THE EPIGENETIC SEDIMENT-HOSTED SERRA PELADA
Au-PGE DEPOSIT AND ITS POTENTIAL GENETIC ASSOCIATION WITH
FE-OXIDE CU-AU MINERALISATION WITHIN THE
CARAJÁS MINERAL PROVINCE, AMAZON CRATON, BRAZIL

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Abstract - The Serra Pelada Au-PGE deposit is located within the Carajás Mineral Province of the
southeastern Amazon Craton, Brazil. Gold-PGE ores are epigenetic and display a strong structural control,
being hosted in sub-greenschist facies carbonaceous and calcareous meta-siltstone, within the hinge zone
of a reclined, tight, regional-scale F2 synform. Although the entire orebody has undergone deep tropical
weathering, some evidence of the original hydrothermal alteration is preserved. Gold-PGE mineralisation
is associated with the formation of magnetite- and hematite-rich hydrothermal breccias, massive zones
of hematite metasomatism, intense sericite (white mica)-kaolin metasomatism, siderite veining and a jasperoid
envelope of amorphous silica alteration hosting rare disseminated pyrite. All other Au-PGE ore-related
mineral assemblages have undergone intense weathering to hydrated Fe-oxides and secondary clay minerals,
preventing further description of primary ore and alteration features. The geochemistry of the primary Au-
PGE ores at Serra Pelada displays many similarities to that of Fe-oxide Cu-Au deposits within the Carajás
Mineral Province, and indeed world-wide, in terms of metal association (eg. Co, Ni, Cu, U), LREE enrichment
and accompanying Fe-metasomatism. The Au-Pd-Pt association also suggests ore metal transport in acid,
oxidising, chloride-rich fluids, similar to those for Fe-oxide Cu-Au deposits. In combination with these
similarities, and the location of the Serra Pelada Au-Pd-Pt deposit, it is suggested that the latter represents
a distal equivalent to the Fe-oxide Cu-Au deposits and, as such, a target that may have been overlooked during
exploration programs around such terrains globally.

Introduction

Serra Pelada, a world-class Au-PGE deposit, is located adjacent to a complex strike-slip system within the
Itacaiunas Belt of the northern Carajás Mineral Province, southeastern Amazon Craton, Brazil (Figs 1 & 2). The
Itacaiunas Belt comprises an Archaean meta-volcanic-sedimentary sequence, the Itacaiunas Supergroup, intruded
by a suite of granitic magmas ranging from Archaean to Proterozoic in age (Fig. 3). Originally identified in the
1960’s as a major iron-ore province hosting the giant Carajás iron mines, the metallogenic province has more
recently been recognised as a premier Cu-Au province, hosting a number of large (>300 Mt) Fe-oxide Cu-Au
(±Mo+Ag+U+REE) deposits (eg. Cristalino, Igapó Bahia Alemanía, Salobo, Sossego).

Since the discovery of the Serra Pelada Au-PGE deposit in the early 1980’s by garimpeiros, a local commune of miners
and prospectors, it has been subjected to one of the largest gold rushes in South American history, being worked by
more than 100,000 garimpeiros at the peak of production activity (Fig. 4). Although the deposit has been exploited
sporadically for almost 20 years, exclusively by garimpeiros, very little scientific research has been carried out. The
original metal content of the deposit has been difficult to calculate given the extensive working by garimpeiros.
However, a current estimated resource, in the unmined portion of the deposit, is 56 t Au, 15 t Pd and 7 t Pt, grading
15.20 g/t Au, 4.09 g/t Pd and 1.89 g/t Pt (CVRD, 1998). Original pre-mining resources have been estimated at ~110 t
Au, ~35 t Pd and ~18 t Pt, although the uncertainty of these figures is high.

Previous scientific studies carried out on the Serra Pelada orebody and in the surrounding area include brief structural
descriptions of the Au-PGE ore-hosting regional-scale syenform exposed in the Serra Pelada open-pit and of the
mine sequence geology (Jorge Joao et al., 1982; Meireles & Teixeira, 1982; Lab & Costa, 1992; Pinheiro, 1997).
Petrographic studies, mapping and drill-core analysis, by Tallarico et al. (2000a), led to their interpretation that the
Serra Pelada deposit was genetically linked to an Archaean diorite and associated skarn mineralisation. They suggested
that Serra Pelada constituted a unique mineral occurrence, distinct from the Fe-oxide Cu-Au deposits in the Carajás
Mineral Province. The object of this paper is to briefly describe the Serra Pelada deposit, and to examine its possible relationship to the Fe-oxide Cu-Au deposits in the Carajás Mineral Province. Field-based observations are stressed, together with geochemical data, although the extreme weathering of the entire deposit hinders application of many conventional analytical techniques.

