




NEW KNOWLEDGE UPDATE ON MAFIC DYKE SWARMS OF MINAS GERAIS (BRAZIL): FRAGMENTS OF ANCIENT LARGE IGNEOUS PROVINCES HIGHLIGHTED BY AEROMAGNETOMETRY

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ABSTRACT. Mafic dyke swarms can be related to important geological events such as the activity of mantle plumes, the formation of large igneous provinces (LIP), the break-up/dispersing of supercontinents or they can even be related to orogenic compressional settings. Updated and available aeromagnetometric, geological, geochemical and geochronological information confirms the existence of seven mafic dyke swarms of basaltic composition in the State of Minas Gerais (Brazil). Six of them (Archean Lavras swarm, Paleoproterozoic Pará de Minas – now understood as subswarms I/II – and Januária – previously understood as Mesoproterozoic in an incorrect way – swarms, Neoproterozoic Formiga swarm, Mesozoic Transminas and Santos-RJ or Serra do Mar swarms) are representative of crustal extensional settings and remnants of ancient LIPs, many of which are associated with mantle plumes and with the formation of important sedimentary basins stored in Minas Gerais. One swarm (Paraopeba) has genesis linked to compressional setting during Transamazonian (Rhyacian-Orosirian) Orogeny.

Keywords: magnetometry, mafic dykes, compressional and extensional settings, LIP, mantle plumes, São Francisco Craton, mobile belts.

RESUMO. Enxames de diques máficos podem estar relacionados a eventos geológicos importantes, como a atividade de plumas do manto, a formação de grandes províncias ígneas (LIP), a quebra/dispersão de supercontinentes ou mesmo a ambientes compressoriais orogênicos. Dados atualizados e disponíveis de aeromagnetometria, geologia, geoquímica e geocronologia confirmam a existência de sete enxames de diques de composição basáltica no estado de Minas Gerais (Brasil). Seis deles (enxame Lavras de idade Arqueana; enxames Pará de Minas e Januária de idade Paleoproterozoica – Januária era incorretamente entendido anteriormente como Mesoproterozoico e Pará de Minas é agora entendido como subenxames I/II; enxame Formiga de idade Neoproterozoica; enxames Transminas e Santos-RJ ou Serra do Mar de idade Mesozoica) são representantes de regimes extensionais da crosta continental e remanescentes de antigas LIPs, muitas das quais são associadas com plumas mantélicas e com a formação de importantes bacias sedimentares em Minas Gerais. Um enxame (Paraopeba) tem sua origem relacionada a regime compressional durante o Ciclo Orogênico Transamazônico (Riaciano-Orosiriano).

Palavras-chave: magnetometria, diques máficos, regimes compressoriais e extensionais, LIP, plumas mantélicas, Craton São Francisco, cinturões móveis.

INTRODUCTION

Basaltic mafic dykes occur in the earth's crust in a wide variety of geotectonic scales and environments, including continental shields. They represent high-angle or vertical tabular conduits used in the way of the mantle magma through the crust, in many cases extruding onto the surface in the form of large igneous provinces (LIP), many of which are related to episodes of mass extinction. Swarms of basaltic mafic dykes can be related to important geological events such as the activity of mantle plumes and the break-up/dispersing of supercontinents, that is, to large extensional events. The restoration of the radiating patterns of dykes of same age can also help in reconstructing ancient supercontinents. Swarms also represent stratigraphic markers per million square kilometers as they go through certain groups of rocks and not others and eventually can be related to orogenic compressional settings (Oliveira & Montes, 1984; Halls & Fahrig, 1987; Parker et al., 1990; Ernst et al., 1995; Chaves & Neves, 2005a; Chaves, 2021).

Although most rock-forming minerals are non-magnetic, certain rock types like basaltic rocks contain enough magnetic minerals to produce significant geophysical anomalies. The magnetic susceptibility contrast between basaltic mafic dykes and their enclosing rocks can enable dyke discrimination (Kearey et al., 2009).

