PGM and Complex Ni-Fe-Cu-Co Arsenide-Sulfide Paragenesis Associated with Fe-Ti-V Oxides of the Gulçari Magnetitite Pod, Rio Jacaré Sill, Bahia, Brazil

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Introduction

Mafic and ultramafic layered intrusions are well known repositories of important magmatic metalic ore deposits. The best example of such intrusions is the Bushveld Complex in South Africa which exhibits mineralization of chromite, platinum-group metals, and Fe-Ti-V magnetic iron ores. Orthomagmatic processes driven by differentiation of large magma chambers are commonly used to explain such mineralization. Special regard has been historically given to Cu-Ni sulfide-related PGE mineralization and also to PGE-enriched sulfide-bearing chromitites. As the magnetitite ore bodies in layered intrusions have been mined solely for the Fe-Ti and V their role as potential PGE carrier have been seldomly studied. In this paper we intend to contribute to this particular issue by investigating one of these magnetite ore deposits as an alternative source of PGE. We present petrographic and mineral chemistry studies of the magnetic iron ores of the layered gabbroic Rio Jacaré Sill (RJS), Bahia (Brazil) and the associated PGE mineralization.

Magnetite pod-like bodies occur in the layered units of the Rio Jacaré Sill. The Gulçari pod is the main RJS magnetite deposit; it is located in the Lower Transition Zone of this intrusion. The pod consists a sequence of magnetitite, pyroxenite and gabbro layers. The known reserves are $2{,}0 \times 10^6$ tons of vanadiferous iron ore, bearing a mean grade of 2% V_2O_5. The magnetic iron ore also exhibits PGE values up to 4 ppm Pt, 1ppm Pd, and average grade of 400 ppb total PGE. Complex platinum-group minerals, PGM, were identified in the anomalous PGE intervals which were studied by Sá et al (1993). They form an oxide-PGM-arsenide/sulfide paragenesis which shows three distinct textural features. The first, considered as a primary feature, refers to exsolved Pt-Cu alloys within complex sulfide grains poikilitically enclosed in cumulus magnetite and ilmenite. The second one corresponds exsolution fringes of PGM on arsenides that occupy intercumulus space. The third textural type is represented by fracture-filling tiny PGE alloy particles in both silicate and Fe-Ti-V-oxide grains.

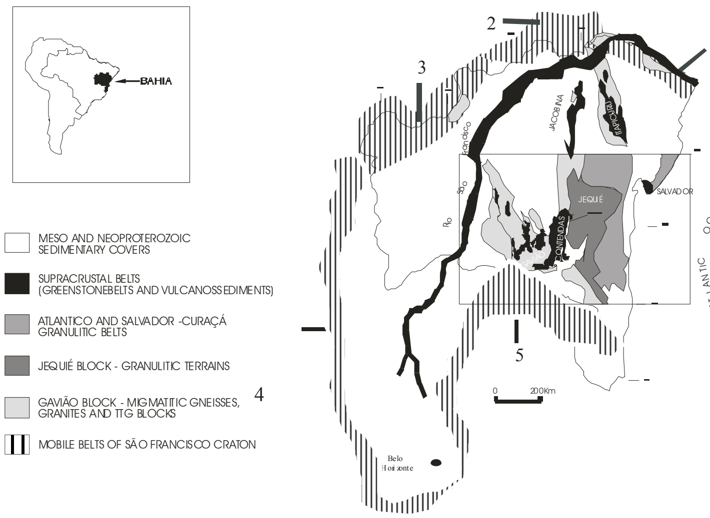

Figure 1. Geological outline of the S. Francisco Craton and the localization of the Rio Jacaré Sill. After Mascarenhas, (1976) and Almeida and Hasui, (1981)

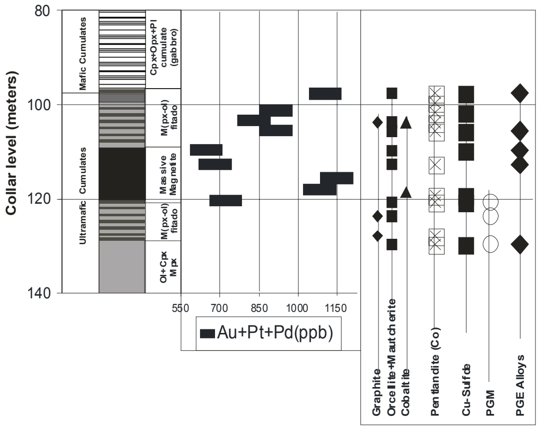

Figure 2. *PGE, PGM and associated sulfide- arsenide paragenesis of the Fe-Ti-V oxide minerallization ofthe FGA40 drill core of. the Gulçari Farm prospect. (After Brito 2000).*

