Neoarchean crustal reworking in the southern São Francisco Craton (Minas Gerais, Brazil). Annals of the Brazilian Academy of Sciences 75(4):497–511

Campos, CA (1938) Atlas Econômico de Minas Gerais. Secretariat of Agriculture, Industry, Commerce and Labour. Brasil

Carneiro MA, Teixeira W, Noce C M, Fernandes RA (1996) Archean growth processes in the Quadrilátero Ferrífero: a geochronological U-Pb and Sm-Nd approach to the Rio das Velhas Event (2780 - 2700 Ma). In: Symposium on Archaean Terrain of the South American Platform. Annals ... Brasília, SBG, Brasília-DF, pp 59–60

Castro PTA (2018) Patrimônio Geo-Mineiro: quando a interrelação entre eles se evidencia. Caderno De Geografia, Special Number 201:39–54. https://doi.org/10.5752/P.2318-2962.2018v28nespp39

Castro PTA, Nalini Jr. HA, Lima HM (2011) Understanding mining around the Quadrilátero Ferrífero. Belo Horizonte: Ecológico, 93p. Available at: https://qfe2050.ufop.br/sites/default/files/qfe2050/files/quadrilatero_ferrifero.pdf?m=1525724467. [Accessed May 03 2021]

Cavalcanti JAD (1999) Mineralização Aurífera de Lages-Antônio Dias, Ouro Preto – MG: Controles Lito-estratigráficos e Estruturais. Master Dissertation, Geoscience Institute of Campinas State University, Campinas-SP

Cavalcanti JAD (2003) Origem dos turmalinitos auríferos do sudeste do Quadrilátero Ferrífero-MG: evidências de campo, petrografia, química mineral e isótopos de Nd e Sr. Doctoral Thesis. Geoscience Institute of Campinas State University, Campinas-SP

Cavalcanti JAD, Crispi M, Lima HM (1997) Ocupação urbana em areas de nineração do período colonial. ln: *Espeleologia.* Speleological Excursionist Society. Ouro Preto-MG. 8(8): 14–21

Cavalcanti JAD, Schrank A (1999) Controles litoestratigráficos dos turmalinitos auríferos da região de Ouro Preto. Quadrilátero Ferrífero-MG, Journal of the School of Mines - REM 52(2):100–108

Cavalcanti JAD, Xavier RP (2006) Origem dos turmalinitos auríferos da região sudeste do Quadrilátero Ferrífero-MG: geologia, petrografia, química mineral e isótopos de Nd. Brazilian Journal of Geosciences 36(4):635–647

Chauvet A, Dossin II, Faure M, Charvet J (1994) A three-stage structural evolution of the Quadrilátero Ferrífero: consequenses for the Neoproterozoic age and the formation of gold concentrations of the Ouro Preto area, Minas Gerais, Brazil. Precambr Res 6:l39-167. https://doi.org/10.1016/0301-9268(94)90069-8

Chauvet A, Piantone P, Barbanson L, Nehlig P, Pedroletti I (2001) Gold deposit during collapse tectonics: structural, mineralogical, geochronological, and fluid inclusion constraints in Ouro Preto gold mines, Quadrilátero Ferrífero, Brazil. Econ Geol 96:25–48. https://doi.org/10.2113/gsecongeo.96.1.25

Chaves AO, Neves JMC (2005) Radiometric ages, aeromagnetic expression, and general geology of mafic dykes from southeastern Brazil and implications for African-South American correlations. J South Amer Earth Sci 19:387–397. https://doi.org/10.1016/j.jsames.2005.04.005

Chemale F Jr, Rosière CA, Endo I (1994) The tectonic evolution of the Quadrilátero Ferrífero, Minas Gerais, Brazil. Precambr Res 65:25–54. https://doi.org/10.1016/0301-9268(94)90098-1

Derby O (1899) Os primeiros descobrimentos do ouro em Minas Gerais. Journal of the Historical Institute of São Paulo, São Paulo 5:240–278

DNPM (2015) Anuário Mineral Brasileiro. National Department of Mineral Production. Ministry of Mines and Energy. Federal Government. Brasília-DF

Dopico CIM, Lana C, Moreira HS, Cassino LF, Alkmim FF (2017) U-Pb ages anf Hf-isotope data of detrital zircons from the late Neoarchean-Paleoproterozoic Minas Basin, SE Brazil. Precambr Res 291:143–161. https://doi.org/10.1016/j.precamres.2017.01.026

Endo I, Machado R, Galbiatti HF, Rossi DQ, Zapparoli AC, Delgado CER, Castro PTA, Oliveira MMF (2019) Estratigrafia e evolução estrutural do Quadrilátero Ferrífero, Minas Gerais. In: Castro PTA, Endo I, Gandini AL (Org.). Quadrilátero Ferrífero: avanços do conhecimento nos últimos 50 anos. 3i Editora, Ouro Preto, pp 70–113

