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A GEOPHYSICAL ANALYSIS OF THE CONCEIÇÃO RIVER REGION QUADRILÁTERO FERRÍFERO, BASED ON FIELD, PETROGRAPHIC, AERIAL IMAGES AND AIRBORNE DATA

ANÁLISE GEOFÍSICA DA REGIÃO DO RIO CONCEIÇÃO, QUADRILÁTERO FERRÍFERO, BASEADA EM DADOS DE CAMPO, PETROGRÁFICOS E DE IMAGENS AÉREAS

Jorge RONCATO, Ana Luisa CARVALHO de ALMEIDA, Bárbara MACEDO, Matheus OLIVEIRA

Universidade Federal de Minas Gerais. Instituto Geociências. Avenida Antonio Carlos, 6.627. Pampulha. Belo Horizonte – MG.
E-mails: roncatojr@yahoo.com.br; anacarvalho.almeida@hotmail.com; macedo956@gmail.com; matheusoc13@hotmail.com

ABSTRACT - The Quadrilátero Ferrífero region, located in the southeast portion of the São Francisco Craton, is one of the main metallogenic provinces in Brazil. Fieldwork, petrography, high-resolution airborne geophysics (magnetic and gamma-ray spectrometry data), and aerial images allowed us to produce a new map at the 1:25,000 scale, with important contributions in the lithotypes detailing, understanding of the geological structures and relationship between the different stratigraphic units. Interpretation of airborne geophysical data integrated with field structural and lithological observations were successfully employed in the creation of the litho-structural framework in a poorly exposed Proterozoic and Archean terrain. Airborne gamma-ray spectrometry data aided in the mapping process in areas with regolith cover including erosional ridges. The magnetic total derivative image revealed regional and local structures. In addition, our work details the units of occurrence of Rio das Velhas and Minas Supergroup. The aerial coverage of the Mindá and Santa Quitéria formations strongly increased, as well as the area of the Cauê Formation was better defined. The new geological map provides many improvements over the pre-existing maps. New lithological facies and structures were identified and others become more visible and lithological boundaries are refined or confirmed.
Keywords: Quadrilátero Ferrífero, Geological mapping, Aerogeophysics, Litho-structural framework.

RESUMO - A região do Quadrilátero Ferrífero, sudeste do Craton de São Francisco, é uma das principais províncias metalogênicas do Brasil. Trabalho de campo, petrografia, geofísica aérea de alta resolução (dados de espectrometria magnética e de raios gama) e imagens aéreas nos permitiram produzir um novo mapa na escala 1: 25.000, com importantes contribuições no detalhamento de litotipos, no entendimento das estruturas geológicas e nas relações entre as diferentes unidades estratigráficas. A interpretação de dados geofísicos aéreos, integrados a observações estruturais e litológicas de campo, foi empregada com sucesso na criação da estrutura litoestrutural em um terreno Proterozóico e Arqueano pouco exposto. Dados de espectrometria de raios gama auxiliaram no processo de mapeamento em áreas com extensa cobertura de regolito, incluindo cinturões erosivos. A imagem derivada total magnética revelou estruturas regionais e locais. Além disso, este trabalho detalha as unidades de ocorrência dos Supergrupos Rio das Velhas e Minas. A cobertura aérea das formações Mindá e Santa Quitéria aumentou fortemente, assim como a área da Formação Cauê foi melhor definida. Novas fácies e estruturas litológicas foram identificadas e outras se tornam mais visíveis e os limites litológicos são refinados e/ou confirmados.
Palavras-chaves: Quadrilátero Ferrífero, Mapeamento geológico, Aerogeofísica, Geologia estrutural.

INTRODUCTION

The area of this study is located in the eastern region of the Quadrilátero Ferrífero (QF; Dorr 1969) between the districts of Santa Bárbara and Barão de Cocais, Minas Gerais state (Figure 1).

The Quadrilátero Ferrífero can be subdivided into four Archean and Paleoproterozoic lithostratigraphic units: (i) Archean metamorphic complexes composed of gneisses,migmatites,

and granitoids; (ii) the Archean Rio das Velhas Supergroup, formed by low-to-medium-grade metavolcanic and metasedimentary rocks; (iii) the Neoarchean and Paleoproterozoic Minas Supergroup, consisting of low-to medium-grade metasedimentary rocks; (iv) the Paleoproterozoic Itacolomi Group composed of metasandstones and conglomerates. (e.g. Dorr et al. 1957, Dorr 1969, Cordani et al. 1980, Schorscher et al. 1982, Romano 1989, Noce 1995, Machado et al. 1996, Endo & Machado 1997, Alkmim & Marshak 1998, Lana *et al.* 2013; Farina *et al.* 2015, Dutra, 2017).

In the focus area, a deformed sequence of schistose sediments of the Nova Lima Group (Figure 2), Rio das Velhas greenstone belt, outcrops out in a series of NE-SW regional lineaments that host gold mineralization and are known as Córrego do Sítio, Cristina and São Bento-Donana shear zones, respectively from the SE to NW (Fig. 3; Lima, 2012; Roncato, 2016). There are also found outcropping itabirites of the Cauê Formation, Minas Supergroup.

The main rock units comprise a repetitive succession of metamorphosed, carbonaceous turbiditic, graywacke-siltstone-shale and slates, which host importants lode-gold mineralization associated with quartz-carbonate-sulfide-sulfosalt veins (Lima, 2012, Ribeiro et al., 2013, Roncato et al., 2015). These rocks are at the greenschist metamorphic facies (*e.g.* Condie 1981, Groves et al., 1998). A series of mafic dikes and sills have been emplaced (*e.g.* Lima, 2012, Roncato et al., 2015). There was recognized two main geological unities on the area: the Rio das Velhas Supergroup and the Minas Supergroup. Both unities englobe clastic and quimic metassediments. The local stratigraphy can be summarized from bottom to top: Santa Quitéria Formation, Mindá Formation, Córrego do Sítio Formation, Palmital Formation, Casa Forte Formation, Moeda Formation and Cauê Formation.

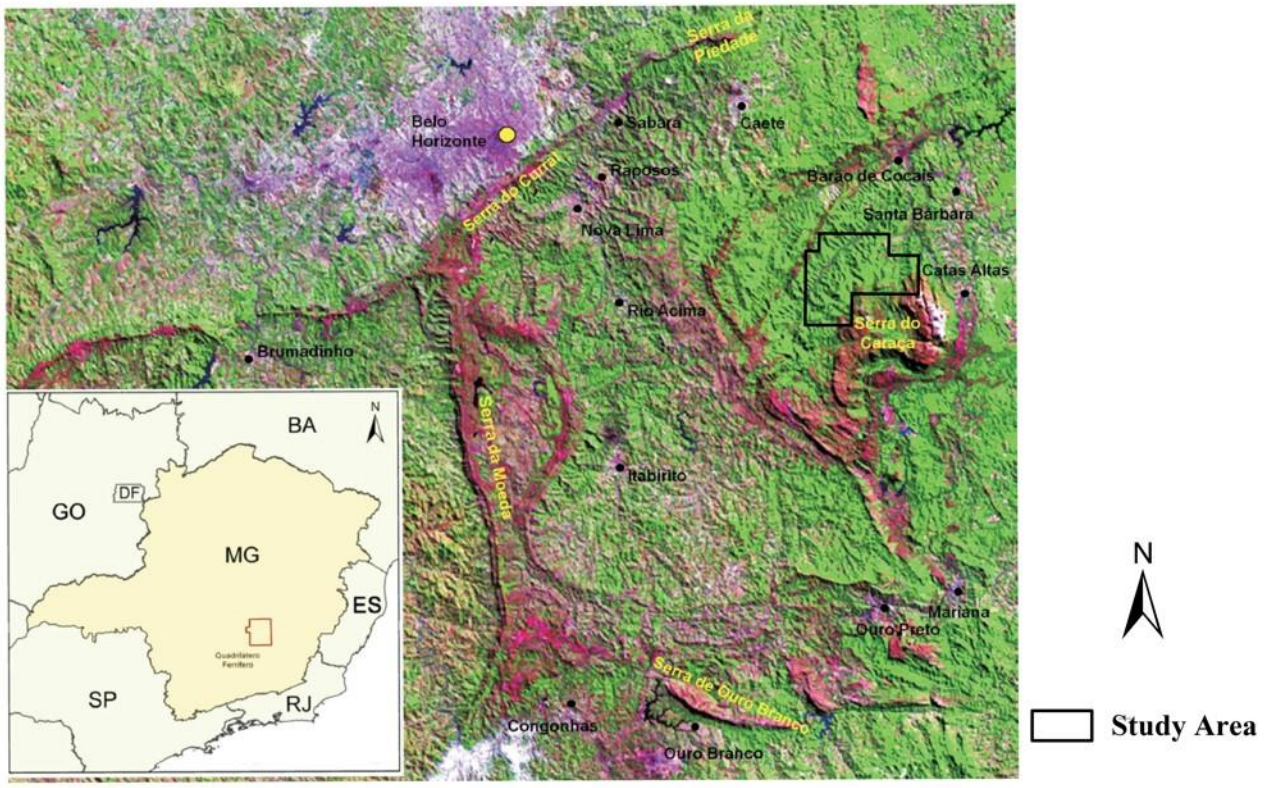


Figure 1. Map of the Quadrilátero Ferrífero region showing the study area.

