Universidade de Brasília
Instituto de Geociências
Programa de Pós-Graduação em Geologia

Tese de Doutorado Nº 180

CONTRIBUIÇÃO GEOFÍSICA À ANÁLISE DO ARCABOUÇO TECTÔNICO NA PROVÍNCIA ALCALINA DE GOIÁS

Geophysical contribution to the analysis of the tectonic framework in the Goiás Alkaline Province

Elainy do Socorro Farias Martins

Orientadora: Profa. Dra. Roberta Mary Vidotti

Brasília, 13 de agosto de 2021

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RESUMO

A quebra do Gondwana e abertura do Oceano Atlântico Sul foram responsáveis pelo magmatismo alcalino mesozoico que afetou a Plataforma Sulamericana. Este magmatismo foi responsável pela implantação de oito províncias alcalinas na porção centro-sul do Brasil, entre elas a Província Alcalina de Goiás, alvo deste trabalho. Alguns dos complexos da Província Alcalina de Goiás afloram e outros foram mapeados indiretamente por dados magnéticos. A morfologia desses corpos e o tipo de emplacement são desconhecidos, e alguns autores afirmam que a reativação de antigas zonas de fraqueza do embasamento pré-cambriano brasileiro, relacionadas à Orogenia Brasiliana, podem ter sido responsáveis pela estruturação e colocação de corpos nessa província. Este trabalho utilizou técnicas de processamento geofísico para interpretar dados magnéticos e gravimétricos, a partir da modelagem direta 2,5 D de dados gravimétricos e inversão do vetor magnético 3D. O processamento dos dados geofísicos mostrou um controle tectônico sobre a Província Alcalina de Goiás, ao longo das estruturas brasilianas e mesozóicas, e não houve predominância de corpos alcalinos ao longo do Azimute 125. Verificamos que as estruturas da Orogenia Brasiliana limitaram o bloco crustal que contém esta Província e a quebra do Gondwana possivelmente criou e reativou essas estruturas. A inversão do vetor magnético 3D permitiu a identificação de dez novos complexos menores. Observou-se que a geometria dos corpos é variada, e as formas de colocação são pipe, t-shape, funnel, finger e dique, e o complexo Registro do Araguaia é o que atinge maior profundidade em subsuperfície, aproximadamente , 19 km.

Palavras chave: Província Alcalina de Goiás; Modelagem gravimétrica; Vetor de inversão magnética; Controle tectônico.

ABSTRACT

The Mesozoic Alkaline Magmatism on the South American Platform is related to the Gondwana breakup and the opening of the South Atlantic Ocean. This magmatism was responsible for the emplacement of the eight alkaline provinces in the central-south of Brazil, among them the Goiás Alkaline Province, target of this work. Some of the Goiás Alkaline Province complexes outcrop and others was indirectly mapped by magnetic data. The morphology of these bodies and type of the emplacement is not know and some authors claim that the reactivation of old zones of weakness from the Brazilian Precambrian basement, Brasiliano orogeny, may have been responsible for the structuring and emplacement of few bodies in these provinces. This work used geophysical processing techniques to interpret magnetic and gravity data, from 2.5 D gravity forward modeling and 3D Magnetic Vector Inversion. The geophysical data processing shows a tectonic control over the Goiás Alkaline Province, along the Brasiliano and Mesozoic structures and there was no predominance of alkaline bodies along the Azimuth 125. We find that the Brasiliano orogeny structures limited the crustal block that contains this Province and Gondwana breakup possibly created and reactivated these structures. The 3D Magnetic Vector Inversion allowed the identification of ten new smaller complexes. It was observed that the geometry of the bodies is varied, and the forms of the emplacement are pipe, t-shape, funnel, finger and dike, and the Registro do Araguaia complex is the one complex that reaches the greatest depth in subsurface, approximately, 19 km.

Keywords: Goiás Alkaline Province; Gravity modeling; Magnetic Vector Inversion; Tectonic control.

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1. INTRODUÇÃO

Esta tese apresenta novas informações sobre a Provincia Alcalina de Goiás (PAGO), obtidas a partir de análises quantitativas, qualitativas, de modelagem direta 2,5 D e inversão 3D, de dados magnéticos de alta resolução e dados gravimétricos.

A tese está dividida em capitulo introdutório, dois artigos, dois resumos submetidos a evento cientifico e considerações finais. No capitulo introdutório foi feito uma revisão da evolução da Plataforma Sulamericana e províncias alcalinas mesozóicas. Neste, também foram inseridas a motivação do trabalho e a justificativa da tese. Nos tópicos 2 e 3 foram especificadas os dados e metodologias, assim como objetivos específicos de cada artigo.

O primeiro artigo “**Another way of looking at an Alkaline Province”**, foi publicado em janeiro de 2021, no periódico Journal of Geodynamics (https://doi.org/10.1016/j.jog.2020.101811). Neste trabalho foram especificados os dados e metodologias, assim como objetivos específicos. Como resultado foi obervada a relação das estruturas tectônicas relacionadas a Orogenia Brasiliana e evolução da Plataforma Sulamericana sobre a PAGO .

O segundo artigo “**MVI in prospecting targets for mineral exploration in the Goiás Alkaline Province**”, foi submetido no periódico Geophysics. Neste trabalho foram especificados os dados e metodologias, assim como objetivos específicos. Como resultado, apresenta de forma detalhada as morfologias 3D dos corpos da PAGO, assim como a identificação de possíveis novos corpos e formas de emplacement.

Foram confecciondos dois resumos, **“Emplacement rock revealed from Magnetic Vector Inversion “e “Matched Filter and voxi MVI to study the Az125 influence under the Goiás Alkaline Province”**, apresentado no 17th International Congress of the Brazilian Geophysical Society & Expogef, realizado em novembro de 2021.

No tópico considerações finais foram inseridas observações gerais a partir dos resultados obtidos nos artigos e resumos.

1.1. Provincias Alcalinas Mesozóicas na Plataforma Sulamericana

A Plataforma Sulamericana foi inicialmente definia como Plataforma Brasileira por Almeida (1967). Este domínio tectônico corresponde a porção da placa sulamericana que permaneceu estável durante a evolução das faixas móveis do Caribe e Andina, ao mesmo tempo em que ocorria a abertura e o desenvolvimento do Oceano Atlântico Sul, no Meso-Cenozóico (Almeida, 1986; Almeida et al., 1976, 2000) (Fig. 1).

De acordo com Hasui et al. (2012) a Plataforma Sulamericana é a parte estável situada a leste dos Andes e a norte da Plataforma Patagônica, sendo delimitada a oeste, convencionalmente, pelas faixas móveis Fanerozóicas andinas e a leste, com a margem Atlântica costeira. É formada por Escudos (Guianas, Brasil Central e Atlântico), Crátons (Amazonas, São Luís, São Francisco e Paraná), Sistemas Orogênicos (Borborema, Tocantins e Mantiqueira), por maciços e por coberturas Fanerozóicas. (Almeida, 1969; Almeida et al., 2000; Cordani et al., 2000; Dardenne & Schobbenhaus, 2001; Hasui et al., 2012; Schobbenhaus & Brito Neves, 2003) (Fig. 1).

A plataforma Sulamericana começou a se formar no Ordoviciano Superior, no final do Ciclo Brasiliano, porém, só foi individualizada como plataforma no Cretácio, e sua evolução pode ser descrita, de maneira simplificada, a partir de três estágios: Transição (Cambriano/Ordoviciano), Estabilização (Siluriano/Jurássico) e Reativação (Jurássico/Cenozóico) (Almeida, 1969; Almeida et al., 2000).

Hasui et al. (2012), baseado em vários trabalhos, também propõem uma divisão em três estágios, porém, com diferenças em termos de períodos geológicos e nome do estágio: estágio de Estabilidade (Neo-Ordoviciano - Eotriássico), de Ativação (Meso/Neotriássio - Mioceno) e estágio Moderno (Mioceno - Recente).

O estágio de transição é marcado pela deposição da sequência Alfa, onde predominam depósitos sedimentares clásticos e imaturos, depósitos vulcano-sedimentares e plutonismo. Aflora nas bordas das sinéclises, em riftes e pequenas bacias pull-apart (Almeida, 1969; Almeida et al., 2000). Este estágio ocorre parcialmente dentro do estágio de estabilidade definido por Hasui et al. (2012) o qual foi considerado como de relativa calma tectônica, com a formação das sinéclises Paleozóicas (Amazonas, Solimões, Parnaíba, Chaco-Paraná), marcadas por quatro sequências deposicionais (Beta, Gama, Delta e Delta-A), influenciadas por eventos de transgressão e regressão marinha, exposição dos escudos e formação de arcos regionais, em resposta à subsidência das sinéclises, desertificação e vulcanismo marcaram a fase final deste estágio.

O Estágio de Ativação, foi designado inicialmente como Reativação Wealdeniana (Almeida, 1967) e, posteriormente, como Ativação Mesozoica (Almeida, 1972). Neste estágio a deposição da sequência Epsilon, está intimamente ligada a fragmentação do Pangea e abertura do Oceano Atlântico, marcada por intenso magmatismo, rifteamento, formação das bacias da margem passiva e reativação de estruturas herdadas principalmente da Orogenia Brasiliana. Este estágio é marcado por cinco fases de magmatismo: Atividade Ígnea Permotriássica, Magmatismo Eocretáceo Pré-Aptiano, Atenuação Ígnea Aptiano-Albiana, Magmatismo Alcalino Neocretáceo-Eocênico, Vulcanismo Neogênico (Almeida & Carneiro, 1989; Hasui et al., 2012; Sadowski, 1987). O Magmatismo Alcalino Neocretácio-Eocênico, alvo deste trabalho, deu preferência à porção centro-sul da Plataforma, nas proximidades da borda da bacia do Paraná. Gibson et al. (1997) afirmam que o magmatismo Cretácico, na porção central e SE do Brasil, está condicionado à faixas Neoproterozóicas (Paraguai e Brasília).

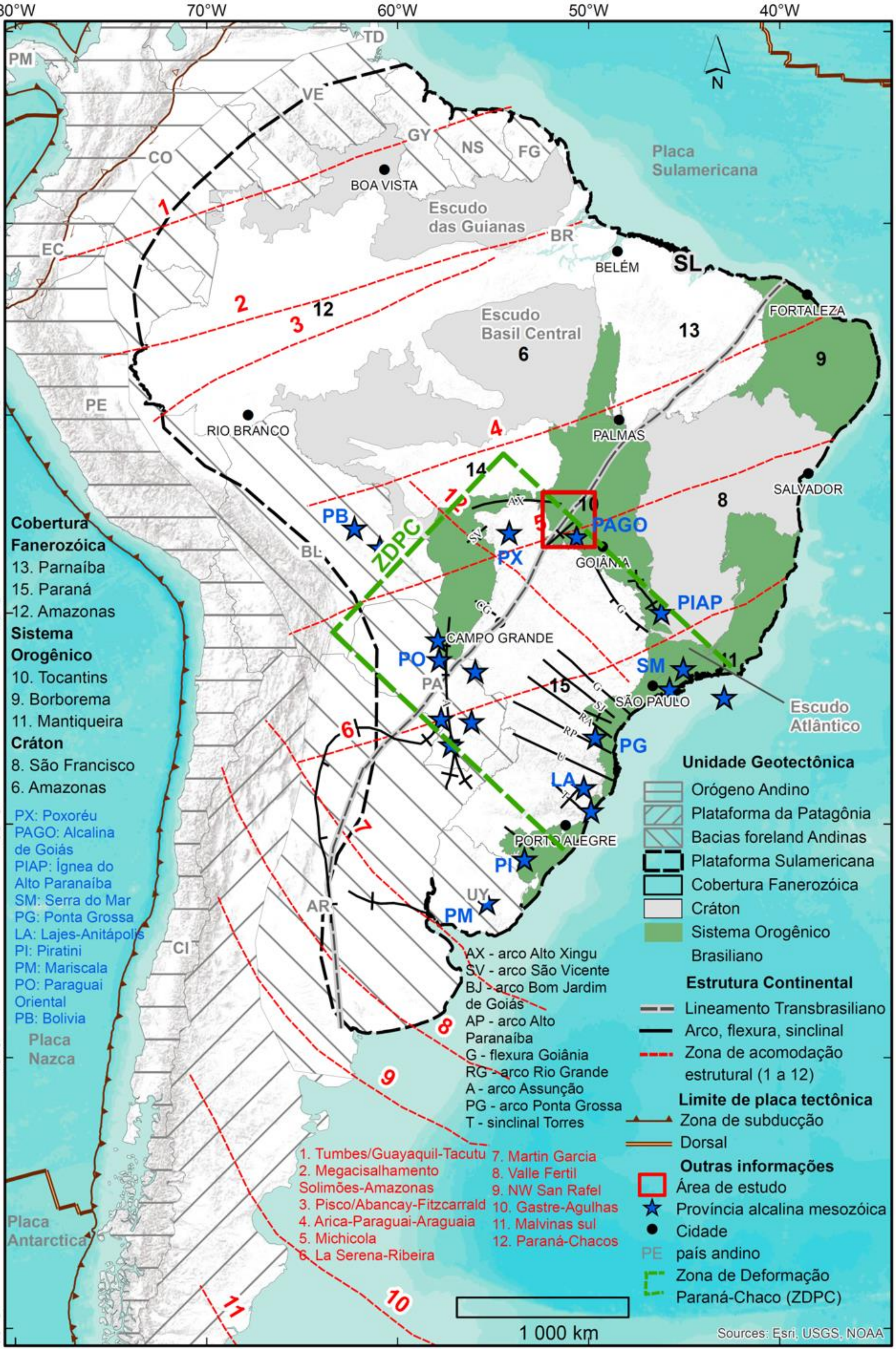

Fig. 1. Distribuição das províncias alcalinas mesozóicas na Plataforma Sulamericana, com destaque para a PAGO (polígono vermelho) (baseado em Gibson et al., 1997; Hasui et al., 2012; Lagorio, 2008).

As linhas tracejadas e enumeradas em vermelho representam zonas de acomodação estrutural (1 a 12, nomeadas em vermelho), os nomes em azul representam as províncias alcalinas mesozóicas.

Jacques (2003a, 2003b; 2004) afirma que na porção central da Plataforma Sulamericana há uma zona de deformação, Zona de Deformação Paraná-Chacos - ZDPC (Fig. 1, polígono verde) que representa uma estrutura litosférica, que em escala regional, forma faixas ou zonas (Fig. 1, linha tracejada vermelha, 1 a 12) que acomodam deformação intraplaca durante episódios de reorganização da placa. Esta zona acomodou stress intraplaca durante a quebra do Gondwana e abertura do Atlântico Sul, entre o Triássico e Jurássico, favorecendo a ascenção do magma oriundo do manto litosférico. Grande parte das províncias alcalinas mesozoicas estão concentradas nesta zona, de orientação NW-SE, delimitadas, aproximadamente, a NE pelo cráton do São Francisco; a W, pela borda sul do cráton Amazonia e Lineamento Transbrasiliano (LTB) e, a S/SE/SW pelos crátons Rio de La Plata e Luis Alves (Fig. 1). Os autores afirmam também que o LTB pode ter contribuído por difundir parte do stress intraplaca ao longo de sua extensão.

Em trabalho de maior detalhe na região da ZDPC, e com base em dados gravimétricos e magnéticos, Pinto & Vidotti (2019) constataram que as províncias alcalinas mesozócas brasileiras se concentram em regiões de faixa móvel ou na borda de crátons, Poxoréu (Faixa Paraguai), Goiás (Faixa Brasilia), Alto Paranaiba (Faixa Ribeira/Faixa Brasília?), Ponta Grossa (Faixa Ribeira) e Amambay (cráton Paranapanema). O magmatismo alcalino mesozoico ocorre dentro do Domínio Brasiliano ou Província Estrutural Brasiliana (Brito Neves & Cordani, 1991; Brito Neves & Fuck, 2014), região onde ocorre a sutura entre os paleocontinentes: Amazonia, Rio de La Plata e São Francisco; e microplacas/microcontinentes: Maciço Goiano, Paranapanema e Rio Apa. Possivelmente as estruturas geradas na Orogenia Brasiliana podem ter sido usadas como conduto para o magma alcalino. A reativação destas estruturas, ao longo da evolução da Plataforma Sulamericana, pode ter gerado stress intraplaca, principalmente na porção centro sul da plataforma, contribuindo para a formação da ZDPC.

O Estágio Moderno (Hasui et al., 2012), faz parte do estágio de Ativação Mesozoica (Almeida, 1972), e é marcado pela evolução da atual fisiografia da plataforma (continental e marinha), ausência de atividade ígnea no continente brasileiro, deposição da sequência Zeta, inversão do deslocamento do Rio Amazonas, mudanças deposicionais em bacias andinas, em resposta a esforços compressivos e reativação de zonas de fraqueza.

O entendimento da evolução do arcabouço tectônico da Plataforma Sulamericana pode contribuir com informações acerca do magmatismo alcalino que afetou a mesma durante o Estágio de Ativação Mesozoica. Diversos autores afirmam que a reativação de antigas zonas de fraqueza, do embasamento Pré-Cambriano, poderia ter sido responsável pela estruturação destes corpos, orientados, principalmente, nas direções NE-SW, NW-SE a WNW-ESE (Almeida & Carneiro, 1989; Black et al., 1985; Comin-Chiaramonti et al., 2007, 2015; Matton & Jebrak 2009; Peyve, 2010).

O magmatismo alcalino mesozoico, na Plataforma Sulamericana, é parte de um evento maior chamado de Província Ígnea Paraná-Etedenka ou Província Paraná-Angola-Namíbia, que é marcada por derrames toleíticos e enxame de diques, associada com complexos alcalinos e alcalino-carbonatíticos do Cretácio Inferior e Superior (Comin-Chiaramonti et al., 1999). Este mesmo evento também foi nomeado como Peri-Atlantic Alkaline Pulse (PAAP), englobando as rochas alcalinas geradas entre 125 Ma a 80 Ma, devido à quebra do Gondwana e abertura do Oceano Atlântico Sul. Durante este contexto ocorreram reorganizações intraplaca, como, mudanças na intensidade e direção do espalhamento oceânico, na movimentação das placas tectônicas e mudanças no polo de rotação, que foram responsáveis pelos dois picos magmáticos do PAAP, 125 Ma e 85-80 Ma. Eeste evento magmático mostra um forte controle estrutural estando localizado, principalmente, no PCDZ (Fig. 1), arco de Ponta Grossa, lineamento Piquiri, Gráben Assunción-Sapuai-Villarica e o lineamento Uruguai, além de outras estruturas (Matton & Jebrak, 2009; Sadowski, 1987).

Este magmatismo deu preferência a porção centro sul da Plataforma Sulamericana, onde foram individualizadas dez províncias alcalinas, com ocorrências no Paraguai, Bolívia, Brasil e Uruguai, e a ocorrência das mesmas está condicionada a sistemas de riftes (aulacógeno, grábens, falha normal, etc.) e/ou lineamentos, orientados preferencialmente nas direções NE-SW, NW-SE e WNW-ESE, resultantes da reativação de antigas zonas de fraqueza crustal (Almeida, 1967, 1972, 1983; Almeida et al., 2012; Comin-Chiaramonti et al., 1999, 2007; Hasui et al., 2012; Jacques 2003a, 2003b, 2004; Matton & Jebrak, 2009; Sadowski, 1987).

a) Províncias alcalinas no Paraguai

No Paraguai há registro de seis províncias alcalinas: Alto Paraguai (242 - 240 Ma), Amambai (140 - 138 Ma), Rio Apa (140 -138 Ma), Central (128 - 124 Ma), Missiones (120 - 116 Ma) e Assunción (60 - 56 Ma) (Antonini et al., 2005) (Fig. 1 e Fig. 2), estas representam o registro mais distante da margem oeste da Plataforma Sulamericana e o mais antigo (Alto Paraguai) relacionados ao magmatismo alcalino Mesozoico. São formadas por basaltos, andesibasaltos, nefelinitos, ankaratritos, fonolitos e carbonatitos, que ocorrem na forma de diques, plugs, lavas, stocks e anéis (Gomes et al., 2013; Gomes & Comin-Chiaramonti, 2017).

As rochas alcalinas estão associadas a feições estruturais como falhas, riftes, flexuras, arcos (Comin-Chiaramonti et al., 2007). Dentre estas estruturas três direções principais controlam as províncias alcalinas: a direção NE-SW (mais antiga) é a mais importante da porção norte, formada pelos arcos de Ponta Porã e Capitán Bado, influenciando a província Amambay. A direção N-S, na porção norte, representa alinhamentos estruturais que parecem ter exercido controle nas intrusões da Província Alto Paraguai (I, Fig. 2) e podem estar relacionadas a antigas estruturas do embasamento reativadas durante o magmatismo Permo-Triássico. O Anticlinal Apa, de direção NW-SE, também parece ter influenciado esta província, assim como a província Rio Apa (III, Fig. 2) (Antonini et al, 2005; Comin-Chiaramonti et al., 2007; Gomes et al., 1996, 2013; Riccomini et al., 2005; Velazquez et al., 1996, 1998).

A direção NW-SE (mais nova), herdada do embasamento Pré-Cambriano, controla as províncias Central (IV, Fig. 2), Missiones (V, Fig. 2) e Assunción (VI, Fig. 2). A província Central está associada a uma zona de rifte, NW-SE, entre as cidades de Asunción e Villarica. Também há ocorrência de corpos desta província próximo aos anticlinais Igatimí e Caagazú, de direção NE-SW; e próximos a interseção de estruturas WNW-ESSE (zona de falha Acahay). Já a Província Missiones ocorre associada ao gráben de Santa Rosa e a província Assunción está associada ao anticlinal Assunción (Gomes et al., 2013; Velazquez et al., 1998) (Fig. 2).

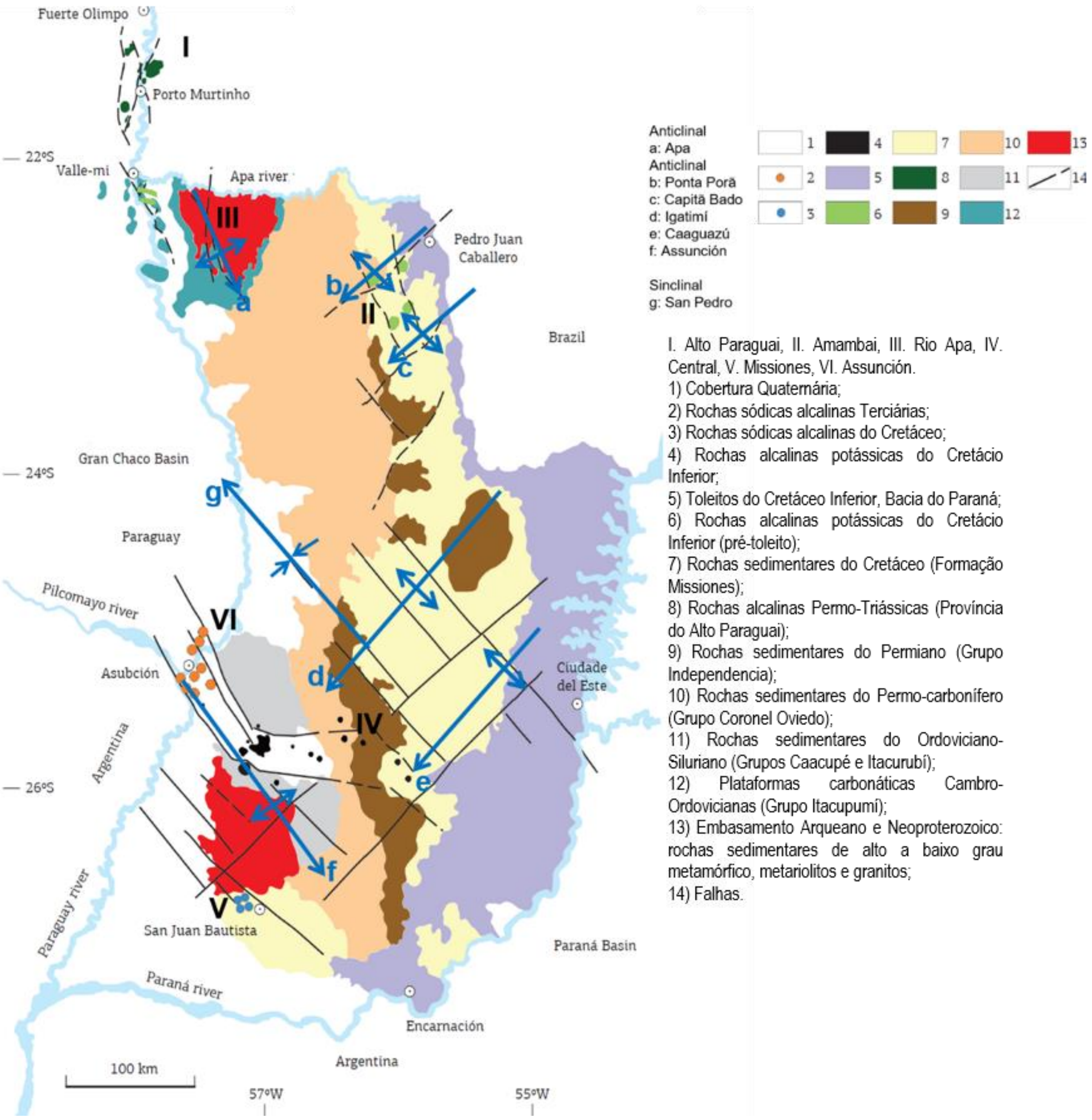

Fig. 2. Distribuição geográfica e estruturas tectônicas na Província do Paraguai Oriental (modificado de Antonini et al., 2005; Gomes et al., 1996).

b) Províncias alcalinas na Bolívia

A Bolivia foi afetada por dois episódios magmáticos, no início e final do Cretáceo, e que deram origem as províncias alcalinas Candelária e Velasco. A Província Velasco (144 - 141 Ma) ocorre em uma estreita faixa de direção NE-SW, associada à rochas do bloco Rondônia, com 80 km de extensão, possivelmente relacionada a uma junção tríplice iniciada durante a quebra do Gondwana e abertura do Oceano Atlântico Sul. É composta por granitos, nefelina sienitos e carbonatitos que ocorrem na forma de plútons anelares a elípticos, encaixados em gnaisses, migmatitos e granitos da Faixa San Ignatio - Rio Guaporé (Comin-Chiaramonti et al., 2005; Fletcher & Litherland, 1981) (Fig. 1 e Fig. 3).

A Província Candelária (aprox. 80 Ma), ocorre associada a Faixa Sunsás, controlada por falhas de direção E-W e WNW-ESE, relacionadas ao rifte Mercedes. É formada por basaltos alcalinos que ocorrem na forma de diques e lavas (Almeida, 1983; Darbyshire & Fletcher, 1979; Fletcher & Litherland, 1981; Riccomini et al., 2005).

Omarini et al. (2016) com base em dados sobre a evolução geodinâmica da porção central dos Andes e do Paraguai-Brasil, considera que as províncias da Bolivia fazem parte da Província Magmática do Atlântico Central (Central Atlantic Magmatic Province - CAMP), no domínio dos Andes Centrais, e não da Província Ígnea Paraná-Etedenka (Comin-Chiaramonti et al., 1999), estando relacionadas a abertura do Oceano Atlântico Central, e não a abertura do Oceano Atlântico Sul.

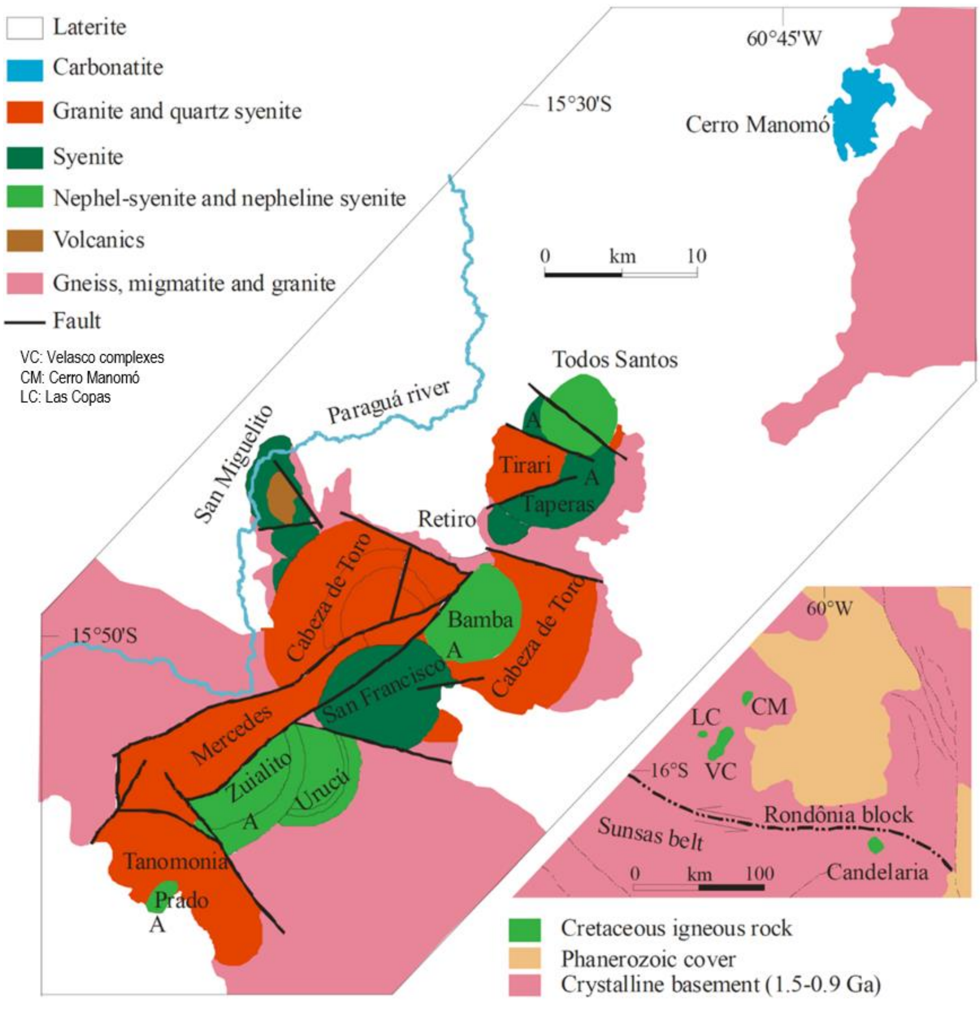

Fig. 3. Localização das Províncias Candelária e Velasco, com destaque para a geologia da Província Velasco (Comin-Chiaramonti et al., 2005).

c) Províncias alcalinas no Brasil

No Brasil ocorrem as Províncias Poxoréu (Gibson et al., 1997), Alcalina de Goiás (Almeida, 1983; Brod et al., 2005; Guimaraes et al., 1968; Gomes et al., 2013, 2018; Lacerda Filho et al.,1999; Ulbrich & Gomes, 1981), Ígnea do Alto Paranaíba (Gibson et al., 1995; Gonzaga & Tompkins, 1991); Serra do Mar (Almeida, 1983; Thompson et al., 1998), Ponta Grossa (Almeida, 1983), Lajes-Anitápolis (Gibson et al., 1999) e Piratini (Almeida, 1983).

A localização destas províncias está associada a sistemas de riftes (aulacógeno, grábens, falha normal, etc.) e/ou lineamentos, orientados preferencialmente nas direções NE-SW, NW-SE e WNW-ESE, resultantes da reativação de antigas zonas de fraqueza crustal (Almeida, 1967, 1983; Almeida et al., 2012; Comin-Chiaramonti et al., 1999, 2007; Hasui et al., 2012; Matton & Jebrak, 2009; Sadowski, 1987).

- **Província Poxoréu**

A Província Poxoréu (84 Ma) está localizada na porção NW da bacia do Paraná, no domínio da Faixa Paraguai, ao longo de uma zona extensional NE-SW, rifte Rio das Mortes. É delimitada a norte pelo Arco Alto Xingú, na porção central pelo Arco São Vicente, e o Linemento Transbrasiliano limita a porção sul. É constituida de basaltos, em forma de lavas e diques; e um complexo sienito-monzonito-granitico, Ponta do Morro (Gibson et al., 1997; Gomes et al., 2018) (Fig. 1 e Fig. 4). De acordo com Gibson et al. (1997) a origem desta província está associada a pluma de Trindade.

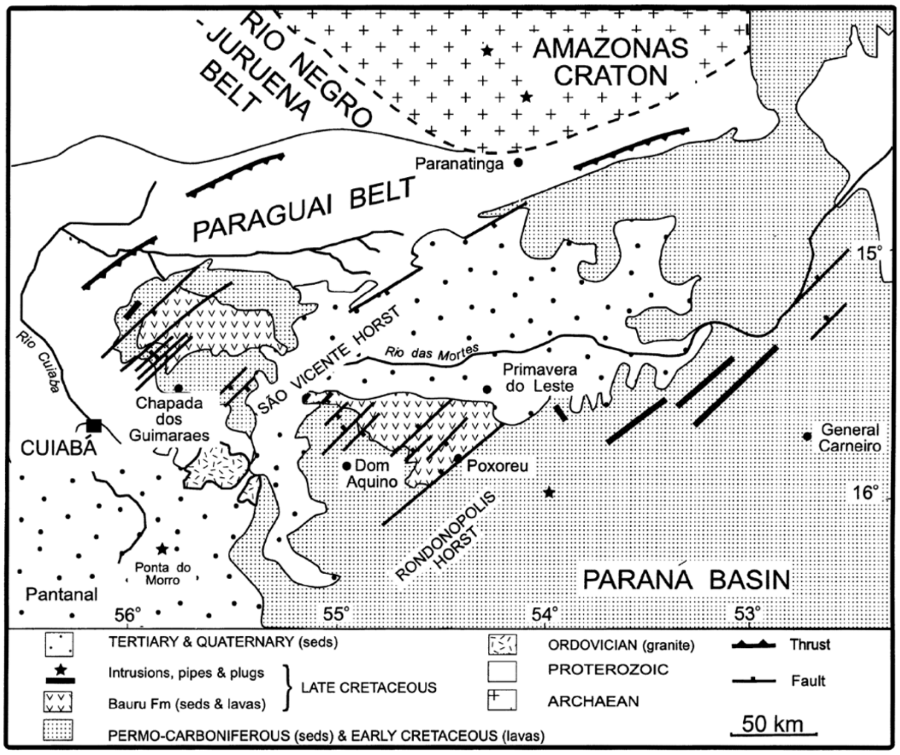

Fig. 4. Mapa geológico da Província Poxoréu (Gibson et al., 1997).

- **Província Alcalina de Goiás**

Esta província foi inicialmente estudada por Guimarães et al. (1968) que a nomearam de Grupo Iporá. Em trabalhos posteriores foi chamada de Província Rio Verde-Iporá (Almeida, 1983); e Província Alcalina do Sul de Goiás: Suíte Vulcânica de Santo Antônio da Barra e Suíte Plutônica de Iporá (Lacerda Filho et al.,1999). Gaspar et al. (2003), com base em dados isotópicos, nomearam estas rochas como Província Alcalina de Goiás (PAGO), sendo formada por vários complexos plutônicos, subvulcânicos e vulcânicos, sendo esta a nomenclatura atualmente utilizada para estas rochas.

