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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 (e.g., 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 Itacaiúnas Belt of the northern Carajás Mineral Province, southeastern Amazon Craton, Brazil (Figs. 1 and 2). The Itacaiúnas Belt comprises an Archaean meta-volcano-sedimentary sequence, the Itacaiúnas 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 (e.g., Cristalino, Igarapé Bahia-Alemão, Salobo, Sossego).

Since the discovery of the Serra Pelada Au-PGE deposit in the early 1980's by garimperos, 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 garimperos at the peak of production activity (Fig. 4). Although the deposit has been exploited sporadically for almost 20 years, exclusively by garimperos, 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 garimperos. 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, ~35t 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 synform exposed in the Serra Pelada open-pit and of the mine sequence geology (Jorge João *et al*., 1982; Meireles and Teixeira, 1982; Lab and 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 Itacaiúnas 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 Itacaiúnas Supergroup of the Itacaiúnas 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 Itacaiúnas 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 Cinzento strike-slip systems (Figs 2 and 3). Transpressional to transtensional deformational phases throughout the Late Archaean, and transpressional reactivation of the Carajás and Cinzento 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 Itacaiúnas 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

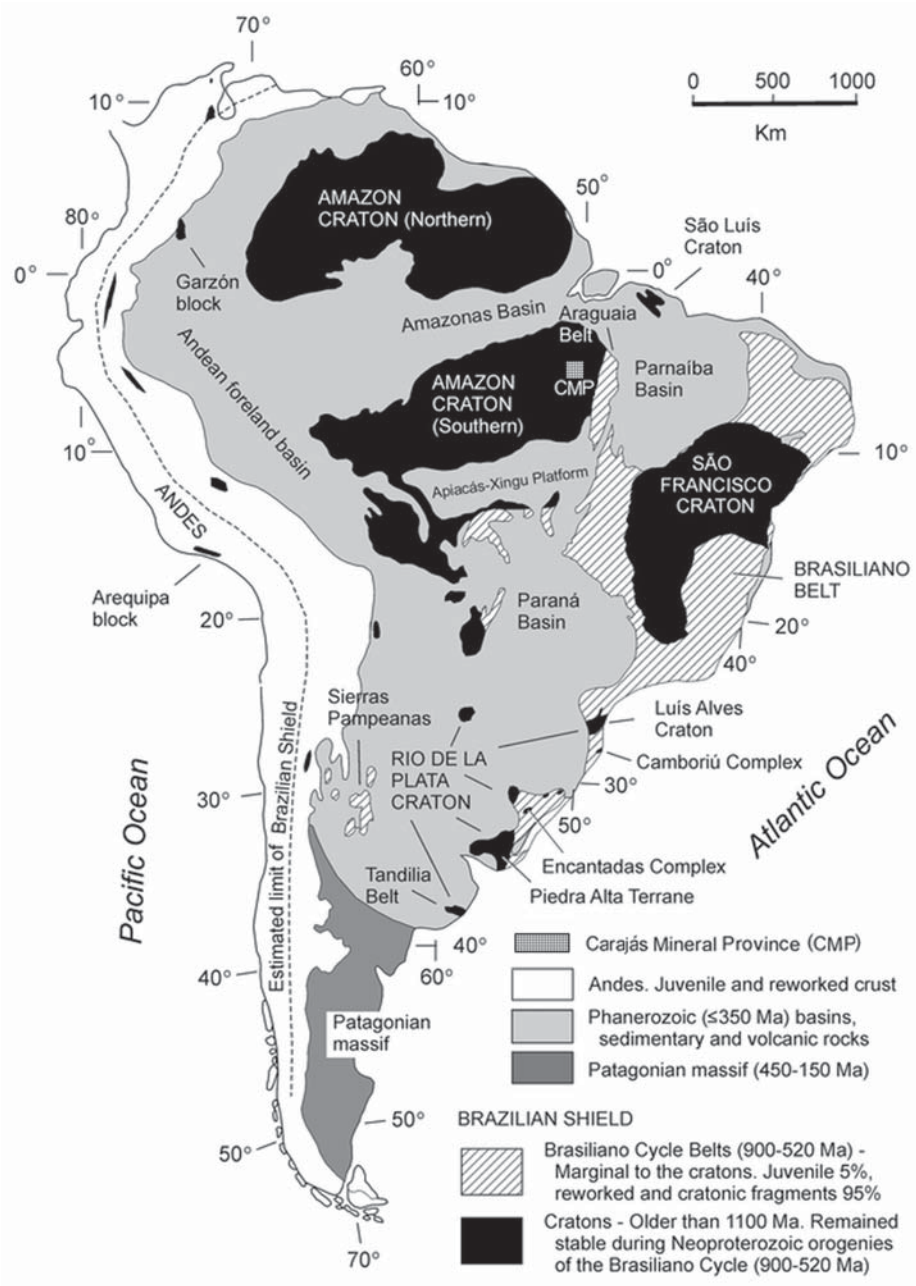

Figure 1: Geological map of the South American Platform showing the location of the Amazon Craton and the Carajás Mineral Province, designated CMP (after Hasui and Almeida, 1985).

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 Itacaiúnas Supergroup have been intruded by several Archaean to Proterozoic granitoids. These include calc-alkaline granitoids and diorites of the ca 2.74 Ga Plaquê Suite (Huhn *et al.*, 1999), the ca 2.57 Ga A-type Old Salobo granite/Estrela alkaline granitoid complex (Machado *et al.*, 1991; Barros *et al.*, 1997), and Paleoproterozoic alkaline to sub-alkaline A- and I-type granitoids of the ca 1.88 Ga Carajás Suite (Machado *et al.*, 1991). There are also ultramafic to mafic intrusions, including the ca 2.75 Ga Luanga mafic-ultramafic complex (Machado *et al.*, 1991).

The Rio Maria granitoid-greenstone terrain and the Itacaiúnas Belt can be differentiated in terms of both their geological setting and associated mineral deposits. The Itacaiúnas Belt is unusual for an Archaean greenstone belt in that it contains a number of Fe-oxide Cu-Au (±Mo±Ag±U±REE) deposits, including Aguas Claras, Cristalino, Igarapé Bahia-Alemão, Salobo and Sossego (Fig. 3). These deposits display a number of characteristic features: (i) strong structural control, commonly in vertical breccia pipes; (ii) epigenetic formation; (iii) strong iron-metasomatism in the form of magnetite and/or hematite; and (iv) copper-gold ores with LREE, Co, Ni, Pb, Zn, As, Bi, W and U enrichment (Soares *et al.*, 2000; Requia and Fontboté, 2000; Souza and Viera, 2000; Tazava and de Oliveira, 2000; Tallarico *et al.*, 2000b; Ronzê *et al.*, 2000). In contrast to the Itacaiúnas Belt, the Rio Maria granitoid-greenstone terrain is more typical in that it is characterised by orogenic lode-gold deposit types (cf. Groves *et al.*, 1998). These are characteristically gold deposits that are poor in base metals, in contrast to the Fe-oxide Cu-Au deposits from the Itacaiúnas Belt, and they generally occur as structurally-controlled quartz veins within the rocks of the greenstone belt (Villas and Santos, 2001).

