DOI: 10.1595/147106705X24391

Platinum Group Minerals in Eastern Brazil

GEOLOGY AND OCCURRENCES IN CHROMITITE AND PLACERS

By Nelson Angeli

Department of Petrology and Metallogeny, University of São Paulo State (UNESP), 24-A Avenue, 1515, Rio Claro (SP), 13506-710, Brazil; E-mail: nangeli@rc.unesp.br

Brazil does not have working platinum mines, nor even large reserves of the platinum metals, but there is platinum in Brazil. In this paper, four massifs (mafic/ultramafic complexes) in eastern Brazil, in the states of Minas Gerais and Ceará, where platinum is found will be described. Three of these massifs contain concentrations of platinum group minerals or platinum group elements, and gold, associated with the chromitite rock found there. In the fourth massif, in Minas Gerais State, the platinum group elements are found in alluvial deposits at the Bom Sucesso occurrence. This placer is currently being studied.

The platinum group metals occur in specific areas of the world: mainly South Africa, Russia, Canada and the U.S.A. Geological occurrences of platinum group elements (PGEs) (and sometimes gold (Au)) are usually associated with Ni-Co-Cu sulfide deposits formed in layered igneous intrusions. The platinum group minerals (PGMs) are associated with the more mafic parts of the layered magma deposit, and PGEs are found in chromite crystals which are a major component of chromitite rock. The PGMs occur in the chromitite matrix, in chlorite and serpentine minerals, and around the borders of the chromite crystals (1). The distribution of PGEs in chromitite is consistent with crystallisation being caused by metamorphic events. PGEs also occur in alluvial, placer deposits (2).

Brazilian Occurrences

In Brazil there are several regions where PGEs occur, for instance, in Goiás State in central Brazil. Here, the Niquelândia mafic/ultramafic Complex (the best known complex in Brazil) is thought to have a PGE content of high potential (3, 4). The mineralisation of the sulfide levels in Niquelândia has been described as similar to those of the Bushveld Complex in South Africa, the Stillwater Complex in the U.S.A., and the Great Dyke in Zimbabwe (5). PGM distribution in chromitites is well documented, especially in the Bushveld Complex (for example, (6)), where Pt, Ru, Ir, Pd, Rh and Os occur together in minerals in various combinations. This particular PGM distribution can also form noble metal alloys (7), and mineralisation has been linked to crystallisation during chromite precipitation of hydrothermal origin.

In central Brazil there are massifs (Americano do Brasil and Barro Alto) that as yet are little studied, and which are thought to contain small PGM concentrations. Other complexes in the north of the country have PGMs, but need exploration (for instance Carajás and Luanga). Fortaleza de Minas (south of Minas Gerais) has PGMs with sulfides in the Ni-Co-Cu ore, and PGMs on the surface associated with the gossans. The PGEs here are a subproduct. However, the best known PGE deposits in Brazil are in Minas Gerais State.

The territory of Brazil is almost identical with the area of the South American Platform, stable from the beginning of the Phanerozoic Eon. Based on the nature of the rocks, the sedimentary cover and on geotectonic evolution, Brazil has been divided into ten geological structural provinces (8) (Figure 1). The geology of the PGE occurrences in three Structural Provinces: Mantiqueira, São Francisco and Borborema, is described here.

Mafic/Ultramafic Complexes in East Brazil

In eastern Brazil, the mafic/ultramafic complexes that comprise the Atlantic Belt contain allochthonous rocks (formed elsewhere and transported by tectonic processes) and metamorphosed

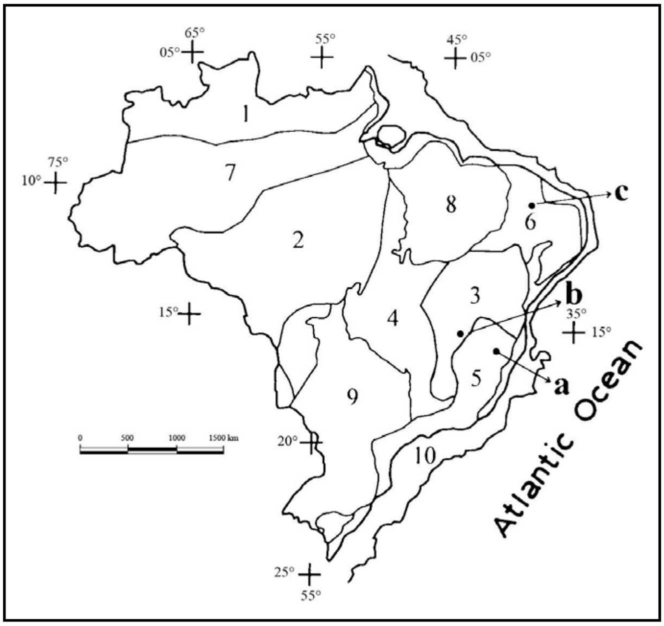

Fig. 1 The structural provinces of Brazil:
1 *Rio Branco*
2 *Tapajós*
3 *São Francisco*
4 *Tocantins*
5 *Mantiqueira*
6 *Borborema*
7 *Amazonian*
8 *Parnaíba*
9 *Paraná*
10 *Coastal Province and Continental Margin (8)*

The black points represent the studied mafic/ultramafic complexes:
a *Ipanema*
b *Serro and Alvorada de Minas*
c *Pedra Branca*

rocks (changed by pressure, temperature and fluid circulation). Some rocks have kept their original structures and textures, as at Ipanema in Minas Gerais (Figure 2). This is an original layered mafic/ultramafic complex. In the east of Minas Gerais State the mafic/ultramafic bodies date from 1.0 to 1.1 Ga (billions of years).

