GEOPHYSICAL AND STRUCTURAL ANALYSIS OF THE GOLD METALLOGENESIS AND STRUCTURAL EVOLUTION IN THE EASTERN PORTION OF THE QUADRILÁTERO FERRÍFERO, MG, BRAZIL

MADEIRA Thiago José Augusto[1], ENDO Issamu[1], BARBOSA Maria Silvia Carvalho[1], BORGES Antonino Juarez[2]
1 - School of Mine – Federal University of Ouro Preto
2 - Geological Survey of Brazil – CPRM

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Abstract

This study aims to provide comprehension about the structural, tectonic and gold metallogenesis models of the eastern portion of the Quadrilátero Ferrífero (QFe) through the integration of structural and geophysical data. Although there exists academic studies on the intensive and extensive mineral exploration activity in the QFe, its three-dimensional structure and geological evolution are a puzzle for many geoscientists. With the application of Euler deconvolution over gravity and magnetic data, integrated with structural observations, it was possible to generate tridimensional models and structural cross-sections that improve the interpretation and elucidation of the structural evolution and metallogenesis of gold. This work shows the importance of semi-automatic integration and fieldwork data to control and obtain the optimal results on the geological framework of the QFe.

Introduction

The Quadrilátero Ferrífero (QFe) is one of the most important mineral provinces in Brazil. During the eighteenth and nineteenth centuries, this region led the world's gold production. The mineral occurrences are associated with massive and/or disseminated sulphates, metachert, banded iron formation, shear zones and quartz veins of several ages and structural control. There are many structural and tectonic proposals presented for the QFe (Barbosa 1949; Guimarães 1951; Dorr 1969; Pires 1979, 2015; Pericon & Quèmenèur 1982, Ladeira & Viveiros 1984, Chemale Jr et al. 1994, Alkmim & Marshak 1998, Endo et al. 2005; Baltazar & Zucchetti 2007), some of which are contradictory.

Geophysics and its in depth estimation has developed suddenly in mineral prospecting and in geological mapping. With the great improvement in digital techniques to integrate different kinds of data, the manipulation and data analysis processing can be quickly executed and the results can be verified with the field outcrop data.

Although there exists intensive and extensive mineral exploration activity and academic studies in the QFe, the three-dimensional structure and it geological evolution are not always well understood by many geoscientists. The purpose of this study is to contribute to the knowledge of the structural and tectonic evolution of the eastern area of the QFe, as well as the understanding of gold metallogenesis. To achieve this, a lot of field work has been done to record structural and lithological observations that were then integrated with 2D geophysical profiles. Afterwards, a 3D gravity model was constructed by interpolating the 2D profiles and integrating the results with magnetic source depth estimations and structural data, which produce an interpretation based on the kinematic evolution.

The QFe is located in the Mineiro belt (Teixeira et al.,1996) at the southern edge of the São Francisco craton (Figure 1), and has a complex structural and metamorphic history. The Mineiro belt hosts metamorphic basal complexes, supracrustal units from the Archean (Rio das Velhas greenstone belt) and Proterozoic (Minas supergroup) Eon, the Itacolomi group and a substantial amount of Archean and Proterozoic granitoids.

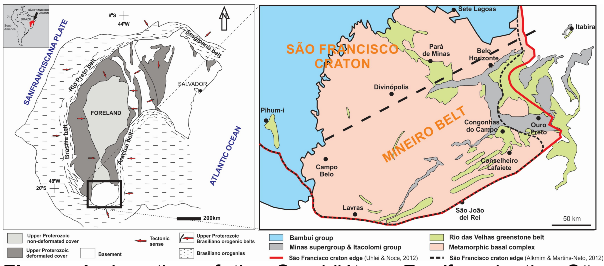

Figure 1: Location of the Quadrilátero Ferrífero in the São Francisco Craton (left) and regional geology of the Mineiro belt (right) (Adapted from Teixeira et al. (1996), Alkmim & Martins-Neto (2012) and Uhlein & Noce (2012)).

Data and Method

Geological data

The geological data, 1:50,000 scale, are from a mapping project for the Geology of the Quadrilátero Ferrífero – Integration and Cartographic Corrections on SIG (Baltazar et al. 2005). These data results are from an agreement between the United States Geological Survey – USGS and the National Department of Mineral Prospecting – DNPM (1952-1969), integrated with the geological mapping from the DNPM in agreement with the Geological Survey of Brazil (CPRM) (1992-1996).

Gravity data

The topographic and free-air data are derived from the TOPEX/Poseidon mission (https://podaac.jpl.nasa.gov/TOPEX-POSEIDON), a joint venture between the Centre National d'Etudes Spatiales – CNES and the National Aeronautics and Space Administration – NASA. With more than 62,000 orbits around the Earth with an accuracy of 4.2 cm, the reference altitude was 1,336 km and the ground track control band was +1 km improving our knowledge of

Earth's gravity field. The files were downloaded in ASCII XYZ format in the WGS84 Geographic Coordinate System (http://topex.ucsd.edu/cgi-bin/get_data.cgi).

