Amalgamation of different crustal blocks in the Southernmost Part of the São Francisco Craton constrained by airborne geophysical data, Brazil

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This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Abstract

The southern part of the São Francisco Craton (SFC) is characterized by limited outcrops, deep weathering and thick regolith cover and lack of systematic mapping. Although previous petrographic, geochemical and geochronological data analysis has led to the definition of several metamorphic complexes and supracrustal sequences in this part of the SFC, many questions about its geologic evolution remain unanswered.

This area is covered by high-resolution aeromagnetic and aerogamaespectrometric data. The geophysical images provide an overview of the partly migmatized gneissic rocks, greenstone belts, granitoid plutons, mafic and ultramafic intrusions (including dolerite dykes), and sets of faults that disrupt Archean and Paleoproterozoic lithological associations.

In this paper, these geophysical data were successfully used to highlight the relationships between the principal crustal blocks, as well as their internal structures and boundaries. Enhancement of gamma-ray spectrometry data showed their usefulness in mapping subtle compositional variations in the area, which concur with and complement available geological data.

Introduction

The southern portion of the São Francisco Craton (SFC), located in the southeastern part of Brazil (Minas Gerais State), is considered one the most prominent tectonic environments in Brazil, including rocks and structures ranging from the Mesoarchean up to the late Neoproterozoic. This area comprises throndjemitic-tonalitic-granitic suites, greenstone belts, granitoid plutons, mafic/ ultramafic intrusions and ductile structures that both shape the geometry and cross-cut Archean and Paleoproterozoic geologic units.

Early petrographic, geochemical and geochronological investigations defined several metamorphic complexes and metamorphic equivalents of volcano-sedimentary sequences in this region. Teixeira *et al.* (2000) summarized the available data on composition, structure and geochronology for the southern SFC, providing regional distinctions among Archean and Paleoproterozoic lithological associations. However, the boundary relationships of several regional units are often obscured in the field, thus limiting current tectonic interpretations. Information yielded from airborne geophysics maybe useful in this scenario for their ability to overcome shallow covers and to provide information on deep, sub-surface rock packages and structure. In particular, airborne gamma-ray spectrometric data are often successfully used as a tool to aid lithological mapping – there is always a good correlation between patterns in the radiometric data and non-weathered rocks or in areas of poor outcrops (Gunn *et al.* 1997, Golysnky & Jacobs 2001). Such observations, if possible in the southern SFC, can foster the understanding of the crustal evolution of this region.

In this paper, an integrated interpretation of airborne magnetic and gamma-ray plus geological data is achieved and used to portray the actual and detailed arrangement of crustal blocks in the southernmost part of the SFC.

Geological Setting

The southern portion of the SFC is composed of Archean throndjemitic-tonalitic-granitic (TTG) complexes; greenstone belts (Rio das Velhas, Barbacena, Fortaleza de Minas, Piumhí, Congonhas and Rio Paraúna); Paleoproterozoic (Minas Supergroup and Itacolomi Group) and Paleoproterozoic-Mesoproterozoic (Espinhaço Supergroup) supracrustal units, as well as mafic-ultramafic and mafic intrusives (Figure 1).

The TTG complexes consist of poly-deformed gneiss, metatonalites to metagranites, amphibolites, and meta-ultramafic rocks formed in amphibolites facies conditions during the Archean and the Paleaoproterozoic (Cordani *et al*. 1980, Teixeira *et al*. 2000). The oldest TTG rocks are comprised in the Campo Belo Complex, with U/Pb ages ca 3.2 Ga (Teixeira *et al*. 1998). Gneissic domes are also abundant within the Quadrilátero Ferrífero (QF) area, including the Bação, Caeté, Bonfim, Belo Horizonte, Santa Rita and Pará de Minas complexes. The contact of these domes with adjacent supracrustal rocks is usually tectonic and they are surrounded by troughs containing Rio das Velhas and Minas Supergroups sequences (Alkmim & Marshak 1998).