With new geological information available during and after the work of Chaves (2013), this article presents the knowledge update on mafic dyke swarms of Minas Gerais, using not only the georeferenced aeromagnetic information produced by CODEMIG-ANP-CPRM (Fig. 1) and elaborated by Borges (2012), but also field, petrographic, geochemical and geochronological data available in the literature, such as the Espinhaço (COMIG-UFMG/IGC-CSR, 1997) and Alto Paranaíba (CODEMIG-UFMG, 2011) projects and published articles (Lima et al., 1984; Machado et al., 1989; Dussin, 1994; Turner et al., 1994; Silva et al., 1995; Pinese, 1997; Novais et al., 2003; Carneiro & Oliveira, 2005; Chaves & Neves, 2005b; Costa et al., 2006; Seer et al., 2011;

Chaves, 2011; Chemale Jr et al., 2011; Chaves et al., 2014; Chaves, 2014a,b; Cederberg et al., 2016; Coelho & Chaves, 2017; Chaves & Dussin, 2018; Chaves et al., 2019; Chaves & Rezende, 2019; Caxito et al., 2020; Moreira et al., 2020). This compilation is summarized below in the form of a map of the seven mafic dyke swarms of Minas Gerais (Fig. 2) and their respective information is presented in the next section of the manuscript.

KNOWLEDGE UPDATE

In the State of Minas Gerais (MG) there are several dyke swarms with ages ranging from Archean to Cretaceous (Turner et al., 1994; Silva et al., 1995; Pinese, 1997; Chaves & Neves, 2005b; Carneiro & Oliveira, 2005; Chaves, 2011; Cederberg et al., 2016; Coelho & Chaves, 2017; Chaves & Dussin, 2018; Chaves et al., 2019; Chaves & Rezende, 2019; Caxito et al., 2020; Moreira et al., 2020), sometimes crossing the São Francisco Craton (SFC), sometimes crossing its Neoproterozoic mobile belts or both (Fig. 2). When outcropping, its rocks usually appear superficially in the form of centimetric to metric-size rounded and weathered blocks or eventually dykes are well preserved in natural drainages or roads (Fig. 3). Chaves & Neves (2005b) have published one of the first compilation articles on the subject with support not only on geological, petrographic, geochemical and geochronological data, but also on aeromagnetic information produced by CODEMIG (Company of Economic Development of Minas Gerais, previously named as COMIG). In 2000/2001, CODEMIG surveyed 5 priority areas with 250 m spacing between flight lines and a total surface of 78000 km², which corresponded only to 14 % of the surface of the State of Minas Gerais. However, in 2005/2006, 3 more areas were surveyed with 400 and 500 m spacing between flight lines and a total surface of 119000 km² and, in 2008/2009, 5 areas were surveyed with 500 m spacing between flight lines and a total surface of 140000 km², which corresponds to 45 % of the surface of the State of Minas Gerais.