This work focuses on the integration of geophysical data (i.e., magnetometry, gamma spectrometry) and aerial imaging analysis to contribute for the published existing data of the eastern region of QF region, describing the local stratigraphic and structural aspects, particularly the detail of the lithostratigraphy according to geophysical data of geological units in the Quadrilátero Ferrífero eastern region. The procedure come to state herein has the potential to serve as a basis for optimizing geological mapping in other areas where geophysical data data are available.

Regional geological setting

The Quadrilátero Ferrífero region (Figures 1 e 2) is situated in the southern portion of the São

Francisco craton (Almeida 1976) and is composed of the Archean Rio das Velhas greenstone belt (Schorscher et al. 1982), the paleoproterozoic Minas Supergroup and the Itacolomi Group. These supracrustal units are surrounded by granite-gneiss domes (Dorr 1969, Lana *et al.,* 2013), which consist of poly-deformed unit. The regional basement metamorphic complexes outcrop out in several distinct domes and with metamorphic grades ranging from greenschist to granulite facies (Herz 1970).

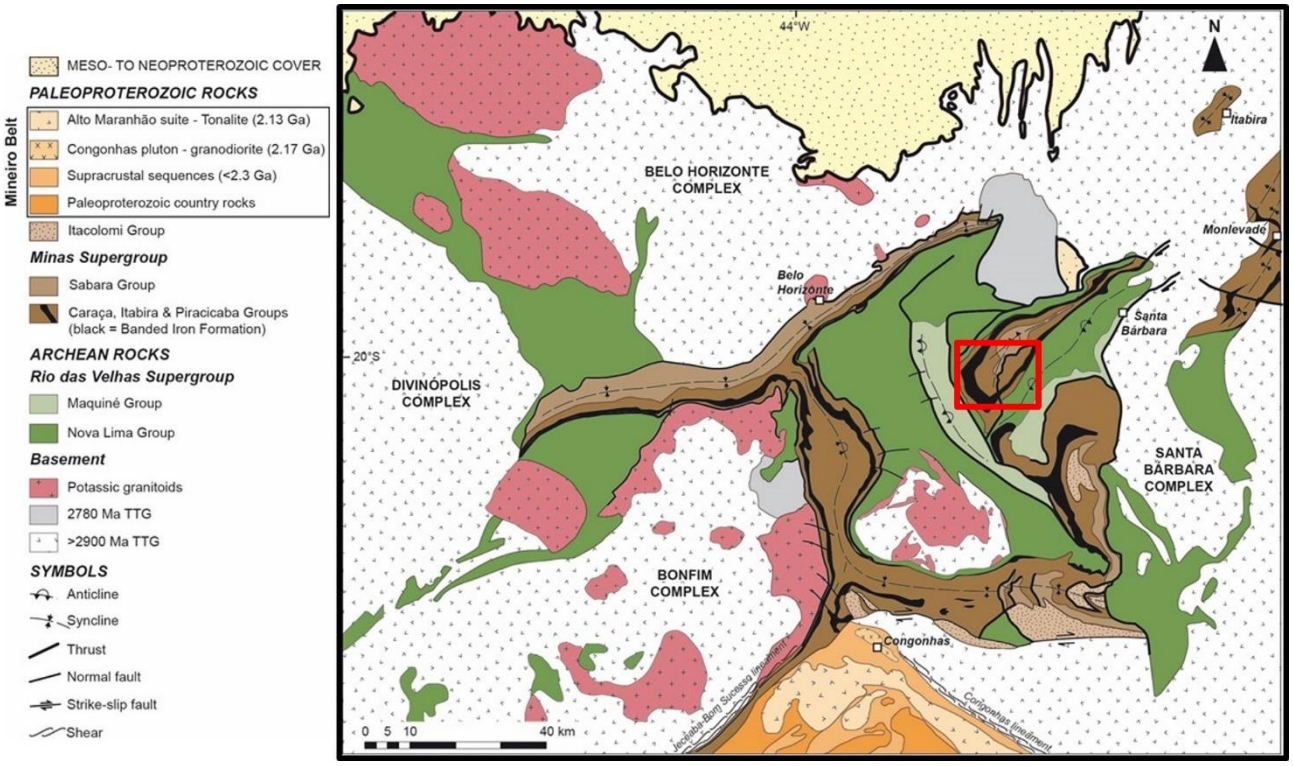


Figure 2. Geological map showing the study area, red quadrangle, in eastern portion of Quadrilátero Ferrífero region (Farina et al, 2015).

The Rio das Velhas greenstone belt corresponds to a metavolcanosedimentary sequence composed from the base to the top of the Nova Lima and Maquiné groups, respectively (Dorr *et al.,* 1957; Almeida, 1977; Schorscher, 1978). The Nova Lima Group, shown on figure 2, comprises a basal unit formed by tholeiitic-komatiitic volcanic rocks, associated with chemical sedimentary rocks; a volcaniclastic intermediate unit, associated with felsic volcanism; and an upper unit with clastic sedimentary rocks (Ladeira 1980, 1991, Zucchetti and Baltazar 2000, Baltazar and Zucchetti 2007). Schorscher (1978) described komatiites at the base of the sequence, naming them the Quebra Osso Group. The Maquiné Group, shown in figure 2, is composed (Gair, 1962) of sequences of graywacke and conglomerates deposited at ca. 2.73 Ga (Moreira et al., 2016). The Rio das Velhas rocks was classified by Baltazar & Zucchetti (2007) according to its volcano-sedimentary characteristics in lithofacies associations (Figure 3) and summarized by Roncato et al. (2015) and Roncato (2016):

(1) Mafic-ultramafic: lavas with minor intrusions of gabbro, anorthosite and peridotite, as well as intercalations of BIF, ferruginous chert, carbonaceous pelite, turbidites, and rare felsic volcanoclastic rocks. It corresponds to the Quebra Ossos Group and Ouro Fino unit of the Nova Lima Group.

(2) Volcano-chemical-sedimentary: tholeiites intercalated with BIF and ferruginous chert and less fine-grained clastic sedimentary rocks, such as carbonaceous turbidites and pelites, intercalated with chemical sedimentary rocks.

(3) Clastic-chemical sedimentary: typified by alternating fine-grained, clastic and chemical rocks. Pelites (micaceous and chloritic schists) are intercalated with lesser BIF, subordinate chert and carbonaceous phyllites. It corresponds to the Santa Quitéria unit in the study area.

(4) Volcaniclastic: made up of volcaniclastic felsic and mafic rocks.