Several remnants of greenstone belts occur within these TTG complexes and many of them have been correlated to the Rio das Velhas Supergroup (Teixeira *et al*. 2000). Fortaleza de Minas, Piumhí, Congonhas and Rio Paraúna are exposed within Paleoproterozoic and Neoproterozoic orogenic belts (Figure 1). The Rio das Velhas Supergroup (RVSG – 3.0-2.7 Ga) is divided in two groups. The stratigraphic lower, Nova Lima Group (NLG) comprises a lower ultramafic unit, an intermediate felsic-mafic unit and an upper clastic unit of mafic-to-felsic provenance (Ladeira 1980). This volcano-sedimentary unit hosts the main gold deposits of the QF area. The NLG is overlain by metassediments of the Maquiné Group. The Barbacena greenstone belt (BGB) occurs as narrow bands usually limited by intrusive Paleoproterozoic granitoid and gabroic plutons (Figure1). The BGB contains a typical ocean basin lithological associations consisting of mafic and ultramafic komatiitic and tholeitic lavas (Noce *et al*. 1987, Toledo 2002).

Mafic-ultramafic layered intrusives were emplaced into the Campo Belo gneiss - Ribeirão das Motas intrusives (Carneiro *et al*. 1997) and into the BGB and RVSG sequences (Pinheiro & Nilson 2000, Toledo 2002). They comprise mainly alternate igneous layers of peridotite and pyroxenite with euhedral crystals and cumulus textures.

A NW-SE swarm of noritic-gabbroic dykes cuts these mafic-ultramafic layered intrusives, as well as their country rocks (Pinese 1997). The dykes are locally overlaid by remnants of ferruginous quartzites (Teixeira *et al*. 2000). Some of these dykes are up to 30km long and 100m wide and shows a Sm/Nd isochron age of 2.658 ± 0.44 Ga (Pinese 1997).

The Minas Supergroup is an ubiquitous Paleoproterozoic sedimentary succession, mainly exposed in the QF area, but also extending southwestwards, towards the city of Bom Sucesso (Figure 1, Teixeira *et at*. 2000, Toledo 2002).

Data concerning the earliest events that generated the continental crust in this region are fragmented. Many lithotypes that constitute the sialic crust of the southern part of the SFC have been dated by different radiometric methods (Cordani *et al* 1980, Teixeira 1985, Machado *et al*. 1992, Machado & Carneiro 1992, Carneiro *et al*. 1996, Noce *et al*. 1997, Teixeira *et al*. 2000), yielding evidence for an Archean crustal evolution older than 3.1 Ga (U/Pb and Sm/Nd data). The Rio das Velhas orogeny (2.78 Ga, Carneiro *et al*. 1997) fostered terrane assembly concomitantly with regional anphibolite facies metamorphism. Neoarchean tectonics are linked to major, regional extension episodes, leading to the emplacement of the Ribeirão das Motas mafic-ultramafic intrusives and gabro-noritic dykes, with simultaneous late tectonic granitic emplacement and cratonization (Teixeira *et al*. 1998).

The Transamazonian Orogeny (2.16-2.0) developed at the margins of the Archean continent in the southern part of the SFC (Teixeira & Figueiredo 1991). Linked to this orogeny are the evolution of the Mineiro mobile belt, which formed granitoid and alkaline plutons, mafic dykes, as well as by the metamorphism of the Minas Supergroup and parts of the Archean Crust. (Teixeira & Figueiredo 1991, Texeira et al. 2000). Alkmim & Marshak (1998) proposed a two-stage model for the evolution of the Mineiro Belt. Firstly, a fold-thrust belt was created in response to a NW-verging contraction related to the accretion of an island arc and/or exotic terranes on the southeastern margins of the SFC. Secondly, an orogenic collapse of the fold-thrust belt occurred and triggered the development of a dome-and-keel structure, which is a dominant structural feature in the QF area.

Data

The Pitangui-Ipatinga São João Del Rey airborne project used in this study was surveyed with two Cessna aircrafts at a constant ground clearance. The airborne data were acquired using 250 m spaced flight lines with orthogonal tie lines flown every 2.500 meters at 100 meters above the ground surface. The survey was carried out in two different blocks with different flight- and tie-line directions, keeping data acquisition perpendicular to the main structures of the surveyed area (Lasa 2001).