A PAGO (90-88 Ma) está localizada na porção NNE da bacia do Paraná, associada a um trend N30W, Azimute 125° (Bardet, 1977), que coincide com falhas do embasamento, além do arco Bom Jardim de Goiás e Lineamento Transbrasiliano (Almeida, 1983; Brod et al., 2005; Hasui et al., 2012; Peyve, 2010) (Fig. 1 e Fig. 5).

No Cretácio Superior, a região onde se encontra a PAGO passou por eventos de extensão, principalmente ao longo do eixo do arco Bom Jardim de Goiás, originando falhamentos normais, grábens (Caiapó, Rio Claro e Morro da Mesa) e horsts (Amorinópolis, Ivolândia), de direção N10-30E, N50-70W e S70-80W. As direções NE e NW, foram os principais condutos para a ascensão do magma alcalino (Pena & Figueiredo, 1972; Pena et al., 1975).

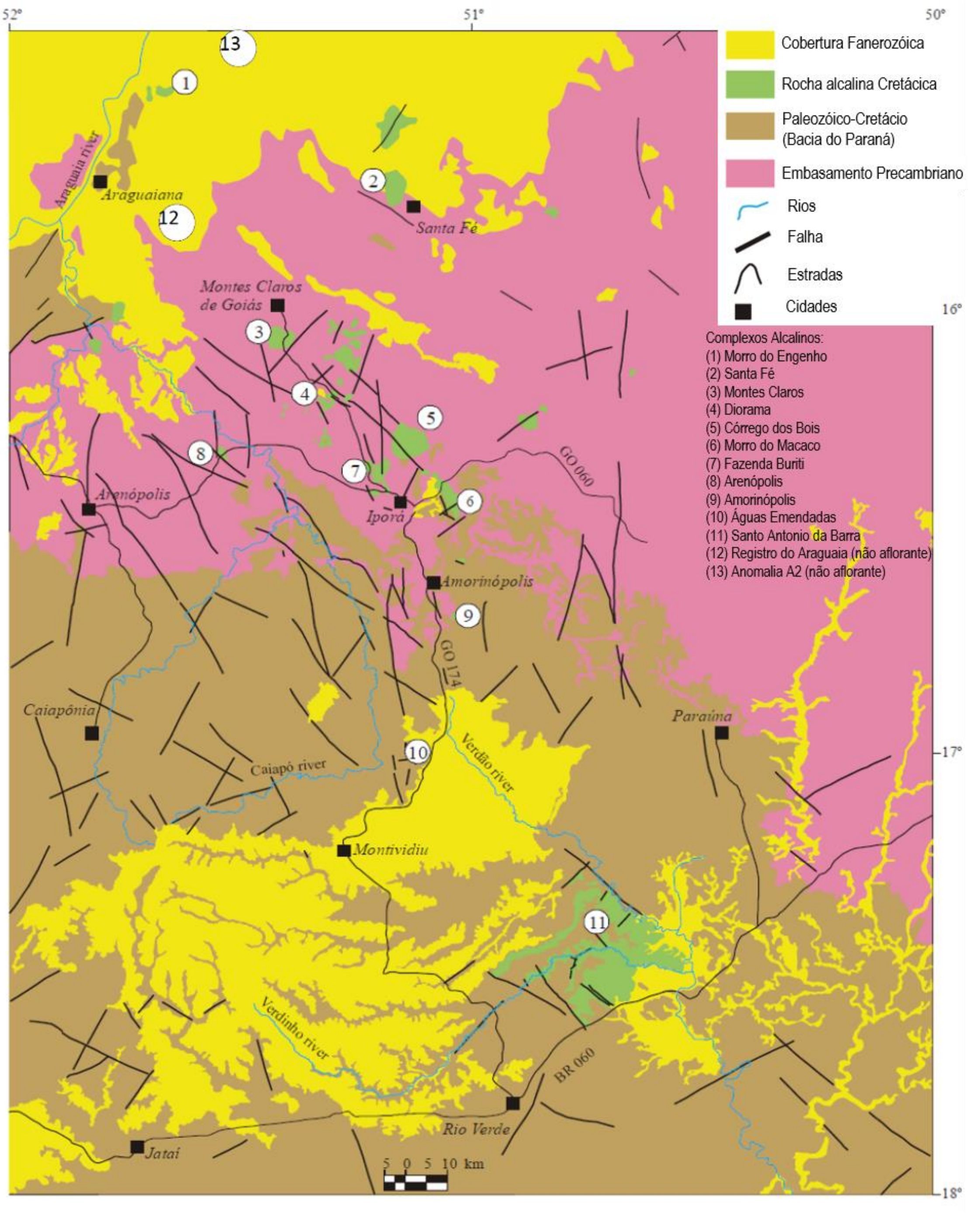

Fig. 5. Mapa geológico da Província Alcalina de Goiás (Brod et al., 2005, Dutra et al., 2012, 2014).

- **Província Ígnea do Alto Paranaíba**

A Província Ígnea do Alto Paranaíba (85 Ma) está localizada na borda NE da bacia do Paraná, em uma região dominada por diques de rochas básicas, de direção N50W, aproximadamente, entre a flexura de Goiânia e o arco do Alto Paranaíba, no domínio da Faixa Brasília (Fig. 1 e Fig. 6). Esta província assim como as províncias de Goiás, Poxoréu e Serra do Mar são associadas ao Azimute 125°, onde aparentemente, há uma grande ocorrência de rochas alcalinas, kimberlitos e carbonatitos (Almeida, 1983; Gibson et al., 1995; Gonzaga &Tompkins, 1991; Omarini et al., 2016; Svisero, 1995).

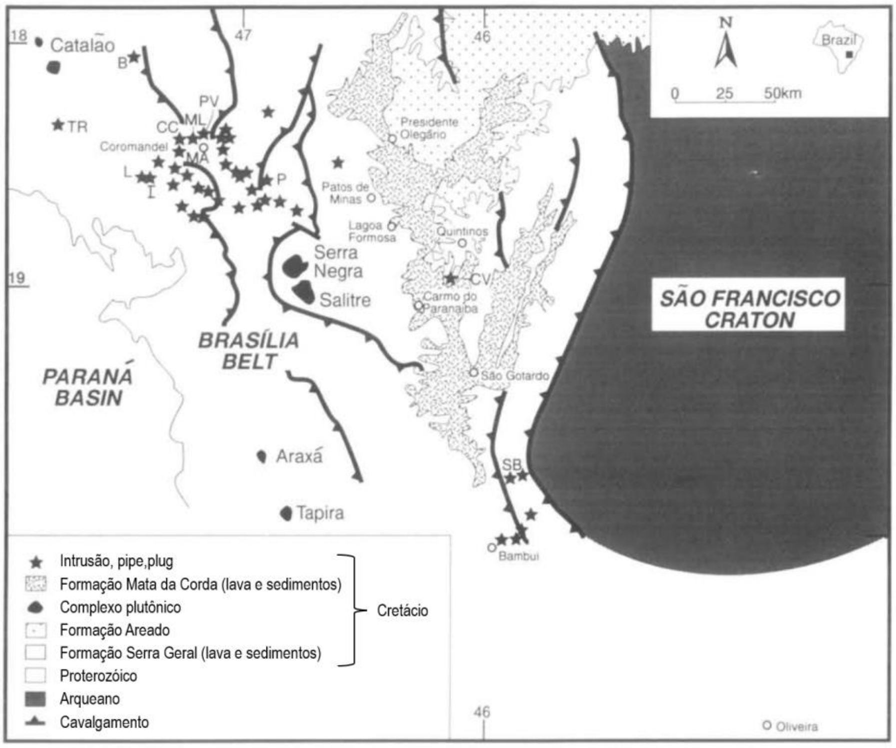

Fig. 6. Mapa de distribuição dos complexos alcalinos da Província Ígnea Alto Paranaíba. B, Bocaina; CC, Córrego do Douro; CV, Córrego Varjão; I, Indaiá; L, Limeira; MA, Morro Alto; ML, Mata do Lençol; P, Pântano; PV, Poço Verde; SB, Serra do Bueno; TR, Três Ranchos (Gibson et al., 1995).

- **Província Serra do Mar**

A Província Serra do Mar (85-55 Ma) está localizada na costa SE do Brasil, a sul do cráton São Francisco e a nordeste da bacia do Paraná, no domínio da Faixa Ribeira (Almeida, 1983; Peyve, 2010, Thompson et al., 1998) (Fig. 1 e Fig. 7).
Almeida (1983) enfatizou que os corpos alcalinos da referida província estão associados a falhas e fraturas do embasamento Pré Cambriano, de direção,

principalmente, NE-ENE. Thompson et al. (1998) estenderam o limite oeste da província até a cidade de São João da Boa Vista, assim como o limite norte também foi ampliado até a latitude 21°S.

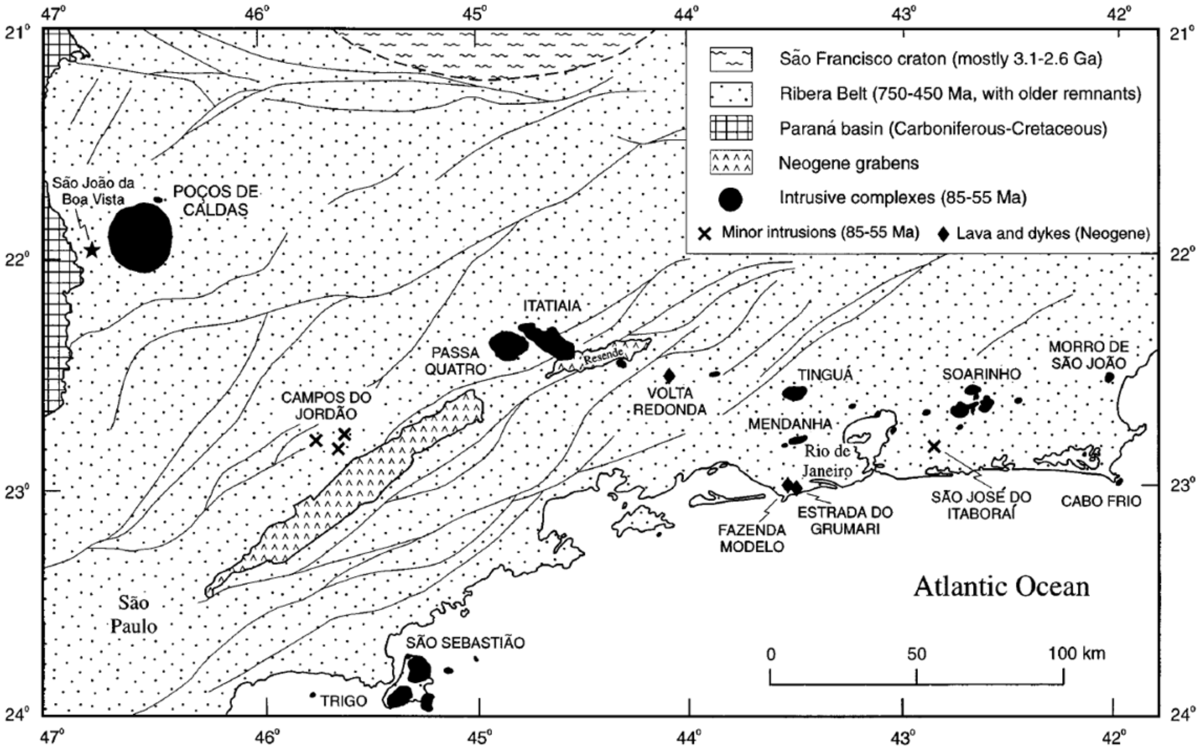

Fig. 7. Mapa geológico da Província Serra do Mar. Principais intrusões alcalinas: 1. Montão de Trigo, 2. São Sebastião, 3. Búzios, 4. Vitória, 5. Ponte Nova, 6. Passa Quatro, 7. Itatiaia, 8. Morro Redondo, 9. Tinguá, 10. Gericinó-Mendanha, 11. Itaúna, 12. Porto das Caixas, 13. Tanguá, 14. Soarinho, 15. Rio Bonito, 16. Morro dos Gatos, 17. Morro São Joao, 18. Cabo Frio, 19. Volta Redonda (Thompson et al., 1998).

- **Província Ponta grossa**

Localizada a leste da bacia do Paraná, entre os estados de São Paulo e Santa Catarina. Nesta são individualizadas duas fases de magmatismo alcalino: 132-122 Ma (Jacupiranga, Juquiá, Ipanema, Piedade e Itanhaém) e 110-105 Ma (Itapirapuã e Tunas), e os mesmos ocorrem sob a influência do arco de Ponta Grossa, com eixo a NW, e alinhamentos paralelos ao arco: Guapiara, São Gerônimo-Curiúva, rio Alonzo e Piqueri, além de falhas E-W e NE-SW (Almeida, 1983; Peyve, 2010; Riccomini et al., 2005) (Fig. 1 e Fig. 8).

Riccomini et al. (2005) afirmam que as rochas desta província podem fazer parte de uma junção tríplice, formadas por estruturas NW-SE, relacionadas ao arco de Ponta Grossa; estruturas ENE-WSW ao longo da costa de São Paulo e Rio de Janeiro; e estruturas N-S na costa dos Estados do Paraná e Santa Catarina.

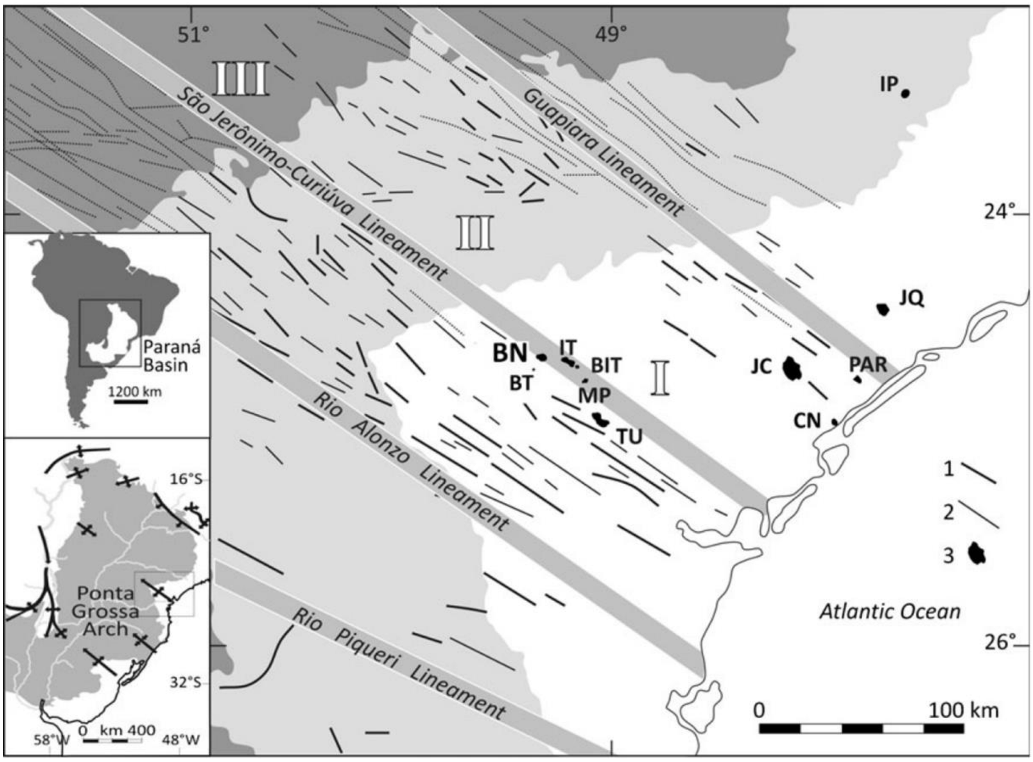

Fig. 8. Magmatismo alcalino cretácico no Arco de Ponta Grossa. Os números 1 e 2 representam diques, e o número 3 os complexos alcalinos (BIT-Barra do Itapirapuã, BN-Banhadão, BT-Barra do Teixeira, CN-Cananéia, IP-Ipanema, IT-Itapirapuã, JC-Jacupiranga, JQ-Juquiá, MP-Mato Preto, PAR-Pariquera-Açu e TU-Tunas. I – embasamento cristalino; II – sedimentos Paleozoicos da Bacia do Paraná; III – derrame basáltico (Ruberti et al., 2005, 2012; Gomes et al., 2011).

- **Província Lajes-Anitápolis**

Está localizada próximo à cidade de Florianópolis e é formada pelos complexos Anitápolis (132 Ma) e Lajes (77-70 Ma). O complexo Anitápolis, ocorre no domínio do cinturão Dom Feliciano, e sua idade é contemporânea ao magmatismo da Província Ígnea Paraná-Etedenka. O complexo Lages aflora 100 km a oeste do complexo Anitápolis, na margem leste da bacia do Paraná e ambos complexos estão distribuídos ao longo do lineamento Uruguai, de direção E-W (Comin-Chiaramonti et al., 2002; Gibson et al., 1999) (Fig. 1 e Fig. 9).

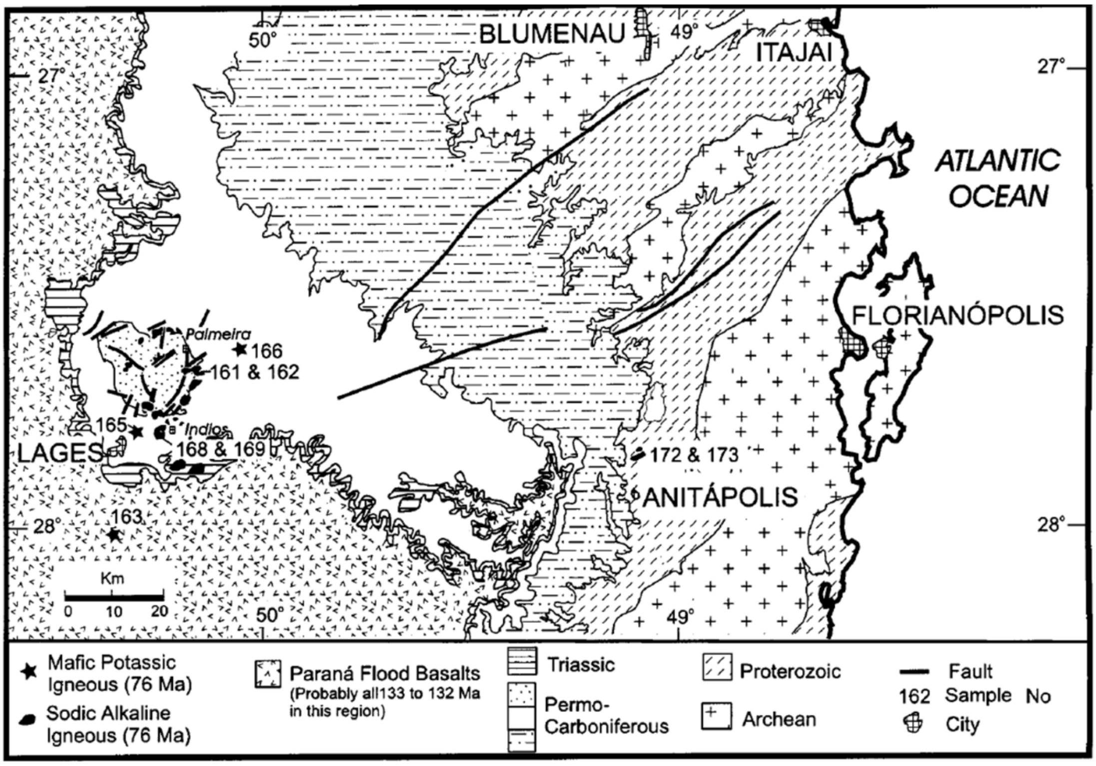

Fig. 9. Mapa geológico dos complexos Lajes e Anitápolis (Gibson et al., 1999).

- **Província Piratini**

As rochas da Província Piratini (99-76 Ma) ocorrem na porção sul do Brasil, principalmente, associadas ao gráben Moirão, de direção NE-SW; além de fraturas de direção NNW-SSE a NW-SE e também sob influência do arco do Rio Grande (Almeida, 1983; Hasui et al., 2012; Riccomini et al., 2005) (Fig. 1).

d) Província alcalina no Uruguai

Província Mariscala (133-127 Ma), está localizada ao sul da bacia do Paraná, no sul do Uruguai, no domínio da Faixa Dom Feliciano. Fazem parte desta província as rochas alcalinas que ocorrem nas bacias de Santa Lucia e Laguna Merín, além do complexo Valle Chico. Estão orientadas pincipalmente na direção N40-60W, secundariamente na direção N20E e ocorrem também associadas ao lineamento Santa Lucía-Aiguá Merin, de direção N70E. São relacionadas ao evento Paraná-Etedenka e abertura do Oceano Atlântico Sul (Almeida, 1983; Cernuschi et al., 2015;

Kirstein et al., 2000; Lustrino et al., 2005; Muzio et al., 2002; Riccomini et al., 2005; Ruberti et al., 2005) (Fig. 1 e Fig. 10).

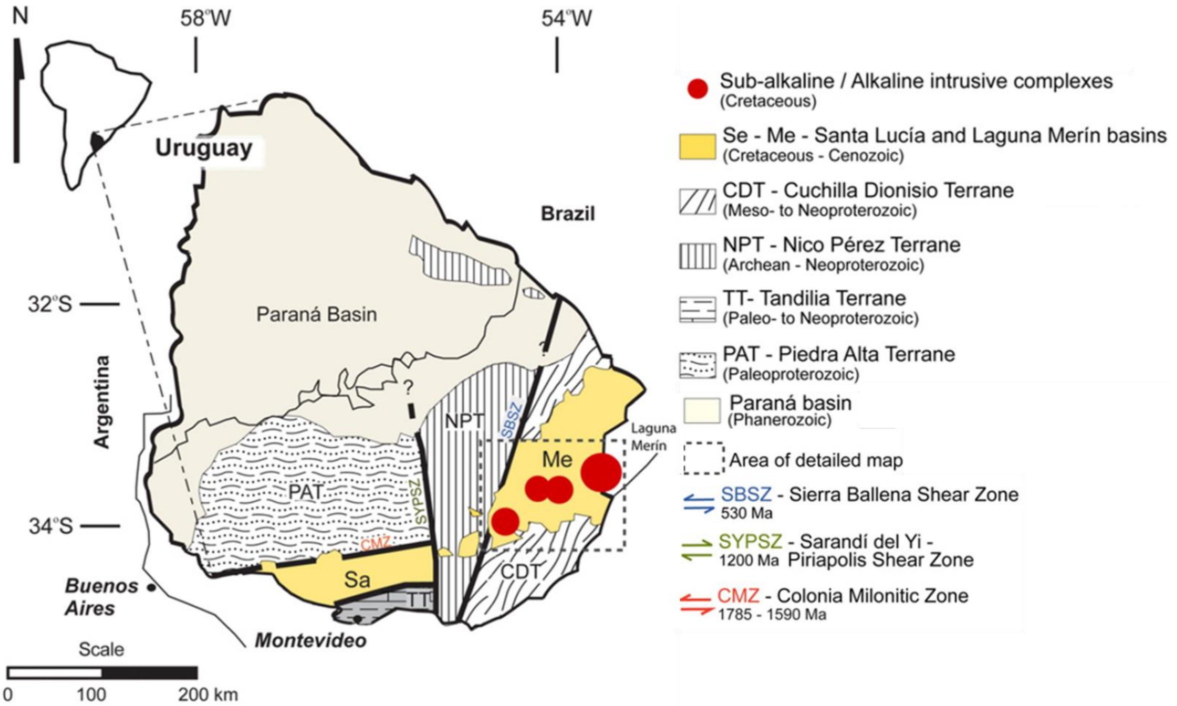

Fig. 10. Mapa geológico esqemático da Província Alcalina do Uruguai (Cernuschi et al., 2015).

1.2. Justificativa

O entendimento da evolução do arcabouço tectônico da Plataforma Sulamericana pode contribuir com informações acerca do magmatismo alcalino durante o estágio de Ativação Mesozoica. Diversos autores afirmam que a reativação de antigas zonas de fraqueza do embasamento Pré-Cambriano pode ter sido responsável pela estruturação destes corpos, orientados, principalmente, nas direções NE-SW, NW-SE a WNW-ESE (Almeida & Carneiro, 1989; Black et al., 1985; Comin-Chiaramonti et al., 2007, 2015; Matton & Jebrak 2009; Peyve, 2010).

Grande parte dos trabalhos relacionados ao magmatismo alcalino mesozoico, na Plataforma Sulamericana, é feita com base em dados geológicos, principalmente, geoquímico e geocronológico (Brod et al., 2005; Comin-Chiaramonti et al., 2007; Junqueira Brod et al., 2004, 2005a, 2005b; Matton & Jebrak, 2009). Há também alguns trabalhos com base em dados geofísicos, porém, nenhum deles trata especificamente a relação do controle tectônico sobre o referido magmatismo como, por exemplo, Dutra & Marangoni (2009), Dutra et al. (2012, 2014), Feitoza (2011), Marangoni &

Mantovani (2013), Mantovani et al. (2015), Marangoni et al. (2015), Oliveira et al. (2015), Rocha et al. (2014, 2019).

Em relação ao controle tectônico sobre as províncias alcalinas mesozoicas, na Plataforma Sulamericana, há ainda inúmeras questões a serem resolvidas, tais quais:

1. As províncias alcalinas mesozoicas estão associadas a alguma estruturação regional?
2. Estas estruturas são reativações de antigas estruturas do embasamento Pré-Cambriano?
3. Porque a maior ocorrência destas rochas está situada na porção centro sul da Plataforma Sulamericana?
4. Verifica-se que a maior parte das províncias alcalinas se situa a leste do Lineamento Transbrasiliano. Sendo assim as reativações do mesmo podem ter influenciado, de alguma forma, o *emplacement* de algumas províncias?
5. Existe relação entre a Zona de Deformação Paraná - Chacos e a Província Alcalina de Goiás?

Trabalhos de maior detalhe são necessários, assim como um amplo estudo sobre a evolução do arcabouço tectônico da porção central da Plataforma Sulamericana, e as principais direções herdadas durante sua evolução. Uma abordagem para verificar o controle tectônico nas províncias alcalinas mesozoicas é a utilização de dados magnéticos e gravimétricos, aliados a dados de campo, para investigar o comportamento das estruturas e das rochas em superfície e subsuperfície.

Os dados geofísicos possibilitam o estudo de grandes áreas, de estruturas e corpos aflorantes e não aflorantes. Tais características são importantes, pois, por vezes, os corpos alcalinos não afloram e as estruturas que possam estar associadas aos mesmos não são identificadas, o que dificulta o entendimento da estruturação dos mesmos.

A proposta deste trabalho é analisar, a partir da interpretação e da modelagem geológico-geofísica, de dados magnéticos e gravimétricos, se existe um controle tectônico na Província Alcalina de Goiás (PAGO) e se existem novos corpos não mapeados/não identificados.

1.3. Objetivos

O objetivo deste trabalho é o estudo do controle tectônico, na PAGO, relacionado ao magmatismo alcalino Mesozoico no contexto da Plataforma Sulamericana.

O controle tectônico foi estudado a partir de informações de subsuperfície, obtidas a partir do processamento e interpretação de dados magnéticos de alta resolução, de dados gravimétrivos terrestres, além de informações geológicas de campo e de bases geológicas digitais. O objetivo principal foi dividido nas seguintes etapas:

a) Analisar qual a influência da evolução da Província Tocantins no *emplacement* da PAGO.

- ✓ Processamento dos dados magnéticos aéreos e gravimétricos terrestres.
- ✓ Estimativa de profundidade das fontes magnéticas a partir da técnica Matched Filter.
- ✓ Interpretação dos lineamentos magnéticos e associação com a PAGO.
- ✓ Associação dos lineamentos magnétios com a região de ocorrência da PAGO.
- ✓ Modelagem gravimétrica direta 2,5 D, estruturas tectônicas e relação com a PAGO.

b) Mapear 3D a PAGO e verificar se anomalias magnéticas dipolares identificadas por Martins & Vidotti (2021) representam novos corpos da PAGO.

- ✓ Modelagem magnética inversa (Magnetization Vector Inversion – MVI).
- ✓ Identificar a geometria dos corpos e formas de emplacement.
- ✓ Calcular o campo magnético dos corpos.
- ✓ Identificar novos corpos.
- ✓ Relação dos corpos da GAP com estruturas tectônicas.

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2. ANOTHER WAY OF LOOKING AT AN ALKALINE PROVINCE

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Highlights

- Magnetic and gravity data show tectonic controlat the Goias Alkaline Provinc (GAP).
- Gravity modeling indicates a thicker crust under the GAP.
- Tectonic structures of the Brasiliano orogen limit the GAP crustal block.
- Gondwana breakup possibly created or reactivated the GAP tectonic structure.

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Another way of looking at an Alkaline Province

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ABSTRACT

The Mesozoic Alkaline Magmatism on the South American Platform is related to the Gondwana breakup and the opening of the South Atlantic Ocean. This event, known as the Mesozoic Activation phase, was responsible for five magmatic pulses, among them the Late Cretaceous-Eocene Alkaline Magmatism, which implemented ten alkaline provinces, eight of which are in the south-central portion of Brazil. Some authors claim that the reactivation of old zones of weakness from the Precambrian basement, Brasiliano orogeny, may have been responsible for the structuring of few bodies in these provinces. This work used geophysical processing techniques to interpret magnetic and gravity data and 2.5 D forward modeling to contribute with the knowledge on the tectonic control over the Goiás Alkaline Province. The geophysical data processing show a tectonic control over the Goiás Alkaline Province, along the Brasiliano and Mesozoic structures, and there was no predominance of alkaline bodies along the Azimuth 125. We find that the Brasiliano orogeny structures limited the crustal block that contains this Province and Gondwana breakup possibly created and reactivated these structures. We discuss the continuity of large structures, at different depths, related to the Tocantins Province, mainly in the Brasília belt, and some of them can be observed down to approximately 20 km depth. The forward gravity modeling beneath the Goiás Alkaline Province shows a thicker crust and we propose that the primitive lithospheric mantle below this province was not altered during the Brasiliano orogeny stages, as in the adjacent crustal blocks, thus allowing for generation of alkaline rocks. Along the modelled section the Arenópolis Magmatic Arc was separated into two different crustal blocks; the western arc whitin the Goias Alkaline Province, and the eastern arc where the mantle was altered due to its collision with the São Francisco Paleocontinent.

1. Introduction

The Tocantins Province (TP) (Fig. 1) is a Neoproterozoic Orogen formed by the collision of the Amazonian, São Francisco, Paranapanema paleocontinents and small allochthonous blocks (Brasiliano orogeny). This collision generated the Araguaia, Paraguay and Brasília Mobile Belts. The Brasília Belt (Fig. 2), the target of this work, is formed by External Domain, Passive Margin, Internal Domain and Goiás Magmátic Arc, were is located the Goiás Alkaline Province (GAP), a Mesozoic Alkaline Province, the focus of this work (Fig. 2) (Fuck et al., 2014, 2017; Pimentel and Fuck, 1992, 1994; Pimentel et al., 2000a, 2000b; Pimentel, 2016; Valeriano et al., 2008).

The External Domain comprises Araí, Paranoá and Bambuí groups (Fuck et al., 2014; Pimentel, 2016) (Fig. 2). Cordeiro and Oliveira (2017) observed that the geological units of the Cavalcante-Natividade Block are similar to the units of the Goiás Massif, showing no evidence of syn-collisional magmatism. According to the authors, this block is part of the Goiás Massif, being classified as Cavalcante-Arraias Domain, whose amalgamation occurred in the Paleoproterozoic. The Passive Margin is formed by Vazante, Paranoá, Canastra, Andrelândia, and Ibiá Groups (Fuck et al., 2014; Pimentel, 2016; Pimentel et al., 2004; Valeriano et al., 2004, 2008) (Fig. 2). The Internal Domain comprises the Metamorphic Core and the Goiás Massif (Fuck et al., 2014; Pimentel, 2016). Cordeiro and Oliveira (2017) subdivided the Goiás Massif into the Crixás-Goiás, Campinorte and Cavalcante-Arraias Domains (Fig. 2). The Goiás Magmatic Arc is divided into Mara Rosa (northern) and Arenópolis (south-southeastern) Magmatic Arcs (Cordeiro and Oliveira, 2017; Fuck et al., 2008, 2014; Laux et al., 2005; Pimentel and Fuck, 1994; Pimentel et al., 2000a, 2000b; 2004; Pimentel, 2016; Valeriano et al., 2008) (Fig. 2).

