Carajása and Tapajós Mineral Provinces:Cratonic and PericratonicLithosphere Keel Metallogeny

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Abstract

Polymetallic ore deposits in the southeast part of the Amazon craton are grouped into three main geotectonic settings: (i) Archean TTG (tonalite-trondhjemite-granites) and greenstone belts that host low tonnage orogenic-gold deposits (e.g. Rio Maria Province); (ii) Archean polymetallic SCLM rift that hosts world-class Fe, Cu-Au, Ni, Au-PGE deposits (e.g. Carajás Mineral Province, CMP); and (iii) Paleoproterozoic (<2 million ounces) gold quartz veins deposits in the rifted edge of the Amazon cratonic lithosphere (e.g. Tapajós Gold Province, TGP). Apart from the orogenic gold deposits of the Rio Maria Province, which will not be discussed here, the tectonic setting and magmatic activity of the CMP and the TGP was most likely bimodal anorogenic. The Carajás' mineral deposits (hydrobiogenic volcanic-exhalative iron, IOCG, redox-associated Mn, lateritic Ni, Au-PGE and Ni-PGE reef) were formed during the evolution of an Archean SCLM rift. The TGP is formed by small epithermal and pluton-related Au ± (Zn-Pb-Cu-Fe) quartz vein deposits (< 2 million ounces). The TGP deposits are hosted by an A-type volcanic-subvolcanic-plutonic magmatic system driven by a mafic underplating-plume event. During the Archean the plume impact focused in the cratonic keel (150 km-thick CMP). Later, during the Paleoproterozoic, a larger plume was deflected and channelled to a rifted-edge keel (100 km-thick) forming the TGP. The CMP and the TGP are an inherited characteristic of the disturbed SCLM during rifting events. They are not related to the formation of a convergent plate margin.

Introduction

This paper compares the mineral deposits and large-scale geology of the CMP and the TGP in the context of the SCLM metallogeny. Although these two regions have different mineralization styles and ages, their main mineral deposits evolved in intracratonic extensional settings where mantle dynamics would play a significant role. The areas discussed comprise parts of the geochronological provinces of Carajás (3.10-2.53 Ga), Tapajós-Parima (2.03-1.88 Ga) and Central Amazonia (1.88 Ga) (Santos et al. 2000).

The Carajás Mineral Province (CMP) is an Archaean rift developed over a TTG-greenstone basement with minor orogenic gold endowment (e.g. Rio Maria Province). This Archaean block is, according to Cordani et al. (1984), surrounded by progressively younger orogenic belts that amalgamated to form a coalescence of accreted terranes.Thus, according to several authors (e.g. Juliani et al. 2014) the Proterozoic mineral deposits of the TGP have been attributed to a long-lived continuous accretionary environment (up to 300 Ma).

This work suggests that the metallogeny of the CMP is typical of extensional processes developed over a thick (SCLM) keel (Grainger et al. 2008; Teixeira et al. 2009). The Tapajós Mineral Province (TGP) is located on the thinned portion of the keel. It also suggests that the Amazon Cratonic keel channeled asthenosphere-derived melts to the rifted margins in the 2.0-1.7 Ga period, generating the huge Parauari- and Maloquinha-like underplate magmatism.