Regional Setting

The Carajás Mineral Province comprises two Archaean tectonic blocks, the older southern Rio Maria granitoid-greenstone terrain (Fig. 3), represented by rocks of the Andorinhas Supergroup (Huhn et al., 1988), and the northern Itacaínas Belt (Fig. 4; Araújo et al., 1988). In contrast to typical granitoid-greenstone terrains, which are widely considered to have developed in arc and back-arc environments, rocks of the Itacaínas Supergroup of the Itacaínas Belt, display similarities to volcanic and sedimentary rock sequences developed on continental crust adjacent to rift zones (Olszewski et al., 1989) or intracratonic basins (Machado et al., 1991). Rocks of the Itacaínas Supergroup, which host the Serra Pelada Au-PGE deposit and the Carajás Fe-oxide Cu-Au deposits, form a structural province represented by the major E-W to NNW-trending Carajás and Cinzentu strike-slip systems (Figs 2 & 3). Transpressional to transtensional deformational phases throughout the Late Archaean, and transpressional reactivation of the Carajás and Cinzentu strike-slip systems in Proterozoic times, dominate the tectonic evolution of the region (Pinheiro, 1997). Deposited during the Late Archaean (ca 2.75 Ga), the Itacaínas Supergroup consists of a sequence of volcano-sedimentary rocks, dominated by mafic volcanic rocks, metamorphosed to greenschist and amphibolite facies (Machado et al., 1991). Unconformably overlying the volcano-sedimentary sequence are rocks of the Aguas Claras and Rio Fresco Formations, extensive platform sequences of Archaean (ca 2.68 Ga) sandstones, conglomerates and siltstones, metamorphosed to lower greenschist and sub-greenschist facies (Trendall et al., 1998). The supracrustal rocks of the Itacaínas Supergroup have been intruded by several Archaean to Proterozoic granitoids. These include calc-alkaline granitoids and diorites of the ca 2.74 Ga Plaqu

Figure 1: Geological map of the South American Platform showing the location of the Amazon Craton and the Carajás Mineral Province, designated CMP (after Hasui and Almeida, 1985).
Geology and Structural Setting of the Serra Pelada Area

The Serra Pelada Au-PGE deposit is located in the northeastern part of the Carajás Mineral Province, at the eastern termination of the Cinzento strike-slip system of the Itaicaínas Belt (Fig. 3). Stratigraphic contacts between rocks of the Rio Novo Group and the Rio Fresco Formation, adjacent to the Serra Pelada deposit, display an E-W trend parallel to the regional trend of most units. The Rio Novo Group is an Archaean greenstone sequence composed mainly of mafic volcanic rocks, BIF and ultramafic schists that were metamorphosed to greenschist facies, and it represents the basal sequence within the Serra Pelada area. Unconformably overlying the Rio Novo Group are the Archaean Rio Fresco Formation metasedimentary rocks, represented by a platform sequence of quartzites, impure marble, meta-conglomerate, carbonaceous and calcareous beds and red meta-siltstone units metamorphosed to sub-greenschist facies (Fig. 5). The Rio Fresco Formation metasedimentary rocks are intruded by diorite plugs, possibly related to the 2.74 Ga Pláquê Granitoid Suite. 1.88 Ga A-type granite of the Carajás Suite, represented by the Cigano granite (Machado et al., 1991), and much younger 198 Ma NW-trending gabbro dykes (Rb/Sr, Metreles & Teixeira, 1982). A mafic-ultramafic intrusion, possibly genetically related to the 2.75 Ga Luanga mafic-ultramafic complex that lies to the east of the Serra Pelada area (Fig. 3), intrudes only the greenstones of the Rio Novo Group (Fig. 5). Additionally, a number of circular, sub-surface,
pipe-like breccia bodies, identifiable only by gravity/magnetic data and deep drilling (unpublished CVRD company reports), associated with intense chlorite ± sericite ± magnetite ± biotite ± siderite ± pyrite alteration, occur in the eastern part of the Serra Pelada area. These pipe-like breccia bodies (Fig. 9a) are currently of unknown origin and age.

The structural evolution of the Serra Pelada area is complex, incorporating five identifiable deformation events (D1-D5)
that produced a polyphase-deformed terrain. These deformation events are associated with a series of transtensional and transpressional reactivation phases of major E-W faults, locally represented by movement along the Cotia Fault (Fig. 6). The D1 event, restricted to the metavolcanic rocks of the Rio Novo Group, incorporated the development of sinistral NNE-SSW-trending shear zones resulting from WNW-ESE transpression. Following deposition of sedimentary cover rocks of the Rio Fresco Formation, D2 dextral strike-slip transpressional movement occurred along major E-W faults. The syn-tectonic intrusion of diorite (ca. 2.74 Ga), and the associated thermal aureole within rocks of the Rio Fresco Formation (with sub-economic skarn-like Cu-Au mineralisation), occurred during the initiation of dextral E-W fault movement. Continued transpressional movement resulted in NNW-SSE compression, which formed regional-scale, reclined, tight, asymmetrical F2 folds. These folds are the main structural hosts of Au-PGE mineralisation. The north-facing, kilometre-scale folds plunge gently (15°-25°) to the west-southwest. Their formation was associated with thin-skinned thrusting within the sedimentary rocks of the Rio Fresco Formation. This thrusting caused the structural emplacement of a diorite block, dismembered from the main diorite body at depth, along a hangingwall thrust to the Serra Pelada reclined fold, and caused major truncation of other lithological units. Peak metamorphic conditions within the Rio Fresco Formation metasedimentary rocks occurred late during the D2 event, based on observed textural relationships between prograde metamorphic minerals and D2 fabrics.

The third deformation event, D3, is directly related to the formation of open F3 folds that plunge to the southwest and deform the D2 thrust planes and F2 folds. This brittle-ductile deformation event was related to WNW-ESE transpression. Continued WNW-ESE compression, and oblique-slip along compressional surfaces, is also responsible for the development of sinistral NNE-NE faults and shear zones, due to competency contrasts in lithologies.