Eschwege WL Von (1833) Pluto Brasiliensis. Ed. Itatiaia / Ed. da Universidade de São Paulo, 2v. Translation published by Domício de Figueiredo Murta (1979). São Paulo

Farina F, Albert C, Dopico CM, Aguilar CG, Moreira H, Hippertt JP, Cutts K, Alkmim FF, Lana C (2016) The Archean Paleoproterozoic evolution of the Quadrilatero Ferrífero (Brasil): current models and open questions. J S Am Earth Sci 68:4–21. https://doi.org/10.1016/j.jsames.2015.10.015

Ferrand MP (1894) L'Or à Minas Gerais, Brésil. Official Press of Minas Gerais State, Ouro Preto, volume 1and 2. Available at https://gallica.bnf.fr/

Ferreira MRA (2011) A gestão do patrimônio arqueológico pelo estado brasileiro: o caso do sítio arqueológico do Morro da Queimada, Ouro Preto-MG. Master Dissertation, School of Architecture, Federal University of Minas Gerais. Belo Horizonte

Fleischer R, Routhier P (1973) The "consanguineous" origin of a tourmaline-bearing gold deposit: Passagem de Mariana (Brazil). Econ Geol 68:11–22. https://doi.org/10.2113/gsecongeo.68.1.11

Fleischer R, Vial DS (1991) Surface and underground geological excursion around and in the Passagem de Mariana gold mine, Minas Gerais, Brazil. In: Deposit Modeling Workshop. Part A: Excursions, pp 53–62

Garcia MGM et al (2018) The inventory of geological heritage of the State of São Paulo, Brazil: methodological basis, results and perspectives. Geoheritage 10:239–258. https://doi.org/10.1007/s12371-016-0215-y

Garcia-Cortés A, Urquí LC (2009) Documento metodológico para la elaboracion del inventario español de lugares de interés geológico (IELIG). Instituto Geológico y Minero de España, Madrid

Garda GM, Schorscher JHD, Beljavskis P, Mansueto MS, Navarro MS, Mota AA (2009) Composição química da turmalina de turmalinitos estratiformes da mina de Passagem de Mariana, sudeste do Quadrilátero Ferrífero (MG). Geologia USP, Scientific Series 9(2):3–22

Gerais, Brazil. Lithos (212–215), pp 415–427. https://doi.org/10.1016/j.lithos.2014.10.011

Germani DJ (2002) A mineração no Brasil. Final Report. The Centre for Management and Strategic Studies. Rio de Janeiro-RJ

Google (2021) Satellite image of Mariana Anticline. Google Earth Pro, Access in April 2021

Gorceix H (1876) Passado da mineração de ouro na província de Minas Gerais. Journal of the School of Mines 45(3):252–258

Heilbron M, Cordani UG, Alkmim F, Reis HLS (2017) Tectonic genealogy of a miniature continent. Chapter 17, In: Heilbron et al. 2017, Craton São Francisco, Eastern Brazil: Tectonic Genealogy of a Miniature continent, Springer, pp 321–331.

Heineck CA, Ribeiro JH, Francescato JA, Silva ES (1986) As mineralizações auríferas de Mata Cavalo, Minas da Passagem, Mariana, MG. ln: 34th Brazilian Congress of Geology. SBG. Annals. Goiânia- GO 5:1932–1937

Koglin N, Zeh A, Cabral AR, Gomes AAS, Neto AVC, Brunetto WJ, Galbiatti H (2014) Depositional age and sediment source of the auriferous Moeda Formation, Quadrilátero Ferrífero of Minas Gerais, Brazil: new constraints from U-Pb-Hf isotopes in zircon and xenotime. Precambr Res 255:96–108. https://doi.org/10.1016/j.precamres.2014.09.010

Kwitko RR, Oliveira CG (2004) O deposito aurífero de Antônio Pereira, Quadrilátero Ferrífero: condições P-T e natureza dos fluidos mineralizadores. Brazilian Journal of Geosciences 34(1):117–126

Kwitko RR, Oliveira CG, Masotti FS, Leal E.D (1998) Bugre: uma nova tipologia de minério aurífero do distrito de Antônio Pereira, Quadrilátero Ferrífero. 40th Brazilian Congress of Geology, Annals..., Belo Horizonte-MG, pp 123

Lacourt F (1837a) Jazidas auríferas de Ouro Preto e Mariana (II). Mineração e Metalurgia, pp 87–95