The magnetic system used was an optically pumped (cesium vapor) magnetometer, installed in a stinger extension behind the tail of the aircraft, G822-A. The output from the magnetometer was sampled at 0.1s to a resolution of 0.001 nT with a noise envelope less than 0.01 nT. The EXPLORANIUM spectrometer, model GR-820, employed 256 spectral channels and consisted of two downward looking groups of crystals (Thallium-doped NaI) of 1024 cubic inches each (for a total of 2048 cubic inches of detector volume), and two upward looking crystals of 256 cubic inches each (for a total of 512 cubic inches; LASA 2001).

Methods

This section gives an overview of the processing of airborne data in the named Pitangui-Ipatinga São João Del Rey project, referring to different methodologies used in this work. The Oasis Montaj software, version 5.07 of GEOSOFT^{TM}, was used in the processing and visualization steps applied to this data.

The magnetic data was expressed as the anomalous magnetic field, or in other words, as the total measured field corrected for the diurnal variation, the main geomagnetic field (IGRF), and leveling errors. The gamma spectrometry data were discriminated into energy channels with reference to the total energy (total count channel, which was expressed in mR/hr), while the potassium channels were expressed in percentage. The uranium and thorium channels were expressed as micro-equivalents and corrected for dead-time; energy variations (spectral stabilization) of the respective background levels of radiation; altitude variations relative to the nominal value for the Project; and for scattering due to the Compton effect.

In the next processing step, the data was interpolated in a regular grid, using the appropriate algorithms to maintain data fidelity to the original sample locations. This was followed by correction of spurious effects caused by the leveling of the original grids. The fourth difference technique was used to track anomalous spikes in the magnetic data and to condition sampling along the flight lines for the spatial Nyquist frequency. This was performed on the selected interpolated grid; i.e., square, 100m on a side, resampled at 50 m. The algorithm was based on a linear interpolation along the direction of the flight lines, and on the Akima spline perpendicular to the flight lines. Microlleveling and decorrugation techniques were further applied to the data, producing several geophysical products (individual and composite thematic maps) for geologic analysis and interpretation.

The analysis of the variation of the anomalous magnetic field was aided by its linear transformations principally that dealing with the amplitude of the analytic signal (orders 0, 1, and 2), which are a critical products to locate the spatial distribution of magnetic sources. The uses of derivatives, principally the first vertical, helped to determine the spatial positions of these sources, and were also extremely useful to characterize linear features. The horizontal derivatives further allowed the mapping of lateral limits of these same sources. All of these steps were guided by the analysis of the radial power spectra of the anomalous magnetic field.

The gamma-spectrometric data (channels TC, K, U, and Th) were also interpolated into a regular grid and microlleveled. The methodology used in the interpretation of these data involved: a) comparison of each micro-leveled grid with digital terrain data, verifying zones where topography influenced the gamma-spectrometry response; b) analysis of the total count channel and other individual channels to define major gamma-spectrometric domains; c) K, Th, and U channels displayed as RBG and CMY false-color maps (ternary images), optionally merged with digital terrain data; and d) computation of U/Th, Th/K, and U/K ratios and analysis of their correlation with gamma-spectrometric domains.

Interpretation of the geophysical images

The integration of information generated by the interpretation of the magnetic and gamma-spectrometric data allowed the discrimination of several litho-structural domains. Each block was analyzed and compared with the available overall geological data for the SFC, which are found at smaller scales than that of the airborne survey. This implies that the information derived from the geophysical data contains much more detail than the existing maps.