The fourth deformation event, D4, is directly related to transtensional tectonism, resulting in the sinistral reactivation of the major E-W faults, locally represented by the Cotia Fault and parallel faults. The sinistral fault movement, with a minor SSW-NNE compressional component, produced open, gently WNW-plunging F4 folds, which locally deform both F2 and F3 folds. Sinistrally deformed NNW- to NW-trending faults are inferred as acting as major fluid conduits to the Serra Pelada F2 fold hinge. Gabbroic dykes were intruded along NW to NNW structures, which offset F2 folds and S2 foliation, and are interpreted as products of the last deformation event, D5. The D5 event is possibly related to a SW-NE extensional episode and the reactivation of NW- to NNW-trending faults.

Geology of the Serra Pelada Au-PGE Deposit

The Serra Pelada Au-PGE mineralisation is hosted entirely by metasedimentary rocks of the Rio Fresco Formation (Fig. 5) that include, in sequence from oldest to youngest, impure

Figure 4: The Serra Pelada open-pit "procissão do formigas" (procession of ants) during garimpero mining activity, October 1982 (photo courtesy of CVRD).
Figure 5: Simplified geological map of the Serra Pelada area (top) and geological map of the area surrounding the Serra Pelada Au-PGE deposit (bottom) showing the stratigraphic log of the area and location of cross sections.
marble, carbonaceous and calcareous meta-siltstone, and red meta-siltstone. The majority (>75%) of the ore is hosted in the black, carbon-rich, lower part of the carbonaceous and calcareous meta-siltstone.

Impure marble: The impure marble is composed of a sequence of dolomitic marble, dolomitic quartzite, and minor dolomitic meta-conglomerates and quartzite beds that represent a dolomitised arenite sequence. The dolomitic marble and dolomitic quartzite, which form the majority of the unit, consist of rounded quartz grains (5-60%) in a matrix of granoblastic dolomite (30-95%), with rare (<2%) clasts of quartz, banded iron formation, chert and mafic volcanic rocks.

Carbonaceous and calcareous meta-siltstone: The carbonaceous and calcareous meta-siltstone forms a well-bedded (1–4 cm-thick beds), grey to black, carbonaceous horizon of amphibolite carbon (2–10%), quartz (40–60%), dolomite (20–25%), fine-grained clays (5–20%), and rare disseminated pyrite (<1%). The basal part of the unit is dominantly a black, carbon-rich layer occurring as discontinuous lenses, which are concentrated in the hinge zone and along the lower limb of the Serra Pelada F2 synform. These carbon-rich lenses become increasingly interbedded and grey in colour upwards.

Red meta-siltstone: The red meta-siltstone is a uniform, well-bedded (1–7 cm-thick beds), red to off-white unit composed of quartz (30–60%), fine-grained clays (20–50%), and fine-grained hydrated Fe-oxides (1–15%). Minor interbeds (1–10 cm-thick) of both grey and black carbonaceous meta-siltstone occur irregularly in the lower parts of the red meta-siltstone lithology.

Lode Geometry

The geometry and localisation of high-grade ore shoots within the Serra Pelada deposit are controlled by three structural factors. These are: (1) the plunge of the major F2 fold hinge within the black carbonaceous and calcareous meta-siltstone, which is the main host for Au-PGE mineralisation; (2) the proximity of the F2 fold hinge to NNW-trending faults that were the ore-fluid channel; and (3) the lithological contacts between the carbonaceous and calcareous meta-siltstone and impure marble units. Each of these factors is described below, as are vertical changes in ore styles.

Geometric Features of Lodes

Structural analysis of the Serra Pelada deposit reveals that the plunge of individual ore shoots is controlled by the gentle plunge of the reclined, tight, F2 synformal fold hinge within the carbonaceous and calcareous meta-siltstone. The size of individual ore shoots in the meta-siltstone are closely related to the amplitude of the fold hinge and the amount of dilatation associated with the hinge zone. Long-sections of the deposit show that the orebody plunges at approximately 15°–25° WSW, parallel to the F2 fold hinge (Fig. 7). The main ore shoots reach 40 m in width in the thicker parts of the meta-siltstone (i.e. F2 fold hinge; Fig. 8a). These major ore zones are located immediately down plunge from the Serra Pelada open-pit. The reduction in dimension, and ultimate termination of the Serra Pelada orebody down plunge, is associated with the tightening of the F2 fold hinge. F3 deformation is supported by an orthogonally-oriented F3 synformal hinge (Fig. 5). This caused the F2 fold hinge to tighten and pinch-out (Fig. 8a), preventing fluid flow down-plunge of this intersecting structure during the D4 mineralising event.

Location of Fluid Conduits

There are a number of faults that are inferred to have acted as fluid conduits to the Serra Pelada deposit. Intense hydrothermal alteration is located along the strike of the E-W-trending Cotia Fault and parts of the NNW-trending Serra Pelada Fault (Fig. 5). This alteration is interpreted to be related to the Au-PGE mineralisation event, as superegen mineralogy and trace-element geochemistry are similar for both. High-grade Au-PGE intersections in the carbonaceous and calcareous meta-siltstone at Elefante (Fig. 5), southeast of the Serra Pelada open-pit, occur in high-angle faults of unknown orientation with normal vertical offset (Fig. 9b). This mineralisation is inferred as having been along strike of the NNW-trending Serra Pelada Fault, or within a parallel fault. The Serra Pelada Fault truncates the F2 synform and the Cotia Fault. Cross-sections show that the majority of the Serra Pelada orebody is located within the fold hinge adjacent to the Serra Pelada Fault, where the meta-siltstone is intersected by the fault (Fig. 8a). In addition, the volume of ore within the hinge zone decreases with increasing distance from the Serra Pelada Fault (Fig. 8b). This evidence suggests that the latter acted as a major fluid conduit for ore fluids entering the dilated, F2 fold hinge during the D4 event.