The GAP is located on the western edge of the Arenópolis Magmatic Arc, NNE of the Paraná basin (Fig. 2, blue dashed polygon), represented by dunites, clinopyroxenites, peridotites, alkali gabbro, trachyte, among others, dated between 88–90 Ma (Almeida, 1983; Brod et al., 2005;

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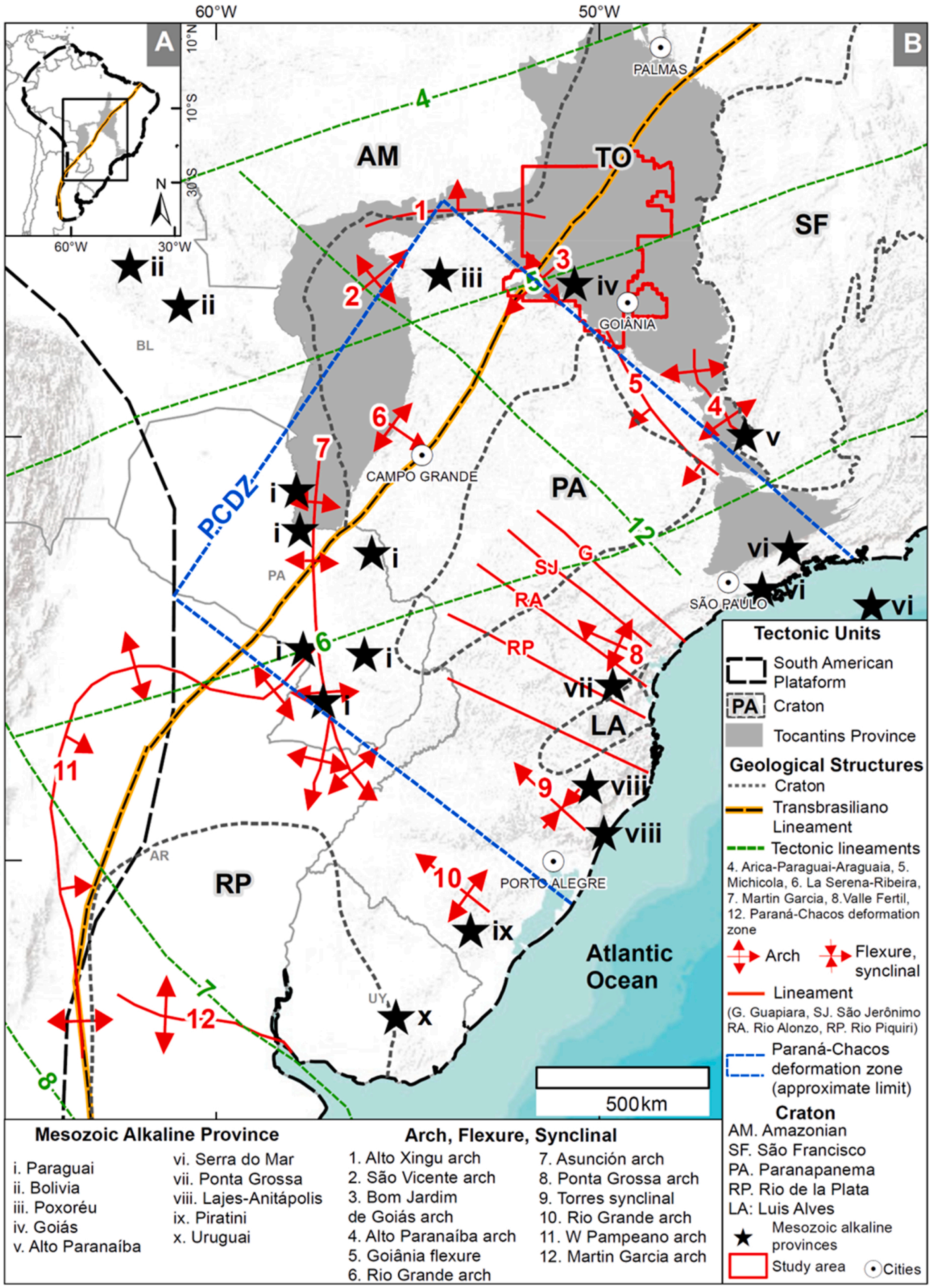

Fig. 1. Map showing the Tocantins Province in the South American Platform (A). Mesozoic alkaline provinces map and associated tectonic structures (B). **PCDZ** Paraná-Chacos Deformation Zone (blue dashed line) (adapted from Almeida et al., 1981; Almeida, 1983, 1986; Bizzi et al., 2003; Brod et al., 2005; Cernuschi et al., 2015; Comin-Chiaramonti and Gomes, 1996; Comin-Chiaramonti et al., 2005; Cordani et al., 2016; Gibson et al., 1995, 1997, 1999; Gomes et al., 1990; Jacques, 2003a, 2003b; 2004; Kirstein et al., 2000; Lagorio, 2008; Lustrino et al., 2005; Matton and Jébrak, 2009; Peyve, 2010; Riccomini et al., 2005; Thompson et al., 1998; Ulbrich and Gomes, 1981; Velázquez et al., 1996) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

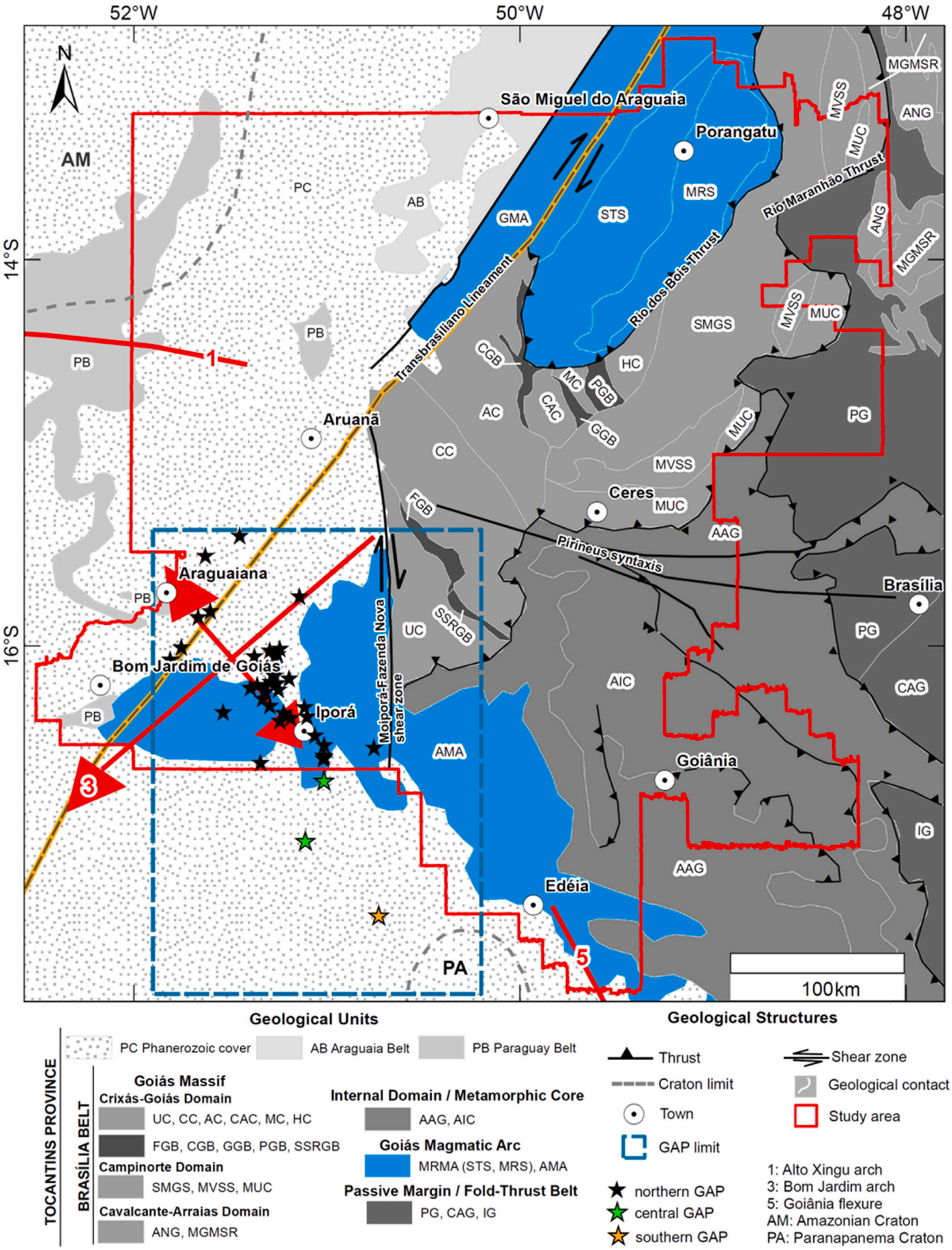

Fig. 2. Geological units of the Tocantins Province highlighting the Goiás Magmatic Arc (**GMA**) (blue polygon) and Goiás Alkaline Province (**GAP**) (blue dashed polygon). Brasília Belt: **UC** Uvá Complex, **CC** Caiçara Complex, **AC** Anta Complex, **CAC** Caiamar Complex, **MC** Moquem Complex, **HC** Hidrolina Complex, **FGB** Faina Greenstone Belt, **CGB** Crixás Greenstone Belt, **GGB** Guarinos Greenstone Belt, **PGB** Pilar Greenstone Belt, **SSRGB** Serra de Santa Rita Greenstone Belt, **SMGS** Serra da Mesa Group/Suite, **MVSS** Metavulcano Sedimentary Sequence, **MUC** Mafic Ultramafic Complex, **ANG** Araí/Natividade Groups, **MGMSR** Metagranite and Meta-sedimentary Rocks. **AAG** Araxá/Andrelândia Groups, **AIC** Anápolis-Itauçu Complex. **MRMA** Mara Rosa Magmatic Arc (**STS** Santa Terezinha Sequence, **MRS** Mara Rosa Sequence), **AMA** Arenópolis Magmatic Arc. **PG** Paranoá Group, **CAG** Canastra/Andrelândia Groups, **IG** Ibiá Group (adapted from Bizzi et al., 2003; Brod et al., 2005; Cordeiro and Oliveira, 2017; Fuck et al., 2014, 2017; Fuck et al., 2008; Jost et al., 2013; Lacerda Filho et al., 2018; Oliveira et al., 2000; Pimentel et al., 2000a, 2000b, 2004; Pimentel, 2016; Valeriano et al., 2008) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

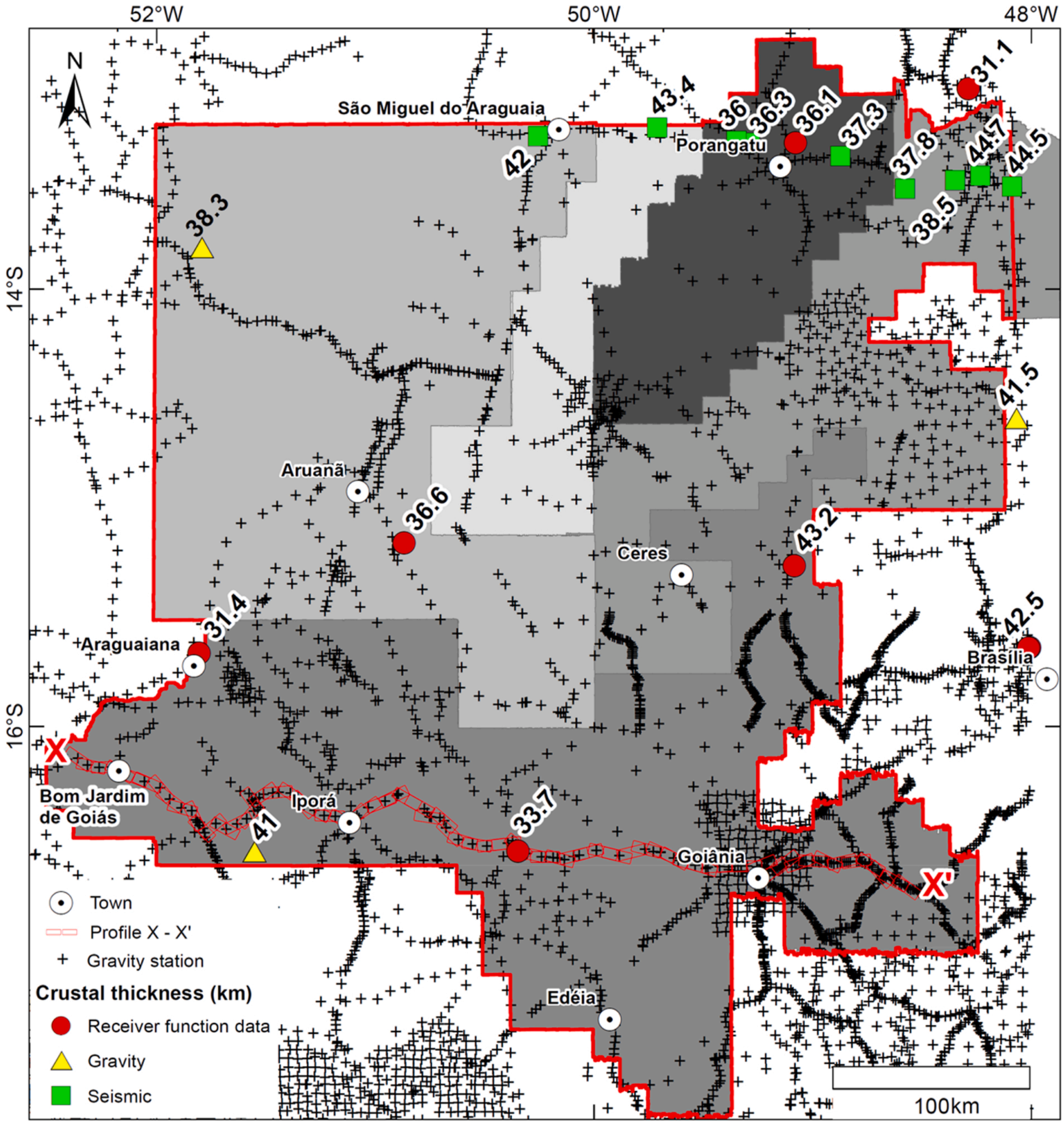

Fig. 3. Map showing the magnetic surveys in gray polygons (compiled from CPRM, 2004a, 2004b, 2005, 2012; LASA, 2006), study area (red polygon), gravity stations in black crosses (compiled from BNDG-ANP), crustal thickness (compiled from Assumpção et al., 2013; Bernardes, 2015; Pavão, 2014) and X-X' localization of the gravity profile forward modeled (red line) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Danni et al., 1990, 1994; Danni and Gaspar, 1994; Junqueira-Brod et al., 2005a, 2005b; Morbidelli et al., 1995; Ulbrich and Gomes, 1981).

The tectonic structures that limit the Geological Units of the Brasília Belt (Fig. 2) are still much discussed, such as the Rio Maranhão Fault, which represents the suture zone between the Goiás Massif and the São Francisco Paleocontinent (Soares et al., 2006). However, a more recent study by Cordeiro and Oliveira (2017) states that the Goiás Massif represents the western border of the São Francisco Paleocontinent while the Rio Maranhão Fault represents an intracontinental structure and not a suture zone (D'el-Rey Silva et al., 2008). In a recent work, Reis et al. (2020) affirm, from the analisys of magnetic and gravity data, that Rio Maranhão and Rio Paranã faults represent intracontinental structures agreening with previous interpretations (D'el-Rey Silva et al., 2008; Cordeiro and Oliveira, 2017). A more detailed study of the relationship of these structures with the GAP is necessary, and gravity and magnetic data can be used to verify this relationship.

The GAP and others Mesozoic Alkaline Provinces are concentrated in the south-central portion of the South American Platform, in the region named the Paraná-Chacos Deformation Zone - PCDZ, associated with arcs, flexures and tectonic lineaments (Jacques, 2003a, 2003b; 2004; Matton and Jébrak, 2009) (Fig. 1). The PCDZ is an intracontinental deformation zone formed by pre-existing basement faults that have been reactivated and accumulated stress during the Gondwana break up. In this period intra-plate reorganizations changed the intensity and direction of oceanic spreading, deep crustal movements, changing pole rotation and reactivations of ancient structures causing the alkaline magmatism that was named Paraná-Etedenka Igneous Province or Peri-Atlantic Alkaline Pulse (PAAP) (Almeida, 1971, 1966, 1983;

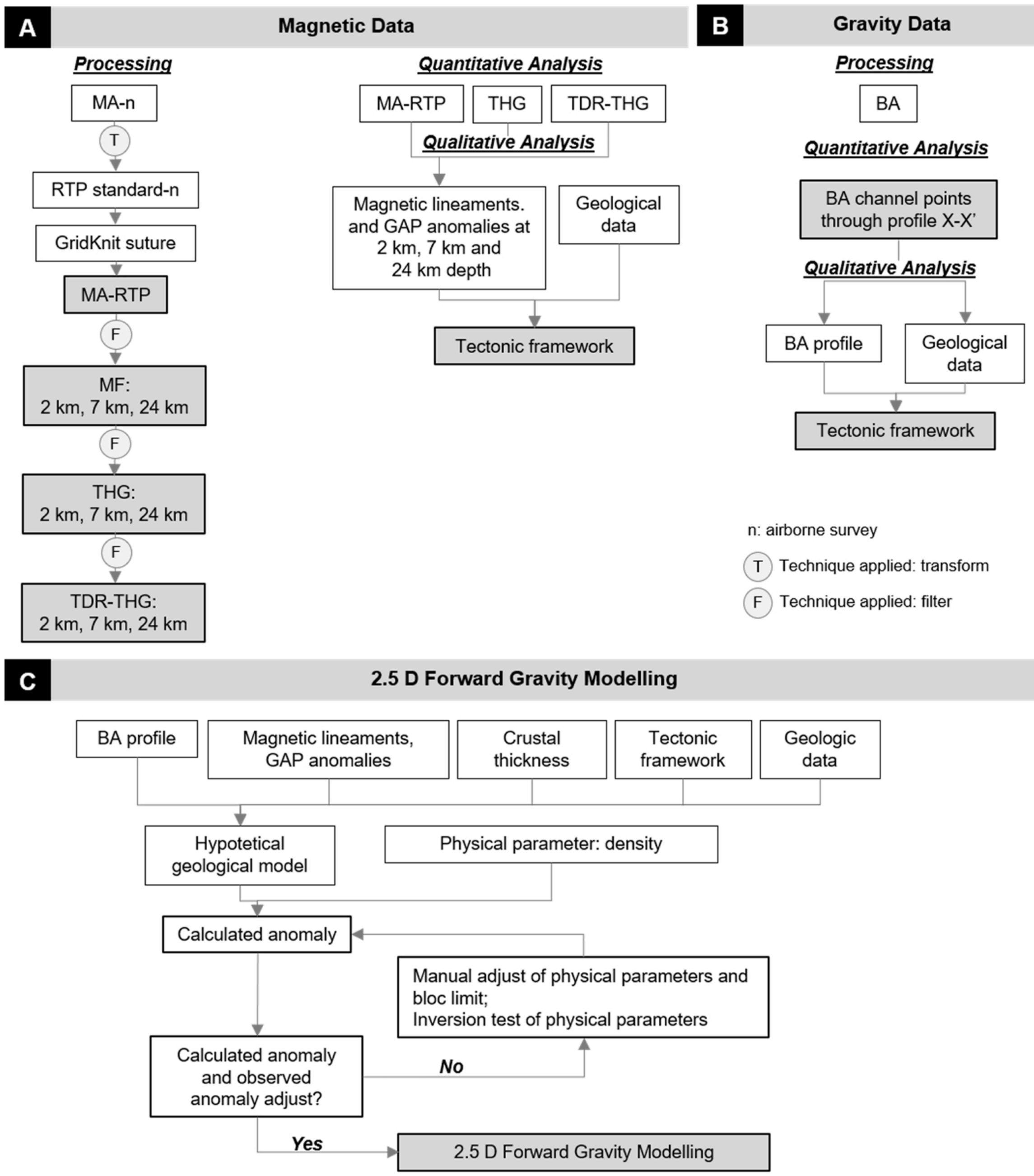

Fig. 4. Workflow chart (based on Blakely, 1996; Pinto and Vidotti, 2019; Revees, 2005). MA: magnetic anomaly, RTP: reduction to pole, MA-RTP: magnetic anomaly reduced to pole, MF: matched filter, THG: total horizontal gradient, TDR-THG: tilt derivative of the total horizontal gradient, GAP: Goiás Alkaline Province, BA: Bouguer Anomaly.

Comin-Chiaramonti et al., 1999, 2005; Gomes et al., 2018; Jacques, 2003a, 2003b; 2004; Matton and Jébrak, 2009; Riccomini et al., 2005; Sadowski, 1987). Changes in plate kinematics and seafloor spreading, opening of the Bay of Biscay – West Iberian Margin, culminated in alkaline intrusions between 105 Ma and 85 Ma in the west coast of Portugal (Miranda et al., 2009). Intracontinental rifting is also a tectono-magmatic event responsible for alkaline rocks generation, like Kola Alkaline and Carbonatite Province (380 Ma), northwestern Russia (Burke et al., 2007). On the other hand, the alkaline rocks can be generated by mantle plumes, as stated by Gibson et al. (1995, 1997, 1999) that affirm that the GAP origin is related to the Trindade Mantellic Plume.

Studies on the Brazilian Mesozoic Alkaline Provinces are mostly based on geochemical and geochronological data (Brod et al., 2005; Comin-Chaiaramoti et al., 2007; Gibson et al., 1995, 1997, 1999; Junqueira-Brod et al., 2005a, 2005b; Matton and Jébrak, 2009). Although there are also works based on geophysical data (Dutra and Marangoni, 2009; Dutra et al., 2012, 2014; Feitoza, 2011; Marangoni and Mantovani, 2013; Mantovani et al., 2015; Marangoni et al., 2015; Oliveira et al., 2015; Rocha et al., 2014, 2015, 2019a, 2019b), but, there is no specific work on the tectonic structure generated during the Brasiliano orogeny and the possible relationship of the Arenópolis Magmatic Arc and GAP.

The Arenópolis Magmatic Arc is the result of the crustal accretion of two arcs, the older arc is located in the west portion, is represented by orthogneisses and granitoids with emplacement ages between ca. 821 Ma and 782 Ma and the younger arc is located in the east portion of the Arenopolis Magmatic Arc and records the crystallization of

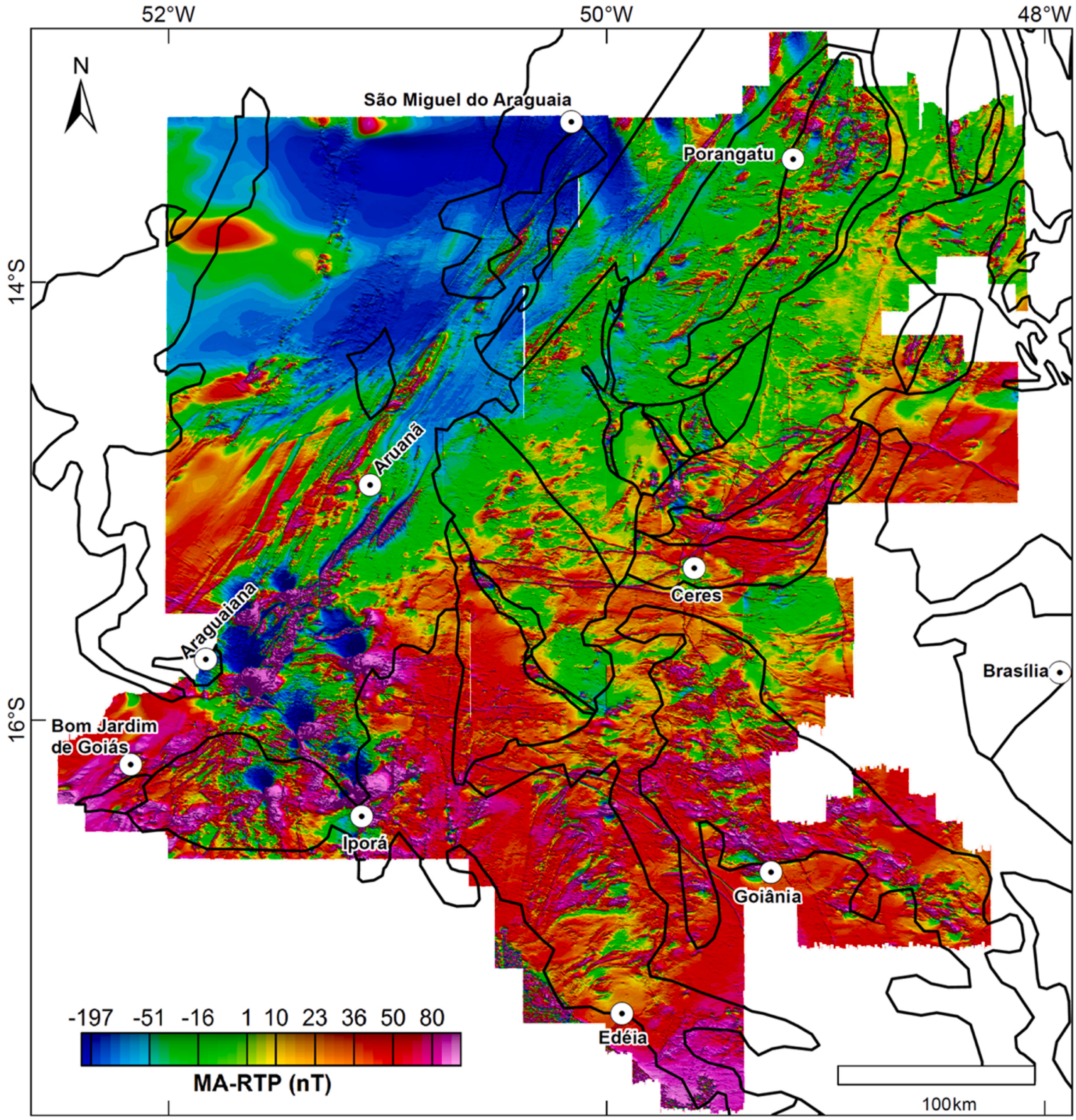

Fig. 5. Magnetic Anomaly-Reduced-to-pole map (MA-RTP). Black polygons represent the limits of the Geological Units according to Fig. 2.

metatonalites and metagranitic rocks between ca. 669 Ma and 630 Ma. However, the suture zone between these two arcs is unknown (Laux et al., 2004, 2005, 2010; Rodrigues et al., 1999). Therefore, this work proposes, based on magnetic and gravity data processing, and 2.5 D forward gravity modeling, of an E–W section, along the Arenópolis Magmatic Arc, to understand the tectonic framework of the Brasilia Belt and Arenopolis Magmatic Arc, in the context of Brasiliano Orogeny and Gondwana break up, and its relationship with the GAP.

2. Data and methods

Was used the magnetic data from five high-resolution aerial surveys (CPRM, 2004a, 2004b, 2005, 2012; LASA, 2006) provided by the Geological Survey of Brazil (CPRM) and ground gravity data provided by the Banco Nacional de Dados Gravimétricos (BNDG) - Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) (Fig. 3). The gravity data used came from different surveys and different campaigns made available by various institutions, including the Instituto Brasileiro de Geografia e Estatística (IBGE), Observatório Nacional (ON), Instituto de Astronomia, Geofísica e Ciências (IAG-USP), Instituto de Geociências (IGC-USP), Universidade de Brasília (UnB) and Petróleo Brasileiro S.A. (Petrobras). These data were processed using the Oasis Montaj® (Seequent) and ArcGIS® (Esri).

The magnetic data were acquired between 2004 and 2012, have N–S flight lines with 500 m spacing, 100 m flight height, 0.1 s sampling rate for magnetometers with 0.001 nT resolution. The 2.5 D gravity forward modeling was performed using GM-SYS Profile Modeling, the crustal thickness was compiled from Assumpção et al. (2013); Bernardes (2015) and Pavão (2014). Rock physical parameters (density and magnetic susceptibility) were based on Telford et al. (1990); Reynolds (1997) and Revees (2005). Seismicity and intraplate stress was acquired from Assumpção et al. (2004, 2013), Soares et al. (2006) and Rocha et al. (2011, 2016). Geological Units used are according to Alvarenga and Trompette (1993); Bizzi et al. (2003); Fuck et al. (2014); Pimentel et al.

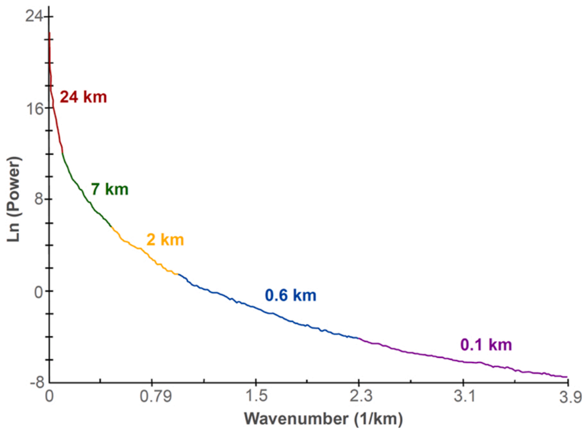

Fig. 6. Radial power spectrum from Reduced-to-pole Magnetic Anomaly, each different colored segment represents the depth to the top of different sources and its respective values.

(2000a) and Pimentel (2016), in addition to other information.

The Reduced to Pole transform (RTP) (Baranov and Naudy, 1964), the Matched Filter (MF) (Phillips, 2001), the Total Horizontal Gradient (THG) (Cordell and Grauch, 1985; Grauch and Cordell, 1987) and the Tilt Derivative of Total Horizontal Gradient (TDR - THG) (Ferreira et al., 2013) filters were used in this work (Fig. 4).

Initially, the Magnetic Anomaly (MA) was generated (MA-n), using the Bidirectional Interpolation method and 125 m cell size (Hinze et al., 2013; Isles and Rankin, 2013) (Fig. 4A). The intermediate latitude of the study area is -13 °S while the displaced from the source magnetic anomalies behave in a dipolar manner. This anomaly is common in intermediate to low latitudes (<90°) and RTP is recommended to centralize the anomalies by positioning them on the causative source (Baranov, 1957; Baranov and Naudy, 1964; Hinze et al., 2013). The MA grids reduced to the pole (RTP-n) were generated by applying RTP standard, and the magnetic field inclination (I) and declination (D), as well as inclination amplitudes, were calculated from the central coordinate and the average date of each survey (Curto et al., 2014; Hinze et al., 2013; Revees, 2005).

Only the magnetic anomalies referring to GAP were not totally centralized in this processing, which can be explained by the remnant magnetization present in these bodies (Dutra et al., 2012, 2014). This characteristic did not affect the interpretation of the referred anomalies because the work objective was to identify the number of anomalies observed at each analyzed depth. Subsequently, the RTP-n grids were joined, by the suture to each other method (Figs. 4A and 5), so the MF was applied. The MF was applied to observe the shape and continuity of magnetic anomalies, at different crustal depths, within the power spectrum (Cowan and Cowan, 1993; Hinze et al., 2013; Isles and Rankin, 2013; Phillips, 2001; Revees, 2005; Spector and Grant, 1970; Spector and Parker, 1979; Syberg, 1972). This work focus on anomalies from the deepest sources, 2 km, 7 km and 24 km depths, while the 0.1 km and 0.6 km were discarded for being related to noisy, highlighting high frequency and low depth anomalies (Fig. 6). All the depths intervals were obtained from band-pass filtering of the RTP magnetic anomaly and for the 2 km depth the wavelength intervals were 3800 m–20093 m. For the 7 km depth the wavelength intervals were 20093 m–252000 m and for the 24 km depth the wavelength greater than 252,000 m. Then THG and TDR-THG were applied (Fig. 4A).

In the qualitative analysis, the magnetic lineaments were interpreted from the MA-RTP, THG, and TDR-THG, in the three depth intervals (Fig. 4A). The magnetic lineaments may represent faults, fractures, geological contact, shear zones or dikes, and were interpreted in the 1: 2,000,000 scale, in the magnetic highs and lows, observing their continuity, following the stratigraphic principle of cross-cutting relationship. The few high-frequency N–S structures were considered as data noise and were not interpreted. Several magnetic lineaments were correlated to previously mapped geological structures, however, those that did not correlate with already mapped structures were named and are this work contribution.

The predominantly dipolar, circular, semicircular or elliptical magnetic anomalies were associated with the GAP (Fig. 4A) and interpreted in the magnetic highs of the CMA and in the center of the THG and TDR-THG (Fig. 4A). As previously mentioned, the THG and TDR-THG filters enhance the anomaly edges whereas the anomaly position in the GAP was interpreted, in this case, in the center of the circular anomalies.

The Bouguer Anomaly (BA) was interpolated from the minimum curvature, using 2000 m cell size and 5487 gravity stations (Figs. 4B and 7). In the quantitative analysis, BA values were extracted along the X-X' section and this information, together with the geological data, were used in the 2.5 D forward gravity modeling (Fig. 4B). Most of the anomalies interpreted in the work area are 2D, however, the anomalies related to the GAP have a three-dimensional (3D) character, are finite and approximately elliptical (length at least twice the width) when observed in plan. Hinze et al. (2013) stated that such characteristics allow classifying these anomalies as 2.5 D and, thus, to facilitate data interpretation and minimize the data ambiguity problem, the 2.5 D forward modeling technique was used in this work. In the 2.5D modeling, the BA information along the X-X' section, the magnetic lineaments, crustal thickness, geological database and other geological were used as input data (Fig. 4C).

A hypothetical geological model was elaborated with the possible limits of the crustal blocks while a spreadsheet was created with the physical (density) and geological parameters to feed this model and support the modeling. Geological and geophysical data (Gravity, Receive Function, Seismic Refraction data and Teleseismic P and S wave tomography) from Tocantins Province and adjacent regions were also compiled from Alvarenga and Trompette (1993); Assumpção et al. (2004, 2013), Azevedo et al. (2015); Bernardes (2015); Berrocal et al. (2004); Brod et al. (2005); Curto et al. (2014, 2015), Fuck et al. (2014); Laux et al. (2010); Macedo et al. (2018); Pavão (2014); Pimentel (2016); Pinto and Vidotti (2019); Rocha et al. (2011, 2016, 2019a, 2019b), Soares et al. (2006); Ussami and Molina (1999).

3. Results

3.1. Magnetic and gravity data

The magnetic (Figs. 5 and 8) and the Bouguer gravity (Fig. 7) anomalies were described separately for each Geological Unit (Table 1), then the magnetic lineaments were interpreted for each analyzed depth (Fig. 9).

The MA-RTP product at 2 km (Fig. 8A, D, G) shows intermediate intensity anomalies, except for the high-intensity anomalies, in the SW portion of the area, that refer to the GAP (black circle). The predominant NE-SW magnetic lineaments (Fig. 9A), have secondary NW-SE, WNW-ESE, ENE–WSW and E–W directions. Between the 15 °S and 16°30'S parallels, the NW-SE lineaments are predominant and secondarily, the NE-SW, NNW-SSE and E–W. In the area southern edge, the NE-SW lineaments predominate, followed by the NW-SE, NNW-SSE and E–W lineaments. At this depth 38 anomalies were associated with GAP (Fig. 8A, D, G).

The MA-RTP product at 7 km (Fig. 8B, E, H) show anomaly intensities vary from medium to low, while the greatest intensity contrast and highest gradients predominate in the GAP. The predominant NE-SW magnetic lineaments (Fig. 9B) have secondary NW-SE and E–W directions. At this depth 18 anomalies were associated with GAP (Fig. 8B, E, H).