Geotectonic Setting and Metallogenic Model

Seismic tomography (Assumpção et al., 2013) reveals that the CMP sits over a thick (>150 km) lithospheric keel. Conversely, the TGP is located where seismic velocities (v_p) decrease at depths of <100 km indicating a thinner lithosphere. The gold mineralization of the TGP is hosted by the Creporizão, Parauari and Maloquinha plutonic-volcanic sequences. They cover an area of approximately 2,000,000 km^2 forming an extensive intra-continental anorogenic magmatic event (Klein et al., 2012). It is well known that world-class mineral deposits and provinces are associated somehow with the mantle dynamics (Groves et al., 2010; Griffin et al., 2013). An essential element to form world-class deposits is a fertile upper-mantle source region. The fertilization is heterogeneous and can form different reservoirs of fluids and metals. For instance, the 1.8 Ga A-type granites of the CMP are richer in copper than anywhere else in the Amazon region, suggesting a previous copper enrichment in the mantle. The fertilization process may be related in part to previous subduction or be an inherited characteristic of the mantle disturbed during plume activity or rifting events. Garnet and spinel xenocrystals in kimberlites of the Amazon Craton show that only a small depleted harzburgite lithosphere of the craton was preserved. The Amazon keel seems to have been deeply fertilized and was rheologically weakened during the Paleoproterozoic, allowing the infiltration of magma and hydrothermal fluids at the Amazon Craton edge.

Carajás Polymetallic Mineral Province

The Carajás Archean rift (Gibbs et al., 1986) hosts a giant 200 x 100km ore system. The basin was initially filled-up by continental tholeiitic basalts and rhyolites (Parauapebas Formation), followed by BIF's and volcanogenic sediments (Carajás Formation), and upper units dominantly composed of sedimentary and volcanoclastic rocks (Pojuca and Igarapé Bahia units) (DOCEGEO, 1988). This sequence was intruded by 2.76 Ga layered mafic-ultramafic intrusions (e.g. Luanga) and A-type granites (e.g. Estrela, Planalto). The rift is unconformably covered by shallow marine to fluvial sedimentary rocks of the Águas Claras Formation. Three main mineralizing mantle-related processes are recognized in the Carajás rift (Teixeira et al., 2009): (i) 2.76 Ga crustal extension (plume or decompressional mafic underplating), resulting in basaltic and rhyolitic flows, giant hydrobiogenic volcanic-exhalative iron deposits (e.g. N4, S11D), minor Cu-Zn disseminated volcanogenic deposits (e.g. Pojuca), PGE-Ni reefs in tholeiitic mafic-ultramafic layered intrusions (e.g. Luanga) and IOCG deposits (e.g. Sequeirinho-Pista, Moreto et al., 2015); (ii) 2.61-2.55 Ga crustal extension, decompression melting of the metasome, formation of saturated (O-H-C-S-Cl-F-rich), blind MMM and IOCG deposits (e.g. Salobo, Alemão); (iii) 1.88 Ga A-type granites reflecting a huge mantle plume event, which covers all the central Amazon Craton, producing in the Carajás Province Cu-(Au-Mo-W-Sn) greisens (e.g. Breves), Cu-Au-Mo-F deposit (e.g. Gameleira), manganese deposits, as well as the unusual, Au-PGM deposit of Serra Pelada, both of which are correlated to the Águas Claras Formation's lowermost unit. Grainger et al. (2008) and Teixeira et al. (2009) considered that the metallogeny of the CMP is petrologically related to the SCLM dynamics involved in an active rift setting.

Tapajós Gold Province

The TGP is hosted by three plutonic-volcanic sequences: Creporizão-Vila Riozinho (2.00 – 1.96 Ga), Parauari-Bom Jardim, (1.89-1.88 Ga) and Maloquinha-Moraes de Almeida (1.89-1.86 Ga). Two gold mineralizing events have been documented (at 1.96 and 1.88 Ga). The youngest is probably related to the calc-alkaline Parauari and/or alkaline Maloquinha granitoid intrusions. The TGP gold deposits are described as high-and low-sulfidation

epithermal (Dreher et al. 1998; Jacobi 1999), porphyry (Juliani et al. 2014), intrusion-related (Villas et al. 2013) and orogenic (Coutinho, 2008) types of deposits. We suggest that the TGP gold deposits are not porphyry-type or *sensu strictu* intrusion-related gold deposits. They represent a new type of mineralization related to intracratonic A-type volcanic-subvolcanic-plutonic gold system. In fact, almost 100% of the artisanal gold production in the last three decades came from granitoid-hosted quartz-gold veins controlled by regional faults and locally by brittle-ductile shear zones. The sericite-chlorite-carbonate alteration is restricted to and adjacent to the veins. According to Juliani et al. 2014, the Paleoproterozoic TGP would be associated with two magmatic arcs: one formed by steeply dipping subduction and the other by a flat one. In contrast, we argue that the TGP gold deposits result from intra-continental magmatism at the edge of a rifted cratonic keel. The large dominance of felsic magmatism and its huge volume can be explained by a megaplume impact that pooled mafic magmas at the base of the crust producing calc-alkaline and A-type magmatism.