Lithological Contacts

The lithological contact zones between the meta-siltstone and marble, particularly at fold hinge zones, are interpreted to have acted as major loci for fluid flow. Slip along these contact zones, due to contrasting rock rheologies during folding, and the influence of fold hinge dilation, are interpreted to have produced planar zones for fluid flow. Ore shoots were formed along these lithological contacts at the hinge of the Serra Pelada F2 synform, predominantly within the carbonaceous meta-siltstone (Fig. 8a).

Vertical Change of Structural Control and Mineralisation Style

Sections through the deposit show that the sub-surface orebody is complex down-dip, and is controlled by a combination of tight to open folding of F2 fold hinges, which cause structural thickening of the carbonaceous and calcareous meta-siltstone. Tight F2 fold hinges result in structural thickening of the meta-siltstone, which occurs as lenses, and not a continuous stratigraphic layer, within and adjacent to the Serra Pelada deposit. These structurally thickened areas at the dilational zone of the F2 fold hinge define the most prospective areas for Au-PGE
mineralisation, which continue with depth along the plunge of the F2 fold hinge, and comprise the major ore shoots of the deposit (Fig. 8a).

**Primary Mineralisation and Hydrothermal Alteration**

Primary mineralisation within the Serra Pelada deposit is epigenetic and represented by two distinct ore types: (i) the predominant Au-Pd-Pt ore that is mainly hosted within the carbonaceous and calcareous meta-silstone, but also associated with magnetite- and hematite-bearing hydrothermal breccias, intense sericite (white mica)-kaolinite alteration zones, and an extensive jasperoid alteration halo with rare disseminated pyrite; and (ii) Au (±Pt±Pd) ore associated with massive hematite metasomatism and siderite veins in marble. All other minor zones of Au-PGE mineralisation, located in both the red meta-silstone and impure marble, are inferred to be related to supergene processes that redistributed the original epigenetic Au-PGE mineralisation. The different mineralisation styles are described below.

**Figure 6:** Structural history of the Serra Pelada area, showing interpreted principal maximum stress directions, the timing of diorite-associated 'skarn' alteration and the Serra Pelada Au-PGE mineralisation.
Carbonaceous and Calcareous Meta-siltstone-Hosted Au-Pd-Pt Ore

High-grade Au-PGE mineralisation (grades of as much as 110,000 g/t Au and 16,000 g/t Pd and Pt) is associated with zones of high carbon content (≤10% C), predominantly within the hinge zone of the Serra Pelada F2 fold. Associated hydrothermal alteration in this ore type is subtle, with kaolin-sericite (white mica) ± hematite ± quartz ± muscovite ± hydrated Fe-oxide ± monazite ± rutile ± manganese oxide being the only indicators of hydrothermal activity (Fig. 9e). Rare zones of micro-brecciated meta-siltstone host rock, associated with a kaolin-quartz-monazite-muscovite alteration assemblage, also occur within this ore type.

Intense zones of sericite-kaolin alteration possibly indicate areas of high fluid flow and the destruction of carbonaceous matter.

Magnetite and Hematite Breccia-Hosted Au-Pd-Pt Ore

Magnetite-rich breccias, mainly weathered to hydrated Fe-oxides (Fig. 9d), commonly contain high-grade Au-PGE mineralisation (as much as 100's g/t of each Au, Pd and Pt). These breccias are typically sited within the hinge zone of the Serra Pelada F2 fold, but are also located along the lower limb. The breccias are matrix supported and contain angular clasts of quartzite and meta-siltstone. Grades of gold and PGE are highly erratic within these breccias, with a strong correlation of these to the amount of matrix material and to the proximity to the carbonaceous and calcareous meta-siltstone. Commonly, barren magnetite breccias are sited within the quartzite and impure dolomite sequence, distal to the F2 fold hinge. Characteristically, hematite-rich breccias display more consistent ore grades and are located primarily within the F2 fold hinge at the contact between the carbonaceous and calcareous meta-siltstone and marble, and within the carbonaceous and calcareous meta-siltstone. This hydrothermal breccia contains clasts of marble and meta-siltstone in a matrix of hematite, and is associated with intense alteration to kaolin-sericite-hydrated Fe-oxide (Fig. 9e & f).

Jasperoid-hosted Gold-PGE Ore

An extensive jasperoid alteration zone envelopes the main ore zone within the hinge of the Serra Pelada F2 fold (Fig. 8a & b). The jasperoid envelope, which occurs as an amorphous, fine-grained silica alteration zone, also extends along the limbs of the fold. The Au-PGE mineralisation occurs where the jasperoid replaces the carbonaceous parts of the meta-siltstone, and is associated with a kaolin-hydrated Fe-oxide ± muscovite ± monazite ± hematite assemblage and rare fine-grained disseminated pyrite (Fig. 9g). Jasperoid replacements of the impure marl sequence generally contain little or no mineralisation.

