Structural framework of the iron district of Itabira, Iron Quadrangle, Minas Gerais

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Abstract

The Itabira Iron District, located at the northeastern end of the Iron Quadrangle, still presents some uncertainties regarding the tectonic origin of its macrostructure. The Itabira synclinorium is characterized by a large synformal structure in the NE-SW direction, with anticlines and synclines distributed "en echelon". The analysis of the relationship between the primary structures and the plane-axial schistosity, linear and planar structures, allowed the development of a three-dimensional model for the region. The increase in deformation from E to W, observed from the Cauê mine to the Conceição mine, and the rotation of the axes of the macrostructural folds, characterized by the Cauê, Dois Córregos, and Conceição synclines, are explained in this study by a model with six deformation phases. The increase in shortening from the Cauê mine towards the Conceição mine can be explained based on the *flanking fold* model. The application of this mechanism to explain kilometric-scale folding has been presented for the eastern flank of the Santa Rita Syncline in the Iron Quadrangle.

Keywords: Structural framework, Iron Quadrangle, flanking folds, Conceição mine.

1. Introduction

The Itabira Iron District is located at the northeastern end of the Iron Quadrangle (QF) (Fig. 1), in the central portion of the state of Minas Gerais, Brazil. It includes the Conceição and Minas do Meio mines, the latter divided into the Periquito, Dois Córregos, Onça, Camarinha and Chacrinha, and Cauê digs. Four geological units composing the Itabira synclinorium (Dorr, 1969; Schorscher and Guimarães, 1976; Chemale Jr. and Quade, 1986) are mapped in this QF region: basement gneisses, the Rio das Velhas Supergroup volcano-sedimentary sequence, metasedimentary units corresponding to the Minas Supergroup, and granitoid bodies. All these sequences are cut by intrusive rocks. There are recent sedimentary covers throughout the study area. Several authors (Chemale Jr. and Quade, 1986; Crocco-Rodrigues *et al*., 1996; Galbiatti, 1999) have presented structural models for the Itabira Iron District; however, in this study, it is demonstrated that the main macrostructure characterized for the region diverges from those postulated by these authors. The increase in deformation from E to W, observed from the Cauê mine to the Conceição mine, is not clearly outlined in these models, nor is the rotation of the axes of the macrostructural folds, characterized by the Cauê, Dois Córregos, and Conceição synclines.

2. Structural framework of the iron quadrangle

According to Chemale Jr. *et al*., (1991), two large deformation events occurred in the Iron Quadrangle after the deposition of the Minas Supergroup: the first one of extensional character, aged between 2.05 and 1.8 Ga (Orosirian), and the second one compressional, aged between 0.6 and 0.5 Ga (Ediacaran).

Alkmim and Marshak (1998) proposed an evolution model for the QF in the Transamazonian, represented by two distinct events: the first compressional and the second extensional. The first event, the result of the closure of a passive margin basin, was responsible for the generation of NW-vergent folds and thrusting. The second event represented the collapse of the continental rocks at 2.095 Ga and was responsible for the structure in domes and troughs of the QF, the domes represented by the metamorphic complexes and the troughs represented by the first-order mega-synclines, filled by the supracrustal units of the Rio das Velhas Supergroup, Minas Supergroup and Itacolomi Group. In contrast, Almeida *et al*. (2002, 2004 and 2005) and Endo *et al*. (2005) suggest that the structural framework of the QF comprises folds of several generations associated with different tectonic phases and events that acted in the region. These folds, of regional scale, are divided into three generations related to the hierarchical degree and period of formation: Curral Nappe, of the first generation and N-NE vergence, Ouro Preto Nappe, second generation and S-SW vergence, and a third generation with amplification and refolding. The Curral Nappe is a north-vergent allochthonous mega-fold, which dominates the structural landscape in the western portion of the QF (Endo *et al*., 2005).