Geology

The Rio Jacaré Sill is a 70km long, 1km wide synvolcanic Archean (2,841 ± 68 Ma Sm-Nd age, Brito et al. 1999) layered intrusion. It is intruded into folded and metamorphosed basaltic and andesitic rocks interbedded with continental sediments of the Archean Mirante Complex (Brito 2000). This Complex consists of the Mirante Formation (MFm.) and RJS; it is equivalent to the intermediate unit of the Contendas-Mirante Group of Marinho et al. (1994). The complex lies along the southern part of the Contendas-Jacobina Lineament, (fig1), which defines the limit between the Jequié and Gavião Blocks in the central-northern part of the São Francisco Craton.

The Rio Jacaré Sill

R.J.S. is divided up into three zones: a Lower Zone (LZ) which is 300m thick, a Transition Zone (TZ), 200-100 thick and an Upper Zone (UZ) which is 600 to 1000m thick. Lz consists of medium-grained gabbros that exhibit increase in clinopyroxene modal proportion and plagioclase grain size decrease towards TZ. TZ is made up of ultramafic cumulates consisting of cumulus olivine, clinopyroxene, magnetite and ilmenite that grade from magnetite peridotite, magnetitite with pyroxene and magnetite pyroxenite and mafic cumulates with cumulus plagioclase and clinopyroxene and minor hypersthene. Magnetite is usually a cumulus phase but sometimes it may be an intercumulus mineral. Monomineralic and bimodal cumulates define a microrythmically layered sequence of pyroxenite and gabbros with variable amounts of magnetite. Varied-textured fine to medium-grained gabbroic rocks occur in TZ as enclaves of decimetric to block size of fine-grained gabbro, sometimes pillow-shaped; they also may be present as thin sill-like sheets of diabasic rocks. These varied-textured rocks are interpreted as the result of mixing between different magmas. The Upper Zone consists of two subzones: UZ1 is gabbroic to pyroxenitic and UZ2 is gabbroic and leucogabbroic to anorthositic. UZ1 is a rhythmically banded sequence of micro-layered gabbro-pyroxenite-magnetitite, pyroxenite-ferro-gabbro and magnetite-bearing anorthosite. UZII consists of modally layered rocks divided in three units, a, b, and c. Unit a is made of medium to coarse-grained leucogabbro, unit b is composed of coarse-grained leucogabbro and unit c consists of medium to coarse-grained leucogabbro and anorthosite.

Mineralization

RJS hosts massive magnetitite pod-like bodies confined to a layered sequence of mafic and ultramafic cumulates. They are named lower and upper magnetite seams.

The lower magnetite seam is represented by the Gulçari pod which occurs within the lower Transition Zone. This pod is a 300m long, 150m thick sequence of magnetite, pyroxenite and gabbro layers carrying 2 million tons of vanadiferous iron ore with mean grade of 2% V2O5, that displays PGE values up to 4 ppm Pt, 1ppm Pd and average grade of 400ppb total PGE. Magnetite layers are interbeded with ultramafic and mafic cumulates (fig 2). The ultramafic cumulates are transgressive towards the contact with the Lower Zone gabbros and consist of olivine-magnetite cumulates, and clinopyroxene-magnetite heteradcumulates.

The massive magnetite layers are made up of ilmenite-magnetite heteradcumulates that form 2 cm to 3 meters thick layers that contain variable amounts of clinopyroxene (En 32-38). Associated mafic cumulates are rythmically microlayered gabbro, magnetite, and magnetite-piroxenite bands. The outer contacts of the magnetite pod exibit hornblende-rich rocks and dunite in places. These features are suggestive of a zoned pattern that Brito (1984) interpreted as similar to the magnetite pipe-like bodies of the Bushveld Complex (Willemse 1979). The upper Transition Zone pod-like magnetite bodies are groupings of magnetite seams and pyroxenites that form 150m long, 20m thick masses of 150,000 tons of vanadiferous iron ore with mean grade of 0.5% V2O5 and maximum total PGE contents of 1.3 ppm and mean grade of 380 ppb. The upper Transition

Zone also contains a low grade Cu sulfide mineralization which is confined to the lowermost layers of the upper magnetite seams.