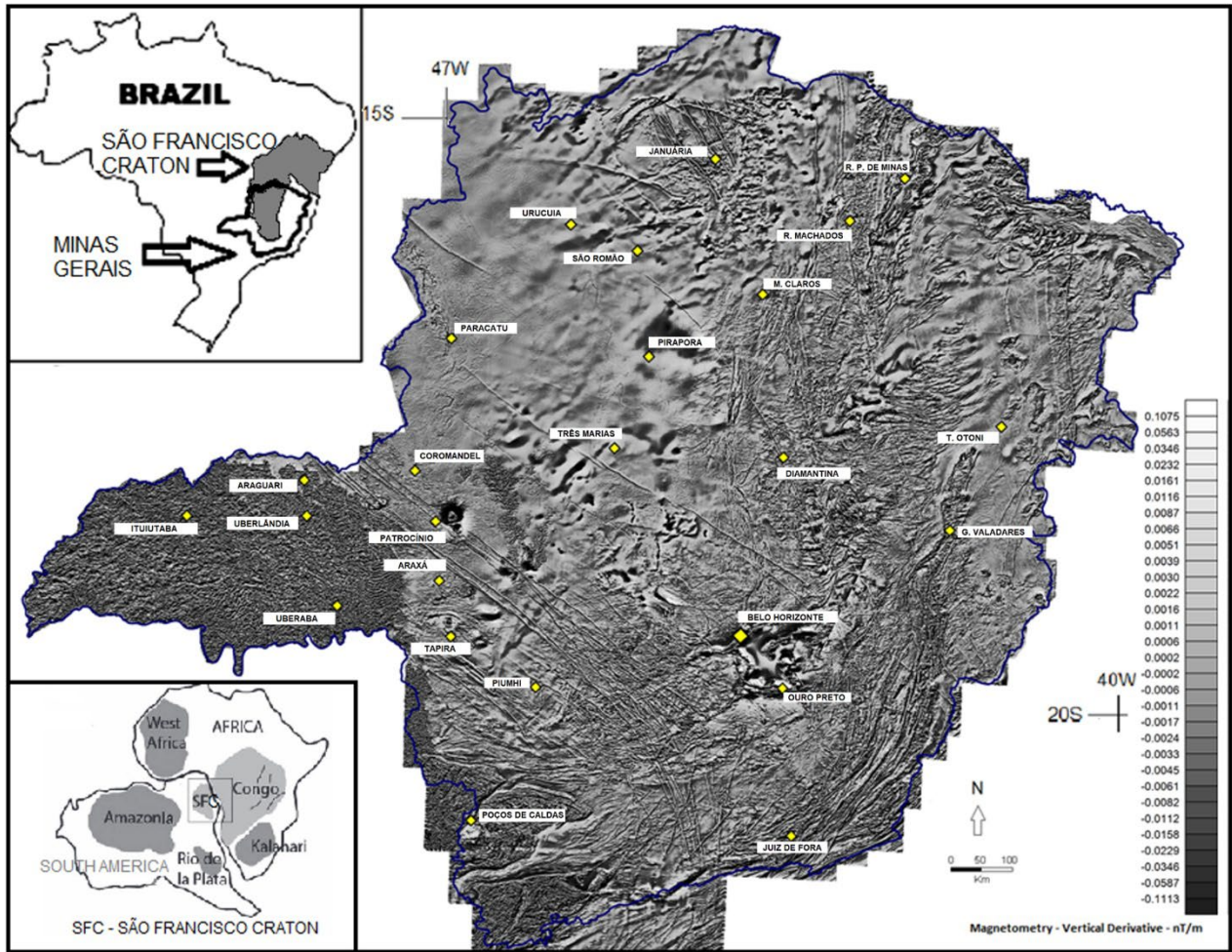


Figure 1 - First vertical derivative image of the total magnetic field of Minas Gerais (prepared by Borges, 2012, with details of resolution, aerial database, flight lines spacing, processing, interpolation method, and cell size adopted for grid generation described in Gomes, 2021) from areas surveyed by CODEMIG-ANP-CPRM between 2001 and 2012. Many lineaments represent mafic dykes. Cratons from South America and Africa are highlighted in inset low-left corner illustration.

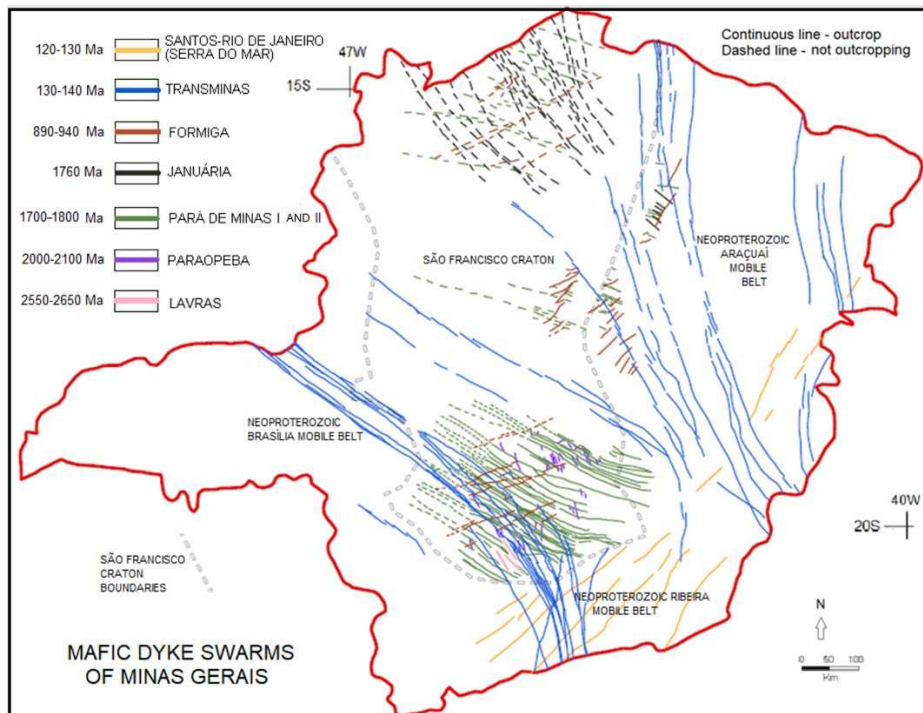


Figure 2 - The seven mafic dyke swarms of Minas Gerais (modified from Chaves, 2013).