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 Itacaiúnas 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 Plaquê 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; Meireles and 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.

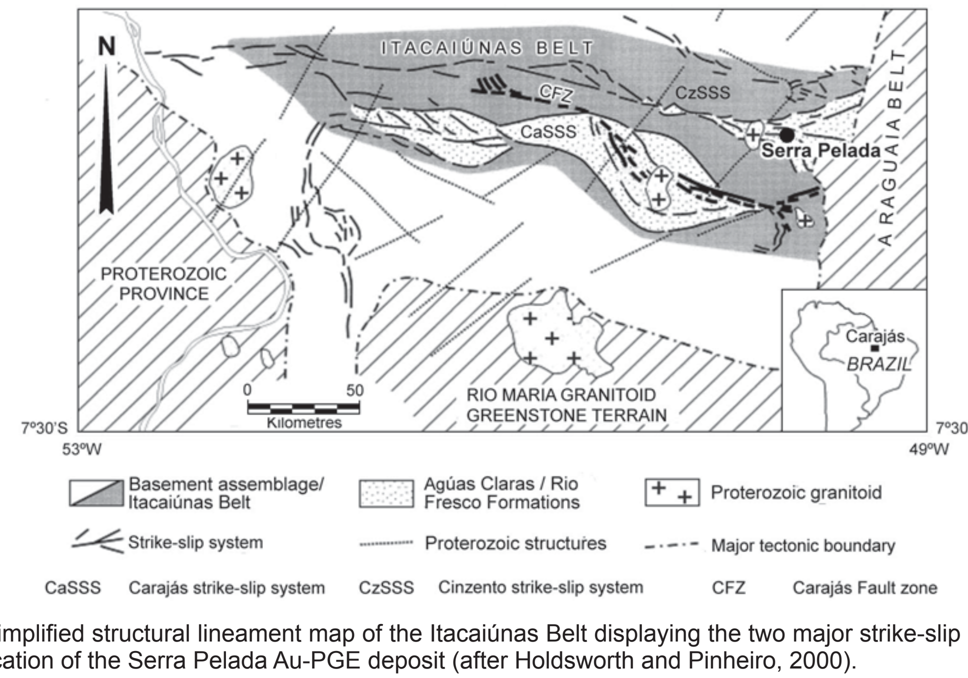

Figure 2: Simplified structural lineament map of the Itacaiúnas Belt displaying the two major strike-slip systems and the location of the Serra Pelada Au-PGE deposit (after Holdsworth and Pinheiro, 2000).

The structural evolution of the Serra Pelada area is complex, incorporating five identifiable deformation events (D_1-D_5) that produced a polyphase-deformed terrain. These deformation events are associated with a series of transpressional and transtensional reactivation phases of major E-W faults, locally represented by movement along the Cotia Fault (Fig. 6). The D_1 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, D_2 dextral strike-slip transpressional movement occurred along major east-west 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 east-west fault movement. Continued transpressional movement resulted in NNW-SSE compression, which formed regional-scale, reclined, tight, asymmetrical F_2 folds. These folds are the main structural hosts of Au-PGE mineralisation. The north-facing, kilometre-scale folds plunge gently (15°-25°) to

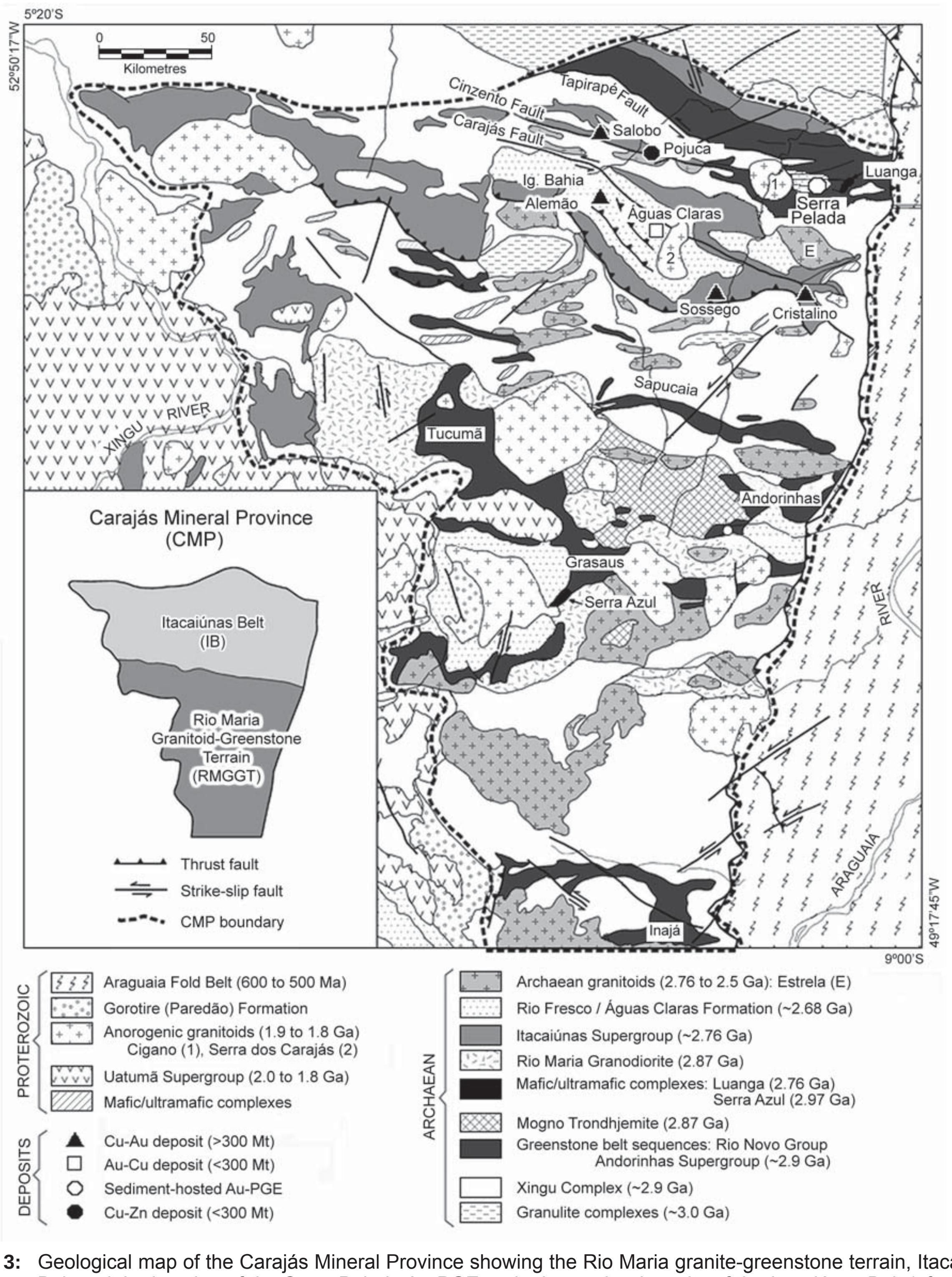

Figure 3: Geological map of the Carajás Mineral Province showing the Rio Maria granite-greenstone terrain, Itacaiúnas Belt and the location of the Serra Pelada Au-PGE and other major deposits of the Itacaiúnas Belt (after Villas and Santos, 2000).