(5) Resedimented: widely distributed in the

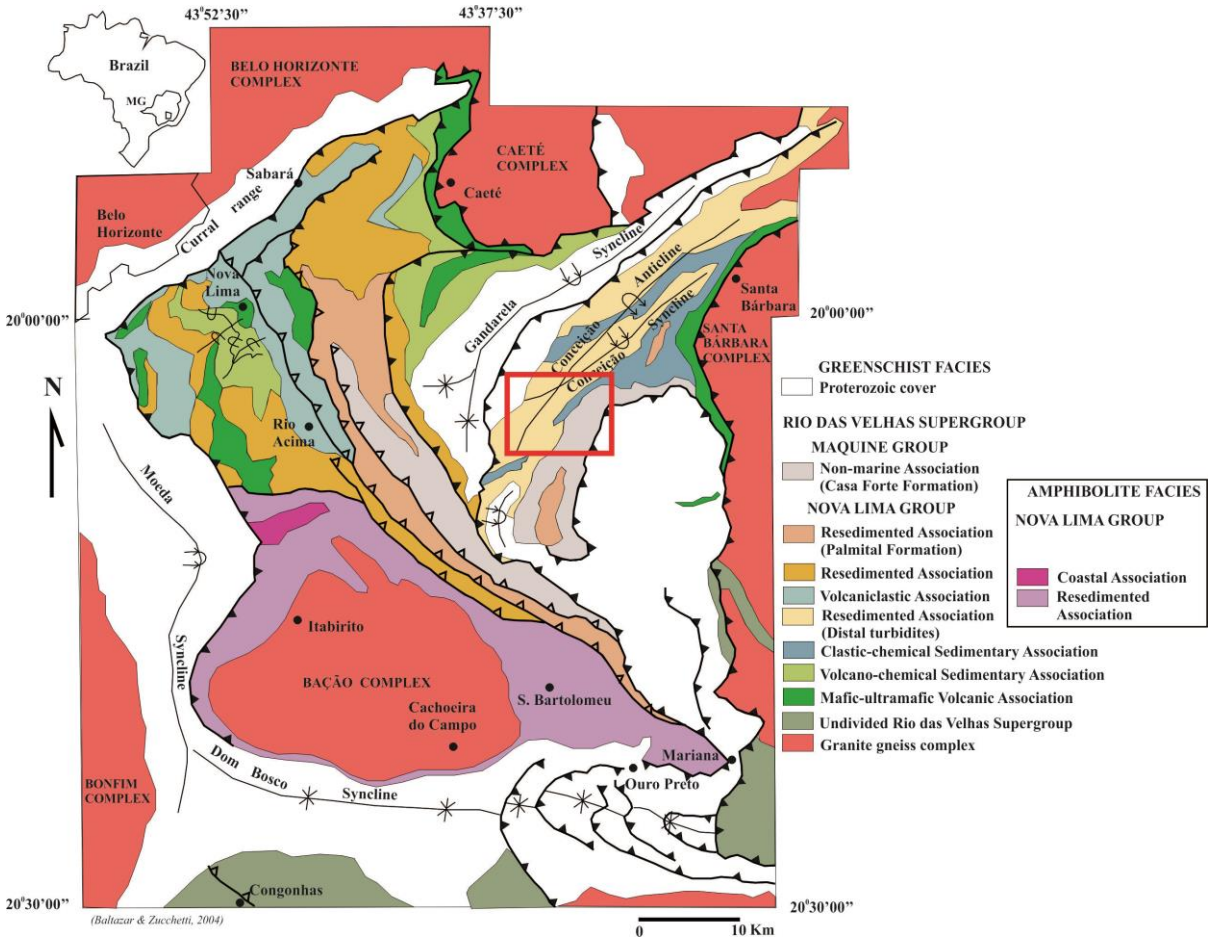


Figure 3. Geological map of the Quadrilátero Ferrífero region showing the study area in the Rio das Velhas Supergroup in detail (modified from Baltazar & Zucchetti 2007).

Quadrilátero Ferrífero, it includes three different sequences of graywacke-argillite, two metamorphosed in the greenschist facies in the N and E sectors (they are composed mainly of graywackes, quartz graywackes, sandstones and siltstones, with cyclic layers and abrupt basal contacts between cycles) and one in the amphibolite facies in the south. In the E and N sectors, it includes the Córrego do Sítio unit outcropping in the study area.

(6) Coastal: restricted to a small area, with sandstones exhibiting preserved sedimentary structures.

(7) Non-marine: conglomerate-sandstone; coarse-grained sandstone, fine- to medium-grained sandstone; it includes the Casa Forte Formation of the Maquiné Group (Dorr et al., 1957).

Conform made summarized by Roncato (2016) about Minas Supergroup, this 2.60-2.10 Ga (Machado et al., 1996; Hartman et al., 2000) unit is subdivided into the Caraça, Itabira, Piracicaba and Sabará Groups (Dorr, 1969), all metamorphosed at low greenschist facies. The basal Caraça Group has metaconglomerate, quartzite and phyllite. The Itabira Group includes the Cauê Formation that hosts the great volume of Superior-lake BIF and iron orebodies in the region (Rosière et al., 2008). The Piracicaba Group is formed by phyllites and quartzites. The Sabará Group unconformably overlies the Piracicaba Group, and its deposition is considered about 2.12 Ga (Machado et al., 1996); it is a flysch sequence with metagraywacke, carbonaceous phyllite, metadiamictites, metaconglomerates, and felsic to intermediate metavolcanic rocks (Dorr, 1969). The Itacolomi Group (Dorr, 1969) is the youngest unit in QF, resting unconformably on the Minas Supergroup, and contains quartzite, metarkose and metaconglomerate.

The Paleo/Mesoproterozoic Espinhaço Supergroup covers a small area in the QF. It is a rift sequence mainly with breccias, conglomerates and sandstone (*e.g.*, Brito-Neves et al., 1996).

"The structural evolution of the QF region took place in three main periods during the Rio das Velhas Orogeny (Baltazar and Zucchetti, 2007): between 2.8 and 2.67 Ga, which relates to the evolution of the Rio das Velhas greenstone belt; 2.10 to 1.90 Ga, the Transamazonian event;

and the Brasiliano orogeny" (Roncato, 2016).

According to Alkmim and Marshak (1998), the Proterozoic tectonic evolution (Minas accretionary orogeny of Teixeira et al., 2015, from 2.35 to 2.00 Ga) took place in three main deformational phases. Fold and thrust belts shortly after 2.125 Ga; orogenic collapse with uplift of Archean granite-gneiss domes and formation of regional synclines at 2.09 Ga (Marshak and Alkmim, 1989); and the Brasiliano orogeny (0.7 – 0.45 Ga), with fold and thrust belts verging to the west.

Published U-Pb ages data from the basement of the QF allowed for the identification of four main magmatic events (Lana et al., 2013; Romano et al., 2013; Farina et al., 2015). Periods of magmatic activity, which registers the tectonomagmatic Archean history of the QF, was described as the Santa Bárbara, Rio dasVelhas I, Rio das Velhas II and Mamona.

Economic geology

The Quadrilátero Ferrífero is one of the great mineral provinces of the planet, being more than 300 years of continuous mineral exploration, especially gold and iron. In the eighteenth century it was the region of Brazil that produced the most gold (Ruchkys & Machado, 2013).

The main gold deposits of the Quadrilátero Ferrífero are hosted in the rocks of the Greenstone Belt Rio das Velhas. These types of gold deposits hosted in Greenstone Belts account for a large part of the world's gold production, and are classified as orogenic (Groves et al., 1998). They are characterized by the hydrothermal origin of mineralized gold fluids derived from metamorphism during the orogenic process in compression environments (Goldfarb et al., 2001).

The eastern portion of QF is recognized as a district that contains a large number of small to medium occurrences and gold deposits (<3 million Au ounces), in distinct lithostratigraphic-structural and geochronological contexts, such as Córrego do Sítio, São Bento, Pilar, Pari, Santa Quitéria, Barra Feliz, Quebra Ossos, Cata Preta, Tesoureiro, Antônio Pereira, Gongo Soco, Santana, São Jorge, Brumadinho, Ápis, among minors other (Roncato, 2016). In this portion of the QF there are sixteen excavations and gold deposits hosted in turbidites sequences of the Nova Lima Group, with or without associated FFB, including Cachorro Bravo, Laranjeiras and Carvoaria. The Cachorro Bravo deposit is the most productive, with 7.65 g / t content, followed by Carvoaria (6.69 g / t) and Laranjeiras (6.32 g / t; Roncato, 2016). It is also worth mentioning the São Bento gold deposit, hosted in FFB, which has a historical production of 56.2 tons between 1986 and December 2006 (Martins Pereira et al., 2007);

Iron, along with gold, is the main mineral resource in the region and is associated with the presence of Banded Iron formation. In the QF dominate the silicate facies ores with hematite and quartz minerals, and, subordinately, occurs facies of carbonate facies with hematite and calcite/dolomite Roncato (2016). BIF's Algoma-type ores are rarer, only associated in the Rio das Velhas Supergroup (Roeser & Roeser 2010). The Baú Mine is located in the northwest portion of the study area where ferruginous cangas and Banded Iron formation outcrops.

MATERIALS

For this work, geophysical data, remote sensing data and geological mapping data were used. The geophysical information was derived from two regional magnetic and gamma-ray spectrometry surveys. The Rio das Velhas survey was conducted in 1992 by the Geological Survey of Brazil (CPRM) with a helicopter, flight line spacing of 250 m, direction of N40ºW, and an average terrain clearance of 60 m.The Minas Gerais.

The gamma-ray spectrometry images includes individual concentrations of the natural radioelements potassium (K), thorium (Th), and uranium (U). The aeromagnetic data were conventionally corrected by subtracting the IGRF (International Geomagnetic Reference Field)

The photointerpretation was done using aerial photos (COPASA) that covered part of the region in scale 1: 30,000 and 1: 60,000. Textural domain maps were also made, as well as identification of structures and photo lineaments. In this way, Google Earth Pro 7.3.1 satellite images were also used to help characterize the domains founded and complement the images of regions not covered by the photos. Analyzes made from these images were aided by the ArcGis 10.5 software, using the UTM datum projection "WGS 1984 Zone 23S".

This research also included geological

information acquired in field campaigns carried out between January and September of 2018. Field data includes about 25 Days of Field, 302 control points for stratigraphy, 421 Structural Measures and 45 colleted samples. Geological information relating to the Rio das Velhas Project (Baltazar and Zucchetti, 1998) was used to complete and confront this study.

The primary outcrop database in this study includes lithological data, structural observations and petrographic rock descriptions. At some outcrops, orientations of dominant structures are given. The existing maps (e.g. Dorr et al, 1957; Dorr, 1969, Baltazar & Silva, 1998, Baltazar & Zucchetti, 2007) cover the entire study area at scale of 1:100,000. We have evaluated these maps to confront the information were derived from the raw outcrop information available.

Methodology and Data Use

Airborne magnetic data

Airborne magnetic data integrated with geological field data, is a tool for deriving both lithological information and structural frameworks from which kinematic relationships can be interpreted (Metelka et al., 2011).

The interpretation of the magnetic signature of the study area was based on the total gradient (Figure 4A) and the tilt derivative (Figure 4B).