The MA-RTP product at 24 km (Fig. 8C, F, I) show anomalies of low-intensity in the NW portion of the area, intermediate to low intensity in the NE portion, intermediate in the SE portion, and high in the SW portion. The high-intensity anomalies are due to the GAP, indicating the

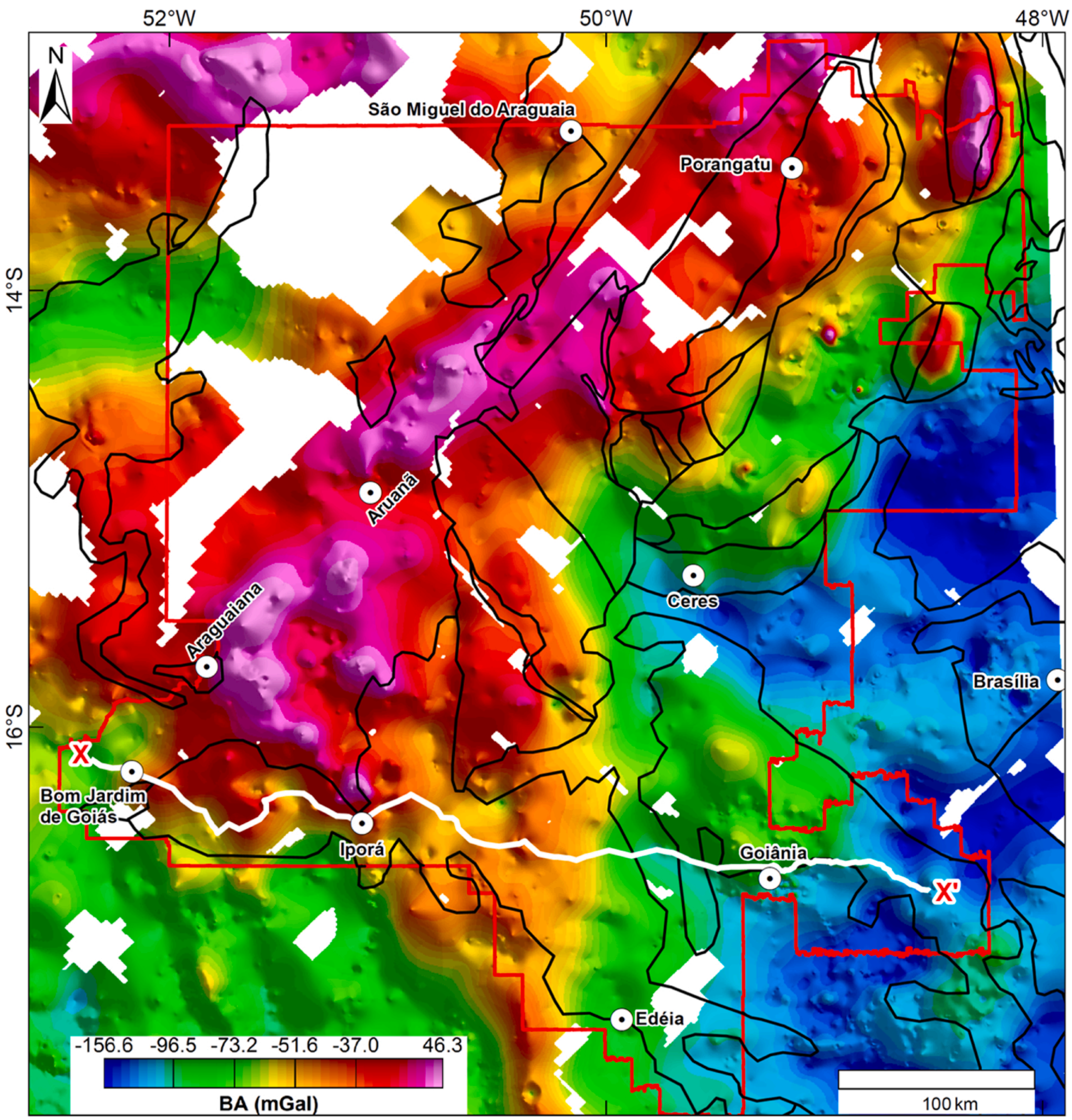

Fig. 7. Bouguer Anomaly map (BA) with gravity profile localization (X-X', white line) and study area limit (red polygon). Black polygons represent the limits of the Geological Units according to Fig. 2 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

body responses in the analyzed depth. The magnetic lineaments (Fig. 9C) have predominant NE-SW direction, while NW-SE lineaments are observed in the central and SE portion of the area. At this depth 11 anomalies were associated with GAP (Fig. 8C, F, I).

A map of the main lineaments was generated from the joint analysis of the lineaments at the three depths (Fig. 9D) and correlated with magnetic anomaly reduced to pole map (Fig. 9E). The longest and shortest magnetic lineaments were interpreted as Major and Minor Lineaments, respectively. The Main Lineaments were numbered from 1 to 15 and correlated to mapped geological structures (Fig. 9D). In the Table 2 it is possible to identify the nomenclature and references for each structure. Furthermore, the lineaments from 16 to 54 were not identified in the bibliography and are this work contribution. The Major Lineaments were named based on their location (Fig. 9D, Table 2), the town-town lineament assigned nomenclature indicates the town closest to the beginning of the lineament and the town close to the end of the lineament, within the interpreted area.

3.2. 2.5 D forward gravity modeling

The modeling resulted in 78 crustal blocks (Fig. 10), separated by fault, shear zone or other discontinuity, according to the identified lineaments and geological structures. The Bouguer Anomaly (Fig. 10A) varies between -25 mGal and -120 mGal along the X-X' section, defining the five predominant patterns that generated the hypothetical model. The hypothetical model used information from the magnetic lineaments (Fig. 9D) assuming they represent the limits between the different crustal blocks, while the Bouguer Anomaly (Fig. 7), was associated with information on the Geological Units. The crustal thicknesses represented by the red stars (Fig. 10B) were compiled by Assumpção et al. (2013); Pavão (2014) and Bernardes (2015), whereas the crustal thicknesses of the other blocks were estimated in the modeling and compared with

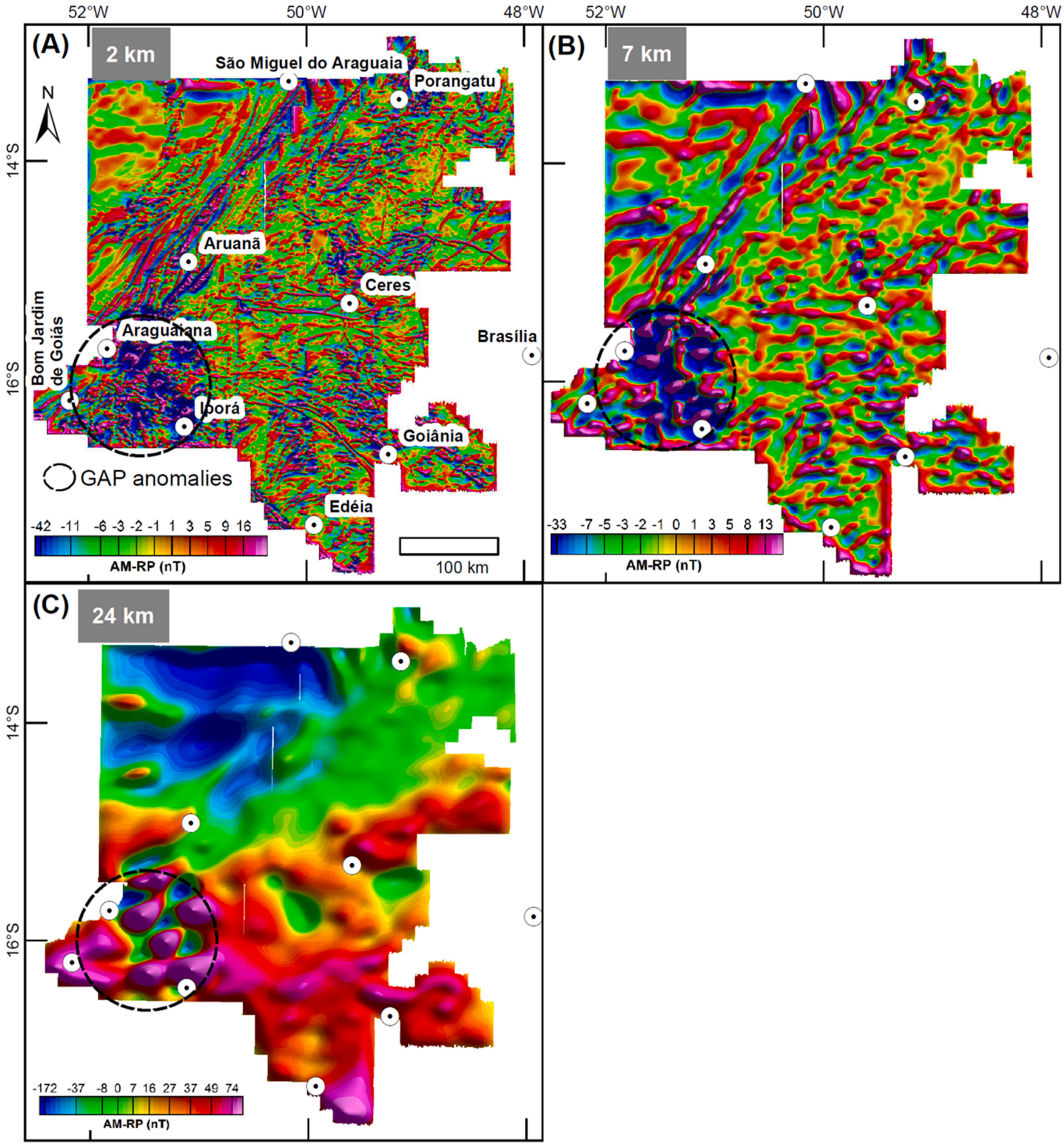

Fig. 8. Matched filter products from Reduced-to-pole Magnetic Anomaly (MA-RTP) at 2 km, 4 km and 24 km depths. Total Horizontal Gradient at 2 km, 4 km and 24 km depths. Tilt derivative from Total Horizontal Gradient at 2 km, 4 km and 24 km depths.

crustal thickness calculated in adjacent areas (Curto et al., 2015; Berrocal et al., 2004; Soares et al., 2006; Ussami and Molina, 1999).

For each Bouguer Anomaly pattern, the columns 1–5 (Fig. 10B) generated were divided into layers (A, B, C, and D), based on the varying vertical density. Column 1 was divided into three layers (A1, B1, and C1), with Bouguer Anomaly starting at -70 mGal and increasing up to approximately -30 mGal. Column 2 was divided into two layers (B2 and C2), with a predominantly constant Bouguer Anomaly pattern at -50 mGal and -25 mGal (M) peaks. Similarly, column 3 was divided into two layers (B3 and C3), with a constant Bouguer Anomaly pattern at about -60 mGal. Column 4 was divided into three layers (B4−1, B4−2, and C4), with the high Bouguer Anomaly gradient varying from -58 mGal to -100 mGal. Column 5 was divided into three layers (A5, B5 and C5), with low Bouguer Anomaly values varying between -100 mGal and -120 mGal and local high-intensity peaks (Fig. 10B).

The mean density of each block, the associated Geological Unit and the associated rock (Table 3) was used to generate the interpreted geological model (Fig. 11). Blocks A1 reach 7 km and B1 10 km depths and correspond to the upper crust. The C1 block reach 35 km depth and represent the lower crust (Fig. 10B). Block A1 was associated with Phanerozoic Cover and Paraguay Belt, and Blocks B1 and C1 were associated with the Goiás Magmatic Arc (GMA), and limited by the Serra Negra Fault to the east (Fig. 11). Block B2 has 24 km thick, represent the upper crust and locally is cut by high density blocks M. Block C2 reach 42 km depth and represent the lower crust (Fig. 10B).

Blocks B2 and C2 were associated with the Arenópolis Magmatic Arc - West (AMA-W), and was differentiated from the GMA by the Bouguer anomaly pattern, different crustal thickness, density and magnetic

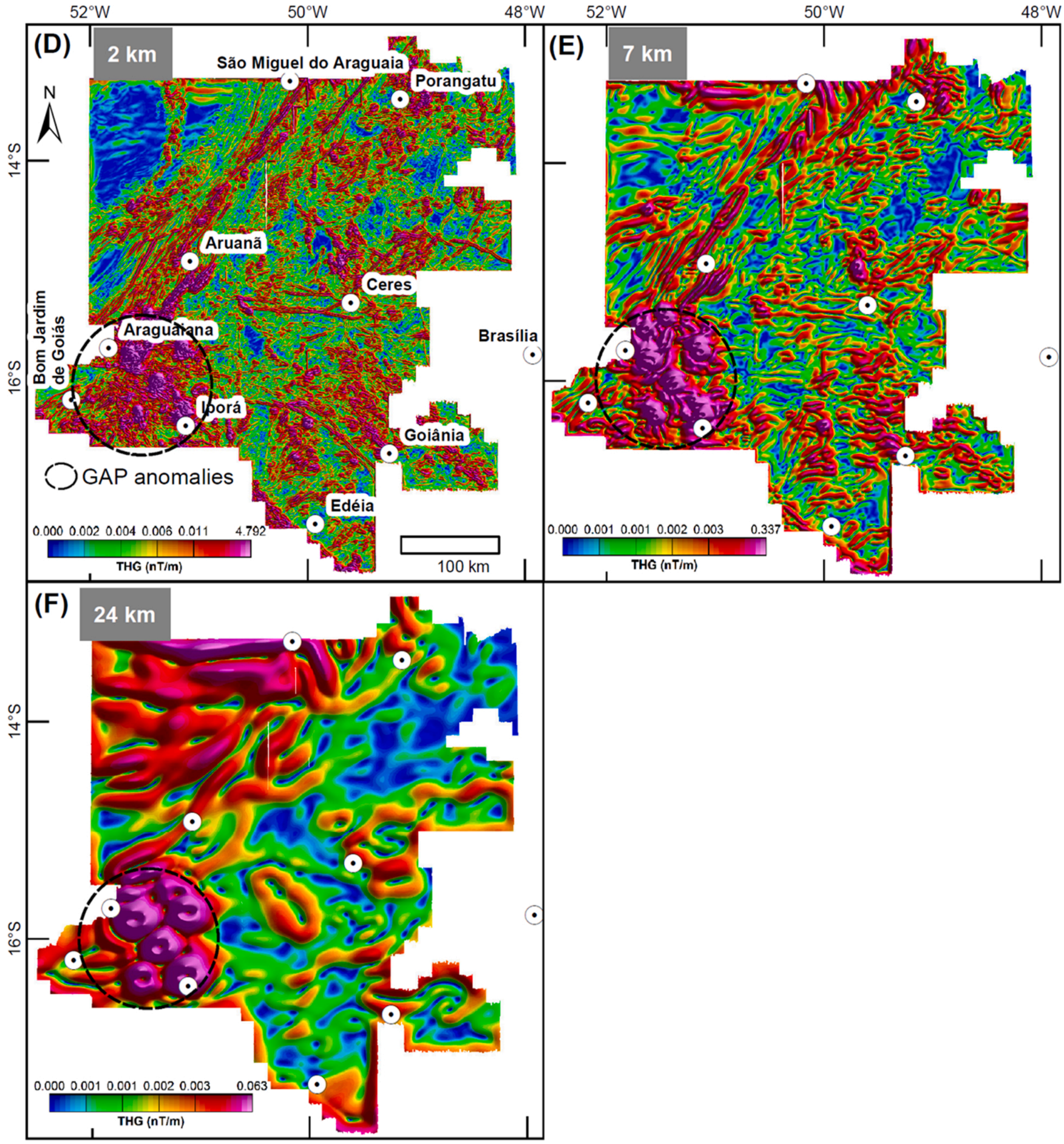

Fig. 8. (*continued*).

anomaly. Additionally, the alkaline bodies, with high Bouguer anomaly and magnetic intensities, only occur in the AMA-W (Figs. 10 and 11). High density Blocks M were associated with the Goiás Alkaline Province (GAP) and due to the proximity to mapped complexes were associated with the Arenópolis Complex (Fig. 11: 1 and 2), Fazenda Buriti Complex (Fig. 11: 3) and Morro do Macaco Complex (Fig. 11: 4). According to our modeling, a large volume of this high-density rock is located in the lower crust and may have been the source of the complex 1–4. The AMA-W eastern edge is marked by the Moiporá-Fazenda Nova Shear Zone (Fig. 11).

Block B3 has about 24 km thick and represent the upper crust. C3 block reach 34 km depth, represent the lower crust (Fig. 10B) and has crustal thickness lower than the AMA-W. Also, unlike the AMA-W, the AMA-E does not exhibit high-intensity Bouguer anomaly peaks and high magnetic anomaly. The AMA-E eastern limit is the Anicuns-Palmeiras Lineament, which represents, in the subsurface, the suture zone between AMA-E and the São Francisco Paleocontinent (SFPC) (Fig. 11).

Blocks B4−1 and B4−2 reach about 23 km thick and represent the upper crust. Block C4 reach 38 km depth and represent the lower crust (Fig. 10B). Based on the density values and geological information, Block B4−1 was also correlated to AMA-E, but as the block thickness and extension decreased to the east, we hypothesized that this block is partially covered by Block A5. The Block B4−2 may represent portions of Araxá/Andrelândia Groups (AAG) and Anápolis-Itauçu Complex (AIC) that were partially covered by AMA-E. In addition, a large part of block B4−2 and Block C4 were associated with SFPC due to the lower average densities compared to AMA-E. These geological units of different densities and thicknesses, together with the suture zone between AMA-E and SFPC, in-depth, caused a strong gradient in the Bouguer anomaly pattern over this region of the X-X' section (Figs. 10 and 11).

Blocks A5 has 7 km thick, B5 has 17 km thick and represent the upper

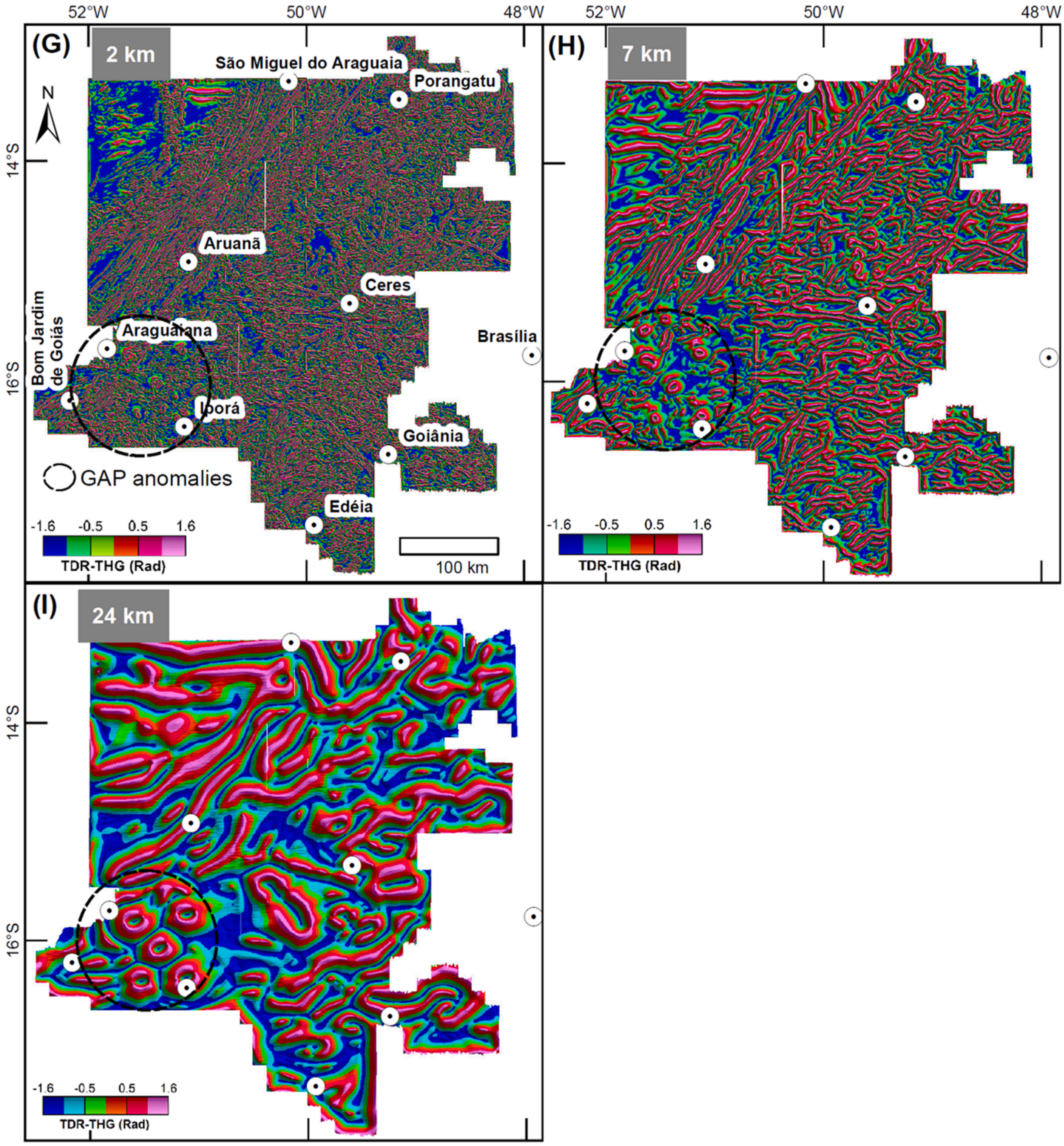

Fig. 8. (*continued*).

crust. Block C5 reach 38 km depth and represent the lower crust. (Fig. 10B). Block A5 was correlated to AAG and AIC, while the varying rock density of these units caused the Bouguer Anomaly to vary greatly over this region and, possibly, the lower Bouguer anomaly values reflect the lower density rocks of the AAG, while the Bouguer anomaly peaks reflect the high-grade metamorphic rocks of the AIC. The B5 and C5 blocks were associated with the SFPC (Fig. 11). Block D has a variable thickness and corresponds to the mantle (Fig. 10B).

4. Discussion

4.1. Magnetic lineaments and GAP relationship

The structures were separated into eight possible formation phases (Fig. 12A through H) based on the cross-cutting relationship and in the evolution of the Tocantins Province. This allowed to verify the relationship of the structures with the GAP (Fig. 9D).

The initial phase (Fig. 12A) affected the Crixás-Goiás Domain and formed Lineaments (41) (NW-SE) and (51) (NE-SW). Lineament (41) is parallel to the Faina and Serra de Santa Rita Greenstone Belts, marking the boundary between the Uvá and Caiçara Complexes (Figs. 12A and 2), and may represent the structure that gave rise to these Greenstone Belts or the suture between the Complex Uvá (Archean) and the other Archean complexes to the north. The collage between the terrains of the Crixás-Goiás Domain occurred before the Brasiliano orogeny (Cordeiro et al., 2014; Jost et al., 2005, 2013). The Uvá Complex represents a terrain formed independently of the terrains in the northern portion of the Crixás-Goiás Domain and, possibly, comes from fragments of the Amazonian or Paranapanema Paleocontinent (Jost et al., 2013).

Later (Fig. 12B) the NE-SW GPL (19), CML (20) and RMF (13) structures were generated during the formation of the Campinorte Domain, being later cut by the WNW-trending GMGL (24), which

Table 1
Magnetic and Gravity anomaly interpreted in the Geological Units of the study area (Geological Units detail see Fig. 2.

Geological Unit	Magnetic anomaly response	Gravity anomaly response
External domain	*This work assumes that the Cavalcante Natividade block is part of the Goiás Massif outside the study area.	
Passive Margin	**Fold-thrust belt:** outside the study area.	**Fold-thrust belt:** low-intensity anomalies are predominant (< -100 mGal).
	Metamorphic core **AAG:** intermediate to high-intensity anomalies (- 4 to 50 nT).	**Metamorphic core** **AAG:** intermediate to low-intensity anomalies (-63 to -100 mGal).
	AIC: high-intensity anomalies (50 to 1000 nT).	**AIC:** intermediate intensity anomalies are predominant (-63 to -100 mGal).
Internal Domain	**Goiás Massif** **CGD:** intermediate intensity anomalies predominate (7 to - 33 nT), high-intensity anomalies observed at UC (30 a 100 nT), greenstone belts and MUC.	**Goiás Massif** **CGD:** intermediate intensity anomalies are predominant (10 to -63 mGal).
	CD: intermediate intensity anomalies (- 30 to 10 mGal), high-intensity anomalies observed at MUC (10 a 30 nT).	**CD:** intermediate intensity anomalies (-80 to -50 mGal), high-intensity anomalies observed at some MUC (> 10 mGal).
	CAD: outside the study area.	**CAD:** outside the study area.
Goiás Magmatic Arc	**MRMA:** intermediate to low-intensity anomalies (7 to – 200 nT).	**MRMA:** intermediate to high-intensity anomalies (> -40 mGal).
	AMA: intermediate to high-intensity anomalies (> 17 nT).	**AMA:** intermediate to high-intensity anomalies (> -40 mGal).

extends to the vicinity of Ceres city, following almost parallel to the eastern limit of the Crixas-Goiás Domain. The Campinorte Domain was affected by two deformational events (Cordeiro et al., 2014; Cordeiro and Oliveira, 2017) and because these structures, as well as the structures observed in the Crixás-Goiás Domain, were identified only in the Goiás Massif, we believe that they may be related to these events that occurred between 3.10 Ga to 1.25 Ga (Cordeiro and Oliveira, 2017).

The Goiás Massif were amalgamated before the Brasiliano orogeny and represent a peripheral portion of the SFPC (Cordeiro et al., 2014; Cordeiro and Oliveira, 2017) whereas the RMF (13), assigned as a suture zone between GM and SFPC, represents an intracontinental structure (D'el-Rey Silva et al., 2008). The structures in Fig. 12A and B were interpreted as representing Pre-Brasiliano features and when associated with the anomalies of the alkaline complexes, indicate no relationship among them.

Between 0.8 Ga and 0.5 Ga, Brasiliano orogeny, four orogenetic pulses affected the Tocantins Province and in the final phase of this Orogeny, the extensive NE and NW shear zones developed (Almeida et al., 2000; Araújo Filho and Kuyumjian, 1996; Brito Neves et al., 2014; Brito Neves and Fuck, 2013; Pimentel et al., 2000a; Pimentel, 2016; Viana et al., 1995) may have been responsible for the structures identified in Fig. 12C, D, E and F.

We believe that the collision between the GMA and the GM formed the NE-SW XL (7), GCF (3), SNF (6), TBL (8), UPL (27), RBF (12), AML (16), APL (15), PIL (44) structures, and lineament (35) (Fig. 12C), and since these structures only affected the GMA, they were, therefore, associated with this collision event between 0.8 Ga to 0.77 Ga (Brito Neves and Fuck, 2013; Cordeiro and Oliveira, 2017; Pimentel et al., 2000b).

After this phase, HAL (18) was formed intercepting the structures observed in the northern portion of GMA (numbers 12, 27, 8 - Fig. 12C) and the eastern edge of the Crixás-Goiás Domain (number 24 - Fig. 12B). Subsequently, the BHF (4) and SLMBSZ (14) structures were formed and limited by HAL (18), and MFNSZ (10a) and MNBSZ (10b) were formed as well, limited by BHF (4) (Fig. 12D). Possibly, in this same phase, the NE-SW structure NXNPL (28) (Fig. 12E) was formed, intercepting the structures in the northern portion of the GMA (numbers 6, 8, 12, 27 - Fig. 12C).

Rodrigues et al. (1999) believed that MFNSZ (10a) and MNBSZ (10b) could represent an extension of TBL (8) however, based on the data analysis (Fig. 8) these structures are limited by BHF (4) to the north and do not connect to the TBL (8). MFNSZ represents an important discontinuity within GMA and between GMA and GM (Motta-Araújo and Pimentel, 2003).

The predominantly NW-SE structures highlighted in Fig. 12F intersect or are limited by the structures identified in Fig. 12C and D, related to the initial orogenetic pulses of the Brasiliano orogeny, being, therefore, associated with its final event (Brito Neves et al., 2014; Brito Neves and Fuck, 2013). At the end of the Brasiliano orogeny extensive tectonics was predominant in Western Gondwana due to the stabilization and collapse of the orogenic belts, and also due to the reflex of the compressive tectonics of Pampeana Orogeny (Cordani et al., 2013). In this period tectonic conditions favored the formation of dike systems, such as Azimuth125 (11), which intercepts the southern portion of the study area (Fig. 12F).

Azimuth 125 represents dike systems dated between 790 Ma and 118 Ma (Rocha et al., 2014, 2019a, 2019b) and possibly was reposinble for the tectonic control of alkaline magmatism in the Goiás Alkaline Province and in the others Brazilian Mesozoic alkaline provinces (Dutra et al., 2014; Marangoni and Mantovani, 2013; Rocha et al., 2014, 2015, 2019a, 2019b). After interpreting the magnetic data Rocha et al. (2019a, 2019b) reported that Azimuth 125 was not observed in the Mato Grosso and Rondônia states and concluded that this structure does not extend much west of the TBL, however, they were unable to detail the reason for its non-continuity.

As interpreted in this study it was noticed that part of Azimuth 125 (11) and FNAL (23) were partially displaced from the NW-SE to the NE-SW direction, and possibly continue under the Paraná Basin. The Azimuth 125, in the west of the TBL, occurs up to the vicinity of Campinápolis (Mato Grosso state), represents second and third-order shallow magnetic lineaments (Silva, 2018). However, this structure continuity into the Paraná Basin domain was not observed in the works by Pinto and Vidotti (2019) and Curto et al. (2015).

We believe that these structures were displaced due to reactivations of MFNSZ (10A) or HAL (18) (Fig. 12F). RMF (13) also displaces part of Azimuth 125 (11) such characteristics clarify the reason for the whole non-continuity of Azimuth 125 (11) in the west of TBL (8) (Figs. 9D and 12 F). Based on the cross-cutting relationship the Azimuth 125 were probably formed at the end of the Neoproterozoic and beginning of the Phanerozoic (Fig. 12F), and has estimated depth between 2 km and 7 km in the study area (Fig. 9A and B).

In the Mesozoic, during the Activation phase of the South American Platform, vertical movements predominated forming flexures and arcs (Almeida et al., 2000), such as the Alto Paranaíba, Rio Grande and Bom Jardim de Goiás Arcs, wich is located in the SW portion of the work area. The arches, as well as the reactivations of the TBL and other structures, played an important role in the emplacement of the alkaline intrusions (Almeida et al., 2000; Brito Neves and Cordani, 1991; Pena and Figueiredo, 1972).

The structures identified in Fig. 12G were associated with the Mesozoic (newly formed or reactivated) because they occur in the vicinity of the TBL and Bom Jardim de Goiás Arc, intersecting the lineaments PAL (26), (39), (38) and Azimuth 125 (11) (Fig. 12F). These are located predominantly in the AMA western edge with prevalent NE-SW direction while a large part is bounded by the BHF (4) to the north.

Several authors reported a high concentration of alkaline bodies throughout Azimuth 125 (Biondi, 2005; Bizzi and Araújo, 2005; Dutra et al., 2014; Marangoni and Mantovani, 2013; Mantovani et al., 2015;

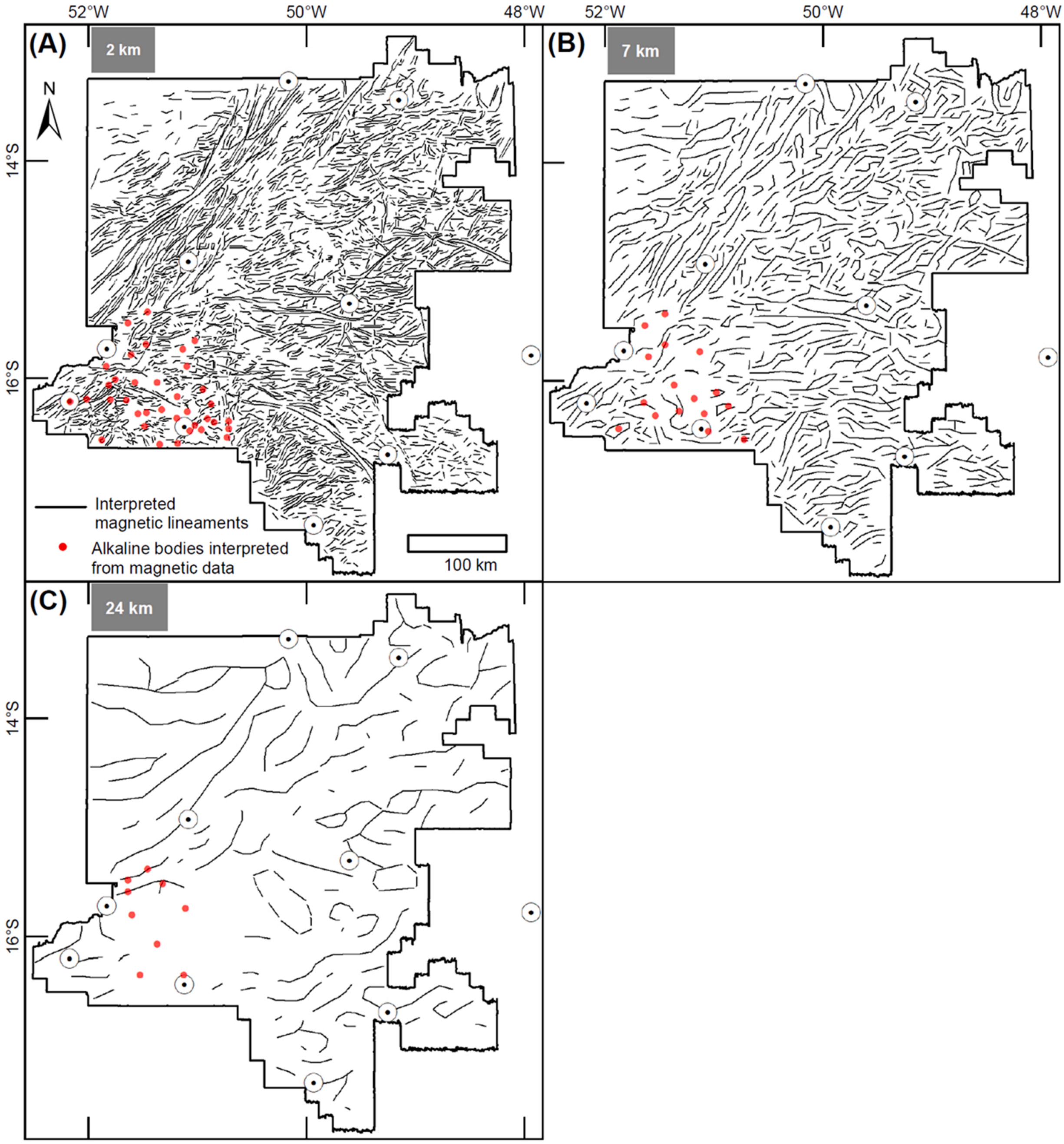

Fig. 9. Magnetic lineaments and alkaline bodies interpreted at 2 km (A), 4 km (B) and 24 km (C) depths. Map of major (numbered 1 to 54) and minor magnetic lineaments (not numbered) with kinematic interpretation, including all alkaline bodies interpreted at all depths (D). X-X' represent the profile modeled. Magnetic anomaly reduced to pole map and major lineaments (E). See Table 2 for magnetic lineament nomenclature details.

Rocha et al., 2014, 2015, 2019a, 2019b), however, our analysis indicated no preferable concentration of the GAP along the Azimuth 125 trend.

Furthermore, in the western edge of the AMA, limited by structures formed during the Brasiliano orogeny (Fig. 12C and D), a large concentration of alkaline bodies has been mapped and interpreted in the NW-SE and NE-SW structures generated in F and G phases, so we believe that the emplacement of GAP occurred preferably in the vicinity of structures generated at the end of the Brasiliano orogeny and the Mesozoic structures.

In the Cretaceous, Pena and Figueiredo (1972) state that the SW portion of the study area was affected by N50W gravity faults, forming a sequence of horsts and grabens, over 120 km long and 50 km wide. Pre-Cambrian structures were reactivated, and the emplacement of the alkaline magma occurred preferentially at the crossing of these structures (CPRM, 1974; Ohofugi et al., 1976; Pena and Figueiredo, 1972; Pena, 1975). Subsequently, the NE structures were reactivated and displaced some bodies of the GAP.

In the last phase (Fig. 12H), the formed E–W structures cross-cutting all the previously formed structures NXML (22), UAL (46), AJL (21), and SVL (5). These structures, of which many are seismogenic, were associated with Neotectonic activities (Hasui, 2010; Riccomini and Assumpção, 1999) (Fig. 13).