Ore mineralogy and Microtextural Features

Fe-Ti-V Oxides. The main ore minerals are the Fe-Ti-V oxides, magnetite and ilmenite, which occur together with olivine (Fo 46), clinopyroxene, and metamorphic minerals such as amphiboles (cummingtonite, and Fe-tschermackite), and serpentine. Clinopyroxene is altered to chlorite, especially at the borders of grains. Magnetite and ilmenite show cumulus texture; ilmenite is the early crystallizing phase.

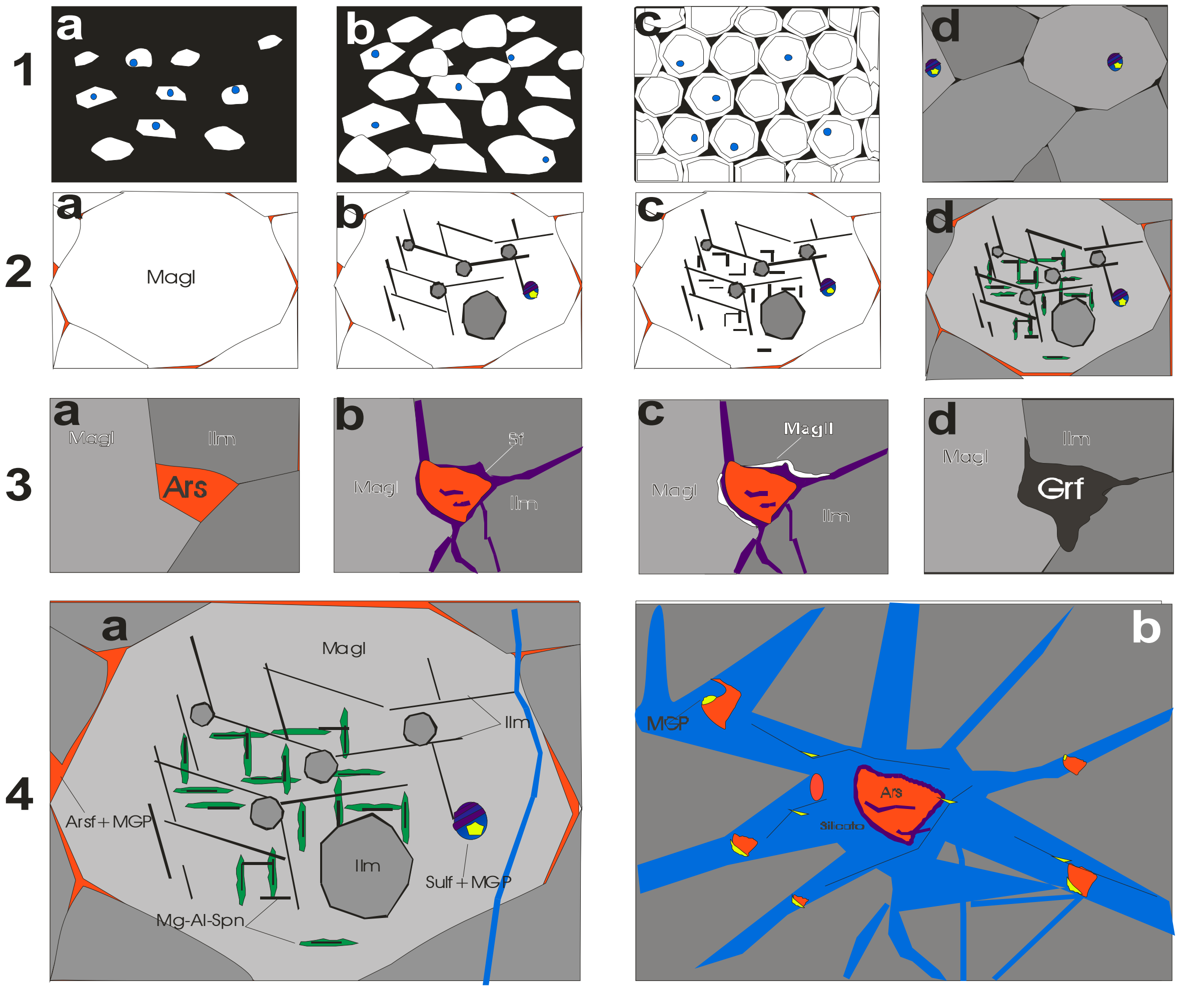

Figure 3. *Microtextural evolution of the mineralization:1-Cumulus stage:1 a-nucleation of ilmenite and magnetite around EGP-rich sulfides. 1b and 1c, adcumulate overgrowth. 1d- Annealing and Al-rich spinel formation external to magnetite.2-Exsolutions: 2a.-Arsenic-bearing fluid injection at triple junctions. 2b- Formation of tellis-type oxiexsolution. 2c - Separation of ulvospinel via cloth texture exsolution. 2d- Exsolution of Mg-Al spinel from ulvospinel.3- Hydrothermal mineralization: 3a. Increasing fluid pressure promotes separation of grains by dilation of conctacts. 3b-Sulphur-enriched fluid arrival at arsenide and oxide interfaces. 3d. - Oxidation of sulfides.4- Current aspect of the mineralization: 4a.- Syngenetic Fe-Ti-V oxide-hosted PGE mineralization. 4b- Hydrothermal PGE mineralization associated with arsenides, sulfides and fracture-bound PGE alloys.Abreviations : Mag1=primary magnetite; Mag2= Secondary (hydrothermal) magnetite; Ilm = Ilmenite; Sf = Sulfide; Ars = Arsenide; Grf = Grafite; Spn = spinel.*

Individual grains of magnetite and ilmenite show round shapes suggesting adcumulate growth. Magnetite and ilmenite also show poligonized shapes, curved borders, and policrystalline mosaics with 120 degrees dihedral angles at triple junctions. This suggests that annealing processes took place during subsolidus cooling. Magnetite shows rare broad ilmenite lamellar intergrowths of the so-called sandwich microtexture. It also show trellis microtextutres, which is a network of fine ilmenite lamellae exsolved at acute angles. Ilmenite also forms round to irregular shaped exsolved grains at the trellis intersections. Magnetite also shows the typical cloth microtexture which the exsolution of ulvospinel lamellae inthe 100 plane of the magnetite crystals. Aluminous magnesian spinel also occurs as fine exsolution lamellae within magnetite grains. Geothermo-barometric studies indicate that these ores underwent interoxide re-equlibration under reducing conditions defined by ilmenite. Ilmenite and olivine show equilibrium temperatures from 950 to 550oC. Ilmenite and magnetite coexisting grains yielded temperatures as low as 450-550 C at low fO2.