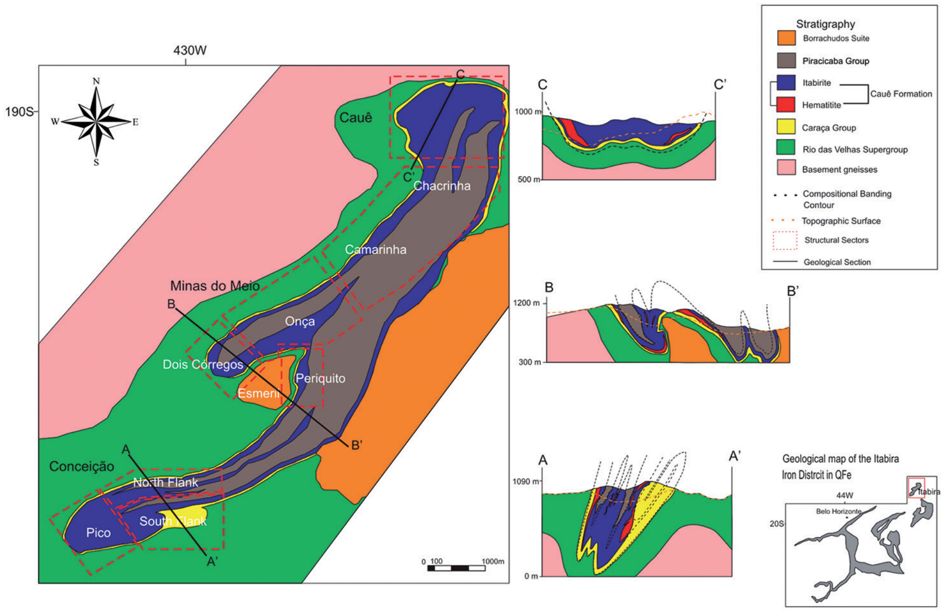

Figure 1
Geological map of the Itabira Iron District, locations of the mines, structural sectors and vertical geological section of mines.

3. Methodology

The present study was developed in two stages. The first stage involved a literature review of the area and the validation of databases in GACPS/VALE internal archives. The second stage consisted of lithostructural mapping at the 1:2,000 scale in the Conceição and Minas do Meio digs.

The sense of shear and vorticity is determined by down-plunge view of fold axis or intersection lineation. Values of deformation magnitude (shortening) are calculated by (Lf / Li) - 1, where Lf is the final length and Li is the initial length.

Stratigraphy and structural geology of the Itabira iron district mines

Conceição Mine

The Conceição mine is located at the southwest end of the Itabira Iron District (Fig. 1). Schists of the Rio das Velhas Supergroup and a set of clastic rocks ranging from phyllites and schists to metacherts with iron formation, associated with the undivided Caraça group, dolomitic itabirites, siliceous itabirites and hematite bodies of the Cauê Formation, and quartzites and silvery phyllites of the Cercadinho Formation, in addition to intrusive rocks, are mapped in a normal stratigraphic position in this area.

Structural Sectors

The Conceição mine is divided into three structural sectors: Pico, North Flank and South Flank (Fig. 1). The characteristics of each sector are:

1. The North Flank sector corresponds to the western region of the Conceição mine. It includes the rocks of the Nova Lima, Caraça, Itabira and Piracicaba Groups. The bedding in this sector (Fig. 2 - a) shows a general ENE-WSW direction and steep NW dip, although sometimes SE. The relationship between the S0 bedding and the S2 schistosity indicates counterclockwise vorticity in an 'S' pattern. The intersection lineation between S0 and S2 presents a moderate NE plunge (Fig. 2 - e) parallel to the B2 mesoscopic fold axes (Fig. 2 - f).

2. The South Flank sector corresponds to the south central portion of the Conceição mine. In this region, the Caraça Group is undivided, quite sheared and greatly thickened (Fig. 1). This thickening is associated with the overlapping of second-order folds. The bedding direction is, in general, ENE-WSW with moderate NW dip (Fig. 2 - b). In this portion of the mine, an extremely thin hematite is found, due to the superimposed deformation phases, called 'blue dust'. The folding axes have a subhorizontal NE plunge.