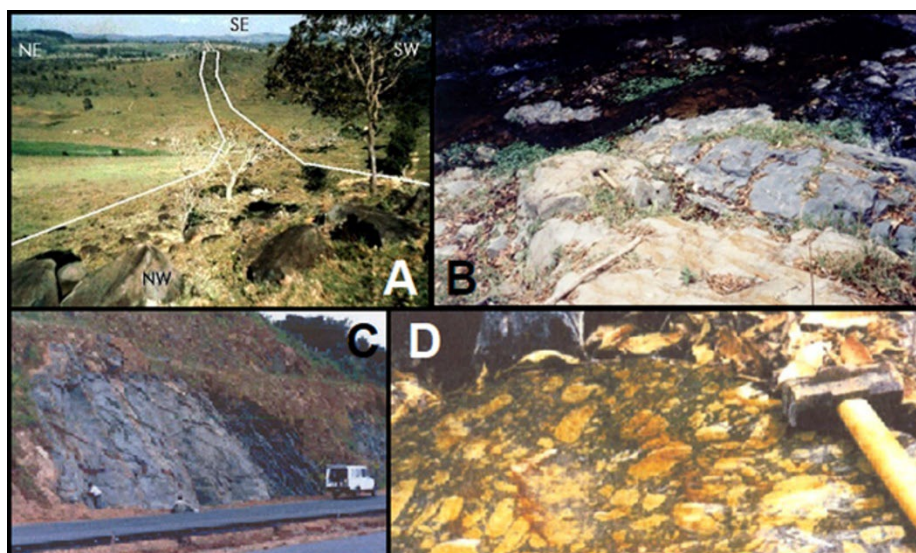


Figure 3 - Typical outcrops of mafic dykes in Minas Gerais (adapted from Chaves, 2013). **A** - Rounded and dispersed blocks on the ground. White lines have been added to demarcate the dyke boundaries. **B** - Contact of dyke (dark rock) with gneiss (light rock) in natural drainage. The darkest part in the upper portion of the photo is the watercourse. **C** - 50 m width mafic dyke. **D** - Porphyritic mafic dyke with plagioclase phenocrysts.

Along with new areas in the state launched in 2012 by CODEMIG, ANP (National Petroleum Agency) and CPRM (Geological Survey of Brazil) this aeromagnetic information was not used in the article by Chaves & Neves (2005b). This large volume of data represented in Figure 1 (whose details of resolution, aerial database, flight lines spacing, processing, interpolation method, and cell size adopted for grid generation are described in Gomes, 2021) represents an important tool in identifying dyke swarms of Minas Gerais and their relationships to ancient LIPs, which are predominantly basaltic magmatic provinces (eventually keeping ultramafic and silicic components), with igneous volumes $>0.1 \text{ Mkm}^3$ and areal extents $>0.1 \text{ Mkm}^2$ that have intraplate tectonic settings. Mafic dykes are, in this case, key portions of LIPs that radiate from a magma center usually linked to mantle plume activity (Bryan & Ernst, 2008).

The seven mafic dyke swarms of Minas Gerais are described below and the nomenclature of the swarms follows that used by Chaves & Neves (2005b).

Santos-Rio de Janeiro or Serra do Mar (120-130 Ma)

The predominant direction of the Santos-RJ or Serra do Mar dyke swarm is N40-50E. It is

possible to find outcropping bodies in the south and east of MG that reach more than 100 km in length and up to 90 m in width (average of 30 m). The petrography consists of phaneritic fine to medium-grained gabbro/diorite (diabase) to basalt (sometimes vitrified), with ophitic to subophitic texture. The main minerals are plagioclase, augitic clinopyroxene, magnetite, ilmenite and apatite. The rocks are classified as tholeiitic andesi- to lati-basalts, but there are alkali-basalts (Turner et al., 1994, Pinese, 1997).

It crosses lithotypes from the Ribeira and Araçuaí Brasileiro Mobile Belts. The geotectonic environment of Santos-RJ dyke swarm is a Cretaceous intracontinental rifting (extensional setting) related to the Paraná-Etendeka LIP and to the opening of the South Atlantic during Gondwana fragmentation (Coelho & Chaves, 2017).