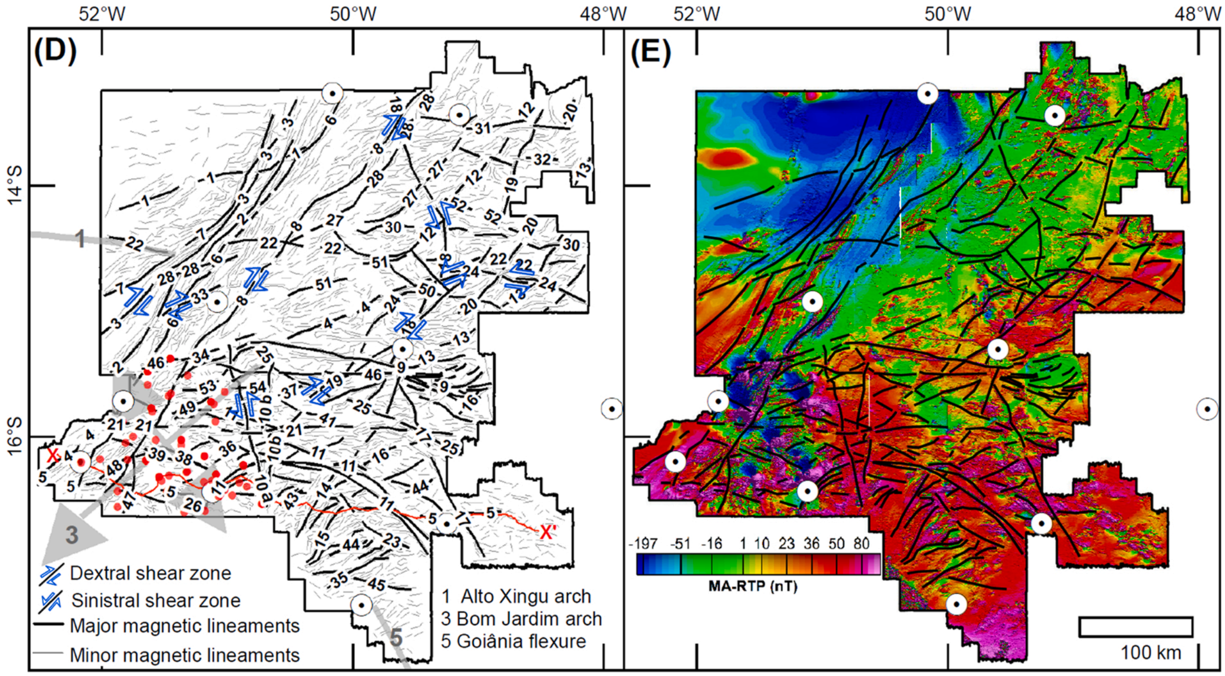

Fig. 9. (*continued*).

4.2. 2.5 D forward gravity modeling, arenópolis magmatic arc and GAP relationship

Along the X-X' section (Fig. 11) we identified the Paraguay Belt (PB), Phanerozoic Cover (PC), Goiás Magmatic Arc (GMA), Arenópolis Magmatic Arc - West (AMA-W), Goiás Alkaline Province (GAP), Arenópolis Magmatic Arc - East (AMA-E), Araxá and Andrelândia Groups (AAG), Anápolis Itauçu Complex (AIC) and São Francisco Paleocontinent (SFPC).

The PB and PC (Fig. 11) were modeled within the same block because well data were not available to used in this modeling. The gravity (Fig. 7) and magnetic (Fig. 5) data, as well as the geological model (Fig. 11), indicate that the geological unit under PB and PC, west of TBL (8), and west of SNF (6) until to the GCF (3) vicinity, represents the continuity of the GMA, while the GCF (3) represents the suture between the GMA and the Amazonian Paleocontinent (APC) (Fig. 13).

GMA (Fig. 11) extends to NE and SW (Pimentel, 2016) and represents the gravity low parallel to the TBL, under the Paraná Basin (Pinto and Vidotti, 2019). The intermediate to low intensity magnetic anomalies (Fig. 5) probably reflect the less magnetic rocks occurring above the GMA (Paraguai and Araguaia Belts, and PC). The Bouguer anomaly varies from intermediate to high (Fig. 7) in the GMA outcropping portion (near Porangatu), while the high values observed in the non-outcropping along NE-SW can be the response of rocks with higher density contrast. The GAP were not identified in the GMA. The predominantly NE-SW magnetic lineaments are observed up to 24 km (Fig. 8: G, H, I), partially coinciding with the occurrence of earthquakes (Fig. 13). On the other hand, seismic tomography data reflect low-speed anomalies of S and P waves (Assumpção et al., 2004; Rocha et al., 2011, 2016, 2019a, 2019b).

The GMA was identified west of the TBL in the São Miguel do Araguaia (Goiás state) vicinity marking the contact with the Amazonian Paleocontinent (Berrocal et al., 2004; Soares et al., 2006). This region was individualized in the Bom Jardim and Rondonópolis Domains separated by Baliza Fault (Curto et al., 2014). The U-Pb, Sm-Nd and Lu-Hf isotopic data of Aruanã (Goiás state) and Bom Jardim de Goiás (Goiás state) show T_{DM} model ages varing between 0.86 Ga and 1.03 Ga, that indicate a isotopic signature of juvenile Neoproterozoic arc, confirm the continuity of the GMA to the west of the TBL (Ferreira, 2009). The SNF (6) is the main fault of the TBL (Curto et al., 2014, 2015) being interpreted as the suture zone between GMA and AMA-W (Fig. 13).

The AMA-W is approximately 135 km long, has the largest crustal thickness, 42 km, and is limited by the MFNSZ (10a) to the east (Fig. 11), exhibiting high intensity magnetic (Fig. 5), high gravity anomalies (Fig. 7) and circular magnetic anomalies attributed to GAP (Fig. 5).

The GAP in the section were assigned to the Arenópolis, Fazenda Buriti and Morro do Macaco Complex (Fig. 11: 1–4). The Arenópolis Complex can be represented by gabbros, nepheline syenites, clinopyroxenites, and subordinate shonkinites (Brod et al., 2005). These bodies are located near the intersection of TBL (8) and lineaments (47) and (48) (Fig. 9). The Fazenda Buriti Complex can be represented by clinopyroxenite, melagabbro, essexites, syenogabbros and syenites (Brod et al., 2005) and are located close to the PJL (36) and Lineament (38) intersection (Fig. 9). The Morro do Macaco Complex can be formed by dunites, wehrlites, olivine pyroxenites and clinopyroxenites (Brod et al., 2005) and are located close to the Azimuth 125 (11), FNAL (23) and Lineament (38) intersection (Fig. 9).

The AMA-W northern limit is marked by BHF (4) which was interpreted as the suture between AMA-W and GM (Fig. 13). This portion is marked by earthquakes (Fig. 13) and to the north of BHF (4) the magnetic data presents the predominantly intermediate anomalies (Fig. 5) characteristic of the GM. It is believed that this arc southern limit occurs underlying the Paraná basin, corresponding to the D4 and D5 geophysical domains (Pinto and Vidotti, 2019), where the gravity anomaly is predominantly low, while the magnetic anomalies are intermediate to high with anomalies characteristic of the GAP.

The MFNSZ (10a) marks the eastern limit of the AMA-W (Fig. 13) and continues toward the south, turning SE where it connects with the Flexura de Goiânia (Pinto and Vidotti, 2019). Some lineaments are not observed in AMA-E, such as PJL (36), PAL (26) and lineaments (38), (39), (48) (Fig. 9).

Currie depth is predominantly greater than 49 km (Rocha et al., 2019a, 2019b) in agreement with the greater crustal thickness of this block (Assumpção et al., 2013; Bernardes, 2015; Pavão, 2014). There are few heat flow stations in the area, however, in general, the heat flow is lower over AMA-W and increase to the east of the X-X' profile modeled (Alexandrino and Hamza, 2007; Hamza et al., 2005, 2020). The anomalies of S and P waves have relatively lower speeds than those observed

Table 2
Nomenclature of major magnetic lineaments. The bold numbers and nomenclature are contribution of this study.

Lineament number	Nomenclature (Prefix)	Source
1	Campinápolis Lineament (CL)	Silva (2018)
2	Barra do Garças Lineament (BGL)	Sousa (2017)
3	General Carneiro Fault (GCF)	Curto et al. (2014, 2015)
4	**Baliza-Hidrolina Fault (BHF)**	Adapted from Curto et al. (2014, 2015)
5	São Vicente Lineament (SVL)	
6	Serra Negra Fault (SNF) (main TBL fault)	Curto et al. (2014, 2015)
7	Xambioá Lineament (XL)	Sousa (2017)
8	Transbrasiliano Lineament (TBL)	Schobbenhaus et al. (2004)
9	Pirineus Syntaxis (PS)	Araújo Filho (2000)
10a	**Moiporá-Fazenda Nova Shear Zone (MFNSZ)**	Adapted from Araújo (2012); Macedo et al. (2018); Pimentel and Fuck (1992)
10b	**Messianópolis-Novo Brasil Shear Zone (MNBSZ)**	
11	Azimuth 125	Bardet (1977); Rocha et al. (2014, 2019a, 2019b)
12	Rio dos Bois Fault (RBF)	Fuck et al. (2014)
13	Rio Maranhão Fault (RMF)	
14	**São Luís dos Montes Belos-Ceres Shear Zone (SLMBSZ)**	Adapted from Araújo (2012); Macedo et al. (2018)
15	Anicuns Palmeiras Lineament (APL)	Lacerda Filho et al. (2018)
16	**Adelândia-Moquém Lineament (AML)**	
17	**Itapuranga-Bela Vista de Goiás Lineament (IBVL)**	
18	**Heitoraí-Araguaçu Lineament (HAL)**	
19	**Guaraíta-Palmeirópolis Lineament (GPL)**	
20	**Ceres-Minaçu Lineament (CML)**	
21	**Aragarças-Jesúpolis Lineament (AJL)**	
22	**Nova Xavantina-Moquém Lineament (NXML)**	
23	**Fazenda Nova-Aragoiânia Lineament (FNAL)**	
24	**Guaraíta-Mimoso de Goiás Lineament (GMGL)**	
25	**Matrinchã-Ouro Verde de Goiás Lineament (MOVGL)**	
26	**Piranhas-Amorinópolis Lineament (PAL)**	**This study**
27	**Uirapuru-Porangatu Lineament (UPL)**	
28	**Nova Xavantina-Novo Planalto Lineament (NXNPL)**	
29	**Itapaci-Santa Terezinha de Goiás Lineament (ISTL)**	
30	**Uirapuru-Niquelândia Lineament (UNL)**	
31	**Porangatu-Minaçu Lineament (PML)**	
32	**Mutunópolis-Campinaçu Lineament (MCL)**	
36	**Piranhas-Jussara Lineament (PJL)**	
44	**Paraúna-Inhumas Lineament (PIL)**	
46	**Uruana-Araguaiana Lineament (UAL)**	
50	**Guarino-Barro Alto Lineament (GBAL)**	

in the GMA, indicating thinner lithosphere under AMA-W, about 150 km, and a possible relationship with the Trindade Plume. The lithosphere thickness increases to the east of the X-X' profile modeled, reaching about 175 km (Assumpçao et al., 2002; Rocha et al., 2011, 2016, 2019a, 2019b; Gibson et al., 1995, 1997, 1999). We believe that the AMA-W thinner lithosphere may have facilitated the partial melting of the mantle and generation of the GAP due to the impact of the Trindade Plume in the Mesozoic.

The AMA-E is approximately 125 km long extending to the APL (15) vicinity to the east, and representing, in-depth, the suture between AMA-E and SFPC (Fig. 11). Geochemical and geochronological data from the Anicuns (Goiás state) suggest that the Araxá/Andrelândia Groups (Fig. 2) represent a fore-arc sequence and mark the tectonic boundary between the GMA eastern edge and the SFPC (Laux et al., 2005, 2010). In the magnetic data, the same magnetic arc response was observed in the region to the east of APL (15) and south of the MOVGL (25), to the vicinity of Goiânia (Goiás state) and Edéia (Goiás state) (Fig. 8). However, the geological data marks the GMA continuity, following only towards Edéia (Pimentel, 2016). The arc eastern boundary, in this portion of the study area, was inconclusive in our modeling, and additional work is needed to verify whether this portion south and southeastern edge of the GMA, is part of the AMA-E or if there is another magmatic arc separated by the APL.

The AMA-E boundary with the southern portion of the GM occurs through the MOVGL (25), MNBSZ (10b) (Pimentel et al., 1996) and HAL (18) (Fig. 13). We believe that the NE limit, south of Ceres (Goiás state) is marked by the MOVGL (25) since, to the north of this structure the PJL (36) and lineaments (37), (49) and (53), occurring in AMA-W and AMA-E are not observed, just like HAL (18) does not occur in GMA (Fig. 12D), being bounded by MOVGL (25).

Magnetic anomalies and lineaments north of MOVGL (25) have a different pattern from that observed in AMA-E (Figs. 8 and 9), which continues towards the south, covered by the Paraná Basin, and the magnetic, gravity and crustal thickness characteristics representing the Geophysical Domain 6 identified by Pinto and Vidotti (2019). The AMA-E has intermediate magnetic (Fig. 5) and gravity anomalies (Fig. 7), crustal thickness of 34 km, less than the AMA-W, and Currie depth between 43 km and 48 km (Rocha et al., 2019a, 2019b), in agreement with the lower crustal thickness of the block (Assumpção et al., 2013; Bernardes, 2015; Pavão, 2014). The lithosphere thickness varies about 150−160 km (Rocha et al., 2019a, 2019b) and the anomalies of S and P waves have high speed, characteristic of a cooler lithosphere (Rocha et al., 2011, 2016, 2019a, 2019b), unlike that observed in GMA and AMA-W. These features allowed us to interpret that the lithosphere under the AMA-E may have been altered during the collision with the SFPC.

The Arenópolis Magmatic Arc was formed by two accretion events between 821 Ma to 782 Ma (Laux et al., 2005) and was responsible for forming the AMA-W. Whereas the second accretion event that formed AMA-E, took place between 669 Ma to 639 Ma, and generated rocks with an Nd isotopic signature indicating ancient sialic material, confirming the SFPC proximity or participation (Laux et al., 2005; Rodrigues et al., 1999).

Our geological model (Fig. 11) shows that in the collision with the SFPC, part of the AMA-E was raised and possibly delamination of the arc root was exhumed, being represented by the AIC. The exhumation of high-grade metamorphic rocks has also been reported in other parts of the Tocantins Province (Della Giustina et al., 2009a, 2009b; Gorayeb et al., 2017). The development of thrust systems with a vergence towards the São Francisco craton may have caused the exhumation of part of the root of the AMA-E (D'el-Rey Silva et al., 2008; Moreira et al., 2008), exposing the AIC, which is formed by high-grade metamorphic rocks, dating from the Neoproterozoic (Fischel et al., 1998; Piuzana et al., 2003a, 2003b, Pimentel et al., 1999).

High grade metamorphic rocks are formed by collisional orogeny (Zhang et al., 2018), examples of these exposure are

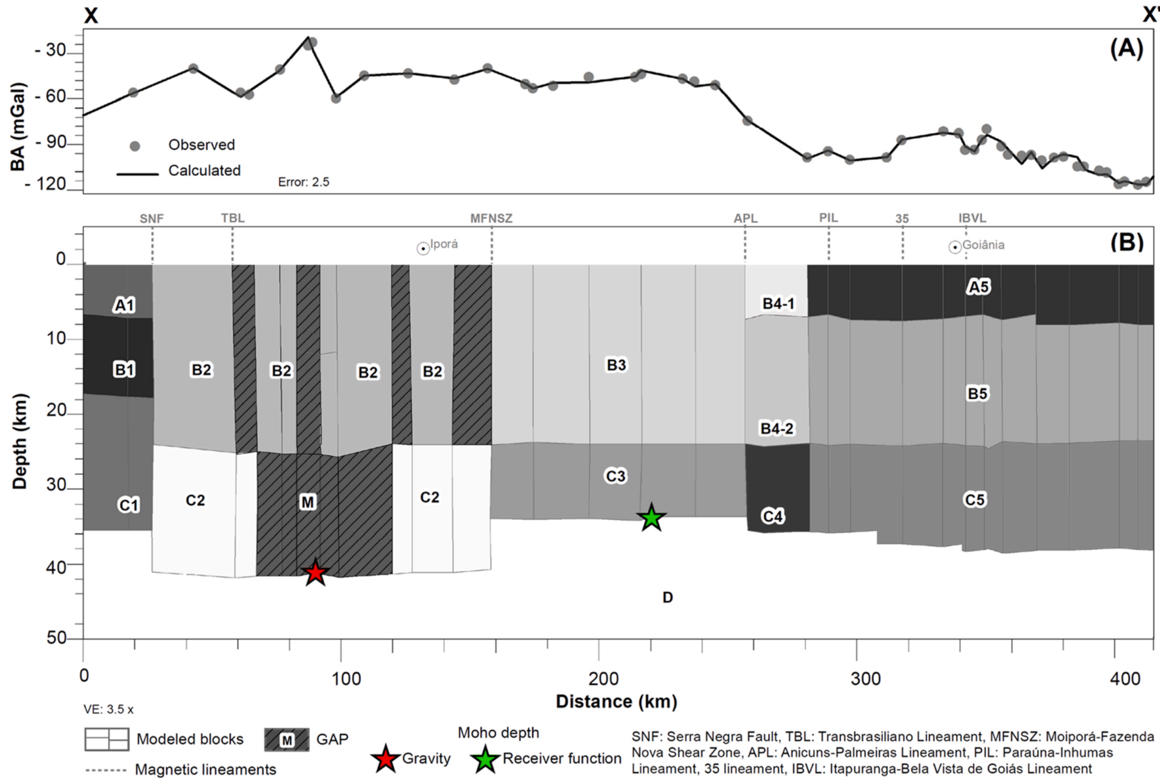

Fig. 10. Bouguer Anomaly profile showing observed anomaly (grey circle) and calculated anomaly (black line) (A). Geophysical model X-X' with modeled block (B), for details of the blocks see Table 3. Moho depth from gravity and receiver fuction are according to Assumpção et al. (2013); Bernardes (2015) and Pavão (2014). VE: vertical exaggeration.

Table 3
Physical and geological parameters of forward gravity modeling.

Lithospheric Domain	Block	Geological Unit	Associate Rock [a]	Density (kg/m^3) [b]		
				Min	Max	Mean
	A1	PB + PC	metasedimentary, granite	2663.8	2823.4	2743.6
	A5	AAG + AIC	quartzite, schist, paragneiss, marble, granulite	2664.8	2856.6	2769.6
	B2	AMA-W	calc alkaline orthogneiss, granite, volcanosedimentary	2975.6	2899.5.0	2858.3
	M	GAP [c]	dunite, pyroxenite, peridotite, nepheline syenite, alkaligrabbro, melanephelinite, olivine analcimite, basanite, etc.	2914.1	2996.9	2946.3
Upper Crust	B3	AMA-E	calc alkaline orthogneiss, granite, volcanosedimentary	2787.6	2812.4	2804.1
	B4−1	AMA-E				2753.8
	B1	GMA	orthogneiss, supracrustal	2708.3	2827.1	2767.7
	B4−2	SFPC	granodiorite, diorite			2683.5
	B5	SFPC		2611.5	2770.6	2716.4
	M	GAP	dunite, pyroxenite, peridotite, nepheline syenite, alkaligrabbro, melanephelinite, olivine analcimite, basanite, etc.	2915.3	2945.8	2926.5
	C1	GMA		2909.2	2937.4	2923.3
Lower Crust [d]	C2	AMA-W		2860.9	2892.5	2867.5
	C3	AMA-E	gabbro, mafic-ultramafic	2876.0	2981.4	2920.7
	C4	SFPC				2876.9
	C5	SFPC		2852.0	2962.1	2903
Mantle [d]	D		harzburgite, lherzolite			3368

PB: Paraguay Belt, PC: Phanerozoic Cover, AAG: Araxá/Andrelândia Groups, AIC: Anápolis Itauçu Complex, AMA: Arenópolis Magmatic Arc (W: West, E: East), GAP: Goiás Alkaline Province, GMA: Goiás Magmatic Arc, SFPC: São Francisco Paleocontinent.

[a] Alvarenga and Trompette (1993); Fuck et al. (2014); Pimentel et al. (2000a, 2000b, 2004); Pimentel (2016).
[b] Telford et al. (1990).
[c] Brod et al. (2005).
[d] Kearey et al. (2009).

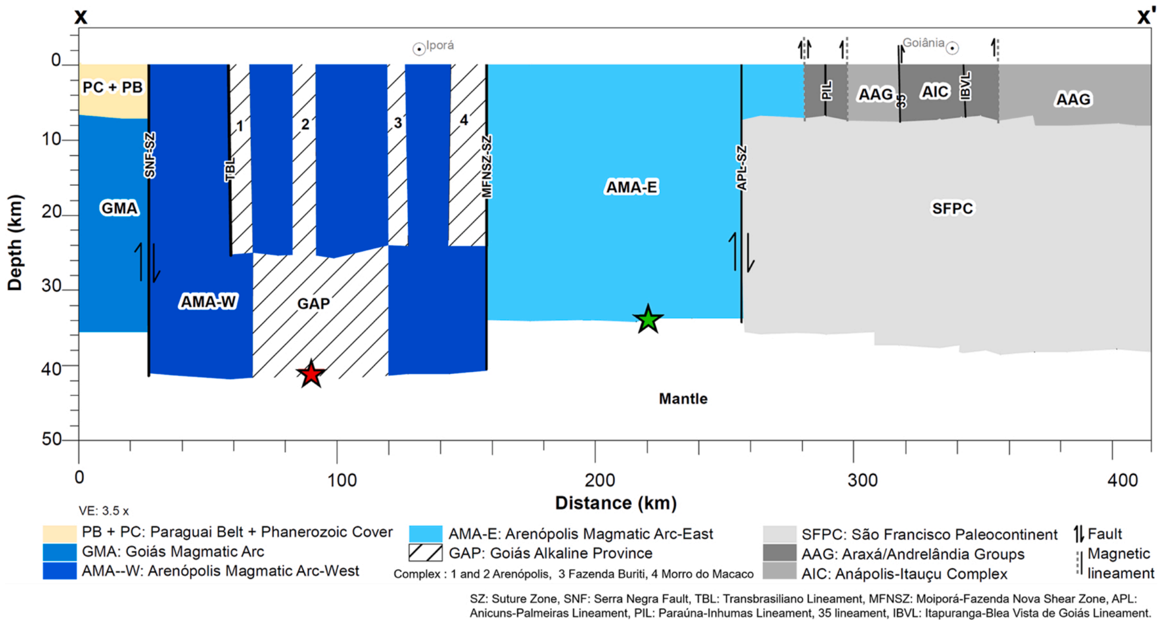

Fig. 11. Geological model based on 2.5 D geophysical model (Fig. 10B) and geological data. VE: vertical exaggeration.

Anápolis-Itauçu-Complex (AIC), in the study area (Moraes et al., 2002, 2007; Piuzana et al., 2003a, 2003b), Altun-Qilian-North Qaidam, NW China orogenc system (Zhang et a., 2018) and the Dabie-Sulu orogenic belt, NE China (Zheng et al., 2020). It indicate metamorphism between 100–150 km depth and surface exposure represents an extreme case of exhumation of root orogen (Ring et al., 1999), that can occur in the early stages of a continental subduction or may be related to a continental collision (Teyssier, 2011). The collisional orogeny evolves from a sin collisional phase with crustal shortening to a post collisional phase with crustal thinning. This transtition is marked by transtensional strucutres formation, such as ductile shear zones, wich can be subject to the exhumation of high grade metamorphic rocks, as reported in Altun-Qilian-North Qaidam orogenic system (Zhang et al., 2018). Structures like these may have been responsible for the exhumation of the AIC (Moraes et al., 2002, 2007) wich has as protoliths the Goiáas Magmatic Arc Neoproterozoic rocks (Piuzana et al., 2003a, 2003b).

There are still many doubts about the origin of the AIC, however, it is known that it does not represent the exposure of an Archean sialic basement as stated by Lacerda Filho et al. (1999). The replacement of the lithospheric mantle by the asthenospheric one, and the displacement of the orogenic root or the slab break-off may have been the possible mechanisms responsible for forming the AIC (Moraes et al., 2002).

During the collision of the Arenópolis Magmatic Arc (AMA) whit the São Francisco Paleocontinente (SFPC) part of the lithosphere of the Arenópolis Magmatic Arc-East (AMA-E) may have been removed by convective forces and exhumed to the surface. The exhumed rocks, AIC, occur interlayed with the Anapolis-Itauçu complex (Fig. 11). After exhumation the AMA lithospheric mantle may have been replaced by astenospheric mantle and this change in mantelic characteristics affected only the AMA-E wich is closer to SFPC (Laux et al., 2005; Rodrigues et al., 1999). We believe that the exhumation process changed the original characteristics of the primitive mantle over AMA-E, not allowing the formation of alkaline provinces.

5. Conclusions

The geophysical data analysis revealed the tectonic structures of the Tocantins Province, one of the most complete Neoproterozoic (Brasiliano – Pan African) Orogen in Western Gondwana, and their relationship with Goiás Alkaline Province.

We interpret the continuity of large tectonic structures in-depth, up to approximately 20 km, such as Rio Maranhão Fault, Baliza-Hidrolina Fault and Guaraíta-Palmeirópolis Lineament.

The GMA was divided into GMA, AMA-W and AMA-E crustal blocks, delimited by Serra Negra Fault, Moiporá-Fazenda Nova Shear Zone and Anicuns Palmeiras Lineament.

The GMA has a smaller crustal thickness than AMA-W, concentrates a large part of the earthquakes and is bounded by the Baliza-Hidrolina Fault to the east and by General Carneiro Fault to the west.

The AMA-W is bounded by the Baliza-Hidrolina Fault and Lineament 34 to the north, Serra Negra Fault to the west, Moiporá-Fazenda Nova Shear Zone to the east, and by the geophysical domains 4 and 5 to the south-southeast (Pinto and Vidotti, 2019). GAP occurs only in AMA-W that has the more primitive mantle and has not changed due to collision processes with the adjacent blocks, allowing the formation of alkaline rocks. In the AMA-W block the modeled section intercepted Arenópolis, Fazenda Buriti and Morro do Macaco complex, indicating a possible common magmatic source for the alkaline complexes located in the lower crust of this block.

The emplacement of the GAP occurred during the Gondwana breakup, preferably in the vicinity of NW-SE and NE-SW structures, generated at the end of Brasiliano orogeny and Mesozoic structures. From our analysis the GAP were not preferably concentrated along the Azimuth 125 trend. We believe that the Gondwana breakup possibly created and/or reactivated the structures related to Goiás Alkaline Province.

Locally the Azimuth 125 is displaced from the NW to the SE direction by the Moiporá-Fazenda Nova Shear Zone, Heitorai-Araguaçu Lineament and Rio Maranhão Fault. Moiporá-Fazenda Nova Shear Zone does not extend up to the LTB since it is limited by the Baliza-Hidrolina Fault to the north.

AMA-E is bounded by the Matrinchã-Ouro Verde de Goiás Lineament to the northeast, by the Anicuns Palmeiras Lineament to the east, and continues under the Paraná Basin to the south. This arc mantle has anomalous characteristics due to collision with the São Francisco Paleocontinent that avoid the formation of alkaline provinces.

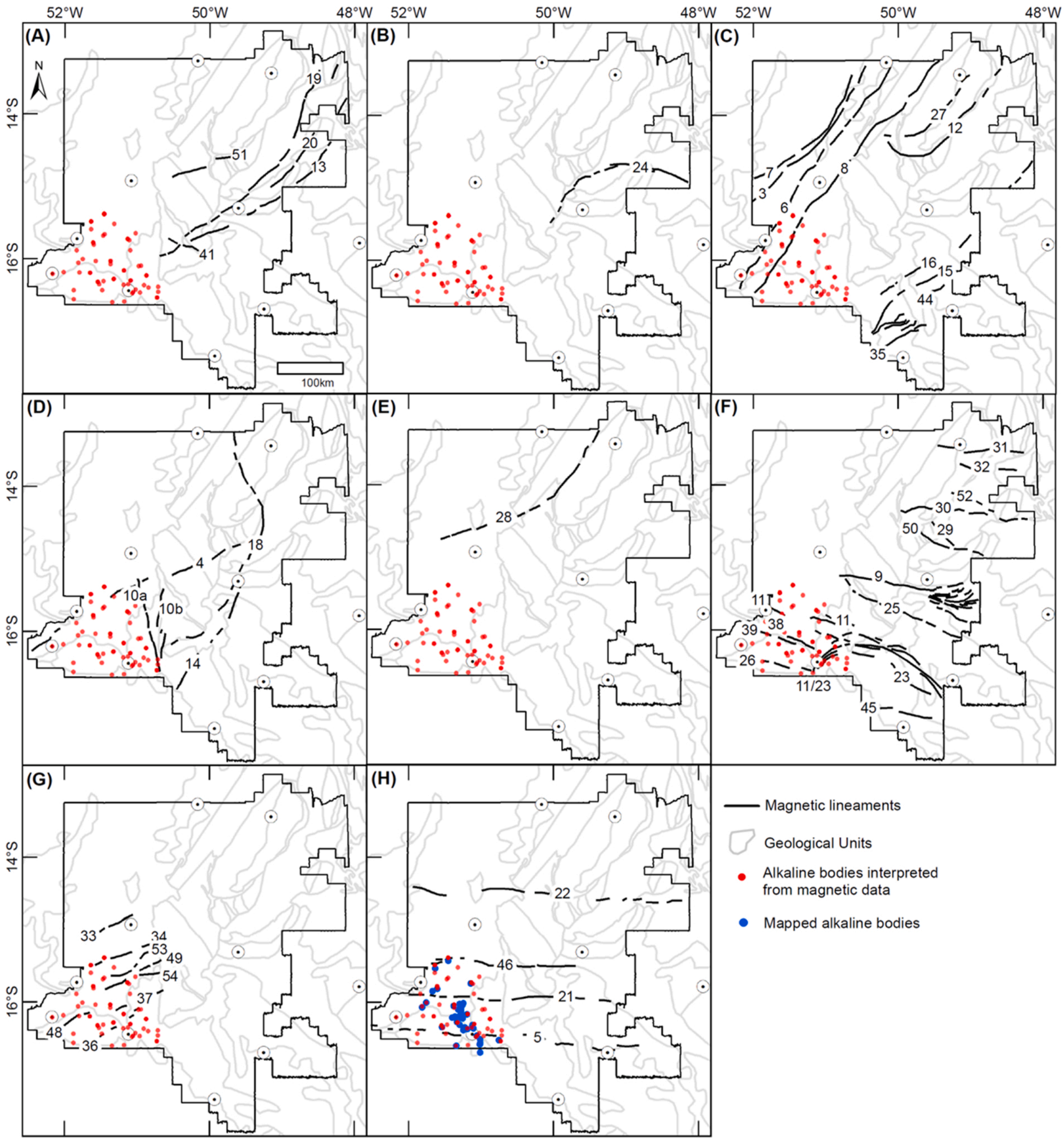

Fig. 12. Major magnetic lineaments associated with the evolution of the Tocantins Province (A, B: Archean/Paleoproterozoic age. C, D, E: Neoproterozoic age. F: Neoproterozoic to early Phanerozoic age. G: Mesozoic age. H: Cenozoic age). Blue circles represent mapped alkaline bodies (Lacerda Filho et al., 2018), Geological Units limits (according to Fig. 2) and magnetic lineament numbers (according to Table 2) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

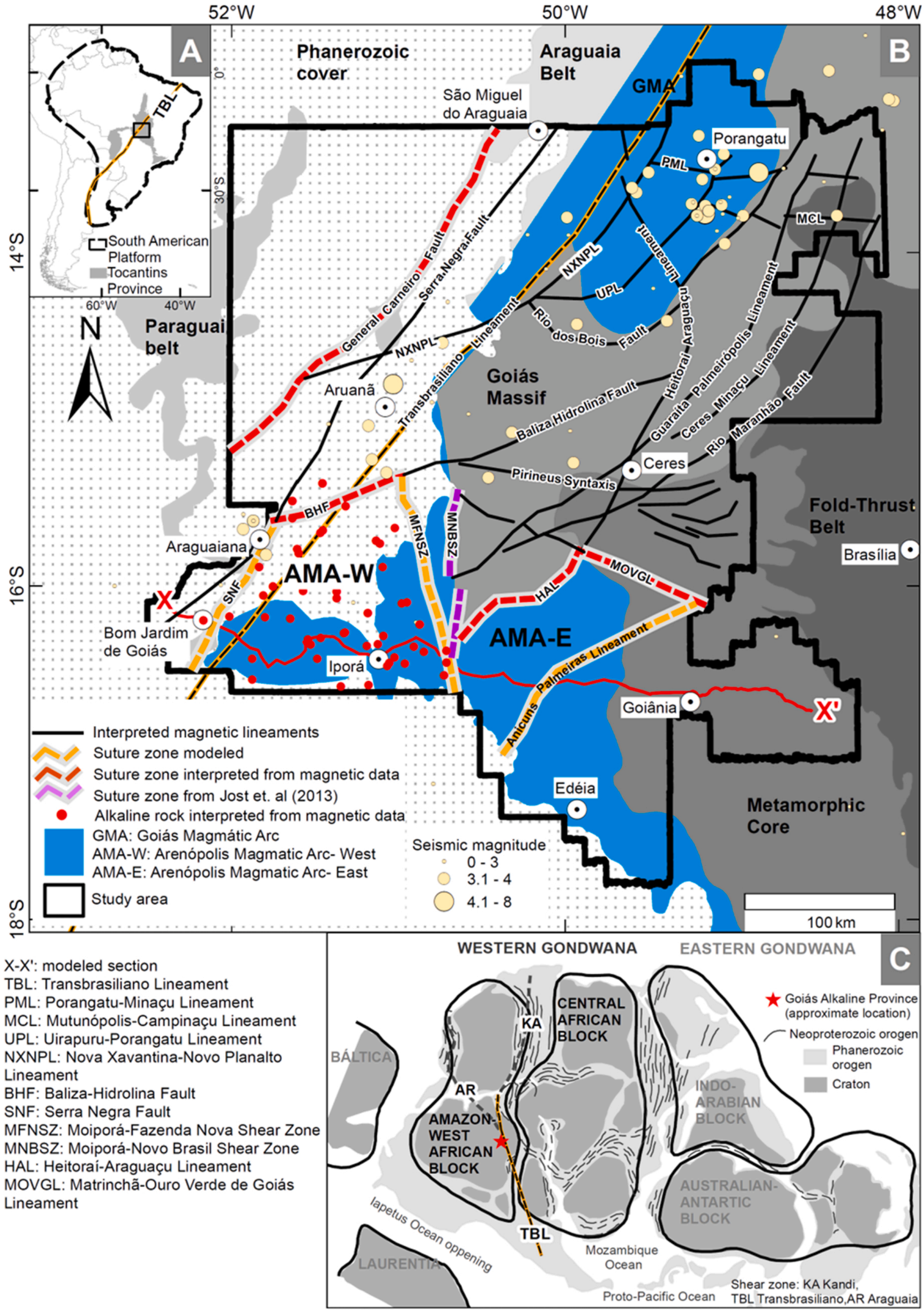

Fig. 13. Geophysical compartmentation of the Goiás Magmatic Arc. Seismic magnitude according to Assumpção et al. (2004, 2013); Cordani et al. (2013); Rocha et al. (2011, 2016); Soares et al. (2006).

The forward gravity modeling highlights a thick crust and a relative thin mantle (Rocha et al., 2019a, 2019b) below the AMA-W. We believe that the primitive mantle lithospheric in this block was not altered during the Brasiliano orogen stages like the adjacent crustal blocks allowing the generation of alkaline rocks.