3. The Pico sector is represented by a portion of the southeast end of the mine. In this sector, there are rocks of the Nova Lima, undivided Caraça, and Itabira Groups. According to the bedding in this region, the generation of a closed synform is observed, inclined and with an axis attitude of 063/34 (Fig. 2 - c). Typical hinge zone features are found in this region of the mine. The generation of this synform is attributed to deformational phase F3.

The Conceição mine is located on a kilometric-scale fold, named in this study the Conceição Syncline (Fig. 1). This fold is characterized as an asymmetrical, closed, inclined fold with a NE-SW attitude, whose core is filled by quartzites and phyllites of the Cercadinho Formation. The north flank is the inverted flank with a steep NW dip. The south flank is in the normal position, with the metasedimentary unit, represented by the undivided Caraça Group, folded and associated with the F2 phase. These tectonics, on a mine scale on the south flank, lead to the thickening of this unit (Fig. 1).

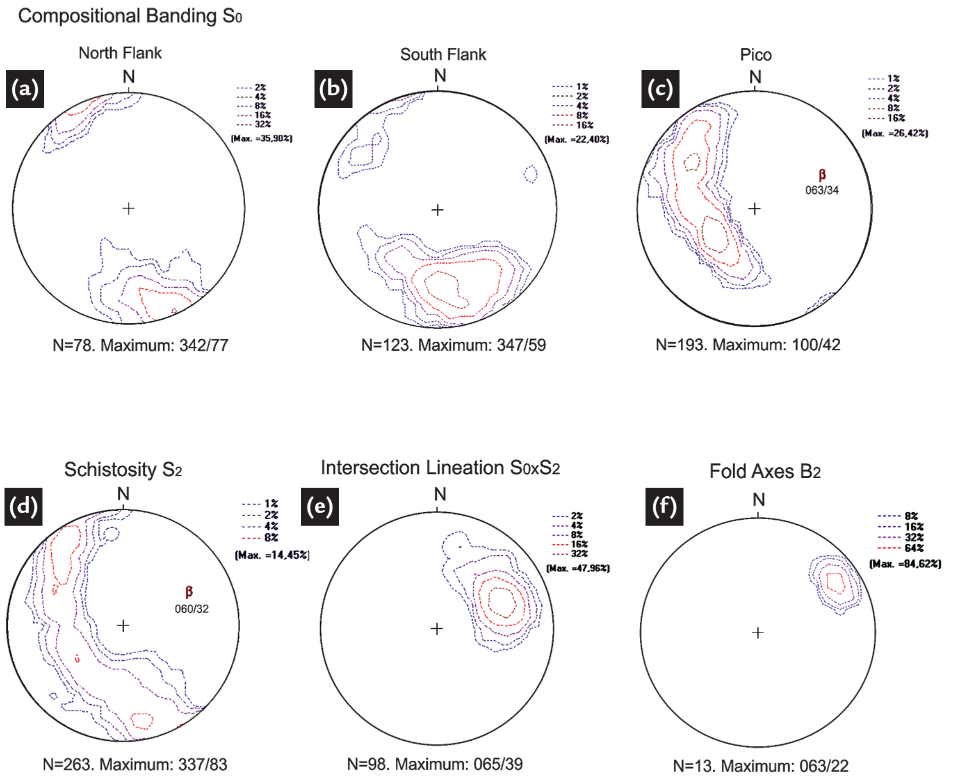

Figure 2
Stereographic diagrams with polar representations of S0 bedding. a) North Flank sector, b) South Flank sector and c) Pico sector. d) Stereographic diagram with polar representation of the S2 schistosity in the Conceição mine. e) Stereographic diagram with polar representation of the intersection lineation L2 between S0 and S2 in the Conceição mine. f) Stereographic diagram with polar representation of the B2 folding axes in the Conceição mine.

Minas do Meio

The Minas do Meio mine is located in the east-central portion of the Itabira Iron District and is composed of the Periquito, Dois Córregos, Onça, Camarinha and Chacrinha digs (Fig. 1). The same sequence of rocks as at the Conceição Mine is mapped in these digs, as well as rocks associated with the Borrachudos Suite (Dorr and Barbosa, 1963; Herz, 1970; Dussin, 1994), which crop out in a dome in Serra do Esmeril (Fig. 1). This granitic unit comprises, in the mine area, tonalites composed of quartz, biotite, feldspar and amphibole. Several elongated xenoliths of granites and gneisses and with centimeter-to-meter dimensions, can be observed in this unit.