The best interpretations of the southernmost part of the SFC were achieved from visual analysis of the ternary radioelement map (Figure 2), the thorium channel map and the analytical signal amplitude map (Figure 3). These maps highlighted key crustal blocks of the SFC and their unique inter-relationships. We recognized the following blocks that illustrate distinct periods of crustal evolution: a) Campo Belo Methamorphic Complex (3.2, SHIRIMP U/Pb zircon, Teixeira et al. 1998, A in the image); b) Bonfim Methamorphic Complex (2.92-2.7 Ga, U/Pb zircon, Carneiro 1992); c) the Paleoproterozoic Mineiro mobile belt (2.2-2.0 Ga, Alkmim & Marshak 1998, Brueckner et al. 2000) that include exotic terranes on the southeastern margins of the SFC and the dome-and-keel structures of the QF (Alkmim & Marshak 1998); d) a Neoproterozoic marginal mobile Belt that encompasses the Dom Silvério shear zone (Araçuaí Belt, Pedrosa Soares et al. 1999b), e) an easternmost block that represents the external tectonic domain of the Araçuaí Orogeny, composed by gneiss and granulitic rocks (Peres & Alkmim 2003); and f) a small part of possible different block, defined by its geophysical signature, showing a structural pattern akin to the Araçuaí Belt.

Several structural features are well enhanced in these images, mainly inner in the Archean domain. A dominantly EW trend in the Bom Sucesso region is evidenced against a NW oriented structures in the Itapecirica and Bonfim areas. Also, complex fold interference pattern are displayed in this area and NE trending shear zones cross cut the oldest structures. The dykes swarm present in the Archean nuclei appears to stop at the boundary with the Mineiro Belt. Some of them, which show crossing the two blocks probably, represent youngest mafic dykes (Silva et al. 1995). A NS fold Belt related to the Araçuaí Orogeny is well evidenced in easternmost part of studied area.

Synthesis

Images derived from the Pitangui-Ipatinga São João Del Rey project provided powerful insights about the tectonic assembly of the SFC throughout the Precambrian, reflecting distinct episodes of crustal accretions and/or crustal reworking (Schrank & Souza Filho 1998; Carneiro et al. 1998, Teixeira et al. 2000).

The gamma-ray response over the study area shows broad correlation with rock units. However, subtle compositional variations and different structural patterns were outstandingly assessed through gamma-spectrometric images (Figures 1 and 2). Combined gamaspectrometric-magnetic images portrayed the lateral continuity and the internal structure of several terranes, particularly the location and geometry of the terrane boundaries. The clearest boundary is that between the Archean core and the Mineiro Belt (Figures 1 and 3). By geophysical contrast, it was possible to separate another block in southeastern portion of the study area. The geologic meaning of this block and its relation to neighbor units is yet unclear and further work is needed to clarify it.

The magnetic images highlighted a clear distinction between the QF and surrounding areas, as a function of the fundamental contrast between highly frequency/amplitude magnetic anomalies of the QF and the generally less magnetic crust of the other accreted terranes in the SFC.

Acknowledgments

Geophysical data are published with the permission of COMIG (State Geological Survey of Minas Gerais). We are thankful to Dr. Marcelo Nassif and Andrea Vaz de Melo França for their distinguished support. This research was funded by FAPESP (State Foundation of São Paulo), through project No. 2002/090038. A.M. Silva acknowledges FAPESP for the post-doctoral grant (Proc. 2001/13350-2) and C.R. Souza Filho acknowledges CNPq for the research grant (Proc. No. 301227/94-2).