Finaly, the geophysical data processing proved to be another way to study tectonic structures and alkaline provinces.

CRediT authorship contribution statement

Elainy S.F. Martins: Formal analysis, Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Roberta M. Vidotti:** Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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3. MVI IN PROSPECTING TARGETS FOR MINERAL EXPLORATION IN THE GOIÁS ALKALINE PROVINCE

Highlights

- The Magnetic Vector Inversion revealed that the Goias Alkaline Province is formed by twenty-one alkaline complexes.
- These bodies were formed by at least three magmatic pulses based on the magnetization vector.
- The emplacement forms observed were pipe, t-shape, funnel, finger, and dike.
- The new bodies bodies have top depths ranging from 0.5 km to 3 km.

Abstract

The Goias Alkaline Province (GAP) is formed by 11 alkaline complexes ranging from mafic and felsics rocks, plutonic to volcanic that also exhibit strong remnant magnetization. This province has great economic importance with strong potential for Ni, Cu, Vermiculite, P_2O_5, among others. Several GAP complexes were previously modeled by the conventional inversion method such as magnetic susceptibility, however, this inversion method is not the most adequate and may lead to erroneous interpretations due to the remnant magnetization of the rocks. The previously inverted bodies were assigned a fixed value of remnant magnetization and cylindrical shape, however, from geological data it is known that these bodies were formed by different magmatic pulses, with different forms of emplacement, reflecting directly on the body shape and remnant magnetic field. Therefore, these bodies are expected to have different geometric shapes and different values of remnant magnetization. A more detailed analysis of each complex becomes necessary to obtain a more updated individual shape, emplacement form and remnant magnetization values. This information on the three-dimensional geometry of subsurface bodies can be obtained from geophysical methods, such as magnetic inversion. In this case, the Magnetic Vector Inversion (MVI), considered the most suitable inversion method, was applied to all GAP complexes in an adjacent area to identify new bodies and types of emplacements as well as their geometry. The MVI proved to be very efficient to study already known complexes and identify new GAP complexes. The data analysis performed revealed 10 new smaller complexes that were assigned to the GAP. These bodies vary between exposed and non-outcropping, and among the non-outcropping, one body has the top located 100 m below the surface. The results indicate that the magnetic susceptibility characteristics of the MVI vary based on the lithology of the alkaline and host rocks, as well as on the size of the modeled area, thus it is not possible to assign a specific magnetic susceptibility value for identifying these complexes, other information is needed. The geometry of the bodies is varied, the types of emplacements observed are pipe, t-shape, funnel, finger, and dike. Many of the bodies are associated with Brasiliano and Mesozoic tectonic structures. These bodies formed at least three magmatic pulses, based on the magnetization vector. Magnetic inversion by MVI was very efficient for identifying the new GAP bodies and

the methodology used can be replicated for prospecting new targets in other geological contexts.

Keywords: Goias Alkaline Province, Magnetic Vector Inversion, emplacement geometry

1. Introduction

The magnetic method is based on the positive or negative variations of the magnetic field due to lateral and vertical variations of the subsurface magnetism. Magnetism is the vector result of induced and remnant magnetization caused by the presence of accessory minerals such as magnetite, titanomagnetite, titanohematite, maghemite, pyrrhotite, greigite, in the causative source. Induced magnetization reflects the magnetic susceptibility of materials and the magnitude and direction of the magnetic field whereas remanent magnetism is the permanent magnetization that reflects the history and origin of the material (Hinze et al., 2013).

The quantitative parameters of the causative source, such as shape, volume, depth, body inclination, among others, can be estimated by inverse modeling or magnetic inversion. Inverse modeling of magnetic data is widely applied to mineral exploration to assist the identification of mineralized targets, drillhole location, body inclination, among others (Hinze et al., 2013; Oldenburg & Pratt, 2007).

In the conventional Magnetic Susceptibility Inversion method (Ellis et al., 2012; MacLeod & Ellis, 2013), the magnetism distribution is smooth and the vertical and horizontal extensions of the anomaly/mineral bodies are not well defined. Additionally, the remnant magnetization is assumed to be insignificant while the vectorial resultant is predominantly formed by induced magnetism (Li & Oldenburg, 1996). Some authors warn that assuming only induced magnetization causes a loss in the data interpretation, leading to misinterpretations of the position, volume and inclination of the body/anomaly (Aisengart, 2015, Aisengart et al., 2016, 2017; Barbosa & Pereira, 2013; Ellis et al., 2012; MacLeod & Ellis, 2013; Pereira et al., 2015).

Magnetic Vector Inversion (MVI) (Ellis et al., 2012) is a more recent magnetic inversion technique that maximizes the anomaly over the causative source and better delimits the anomaly boundary. It is based on induced and remnant magnetization, with no need for prior knowledge of the direction and strength of the remnant field. This magnetic inversion technique is indicated for regions of low magnetic latitude, where the inclination of the Earth's magnetic field is ≤ 20° (Johnson & Aisengart, 2014).

The MVI method was applied in the Goiás Alkaline Province (GAP), which is situated in a region of low magnetic latitude with strong remnant magnetization (Dutra & Marangoni, 2009; Dutra et al., 2012, 2014). Based on these characteristics, the MVI method is recommended instead of the conventional inversion by magnetic susceptibility. This alkaline province has great economic importance for the State of Goiás and is formed by at least 11 alkaline complexes consisting of felsic to mafic rocks (Fig. 1), with strong potential for Ni, Cu, Vermiculite, P_2O_5, among others (Biondi, 2005; Radaelli, 2000a, 2000b; Souza & Gollmann, 2020) while some of these complexes are already economically explored. Approximately 37% of the measured Ni reserves are concentrated in the state of Goiás, the Diorama, Morro do Macaco, Montes Claros and Santa Fé complexes stand out among them, where nickeliferous laterites, formed from the weathering of mafic-ultramafic rocks and supergenic enrichment, predominate (ANM, 2021). Morro Preto Norte and Morro Preto Sul complexes, with phosphate mineralization in carbonatite, can be mentioned as an example of P_2O_5 reserves (Navarro et al., 2014; Nascimento, 2018).

Highly important economically, the alkali and alkaline-carbonatitic complexes may host metallic and non-metallic mineral deposits (Simandl & Paradis, 2018; Wang et al., 2020). For example, the Phalaborwa phoscorite-carbonatite complex in Limpopo Province, South Africa, hosts deposits of Cu, apatite, vermiculite, uranothorianite, baddeleyite, rare earth elements, Ni, Au, Ag, and platinum-group elements (Bolhar et al., 2020).

The GAP has been previously studied by the conventional magnetic susceptibility inversion method (Dutra & Marangoni, 2009; Dutra et al., 2012, 2014; Marangoni & Mantovani, 2013) and these studies yielded information on the shape and top depth of some complexes. It is highlighted that Dutra et al. (2012, 2014) also used an average value of remnant magnetization and fixed a single geometric shape for all inverted bodies. However, the alkaline complexes are known to consist of different lithologies with distinct crystallization intervals, age and geography, which are reflected in different values of the Köenigsberger ratio, as well as different inclination and magnetic declination values, therefore, a more detailed analysis of each complex becomes necessary to obtain a more updated individual shape, emplacement form and remnant magnetization values.

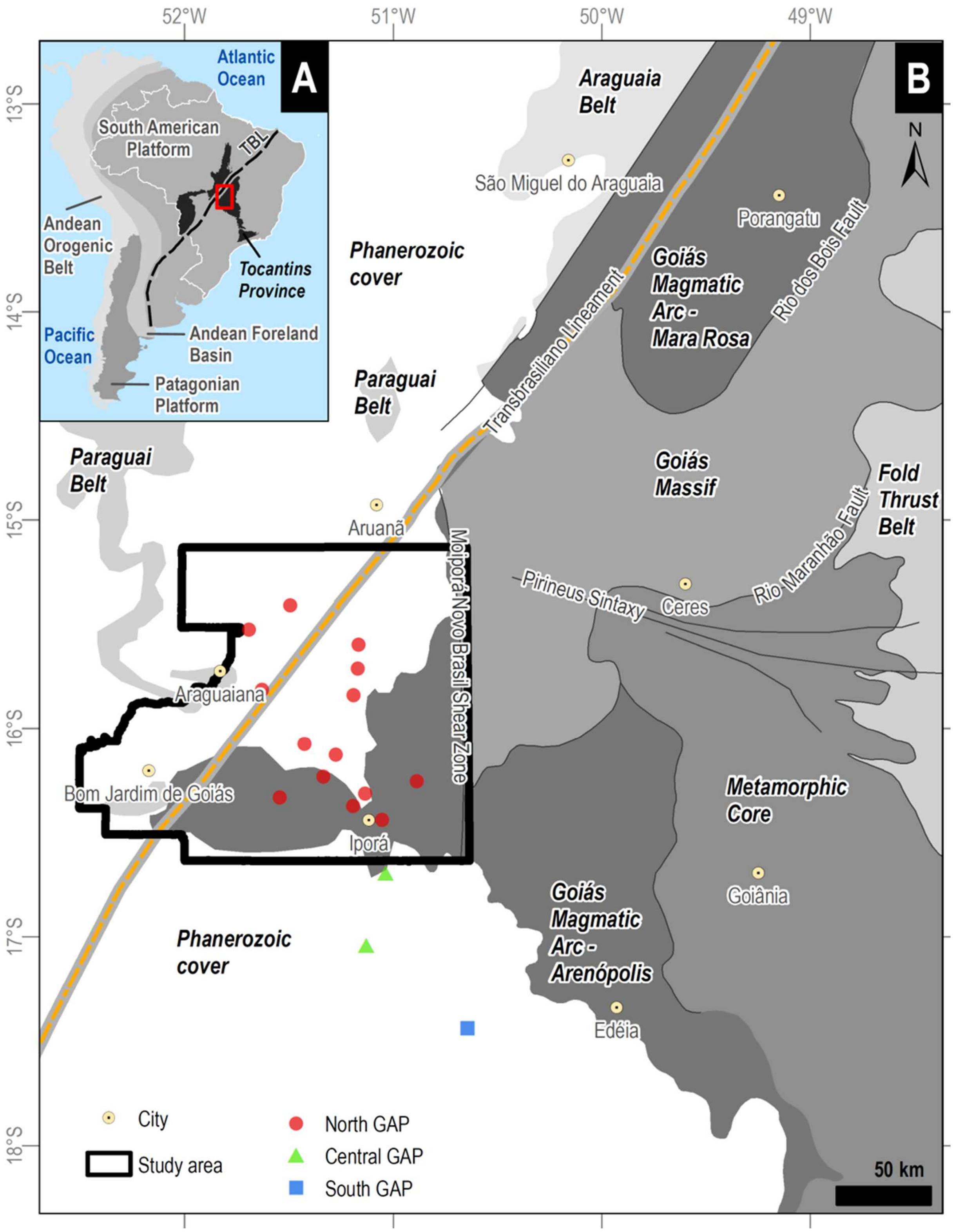

Fig. 1. Map showing the Tocantins Province in the South American Platform (A). Simplified geological units of the Tocantins Province highlighting the Brasília Belt units: Goiás Magmatic Arc, Goiás Massif, Metamorphic core and Fold Thrust Belt; and the mapped Goiás Alkaline Province complexes (colored circle, triangle and polygon) (B) (According to Bizzi et al., 2003; Brod et al, 2005; Cordeiro & Oliveira, 2017; Fuck et al., 2014; Lacerda Filho et al., 2020; Pimentel et al., 2000a, 2000b; Pimentel, 2016).

Thus, the MVI technique was applied to the GAP to obtain the 3D distribution model of magnetic susceptibility (*k*), to verify the existence of new complexes associated with the dipole anomalies described by Martins & Vidotti (2021), which possibly correspond to previously non-identified alkaline bodies, and to estimate the dimensions (top and base depth), types of emplacement (accommodation) and their possible association with tectonic structures. The dimensions of most of the GAP complexes have not been estimated yet and since many of the bodies do not outcrop, the GAP real extent and the exact number of alkaline complexes forming it remains unknown. This information on three-dimensional geometry of subsurface bodies can be obtained from geophysical methods, such as magnetic inversion, and in this work, may contribute to identifying new targets for mineral exploration in the state of Goiás, while the methodology used can be replicated for prospecting new targets in other geological contexts. It will also allow determining whether the bodies have either a single or more than one magnetism direction, which may reflect in different magmatic pulses, as confirmed by contact relationships in geological mappings conducted in the region (Pena & Figueiredo, 1972; Pena, 1975). The MVI inversion can also highlight the tectonic structures present in the region, thus allowing to determine the relationship between these structures and the alkaline complexes. This information together with geochemical, geochronological, and paleomagnetism data can contribute to the understanding of the GAP origin.

2. Geological Setting

The Goiás Alkaline Province (Brod et al., 2005; Guimarães et al., 1968; Gaspar et al., 2003) is located in the extreme SW of the Brasília Belt, in the Goiás Magmatic Arc – Arenópolis Magmatic Arc (Fig. 1). The Brasília, Araguaia and Paraguay Belts form the Tocantins Province (Fig. 1), an important Neoproterozoic Orogen established by the collision of the Amazônia, São Francisco, Paranapanema paleocontinents and small allochthonous blocks during the amalgamation of West Gondwana (Pimentel, 2016; Pimentel et al., 2000a, b, 2011). The Arenópolis Magmatic Arc is an important juvenile crust exposure area within the Brasília Belt, consisting of granite, mylonite, ultramafic and volcano-sedimentary sequences that originated from the accretion of different arcs during the Neoproterozoic (Pimentel & Fuck, 1992; Pimentel, 2016).

Based on 2.5D direct gravity modeling and geological data, this geological unit was subdivided into Arenópolis Magmatic Arc West and East, whereas the GAP occurs only in the region of Arenópolis Magmatic Arc West (Martins & Vidotti, 2021).

The GAP consists of plutonic to volcanic rocks, with mafic to felsic varieties, of alkaline filiation, which occur as zoned intrusions of the central type, subvolcanic intrusions (sills, dikes, plugs, and pipes), besides lava and pyroclastic deposits (Brod et al., 2005; Danni et al., 1992; Danni et al., 1994; Danni, 1994). Intrusions with zoned shapes and association with intersecting tectonic structures are common in alkaline and alkaline carbonate complexes, as observed in the Pungnyon and Ssangyong carbonate complexes, in the Korean Peninsula (Ju et al., 2020). And the pipe-shaped alkaline intrusions observed in the Palabora carbonatite complex, in South Africa (Giebel et al., 2019).

In the GAP northern portion (Fig. 2), the following plutonic complexes are observed the Morro do Engenho, Santa Fé (Água Branca and Tira Pressa, 76.2 Ma to 90.4 Ma, Radaelli, 2000a; Sonoki & Garda, 1988), Montes Claros (88.7 Ma to 94.0 Ma, Sonoki & Garda, 1988), Morro dos Macacos (53.2 Ma to 82.9 Ma, Sonoki & Garda, 1988), Fazenda Buriti, Arenópolis and Morro Preto (north and south). These complexes consist primarily of dunite, peridotite, pyroxenite, gabbros, syenogabbro, phenite, and syenite, with Ni, Cr, Co, P_2O_5, and vermiculite mineralizations (Moreton, 2001; Nascimento, 2018; Navarro et al., 2014; Pena & Figueiredo, 1972; Radaelli, 2000a, 2000b). In this region, subvolcanic intrusions of picrites and smaller bodies of little regional expression also occur (Junqueira-Brod et al., 2002).

In the GAP central portion (Fig. 2), the subvolcanic intrusions are represented by the Amorinópolis complex (72.4 Ma, Danni & Gaspar, 1994), which is formed by olivine leucite melanephelinite, melanalcimite, and olivine nepheline melaleucitite dikes. There are also volcanic to subvolcanic associations represented by the Águas Emendadas complex, which consists of olivine melanephelinite, olivine analcime, melanephelinite, olivine analcimite, nephelinites, micro-ijolite, basanite, and tephrite (Brod et al., 2005; Danni, 1994; Junqueira-Brod et al., 2002).

In the GAP southern portion, the Santo Antônio da Barra complex (85 Ma, Hassui et al., 1971; 88-89 Ma, Sgarbi et al., 2000) consists of analcimite, olivine analcimite, analcimitic breccias and carbonatitic pyroclastic rocks (Brod et al., 2005; Junqueira-Brod et al., 2002). In the domain of the northern portion of the Paraná Basin, Pinto & Vidotti (2019) identified dipolar magnetic anomalies that may represent the continuity of the GAP south of the Santo Antônio da Barra complex. This information is important since it indicates the possibility that the GAP extends even longer with a higher number of complexes.

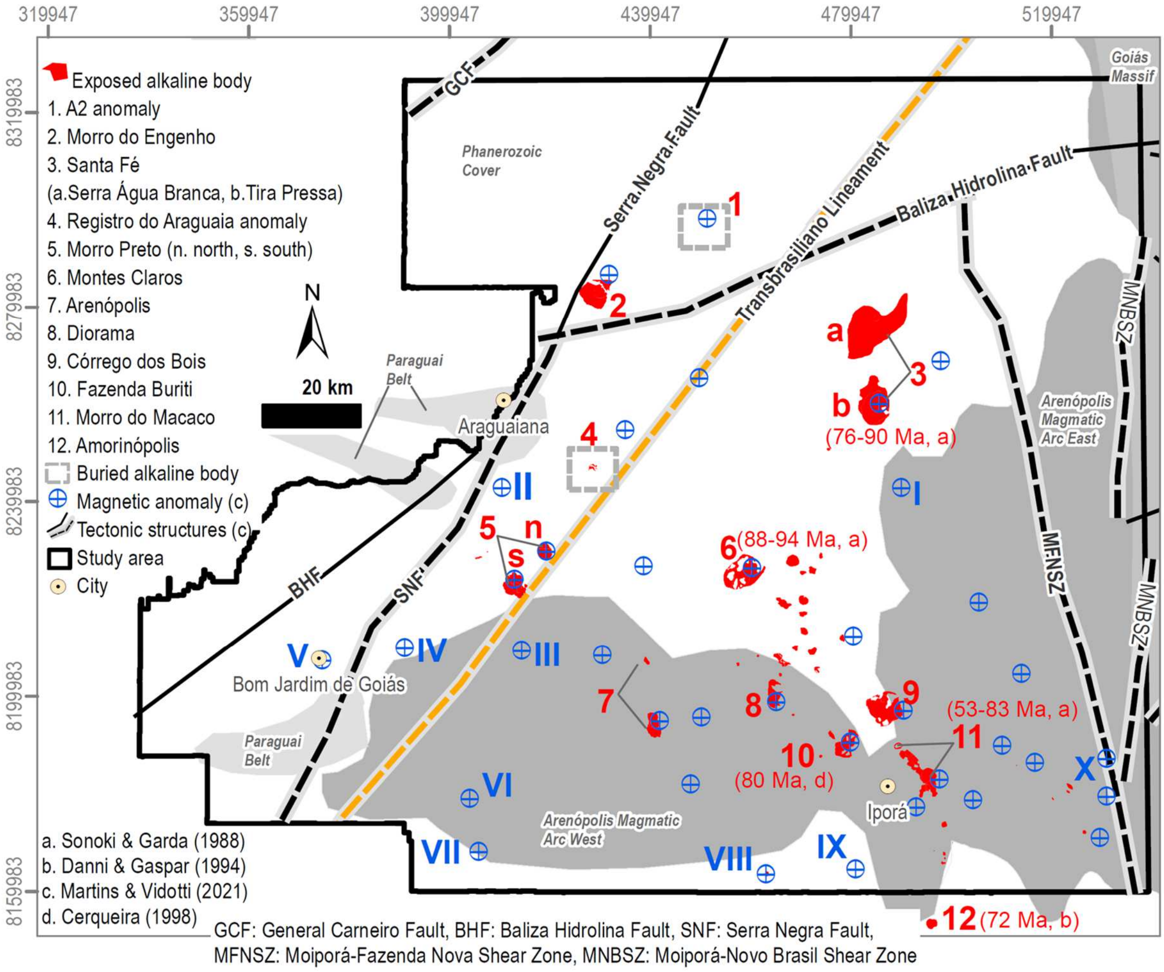

Fig. 2. Simplified geological units highlighted the GAP (according to Brod et al., 2005; Dutra et al., 2012, 2014; Fuck et al., 2014; Lacerda Filho et al., 2020), magnetic anomalies and tectonic structures (according to Martins & Vidotti, 2021).

The lithological variety observed in the GAP complexes may represent different magmatic pulses. The ultramafic rocks are the oldest and were affected by successive magmatic injections of increasingly acidic character, as observed in the Montes Claros and Fazenda Buriti Complexes. However, the Montes Claros and Morro dos Macacos Complexes derived from magmatic differentiation of the same magmatic event (Pena & Figueiredo, 1972).

The GAP is associated with two distinct origins: 1. Magmatism resulting from an extensional tectonic event (Wealdenian Reactivation) due to the fragmentation of

Gondwana and the opening of the South Atlantic Ocean (Almeida, 1966, 1983, 1986; Gomes et al., 2018; Pena & Figueiredo, 1972; Ulbricht & Gomes, 1981); 2. Anorogenic magmatism due to the Trindade mantle plume (Gibson et al., 1995a, 1995b; 1997).

3. Data and Methods

This study used the magnetic data from two high-resolution aerial surveys conducted for the Southeast Mato Grosso Project – code 1113 and Arenópolis Magmatic Arc – code 3009 (Fig. 3A, Fig. 3B) in 2004 and 2012, provided by the Geological Survey of Brazil (CPRM, 2004a, 2012). The magnetic data were acquired with N-S flight line, 500 m spacing, 100 m flight height, 0.1 s sampling rate, using magnetometers with a 0.001 nT resolution. The Digital Elevation Model of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Fig. 3C), obtained from the Jet Propulsion Laboratory (https://lpdaac.usgs.gov/products/ast_l1tv003/); geological charts to the millionth SD.22 – Goiás (CPRM, 2004b), SE.22 – Goiânia (CPRM, 2004c) and geological chart in the 1:250,000 scale – West Goiás Project (Lacerda Filho et al., 2020), which helped to locate the alkaline complexes. All data were processed in Oasis Montaj (Seequent) and VOXI Earth Modelling (Seequent).

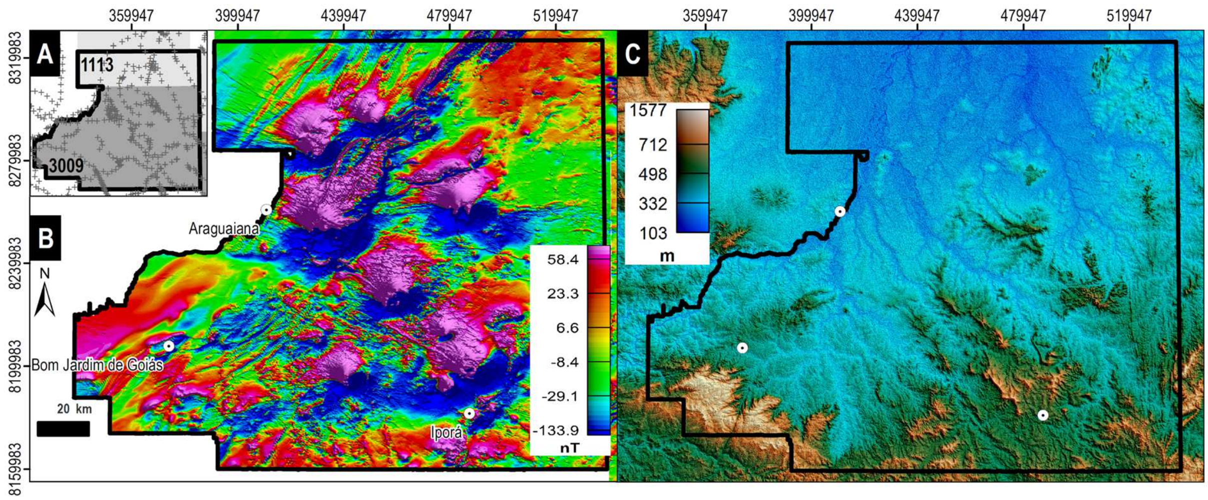

Fig. 3. Map showing the aeromagnetic surveys that provided the data used; gray crosses represent ground gravity data (A) according to CPRM surveys - codes 3009 and 1113 (CPRM, 2004a, 2012); the Magnetic Anomaly map (B) and the Aster digital elevation model (C). Black polygon represents the study area covered by magnetic data.

The magnetic data were used to generate a VOXI magnetic inversion from the Magnetic Vector Inversion tool (Ellis et al., 2012). This inversion method considers the induced and remnant magnetic fields, providing a more correct interpretation of the magnetic field. When the remnant magnetic is not considered, the magnetic anomalies are not centered and the dimension, top and bottom characteristics of the magnetic anomaly are underestimated and/or displaced (Aisengart, 2013). The MVI was chosen because the GAP is marked by a strong remanent magnetism (Dutra et al., 2014), which is the magnetism generated in the ferrimagnetic materials during their crystallization, and which, therefore, reflect the inclination and declination conditions of the magnetic field at the time of mineral crystallization (Hinze et al., 2013). This remanent magnetism was calculated for some complexes (Morro do Engenho, A2, Santa Fé and Registro do Araguaia) (Dutra & Marangoni, 2009; Dutra et al., 2014), however, this information does not exist for the vast majority of the GAP complexes.

Each magnetic survey was interpolated by bidirectional interpolation, with a 125 m cell size (Hinze et al., 2013; Isles & Rankin, 2013), then GridKnit™ sutured to each other and clipped at the boundary of the area of interest. Subsequently, the Digital Elevation Model (DEM) grid was generated (Fig. 4A). In the MVI inversion, the filter constrained IRI $^{2+}$ was adopted to centralize and better delimit the edges of the magnetic anomalies (Fig. 4B) (Barbosa & Pereira, 2013, Ellis et al., 2012; Mcleod & Ellis, 2015). The 3D MVI generates three components of the magnetic field, amplitude component (AMP), perpendicular component (EPERP) and projected component (EPROJ) (Aisengart, 2013; Ellis et al., 2012) (Fig. 4B, Fig. 4C), and the magnetic vector is the vector component of AMP (Fig. 4B). AMP (Fig. 4C) is the amplitude of the magnetic vector for each point on earth, divided by the induced field strength and it is always positive. The Eproj (Fig. 4C) is the projection of the magnetic vector in the direction of the induced field, which can have positive (the same direction of the induced field) or negative (opposite direction to the induced field) values. This data highlights, mainly, the induced field.

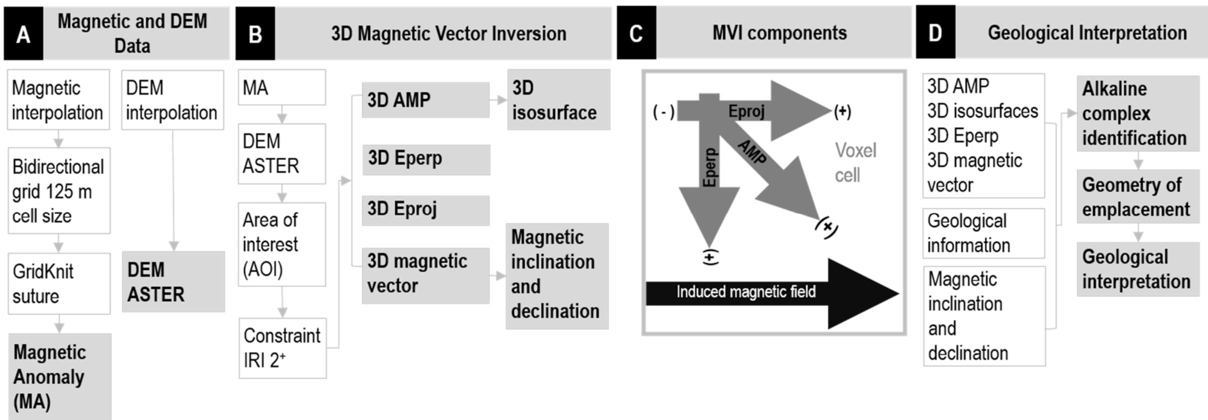

Fig. 4. Work flowchart.

The Eperp magnetism (Fig. 4C) is the amplitude of the magnetic component perpendicular to the direction of the induced field and it is always positive. This data highlights the anomalies of the non-induced field: remnant magnetization, demagnetization and anisotropy (Ellis et al., 2012), being quite suitable for studying the GAP. Magnetic Vector (Fig. 4B) provides information on the magnitude of the magnetic field and the direction of physical properties (Aisengart, 2013) while indicating effective magnetism. The vectors are aligned parallel to the induced magnetic field (induced magnetism) or pointing to different directions, in this case, indicating non-induced magnetism (remnant magnetism, demagnetization, anisotropy) (Barbosa & Pereira, 2013, Ellis et al., 2012; Johnson & Aisengart, 2014). The magnetism peak of a vector within a strong magnetization indicates the magnetization direction (Mcleod & Ellis, 2015).

The first inversion generated covered the entire working area (Fig. 3), 800 m cell size on the X and Y axes, 50 m on the Z-axis, as well as 1024 m and -25000 m top and base depths, respectively. After the inversion step, the generated 3D isosurfaces with different *k* susceptibility intervals (Fig. 4B) were compared with geological data so that isosurfaces with $k \geq 0.01$ SI were selected because they adjusted to the region where the GAP exposed bodies and are similar to the contrast values of the magnetic susceptibility of the Brazilian alkaline complexes modeled by Aisengart (2015), Aisengart et al. (2016), Mantovani et al. (2016), Pereira et al. (2015), Ribeiro et al. (2013), and Santos et al. (2019). Subsequently, magnetic anomalies with high-intensity magnetic vectors were selected (Mcleod & Ellis, 2015), each anomaly was clipped separately, and the vectors (magnetization vector) were converted into voxel and later into a geodatabase, to obtain the average values of the magnetic field (amplitude, magnetic inclination and declination) for each anomaly (Aisengart, 2015; MacLeod & Ellis, 2015) (Fig. 4C, Fig. 4D). Subsequently, the average value of the magnetic field vector of each inverted body was plotted in an online polar-centered equal-area projection diagram (http://mage-p.org/mageplot/mpd-e.php) (Hatakeyama, 2018) and magnetization vector (https://paleomagnetism.org/ntr/) (Koymans et al., 2016) to check for the presence of grouped bodies.

To determine whether the inverted bodies correspond to GAP bodies, the geological interpretation was based on the following criteria (Fig. 4D): inverted bodies should coincide with both GAP mapped bodies (CPRM 2004b, 2004c; Lacerda Filho et al., 2020) and dipolar magnetic anomalies (Martins & Vidotti, 2021); have high amplitude in the magnetization vector; be close to mineral occurrences common to alkaline rocks (https://geoportal.cprm.gov.br/geosgb/); coincide with or be close to areas with mineral research processes for minerals and rocks common to alkaline rocks (https://app.anm.gov.br/dadosabertos/SIGMINE/); comparison of the shape of inverted bodies with alkaline bodies modeled from geophysical data (Andersson & Malehmir, 2017; Mantovani et al., 2016; Ribeiro et al., 2013), using a numerical model (Gorczyk & Vogt, 2018), and types of emplacement (Simandl & Paradis, 2018; Wang et al., 2020).

4. Results

The 3D Magnetic Vector Inversion highlighted the *k* contrast across the study area up to approximately 26 km deep. The regions with high *k* contrast and high intensity of the magnetic vector are positioned in the central and southern portions of the area, correspond to intervals of $k \geq 0.01$SI (Fig. 5A: 1 to 11), and coincide with the mapped alkaline bodies. This initial inversion did not generate bodies in dipole anomalies I to X (Fig. 2), so another 19 higher resolution inversions were applied in smaller areas (Table 1).

The vertical slices of the AMP, EPERP and EPROJ components (Fig. 6) highlighted the geometry and vertical extension of the magnetic anomalies, as well as linear features that may be associated with tectonic structures. Longer AMP anomalies with high *k* contrast are situated in the central and southern portions of the study area, with depths varying between 5 and 10 km. At a depth of 20 km, these anomalies converge to two distinct regions where the anomalies are relatively elongated in the NE and NW directions, these anomalies were associated with GAP (Fig. 6A to 6E).

The EPERP component highlights the anomalies of the non-induced magnetic field (remnant magnetization, demagnetization, etc). This product highlighted the high remnant magnetization, in the central region, reaching more than 20 km deep, and the predominant low remnant magnetization in the extreme east and west portions of the area (Fig. 6F to 6J). High-k GAP magnetic anomalies (AMP, Fig. 6AF to 6E) coincide with regions that have strong remnant magnetization (EPERP, Fig. 6F to 6J). Notably, Dutra et al. (2014) confirmed that the GAP region has strong remanence and, therefore, we found that these two components have a correlated magnetic response in the analyzed area.

The EPROJ component highlights the anomalies in the direction of the induced magnetic field while identifying the elongated predominantly NE-SW anomalies, observed along the entire depth analyzed, and also elongated, but shallower anomalies in the NW-SE direction (Fig. 6K to 6O).

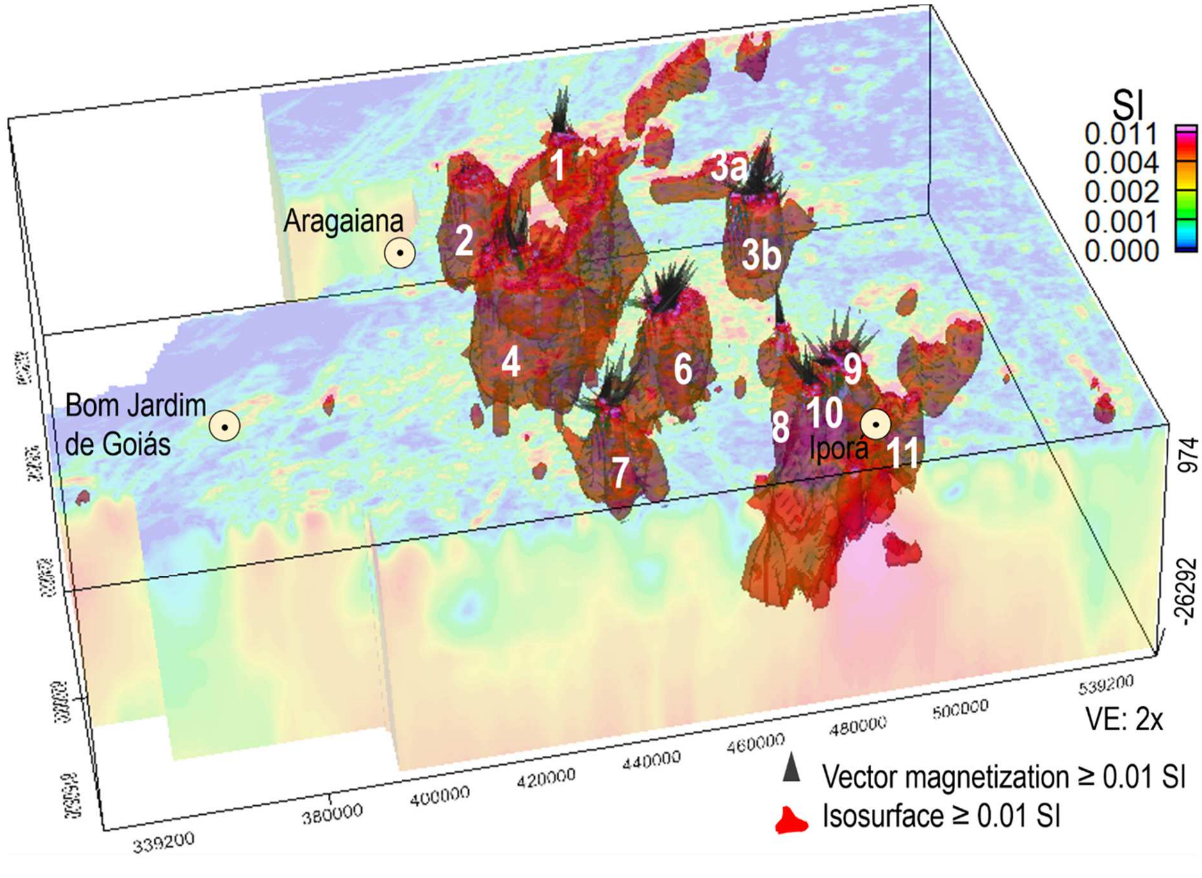

Fig. 5. 3D AMP (shaded in the background) showing the magnetic susceptibility contrast, clipped MVI isosurfaces (red polygon) and vector magnetization (black cones) up to 26 km deep. Perspective view, VE: Vertical Exaggeration.