Magnetic data

The magnetic data combine three surveys from two distinct airborne projects, the Rio das Velhas Project (RVP) (Borges 1998) and the Minas Gerais Airborne Survey Program – 2001 (PLAMG – 2001) (LASA 2001, MEGAFÍSICA 2001).

RVP is a cooperation between the Government (DNPM and CPRM), mineral industry and scientists and is the major geological and geophysical high-resolution survey in Brazil (Borges 1998). This project covers the Archean greenstone belt in the Quadrilátero Ferrífero along parallel survey lines with 250 m spacing and perpendicular tie lines spacing that are 20 times the survey line spacing.

In the PLAMG – 2001, Area 2 and Area 3, the data have been acquired along parallel survey lines having a spacing of 250 m, and perpendicular tie lines flown with a spacing of 10 times the survey line spacing.

Euler Deconvolution

The Euler deconvolution is an established method to interpret gravity and magnetic data to localize and estimate the depth of the causative source. This method has been enhanced and applied by plentiful researchers and professionals with astonishing results (Thompson 1982, Reid et al. 1990, Reid 1995, Durrheim & Cooper 1998, Mushayandebvu et al. 2001, Fitzgerald et al. 2004, Cooper 2004, Dewangan et al. 2007, Cooper 2009, Githiri et al. 2011, Ghosh et al. 2012). To estimate the source depth of gravity and magnetic data, mathematically processed grid profiles from Geosoft Oasis Montaj 7.0.1 have been processed and used as input in the Euldep 1.00 software from the University of the Witwatersrad (Durrheim & Cooper 1998). Four parameters were considered as input in the Euldep 1.00 as follows: survey height, depth limit for the estimative, structural index and window size (Thompson 1973, Thompson 1982, Reid et al. 1990, Fitzgerald et al. 2004).

Several deconvolution profiles were constructed perpendicular or almost perpendicular to the São Vicente shear zone (SVSZ) with the purpose of determining the optimal results connecting the outcrop structures with the depth anomalies. The Euler deconvolution profiles from magnetic and gravity data were imported into a 3D SIG environment and integrated, whereupon they were interpreted for the relationship amongst the gravity, magnetic and structural fieldwork data. The 2D gravity profiles had to be interpolated in a spherical kriging to produce a 3D surface. The high source depth varies approximately between 6,975 m and 12,448 m from gravity inversion data and between 4,500 m and 7,512 m from magnetic inversion data.

Outcrop data

Outcrop data was gathered at the São Vicente shear zone and in the hanging wall rocks of the structure to characterize the kinematic and geometry of the regional geological framework. Structural cross-sections were constructed to visualize the geological frame and prove geophysical anomalies in the field. Established methods were adopted to determine the spatial arrangement and geometry of the inverse and normal limbs (*e.g.* Ramsay 1967, Loczy & Ladeira 1976, Ramsay & Huber 1987, Twiss & Moores 1992). Quantitative vorticity analysis was essential for studying the kinematic flow and could be performed using a range of methods. The fabric elements have been characterized in the dip direction of the intersect lineation amongst the bedding (Sb), schistosity (Sn) and S/C foliation, also in the dip direction of the axis folds (*e.g.* Passchier & William 1996, Xypolias 2010).

Results and Discussion

Gair (1962) and Dorr (1969) postulated that the master structure in the Quadrilátero Ferrífero (QFe) is the Rio das Velhas uplift. Currently called São Vicente shear zone (SVSZ), all major synclinal structures inside the QFe are at least to some extent conjugate to this great structure. This zone is traceable for 100 km from the northern to southern edge of the Bação complex to near Nova Lima and thence northeast, where it disappears into the granitic rocks of the Caeté complex. This central uplift is the key to the structural development of most of the region. Scarpelli (1991) and Baltazar et al. (1993) interpreted the SVSZ as a counterclockwise shear zone, representing an important crustal discontinuity and locus of expressive gold mineralization. Zucchetti & Baltazar (1998) illustrated the SVSZ as a thrust fault and Araújo (2010) suggested that the structural evolution of this structure is not clear.

Madeira et al. (2014) and Madeira (2016) prove two geological and geophysical profiles at the northern portion within the Quadrilátero Ferrírefo (QFe). The structural field data concentrates at the SVSZ and in the hanging wall rocks. Adjacent to the SVSZ, those authors suggest the closure of a regional fold verging from NNE to SSW with counterclockwise rotation, wherein the metamorphic complex nucleates the core fold along the Tranzamazonian event. The transport of the regional rocks occurs over the basal detachment of the Ouro Preto nappe (OPN), materialized in the SVSZ (Figure 2 A and B).