Structural Sectors

According to the structural analysis, the Minas do Meio area can be divided into four distinct structural sectors, represented by the Dois Córregos, Periquito, Onça and Camarinha-Chacrinha digs (Fig. 1). The characteristics of each sector are as follows.

1. The Dois Córregos sector corresponds to the southwestern region of the Minas do Meio mine. It includes the rocks of the Nova Lima, Caraça, Itabira, Piracicaba Group and of the Borrachudos Suite. The bedding in this sector shows SE and NW dips, producing a synform with a modal maximum of 127/51 and comprising a hinge zone trending 077/38 (Fig. 3 - a). This synform is related to the F3 deformational phase.

2. The Onça sector corresponds to the west-central portion of the Minas do Meio mine. In this region, the Cauê Formation is quite thickened, due to the refolding imposed by the intrusion of the granitoid (F_3). It represents an antiform that joins the Dois Córregos and Periquito digs, with a subtly NE-plunging axis (Fig. 3 - b).

3. The Periquito sector represents the north flank that extends to the Conceição Mine. It presents bedding with a maximum attitude of 117/60 (Fig. 3 - c). Hematitites predominate in this area with interfingering itabirites.

4. The Chacrinha sector is located in the northeastern portion of Minas do Meio, represented by the north flank that connects this mine to the Cauê mine. The S_0 bedding shows a modal maximum of 134/55 (Fig. 3 - d). In this portion, large hematite bodies crop out, which are thick in this region. In this area, normal faults are observed (F_6), which were responsible for the generation of small basins filled by laterites.

In the Dois Córregos and Onça sectors, the intersection lineation between S_0 and S_2 presents a moderate ENE plunge (Fig. 3 - i, j) parallel to the B2 mesoscopic fold axes. Meanwhile, in the Periquito and Camarinha/Chacrinha sectors, the intersection lineation shows a NE plunge (Fig. 3 - l, m).

Cauê Mine

The Cauê mine is located in the northeastern portion of the Itabira Iron District (Fig. 1). For this portion of the studied area, systematic bench mapping was not performed as for the other mines. The lithostratigraphic sequence of the Cauê mine is represented by a metamorphic complex composed of gneissic-migmatitic rocks; schists and amphibolites of the Rio das Velhas Supergroup, which surround the Cauê synclinorium; units metasedimentary of the Minas Supergroup, comprising itabirites and hematite bodies of the Cauê Formation; and ferruginous quartzites and phyllites of the Piracicaba Formation (Galbiatti, 1999). According to Galbiatti (1999), the Cauê synclinorium is delineated by the Cauê Formation and has an ENE subhorizontal axis. The intersection, mineral and stretching lineations are subparallel to the axes of the folds associated with the second deformation phase with E plunges.