Transminas (130-140 Ma)

The Transminas dyke swarm has trending N to NNW in the Ribeira and Araçuaí Belts, deflecting to NW in the SFC, where the dykes follow the direction of the Pará de Minas and Januária swarms. Its bodies cross Minas Gerais over 500 km long and 30 m wide. It ranges from fine to medium-grained phaneritic gabbro (diabase) to

basalt (sometimes vitrified), with an intergranular to subophitic texture and the mineralogy is characterized by the presence of plagioclase, augitic clinopyroxene and some olivine. Magnetite, ilmenite and rare apatite occur dispersed throughout the rock. In some bodies there are millimetric plagioclase phenocrysts. As a post-Brasiliano Orogenesis unit, its dykes show non-existent deformational features. The rocks of this dyke swarm are geochemically classified as tholeiitic andesi-basalts (Lima et al., 1984; Dussin, 1994; Novais et al., 2003; Chaves & Neves, 2005b; Seer et al., 2011).

The Transminas swarm does not cross the Upper Cretaceous Mata da Corda Group, but it crosses older SFC covers (e.g. Bambuí Group), as well as the Araçuaí and Ribeira Brasiliano Mobile Belts. Its geotectonic setting consists of a Juro-Cretaceous intracontinental rifting (extensional setting) related to the Paraná-Etendeka LIP and to the opening of the South Atlantic during Gondwana fragmentation (Chaves, 2014b; Coelho & Chaves, 2017).

Formiga (890-940 Ma)

Formiga is an N50-70E dyke swarm with outcropping bodies in southern SFC and Araçuaí Belt. They extend under the Neoproterozoic and Phanerozoic covers of the SFC in Minas Gerais and the dykes reach 150 km in length with an average width of 40 m. The main rocks are gabbrodiorites (diabases) with ophitic to intergranular texture and basaltic edges. There are porphyritic bodies, with plagioclase phenocrysts of up to 5 cm, and some bodies keep felsic differentiates. The mineralogy is composed of augite (uralitized edge), saussuritized plagioclase, opaque, biotite, apatite and quartz. They are metadiabases on the eastern edge of the SFC (metamorphism related to the Brasiliano Orogenesis) and are classified as basalts and tholeiitic andesi-basalts (Machado et al., 1989; Chaves & Neves, 2005b; Carneiro & Oliveira, 2005; Chaves et al., 2014, 2019; Chaves & Dussin, 2018; Caxito et al., 2020; Moreira et al., 2020).

This swarm crosses the Lower and Upper Espinhaço Group (Chemale Jr et al., 2011) and does not cross the Macaúbas and Bambuí Groups. The dykes and sills from the Pedro Lessa metabasic suite are correlated to the Formiga swarm. Its environment consists of a Tonian intracratonic rifting (extensional setting) correlated to Dashigou-Chulan LIP of North China craton. The intrusion of the Formiga swarm has a relationship with the formation of the Macaúbas Basin (Chaves et al, 2019; Caxito et al., 2020).

Januária (1760 Ma)

Previously understood as Mesoproterozoic in an incorrect way (Chaves, 2013), the Paleoproterozoic Januária dyke swarm has predominant direction N20-50W. It is notable by aeromagnetometry under the Neoproterozoic and Phanerozoic covers of the SFC, practically not outcropping. Diabase (dolerite) with preserved phaneritic subophitic igneous texture was collected close to Januária (Minas Gerais), at the central part of the SFC. In this place, the Januária swarm is only exposed in a small area but can be traced under cratonic cover. The overall extent of the swarm is estimated as 500 km by 250 km based on aeromagnetometry. The dykes reach more than 200 km in length and have an average width of 40 m (Chaves & Rezende, 2019). However, according to the outcropping in the Porteirinha Archean Complex (north of Minas Gerais), it is shown as metadiabases with tremolite/actinolite, epidote, clinozoisite/zoisite, and chloritized biotite, a paragenesis of high greenschist facies related to the metamorphism of Brasiliano Orogenesis. The geochemical classification is not known (COMIG-UFMG/IGC-CSR, 1997; Chaves & Neves, 2005b; Chaves & Rezende, 2019).

The Januária swarm does not cross the Macaúbas and Bambuí Groups, but it probably crosses Bandeirinha Formation of Espinhaço Supergroup. Sthaterian intracratonic rifting (extensional setting) associated with mantle plume correlated to Timpton LIP of Siberia craton and to the formation of the Espinhaço Basin in Minas Gerais characterize its geotectonic scenario (Chaves & Rezende, 2019; Chaves, 2021).