For the southern-central region within the QFe, Angeli (2015) and Madeira et al. (2015) record the closure of a mega fold verging from the NNE to the SSW, whose structure was defined as an antiformal syncline named Maquiné. Near the SVSZ, there has been observed a transposing of clockwise structures, related to the basal detachment fabric of the OPN, over counterclockwise structures associated with the closure of the Maquiné mega fold by Angeli (2015) (Figure 2 C-1 and C-2). Proximate to an inactive underground gold mine, the trending of SVSZ has been detected near the surface by ancient mining excavations developed in colonial times (Figure 2 picture D). Over this structure, the relationship between the S/C foliations (44/58[46/35]) with intersection lineation (121/09) suggests clockwise vorticity verging to SSW. Lineation is defined by the alignment of a long axis of prolate-shape grains (*e.g.* L_{min}=90/38) invariably parallel to the fold axis and was observed in the overall study area (Figure 2 E). This structure records a constrictive B-type deformation as described by Flinn (1965).

Related to Brasiliano orogeny, Endo & Machado (1998) and Endo et al. (2005) encountered crenulation lineation, and open folds with an NNE axis verging towards the WNW, which was confirmed in the fieldwork done by us.

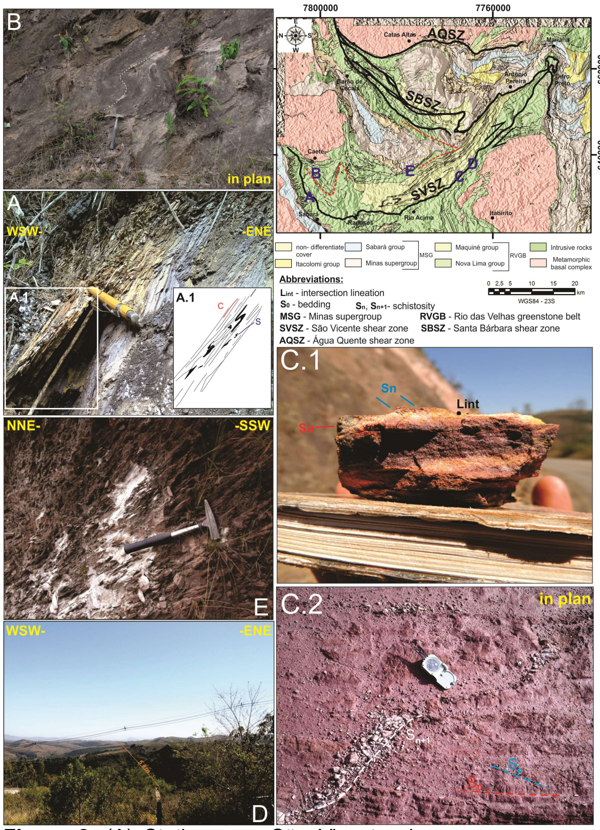

Figure 2: (A) Station over São Vicente shear zone, apparent view; (B) station close the Caeté metamorphic complex shows the structural fabric; (C-1) fabric of normal limb; (C-2) transposing of two structural events; (D) ancient mining excavations developed in colonial time; (E) prolate lineation recording a constrictive B-type deformation (modified from Madeira 2016).

Guild (1957) describes mineral lineation and elongated pebbles in the QFe, notably parallel to the intersection lineation between bedding and schistosity. Besides being the most common geological fabric in bulk metamorphic rocks, this lineation shows element orientation to be more uniform than planar. Independent of the orientation of other structures, these structures almost invariably preserve their orientation. In the overall study area, the mineral and elongated lineation allows general dip/directions 30°-45°/80°-130°, always parallel to the fold axis. Guild (1957), Dorr (1969), Chemale et al. (1994), Marshak & Alkmim (1989) interpret the lineation in the QFe as having the bulk strain related to the S and S>L tectonites developed in the flattening type strain, or A-type from Flinn (1965). This structure is associated with folds and fractures verging from the E to the W. Barbosa (1949), Pires (1979, 2015), Pericon & Quèmenèur (1982), Zavaglia (1995), Almeida et al. (2002), Franco & Endo (2004), Almeida et al. (2005), Endo et al. (2005), Madeira et al. (2014, 2015), Rossi & Endo (2015), Angeli (2015) attribute the parallelism between mineral lineation and fold axis in the QFe with the development of linear fabrics in the hinge zones of the folds, L and L>S tectonites or B-type, from Flinn (1965).

Sullivan (2013) suggests that extensive domains of L and L>S tectonites also appear to be more common in the Archean and Paleoproterozoic orogenic belts worldwide. One possible explanation for the greater occurrence of L tectonites in very old orogenic belts is that the higher thermal gradients of these orogens favored both orogeny-parallel elongation, diapirism, and the formation of gneiss domes. These geological frameworks are the encountered in the QFe.