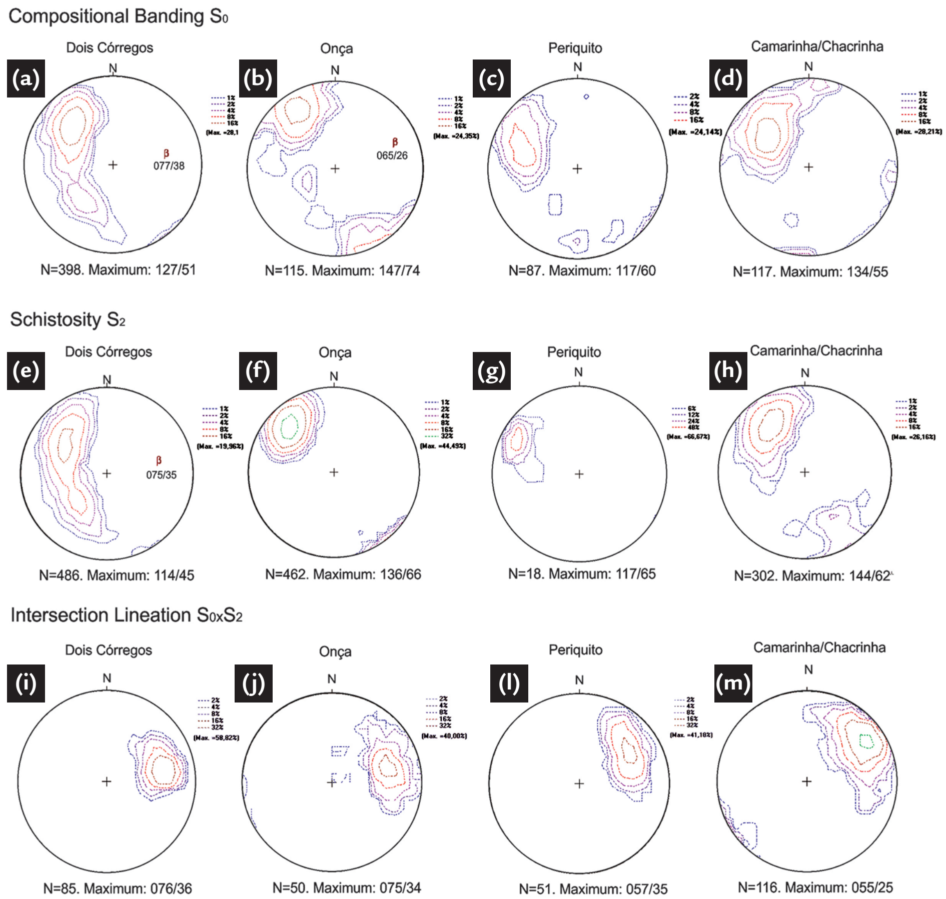

Figure 3
Stereographic diagrams with polar representations of S_0 bedding. a) Dois Córregos sector, b) Onça sector, c) Periquito sector,and d) Camarinha/Chacrinha sector. Stereographic diagrams with polar representations of the S_2 schistosity. e) Dois Córregos sector, f) Onça sector, g) Periquito sector and h) Camarinha/Chacrinha sector. Stereographic diagrams with polar representations of the intersection lineation L_2 between S_0 and S_2. i) Dois Córregos Sector, j) Onça sector, l) Periquito sector, and m) Camarinha/Chacrinha sector.

4. Itabira structural framework

The structures of the first deformation phase are restricted to S-C type foliations (Fig.4 - a), found in the gneisses of the metamorphic complex, near the contact with the rocks of the Rio das Velhas Supergroup, in the northwestern portion of Minas do Meio (Fig. 1). These structures indicate dextral sense of shearing, corresponding to a general material movement from north to south under ductile conditions. Thus, the gneisses of the metamorphic complex behave as a basal detachment zone, and the trace of this surface is represented by the contact of the supracrustal rocks with the basement gneisses. Other structures of this deformation phase were probably obliterated by subsequent deformation phases.

The S_2 schistosity constitutes the most penetrative structure of the second deformation phase. This structure is associated with regional F_2 folds and is plane-axial to these folds. The S_2 schistosity is observed in all of the mapped units in the area, mainly in the itabirites of the Cauê Formation, and is characterized by the preferred orientation of hematite, quartz, and sericite crystals. The vorticity relationship between the compositional banding and the S_2 schistosity presents counterclockwise vorticity with an 'S' pattern, which can be observed throughout the studied area (Fig.4 - b). The intersection lineation between the compositional bundle and the S_2 schistosity shows a moderate ENE plunge and is subparallel to the folded axes of this deformation phase.