Massive Hematite Gold Ore

Massive hematite, located on the lower limb of the Serra Pelada F2 fold hinge, displays Au (±Pd±Pt) enrichment. This ore type is characterised by massive hematite-chlorite metasomatism ± monazite ± apatite ± rutile alteration of the impure marl sequence (Fig. 9h), and is associated with minor siderite veins (Fig. 9i).

Fracture-fill Gold-PGE Ore

To the southeast of the Serra Pelada open-pit, and along a NNW-trending fault corridor, high-grade Au-PGE mineralisation occurs within the Elefante area (Fig. 5). High-angle fractures displaying a normal vertical offset are host to high-grade Au-PGE mineralisation (as much as 100's g/t of Au, Pd & Pt) within the carbonaceous and calcareous meta-siltstone (Fig. 9b). Free gold, palladium and platinum occur within micro-fractures that display minor selvages of kaolin associated with minor Fe-oxide ± monazite alteration.

Figure 7: Long-section of the Serra Pelada Au-PGE orebody, showing the plunge of the mineralisation at 15°-20° to the WSW. Outline of mineralisation at 1 g/t Au+PGE cut-off
Figure 8a: Cross-section of the down plunge extension to the Serra Pelada Au-PGE deposit showing the location of the Au-PGE mineralisation within the F2 fold hinge adjacent.

Figure 8b: Cross-section of the Serra Pelada Au-PGE deposit showing the termination of ore due to the tightening of the F2 fold hinge. Also note the thrust fault on the upper limb of the synform and the dislocated diorite intrusion from depth.
Deep Weathering of the Serra Pelada Au-PGE Deposit

The Serra Pelada Au-PGE deposit is located within a heavily-weathered tropical terrain of sub-greenschist facies Archean metasedimentary rocks. Since its discovery, the deposit has been mined extensively, but intermittently, leaving no surface expression of the original Au-PGE mineralisation. Access to the mined open-pit is impossible due to flooding, and the remaining sub-surface orebody has also undergone extensive tropical weathering. The calcareous rocks have been decalcified generally to ~350 m below surface (Fig. 8a & b). Whereas this may be due to decalcification during hypogene alteration, by analogy with similar decalcification in the Carlin-type gold deposits (Hofstra & Cline, 2000), deep weathering is more likely because the decalcification everywhere terminates at essentially the same depth below surface, irrespective of position with respect to the reclinésynformal fold and the orebody.

Decalcification has resulted in the transformation of the carbonaceous and calcareous meta-silstone to an amorphous carbonaceous unit, and the impure marble to a loose, friable sandstone, within the vicinity of the Serra Pelada deposit. Weathering has also transformed pre-existing magnetite and/or hematite and/or Fe-sulphides to hydrated Fe-oxides, such as goethite, and has probably transformed hydrothermal sericite, minor amounts of which are preserved, into kaolinite. Secondary manganese oxides are common, and extensive collapse breccias rich in manganese oxides occur on the limbs and hinge of the Serra Pelada F2 fold.

These collapse breccias are inferred to be related to volume reduction due to decalcification of the impure marble, under secondary weathering conditions, and are not associated with the Au-PGE mineralisation. Most of the ore components have been redistributed during weathering, with REE now mainly concentrated in secondary minerals, base metals concentrated in manganese oxides, and Au-Pd-Pt being primarily associated with amorphous carbon and Fe- and Mn-oxides. Gold and PGE's also occurred as nuggets, to 60 kg in mass, in the open-pit workings.

Ore Geochemistry

Whole-rock analyses of major, trace and REE for gold and PGE enriched samples display anomalous values for LREE, Co, Cu, Ni, Pb, Zn, As, Bi, W and U (Table 1). The Au-PGE enrichments, related to the carbonaceous meta-silstone ore, magnetite and hematite breccias, and intense zones of kaolinite alteration, display a constant enrichment signature of these trace elements. The magnetite breccias commonly display additional enrichment in Ni and Zn. The Au-PGE mineralisation within the jasperosites generally is also anomalous in Ag, Bi and W. The Au (±PGE) enrichment associated with massive hematite metasomatism displays similar enrichment in many of the above trace elements.

Stable Isotopes

Carbon and oxygen isotope ratios were measured on hydrothermal siderites associated with massive hematite Au (±Pd±Pt) ore from Serra Pelada, and from petrographically and texturally similar siderite veins from the barren pipe-like breccia bodies adjacent to the Serra Pelada deposit. Only four samples from the Serra Pelada deposit were analysed, due to a lack of suitable fresh carbonate material. Carbon isotope data for the samples exhibit a narrow range of δ13C (-0.6 to -2.2‰) and δ18O (13.8 to 14.7‰). The pipe-like breccia bodies also display a narrow, although different range of δ13C (-7.1 to -7.6‰) and δ18O (8.8 to 14.2‰). These results are plotted in Figure 10, and compared with other known reservoirs and the Igarapé Bahia Fe-oxide Cu-Au deposit.

Although the data are not definitive, the narrow range of negative δ13C values indicates the presence of magmatic fluids in the Au-PGE ore forming process of Serra Pelada. A magmatic origin may also be suggested for the pipe-like breccia bodies adjacent to Serra Pelada. Their isotopic association with the carbonate reservoir may designate an alkali magmatic genetic association, as does the isotopic similarity of the Serra Pelada Au-PGE ores with the Olympic Dam reservoir (Öreskes and Einaudi, 1992).