The pattern in the structural position from the QFe with dip/direction 30°-45°/80°-130° is associated with the Abre Campos suture by Hasui et al. (1993) and Hasui (2010). This structure was developed during the agglutination and stabilization of the South American Platform. This event flattened the QFe's crust through a tectonic subduction zone verge from W to E, tectonically positioning the QFe's region in the inflection ramp of the subduction zone (Figure 3). This deformation originates a widespread rotation in the overall structures of the QFe to the E. The Upward Continuation (10.000, 25.000 and 50.000) maps from gravity data enable this interpretation, proven by the increase in the wavelength of gravity anomalies in the same direction (E).

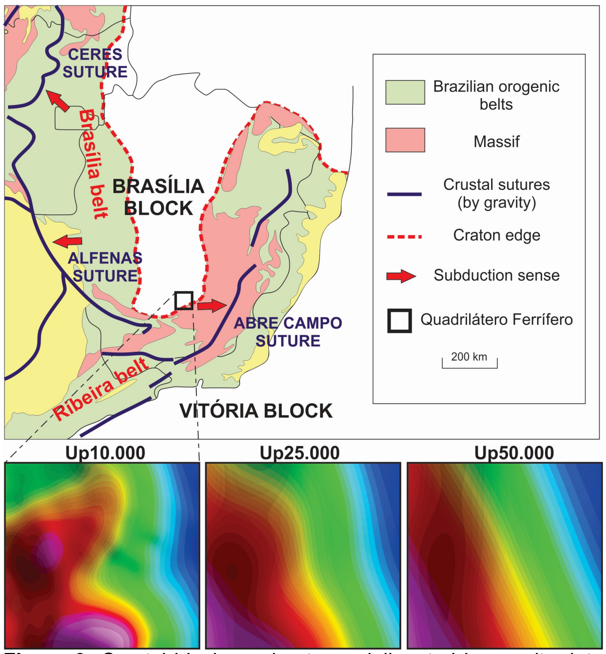

Figure 3: Crustal blocks and sutures delineated by gravity data and Up10.000, Up25.000 and Up50.000 Gravity Upward Continuation maps (adapted from Hasui et al. 1993 and Madeira 2016).

The tridimensional magnetic and gravity blocks are the largest contribution for this study (Figure 4). The magnetic deconvolution data shows a strong relationship with surface gold occurrences (Figure 4 A). For both deep magnetic anomaly and gold occurrence, there is an irregular dispersion in the northern and southern areas. In the central area, the gold occurrence interfaces the contact between Nova Lima and Maquiné groups from the Rio das Velhas greenstone belt. From the same area, the underground magnetic data shows similar results, where the magnetic sources display as a linear geometry equivalent with the ground data. In this region, the gold bearing was trapped in the black shale in contact with the top of the Nova Lima group and the base of the Maquiné group.

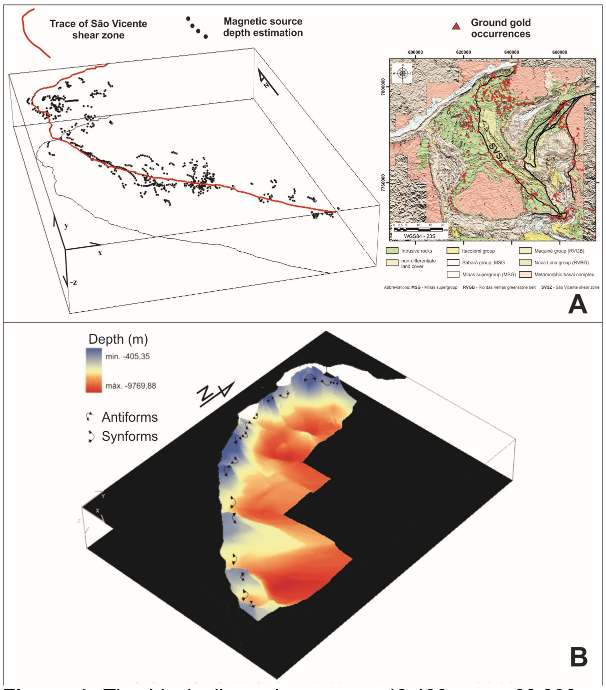

Figure 4: The block dimensions are x=43,400 m, y=60,000 m and z=9,800 m. (A) Magnetic source depth estimation and ground gold occurrences along São Vicente shear zone; (B) 3D gravity model and alternating antiforms and synforms along the SVSZ (modify from Madeira 2016).

