A structural model of the Fábrica Nova region, Santa Rita syncline, Quadrilátero Ferrífero: flanking folds as a folding mechanism

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Abstract

This study focuses on the eastern flank of the Santa Rita syncline (Dorr 1969), with specific emphasis on the region known as Fábrica Nova. Important iron ore deposits are located on the flanks of this structure, such as Timbopeba, Alegria, São Luiz, Tamanduá, Almas and Fábrica Nova. The Santa Rita syncline is a fold with N-S axial direction and of subregional scale, with roots in the adjacent basement of the Santa Bárbara Complex and sectioned by the Água Quente thrust fault. The hypothesis of this study is that the structural framework of the region resulted from the superposition of at least three deformation phases on the Ouro Preto nappe. The Fábrica Nova mine, located in the central portion of the study area, is embedded in a synformal structure with a 100/20 trending axis named Fábrica Nova synform. The proposed model to explain the particular structural geometry of this region is based on the flanking folding mechanism (Passchier 2001). This mechanism may have been developed by E-W crustal shortening during the F₄ tectonic deformation phase.

Keywords: Geologia Estrutural, Quadrilátero Ferrífero, Sinclinal Santa Rita, Fábrica Nova de Minas.

Resumo

O presente trabalho se concentra na aba leste do sinclinal Santa Rita, (Dorr 1969), a partir da região conhecida como Fábrica Nova. Importantes depósitos de minérios de ferro estão localizados nos flancos dessa estrutura, como os de Timbopeba, Alegria, São Luiz, Tamanduá, Almas e Fábrica Nova. Esse sinclinal é uma dobra de escala sub-regional de direção axial N-S com raízes no embasamento adjacente do Complexo Santa Bárbara e seccionada pela falha de Água Quente. A investigação propõe a hipótese de que o arcabouço estrutural da região é resultante da superposição de pelo menos três fases de deformação sobre a nappe Ouro Preto. A mina de Fábrica Nova, localizada na porção central da área estudada, está inserida em uma estrutura sinformal de eixo 100/20, o sinforme de Fábrica Nova. Para a geometria particular dessa região, é proposto um modelo com base no mecanismo de dobramento por Flanking Folds (Passchier 2001). Esse mecanismo se daria através de um encurtamento crustal de direção E-W da fase de deformação F₄.

Palavras-chave: Geologia Estrutural, Quadrilátero Ferrífero, Sinclinal Santa Rita, Fábrica Nova de Minas. 
1. Introduction

The area of this study is located along the eastern edge of the Quadrilátero Ferrífero (QFe) (Dorr 1969) in the central portion of Minas Gerais state between the districts of Santa Rita Durão and Bento Rodrigues in a region known as Fábrica Nova (Fig. 1). In general, the QFe is comprised of three major sets of rock units: the metamorphic complexes of Archean age, the metavolcanic-metassedimentary rock-type sequence of the greenstone-belt of Archean age, corresponding to the Rio das Velhas Supergroup, and the Paleoproterozoic supracrustal rocks of the Minas Supergroup and Itacolomi Group (e.g. Dorr et al. 1957, Dorr 1969, Cordani et al. 1980, Schorscher et al. 1982, Romano 1989, Noce 1995, Machado et al. 1996, Alkmim & Marshak 1998).

The regional structure of the QFe is the result of the superposition of two main tectonic events (Chemale Jr. et al. 1991), namely the Transamazonian (2.1 – 2.0 Ga) and Brasiliano (0.8 – 0.6 Ga) orogenies. The first event produced the regional recumbent synclines and anticlines on the supracrustal rocks and the uplifting of gneissic-granite rocks arranged in structures like a nappe (Almeida 2004, Endo et al. 2005), and the second caused the inversion, amplification, translation and crustal rotation of the synclines and anticlines around the dome structures.