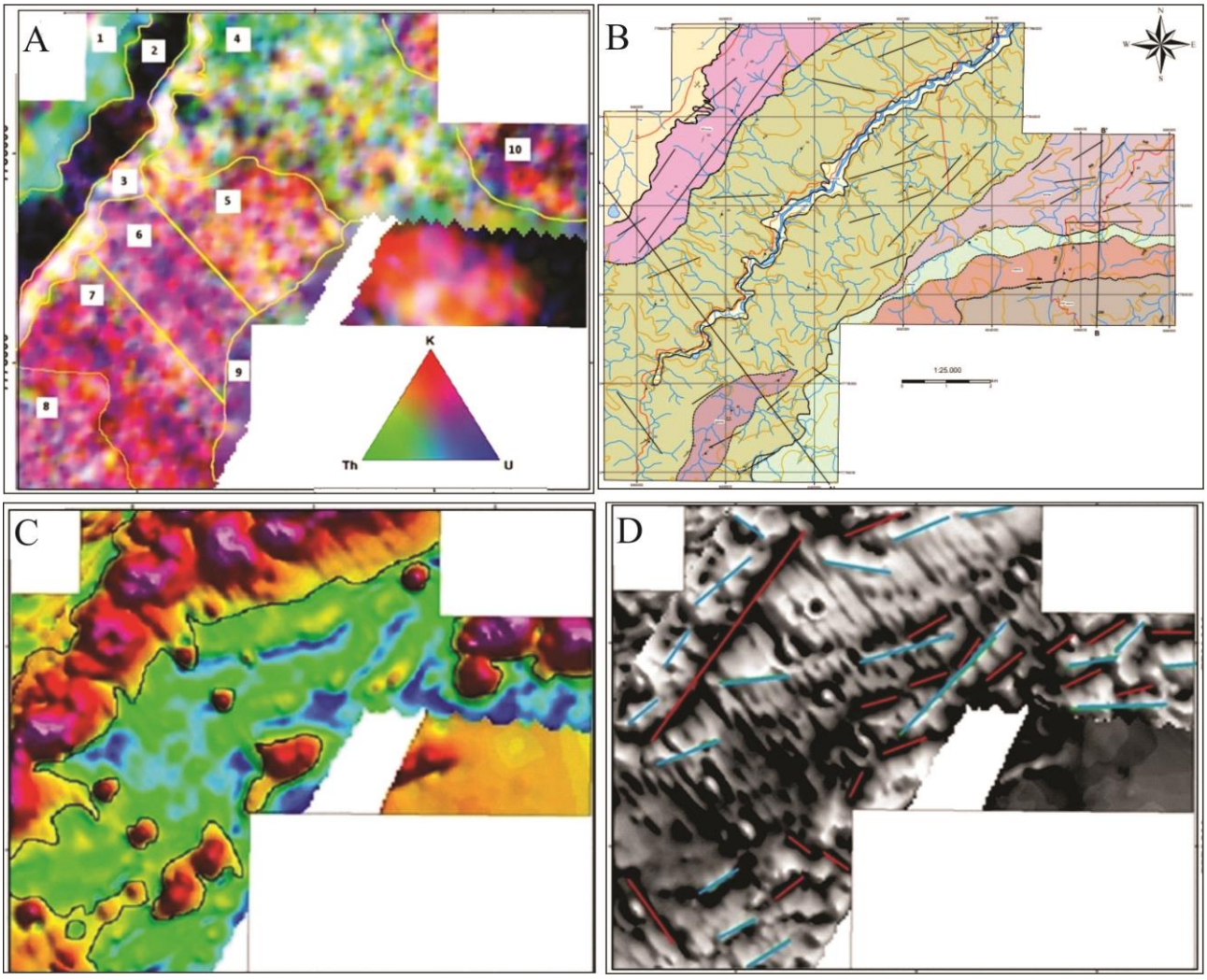


Figure 4. (A) Ternary gamespectometric image of RGB color composition of the mapped area; (B) Schematic maps of the study area (deitaled in fig. 5); (C) Magnetometric image of analytical signal. Pink, red, orange and yellow represent high magnetic values, while green and blue represent low values; (D) Total derivative magnetometric image with major marked lineaments. In red the negative lineaments are marked and in blue the positive lineaments.

Airborne gamma-ray spectrometry

Conform made summarized by Martelet et al. (2006) and Metelka et al. (2011), the gamma-ray signal sensed over the surface of the Earth reflects the content and distribution of the radioactive elements in both rocks and the derived regolith material including anomalies created by geochemical alterations (mineralization, hydrothermal alterations, weathering; quite evident in this region). Gamma-ray spectrometry is perfectly suited for deriving detailed lithological information but serves equally well as

a tool for efficient regolith mapping.

The gamma-ray spectrometry data were acquired in the same survey as the magnetic data. The interpretation of the radiometric response of the study area was based of the images of K, eTh and eU, but maily on the ternary image of K, eTh, and eU in RGB (Red, Green and Blue) colors (Figure 4C). Aerial images were integrated with the gamma-ray spectrometry data to help characterize the surface lithologies and regolith units and assist in differentiating regolith patterns from lithological signatures.

PROPOSED LITHOSTRATIGRAPHY

Based on field observations, here we present the information detected for the construction of the geological map in detailed scale 1: 25,000. The contribution of this study can be compared in Figures 5A and 5B, where the difference between the 1998 and 2018 mapping are presented. In the mapped area, seven stratigraphic units outcropped: Santa Quitéria, Mindá, Córrego do Sítio, Palmital and Casa Forte units, belonging to the Archean greenstone belt, Rio das Velhas Supergroup (RVGB); as well as Moeda and Cauê formations, belonging to Paleoproterozoic Minas Supergroup (MSG). Covering these stratigraphic units it is possible to find recent coverings of the Cenozoic age (Figure 5B). The description that follows refers to rocks that are metamorphosed; hence, the prefix "meta" applies to rock names but is hereafter omitted for brevity.

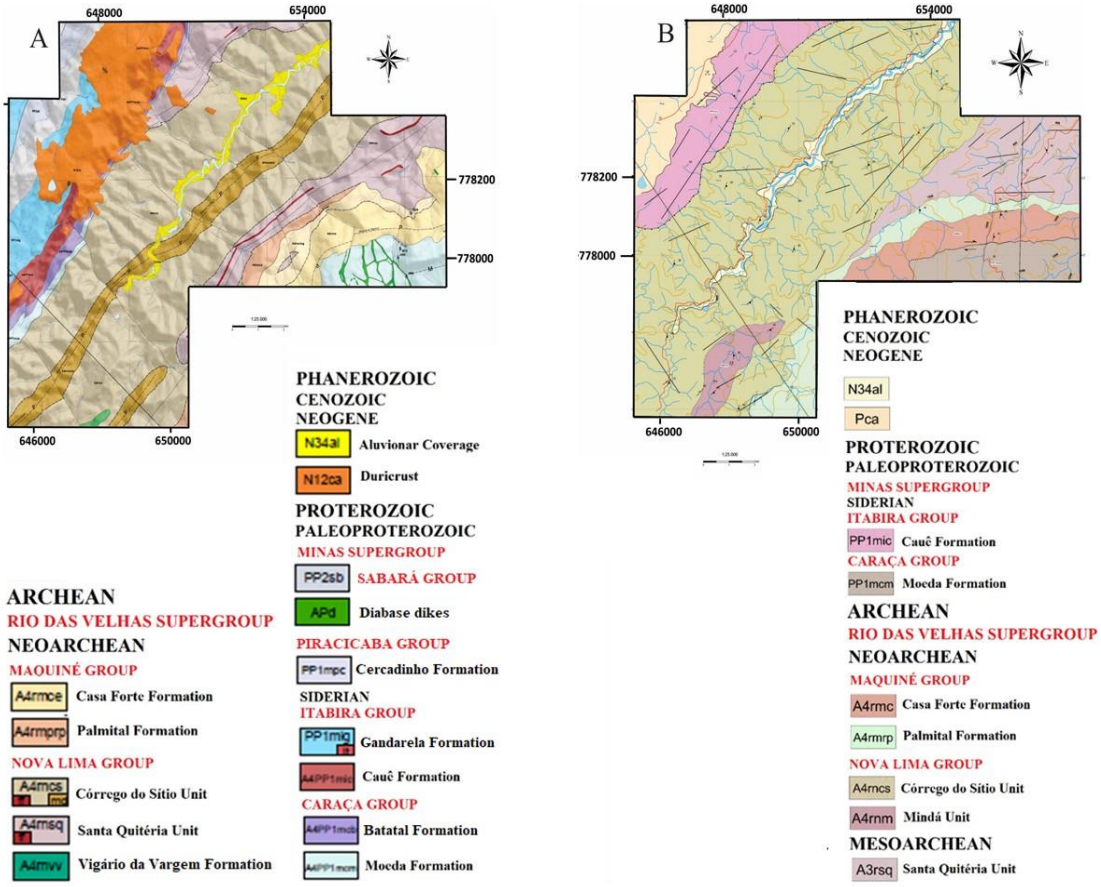


Figure 5. Schematic maps of the study area. A) Previous map produced by Baltazar and Zucchetti (1998); B) Schematic map updated by this study.