The gravity model resultant illustrates a detachment surface recognized in the field. The pattern of alternating synforms and antiforms from N to S of the QFe suggests a uniaxial refold of the basal detachment after its development (Figure 4 B). Magnetic anomalies (i.e. sulfides) concentrate in the antiforms from the gravity model point to the main gold bearing mineralization event at the time of sin or post refold event, a N-S compression along the Tranzamazonian cycle (Figure 5). This significant mineralization event occurred during the formation of these structures, or after, given that these structures provided the trapping of hydrothermal fluids.

In view of the field and geophysical data, the following evolution phases to the hanging wall rocks over the SVSZ has been proposed:

The E_1 event is characterized by two deformation phases (F_1 and F_2) in a compressional deformation verging from NNE to SSW. The F_1 axis folds deep to the ESE and verges towards the SSW as registered by Barbosa (1949), Perícon & Quèmenèur (1982), Almeida et al. (2005), Rossi & Endo (2015), aall within the QFe. The F_2 phase (Figure 6) corresponds to the coaxial refold of a normal limb fragment and fault accommodation folds of the precursor nappe of OPN. This phase represents the predominant tectonic-metamorphic fabric in the QFe, where São Vicente (Almeida et al. 2005, Madeira 2016), Santa Bárbara (Angeli, 2015) and Água Quente (Rossi & Endo 2015) shear zones are developing, along with other correlated mega structures (regional synclines, anticlines, faults and shear zones) (Franco & Endo 2004, Endo et al. 2005, Oliveira et al. 2005). This event is the best registered by many authors for the overall QFe, and is relatively concise in its temporal position on the Transamazonian cycle.

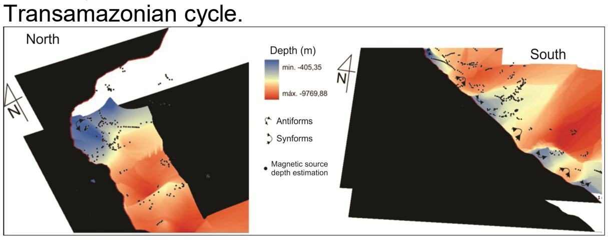

Figure 5: Relationship between magnetic and gravity anomalies, wherein the magnetic source concentrates on the antiform's gravimetric model (modified from Madeira 2016).

The E_2 event (F_3 phase), is understood as the N-S compression deformation that generated soft and open folds from tens to hundreds of meters with the hinge line direction being E-W. The SVSZ surface has been deformed, and synforms and antiforms have developed from N to S (Figure 4). This is a Brasiliano event that represents the collapse of the hanging wall rocks and the nucleation of the Bação metamorphic complex in the Mariana anticline core (Figure 6).

The latest event (E_3) represents the final arrangement of the QFe structures, which amplify the folds and boudins from the F_2 phase, besides generating decametric folds with sub meridian axial orientation. This is a shortening crustal event verging from E to W with a general planar rotation and linear structures developed in previous events. This phase is associated with the development of the Abre Campos suture in the course of the collision between the South American and African plates (Brasiliano event) (Hasui et al., 1993) (Figure 3).

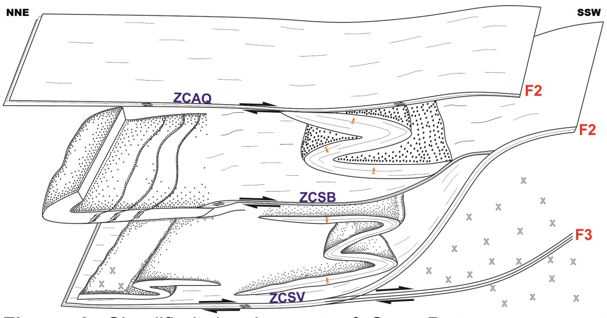

Figure 6: Simplified development of Ouro Preto nappe, east portion of Quadrilátero Ferrífero. F2 – second phase, F3 – beginning of the second event. Orange arrowheads display the direction of geopetal structures.

Conclusions and suggestions

With the integration of structural fieldwork data and the tridimensional geophysical models, it is evident that the more adequate tectonic evolution models for the Quadrilátero Ferrífero (QFe) are those that deal with the development of nappes systems (Barbosa (1949), Pires (1979, 2015), Pericon & Quèmenèur (1982), Endo et al. (2005), Oliveira et al. (2005), Almeida et al. (2005), Rossi & Endo (2014) and Madeira et al. (2014, 2015). The invariable parallelism between the long axis of prolate-shape grains and the fold axis makes clear that this evolution history occurred in an orogeny of higher thermal gradients, which favored both orogeny-parallel elongation and diapirism and the formation of gneiss domes (Sullivan, 2013).

The connection of ground gold occurrences with underground magnetic sources provides the state of the art in gold prospecting in the QFe. The combination of gravity and magnetic tridimensional models shows a coherent concentration of magnetic anomalies in the antiformal structures from the gravity data. This demonstrated the importance in the use of more than one geophysical method to visualize and validate the data.