Preliminary Genetic Model for Au-PGE Mineralisation

The Serra Pelada Au-PGE deposit is clearly epigenetic, based upon its strong structural control by F2 folds and the associated wallrock alteration within stratigraphic horizons and along D4 faults. It appears most likely that fluids were initially channeled during D4 along E-W faults, such as the Cotinga Fault, into NW- to NNW-trending faults, such as the Serra Pelada Fault, and finally into the dilated, recliné F2 fold-hinge within the carbonaceous and calcareous metasilstone. Such a model is consistent with the occurrence of additional Au-PGE mineralisation adjacent to a recliné synformal fold-hinge at Elefantó, which is close to the southeastern extension of the Serra Pelada Fault (Fig. 5). The structural timing of mineralisation is inconsistent with the models of Villas and Santos (2001) and Tallarico et al. (2000a), which postulate that the Au-PGE mineralisation is related to diorite-associated skarn development. This skarn is also geochemically very distinct from the Serra Pelada ores, in particular, it does not display the LREE enrichment shown by Fe-oxide-dominated mineralisation styles in the Serra Pelada orebody (Table 1).

The extreme weathering of the deposit, with destruction of primary ore and alteration minerals, means that deduction of fluid conditions from mineralogical assemblages and compositions is not possible. Similarly, the main mineralised zones contain no minerals suitable for fluid inclusion studies. Hence, the nature of the ore fluids and transport and depositional mechanisms must be surmised from the metal association of the ores. Gold and PGEs, particularly palladium, can be efficiently transported in
Figure 9:

a Chlorite-rich breccia pipe, hosting granite, mafic metavolcanic and BIF clasts;
b Thin-section (x10 magnification; reflected light) of high-grade Au-PGE mineralisation associated with high angle fractures and sericite alteration within the carbonaceous and calcareous metasiltstone from the Elefante area;
c Carbonaceous and calcareous metasiltstone Au-PGE ore with minor kaolin alteration;
d Limonite-goethite (after magnetite) breccia Au-PGE ore;
e Hematite-rich hydrothermal breccia Au-PGE ore within the carbonaceous and calcareous metasiltstone;
f Kaolin alteration in Au-PGE ore zone within the carbonaceous and calcareous metasiltstone;
g Jasperoid Au-PGE ore within the carbonaceous and calcareous metasiltstone;
h Massive hematite Au (±PGE) ore.
i Siderite veins adjacent to massive hematite Au (±PGE) ore.
highly saline, oxidising, and acidic fluids, as chloride complexes in equilibrium with hematite (eg. Mountain and Wood, 1988; Wood et al., 1992). Deposition of the gold and Pd-Pt can be induced by a decline in temperature, with a rapid decrease in solubility of all three elements below 300°C, by reduction of the fluid, and/or by an increase in pH. The most obvious mechanism for deposition of high-grade Au-Pd-Pt ores is reduction caused by the extremely carbonaceous meta-siltstone host rocks, with an increase in pH due to carbonate dissolution being an additional factor. Fluid reduction would also explain the deposition of other redox-sensitive elements such as U, As, Cu, Co and Ni. Temperature decline could similarly be a factor, because the source of the fluids was presumably below the present exposure level, and the deposit is sited in the low metamorphic-grade, stratigraphically and structurally highest parts of the Carajás Basin lithostratigraphic section, where temperatures would have been relatively low during the mineralisation event.

Although the present distribution of decalcified carbonate rocks appears to mainly relate to tropical weathering, the occurrence of extensive jasperoid, some with preserved pyrite, that forms an envelope around the ore zone, suggests that acidic hydrothermal fluids also dissolved carbonate with resultant silica replacement. The co-existence of hypogene sericite and kaolin is also consistent with acidic fluids during alteration and mineralisation.

The deposit is clearly unusual in the association between gold and PGE, particularly palladium. There appear to be two potential sources for the PGE’s. The most obvious is leaching, by hydrothermal fluids, of the PGE’s from the adjacent Luanga mafic-ultramafic complex (Fig. 3) or other ultramafic intrusions in the Serra Pelada area. Such leaching and remobilisation of PGE’s, particularly palladium and platinum, have been documented in several studies, for example at Rathbun Lake, Ontario (Rowell & Edgar, 1986) and New Rambler, Wyoming (McCallum et al., 1976). However, hydrothermal fluids in these deposits are suggested to contain bisulphide or hydroxide complexes for Au-PGE transport. These are clearly not responsible for the transport of metals in Serra Pelada, given the extensive acidic alteration in the form of sericite and/or kaolin and oxidised mineral assemblages (eg. hematite; Wood et al., 1992). Potentially more interesting is the association between gold and some PGE’s, particularly palladium and platinum, in alkaline porphyry-style deposits that include the Allard Stock, Colorado (Werle et al., 1984), the Similkameen deposit, British Columbia (Fahrm et al., 1976), and the Skouries copper deposit, northern Greece (Eliopoulos & Economou-Eliopoulos, 1991; Frei, 1995). Such deposits were formed from acidic, oxidising fluids, with metals transported as chloride complexes, as is inferred for Serra Pelada.