The stratigraphic units of the Nova Lima Group (RVGB) were mapped according to lithostratigraphic units of Baltazar & Silva (1998) and correlated to the litofacies associations suggested by Baltazar & Zucchetti (2007).

Rio das Velhas Supergroup – Nova Lima Group

Santa Quitéria Unit

This unit occurs in the upper east portion of the area (Fig. 5), between heights of 800 to 1000 meters. The contact with the Córrego do Sítio unit and the Palmital Formation is interpreted as erosive. The main litotipe are clastic sediments, predominantly phyllites, and rhythmites, and subordinate graywacke occurrences. The coloration of these rocks varies from gray, beige and brown. The bedding is locally preserved, marked by the millimeter intercalation of

rithmits. The composition of subordinate graywacke is essentially quartz, with granulometry varying between fine and very fine sand. The very fine matrix presenting clay. These gravacas are restricted to the upper portions of the unit.

According to Lima (2012), this clastic sedimentary sequence present fine granulometry, granoblastic to lepidoblast texture, which a compositional banding is noticed. Bands with sericite are accompanied by small amounts of quartz, carbonate, plagioclase, epidote, chlorite, biotite and titanite that alternate with granoblastic levels rich in quartz, carbonate and chlorite.The sediments of chemical origin are represented by banded iron formations sustaining the highest topographies and present relative magnetism.

Mindá Unit

The Mindá unit occupies the smallest occurrence in area, locating in the southeast portion (Fig. 5). Displays an elongated geometry, with approximately parallel direction to the NE-SW. This unit is surrounded by the Córrego do Sítio unit, whose contacts were inferred and considered gradational. The exposure of the Minda unit, such as the Santa Quitéria unit, is associated with a thick weathered mantle, which is represented by a brown sandy soil. This unit is composed of clastic, schistous sediments intercalating between fine and medium granulometry. When medium granulometry is observed, it is possible to perceive the occurrence of chlorite and sericite. Subsequently, dark-gray carbonaceous phyllite with dispersed magnetite is present, as well as banded iron formation.

The rocks have granolepidoblástica texture, with a continuous foliation, defined by the orientation of the micaceous minerals. They are composed of white mica, sericite variety, quartz and opaques. The quartz grains are angular and enveloped by foliation.

Córrego do Sítio Unit

The Córrego do Sítio unit (Figure 5) is the predominant unit of the mapped area, occurring in all central, southwest and northeast portions. Porto (2008), Lima (2012) and Roncato et ali. (2015) consider the Córrego do Sítio unit as a package of sedimentary rocks consisting of alternating graywackes and phyllites in a turbidite sequence with incomplete Bouma cycles (Bouma 1983), metamorphosed to the greenschist facies. Mafic dikes and sills are subparallel to discordant.

The Córrego do Sítio unit (Baltazar & Silva 1998b) is widely distributed in many parts of the Quadrilátero Ferrífero, also in the mapped area, and includes sequences of graywacke and argillite. Graywackes, quartz graywackes, sandstones and siltstones display cyclic layers and abrupt basal contacts between cycles. The features of this association indicate that it was deposited by turbidity currents (Lima, 2012; Roncato et ali., 2015), and this unit is considered part of the resedimented association (Table 1; Baltazar & Zucchetti, 2007). The contacts and planar structures are marked by the development of hydrothermal alteration zones containing carbonate, sericite, quartz and sulfide minerals (Roncato et ali., 2015).

From bottom to top mapped Córrego do Sítio unit based on the relative proportion of the different rock types with (i) thick carbonaceous phyllite and graywacke sequence. It contains subordinate metric-decimetric BIF layers, some of which are magnetic and intercalated with carbonaceous phyllites; (ii) carbonaceous phyllite with an anastomosing schistosity hosting millimetric to metric quartz-carbonate veins and microfolded layers, representing an important zone of hydrothermal alteration; (iii) intercalation of a thick graywacke sequence and subordinate carbonaceous phyllite in incomplete Bouma cycles. Bedding exhibits upward grain-size fining in normal and inverted sequence. This rock types differentiation was already been reported by Lima (2012) and Roncato et al. (2015).

The phyllite portions, the most abundant lithotype, are composed of sericite, quartz and opaques, these last ones represented by sulphides. Its texture is lepidoblástica, with fine equigranular minerals and continuous foliate structure. The main foliation is cutted by a second direction of foliation reifying a crenulation cleavage. The orientation of the sericites marks the main foliation in the rock and the quartz appears, sometimes, filling up venules.

Rio das Velhas Supergroup – Maquiné Group

Palmital Formation

The Palmital Formation outcrop the southeast and east portions (Fig. 5), presenting an arched geometry. It makes gradational contacts with the Córrego do Sítio unit and the Casa Forte Formation. The lithotypes are represented by quartzites varying from fine to very fine granulometry, consisting of fine sand to the silt,

with subrounded and spherical grains. They are presented as mottled quartzites; white to greenish sericitic and chlorites quartzites. These clastic rocks are composed of quartz, opaques, sericite and chlorite, these last two ones which gives the greenish tone. The rocks records granolepidoblastic texture with inequigranular and xenomorphous minerals, as well as continuous foliation defined by the orientation of micaceous minerals.

Casa Forte Formation

This unit occurs in the eastern portion, which the contact between the rocks of this unit and the rocks of the Moeda Formation (to the south) occurs through transverse fault, already with the rocks of the Palmital Formation (to the north) is interpreted as gradational contact. The quartzites, main litotype, have greenish gray color with yellow color whenever alterated. The granulo-metry varies from fine to medium sand, with subangled quartz grains. The sericites and / or chlorite gives the rock the greenish tone. In thin section, is composed by quartz, white mica, chlorite and opaques. It presents granolepidoblastic texture with inequigranular and hipidiomorph minerals. White micas and chlorites are thin and oriented, defining the foliation. This foliation contours the quartz grains and marks concave-convex contacts. The paraconglomerates, secondary lithotype, become of the basal portions of this unit. The matrix record granulometry fine sand and silt, and can assume greenish to reddish color. The thin section of matrix is composed by quartz, kyanite and sericite. It has granolepidoblastic texture with unequigranular grains. The quartz grains have concave-convex contacts up to polygonal; kyanites present tabular habit, in isolated crystals and aggregates forming fans. Between the quartz grains and the cyanites occurs fine white micas, with no preferential orientation.

Minas Supergroup – Caraça Group

Moeda Formation

The Moeda Formation crop up in contact with the rocks of the Casa Forte Formation in a tectonic type contact – thrust fault. This lithological unit is composed of white quartzites, with ocher and red weathered color. Alternate between medium and coarse sand, with fine sand and silt intercalations. The lithotype is poorly texturally selected, with angular and sub spherical grains, consisting essentially of quartz and sericite. It is possible to recognize preserved sedimentary structures, such as small cross stratifications. Mineralogically is composed by quartz, white mica and opaques minerals with granolepidoblastic texture and unequigranular grains. Foliation direction are defined by orientation of sericites.

Minas Supergroup – Itabira Group

Cauê Formation

The Cauê Formation, in the mapped area, appearance elongated geometry, with parallel direction to NE-SW. It is discordant with contact of the Córrego do Sítio unit. This unit is characterized by a banded iron formation, with an evident centi-millimeter thick band consisting of rich layers of silica, alternated with hematite and magnetite rich layers. In a thin section the rock presents granoblastic texture, consisting of opaque minerals and quartz grains. The compositional banding is folded.

Mafic Intrusive Rocks

The mapped mafic intrusive rocks are dikes cutting the Santa Quitéria unit on the road to the Caraça Sanctuary. Regionally it are cutting several units of the Rio das Velhas and Minas supergroups in the region (Dorr, 1969; Porto, 2008; Lima, 2012; Roncato, 2016). Its thickness varies from decimetric to metric and are extremely weathered.

Mafic dikes and sills have a NNE-SSW direction, dipping to the SE. Mafic rocks with chlorite and muscovite alteration are epidote-rich dolerites. Quartz-bearing, schistose chlorite-carbonate dominated mafic rocks are the most hydrothermally altered; locally bearing gold. The incipiently altered mafic rocks represent a fine-grained dolerite with relict pyroxene, amphibole and plagioclase (Roncato et al., 2015).

Hard Lateritic Cap - Canga

Weathering is one of the main processes responsible for the large volumes of iron rich ores in the Quadrilátero Ferrífero (Rosiere & Chemale Jr., 2000). Water percolation with pH ~ 5.5 or lower under conditions of tropical weathering induces leaching of carbonates, SiO_2 and Fe from the different itabirite types. Fe migrates as Fe^{2+} mainly from magnetite and precipitates under oxidizing conditions as hematite or goethite. Development of a hard lateritic cap ("canga") that protects the underlying iron formation from further oxidation may promote leaching of SiO_2. (Rosiere &

Chemale Jr., 2000).

The mapped Canga unit is characterized by a clastic-supported ferruginous cap, in which its framework is formed by clasts of banded iron formation pebble-size. The matrix is composed essentially by silt and fine sand grains, wherever magnetism in the clasts. Hematite of the specularite variety is observed.