To improve theses data, it is suggested that geochronology and geochemistry knowledge be applied across the São Vicente shear zone and in the lithological domains recognized.

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References

ALKMIM FF, MARSHAK S. 1998. Tranzamazonian Orogeny In the Southern São Francisco Craton Region Minas Gerais, Brazil: evidence for Paleoproterozoic collisional and collapse in the Quadrilátero Ferrífero. Precambrian Research, 90: 29-58.

ALKMIM FF, MARTINS-NETO MA. 2012. Proterozoic first-order sedimentar sequences of the São Francisco craton, eastern Brazil. Marine and Petroleum Geology, 33(2012): 127-139.

ALMEIDA L.G., ENDO I., FONSECA M.A. 2002. Sistema de nappes na porção meridional do Quadrilátero Ferrífero, MG. In: SBG, Congresso Brasileiro de Geologia, 41, João Pessoa, Anais, p. 615.

ALMEIDA L.G., CASTRO P.T.A., ENDO I., FONSECA M.A. 2005. O Grupo Sabará no sinclinal Dom Bosco, Quadrilátero Ferrífero: Uma revisão estratigráfica. Revista Brasileira de Geociências 35(2005): 1-12.

ANGELI G. 2015. Arcabouço estrutural e contribuição à estratigrafia do Grupo Maquiné, Quadrilátero Ferrífero, Minas Gerais. Dissertação de Mestrado, Departamento de Geologia da Universidade Federal de Ouro Preto.

ARAÚJO JGM. 2001. Influência das zonas de cisalhamento de São Vicente e Tapera na mineralização aurífera do Quadrilátero Ferrífero, Minas Gerais. Dissertação de Mestrado, Universidade de Brasília, 103 p.

BALTAZAR OF, RAPOSO FO. 1993. Folha Mariana SF.23-X-B-I: estado de Minas Gerais. Escala 1:100.000. Brasília: CPRM, 1993. 183p. il. Programa Levantamentos Geológicos Básicos do Brasil – PLGB.

BALTAZAR OF, ZUCCHETTI M. 2007. Lithofacies associations and structural evolution of the Archean Rio das Velhas greenstone belt, Quadrilátero Ferrífero, Brazil: A review of the setting of gold deposits. Ore Geology Reviews 32(2007):471–499.

BALTAZAR OF, BAARS FJ, LOBATO LM, REIS LB, ACHTSCHIN AB, BERNI GV, SILVEIRA VD. 2005. Mapa geológico do Quadrilátero Ferrífero, escala 1:50.000, com Nota Explicativa. In: LOBATO LM et al (Eds). Projeto Geologia do Quadrilátero Ferrífero – Integração e Correção Cartográfica em SIG com Nota Explicativa. Belo Horizonte, CODEMIG.

BARBOSA O. 1949. Contribuição à geologia do centro de Minas Gerais. Mineração e Metalurgia, 14(79): 3-19

BORGES AJ. 1998. Levantamentos geofísicos. In: ZUCCHETTI M, BALTAZAR (Eds.). Projeto Rio das Velhas – Texto explicativo do mapa geológico integrado, escala 1:100.000. 2nd ed. DNPM/CPRM. Belo Horizonte, 11-12 pp.

CHEMALE Jr. F., ROSIÈRE C.A., ENDO I. 1994. The tectonic evolution of the Quadrilátero Ferrífero, Minas Gerais, Brazil. Precambrian Research 65(1994): 25-54.

COOPER GRJ. 2004. Euler deconvolution applied to potential field gradients. Exploration Geophysics, 35:165-170.

COOPER GRJ. 2009. A solution-space approach to the Euler deconvolution of map data. In: 11th SAGA Biennial Technical Meeting and Exhibition Swaziland, 16-18 september 2009, pp.300-302

DEWANGAN P, RAMPRASAD T, RAMANA MV, DESA M, SHAILAJA B. 2007. Automatic interpretation of magnetic data using Euler deconvolution with nonlinear background. Pure and Applied Geophysics, 164(2):359-372

DORR II JV. 1969. Physiographic, stratigraphic and structural development of the Quadrilatero Ferrifero, MG, Brazil. United States Geological Survey Professional Paper 614-A. 110 pp.

DURRHEIM RJ, COOPER GRJ. 1998. EULDEP: a program for the Euler deconvolution of magnetic and gravity data. Elsevier – Computer & Geosciences, 24(6):545-550.

ENDO I., MACHADO R. 1998. The geology architeture of the Quadrilátero Ferrífero (Minas Gerais – Brasil) after multiple transpressional and transtensional tectonic events. In: International Confetence on Basement Tectonics, 14., Ouro Preto, 1998. Anais. p. 126-127.