Importantly, there are two generations of sub-alkaline to alkaline intrusive rocks in the Carajás Mineral Province, the 2.57 Ga Old Salobo granite/Estrela A-type alkaline granitoid complex and the 1.88 Ga A-type granitoid suite, which includes the Ciganó granite of the Serra Pelada area. The latter are associated with hematitic breccias not unlike those at Serra Pelada. Furthermore, a genetic association with alkaline (or shoshonitic) magmatism is proposed for a number of Fe-oxide Cu-Au deposits, notably Olympic Dam (Hauck, 1990; Reeve et al., 1990; Mutscher & Mooney, 1993; Pollard et al., 1998; Jensen & Barton, 2000), which are located within cratonic areas with Archaean basement, such as at Carajás.

**Figure 10:** Plot of δ¹³C vs. δ¹⁸O showing the isotopic composition of siderite from the Serra Pelada Au-PGE deposit and adjacent Aeroporto breccia pipes, relative to carbonatites, siderite and calcite from the Igaraçú Bahia Fe-oxide Cu-Au mineralisation (Tallarico et al., 2000b), Olympic Dam mineralisation, freshwater limestone and marine limestones (Oreskes and Einaudi, 1992).
Table 1:

<table>
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<tr>
<th>Localities</th>
<th>Serra Pelada (S.P.) Ore Types</th>
<th>Adjacent S.P.</th>
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Chemical composition of Serra Pelada Au-PGE ores types, regional alteration of the Serra Pelada area, and the Igarapé Bahia and Salobo Fe-oxide Cu-Au deposits. Major elements (wt.%) and trace elements (ppm). Sample identification by drill core and depth (m): CMS = Carbonaceous and calcareous metasiltstone Au-PGE ore (Serra Pelada); HB = Hemitite breccia Au-PGE ore (Serra Pelada); MB = Magnetite breccia Au-PGE ore (Serra Pelada); MH = Massive hematite metasomatism Au-PGE ore (Serra Pelada); KZ = Kalskellerite alteration Au-PGE ore (Serra Pelada); SK = Skarn alteration magnetite (adjacent Serra Pelada); Absx = Breccia pipe (adjacent Serra Pelada); Ig&Bah = Magnetite breccia Cu-Au ore (Igarapé Bahia; Tazava & Oliveira, 2000); Sal = Magnetite Cu-Au ore (Salobo).

Geological Similarities and Genetic Relationship to Fe-Oxide Cu-Au Mineralisation

Deposits of the Fe-oxide Cu-Au class (eg. Hitzman et al., 1992) display a strong structural control, are epigenetic, and display a direct association with extensional tectonism of Paleoproterozoic to Mesoproterozoic age (Kerrich et al., 2000). Classic economic examples of this deposit type include Olympic Dam, South Australia (Reeve et al., 1990; Campbell et al., 1998) and Ernest Henry, Queensland (Twyvorold, 1997; Mark et al., 2000). From the viewpoint of Serra Pelada, it is important that it is sited in the same Carajás Mineral Province, which arguably is a region with the most extensive group of world-class deposits of this type, including Igarapé Bahia-Alemão, Cristalina, Salobo and Sossego (eg. Huhn & Nascimento, 1998; Tallarico et al., 2000; Kerrich et al., 2000). The province is also at the margin of one of the world's largest A-type granite provinces (Santos et al., 2000).

The Serra Pelada deposit displays many similar characteristics to the Fe-oxide-Cu-Au class of mineral deposits in that: (i) the Au-PGE mineralisation is genetically related to strong Fe-metasomatism in the form of magnetite and hematite breccias; (ii) the Au-PGE ore is associated with LREE, Co, Cu, Ni, Pb, Zn, As, Bi, W and
Unrichment; (iii) the REE distribution in the ores shows similar patterns and enrichment factors (Fig. 11); (iv) the ore is epigenetic and displays a strong structural control; (v) there is a potential alkaline magmatic source; and (vi) mineralisation is interpreted to be associated with an extensional tectonic event (D4).

The recent suggestions that the Palabara carbonatite magnetite-copper deposit may be an end member of the Fe-oxide Cu-Au deposit group (Groves & Vieleircher, 2001) provides a potential connection between gold and PGE's, particularly palladium and platinum, as Palabara produces about 9 000 oz. per annum of both metals as a by-product of copper mining (Vervoord, 1986). It also indicates that the Au-Pd-Pt association may reflect an alkaline magmatic source, in agreement with the same associations in alkaline porphyry systems, as discussed above.

If the Serra Pelada deposit is, in fact, related to the Carajás Fe-oxide Cu-Au deposits, it is important to establish the nature of the connection. Clearly, the fluids implicated for Au-PGE mineralisation at Serra Pelada are similar acid, oxidising fluids to those depositing Fe-oxide Cu-Au deposits (eg. Large et al., 1989, Murphy et al., 1999). Hitzman et al. (1992) suggested that there was vertical zonation in Fe-oxide Cu-Au systems in terms of their Fe-oxide mineralogy, magnetite vs. hematite, and wallrock alteration, as well as structural style. Both Kerrich et al. (2000) and Groves and Vieleircher (2001) emphasise this theme, and suggest that there could be vertical temperature gradients within the systems that produce the vertical zonation. Gold solubility as chloride complexes is strongly dependant on temperature, with declining solubility at lower temperatures (eg. Seward and Barnes, 1997). There is some evidence that this is reflected in Cu:Au ratios of the ores, with those inferred to be higher-temperature, deeper-level deposits on the basis of their mineralogy (eg. Salobo, Ernest Henry) having lower gold contents and higher Cu:Au ratios than those inferred to have been deposited at higher crustal levels (eg. Olympic Dam, Igarapé Bahia-Alemão, Agua Claras). It is significant that the Palabara deposit, inferred to be the most proximal to source, has a very high Cu:Au ratio (Groves & Vieleircher, 2001), and that there is evidence of copper to gold zonation in the potentially most distal, hematite-dominated Olympic Dam deposit (Reeve et al., 1990).