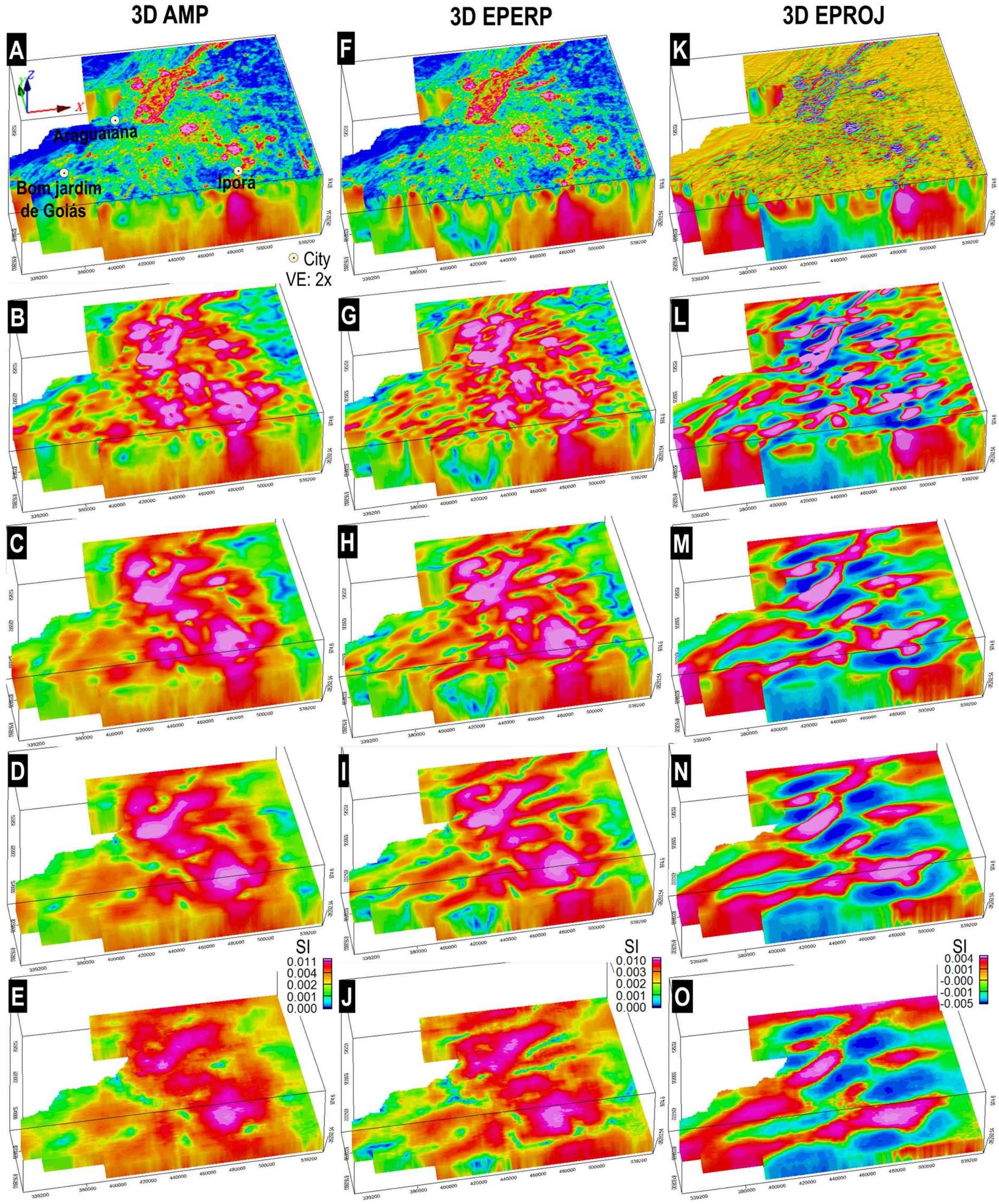

Fig. 6. Vertical slices of the maps: 3D AMP, 3D EPERP and 3D EPROJ at topography (A, F, K), 5 km (B, G, L), 10 km (C, H, M), 15 km (D, I, N) and 20 km (E, J, O) deep, showing the vertical and horizontal pattern of the magnetic anomalies. Perspective view, VE: Vertical Exaggeration.

Table 1. Geometric and magnetic characteristics of each inverted anomaly. MVI bodies number 1 to 11 are observed in Fig. 2 and MVI bodies I to X are shown in Fig. 5, *Gorczk and Vogt (2018).

MVI number	MVI size (m) x,y,z	Susceptibility contrast (SI) Min/Max	Approx. anomaly Shape	Emplacement geometry*	Approx anomaly dip
1,2,4,4*	400,400,20	0.0/3.8	Round, Long (4*)	1, 2. stock like (pipe)	Vertical
				4. T-shape intrusion	
3 (a,b)	300,300,30	0.0/5.9	Long (a) Round (b)	3a. dike	
				3b. stock like (pipe) or funnel-shaped	
5 (n,s), 5*	60,60,50	0.0/0.25	Round and Long	stock like (pipe)	SW (n, 5*) SE (s)
6	300,300,20	0.0/8.24			Vertical
7	180,180,10	0.0/3.2	Round/Conic	funnel shapped (inverted)	
8	120,120,10	0.0/1.81	Round	stock like (pipe)	
9		0.0/0.20	Long	finger-shaped	WNW
10	200,200,10	0.0/4.66	Round and Long	stock like (pipe)	Vertical
11	120,120,10	0.0/0.99			
I	100,100,5	0.0/0.09		finger-shaped	E
II		0.0/0.17			
III	60,60,5	0.0/0.14	Long		
IV		0.0/0.33		stock like (pipe)	Vertical
V	80,80,5	0.0/0.07		dike	
VI	50,50,5	0.0/0.05	Round	stock like (pipe)	
VII		0.0/0.08	Long	dike	
VIII		0.0/0.7	Round	finger-shaped	
IX	80,80,5	0.0/1.27			SE
X	100,100,5	0.0/0.6		dike	

The higher resolution inversions allowed to obtain detailed information on the top and bottom depth of the anomalies, *k* contrast, shape, emplacement geometry and body inclination (Table 1). In general, it was observed that the GAP complexes (Fig. 2, numbers 1 to 11) are formed by nearly concentric rocks, with a predominant circular shape, sometimes with a more magnetic core, such as the Santa Fé complexes (Fig. 7B-b) and Montes Claros (Fig. 7D), both complexes have a pipe-type emplacement form (Table 1). On the other hand, the Arenópolis complex (Fig. 7E) has an approximately conical shape and funnel emplacement form (Table 1). There are also dike-shaped complexes, Santa Fé (Fig.7B-a), Morro do Macaco (Fig. 7I) and Registro do Araguaia dike (Fig. 7a-4*), among others (Table 1). Furthermore, Registro do Araguaia has the greatest vertical extension, approximately 20 km, from which a shallower NE-SW dike emerges (Fig. 7a-4*), and has T-shape intrusion emplacement form (Table 1). It was also observed that isosurfaces with lower *k* contrasts link the

Morro do Engenho, A2 and Santa Fé (Serra Água Branca) complexes with the Registro do Araguaia complex. The Montes Claros, Arenópolis and Fazenda Buriti are between 12 km and 15 km bottom deep (Fig. 7D, Fig. 7E, Fig. 7H) and the other GAP mapped bodies have a maximum bottom depth of less than 6 km (Table 1, Fig. 7); pipe is the predominant emplacement geometry (Fig.7B-b, 7C, 7F, 7I) while finger-shaped is present as well (Fig.7G). The higher resolution of the models allowed the delimitation of new bodies that were not mapped and were not identified by dipole anomalies, such as two large bodies east of the Morro Preto S complex and smaller bodies between the two complexes (Fig. 7C). Finger-shaped is the predominant emplacement geometry (Fig.9A to 9C, 9H, 9I), while dike (Fig.9E, 9G, 9J) and pipe (Fig.9D, 9F) shaped are observed as well (Table 1).

The magnetic susceptibility values obtained with the MVI (Fig.7) were compared with the mean k values measured in the field. Magnetic susceptibilities were measured in three different complexes (Fig. 8) and the mean values of 0.03, 0.08 and 0.04 SI were similar to the magnetic susceptibility contrasts obtained by the MVI of each complex, Fazenda Buriti complex > 0.04 SI (Fig.7H), Montes Claros complex >0.06 SI (Fig.7D) and Morro do Macaco complex >0.04 SI (Fig.7I).

The MVI of the GAP complexes and interpreted dipole anomalies exhibit a high-intensity main direction, however, some variations are observed in the direction and intensity of few magnetization vectors. Vectors with high intensity and different inclination directions are observed mainly in the upper portion of some modeled bodies, for example, Fig. 7B, Fig. 7E, Fig. 7H and Fig. 9H. For this reason, new magnetic vectors were generated for each anomaly to isolate lower intensity adjacent anomalies with magnetization directions different from the main direction. This process allowed us to identify the mean magnetic vector direction and to calculate the magnetic field for each analyzed magnetic anomaly (Fig. 10, Fig. 11, Table 2).

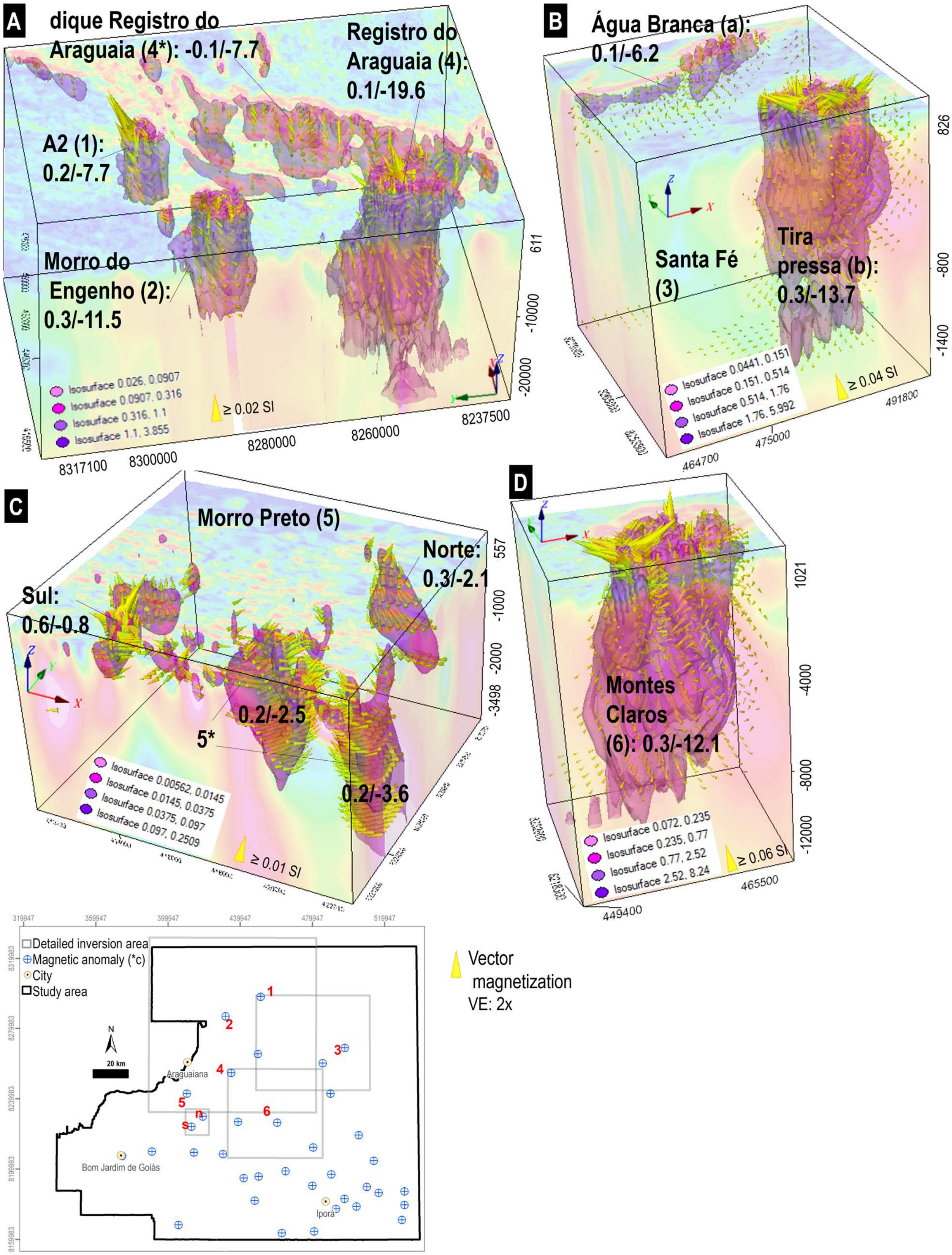

Fig. 7. 3D Amplitude (shaded in the background), MVI isosurfaces (colored 3D polygons), vector magnetization (yellow cones), top/base depth (km) of the modeled bodies, GAP 1 to 11 bodies labeled according to Fig. 2, and modeled area shown in the map at the bottom of the figure.

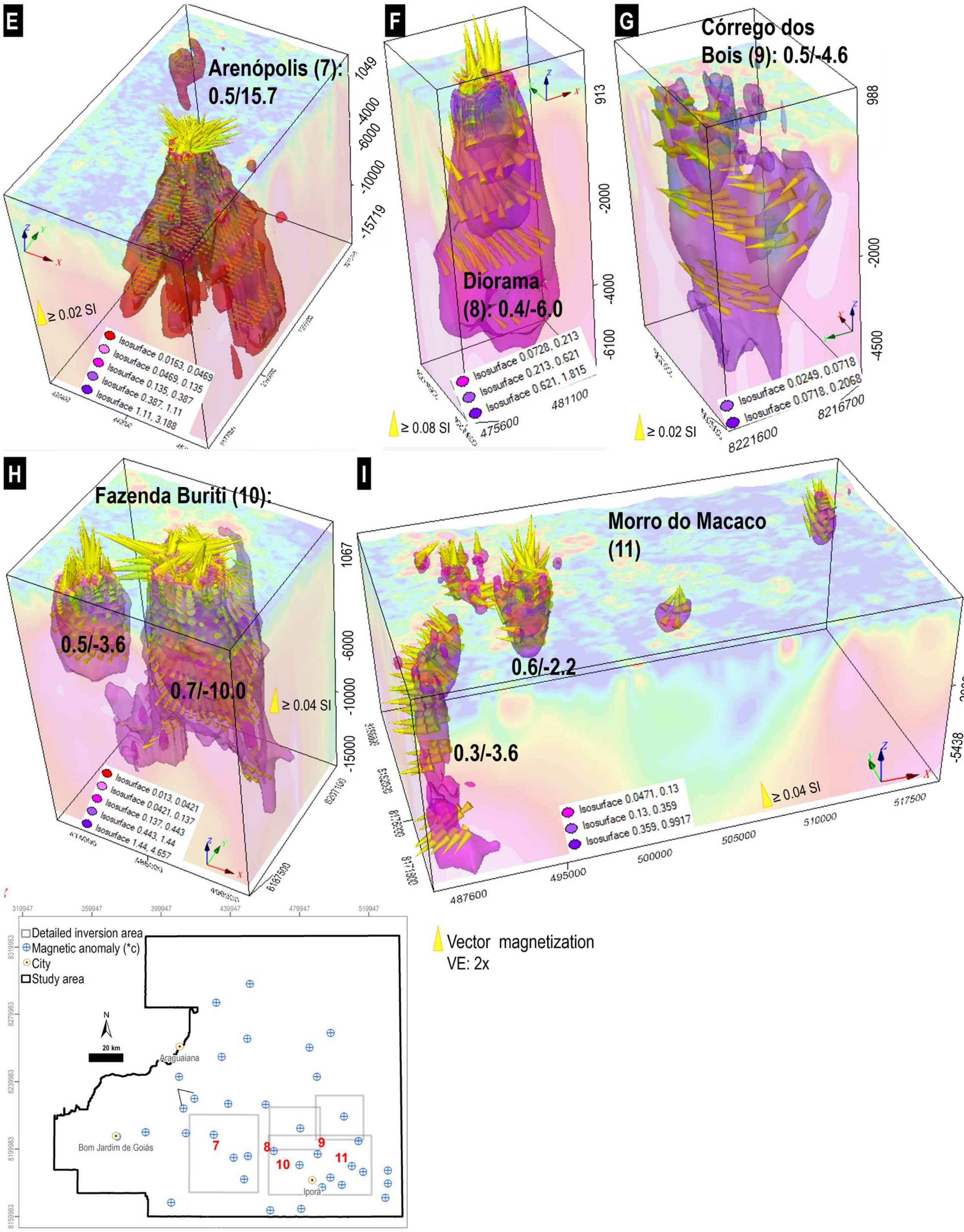

Fig. 7. Continuation.

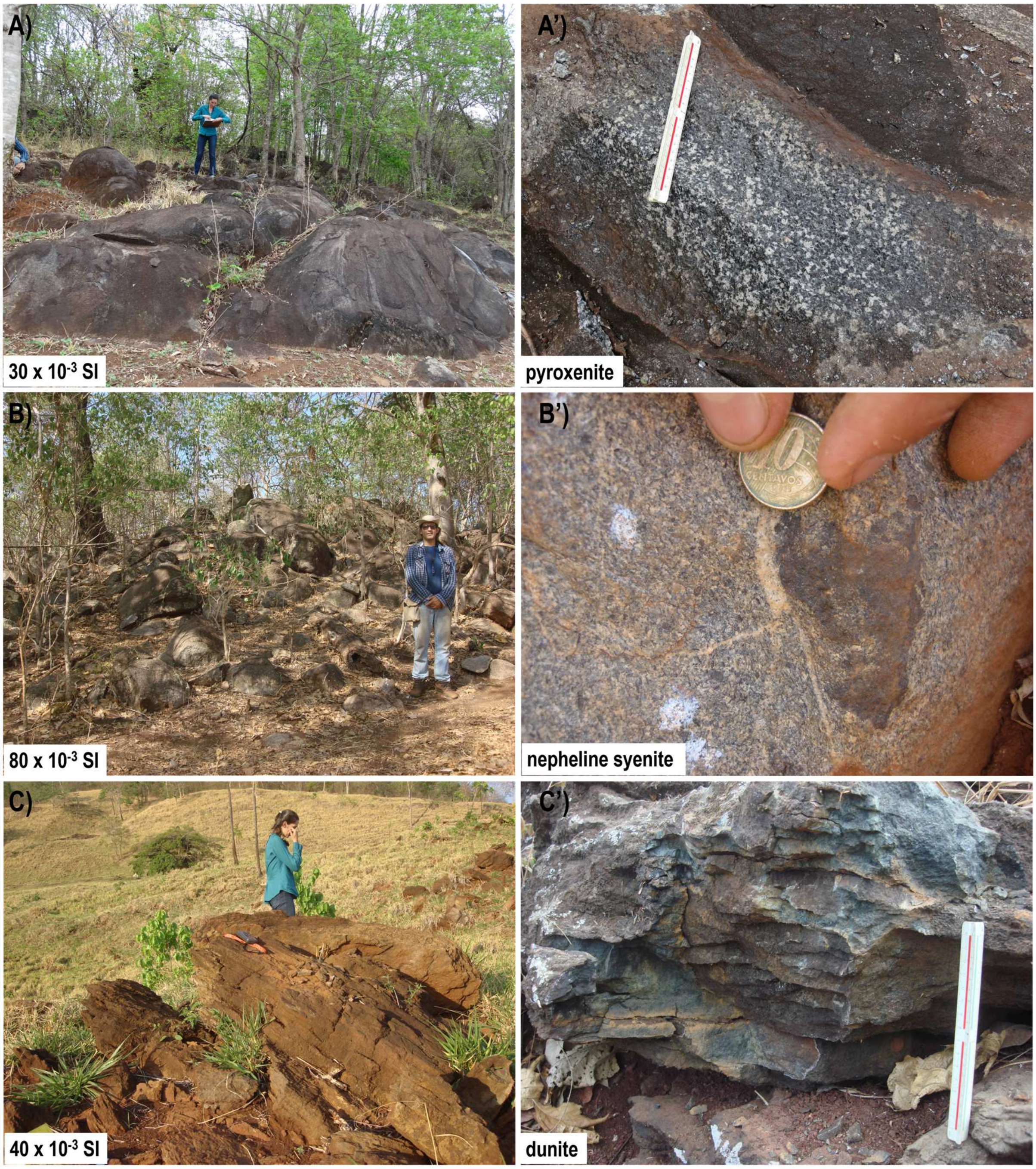

Fig. 8. Outcrop overview, mean magnetic susceptibility and rock samples of the Fazenda Buriti (A, A'), Montes Claros (B,B') and Morro do Macaco (C, C') complexes.

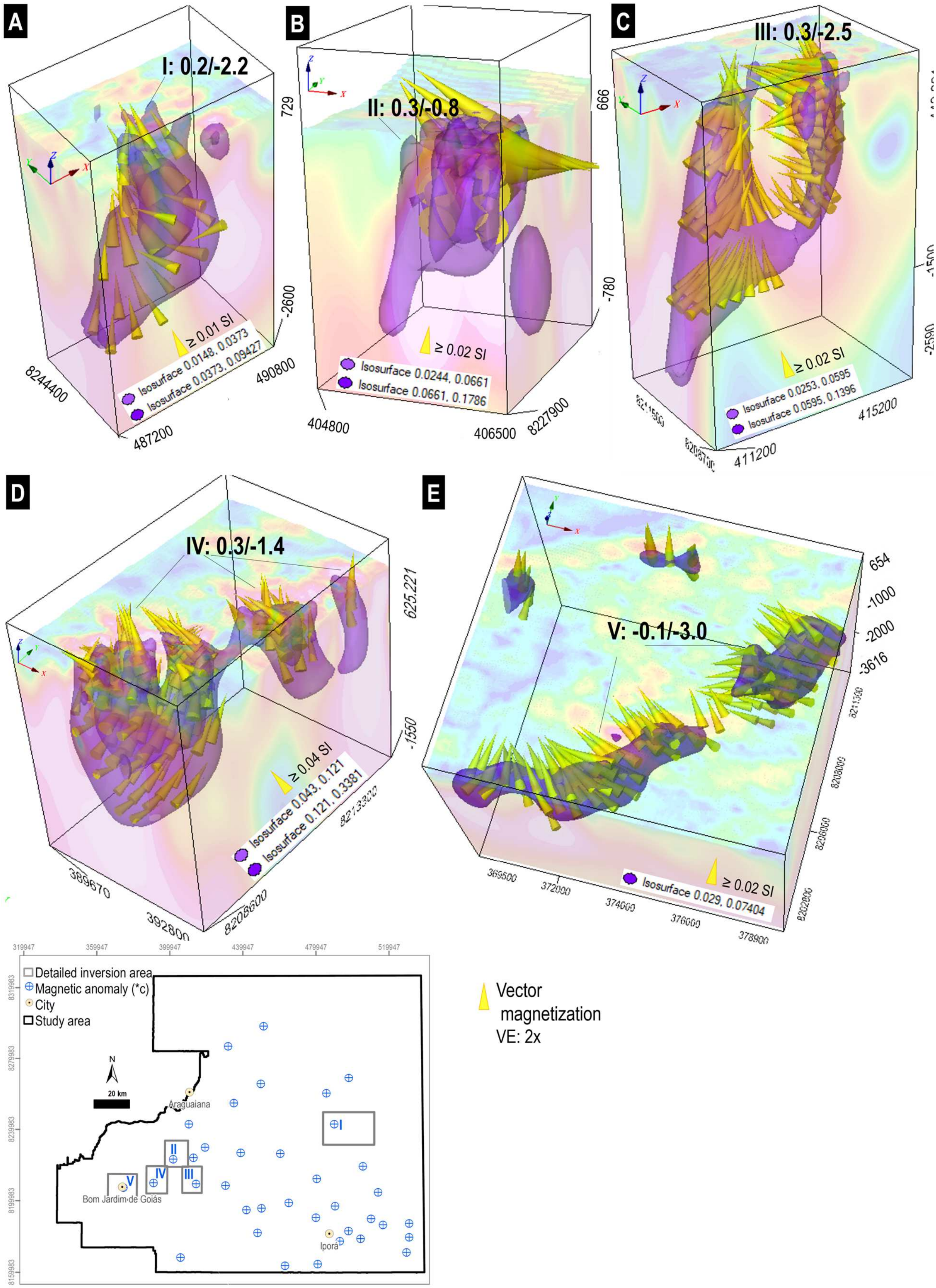

Fig. 9. 3D Amplitude (shaded in the background), MVI isosurfaces (colored 3D polygons), vector magnetization (yellow cones), top/base depth (km) of the modeled bodies, magnetic anomalies I to X labeled according to Fig. 2, and modeled area shown in the map at the bottom of the figure.

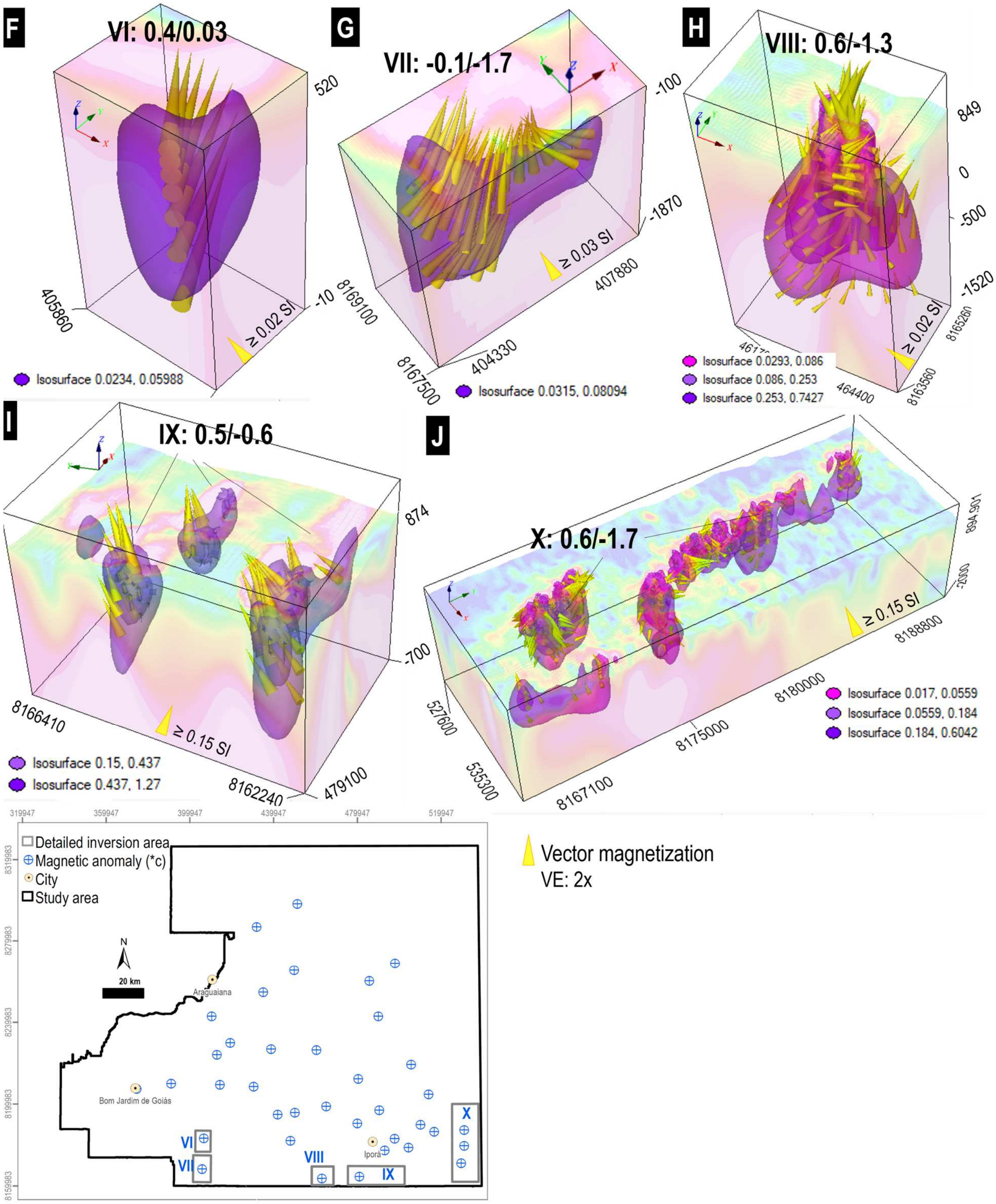
F
VI: 0.4/0.03
520
-10
405860
≥ 0.02 SI
Isosurface 0.0234, 0.05988
G
VII: -0.1/-1.7
-100
-1870
407880
≥ 0.03 SI
8169100
8167500
404330
Isosurface 0.0315, 0.08094
H
VIII: 0.6/-1.3
849
0
-500
-1520
≥ 0.02 SI
8165260
8163560
464400
Isosurface 0.0293, 0.086
Isosurface 0.086, 0.253
Isosurface 0.253, 0.7427
I
IX: 0.5/-0.6
874
-700
8166410
≥ 0.15 SI
8162240
479100
Isosurface 0.15, 0.437
Isosurface 0.437, 1.27
J
X: 0.6/-1.7
≥ 0.15 SI
8188800
8180000
8175000
8167100
527600
535300
Isosurface 0.017, 0.0559
Isosurface 0.0559, 0.184
Isosurface 0.184, 0.6042
319947
359947
399947
439947
479947
519947
8319983
8279983
8239983
8199983
8159983
Detailed inversion area
Magnetic anomaly (*c)
City
Study area
N
20 km
Araguaiana
Bom Jardim de Goiás
Iporá
VI
VII
VIII
IX
X
Vector magnetization
VE: 2x

Fig. 9. Conti.

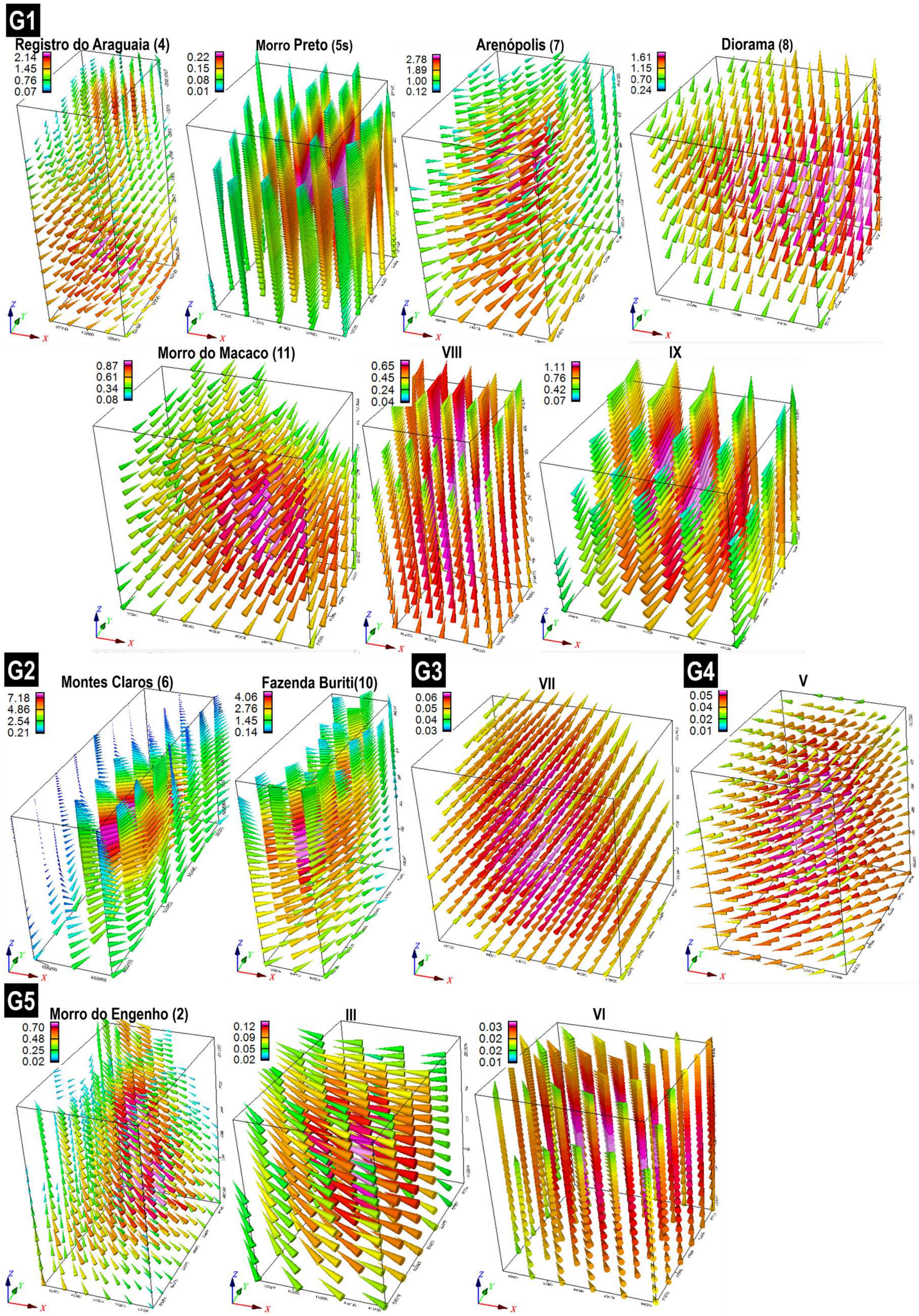

Fig. 10. Mean magnetic field calculated for each inverted body. G1 to G9 represent interpreted magnetic groups according to Fig. 11 and Table 2. Colored cones indicate the amplitude (nT), direction (degree) and inclination (degree) of the magnetic field.