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 D_2 event, based on observed textural relationships between prograde metamorphic minerals and D_2 fabrics.

The third deformation event, D_3, is directly related to the formation of open F_3 folds that plunge to the south-southwest and deform the D_2 thrust planes and F_2 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, D_4, 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 F_4 folds, which locally deform both F_2 and F_3 folds. Sinistrally deformed NNW- to NW-trending faults are inferred as acting as major fluid conduits to the Serra Pelada F_2 fold hinge. Gabbroic dykes were intruded along NW to NNW structures, which offset F_2 folds and S_2 foliation, and are interpreted as products of the last deformation event, D_5. The D_5 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 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 to 60%) in a matrix of granoblastic dolomite (30 to 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- to 4-cm-thick beds), grey to black, carbonaceous horizon of amorphous carbon (2 to 10%), quartz (40 to 60%), dolomite (2 to 20%), fine-grained clays (5 to 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 F_2 synform. These carbon-rich lenses become increasingly interbedded and grey in colour upwards.

Figure 4: The Serra Pelada open-pit "procissão do formigas" (procession of ants) during garimpero mining activity, October 1982 (photo courtesy of CVRD).

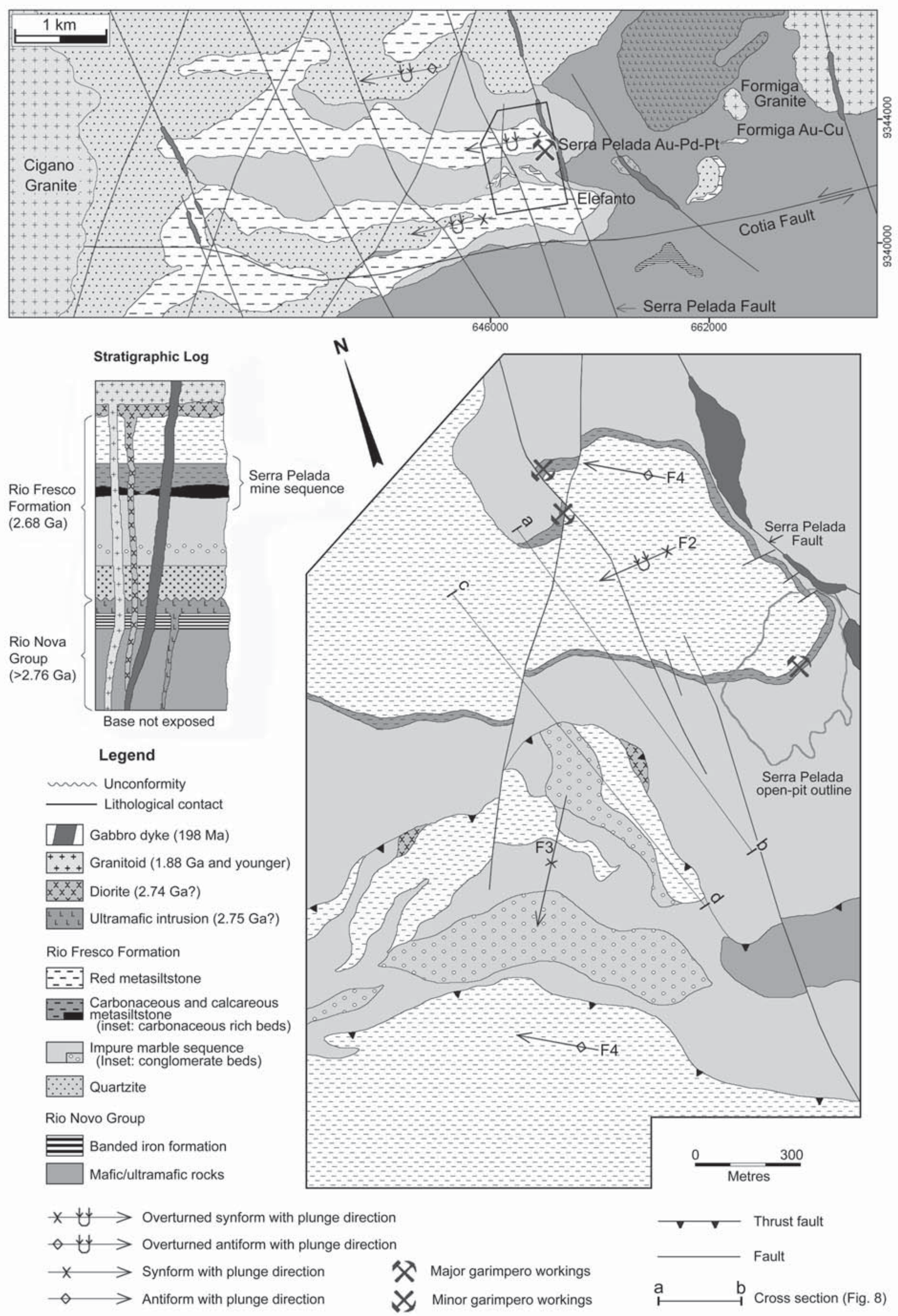

Figure 5: Simplified geological map of the Serra Pelada area (top) and geological map of the area surrounding the Serra Pelada Au-PGE deposit (bottom) showing the stratigraphic log of the area and location of cross sections.