Platinum-Group Minerals and associated sulfides and Asenides

Eleven PGM-bearing phases have been identified. These minerals are associated with sulfides and arsenides within the iron-oxide grains and sometimes they are silicate-hosted. Sperrylite occurs as tiny (10σm) round grains whithin magnetite; sometimes it is silicate-hosted. It also shows external exsolution of gversite which is associated to cobaltite. Gversite also is associated with cobaltite in grains where it forms coronas around mautcherite. Cabriite occurs as very tiny grains (1σm) external to orcellite, in contact with silicate (cummingtonite). Cabriite also forms fracture-filling tiny grains (1σm) associated with oxidized chalcopyrite , orcellite and secondary magnetite (pure Fe3O4) . Cu-Pt alloys are usually enclosed in magnetite and form complex grains, that exhibit intergrowths with pyrrotite, chalcopyrite and bornite. These Pt-Cu alloys have been identified as isoferroplatinum. Platinum also occurs as platinian awaruite (5% Pt) forming 5σm round euhedral grains. Pt-free awaruite usually forms larger grains (10σm).

Discussion

The PGM, arsenides, sulfides, Fe-Ti-V oxides and silicate paragenesis exhibit textural features indicative of a sequence of magmatic and hydrothermal events. Aiming to explain the exotic relationship between Fe-Ti-V spinels and PGE mineralization we present a simple model of textural evolution via a three stage mineralizing process (figure 3). We suggest a first stage represented by the classic PGE collection by sulfides which were later captured within Fe-Ti-V oxides during cumulus processes. The second stage consisted of PGE-bearing arsenic post-cumumlus fluid injections which were deposited as PGE-bearing arsenides in intercumulus space. The third stage refers to the redistribution of these syngenetic PGE concentrations by late post-magmatic/metamorphic fluids.

The first stage represents orthomagmatic PGE mineralization which could to a certain extent be compared with PGM particles enclosed in chromite grains as shown in other layered intrusions. The second stage could be related to hydrothermal late arsenic-rich syn-magmatic fluids possibly related to crystallization compaction. The last phase may be ascribed to post-magmatic redistribution of PGE via a metamorphic fluid.

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