The eastern edge of the QFe represents the border between the São Francisco craton and the Araçuaí Belt (e.g., Alkmim et al. 2006), and its structure is conditioned by the Fundão-Cambotas (Endo & Fonseca 1992) and Água Quente thrust fault systems (Maxwell 1972, Ferreira Fº. 1999). The Santa Rita syncline (Fig. 1) is located within this system and, according to Dorr (1969) and Maxwell (1972), it is characterized as an asymmetric synform with a N-NE and N-S trending axis; it is open in the southern section and narrow in the northern section, with a subhorizontal plunge. The flanks are subparallels, and the overturned flank is sectioned by the Água Quente fault, which is of submeridian trace. The stratigraphic units on the overturned flank are thinner than its normal counterpart flank located to the west. Schists, phyllites, and ferruginous quartzites belonging to the Piracicaba and Sabará groups are present in the core.


According to the models of Dorr (1969) and Maxwell (1972), the correct position of the Santa Rita syncline hinge has not been determined so far. Contemporary structures such as the Gandarela and Ouro Fino synclines, have hinges with E-SE plunges parallel to the intersection and mineral stretching lineations at approximately 100/45 (Franco 2003, Endo et al. 2004). The bedding trace contour of the Minas Supergroup units of the Fábrica Nova region seems to indicate a “Z” type folding geometry (Fig. 3). If this hypothesis is correct, the syncline closure should occur in its southern section.

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**Figure 1**
2. Materials and Methods

This study was conducted in two phases. The first phase involved regional lithostructural mapping on a 1:5,000 scale, and the second stage included detailed mapping of the northern and southern pits of the Fábrica Nova mine (Fig. 2) on a 1:2,000 scale. The lithostratigraphic and structural data collected from this semi-detailed geological map enabled the proposal of a geological model for the Santa Rita syncline, especially with regard to the geometry of the Fábrica Nova region. The structural data collected during the mapping were launched in stereograms using GEOrient (v. 9.0) software.

Based on structural criteria proposed by Harland (1956), Hansen (1971), Robertson (1994), Hsue (1995), and Xypolias (2010), the study area was divided into two structural domains according to their structural styles, geometry, and fabric properties: eastern and western (Fig. 3).
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3. Results

The structural analysis was based on the structural framework from different observation scales (e.g. Williams 1985, Xypolias 2010). To better describe the structures, they were arranged into mesoscopic and macroscopic categories.

Mesoscopic Structures

Bedding

The bedding planes of quartzites of the Sabará Group in the eastern domain shows a NW-SE direction and dipping toward NE at 056/54 (Fig. 6a). The bedding in the western domain was preserved in all of the units of the Minas Supergroup with a preferential NW-SE direction at the south and an E-W direction at the north of the domain, with a maximum of approximately 172/48 (Fig. 6b). The dispersion of the bedding orientation suggests the acting of the F4 folding phase with an axial trend at approximately 117/33. This fold, named Fábrica Nova synform, is characterized as an open, subcylindrical and asymmetric fold with plunge.

Structures of the First Deformation Phase (F1)

The structures that reflect this phase are represented by tight and asymmetric mesofolds, most likely associated with an S1 foliation oblique to the bedding. The rare asymmetric folds, relics of this phase, have a “Z” pattern. In one of the few outcrops where the structures of this deformation phase were found, the bedding and S1 foliation relationship observed presents a clockwise vorticity in a “Z” pattern, which are preserved in the sericitic schist. In the silvery phyllite layer, the bedding and S1 foliation relationship exhibits a counterclockwise vorticity in an “S” pattern. The interference relationship is characterized by the superposition of the S1 regional schistosity folding the S1 foliation with the same vorticity pattern as the F1 deformation phase (Fig. 4).

However, the original characteristics of this fabric were mostly obliterated by the subsequent deformation phases in most of the studied region.