Lacourt F (1837b) Jazidas auríferas de Ouro Preto e Mariana (I). Mineração e Metalurgia, pp 3–6

Ladeira EA (1991) Genesis of gold in Quadrilatero Ferrifero: a remarkable case of permanency, recycling and inheritance - A tribute to Djalma Guimarães, Pierre Routhier and Hans Ramberg. In: Ladeira EA (Ed.), Brazil Gold'91. Belo Horizonte, Balkema, 11-30

Lana C, Alkmim FF, Armstrong R, Scholz R, Romano R, Nalini HA (2013) The ancestry and magmatic evolution of Archaean TTG rocks of the Quadrilátero Ferrífero province, southeast Brazil. Precambrian Res 231:157–173

Lanari C (1977) A mineração do ouro. In: SICEG / Society for Cultural Exchange and Geological Studies, 17th Study Week, Gold Symposium, Ouro Preto-MG, 21–52

Machado N, Noce CM, Ladeira EA, Belo de Oliveira O (1992) U-Pb geochronology of Archean magmatism and Proterozoic metamorphism in the Quadrilátero Ferrífero, southern São Francisco Craton, Brazil. Geological Society American Bulletin 104:1221–1227. https://doi.org/10.1130/0016-7606(1992)104%3c1221:UPGOAM%3e2.3.CO;2

Machado N, Schrank A, Noce CM, Gauthier G (1996) Ages of detrital zircon from Archean-Paleoproterozoic sequences: implications for greenstone belt setting and evolution of a Transamazonian foreland basin in Quadrilátero Ferrífero, southeast Brazil. Earth Planet Sci Lett 141:259–276. https://doi.org/10.1016/0012-821X(96)00054-4

Maia J (1948) Considerações sobre a prática de lavra em Passagem, MG. Ouro Preto School of Mines. Lecturer's Thesis, 125p.

Martinez JEA (2019) Patrimônio Geomineiro do Brasil: inventário e valorização no Caminho dos Diamantes (Estrada Real, Minas Gerais). Doctoral Thesis, Minho University, Portugal

Mata-Perelló J, Carrión P, Molina J, Villas-Boas R (2018) Geomining heritage as a tool to promote the social development of rural communities. In: Emmanuel Reynard and José Brilha (ed), Geoheritage: Assessment, Protection and Management, pp 167–177. https://doi.org/10.1016/C2015-0-04543-9

Miranda JF, Curi A (2017) Uso turístico da mina subterránea brasileira de ouro de Passagem (MG). Revista De Medio Ambiente y Mineria 3:35–42

Nalini HA Jr, Rosière CA, Endo I (1992) Sobre a geologia estrutural do Anticlinal de Mariana, região sudeste do Quadrilátero Ferrífero, Minas Gerais: uma revisão. Journal of the School of Mines - REM, Ouro Preto-MG 45(1–2):18–20

Noce CM, Zuccheti M, Baltazar OF, Armstrong R, Dantas E, Renger FE, Lobato LM (2005) Age of felsic volcanism and the role of ancient continental crust in the evolution of the Neoarchean Rio das Velhas Greenstone Belt (Quadrilátero Ferrífero, Brazil): U-Pb zircom dating of volcaniclastic graywackes. Precambriam Research 141:67–82

Oliveira FR (1998) Contribuição ao estudo da geologia estrutural e da gênese do depósito aurífero de Passagem de Mariana-MG. Geoscience Institute, Campinas State University, Master Dissertation, Campinas-SP

Oliveira TB (1977) Ouro nas Minas Gerais. In: SICEG, Study Week, 27th Gold Symposium, p. 17–58

Pinto CP, Silva MA (2014) Geologic Map of Minas Gerais State. Geology of Brazil Program, Geological Survey of Brazil/CODEMIG. Available in https://www.portalgeologia.com.br/index.php/mapa. Accessed January 2021

Prefeitura Municipal de Mariana (2008) Conjunto Paisagístico e Arqueológico dos morros Santana e Santo Antônio. Preservation Dossier. 282p

Queiroz YS, Guirra APM, Madeira MR, Costa AT, Castro PTA (2014) Estudo e fomento do potencial para turismo do patrimônio mineiro na Serra de Ouro Preto, Minas Gerais. 47th Brazilian Congress of Geology, Annals..., Salvador-BA, pp 804.