Red meta-siltstone: The red meta-siltstone is a uniform, well-bedded (1- to 7-cm thick beds), red to off-white unit composed of quartz (30 to 60%), fine-grained clays (20 to 50%), and fine-grained hydrated Fe-oxides (1 to 15%). Minor interbeds (1- to 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 F_2 fold hinge within the black carbonaceous and calcareous meta-siltstone, which is the main host for Au-PGE mineralisation; (2) the proximity of the F_2 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, F_2 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 dilation associated with the hinge zone. Long-sections of the deposit show that the orebody plunges at approximately 15 to 25° WSW, parallel to the F_2 fold hinge (Fig. 7). The main ore shoots reach 40 m in width in the thicker parts of the meta-siltstone (ie. F_2 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 F_2 fold hinge. F_3 deformation is supported by an orthogonally-orientated F_3 synformal hinge (Fig. 5). This caused the F_2 fold hinge to tighten and pinch-out (Fig. 8a), preventing fluid flow down-plunge of this intersecting structure during the D_4 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 east-west-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 supergene mineralogy and trace-element geochemistry are similar for both. High-grade Au-PGE intersections in the carbonaceous and calcareous meta-siltstone at Elefanto (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 F_2 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, F_2 fold-hinge during the D_4 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 F_2 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 F_2 fold hinges, which cause structural thickening of the carbonaceous and calcareous meta-siltstone. Tight F_2 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 F_2 fold hinge define the most prospective areas for Au-PGE mineralisation, which continue with depth along the plunge of the F_2 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: (1) the predominant Au-Pd-Pt ore that is mainly hosted within the carbonaceous and calcareous meta-siltstone, but also associated with magnetite- and hematite-bearing hydrothermal breccias, intense sericite (white mica)-kaolin alteration zones, and an extensive jasperoid alteration halo with rare disseminated pyrite; and (2) Au (±Pd±Pt) 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-siltstone 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.

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 F_2 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. 9c). 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 F_2 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 F_2 fold hinge. Characteristically, hematite-rich breccias display more consistent ore grades

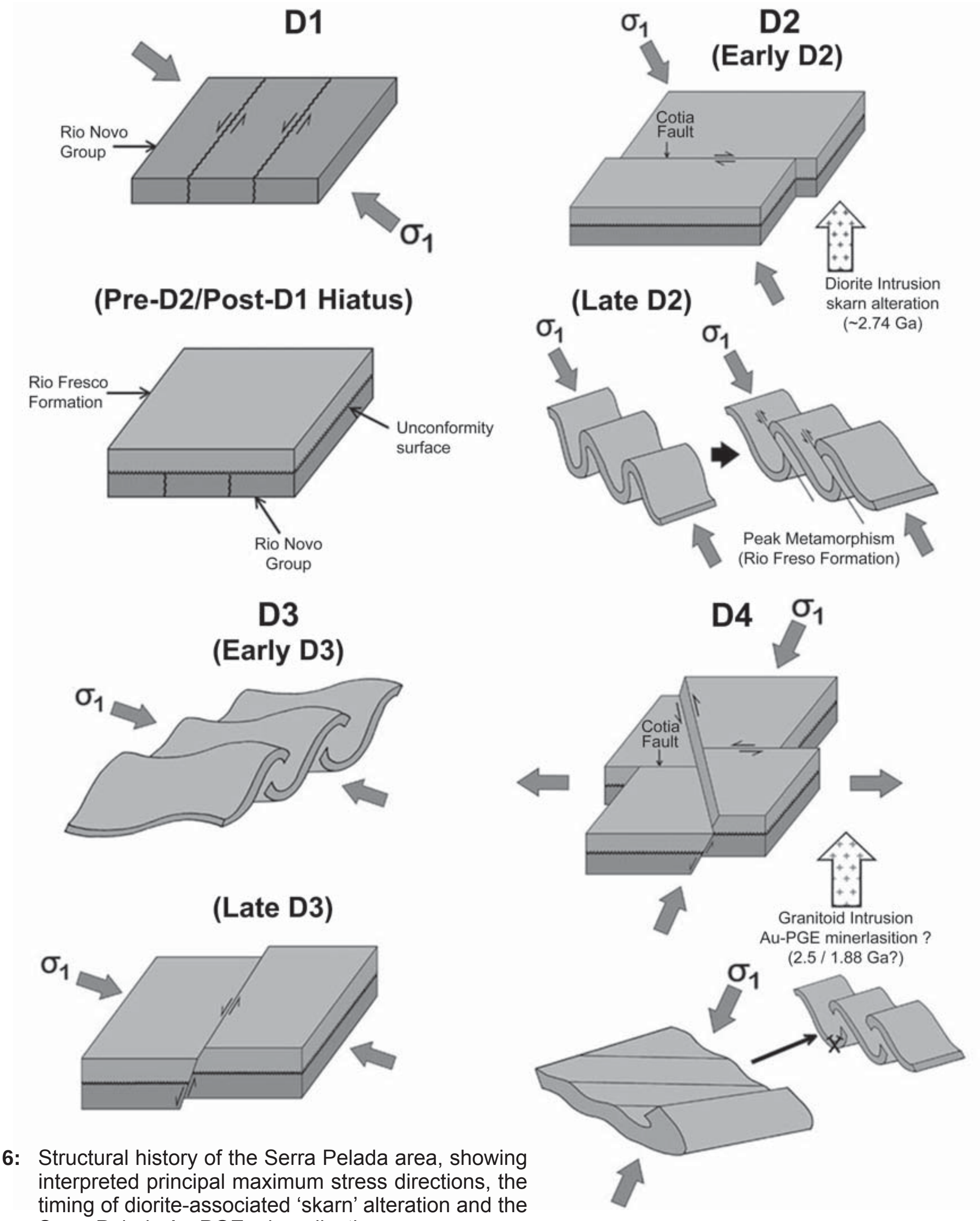

Figure 6: Structural history of the Serra Pelada area, showing interpreted principal maximum stress directions, the timing of diorite-associated 'skarn' alteration and the Serra Pelada Au-PGE mineralisation.

and are located primarily within the F_2 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 and f).

Jasperoid-hosted Gold-PGE Ore

An extensive jasperoid alteration zone envelops the main ore zone within the hinge of the Serra Pelada F_2 fold (Figs. 8a and 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 marble sequence generally contain little or no mineralisation.

Massive Hematite Gold Ore

Massive hematite, located on the lower limb of the Serra Pelada F_2 fold hinge, displays Au (±Pd±Pt) enrichment. This ore type is characterised by massive hematite-chlorite metasomatism ±monazite ±apatite ±rutile alteration of the impure marble 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 Elefanto area (Fig. 5). High-angle fractures displaying a normal vertical offset are host to high-grade Au-PGE mineralisation (as much as hundreds of g/t of Au, Pd and 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.

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 Archaean 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 (Figs. 8a and b). Whereas this may be due to decalcification during hypogene alteration, by analogy with similar decalcification in the Carlin-type gold deposits (Hofstra and 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 reclined synformal fold and the orebody.

Decalcification has resulted in the transformation of the carbonaceous and calcareous meta-siltstone 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 F_2 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.