The effects of metamorphism increase the Fe^{3+} at the expense of Al and Fe^{2+}, which are lost to crystal borders or to matrix minerals, and tend to reduce the PGM content ((9) and references in (10)). This shows the importance of the serpentinisation process when temperature, pressure, water and carbon dioxide affect (1):

- PGE mobilisation,
- PGE enrichment of the chromitite levels, and
- PGM formation (11, 12).

During a metamorphic event, chemical and textural/structural changes occur to the chromite grains (mineral zoning). Chromite crystals usually have a core of aluminous chromite, and a broad margin of ferriferous chromite (14, 16). The variation in the composition of the chromite grains is related to the noble metal content (for example (13), and references in (11)). The textures, size and shapes of chromite crystals are associated with serpentinisation and deformation of the ultramafic rocks. There are Cr-spinel crystals in the chromitite that appear to be the remains of original peridotite minerals. The Cr-spinel crystals usually have three zones: a dark grey core, a grey intermediate zone and a light-grey rim. Fractures occur frequently. The crystal core contains high Cr_2O_3 and Al_2O_3 contents; the intermediate zone has increasing Fe_t (total iron content, with $Fe^{2+} > Fe^{3+}$) and decreasing Al_2O_3 and MgO (transition of Cr-spinel to ferritchromite); while the outer zone is rich in Fe (mainly Fe^{3+}) and poor in Cr (the magnetite zone). Sperrylite crystals ($PtAs_2$) may be present as inclusions in the chromites or disseminated in the silicatic matrix (16). Many chromite grains contain lamellar inclusions of chlorite, oriented parallel to {111} planes (15).

Mantiqueira Structural Province

Ipanema Mafic/Ultramafic Complex

The Mantiqueira Structural Province in Minas Gerais State lies along the southern part of the Atlantic coast. In Minas Gerais, two PGE/PGM-bearing mafic/ultramafic belts can be identified. The first belt, outside the cratonic area (a central stable area during the action of new tectonic processes) is in Mantiqueira Structural Province. This belt has Neoproterozoic age (1.1 Ga) (16).

Glossary	
Geological term/mineral	**Meaning**
Mafic/ultramafic	Magmatic rock, with high ferrous-magnesium minerals content (mainly olivine and pyroxenes)
Chromitite	Levels or lenses with high concentrations of chromite
Intrusions	Rock massifs which penetrate into previously consolidated rocks
Chromite	A mineral of general formula: $(Mg,Fe^{2+})Cr_2O_4$
Serpentinites	Metamorphic rocks composed of mostly serpentine group minerals (antigorite, chrysotile and lizardite) – magnesium-rich silicate minerals
Placer deposit	An alluvial zone, where rock fragments and minerals are sometimes exploitable, and (gold, platinum, sand) can accumulate.
Gossans	Superficial covers of mafic/ultramafic rocks, formed by sulfide alterations
Serpentinisation	Metamorphic/hydrothermal processes in which Mg-rich silicate minerals (e.g. olivine, pyroxenes) are converted into, or are replaced, by serpentine group minerals.
Ferriferous chromite	A component of chrome-spinel, rich in Fe; simplified formula: $(Mg,Fe^{2+})Cr_2O_4$
Aluminous chromites	A component of chrome-spinel, rich in Al; simplified formula: $(Mg,Fe^{2+})Al_2O_4Cr_2O_4$
Phanerozoic Eon	Geological time after the Proterozoic era (570 Ma (millions of years))
Precambrian age	Age between 3.8 Ga (billions of years) to 550 Ma
Chlorite/tremolite schists	Metamorphic rocks composed of chlorite and/or tremolite with pronounced orientation of these minerals