The Cauê, Dois Córregos and Conceição synclines, which form the geometry of the Itabira Iron District, are the main structures of the third deformation phase. The generation of these mega-structures is associated with the intrusion of the granitoid that crops out between the Periquito and Dois Córregos digs, in a region known as Esmeril (Fig.4 - c). This intrusion is responsible for the reorganization of the structures of phases F_1 and F_2 through coaxial refolding. Closed folds of metric scale, with subhorizontal plunge axes and recorded in the undivided Caraça Group in contact with the granitoid, may be associated with this intrusion. The F_4 phase, characterized by crustal shortening in the N-S direction, promotes the general rotation of the planar and linear structures generated in the previous phases, especially the ones from the F_3 phase, to the W around a N-S axis. In response to this shortening, symmetric folds, ranging from open to isoclinal, are generated with NE subhorizontal plunge axes. The isoclinal folds are locally observed in the compact itabirites of the Conceição mine (Fig.4 - d), while the open folds can be observed in the Minas do Meio and Cauê mines. This progressive deformation from NE to SW can be distributed to the base of the iron formation, reducing its effect on the rocks with more competent rheology that comprises the basement of this region.

The structure of the F_5 phase consists of open folds with N-S axes and decametric wavelengths and amplitudes, with a fairly homogeneous distribution throughout the iron district. The S_5 crenulation cleavages are attributed to this deformation phase, with N-S directions and subvertical to W dips (Fig. 4 - e). The structures of deformation phase F6 are represented by joints, fractures and small-throw faults, which affect the rocks of the Minas Supergroup, mainly the itabirites and compact hematite bodies of the Cauê Formation (Fig.4 - f). These structures show signs of generation in multiple phases and different periods. A family of normal faults of distensible character is associated with large lateritic deposits, which can be mapped in the southeast portion of the Chacrinha dig.