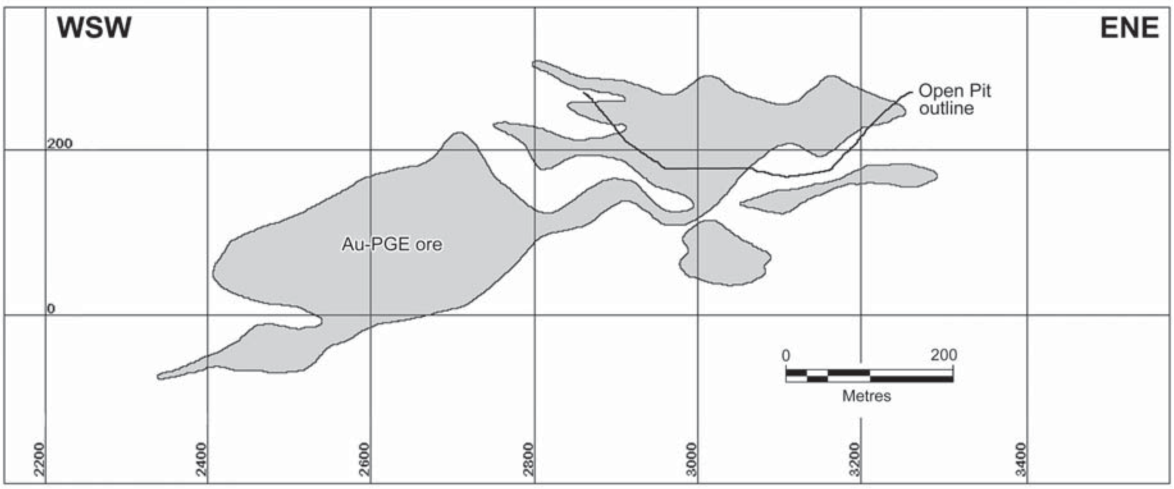

Figure 7: Long-section of the Serra Pelada Au-PGE orebody, showing the plunge of the mineralisation at 15 to 20° to the WSW. Outline of mineralisation at 1 g/t Au+PGE cut-off

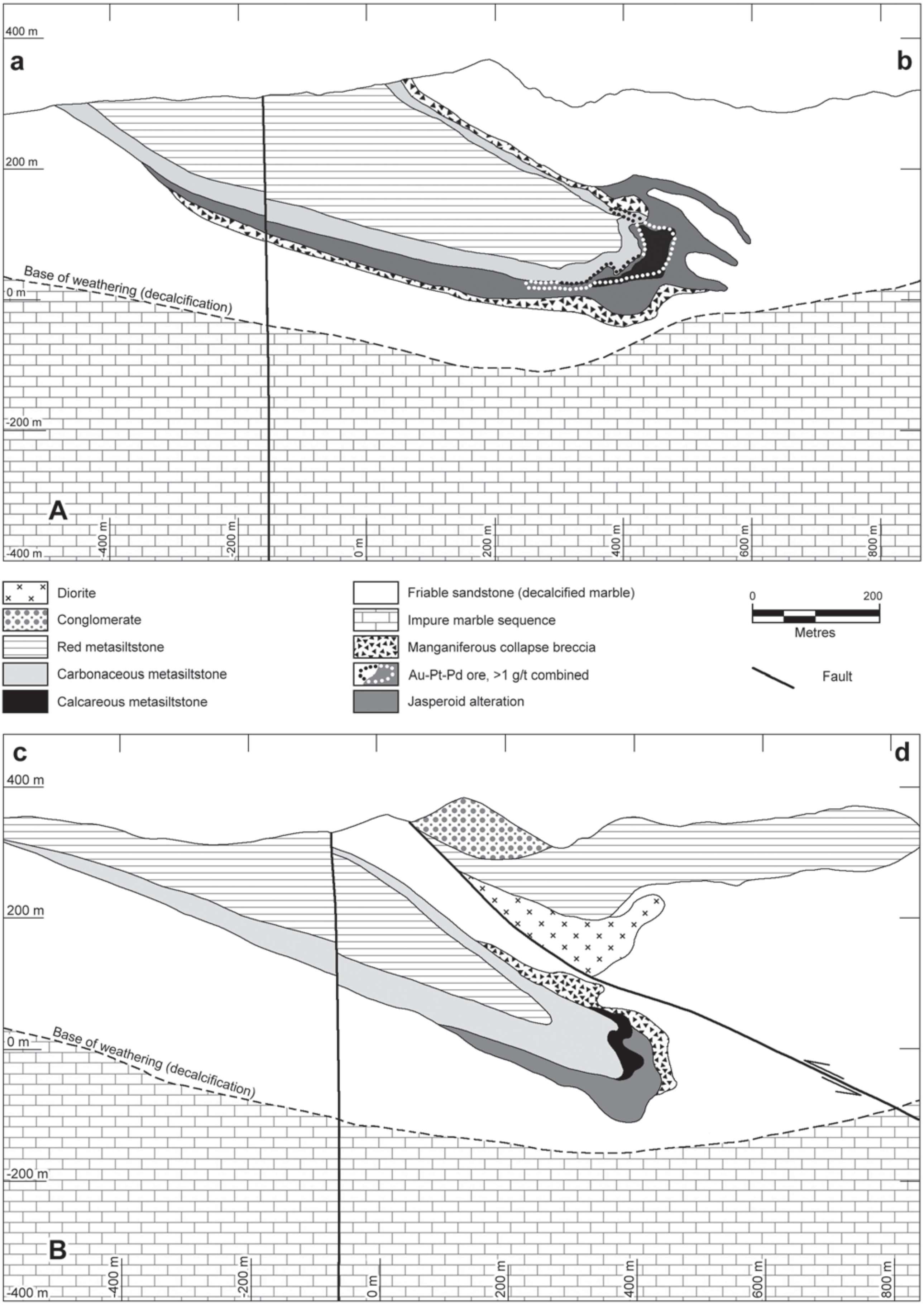

Figure 8: Cross-sections through the Serra Pelada Au-PGE deposit (section lines shown on Fig. 5). **A** - down plunge extension of the ore deposit showing the location of the Au-PGE mineralisation within the F_2 fold hinge; **B** - showing the termination of ore due to the tightening of the F_2 fold hinge. Note the thrust fault on the upper limb of the synform and the dislocated diorite intrusion from depth.

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-siltstone ore, magnetite and hematite breccias, and intense zones of kaolin 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 jasperoids 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 $\delta^{13}C$ (-0.6 to -2.2‰) and $\delta^{18}O$ (13.8 to 14.7‰). The pipe-like breccia bodies also display a narrow, although different range of $\delta^{13}C$ (-7.1 to -7.6‰) and $\delta^{18}O$ (8.8 to 14.2‰). These results are plotted in Fig. 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 $\delta^{13}C$ 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 carbonatite reservoir may designate an alkaline magmatic genetic association, as does the isotopic similarity of the Serra Pelada Au-PGE ores with the Olympic Dam reservoir (Oreskes 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 F_2 folds and the associated wallrock alteration within stratigraphic horizons and along D_4 faults. It appears most likely that fluids were initially channelled during D_4 along E-W faults, such as the Cotia Fault, into NW- to NNW-trending faults, such as the Serra Pelada Fault, and finally into the dilated, reclined F_2 fold-hinge within the carbonaceous and calcareous meta-siltstone. Such a model is consistent with the occurrence of additional Au-PGE mineralisation adjacent to a reclined synformal fold-hinge at Elefanto, 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 PGE's, particularly palladium, can be efficiently transported in highly saline, oxidising, and acidic fluids, as chloride complexes in equilibrium with hematite (e.g., 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 and 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 (e.g., hematite; Wood *et al*., 1992). Potentially more interesting is the association between gold and some PGE's, particularly palladium and platinum,