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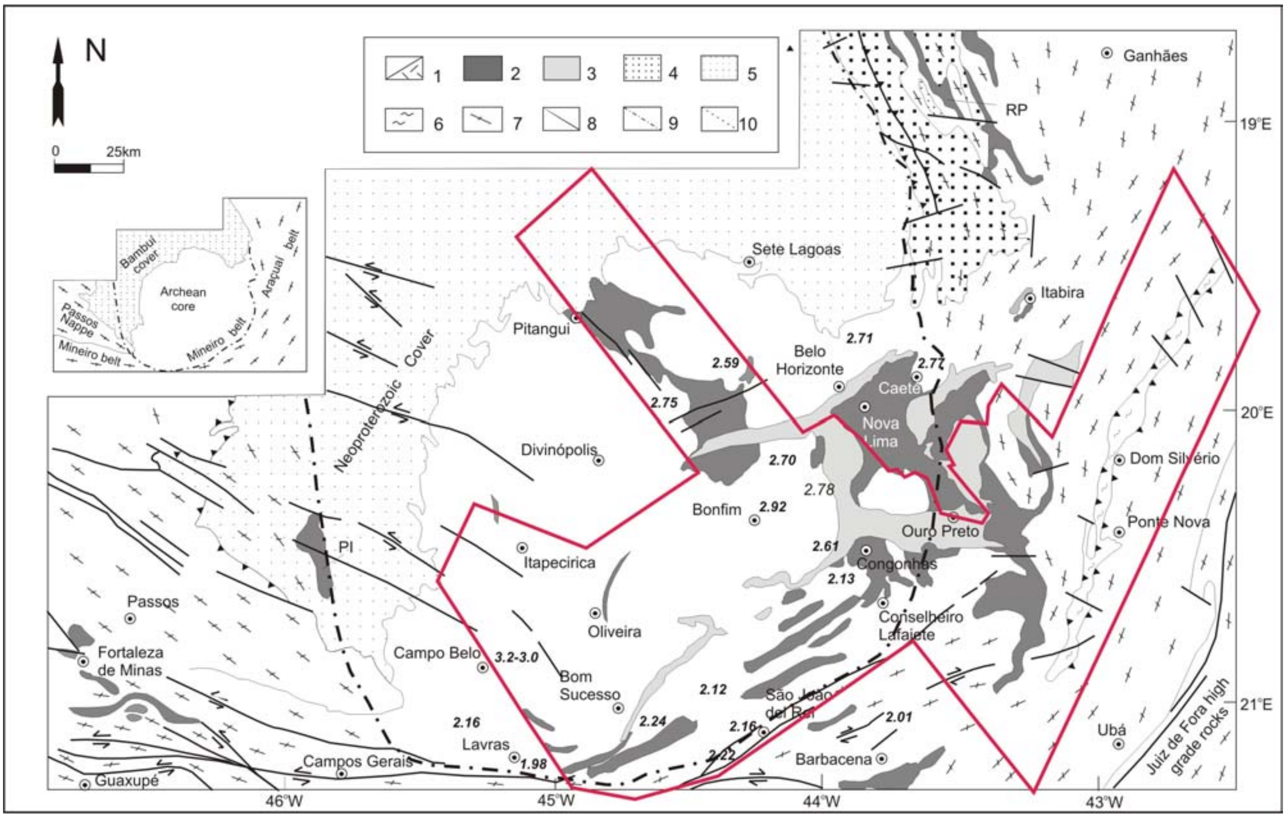

Figure 01- Geological sketch map of the southern part of the SFC, showing the Archean and Paleoproterozoic terranes, as well as the Neoproterozoic, marginal orogenic belts (modified from Teixeira *et al*. 2000). The red polygon is the area covered by the Ipatinga São João Dey Rey Airbone Geophyical Project. 1 – granitoid-gneiss-migmatite rocks and granulite, partially reworked in the Paleoproterozoic (Archean); 2- Greenstone Belts; 3-Minas Supergroup (Paleoproterozoic); 4-Espinhaço rift system (Paleo to Mesoproterozoic); 5-Bambuí Cover (Neoprotezoic); 6-Shear zone/shear belt; 7-Brasiliano structures of the marginal belts (Araçuaí, southern Brasília and Passos nappe), partly overprinting crystalline basement rocks (>1.8Ga), 8- major faults; 9-Limit of the Craton; 10- Gneiss foliation. Keys: PI, RP, FM, CO= Piumhí, Rio Paraúna, Fortaleza de Minas and Congonhas Greenstone belts; DS-Dom Silvério Group (Neoproterozoic).

Figure 2- Enhanced three band CMY gamma-ray spectrometric image (KthU). A) Campo Belo Complex; B) Bonfim Complex, C) Mineiro mobile belt. D) Araçuaí Belt, E) external tectonic domain of the Araçuaí-West Congo Orogen and F) a small part of a possible (?) different block.