Romano R, Lana C, Alkmim FF, Stevens GS, Armstrong R (2013) Stabilization of the southern portion of the São Francisco Craton, SE Brazil, through a long-lived period of potassic magmatism. Precambr Res 224:143–159

Rugendas M (1835) Malerische Reise in Brasiliem. Paris. Digital book available in National Library (Rio de Janeiro), http://objdigital.bn.br/acervo_digital/div_iconografia. Accessed January 2021

Sanmiquel L, Alfonso P, Bascompta M, Vintró C, Parcerisa D, Oliva J (2018) Analysis of the European tourist mines and caves to design a monitoring system. DYNA 85(205):249–255

Santos AM (2019) O Grande Anganga Muquixe Chico Rei: a presença do mito negro no Reinado do Alto da Cruz e nas escolas de Ouro Preto/MG. Master Dissertation. Institute of Human and Social Science, Federal University of Ouro Preto, University Campus of Mariana

Schobbenhaus C (2019) South America Geological Heritage Map Project: methodological proposal. Internal Report, Geological Survey of Brazil, Brasília-DF

Schobbenhaus C, Berbert-Born M (2021) GEOSSIT – registration of geological sites. Geological Survey of Brazil. Available at https://www.cprm.gov.br/geossit/. Accessed January 2021

Schobbenhaus C, Campos DA, Derze, GR, Asmus HE (1984) Geologia do Brasil: texto explicativo do mapa geológico do Brasil e da área oceânica adjacente incluindo depósitos minerais. DNPM, Brasília-DF

Schrank A, Machado N (1996) Idades em monazita e zircão das minas Morro Velho e Passagem de Mariana - Quadrilátero Ferrífero (MG). In: 39th Brazilian Congress of Geology. Recife, Annals…, Recife-PE, 6:470–472

Schrank A, Machado N (1996) Idades U-Pb em monazitas e zircões das minas de Morro Velho e Passagem de Mariana - Quadrilátero Ferrífero (MG). In: SBG, 39th Brazilian Congress of Geology, Annals … Salvador-BA, 6: 470–472

Sobreira FG (2014) Mineração do ouro no período colonial: alterações paisagísticas antrópicas na Serra de Ouro Preto. Minas Gerais Quaternary and Environmental Geosciences 05(1):55–65

Sobreira FG, Maia AC, Ferreira EE, Lucon TN, Lima HM (2014) Divulgação do acervo arqueológico mineração no período colonial em Ouro Preto e Mariana. Revista Ciência Em Extensão 10(1):17–36

Souza RF (2009) Trabalho e cotidiano na mineração aurífera inglesa em Minas Gerais: a Mina da Passagem de Mariana (1863–1927). Doctoral Thesis. Department of History, São Paulo University, São Paulo-SP

Souza TMF (2014) Notas sobre os saberes e as práticas na mineração oitocentista em Minas Gerais: a influência dos técnicos e engenheiros franceses. In: Eletronic Annals of 14th National Seminar on the History of Science and Technology – 14th SNHCT, Belo Horizonte-MG, 16p

Souza TMF, Reis L (2015) Técnicas mineratórias e escravidão nas Minas Gerais dos séculos XVIII e XIX: uma análise comparativa introdutória. In: Annals of 12th Seminary about economy of Minas Gerais. Cedeplar, Federal University of Minas Gerais

Souza WT, Menezes MG (1996) Cronologia da mineração no Brasil. Journal of the School of Mines 49:39–45

Teixeira NL, Caxito FA, C.A. Rosière CA, Pecoits E, Frei R, Sial AN, Poitrasson F, (2017) Trace elements and isotope geochemistry (C, O, Fe, Cr) of the Cauê iron formation, Quadrilátero Ferrífero, Brazil: evidence for widespread microbial dissimilatory iron reduction at the Archean/Paleoproterozoic transition. Precambr Res 298:39–55. https://doi.org/10.1016/j.precamres.2017.05.009

Trumbull RB, Garda GM, Xavier RP, Cavalcanti JAD, Codeço MS (2019) Tourmaline in the Passagem de Mariana gold deposit (Brazil) revisited: major-element, trace-element and B-isotope constraints on metallogenesis. Miner Deposita 54:395–414. https://doi.org/10.1007/s00126-018-0819-z

Vial DS (1988) Mina de ouro de Passagem de Mariana, Minas Gerais. In: Schobbenhaus C, Coelho CES (Eds.), Principals Depositos Minerais do Brasil. DNPM, Brasilia, 3: 421–430.

Vial DS, Duarte BP, Fuzikawa K, Vieira MBH (2007) An epigenetic origin for the Passagem de Mariana gold deposit, Quadrilátero Ferrífero, Minas Gerais, Brazil. Ore Geol Rev 32:596–613. https://doi.org/10.1016/j.oregeorev.2005.03.017

Zalán PV (2004) Evolução fanerozoica das bacias sedimentares brasileiras. In: Mantesso-Neto V, Bartorelli A, Carneiro CDR, Brito Neves BB (Eds.), Geologia do Continente Sul-Americano, Editora Beca, Brasil, pp 595–615