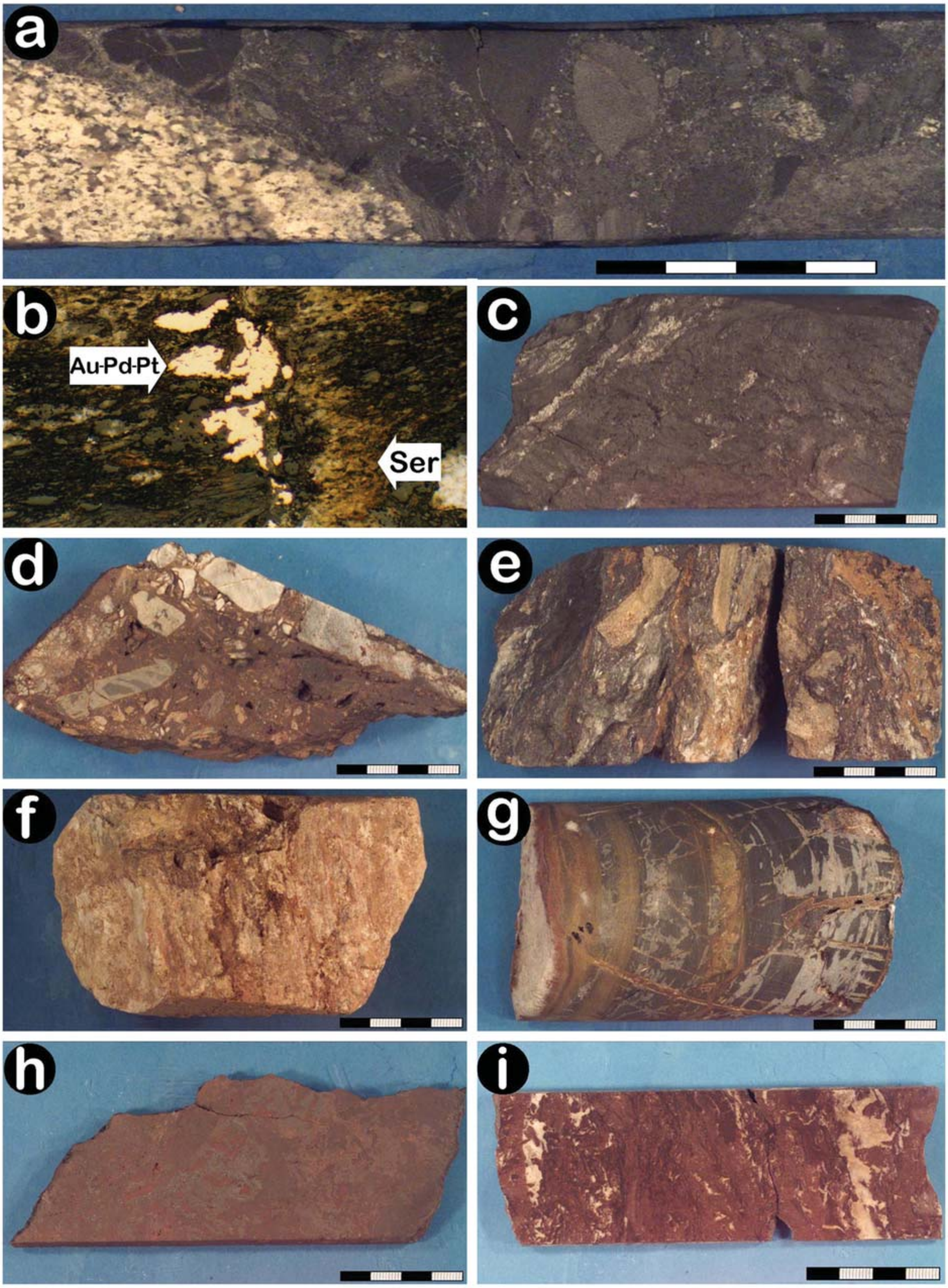

Figure 9: **a** Chlorite-rich breccia pipe, hosting granite, mafic metavolcanic and BIF clasts;
b Thin-section (x10 magnification; reflected light) of high-grade Au-PGE mineralisation associated with high angle fractures and sericite alteration within the carbonaceous and calcareous metasiltstone from the Elefanto 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.

in alkaline porphyry-style deposits that include the Allard Stock, Colorado (Werle *et al*., 1984), the Similkameen deposit, British Colombia (Fahrni *et al*., 1976), and the Skouries copper deposit, northern Greece (Eliopoulos and 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 Cigano 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; Mutschler and Mooney, 1993; Pollard *et al*., 1998; Jensen and Barton, 2000), which are located withincratonic areas with Archaean basement, such as at Carajás.

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

Deposits of the Fe-oxide Cu-Au class (e.g., 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 (Twyerould, 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, Cristalino, Salobo and Sossego (e.g., Huhn and Nascimento, 1998; Tallarico *et al*., 2000b; 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: (1) the Au-PGE mineralisation is genetically related to strong Fe-metasomatism in the form of magnetite and hematite breccias; (2) the Au-PGE ore is associated with LREE, Co, Cu, Ni, Pb, Zn, As, Bi, W and U enrichment; (3) the REE distribution in the ores shows similar patterns and enrichment factors (Fig. 11); (4) the ore is epigenetic and displays a strong structural control; (5) there is a potential alkaline magmatic source; and (6) mineralisation is interpreted to be associated with an extensional tectonic event (D_4).

The recent suggestions that the Palabora carbonatite magnetite-copper deposit may be an end member of the Fe-oxide Cu-Au deposit group (Groves and Vielreicher, 2001) provides a potential connection between gold and PGE's, particularly palladium and platinum, as Palabora produces about 0.28 tonnes per annum of both metals as a by-product of copper mining (Verwoerd, 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