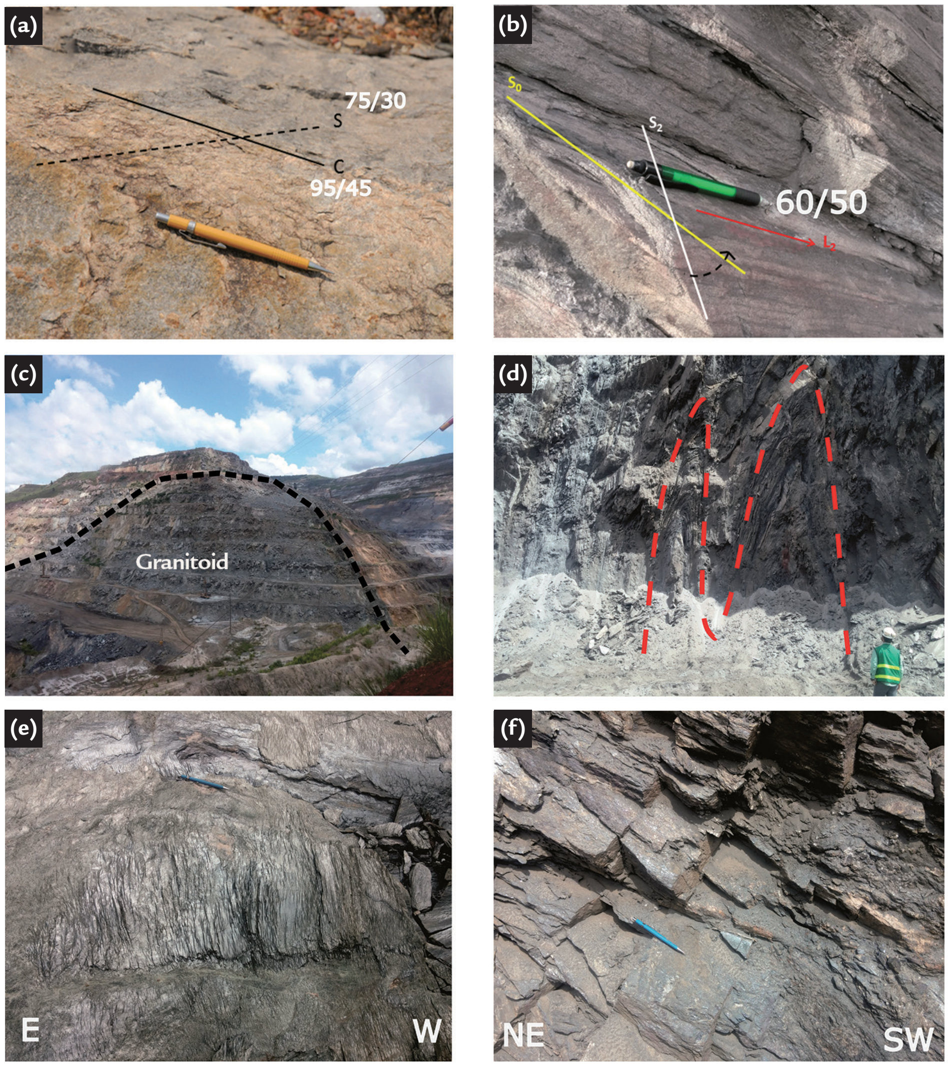

Figure 4
a) S-C type foliation, with clockwise vorticity, found in gneisses of the metamorphic complex. b) Vorticity relationship between the compositional banding and S_2 schistosity. c) West view of the Borrachudos granitoid in Serra do Esmeril. d) Tight "M"-pattern folds observed in the itabirites of the Conceição mine (W view). e) Crenulation cleavages S_5 found in the schists of the Rio das Velhas Supergroup. f) Orthogonal fractures found in the itabirites of the Cauê Formation.

5. Discussion and conclusions

The lithostratigraphic and structural information collected from a detailed geological map allowed the proposal of a geological and structural model for the Itabira Iron District. For the final conformation of the Itabira syncline, a tectonic evolution is proposed that is divided into four deformational events. The first deformation event, E_1, is marked by compressive tectonics that include deformation phases F_1 and F_2. The Itabira synclinorium was nucleated during the Rhyacian event at approximately 2,125 Ma, and it comprises a syncline resulting from refolding (F_2) of the inverted flank of the Ouro Preto Nappe (F_1) (Almeida, 2004). This nappe, a manifestation of deformation phase F_1, is S- to SW-vergent. Structures, such as S-C type foliation, indicates clockwise vorticity that corresponds to a general material movement from north to south under ductile conditions. The second deformational phase, F_2, consists of coaxial refolding of the inverted flank of the nappe. The presence of mesoscopic folds with superposition patterns indicates that this deformation phase was responsible for the generation of folds at different scales with counterclockwise vorticity or "S"-pattern folds.

After these tectono-metamorphic events, there is a phase of post-Minas magmatism, attested by the intrusion of the Borrachudos Suite granitoid. This second tectonic event, E_2, is responsible for the tilting of the supracrustal rocks of the Rio das Velhas and Minas supergroups and the structural conformation into the syncline troughs called Cauê, Dois Córregos and Conceição. The relationships between the structures of the third deformational event, E_3, are the most complex ones and are characterized by the rotation of the planar and linear structures generated in the previous phases, through a shortening component in the N-S direction. An increase in the magnitude of deformation (shortening) from NE to SW is observed in the Itabira Iron District. This increase in deformation can be measured by calculating the tectonic shortening. In this study, the shortening value is measured through the vertical sections generated for the three mines (Fig. 1). An increase in the shortening magnitude of the Cauê mine towards Conceição is observed (Table 1) from NE to SW.

Table 1
Deformation magnitude values calculated for each mine.

Structure	Li	Lf	Shortening	% Shortening
Cauê Syncline	1420	1250	-0.1197	11.97
Dois Córregos Syncline	5350	2500	-0.5327	53.27
Conceição Syncline	2285	625	-0.7264	72.64

Therefore, to explain this increase in deformation, the *flanking fold* model is used as the basis, which was described and established by Passchier (2001) and Wiesmayer and Grasemann (2005). The kinematic indicators, the symmetry of the F_4 phase structures and the variation in the shortening magnitude of the synclines (Table 1) are compatible with the deformation mechanism and partition related to the *flanking fold* model. The application of this mechanism to explain kilometric-scale folding was presented by Rossi and Endo (2015) for the east flank of the Santa Rita Syncline (Dorr, 1969; Maxwell, 1972) in the Iron Quadrangle. Gomes *et al.* (2015) presented analog flanking structure models developed under simple shear conditions in an experimental rectangular box. These authors observed a thickening and shortening of the silicon at the ends of a transverse element (TE), which could represent structures such as faults or veins, in accordance with simple sinistral shear. During a progressive deformation, regardless of the initial TE position, the fabric was always disturbed, with local thickening and thinning at opposite ends of the TE (Gomes *et al.*, 2015). According to Exner *et al.* (2006), the flow disturbances along the TE were independent of the structural scale.