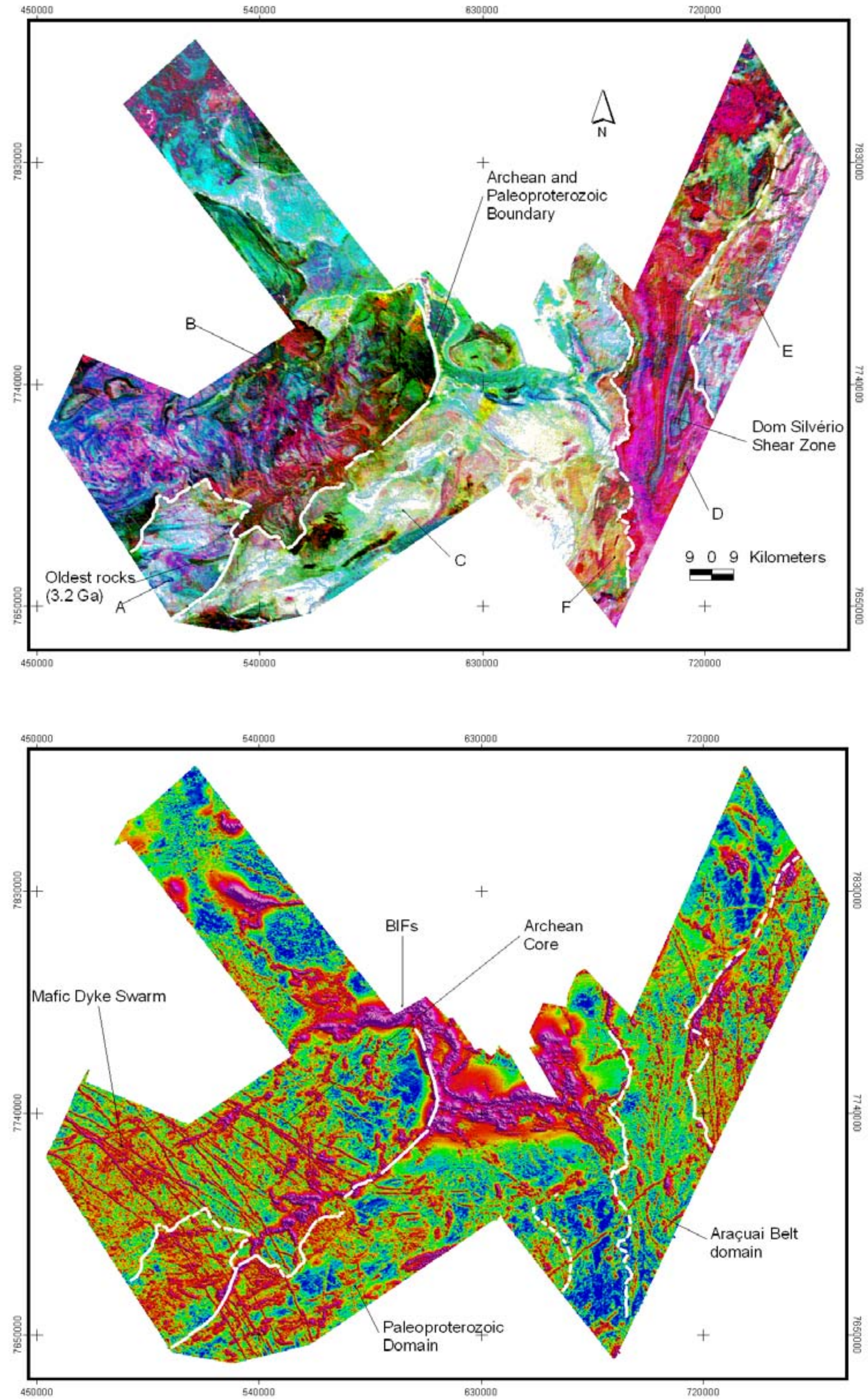

Figure 3- Analytical signal amplitude image of the southernmost part of the SFC.