ENDO I, OLIVEIRA A.H., PERES G.G., GUIMARÃES M.L.V., LAGOEIRO L.E., MACHADO R., ZAVAGLIA G., ROSAS C.F., MELO R.J. 2005. Nappe Curral: Uma megaestrutura alóctone do Quadrilátero Ferrífero e controle da mineralização. In: X Simpósio Nacional de Estudos Tectonicos / IV International Symposium on Tectonics, Curitiba. Boletim de resumos expandidos. p.279-282.

FITZGERALD D, REID AR, MCLENERNEY P. 2004. New discrimination techniques for Euler deconvolution. Manuscript Number: 03-132 << http://www.intrepid-geophysics.com/ig/uploads/papers/2003_FitzGerald_etal_Euler_Discrimination_SAGA2003.pdf >>

FLINN D. 1965. On the statistical analysis of axial distribution diagrams. Newes Jb. Miner, Mh., 54-64.

FRANCO A.S.P. & ENDO I. 2004. Sinclinal Ouro Fino Revisado, Quadrilátero Ferrífero, Minas Gerais: Uma hipótese sobre a sua origem e evolução. Rev. Brasil. Geoc. 34(2): 167-174.

GAIR, JE.1962. Geology and ore deposits of the Nova Lima and Rio Acima quadrangles, Minas Gerais, Brazil: U. S. Geol. Survey Prof. Paper 341-A, 67p.

GHOSH GK, DAS GUPTA R, KHANNA AK, SINGH SN. 2012. Application of Euler deconvolution of gravity and magnetic data for basement depth estimation in Mizoram area. GEOHORIZONZ, 7:13-19.

GITHIRI JG, PATEL JP, BARONGO JO, KARANJA PK. 2011. Application of Euler deconvolution technique in determining depths to magnetic structures in Magadi area, southern Kenya rift. JAGST, 13(1):142-156.

GUILD PW. 1957. Geology and mineral resources of the Congonhas district, Minas Gerais, Brazil. Washington, USGS/DNPM. Professional Paper 290. 89p.

GUIMARÃES D. 1951. Arqui-Brasil e sua Evolução Geológica. Rio de Janeiro, DNPM/DFPM, 314p. (Boletim 88).

HASUI Y. 2010. A grande colisão pré-cambriana do Sudeste Brasileiro e a estruturação regional. Geociências,29(2):141-169. URL:
http://www.revistageociencias.com.br/29_2/Art_1_Hasui.pdf (acesso em 05/08/2015).

HASUI Y., HARALYI N.L.E., Costa J.B.S. 1993. A megaestruturação do Pré-Cambriano brasileiro com base em dados geofísicos e geológicos. Geociências, 12:7-31.

LADEIRA EA, VIVEIROS JFM. 1984. Hipótese sobre a estruturação do Quadrilátero Ferrífero com base em dados disponíveis. Belo Horizonte, SBG/Núcleo Minas Gerais, Boletim 4, 18p.

LASA ENGENHARIA E PROSPECÇÕES S.A. 2001. Relatório final do levantamento e processamento dos dados magnetométricos e gamaespectométricos. Levantamento aerogeofísicos de Minas Gerais, Área 2. Projeto Pitangui – São João Del Rey – Ipatinga. Volume I, Texto técnico.

LOCZY L DE, LADEIRA E.A. 1976. Geologia estrutural e introdução à geotectônica. Ed. Blücher, 528 pp.

MADEIRA, TJA. 2016. Análise geofísica e estrutural da zona de cisalhamento São Vicente, Quadrilátero Ferrífero, MG. Dissertação de Mestrado, Departamento de Geologia da Universidade Federal de Ouro Preto.

MADEIRA T.J.A., ENDO I., BARBOSA M.S.C., NEYER B.O. 2014. Caracterização geofísica e estrutural da principal estrutura mineralizada em ouro na região nordeste do Quadrilátero Ferrífero: Um guia para prospecção. In: Simpósio Brasileiro de Geofísica, 12, Porto Alegre. Anais, CD-ROM.

MADEIRA T.J.A., BARBOSA M.S.C., ENDO I., ANGELI G. 2015. Geofísica profunda (<10.000m) da megaestrutura mineralizada em ouro no greenstone belt Rio das Velhas, Quadrilátero Ferrífero, MG, Brasil. In: XV Simp. Int. Estudos Tect. & IX International Symp.Tectonics. Vitória-ES. Anais. CD-ROM.

MARSHAK S. & ALKMIM F.F. 1989. Proterozoic contraction/extension tectonics of the southern São Fracisco region, Minas Gerais, Brazil. Tectonics 8(3):555-571.