In the case of the Itabira region, the transverse element to the regional "S" fabric is the crustal discontinuity represented by a system of mafic E-W-directed dikes whose crustal expression is given by the magnetic lineament and the geomorphological expression represented by the Santa Bárbara river alignment, both in the E-W direction (Fig. 5 - a). Based on this mechanism, the F_4 phase structures can be understood as the manifestation of the deformation partitioning process around the main discontinuity, shown by the counterclockwise rotation of the F_3 phase syncline axes and the increase of deformation magnitude from NE to SW. The region of Itabira, following the model proposed by Gomes *et al.* (2015), is in the sector that underwent shortening, which is closer to the center of rotation and decreases to the NE (Fig. 5 - b). This counterclockwise rotation of the TE results from a crustal shortening in the N-S direction during the Ediacaran event (0.66 - 0.56 Ga) (Fig. 5 - b). Peres *et al.* (2004) demonstrated that the first phase of the Araçuaí orogen, synchronous with regional metamorphism of amphibolite facies, is associated with tectonic transport to the north. The structures of the fourth deformation event, E_4, arise from a period of intense crustal fracturing, probably related to the South-Atlantean event (e.g. Schobbenhaus *et al.* 1984). This event caused the formation of grabens and horsts for detrital sedimentation observed through lateritic covers around the mines.

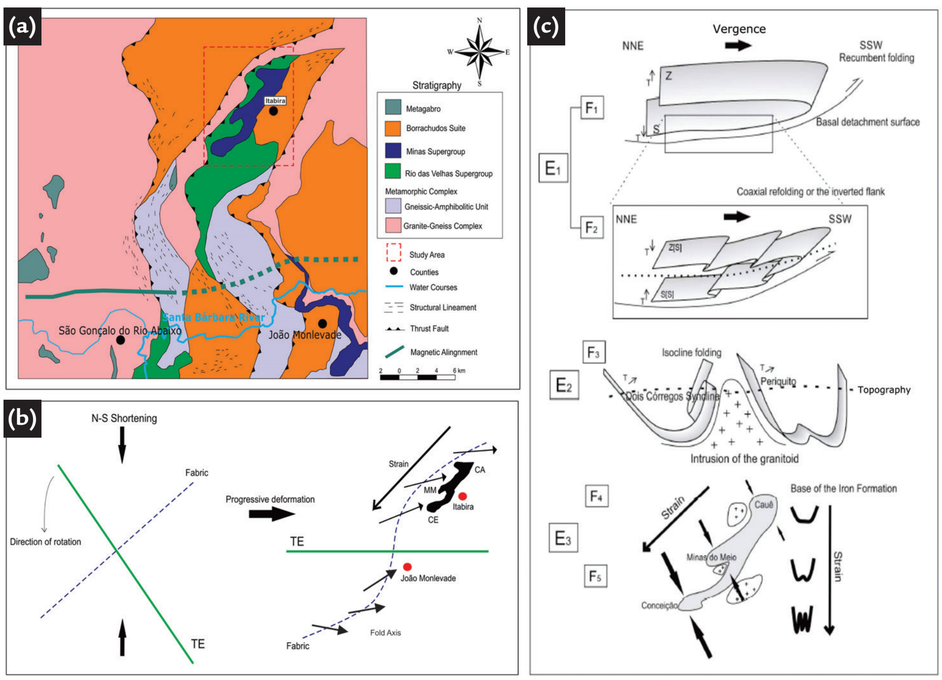

Figure 5
a) Extract from the Itabira sheet geological map indicating the region of the Itabira Iron district and the magnetic lineament of mafic dikes (Padilha et al., 2000). b) *Flanking folds* mechanism developed for the Itabira region. c) Synthesis of the tectonic evolution of the Itabira Iron District.

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