STRUCTURAL FRAMEWORK

The sedimentary rocks are deformed into the Conceição anticline which consists of a complexly folded belt of schist and iron-formation. The anticline is a major feature in the mapped area and in the adjacent region. The structural details are largely obscured by deep weathering of the schist, phyllite and iron-formation that make up the core of the anticline. The overturned northwest limb includes rocks of the Minas Supergroup Nova Lima Group that dip about 30°-85° SE. The southeast limb dips about 30° E. Lineaments were identified on stereopairs of black-and-white aerial photographs and satellites images. Our observations indicate that high-numbered lineaments, with NW-SE direction, tend to correspond with scarps and drainage directions.

The bedding S_0 is often preserved in the units of the Nova Lima Group, banded iron formations of the Cauê Formation and in the quartzites of the Maquiné and Caraça Group, due to the low metamorphic degree, which these lithologies were submitted. Chemical rocks centimetre-scale interbeds of Banded Iron Formations (Mindá and Santa Quitéria units; Cauê Formation) consists of alternation of light and dark bands. Weathering has enhanced the apparent sharpness contacts. Those alternation reflect a compositional banding of that rocks.The first structures are registered in the Córrego do Sítio Unit by the deposition of the sedimentary rocks and produced millimetric to metric bedding in scale. These structures are represented by gradational bedding and cross-bedding stratification of small range.

Although the main regional foliation S_1 is the most evident structure in the mapped area, occurring in practically all the identified lithotype. It dips subparallel to bedding, and is difficult to distinguish them from one another. There are rock strips that show mylonitic foliation subparallel to regional foliation, which are interpreted to be contemporaneous and cogenetic, reflecting a strong shearing component of a single progressive event.

The crenulation cleavage S_2 strikes NNE, crosscutting S_1 at a high angle (70−80°) to the northwest. Associated with the S_2, folds that arched the bedding, the foliation S_1 and the crenulation cleavage S_2. The newer structure recognized is associated with transitional ductile-brittle conditions, and are composed by parallel fractures predominate, spaced from centimeters to meters. Two fault zones were mapped, the first one is an inferred thrust fault from the contact between the Minas Supergroup and the Córrego do Sítio unit – Nova Lima Group. The second one is a transcurrent fault in the eastern portion, in the contact between the Moeda Formation and Casa Forte Formation; the last one is marked by the presence of conglomerates with stretched clasts.

Structural Analysis

In order to simplify the understanding of the tectonics of the mapped area, the structures has been subdivided in domains according to the trend of the regional foliation S_1. These domains are: (i) Conceição; (ii) Caraça.

The Conceição Domain (Figure 6) is located in the western and central region of the area, and included the Córrego do Sítio e Mindá units, besides the Cauê Formation. The structures S_0, S_1 and S_2 are observed, as well as an inferred thrust fault in the contact between the Cauê Formation and the Córrego do Sítio unit.

The bedding S_0 of the units records a modal attitude of 146/39. Some measures plunges to the northwest quadrant, which are associated with parasitic folds. The Banded Iron Formations of the NW portion exhibit axis folds oriented to the NE direction, however, the modal banding follows the common tendency of domain trend, with dip for SE, 150/33. The regional foliation S_1 present modal attitude 111/39, thus diving to ESE. The maximum density of the crenulation cleavage (S_2) is 283/39.

The Caraça Domain (Figure 7) is the eastern and central region domin, consisting of the Santa Quitéria unit, Palmital and Casa Forte formations, belonging to the Rio das Velhas Supergroup, as well as the Moeda Formation of Minas Supergroup. In this rocks are observed the structures denoted as S_0, S_1 and S_2, in addition, it was inferred a transcurrent fault.

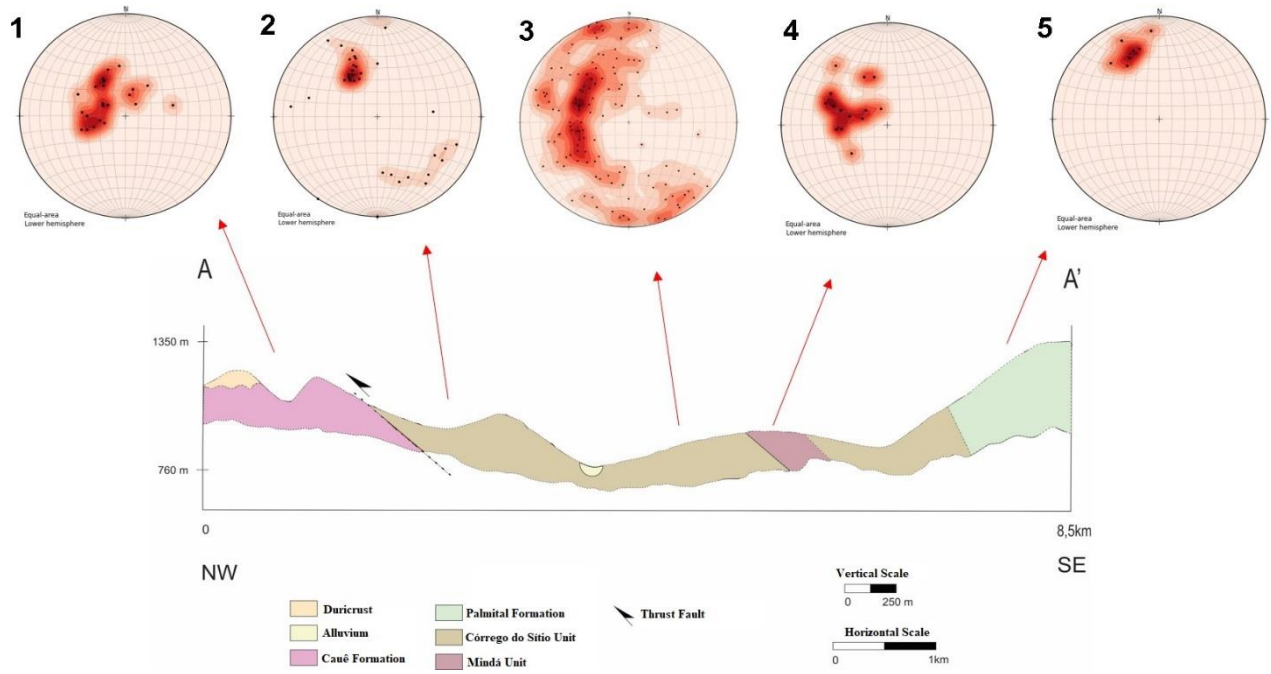


Figure 6. Schematic cross-section of the Conceição Domain with detail of its Stereograms and internal structures. 1- Cauê Fm bedding S_0 Stereogram; 22 measures; maximum density at 150/33. 2 - Córrego do Sítio unit bedding S_0 Stereogram; 37 measures; density measurement in 146/39. 3 - Córrego do Sítio unit foliation S_1 Stereogram; 153 measures; maximum density at 111/39. 4- Mindá unit foliation S_1 Stereogram; 14 measures; maximum density measurement: 113/50. 5 - Palmital Formation bedding S_0 Stereogram; 7 measures; density measurement at 156/56.