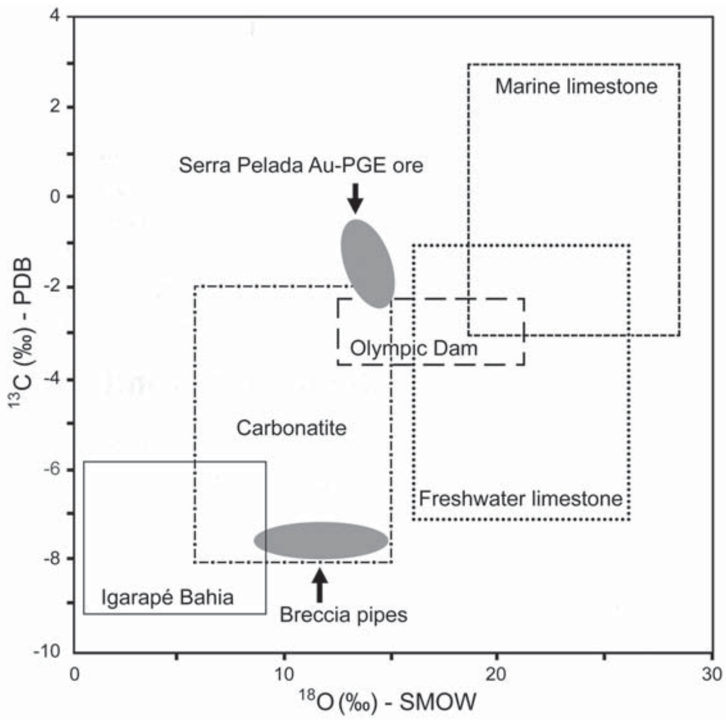

Figure 10: Plot of $\delta^{13}C$ vs. $\delta^{18}O$ showing the isotopic composition of siderite from the Serra Pelada Au-PGE deposit and adjacent Aeroporto breccia pipes, relative to carbonatites, siderite and calcite from the Igarapé Bahia Fe-oxide Cu-Au mineralisation (Tallarico *et al*., 2000b), Olympic Dam mineralisation, freshwater limestone and marine limestones (Oreskes and Einaudi, 1992).

Au-PGE mineralisation at Serra Pelada are similar acid, oxidising fluids to those depositing Fe-oxide Cu-Au deposits (e.g., 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 versus hematite, and wallrock alteration, as well as structural style. Both Kerrich *et al*. (2000) and Groves and Veilreicher (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 (e.g., 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 (e.g., Salobo, Ernest Henry) having lower gold contents and higher Cu:Au ratios than those inferred to have been deposited at higher crustal levels (e.g., Olympic Dam, Igarapé Bahia-Alemão, Aguas Claras). It is significant that the Palabora deposit, inferred to be the most proximal to source, has a very high Cu:Au ratio (Groves and Veilreicher, 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).

Table 1: 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 = Hematite breccia Au-PGE ore (Serra Pelada); MB = Magnetite breccia Au-PGE ore (Serra Pelada); MH = Massive hematite metasomatism Au-PGE ore (Serra Pelada); KZ = Kaolin-sericite alteration Au-PGE ore (Serra Pelada); SK = Skarn alteration magnetite (adjacent Serra Pelada); Abx = Breccia pipe (adjacent Serra Pelada); IgBah = Magnetite breccia Cu-Au ore (Igarapé Bahia; Tazava and Oliveira, 2000); Sal = Magnetite Cu-Au ore (Salobo; Requia and Fontboté, 2000).

Locality	**Serra Pelada (S.P.) Ore Types**					**Adjacent S.P.**		**Fe-Oxide Cu-Au**	
	FD-156	FD-126	FD-172	FD-201	FD-126	FD-196		353AC	KRI-65
Sample	236.6	179.2	141	145	181	192.35		184.7	IR I
Type	CMS	HB	MB	MH	KZ	SK	Abx	IgBah	Sal
SiO_2	66.1	64.6	48.4	14.3	67.6	48.4	67.4	21.1	10.9
Al_2O_3	17.1	12.6	7.0	6.2	10.8	12.4	9.6	3.3	1.6
Fe_2O_3	1.3	13.2	33.3	62.1	12.8	17.5	12.6	55.5	83.4
MnO	1.1	<0.01	1.9	0.1	0.4	0.1	0.1	0.5	0.4
MgO	0.3	0.2	<0.01	10.9	0.1	4.9	3.8	1.8	0.2
CaO	0.1	0.1	<0.01	<0.01	0.1	10.6	0.1	4.6	3.7
Na_2O	0.2	0.1	<0.01	<0.01	<0.01	<0.01	0.1	0.5	<0.01
K_2O	1.5	0.2	0.06	<0.01	<0.01	<0.01	2.6	0.5	0.1
TiO_2	0.9	0.6	0.3	0.4	0.4	2.2	0.5	0.2	0.1
P_2O_5	1.0	0.7	0.9	<0.01	0.7	0.3	0.1	1.1	0.2
LOI	7.5	6.8	7.6	5.0	6.4	2.8	2.6	0.4	0.3
Total	97.0	99.1	99.4	99.2	99.2	99.3	99.4	89.6	101.0
Au	71.5	6.0	26.0	47.6	6.0	2.5	<0.01	7.7	2.6
Ag	88.7	0.6	<0.5	<0.5	<0.5	<0.5	<0.5	29.3	4.2
Pd	29.5	3.5	691.0	0.2	1.5	<0.01	<0.01	na	na
Pt	18.6	4.0	180.0	0.2	1.0	<0.01	<0.01	na	na
Co	1552.0	158.0	558.0	153.0	1650.0	34.0	45.0	94.0	87.0
Ni	123.0	117.0	608.0	155.0	655.0	87.0	59.0	141.0	46.0
Cu	1102.0	469.0	337.0	1825.0	1234.0	353.0	41.0	55127.0	31521.0
Zn	192.0	187.0	400.0	372.0	443.0	66.0	71.0	58.0	6.0
Pb	1636.0	921.0	335.0	180.0	763.0	8.0	6.0	119.0	na
Mo	<2.0	<2.0	<2.0	20.0	4.0	<2.0	<2.0	110.0	269.0
Bi	345.0	54.0	17.3	277.0	21.0	0.5	0.4	<5.0	na
As	134.0	50.0	106.0	17.0	16.0	<0.5	<0.5	59.0	14.4
W	133.0	179.0	86.0	23.0	48.0	72.0	120.0	<0.3	126.0
U	23.0	115.0	158.0	31.0	251.0	1.0	2.2	160.0	57.4
La	1039.0	1314.0	569.0	145.0	53.0	17.0	25.0	777.0	712.0
Ce	1178.0	1617.0	712.0	355.0	109.0	32.0	48.0	940.0	681.0
Nd	282.0	286.0	158.0	106.0	60.0	24.0	22.0	280.0	166.0
Sm	12.0	32.0	7.5	15.0	17.0	6.4	4.2	31.0	35.2
Eu	1.5	8.0	1.6	1.7.0	4.9	1.9	1.0	9.6	13.2
Tb	1.0	4.0	1.5	1.6	2.9	1.2	0.5	4.0	na
Yb	3.4	9.0	4.8	6.4	7.9	5.0	1.6	4.7	4.4

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 (e.g., Salobo) occur in, or adjacent to, the basement complex, whereas the inferred lower-temperature deposits (e.g., Igarapé Bahia-Alemão, Aguas Claras) are sited in, or adjacent to, the low metamorphic-grade sedimentary rocks of the uppermost Aguas Claras Formation (Fig. 12). Serra Pelada also occurs in rocks of the stratigraphically high Rio Fresco Formation in a position that is distal to the major concentration of Fe-oxide Cu-Au deposits, which occur in a corridor adjacent to the Cinzento and Carajás strike-slip fault systems (Figs 2 and 3). It is, therefore, possible that the Serra Pelada deposit represents a distal equivalent of the Fe-oxide Cu-Au deposits in a broadly zoned mineral district.