Structures of the Second Deformation Phase (F2)

The S2 regional schistosity is a penetrative planar fabric characterized by the preferential orientation of minerals such as sericite (Fig. 5a), hematite, and quartz. In the eastern domain, the S2 schistosity has an attitude of approximately 066/55 (Fig. 6c). In the western domain, the arrangement of the mapped units clearly expresses a folded system in which the S2 schistosity shows an attitude of approximately 082/43 (Fig. 6d). The attitude of the axis of this fold (B2) is 104/40. The F2 folds, which have been mostly mapped in the Fábrica Nova mine, are tight folds with an axis plunging slightly to the ESE and a major attitude of approximately 119/21 in the northern pit (subdomain IIa; Fig. 6e) and 093/17 in the southern pit (subdomain IIb; Fig. 6f). These folds are asymmetric with “S” patterns, furthermore, they have wavelengths and amplitudes on the order of 2.5 cm and 1 cm, respectively.
of a few meters (Fig. 5b). A box-fold pattern can be observed in subdomain IIa and is interpreted as the manifestation of the superposition of the F₂ folds over the F₁ folds with opposite vorticities. The “S” folds in this system are better preserved than the “Z” folds, attesting to the superposition of the deformation phases. The intersection between the S₀ bedding planes and the S₂ schistosity is the predominant fabric in the itabirites of the Fábrica Nova mine. This structure shows moderate plunging to the ESE with average attitudes of approximately 094/22 (Fig. 6g). The mineral lineation, characterized by the preferential orientation of the mica and hematite crystals, shows an orientation parallel to the L₂ intersection lineation (SₓS₂) and B₂ fold axis, with moderate plunging to the ENE of approximately 080/25 (Fig. 6h).

Structures of the Third Deformation Phase (F₃)

The structural framework of phase F₃ consists of open folds with an E-W axis featuring wavelengths and amplitudes of decametric dimensions that primarily outcrop in the Fábrica Nova mine.

The S₃ foliation is a disjunctive cleavage of the E-W direction and the subvertical plunges that dips or to the north or to the south with an attitude of approximately 018/80 (Fig. 7a) and are attributed to the third deformation phase. The open F₃ mesofolds or undulations of the bedding that show an axis with moderate plunging to the ENE and kink folds with an axial plane that dips to the south are also attributed to this phase. Among the structures of this phase, a mesofold occurring in the western portion of the Fábrica Nova northern pit stands out. This fold is an open antiform with a wavelength of approximately 200 meters and an amplitude of a few tens of a meter whose axis exhibits an attitude of 081/43 (Fig. 7b). The core of this fold is formed by silvery phyllites of the Cercadinho Formation.

Figure 6
Stereograms of the major structures.

Structures of the Fourth Deformation Phase (F₄)

The F₄ deformation phase was responsible for the final arrangement of the Fábrica Nova region, and its manifestation is represented in the Fábrica Nova synform, a fold with an ESE plunging axis and a boomerang-like geometry in plain view. The structures of this phase are primarily represented by S₄ crenulation cleavages observed in itabirites of the Cauê Formation and in schists of the Sabará Group. The general direction of the S₄ cleavage is N-S with an average attitude of 280/72 (Fig. 7c). Tight folds with steep axial plane and N-S trending axis are also attributed to this deformation phase.

Structures of the Fifth Deformation Phase (F₅)

The records of the fracture system in the Fábrica Nova mine demonstrate the occurrence of two preferential directions, orthogonal to each other. These directions are N10-20E and N80-90W (Fig. 7d).
Macroscopic Structures
Bento Rodrigues Fault: General Aspects and Kinematics

The major fault of the Fábrica Nova region, hereafter called the Bento Rodrigues fault, bisects the entire mapped area, from south of Bento Rodrigues village, crossing the border east of the Fábrica Nova mine to north until Santa Rita Durão village. In the southern portion of the map, west of Bento Rodrigues, the fault trace has an NNW-SSE direction. In the central portion, near the Fábrica Nova mine, the fault trace changes its orientation to E-W, bearing toward NNE-SSW in the northern portion of the mapped area. This structure is related to the F₂ deformation phase, which corresponds to the development of the S₂ regional schistosity and the apparent thrust of the Santa Bárbara Complex over the Minas Supergroup.