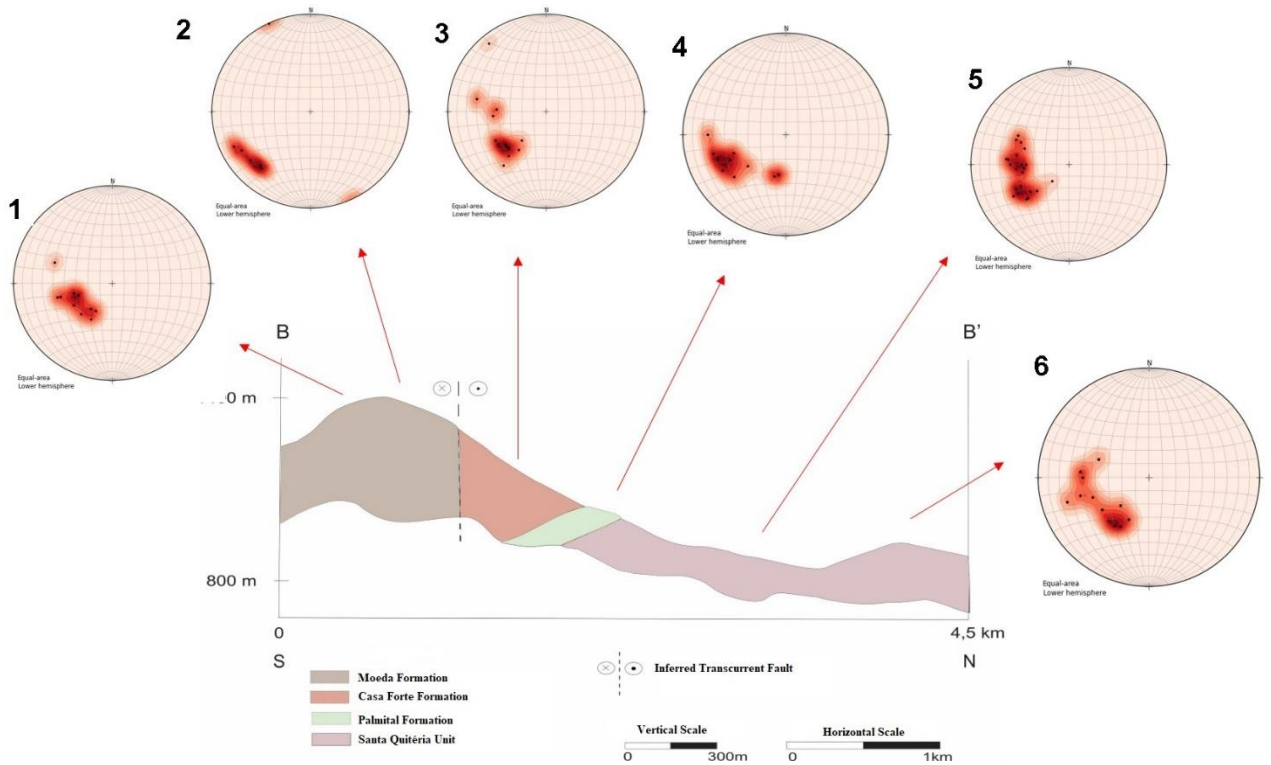


Figure 7. Profile N-S of Caraça Domain. Stereograms representing S_0 and / or S_1 of the units. 1- Moeda Quartzite bedding S_0; 11 measures; maximum density measurement: 70/33. 2- Moeda Quartzite foliation S_1; 6 measures; maximum density measurement: 46/69. 3 – Casa Forte Formation foliation S_1; 16 measures; maximum measure: 45/44. 4- Palmital Formation foliation S_1; 10 measures; maximum density measurement: 66/56. 5- Santa Quitéria Unit foliation S_1, 25 measures; maximum density measurement: 66/56. 6- Santa Quitéria Unit bedding S_0; 12 measures: 38/44.

Bedding S_0 was noticed in the Moeda Formation and in the Santa Quitéria unit, with modal attitudes 70/33 and 38/44, respectively. The S_1 foliation presents a modal measure of 53/44, dipping to the northeast and parallel direction to the rock beddings, although it has a larger dip. The S_2 foliation, has a maximum density of 240/39 and dip to the southwest.

The transcurrent failure inferred in the contact between the Minas Supergroup and the Rio das Velhas Supergroup is evidenced by the stretching of the clasts of the conglomerate of the Casa Forte Formation, in the E-W direction. Fractures are develop and are best detected in less weathered outcrops. In general, the fractures shown high angles, with main direction for SW and modal attitude 230°.

DISCUSSION

The combination of magnetic, radiometric, field data, petrography and aerial images allowed the consolidation of a new geological map for the eastern portion of the Quadrilátero Ferrífero drawn at the 1:25,000 scale (Figure 5). The stratigraphic units occurring within the study area are described below. Due to access difficulties in some part of this area, the definition of one unit was made only by analogy between the geophysical and an aerial interpretation.

The region is dominated by a package of sedimentary rocks consisting of alternating graywackes and phyllites in a turbidite sequence. The stratigraphic stacking of the identified lithotypes becomes complex due to the tectonic and intemperic processes which they have been submitted over the time. The most convenient correlation of the outcropping lithotypes in the mapped area, belonging to the Rio das Velhas Supergroup, is with the litofacies association proposed by Baltazar and Zucchetti (2007). This proposal adopts petrographic features, association of depositional environments, as well as the disposition of the lithotypes to unify them in genetically related sets. The Santa Quitéria Unit can be correlated to the Clastic-chemical sedimentary lithofacies, whereas Palmital, Córrego do Sítio and Mindá units are related to the Resedimented lithofacies. The Casa Forte Formation is framed in non-marine lithofacies.

The oldest mapped unit, Santa Quitéria, is present as clastic sediments like phyllites and rhythmites with subordinate graywackes and BIF's. It is marked by a clastic-chemical sedimentation differentiating the BIF's of that unit belonging to the Cauê Formation, as the former are intercalated with clastic lithotypes like phyllites, in addition to not presenting specularite.

Porto (2008) and Lima (2012) consider the Córrego do Sítio lineament as a package of sedimentary rocks consisting of alternating graywackes and phyllites in a turbidite sequence with incomplete Bouma cycles (Bouma 1983), metamorphosed to the greenschist facies; where mafic dikes and sills are subparallel to discordant. The Córrego do Sítio unit is widely distributed in many parts of the Quadrilátero Ferrífero and includes sequences of graywacke and phyllites. Graywackes, quartz graywackes, sandstones and siltstones display cyclic layers and abrupt basal contacts between cycles. The features of this association indicate that it was deposited by turbidity currents (Lima, 2012; Roncato et al., 2015).

The contacts with the sedimentary units are abrupt, oblique and marked by the development of hydrothermal alteration zones containing carbonate, sericite, quartz and sulfide minerals. The Córrego do Sítio Unit shown carbonaceous phyllite and graywacke sequence, with metric-decimetric BIF layers; carbonaceous phyllite with an anastomosing schistosity hosting millimetric to metric quartz-carbonate veins and microfolded layers. This is where the auriferous mineralization is concentrated, with sulfide and sulfosalts in quartz-carbonate veins (Roncato et al., 2015).

The Maquiné Group appears with its two typical formations: Palmital and Casa forte, where the first predominant among these. The Palmital Formation records a mature sericitic quartzites with chlorite. For Baltazar and Zuchetti (2007) this unit would be within the context of resedimented lithofacies associated with turbidites, in a transitional context for volcano-clastic lithofacies, interpreting it as of marine deposition in regions near volcanic zones. The compiled data on this formation corroborate this hypothesis, since the rock presented thin clasts and presence of sulphides. On the other hand, the Casa Forte Formation has thick and poorly selected granulometry. Baltazar and Zuchetti (2007) classify this unit as a non-marine lithofacies formed from fluvial and alluvial deposits.

The Quartzites of Moeda Formation don't record an expressive seritic content and doesn't contain chlorite in its framework. Stretched conglomerate clasts register the presence of a transcurrent fault in contact with the Casa Forte Formation.

The Banded Iron Formation present in the northwest portion of the area is interpreted as belonging to Cauê Formation. This interpretation

is due to the expressive extension and the absence of intercalation or even association with characteristic lithotypes of the Nova Lima Group. Mafic dikes and sills have a NNE-SSW direction, dipping to the SE.

Based on mineral assemblages, it was possible to recognize two mineral paragenesis P1: chlorite + quartz + white mica, sericite variety, in the Córrego do Sítio unit and in the Casa Forte Formation; and P2: quartz + kyanite + white mica, sericite variety, identified in the Casa Forte Formation.

The presence of the mineral chlorite index in the P1 paragenesis and the absence of other index minerals such as biotite, typifies the metamorphism as belonging to the Chlorite Zone. Thus, it is possible to characterize the metamorphism in the greenschist facies, as already mentioned by some authors (Herz, 1978; Baltazar & Zucchetti 2007; Rossi, 2014; Roncato, 2016). The presence of kyanite is associated to an increase in pressure due to the proximity of more deformed portions, in the Caraça domain where a transcurrent fault has been described.

Four deformation events affected the region, and these are in part progressive. Event D1 is characterized by a progressive foliation S1-2, striking NNE, and dipping to ESE, producing tight, asymmetric, isoclinal and disharmonic, kink folds; D2 is typified by a crenulation cleavage and a spaced crenulation cleavage S3, which strikes NNE crosscutting the regional foliation S1-2 at a high angle to the NW; D3 is represented by large-scale, open folds, arching S0, S1-2 and S3. These structures may represent more recent orogeny; and D4 has parallel fractures, spaced from centimetres to metres along with open folds or subordinate kink folds with high angle vertical axial plane, striking mainly towards NW.

Some works in gold deposits typified de hydrothermal alteration in region (Lima, 2012; Sequetto-Pereira, 2013; Ribeiro et al., 2013, Roncato et al., 2015, Roncato, 2016) where two different vein types are important to mineralization, smoky-quartz-carbonate-sulfide-sulfosalt veins, which are very deformed; and milky-quartz-carbonate veins that represent the recrystallization product of the smoky quartz-carbonate veins.

Geophysical Data

In the following section, we describe the lithological units and structures and briefly discuss their response in geophysical and aerial photos. Their petrophysical properties (magnetic analytical sign Image, magnetic total derivative, concentration of K, Th, U), field data, are summarized in Table 1, along with the, mineralogy and typical structures.

Resedimented lithofacies (Santa Quitéria, Mindá and Córrego do Sítio Formation)

The resedimented units comprise mainly intercalation of greywacke, carbonaceous phyllite, phyllite, rhythmites, graywacke and schistous sediments. They crop out in the most of the area, fine-grained, lepidoblastic texture and intense foliation. The most common mineral assemblage consists generally of quartz, sericite, plagioclase, chlorite, biotite, titanite, sulphides and carbonate.