Pará de Minas I (1800 Ma) and II (1700 Ma)

Pará de Minas I and II are now understood as side by side N60W dyke swarms with outcropping bodies in southern SFC. They extend under Neoproterozoic and Phanerozoic covers throughout the SFC in Minas Gerais. The dykes reach more than 400 km in length and up to 100 m in width (average 50 m). The main rocks are gabbro-diorites (diabases) with ophitic to subophytic texture and basaltic edges. They are porphyritic in some bodies, with plagioclase phenocrysts of up to 15cm. The mineralogy consists of augite (uralitized edge), saussuritized plagioclase, opaque, biotite, titanite, apatite. Sometimes they show amygdules with chlorite, quartz and carbonate. They are metadiabases on the eastern edge of the SFC due to the actuation of Brasiliano metamorphism. They keep horizontal magmatic flux from NW to SE and they range from tholeiitic andesi-basalts to trachy-basalts (Silva et al., 1995; Chaves & Neves, 2005b; Carneiro & Oliveira, 2005; Cederberg et al., 2016; Caxito et al., 2020).

The Pará de Minas swarms I and II cross lithotypes of the Minas Supergroup, Mineiro Belt and cross the Bandeirinha Formation of Espinhaço Group (Chemale Jr et al., 2011). They are contemporary to Borrachudos anorogenic granites/rhyolites and the geotectonic environment is an active intra-continental rifting (extensional setting) associated with Statherian mantle plume. It is related with Avanavero-Xiong'er LIP (Chaves, 2021) and with the formation of the Espinhaço Basin in Minas Gerais (Chemale Jr et al., 2011).

Paraopeba (2000-2100 Ma)

It has NNW and ENE trendings (conjugate pairs) and the outcropping bodies in the south of the SFC with up to 20 km in length and an average width of 30 m. The main rocks are orthoamphibolites with granoblastic texture in the center of the dykes and nematogranoblastic texture in the shear margins. Originally porphyritic, these dykes have rotated plagioclase

megacrystals. It is possible to find plagioclase and augite, replaced by hornblende and almandine in progressive metamorphism of high amphibolite facies. Chloritized biotite, sericite, epidote and carbonate mark regressive metamorphism in greenschist facies. Ilmenite, quartz and zircon also occur. According to the geochemical classification, Paraopeba dykes are tholeiitic basalts to transitional basalts (Chaves & Neves, 2005b).

This swarm crosses migmatitic gneisses and granitoids of the Belo Horizonte, Campo Belo and Bonfim Complexes, and lithotypes of the Rio das Velhas Supergroup. The geotectonic environment is a NW syntectonic compressional setting associated with the Transamazonian orogeny associated to the Rhyacian Mineiro Belt around 2100 Ma (Chaves, 2011).

Lavras (2550-2650 Ma)

Lavras swarm has outcropping bodies with N40-60W predominant direction in the extreme south of the SFC, with up to 30 km in length and an average width of 30 m. It consists of fine to medium-grained gabbro-norites, with sometimes cumulate, sometimes intergranular to subophytic textures. The original minerals are plagioclase, augite/pigeonite (Cpx), bronzite (Opx), opaque, biotite, olivine and apatite. The post-magmatic minerals are chlorite, sericite, calcite, epidote, amphibole. The geochemical classification of the rocks from the Lavras dyke swarm are tholeiitic basalts and andesi-basalts (Pinese, 1997).

It crosses Archean gneisses and migmatites of the Campo Belo Complex and the geotectonic environment consists of a Neo-Archaean extensional setting after the occurrence of the Rio das Velhas Orogeny at 2770 Ma. It has a relationship with Lavras LIP and with the formation of the Minas Basin in Minas Gerais (Caxito et al., 2020).

According to Chaves & Neves (2005b), the Formiga, Transminas and Santos-Rio de Janeiro (Serra do Mar) swarms preserve corresponding bodies in the Congo Craton (Africa – Fig. 1).

CONCLUDING REMARKS

Regarding the seven mafic dyke swarms of Minas Gerais highlighted by aeromagnetometry and characterized by their geological, geochemical and geochronological peculiarities, six of them (Santos-RJ or Serra do Mar, Transminas, Formiga, Januária, Pará de Minas I/II, Lavras) are representative of crustal extensional settings and remnants of ancient large igneous provinces (LIP), many of which associated with mantle plumes and with the formation of important sedimentary basins stored in Minas Gerais. One swarm (Paraopeba) has genesis linked to compressional setting during Transamazonian (Rhyacian-Orosirian) Orogeny.

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