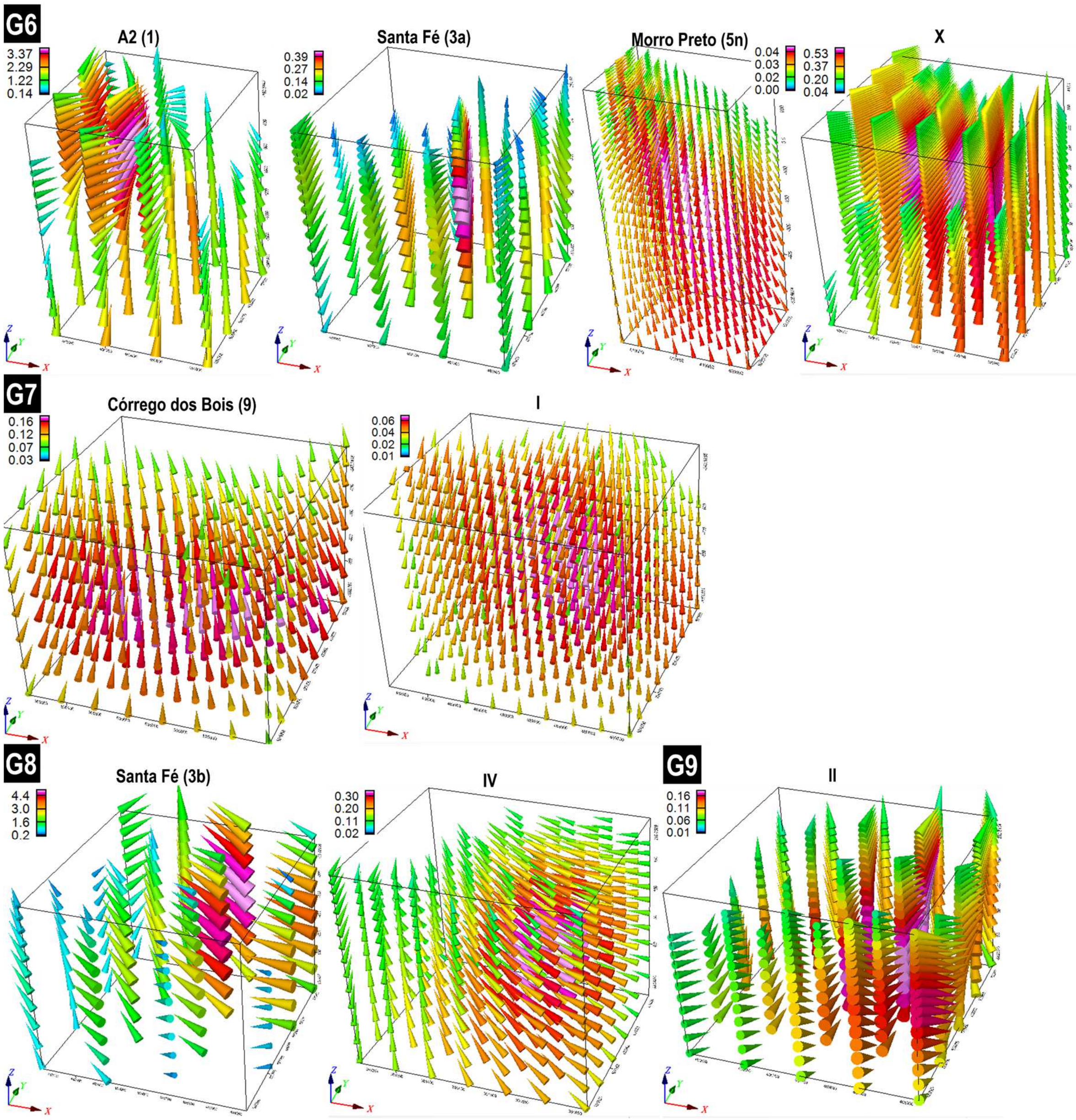
G6
A2 (1)
3.37
2.29
1.22
0.14
Santa Fé (3a)
0.39
0.27
0.14
0.02
Morro Preto (5n)
0.04
0.03
0.02
0.00
X
0.53
0.37
0.20
0.04
G7
Córrego dos Bois (9)
0.16
0.12
0.07
0.03
I
0.06
0.04
0.02
0.01
G8
Santa Fé (3b)
4.4
3.0
1.6
0.2
IV
0.30
0.20
0.11
0.02
G9
II
0.16
0.11
0.06
0.01

Fig. 10. Cont.

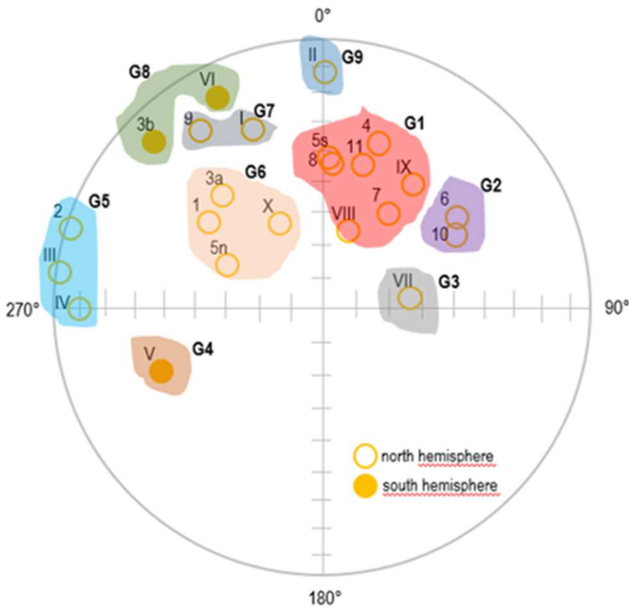

Fig. 11. Equal-area plot of the mean magnetic vector field of the inverted bodies.

Table 2. Mean magnetic vector field from each inverted body.

MVI body number	Magnetic field (vector magnetization)			Interpreted group
	Amplitude (SI)	Declination (°)	Inclination (°)	
Registro do Araguaia (4)	0.27	20.6	-35.5	G1
Morro Preto (5s)	0.11	2.5	-43.8	
Arenópolis (7)	0.76	37.4	-54.2	
Diorama (8)	1.10	4.5	-45	
Morro do Macaco (11)	0.47	15.1	-44.4	
VIII	0.38	21.7	-65.3	
IX	0.46	37.8	-43.2	
Montes Claros (6)	2.08	56.4	-38.3	G2
Fazenda Buriti (10)	1.55	62.7	-41.6	
VII	0.04	82.8	-62.5	G3
V	0.03	-111.4	36	G4
Morro do Engenho (2)	0.16	-72.2	-2.9	G5
III	0.07	-82.6	-2.9	
IV	0.83	-90.9	-12.2	
A2 (1)	0.82	-53.7	-45.5	G6
Santa Fé (3a)	0.12	-42.7	-43.5	
Morro Preto (5n)	0.02	-66.1	-59.5	
X	0.27	-26.9	-63.1	
I	0.03	-20.4	-30.8	G7
Córrego dos Bois (9)	0.11	-34.1	-22.2	
Santa Fé (3b)	1.24	-46	14	G8
VI	0.02	-26.7	14	
II	0.10	-12	0	G9

The main magnetic field of the modeled bodies (Fig. 11) is variable, however, it was possible to divide the modeled complexes into 9 groups, based on the parameters of the magnetic field and their position in the pole graph (Fig. 11: G1 to G9, Table 2).

Groups G1 to G3 have positive magnetic declination and negative magnetic inclination. G4 has negative magnetic declination and positive magnetic slope, and plots in the graph southern hemisphere. G5 to G7 have negative magnetic declination and inclination. G8 has negative magnetic declination and positive magnetic slope, and plots in the graph southern hemisphere. The G9 has negative magnetic declination and magnetic inclination of 0°.

5. Discussion

The resolution of the initial MVI model was not adequate to identify bodies at all points of the dipole anomaly that had been previously identified by Martins and Vidotti (2021) (Fig. 2). It is noteworthy that these dipolar anomalies may represent new non-outcropping and unmapped alkaline bodies, thus, new inversions with higher resolution were generated (19), that is, with smaller VOXI, in the vicinity of each anomaly (Table 1). From the generated inversions, it was verified that the magnetic susceptibility contrast in the MVI depends on the alkaline and enclosing rock lithology, as well as on the VOXI size (x, y, z). There is no standard magnetic susceptibility value that can be adopted for all complexes.

Dipolar anomalies I to X (Fig. 9) possibly correspond to new alkaline bodies, we observe that these bodies are close to areas required for asbestos, Cu, diamond, Nb, ilmenite, Au, Fe and P_2O_5, based on the data available on SIGMINE-ANM and Geological Survey of Brazil. Thus, the GAP is possibly formed by twenty-one complexes (Fig. 12) distributed in the Arenópolis Magmatic Arc – West (complexes 7 to 11, I, III, VI to X; Fig. 12) and under the Phanerozoic cover (complexes 1 to 6, II, IV, V; Fig. 12), with varied types of emplacement (Table 1) and most of the bodies are associated with tectonic structures (Fig.12) generated or reactivated in the Mesozoic or Brasiliana structures reactivated in the Mesozoic (Martins & Vidotti, 2021). The relationship of the alkaline provinces with the tectonic structures has also been observed and reported in other alkaline provinces, such as the Eastern Paraguay (Comin-chiaramonti et al., 1999, 2007, 2014; Gomes et al., 2011a, 2013), in the Andes (Altenberger et al., 2003), and in the Ponta Grossa Arch (Gomes et al., 2011b).

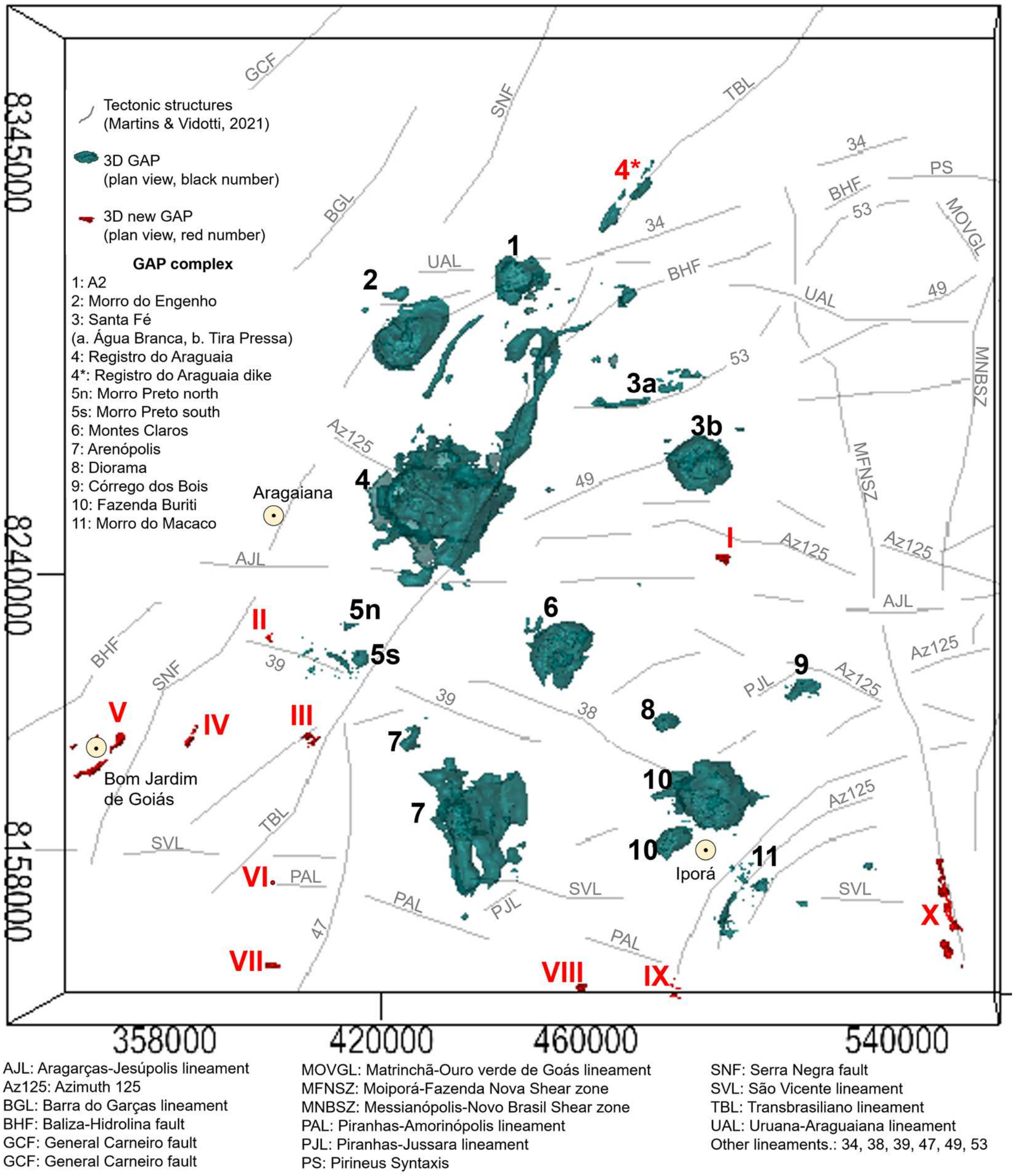

Fig. 12. 3D modeled Goias Alkaline Province and tectonic structures association. The numbers 1 to 11 and I to X are labeled according to Fig. 2.

Dutra et al. (2014) performed 3D magnetic inversion of some GAP complexes, but these authors pre-shaped the bodies as elliptical with single remnant magnetization. However, our analysis of the MVI data (Table 1, Table 2) indicated that the shape, emplacement geometry, dip and magnetic field vary for each complex. There is no universal morphology and geometry model that can be applied to alkaline and alkaline-carbonatitic rocks. The emplacement of magma chambers, radial dikes, ring dikes, and other types of emplacements are understood based on geological field data, experiments, and mathematical modeling (Gorczyk & Vogt, 2018; Simandl & Paradis, 2018).

The magnetization vectors generated by the MVI (Fig.7) show, in some complexes (Fig.7H), varying magnetization direction and intensity in the body upper portion. The high intensity and variable direction of the vector in the body upper portion occur due to the size reduction of magnetite, which is common when the body undergoes supergenic alteration, as is the case of the GAP complexes (Pena, 1975; Pena & Figueiredo, 1972; Radaelli, 2000a, 2000b). Therefore, the magnetization vectors were filtered to remove this interference and the resulting vectors were used in the interpretations (Fig.10, Fig.11).

The magnetization vectors observed in this work represent the Natural Remnant Magnetization (NRM). The NRM is the component acquired during rock formation (primary NRM): (1) thermo-remnant magnetization, (2) chemical remnant magnetization, and (3) detrital remnant magnetization. However, secondary NRM components can be acquired after the rock formation, chemical changes affecting ferromagnetic minerals, exposure to nearby lightning strikes, or long-term exposure to the geomagnetic field after rock formation and can alter or obscure primary NRM (Buttler, 1998).

Pena (1975) and Pena & Figueiredo (1972) state that the Montes Claros complex was formed by 3 different magmatic intrusions, determined from the contact relationship between the rocks. Thus, based on the results of the magnetization vector of the modeled bodies (Fig. 10, Gig.11, Table 2) and the available ages of some complexes (Fig. 2), we believe that the GAP was formed by at least three different magmatic pulses (Fig.13). We believe that G2 may represent the complexes formed by an older magmatic pulse, between 88-94 Ma, based on the age of the Montes Claros (Sonoki & Garda, 1988) and Fazenda Buriti (Cerqueira, 1995) complexes. These complexes were housed as pipe-shape in the upper crust (Fig. 13).

Possibly a second pulse occurred between 76-90 Ma, based on the age of the Santa Fé complex (Sonoki & Garda, 1988), responsible for the formation of G8, both as pipe-shape. The Santa Fé complex (3b) is rooted in the lower crust and complex IV is lodged in the superficial portion of the upper crust (Fig. 13).

A third pulse, G1, may have occurred between 53-83 Ma, based on the age of the Morro do Macaco complex (Sonoki & Garda, 1988). These complexes were housed predominantly in the upper portion of the upper crust, shaped as pipe, finger and dike. However, two complexes with T-shape and funnel emplacement are rooted in the intermediate crust (Fig.13). Groups G5 and G6 possibly formed soon after G1, because from our modeling, we observed that the Registro do Araguaia (G1) complex was the magmatic chamber that gave rise to the Morro do Engenho (G5), A2 complexes (G6) and Santa Fe (G6). The lack of dating of the alkaline complexes made this type of correlation impossible for the other groups analyzed (G3, G4, G7 and G9).

The forms of emplacement observed in the analyzed bodies may represent intrusions in cold crust conditions, with Moho temperature around 400°C. Under these conditions, the finger and pipe shapes reach the surface, generating uplift and fractures. Pipe-shaped bodies can occur in the upper crust while finger- and dike-shaped bodies predominate in the upper portion of the upper crust (Gorczyk & Vogt, 2018). We verified that these depths were observed in all bodies with pipe, finger and dike emplacement (Fig. 13).

Funnel-shaped intrusion occurs when magma has a basaltic characteristic and represents the most common expression of ultramafic intrusion in the continental crust (Gorczyk & Vogt, 2018). In our work, only the Arenópolis complex presented a funnel-shaped emplacement (Fig. 13), with an ultramafic composition formed predominantly by pyroxenites (Junqueira-Brod et al., 2002). The intrusion of low-density magma results in a t-shape emplacement (Gorczyk & Vogt, 2018), which was only observed in the Morro do Engenho complex (Fig. 13). Possibly the magma that gave rise to this complex should have about 5% H_2O and 11.34% CO_2, the favorable conditions for the magma to break through the intermediate crust barrier and reach the upper crust (Junqueira-Brod et al., 2005).

A large part of the complexes in the northern portion of the GAP represents exhumed magmatic chambers, possibly due to uplifts in the late Cretaceous (Junqueira-Brod et al., 2005). During this period, the northern edge of the Paraná basin arched and the Bom Jardim de Goiás arc formed in the region where the GAP occurs, generating predominantly NE-SW normal fault systems, and reactivating predominantly NW-SE Brasiliana faults (Martins & Vidotti, 2021; Pena & Figueiredo, 1972, Pena, 1975).

Based on paleomagnetic reconstruction, Ernesto (2005) states that the alkaline magmatism giving rise to GAP is not associated with the mantle plume of Trindade as stated by Gibson et al. (1995a, 1997). In the late Mesozoic and early Cenozoic, the South American Plate was affected by a thermal anomaly in the mantle that transferred heat to the lithosphere. The intraplate stress caused by changing rotation pole and plate velocity, associated with tectonic factors, during this period, favored the alkaline magmatism that gave rise to GAP (Ernesto, 2005). Between 130-80 Ma the separation speed of the South American and African Plates was approximately 23 mm/year (Ernesto, 2005), the magnetic field had predominantly normal polarity and possibly, G2 was formed in this period (Fig.13). Between 80-50 Ma, the velocity reduced to 7 mm/year (Ernesto, 2005), and the magnetic field had predominantly reverse polarity, we believe that in this interval G8 formed while G1, G5 and G6 formed later (Fig.13). Intraplate stress has also been associated with alkaline magmatism in northeastern Iberia (Ubide et al., 2014) and the Canary Islands (Blanco-Montenegro et al., 2018).

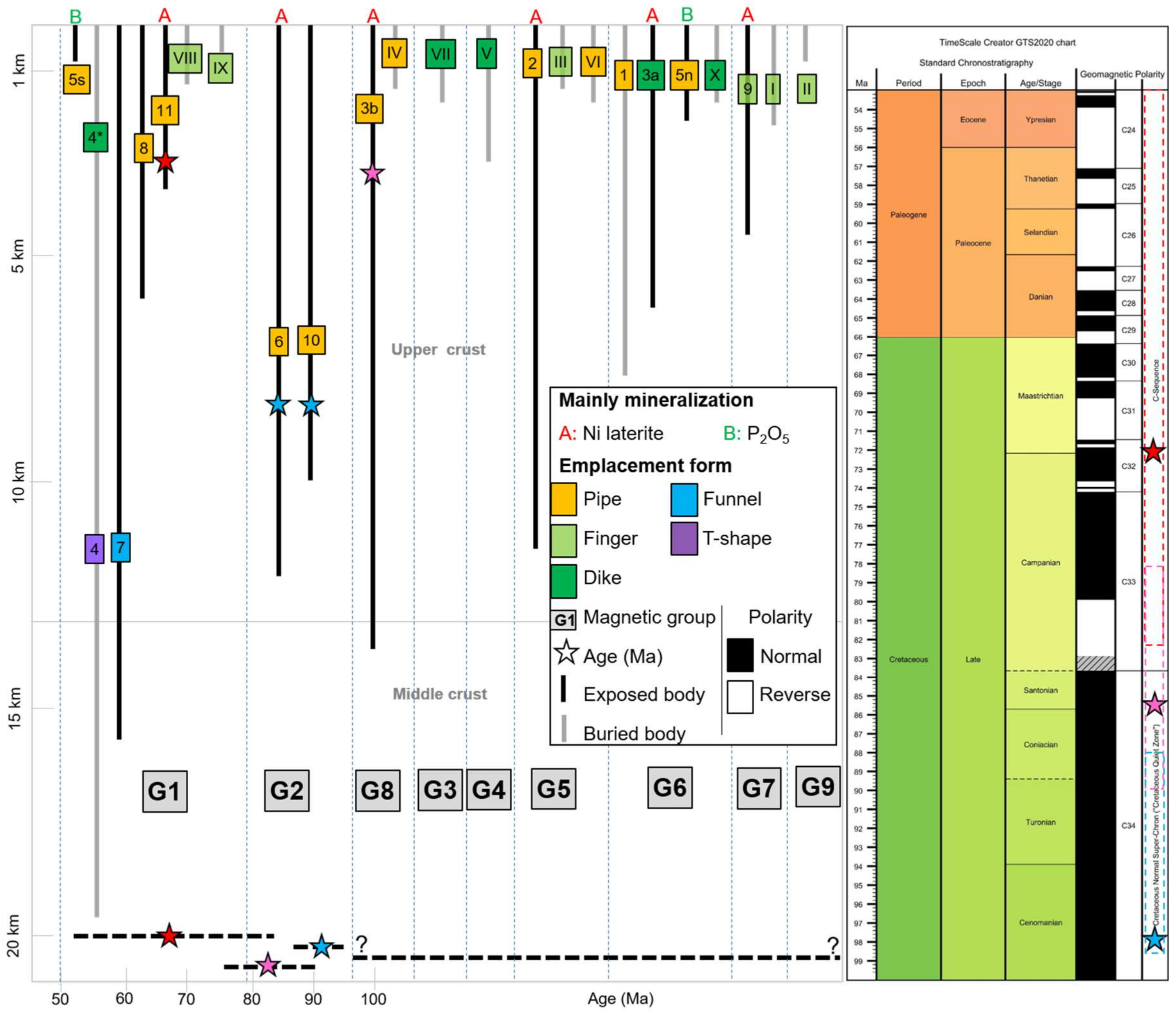

Fig.13. Magnetic GAP groups and geological correlation (1 to 11 represent GAP and I to X the new GAP bodies). Late Cretaceous-Paleogene geomagnetic time scale (https://timescalecreator.org/index/index.php).

6. Conclusion

The MVI technique used showed that the GAP is formed by twenty-one alkaline complexes with varying geometry and magnetic field, as well as different types of emplacements such as pipe, dike, t-shape, finger and funnel, while many are associated with Brasiliano and Mesozoic tectonic structures. These bodies were formed by at least three magmatic pulses, based on the magnetization vector.

Among the new bodies modeled, only Complex VI crops out, whereas the others have top depths ranging from 0.5 km to 3 km. There are possibly other smaller bodies in the GAP that were not inverted due to the size limitation of the MVI and magnetic data. To investigate whether there are smaller bodies of GAP, it is suggested to carry out a terrestrial magnetic survey, so that the MVI can be generated with higher resolution.

The previously identified complexes have varied top and base depth, and the Registro de Araguaia exhibits the greatest vertical extension, reaching approximately 19 km, this magmatic chamber gave rise to complexes A2, Morro do Engenho, dike do Registro do Araguaia and Água Branca.

Magnetic susceptibility contrast cannot be a standard to differentiate alkaline rocks, as it depends on the alkaline rock lithology, the host rock lithology, and the VOXI size. The MVI does not allow identifying the lithologies of the bodies that do not crop out, a drilling survey is an option to obtain these data.

MVI is an important tool to investigate alkaline rocks, and new targets, without requiring prior knowledge about them, and the methodology used could be replicated for prospecting new targets in other geological contexts.

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4. RESUMO SUBMETIDO EM EVENTO

Emplacement rock revealed from Magnetic Vector Inversion

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Abstract

The Goiás Alkaline Province has great economic importance because it is formed by rocks that host metallic and non-metallic mineral deposit, such as Ni, Cu, Vermiculite, phosphate, among others. Some complexes of the Goiás Alkaline Province do not outcrop, which makes the preliminary geometry study difficult in mineral exploration. So, an alternative to obtain this information is the application of the magnetic inversion methods. In this work, the magnetization vector inversion was applied in the Registro do Araguaia complex, to obtain its geometry and form of the emplacement. The results revealed that this inversion technique is effective in the study of body geometry, body dip and form of the emplacement.

A inversão de dados magnéticos é muito aplicada em exploração mineral para auxiliar a identificação de alvos mineralizados, estimativa de geometria, inclinação do corpo, locação de furos de sondagem, entre outros. Há duas técnicas de inversão magnética, susceptibilidade magnética e vetor de inversão magnética. Na susceptibilidade magnética assume-se que a magnetização remanente é insignificante e a magnetização é formada predominantemente pela magnetização induzida. Isto pode levar a interpretações errôneas da geometria do corpo, principalmente em regiões de baixa latitude magnética e com magnetização remanente. O vetor de inversão magnética baseia-se nas magnetizações induzida e remanente e é indicado para regiões de baixa latitude magnética. A inversão magnética pelo vetor de inversão magnética foi aplicada ao complexo Registro do Araguaia, Goiás Alkaline Province, com o objetivo de estimar a geometria e forma de emplacement. Este complexo está localizado em região de baixa latitude magnética e possui forte magnetização remanente. Neste trabalho foram utilizados dois levantamentos magnéticos aéreos de alta resolução, projeto sudeste do mato grosso e arco magmático de Arenópolis, adquiridos entre 2004 e 2012, com linhas de voo N-S, espaçamento de 500 m e altura de voo de 100 m; foi usado também o modelo digital de elevação do Advanced Spaceborne Thermal Emission and Reflection Radiometer. Os dados foram processados no Oasis Montaj® e VOXI Earth Modelling®. O processamento consistiu na interpolação, sutura e recorte da área do complexo. Em seguida, no vetor de inversão magnética, adotou-se o constraint IRI^{2+}. Posteriormente foram gerados isosurfaces com contraste de susceptibilidade magnética ≥ 0.01 SI, este valor ajustou-se a região de ocorrência do complexo, coincide com anomalia magnética dipolar atribuída a província alcalina de goiás, possui alta amplitude no vetor de magnetização, está próximo de ocorrências minerais comuns a rochas alcalinas e áreas com processos minerais de pesquisa para minerais e rochas comuns a rochas alcalinas. O complexo Registro do Araguaia é formado por rochas com contraste de susceptibilidade magnética entre 0.02 a 3.8 SI, em planta é formado por rochas quase concêntricas, com forma predominantemente circular, com núcleo mais magnético e atingiu a extensão vertical aproximada de 20 km. A inversão revelou que há um dique, entre 0.1 km e 7 km de profundidade, de direção NE-SW, ligado a este complexo. O complexo e o dique possuem *dip* vertical e a forma de *emplacement* é intrusion T-shaped. A partir da inversão do vetor de magnetização verificou-se que o contraste de susceptibilidade magnética depende da litologia da rocha alcalina, da litologia da rocha encaixante e do tamanho do voxi, não há um valor de susceptibilidade magnética padrão que pode ser adotado para vários complexos. Esta técnica revelou facilmente a geometria e forma de emplacement do complexo, podendo ser adotado para os outros complexos da província alcalina de goiás e para investigação de outros tipos de rochas, sem a necessidade de conhecimento prévio sobre as mesmas. Para investigar corpos menores e com maior grau de detalhe, sugere-se realizar um levantamento magnético terrestre para gerar um modelo com maior resolução.

Matched Filter and voxi MVI to study the Az125 influence under the Goiás Alkaline Province

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Abstract

The Goiás Alkaline Province is formed by rocks that host metallic and non-metallic mineral deposit, such as Ni, Cu, Vermiculite, phosphate, among others. Some works state that the Goiás Alkaline Province is tectonically controlled by Azimuth 125. To verify if there is a relationship between Az125 and the Goiás Alkaline Province of Goiás, two techniques were applied, Matched Filter and voxi Magnetic Vector Inversion. The analysis of the two methods revealed that there is no tectonic control of the Az125 over de Goiás Alkaline Province.

A Província Alcalina de Goiás está localizada no Arco Magmático de Arenópolis Oeste, NNE da bacia do Paraná, na região denominada de *Paraná-Chacos Deformation Zone*. É formada por 11 complexos alcalinos, mineralizados em Ni, Cu, apatita, vermiculita, dentre outros, hospedados em rochas ultrabásicas e ácidas, associadas a arcos, flexuras e lineamentos tectônicos. Alguns trabalhos afirmam que as rochas desta província são tectonicamente controladas pelo Azimute 125. Para verificar se há relação entre o Az125 com a Provincia Alcalina de Goiás, foram aplicadas duas técnicas, *Matched Filter* e voxi *Magnetic Vector Inversion*, utilizando os dados magnéticos de cinco levantamentos aéreos de alta resolução, adquiridos entre 2004 e 2012, com linhas de voo N-S, espaçamento de 500 m e altura de voo de 100 m. Foi usado também o modelo digital de elevação do Advanced Spaceborne Thermal Emission and Reflection Radiometer. Os dados foram processados no Oasis Montaj® e VOXI Earth Modelling®. O processamento inicial consistiu na interpolação, redução ao polo, sutura e aplicação do Matched Filter. No segundo processamento foi feita a interpolação, sutura, recorte da área, e geração do modelo do vetor de inversão magnética com constraint IRI^{2+}. A partir do *Matched Filter* foram selecionadas três profundidades para interpretação de lineamentos magnéticos, dentre eles o Az125, 2 km, 7 km e 24 km. Observou-se que o Az125 ocorre somente em níveis crustais rasos, até aproximadamente 7 km, esta estrutura é localmente deslocada por outras estruturas tectônicas e não há relação desta estrutura com os complexos da Provincia Alcalina de Goiás. A inversão a partir do *Magnetic Vector Inversion* demonstrou que o Az 125 ocorre em profundidades inferiores a 5 km, aparentemente uma pequena parte desta estrutura se prolonga a oeste do Lineamento Transbrasiliano. Com a visão tridimensional do voxi verificou-se que os complexos alcalinos que estão próximos a esta estrutura têm forma circular a semi-circular, em planta e alcançam profundidades, na maioria das vezes, superiores a 5 km. Não foram identificados corpos alongados na direção NW-SE, paralelo a direção do Az125, portanto, não evidenciando nenhum controle tectônico do Az125 sob as rochas da Provincia Alcalina de Goiás. O *Matched Filter* forneceu informações sobre os lineamentos magnéticos, em duas dimensões, enquanto que no voxi *Magnetic Vector Inversion* estas mesmas informações foram ressaltadas tridimensionalmente, sendo mais fácil a interpretação das estruturas tectônicas, no caso do Az125, e a correlação deste com as rochas da Província Alcalina de Goiás. As duas metodologias revelaram que o Az125 não exerce controle tectônico nas rochas da Provincia Alcalina de Goiás.

5. CONSIDERAÇÕES FINAIS

A técnica matched filter permitiu observar a continuidade das estruturas tectônicas em diferentes níveis crustais, assim como anomalias magnéticas dipolares associadas à Província Alcalina de Goiás. Foram identificadas 15 estruturas tectônicas já mapeadas e 38 novas estruturas tectônicas foram contribuições deste trabalho.

Foi observado que ao longo das estruturas interpretadas e também na interseção das mesmas, há concentração de sismos, o que indica seu caráter ativo ou que sofre reativação. Estes concentram-se, principalmente, no interior do Arco Magmático de Mara Rosa, no limite entre o Arco de Mara Rosa e o Maçico Goiano, localmente no interior do Maciço Goiano, na interseção entre a falha Baliza-Hirolina, falha Serra Negra e Lineamento Transbrasiliano.

A partir das relações de interseção as estruturas foram associadas a evolução da Provínca Tocantins e fragmentação do Gondwana e, posteriormente foi feita a correlação com a Provincia Alcalina de Goiás. Verificou-se que o *emplacement* da PAGO ocorreu preferencialmente nas proximidades de estruturas tectônicas de direção NW-SE e NE-SW, geradas no estágio final da Orogenia Brasiliana e reativadas durante a quebra do Gondwana, e estruturas geradas no Mesozóico.

Não foi observada relação dos complexos da PAGO com o Az125. Esta estrutura possivelmente foi formada no final do Proterozóico e inicio do Fanerozóico, atinge profundidade relativamente rasa, < 7 km, foi localmente deslocada, da direção NW para a direção SE, pela zona de cisalhamento Moiporá-Novo Brasil, pelo lineamento Heitorai-Araguaçu e pela falha Rio Maranhão. Curto et al. (2015) e Rocha et al. (2019a) afirmam que não há evidencia da extensão do Az125 na porção oeste do Lineamento Transbrasiliano, porém, neste trabalho foi observado que esta estrutura extende-se até as proximidades de Campinápolis (MT). Já na porção a sul da área de estudo, domínio da bacia do Paraná, a continuidade do Az125 também não foi observada por Pinto & Vidotti (2019).

A modelagem gravimétrica 2,5 D revelou que parte das estruturas tectônicas interpretadas separa diferentes blocos crustais, como as falhas Baliza-Hidrolina e Serra Negra, a zona de cisalhamento Moiporá-Novo Brasil, o lineamento Anicuns-Palmeiras, dentre outros. A PAGO ocorre somente no bloco crustal nomeado de Arco

Magmático de Arenópolis Oeste. Este bloco possui uma crosta espessa e manto aparentemente mais fino (Rocha et al., 2019b). Possivelmente este manto mais primitivo não foi alterado durante a Orogenia Brasiliana permitindo a fusão parcial e geração da PAGO.

A inversão magnética pelo MVI revelou que a PAGO é formada por vinte e um complexos alcalinos, 11 previamente identificados e 10 corpos novos e menores identificados neste trabalho. Os complexos possuem forma variada, a geometria de emplacement é do tipo *pipe*, *t-shape*, *dike*, *funnel* e *finger*, muitos corpos ocorrem associados a estruturas geradas durante a Orogenia Brasiliana e outros ocorrem associados a estruturas Mesozóicas. A partir da análise do vetor de magnetização, acreditamos que estes corpos foram gerados, por pelo menos, três diferentes pulsos magmáticos.

O MVI é uma ferramenta importante na investigação de rochas alcalinas, e de novos alvos, sem a necessidade de conhecimento prévio sobre as mesmas, e esta metodologia pode ser replicada para prospecção de outros alvos em diferentes contextos geológicos.

5.1. REFERÊNCIAS

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