The gamma spectrophotometric of the Santa Quitéria, Mindá formations records high potassium, medium uranium and low thorium response. The Córrego do Sítio Formation register high potassium, medium thorium and low uranium response, but in some portions of the area, a high response on all three channels are verified. The aerial images do not present great distinctions between the three units.

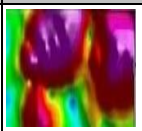
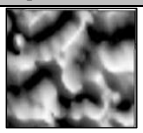
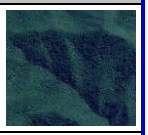
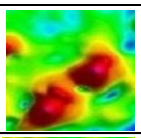
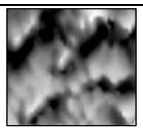
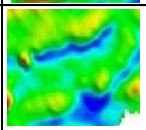
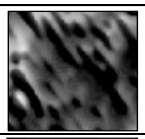
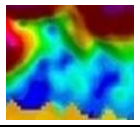
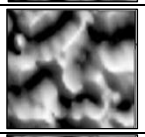
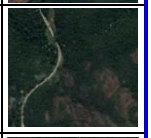
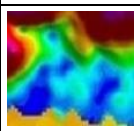
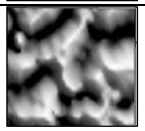
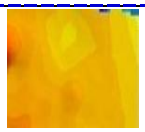
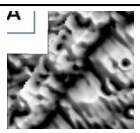
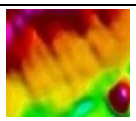
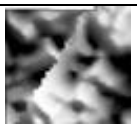
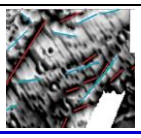
In the analysed grids, the magnetic total derivative response of the resedimented units ranges from intermediate to high. The Córrego do Sítio Formation show higher magnetic total derivative responses. The analytical signal images reveals the presence of anomalous concentrations of magnetic minerals, evidenced by concentric regions with violet and red colors. The presence of magnetic portions in the resedimented units becomes more important according to the sequence Córrego do Sítio Formation < Mindá Formation < Santa Quitéria Formation. The rougher textures indicate anomalies resulting from more superficial bodies, while the smoother ones result from deeper anomalies.

Palmital and Casa Forte formations

The Palmital and Casa Forte formations contain facies ranging from sericitic/chloritic quartzites and paraconglomerates; with quartz, sericite, chlorite, aopques and kyanite. The aerial image differences between the two units are clear, with the Casa Forte Formation presenting slightly coarser texture than the Palmital Formation.

A high thorium and medium potassium prevalence, and a low uranium response are verified. In the magnetic total derivative images, the response of the units are exactly the same, ranging from intermediate to low. The analytical signal images reveals a little influence of magnetic minerals, evidenced by medium response with a concentration of blue color and smoother texture.

Table 1. Summary table of the lithologies; their mineralogical, petrophysical characteristics, and expression in the airborne geophysical data. DTM – digital terrain model, qtz – quartz, pl – plagioclase, chl – chlorite, bt – biotite, carb – carbonate, hem – hematite, Ky - Kyanite, mag - magnetite, op – opaques, se - sericite, sph - sulphides, tit - titanite. Faults and Planar structures – red and blue lines

Geological Unit	Lithology and Structures	Mineralogy	Total gradient of the magnetic field Image	Magnetic Total Derivative Response	gamma spectrophotometric Response	Aerial photos
Santa Quitéria	Phyllites, metarrhythmites, and subordinate metagraywacke	Qtz, carb, pl, ep, chl, bt, tit			High potassium, medium uranium and low thorium response.	
Mindá	Schistous metasediments	Se, qz, op, chl			High potassium, medium uranium and low thorium response.	
Córrego do Sítio	Intercalation of graywacke and carbonaceous phyllite, phyllite	Se, qz, op, Sph			High potassium, medium thorium and low uranium response. Some portions in the area have a high response on all three channels.	
Palmital	Sericitic and chlorites quartzites	Qz, op, se, chl			High thorium and medium potassium prevalence; low uranium response.	
Casa Forte	Quartzites, metaparaconglomerates	Qz, se, chl, op, Ky			High thorium and medium potassium prevalence; low uranium response.	
Moeda	Quartzites	Qz, se, op			Low response in uranium, thorium and potassium.	
Cauê	Banded iron formation	Qz, hem, mag			Low response in uranium, thorium and potassium.	
Recent coverings	Fe-rich duricrust, colluvium	Qz, hem, mag, se, chl			High response in uranium, thorium and potassium.	
Folds/Faults	Structural Patterns	NA	NA		NA	NA

Moeda Formation

It formation is composed essentially of quartzites with quartz, sericite and opaques. The aerial image and the analytical signal images do not present sufficient definition to differentiate them from other lithotypes. A low response in uranium, thorium and potassium differentiate them from the units mentioned above. In the magnetic total derivative images, the response ranges from low to very low texture.

Cauê Formation

The Cauê Formation may be broadly divided into two categories: the iron-rich duricrusts and the banded iron formation (BIF). The duricrusts form plateaus of various shapes and the banded iron formation extends by some tops of hills in the region, as verified in the aerial images, very weel used in order to delimit the lateritic BIF's, duricrusts and soils. Their mineral composition consists mainly of magnetite, hematite and quartz.

The duricrusts and the BIF have the same geophysical responses to the mapping scale applied. They are depleted in both potassium, thorium and uranium. In the magnetic total derivative images, the Cauê Formation displays violet and red colors while in the magnetic total derivative images ranges from high to very high. Data interpretation suggests that the residual Fe-rich material accumulates thorium and uranium,

while potassium is generally leached due to weathering. The erosional escarpments of the iron-rich duricrust plateaus may correspond to the actual lithological contacts, especially at places, where the duricrust is preserved.

Soft Sediments

The present study, along with the accompanying tectonic model, is focused on the lithological assemblages and structures of the Rio das Velhas Supergroup, the main occurrence in the area. Therefore, Minas Supergroup, which is covered in some portions in the NW, is considered an important unit in the proposed map. Its limit was established mainly usingaerial images, combined with magnetic analytical sign image and field data. In the analysed magnetic total derivative the response ranges from intermediate to high. The rougher textures and the smoother are present in this geophysical association.

Faults

The planar structures such trending mainly in the NE-SW direction, represent thrust faults barely visible in the regional scale aerial images. Some of the small-scale structures observable in the magnetic total derivative images might correspond to the thrust faults.

Lithological associations and structures: petrophysics and expression in geophysical data

The magnetic total gradient image (Figure 4A) was important in the delimitation of the duricrusts and Banded Iron Formation in the northwestern portion, as well as in the identification of the Santa Quitéria unit in the eastern sector, since this unit has iron formations with expressive extension.

In addition, , the magnetic discontinuities (Figure 4B) follow, in general, the regional structure with preferential NNE-SSW direction, as well as the most striking feature is an anomalous magnetic signal interpreted as NNE-SSW trending faults, between lithologies belonging to Minas and Rio das Velhas supergroups.

The RGB gamma-ray spectrometry image (Figure 4C) allowed to discriminate the geological map units (Figure 5). It's important to emphasize the ferruginous canga with an enrichment in Thorium in relation to the other elements, wich can be related to the plateau canga being higher than the surroundings areas. As thorium is a more immobile than potassium and uranium, it tends to concentrate on high regions. The Banded Iron Formation domain is depleted in the three elements, wich reflects the lithotype chemical composition, essentially composed by iron oxide, mainly hematite, and silica. The Córrego do Sítio Formation register a high thorium response in relation to the others. In general, the domains of this unit are characterized by a high potassium response, which can be explained by the high content in sericites and clay minerals and/or might have been produced by changes in facies or by hydrothermal processes. The Palmital Formation present in the southeast portion of the geological map, highlighting a high response in uranium; intermediate response in thorium, and low in potassium. However, since the quartzites described are sericitic, a high potassium response was expected. The low response in this element can be explained by the leaching of potassium, a mobile element, promoting a higher relative concentration of the other two elements. The Santa Quitéria associated domain presents a high response in potassium, which is consistent, since it is composed by sericitic pelites and clay minerals containning potassium. The Moeda Formation occurrence was set up from another aerogeophysical survey, therefore no interpretation was possible. .

CONCLUDING REMARKS

The fieldwork, petrography, and airborne geophysics, in addition to published information, allowed improving significantly the knowledge about the geology and stratigraphy of the eastern portion of the Quadrilátero Ferrífero region. The Rio das Velhas Supergroup units can be correlated to the litofacies associations proposed by Baltazar and Zucchetti (2007). The new geological map provides many improvements over the pre-existing maps, like as important contributions in the lithotypes detailing, understanding of the geological structures and relationship between the different stratigraphic units. New lithological facies and structures were identified and others become more visible and lithological boundaries are refined or confirmed. Moreover, the new synthesis gives sufficient details of different structural patterns including faults, foliation and others structures.

All of the geophysical methods described are suitable for detailed site investigations in

appropriate circumstances. This contribution forms the basis for future works, which have to deal with the crustal evolution of this region. These studies will allow a more confident discussion about the tectonic setting in which formed the mapped lithological units, and the crust forming events that produced this part of the São Francisco Craton.

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