Conclusion

The main successive ore-forming events at 2.70, 2.55, 1.88 Ga of the Amazon craton are consistent with rifting and the breakup of supercontinents with specific examples involving the Ur, Kenorland and Columbia. The CMP and TGP are located within a cratonic keel and its borders. The first exemplifies the typical metallogeny of a SCLM rift. The CMP results directly from two major magmatic-extensional periods: 1) continental tholeiitic basalts at the base of the rift; and 2) small volumes of alkaline mantellic magmas, which exsolved expressive volumes of volatiles before reaching the upper crust. The rifting activity was accompanied initially by large exhalative and bacteria activity (BIF), coeval with copious bimodal magmatism, exemplified by the Ni-PGE reefs in mafic-ultramafic magma chambers and granites. At 2.55 Ga the blind alkaline mantellic magmas were responsible for the escape of a significant amount of volatiles (Cl, F, H_2O, CO_2, SO_2) through translithospheric faults forming the world-class IOCG deposits ultimately. The TGP, in turn, results from widespread A-type magmatism produced by underplating and plume impact at the craton border. Although high- and low-sulfidation deposits have been described in the Paleoproterozoic TGP, most of the gold production comes from ephitermal and pluton-related quartz vein deposits. The absence of world-class gold deposits in the TGP could be related to the metals'dilution by huge volumes of asthenospheric melts. This is different for the CMP where magmatism focused on extensional structures in a smaller area. The CMP and TGP were formed in the SCLM keel rather than in a convergent subduction setting (**Figure 1**). Moreover, these conclusions could be further extended to the Alta Floresta Gold Province.

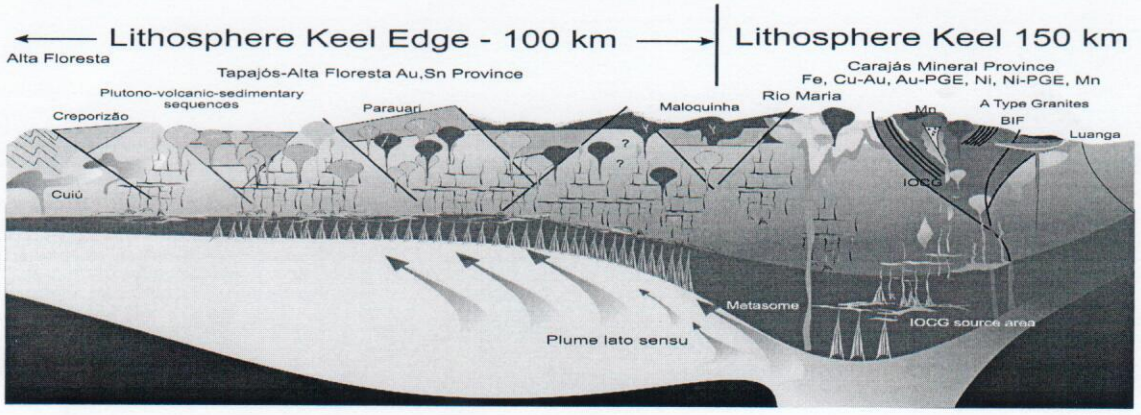

Figure 1:Tectonic scheme illustrating the role of the SCLM in the metallogeny of the SE Amazon Craton.

References

Assumpção, M., Feng, M., Tassara, A., &Julià, J. (2013). Models of crustal thickness for South America from seismic refraction, receiver functions and surface wave tomography.Tectonophysics, 609, 82-96.Assunção & Klein (2014) Journal of South American Earth Sciences 49, pp 85-105.