Unlike what was proposed by Dorr (1969), Maxwell (1972), Chemale Jr. et al. (1991), and Ferreira Fº (1999), the fault kinematics seems to be essentially of a dextral strike-slip character with a small reverse component. The fault trajectory shows a deflection to the left relative to the bedding trace, thereby providing an extension of the layer that results in the generation of an extensional megaboudin structure. These mine-scale tectonics lead to the thinning and disappearance of the units from the Moeda and Batatal formations in the frontal portion of the Fábrica Nova mine pit.

Folds and Folding: Geometry and Relationships

Two subregional-scale folds occur in the Fábrica Nova region: the Fábrica Nova synform from the F₂ deformation phase and the Bento Rodrigues anticline (Fig. 8). In addition, a tight antiform in the eastern section of the northern pit of the Fábrica Nova mine exists, known as the Alto Pai Miguel antiform. The axial-plane foliations that might be genetically associated with these folds were not clearly or convincingly observed.

The Fábrica Nova synform is an open fold a few kilometers in size, characterized by the rotation of the primary structures and tectonic foliations located in the northern pit of the Fábrica Nova mine (subdomain IIa) and its surroundings (Fig. 8). Only the stratigraphic units of the Minas Super-

4. Discussions and conclusions

The proposed model suggests that the Santa Rita syncline is a reclined fold of a subregional scale, with a WNW-ESE axial direction and roots in the adjacent basement of the Santa Bárbara Complex. The inverse flank of this syncline is bisected by the Água Quente thrust fault. This fold was generated during the Transamazonian event approximately 2,125 Ma ago and consists of a reclined synclinalor fold resulting from the refolding of the normal flank of the Ouro Preto nappe (e.g. Almeida 2004). The hinge zone is located in the Caraça region (Fig. 2) with axes that exhibit moderate-to-steep ESE plunging. The flanks are subparallel and the stratigraphic units are thinner in the overturned flank compared with its normal flank counterpart located to the west. Schists, phyllites, and ferruginous quartzites belong to the Piracicaba and Sabará groups are located in the core of the fold. The southern portion of the inverse flank of the Santa Rita syncline is sliced by a complex thrust fault system that Barbosa (1968) called Ouro Fino nappe. After these tectono-metamorphic events, a phase of mafic and ultramafic magmatism occurred during the pre-
Brasiliano age.

The Fábrica Nova mine is embedded in a Fábrica Nova synform structure with axes oriented at 100/20. The direction of the bedding of the units that comprises the west flank behaves consistently and homogeneously as a homoclinal, which was slightly disturbed by undulations from the F₃ deformation phase. The east flank bedding, in turn, was strongly disturbed by folding partially associated with two shortening fields due to F₃ and F₄ deformation phase, respectively, in the N-S and E-W direction. In addition, the brittle tectonic structures that form the sedimentary basin of the Cata Preta Formation (e.g. Castro et al. 1998, Lipski 2002) might have contributed to the rotation of the basement structures.

The relationships between the structures from the F₄ deformation phase are the most complex because they do not directly respond to the regional E-W shortening field and are not laterally or regionally replicated. Cover deformation mechanisms induced by a basement-involved structures can behave actively (e.g. Wilcox et al. 1973, Naylor et al. 1986, Brink et al. 1996, Erslev 1991, Narr & Suppe 1994, Erslev & Mayborn 1997, Tindall 2000) or passively (e.g. Passchier 2001, Grasemann & Stüwe 2001, Exner et al. 2004).

In the case of Fábrica Nova, the cross-cutting element to the regional fabric element is the crustal discontinuity that feeds the mafic rock dikes in the NW-SE direction present in this segment of the QFe (Fig. 10). Based on this mechanism, the structures of the F₄ deformation phase can be understood as the manifestation of the deformation partitioning process around the major discontinuity and second-order subsidiary structures in response to the crustal shortening in the EW direction.

When considering this subregional deformation mechanism using the flanking fold as a model to understand the Fábrica Nova structural framework, the strain ratio (Rf) can be measured considering:

i) the angular relationship of the direction of the layers in the short and long flanks and
ii) the angular relationship between the crustal discontinuity, the transverse element direction, and the direction of the short flank layers (Passchier 2001). The Rf value is approximately 18.7 (Fig. 10).
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