MEGAFÍSICA SURVEY AEROLEVANTAMENTO S.A. 2001. Relatório final do levantamento e processamento dos dados magnetométricos e gamaespectométricos. Levantamento aerogeofísico de Minas Gerais, Área 3. Projeto Morro do Pilar – Serro – Guanhães. Texto técnico.

MUSHAYANDEBVU MF, VAN DRIEL P, REID AB, FAIRHEAD JD. 2001. Magnetic source parameters of two-dimensional structures using extended Euler deconvolution. Geophysics. 66(3):814-823.

OLIVEIRA NV, ENDO I, OLIVEIRA LGS. 2005. Geometria do Sinclinal Gandarela baseada na deconvolução Euler 2D e 3D – Quadrilátero Ferrífero, MG. Ver. Bras. Geof. 23(3):221-232.

PASSCHIER CW, WILLIAMS PR. 1996. Conflicting shear sense indicators in shear zones: the problem of non-ideal sections. Journal of Structural Geology, 18(10):1281-1284.

PERICON H.Z., QUÈMENÈUR J.J.G. 1982. Tectönica de nappes e séries transgressivas no Quadrilátero Ferrífero. In: SBG, Congr. Bras. Geol. 32, Salvador, Anais, 1:153-167

PIRES F. R. M. 1979. Tectonic Regimes of the Quadrilátero Ferrífero, Mg. In Simp. Geolo. Do Craton S. Francisco e suas Faixas Marginais. Anais,...

PIRES F. R. M. 2015. Curral anticline – a puzzling recumbent structure at the northern portion of Quadrilátero Ferrífero, Minas Gerais, Brazil. In: XV Simp. Int. Estudos Tect. & IX International Symp.Tectonics. Vitória-ES. Anais. CD-ROM.

RAMSAY JG. 1967. Tectonics of Halvetic Nappes. In: MCCLAY KR, PRICE NJ (Eds.). Thrust and nappe tectonics. Blackwell, Boston, 293-309 pp.

RAMSAY JG, HUBER MI. 1987. The techniques of modern structural geology: folds and fractures. London, Academi Press, 307 pp.

REID AB. 1995. Euler deconvolution: past, present and future, a review. In: 65th Ann. Internat. Mtg., Soc. Expl. Geophys. Expanded Abstract, 272-273.

REID AB, ALLSOP JM, GRANSER H, MILLET AJ, SOMERTON IW. 1990. Magnetic interpretation in three dimensions using Euler deconvolution. Geophysics,55:80-91.

ROSSI D.Q. & ENDO I. 2015. A structural model of the Fábrica Nova region, Santa Rita syncline, Quadrilátero Ferrífero: flanking folds as a folding mechanism. R. Esc. Minas, Ouro Preto,68(2), 153-162.

SCARPELLI W. 1991. Aspects of gold mineralization in the Iron Quadrangle, Brazil. In: Economics, Geology, Geochemistry and Genesis of Gold Deposits. ed. Ladeira E.A., Proceeding, Rotterdam, A.Balkema, 151-157.

SULLIVAN W. A. 2013. L tectonites. Journal of structural geology. 50(2013):161-175.

TEIXEIRA W, CARNEIRO MA, NOCE CM, MACHADO N, SATO K, TAYLOR PN. 1996. Pb, Sr, and Nd isotope constraints on the Archean evolution of gneissic-granitoid complexes in the southern São Francisco Craton, Brazil. Precambrian Research, 78: 151-164.

THOMPSON DT. 1973. Identification of magnetic source types using equivalent simple models. In: Fall Annual AGU Meeting in São Francisco.

THOMPSON DT. 1982. EULDPH: A new technique for making computer-assisted depth estimates from magnetic data. Geophysics, 47:31-37.

TWISS B, MOORES EM. 1992. Structural Geology. W.H. Freeman and Company, New York. 532 pp.

UHLEIN A. & NOCE C.M. 2012. Quadrilátero Ferrífero. In: Hasui Y., Carneiro C.D.R., Almeida F.F.M., Bartorelli A. (eds) Geologia do Brasil. São Paulo: Beca, 228-229.

XYPOLIAS P. 2010. Vorticity analysis in shear zones: A review of methods and applications. Journal of Structural Geology, 32(2010):2072-2092.

ZAVAGLIA, G. 1995. Condicionantes geológicos do comportamento dos minérios de ferro do depósito de Tamanduá (MG) no processo metalúrgico de redução direta. Dissertação de mestrado, Departamento de Geologia da Universidade Federal de Ouro Preto, 200p.

Zucchetti M, baltazar OF, RAPOSO FO. 1998. Estratigrafia. In: ZUCCHETTI M, BALTAZAR OF (Eds.), Projeto Rio das Velhas–Texto explicativo do mapa geológico integrado, escala 1:100.000. 2nd ed. DNPM/CPRM–Serviço Geológico do Brasil, Belo Horizonte, p. 13–42