Cordani, U. G. ;Tassinari, C. C. G. ; Kawashita, K. . A Serra dos Carajás como região limítrofe enre províncias tectônicas.. Revista Ciências da Terra, v. 9, p. 6-10, 1984.

Coutinho (2008) Província Mineral do Tapajós e Mapa Previsional para Ouro em SIG. CPRM, Rio de Janeiro, 420p.

DOCEGEO, 1988, Revisão litoestratigráfica da Província Mineral de Carajás—Litoestratigrafia e principais depósitos minerais: Congresso Brasileiro de Geologia, 35th, Belém, Sociedade Brasileira de Geologia, Proceedings, p. 11−54.

Dreher, A. M., Vlach, S. R., & Martini, S. L. (1998). Adularia associated with epithermal gold veins in the Tapajós Mineral Province, Pará state, northern Brazil. *Brazilian Journal of Geology*, *28*(3), 397-404.Jacobi, P. (1999). The discovery of epithermal Au-Cu-Mo proterozoic deposits in the Tapajós Province, Brazil. *Brazilian Journal of Geology*, *29*(2), 277-279.

Gibbs, A.K., Wirth, K.R., Hirata, W.K., and Olszewski, W.J., Jr., 1986, Age and composition of the GrãoPará Group volcanics, Serra dos Carajás: RevistaBrasileira de Geociências, v. 16, p. 201–211.

Grainger, C.J., Groves, D.I., Tallarico, F.H.B., and Fletcher, I.R., 2008, Metallogenesis of the Carajás mineral province, southern Amazon craton, Brazil: Varying styles of Archean through Paleoproterozoic to Neoproterozoic base- and precious-metal mineralisation: Ore Geology Reviews, v. 33, p. 451−489.

Groves, D.I., Bierlein, F.P., Meinert, L.D., and Hitzman, M.W., 2010, Iron oxide-copper-gold (IOCG) deposits through Earth history: Implications for origin, lithospheric setting, and distinction from other epigenetic iron oxide deposits: Economic Geology, v. 105, p. 641−654.

Griffin, W. L., Begg, G. C., & O'Reilly, S. Y. (2013).Continental-root control on the genesis of magmatic ore deposits. *NatureGeoscience*, *6*(11), 905-910.Juliani *et al.* (2014) In: Silva et al. (org) Metalogênese das Províncias Tectônicas Brasileiras. CPRM, Belo Horizonte, pp 229-268.

Klein, E.L., Almeida, M.E., and Rosa-Costa, L.T., 2012. The 1.89-1.87 Ga Uatumã Silicic Large Igneous Province, northern South America: Large Igneous Province Commission, November 2012 LIP of the Month.Lloyd*et al.* (2010) Journal of Geophysical Research: Solid Earth (1978–2012)115(B11).

Moreto, C.P.N.; Monteiro, L.V.S.; Xavier< R.P.; Creaser, R. A.; Dufrane, A.; Tassinari, C.C.G.; Sato, K.; Kemp, A.I.S.; Amaral, W.S. 2015. et al. 2015. Neoarchean and Paleoproterozoic Iron Oxide-Copper-Gold Events at the Sossego Deposit, Carajas Province, Brazil: Re-Os and U-Pb Geochronological Evidence. Economic Geology and the Bulletin of the Society of Economic Geologists, 110, p. 809-835, 2015.

Teixeira *et al.*(2009) III Simpósio Brasileiro de Metalogenia, Gramado, RS.

Villas, R.N.; Santiago, E.S.B.; Castilho, M.P.2013. Contexto geológico, estudos isotópicos (C, O e Pb) e associação metálica do depósito aurífero Tocantinzinho, domínio Tapajós, Província Tapajós-Parima. Revista de Geologia – USP, sériecientífica, vol. 13, nº 1, p. 1-20.