Although it is not possible to make palaeo-reconstructions of the Carajás Mineral Province at the time of Fe-oxide Cu-Au mineralisation, as the timing of mineralisation is currently poorly constrained, it is significant that the inferred higher-temperature deposits (eg. Salobo) occur in or adjacent to, the basement complex, whereas the inferred lower-temperature deposits (eg. Igarapé Bahia-Alemão, Agua Claras) are sited in, or adjacent to, the low metamorphic-grade sedimentary rocks of the uppermost Agua Claras Formation (Fig. 12). Serra Pelada also occurs

Figure 11: REE plot comparing the Serra Pelada Au-Pd-Pt ores to Fe-oxide Cu-Au deposits of the Carajás Mineral Province (Igarapé Bahia, Alemão, Salobo) and Olympic Dam. Chondrite normalized according to Nakamura (1974). Lines not drawn to join data from Carajás Fe-oxide Cu-Au and Olympic Dam because not all REE are quoted for these samples.
Conclusions

1. Serra Pelada is a Au-PGE (Pd-Pt) deposit sited within the Carajás Mineral Province of the southeastern Amazon Craton, Brazil. This province is best known for its giant iron-ore deposits and its world-class Fe-oxide Cu-Au deposits.

2. The deposit has been strongly affected by tropical weathering, such that its original mineralogy and wallrock alteration is largely destroyed. Despite this, there is strong evidence for the former existence of magnetite and hematite, plus sericite-kaolin, siderite and quartz alteration minerals, in a deposit with an element association of Au-PGE with LREE, Co, Cu, Ni, Pb, Zn, As, Bi, W and U.

3. The deposit is clearly epigenetic with a strong structural control. It is hosted in a sub-greenschist facies, carbonaceous and calcareous meta-siltstone unit within the hinge zone of a reclined, tight, regional-scale F2 synform. The deposit is sited close to the E-W trending D2 Cotia Fault, near its intersection with numerous NW- to NNW-trending D4 faults, the most easterly one being the Serra Pelada Fault. These are interpreted as the major ore-fluid conduits.

4. Despite weathering, the high-grade Au-PGE deposit within the exceptionally carbon-rich meta-siltstone is considered to have been associated with magnetite- and hematite-rich hydrothermal breccias, massive zones of hematite metasomatism, siderite veins, intense zones of sericite (white mica)-kaolin alteration, and a jasperoid envelope related to hydrothermal decalcification of the calcareous rocks.

5. The deposit is interpreted to have formed from acid oxidising fluids that migrated along E-W and NW-to NNW-trending fault systems during D4 into the dilated fold hinge in the highly carbonaceous and calcareous meta-siltstone host unit. Gold and Pd-Pt are interpreted to have been transported as chloride complexes and deposited due to declining temperature, reduction by the carbonate host rock, and possibly increase in pH due to carbonate dissolution.

6. Although the PGE’s could have been leached from adjacent ultramafic complexes by the mineralising fluid, it is more likely that they are from fluids exsolved from an alkaline magmatic source, as Au-Pd-Pt-bearing copper-rich porphyry systems are consistently associated with alkaline intrusive rocks.

7. The Serra Pelada deposit shows a number of similarities to the Fe-oxide Cu-Au deposits (eg. Agua Clara,
Cristalino, Igarapé Bahia-Alemão, Salobo, Sossego) in the Carajás Mineral Province. These include similar element associations (particularly LREE, Co, Ni, U), very similar REE patterns, association with magnetite- and/or hematite-rich breccias, epigenetic character and strong structural control.

8. Based on its distal position to the strike-slip fault corridor containing the Carajás Fe-oxide Cu-Au deposits, and its sitting in the upper part of the exposed lithostratigraphic sequence, Serra Pelada is tentatively interpreted to have a distal relationship to the Fe-oxide Cu-Au deposits. It is interpreted to have been deposited at lower temperatures from similar, acid, oxidising ore fluids.

9. In terms of its structural timing (Fig. 6), the Serra Pelada Au-PGE deposit was most likely genetically related to either the ca 1.88 Ga subalkaline to alkaline granites that form small plutons within a few kilometres of the deposit, or possibly the alkaline A-type ca 2.57 Ga Old Salobo granite/Estrêla granitoid complex. However, there is no published dating of the deposit, and the ages of the Fe-oxide Cu-Au deposits, with which Serra Pelada is compared, are also poorly constrained.

10. If Serra Pelada is a distal equivalent of the Fe-oxide Cu-Au deposit group, it may represent a deposit style that has been overlooked in provinces of this deposit group. In view of the current high price of PGE’s, it is an attractive target type, although the geometry of the Serra Pelada ore would make it a particularly difficult target in a geologically poorly-defined terrain.

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