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 F_2 synform. The deposit is sited close to the E-W trending D_2 Cotia Fault, near its intersection with numerous northwest- to NNW-trending D_4 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 east-west and northwest- to NNW-trending fault systems during D_4 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 carbonaceous host rock, and possibly increase in pH due to carbonate dissolution.

6. Although the PGE ís 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 (e.g., Aguas Claras, 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 siting 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.

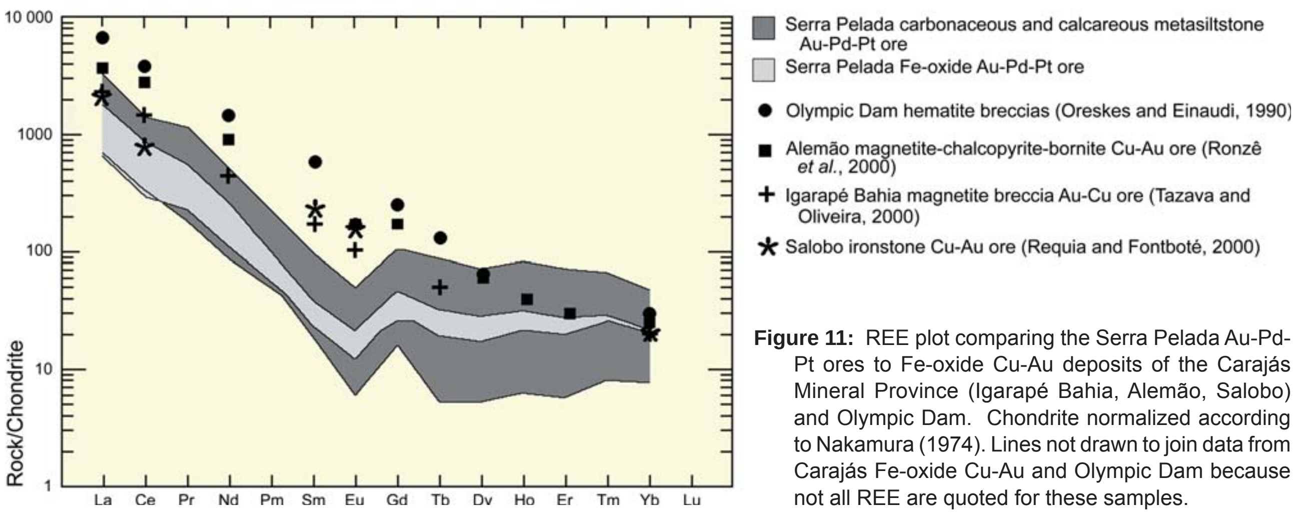

Figure 11: REE plot comparing the Serra Pelada Au-Pd-Pt ores to Fe-oxide Cu-Au deposits of the Carajás Mineral Province (Igarapé Bahia, Alemão, Salobo) and Olympic Dam. Chondrite normalized according to Nakamura (1974). Lines not drawn to join data from Carajás Fe-oxide Cu-Au and Olympic Dam because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

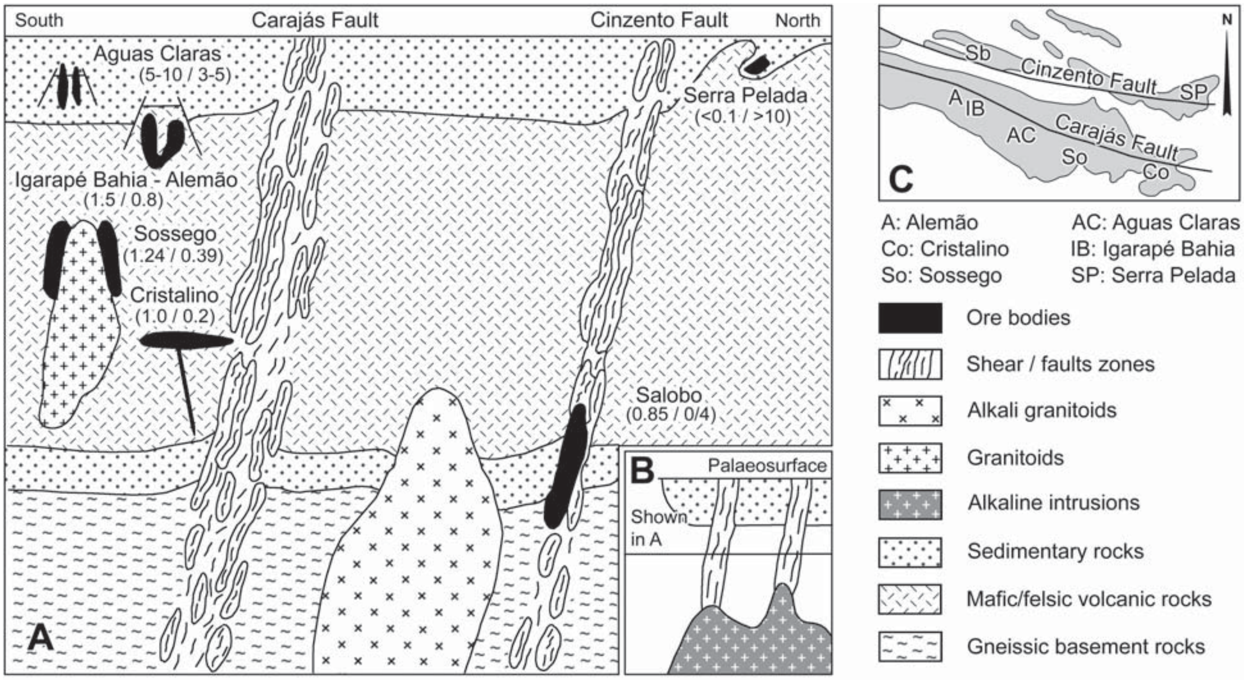

Figure 12: Schematic diagram of Fe-oxide-Cu-Au deposits in the Carajás Mineral Province, showing the interpreted spatial and depth position of the Serra Pelada Au-PGE deposit. **A** is a schematic cross section; **B** shows the conceptual relationship between the cross section, crustal-scale faults and alkaline intrusions below the depth of exposure of the ore bodies, and **C** is a schematic plan showing the spatial position of the deposits relative to the Cinzento and Carajás Faults. Average Cu (%) and Au (g/t) grades are shown (1.0 / 0.2 = 1.0% Cu, 0.2 g/t Au). Aadapted from a figure in Kerrich *et al.* (2000).

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 sub-alkaline 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/Estrela 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 PGEs, 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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