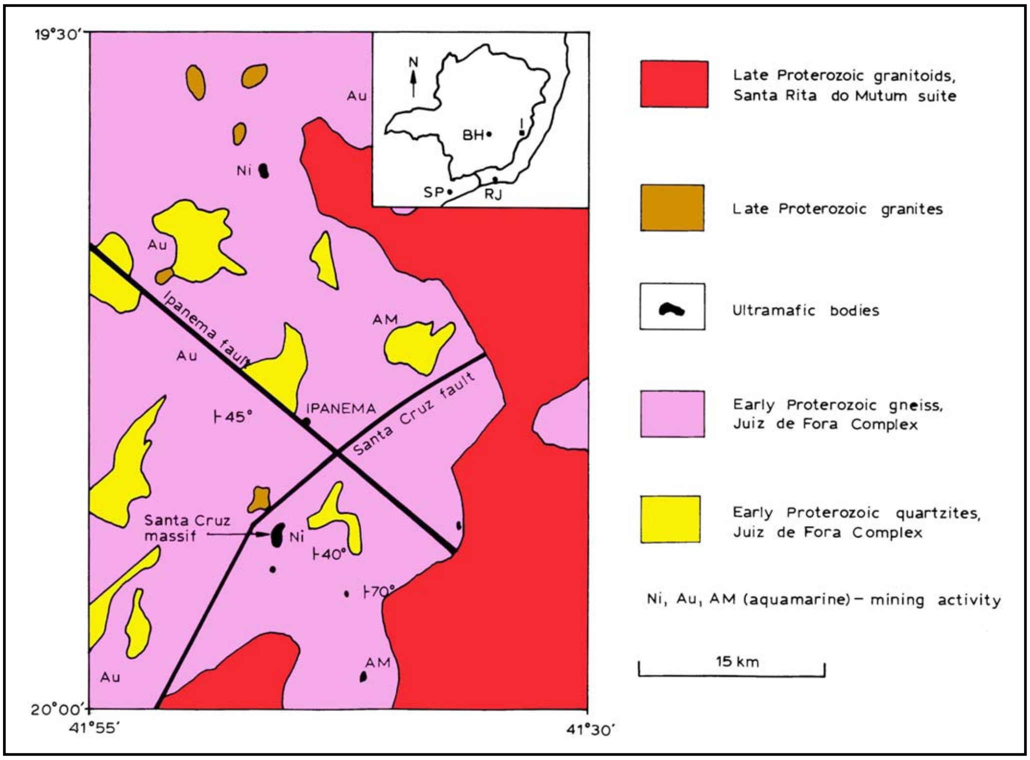

Fig. 2 Geological map of the Ipanema mafic/ultramafic Complex in Minas Gerais State, Brazil (inset). The Santa Cruz massif is shown. BH is Belo Horizonte, SP is São Paulo, RJ is Rio de Janeiro and I is Ipanema (from (18))

The second belt, in the cratonic area, is related to São Francisco Structural Province with Paleo to Mesoproterozoic age (1.5 to 2.0 Ga years ago) (17).

The first belt contains the important Ipanema mafic/ultramafic Complex (Figure 2). This complex is composed of four massifs separated by geological faults. The largest massif is the Santa Cruz massif.

The country (older) rocks of the Ipanema Complex are composed of orthogneisses, paragneisses, migmatites, charnockites and quartzites (from the Paleo-Mesoproterozoic age). In this region the youngest rocks are granitoid unity igneous rocks (known as the Santa Rita do Mutum Intrusive Suite) dating from the Neoproterozoic age (630 Ma (millions of years) (17)). These rocks cut across the oldest rock sequences (the gneisses, migmatites, charnockites and quartzites). The granitoid suite is important because of the serpentinisation of rocks of the Ipanema Complex.

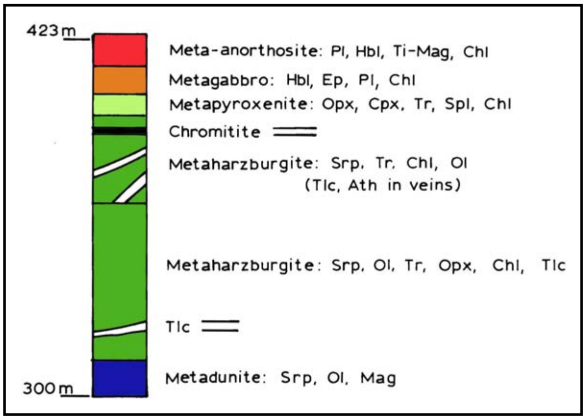

Fig. 3 Geological section of part of the Santa Cruz massif showing the main chromitite layer. The elevations are above sea level. The glossaries explain some of the abbreviations of mineral terms used (10, 17)

The second massif in size in the Ipanema Complex is the Santa Maria massif, but this has little differentiation, and no PGEs have been found. In the past the Santa Cruz and Santa Maria bodies were mined for nickel.

The Santa Cruz Massif

In the Santa Cruz massif the rocks are layered, with intense faulting and folding (Figure 3). The Santa Cruz massif has a differentiated sequence with layerings of dunites, peridotites, pyroxenites, gabbros and anorthosites. The minerals containing the PGEs are in an important layer of chromitite, lying between the peridotites and pyroxenites. This layer bears PGEs that occur as lenses, due to being disrupted by tectonic processes.

In the Santa Cruz massif, the dunites and peridotites contain chromite as an accessory mineral; chromite occupies 7–10% by volume, olivine occupies > 80% and pyroxene (predominantly orthopyroxene) ~ 10%. On top of the peridotites is an important level of chromitite, 1.5 m thick (18). This level comprises chrome-spinel (75–90% by volume), silicates (5–25% serpentines, chlorite, talc, tremolite-actinolite and anthophyllite), and oxides (2–10% magnetite, titanium magnetite and ilmenite).

In the chromitite the chromite crystals are primary; the crystals are all elongated in the same direction, parallel to a direction of slide, and their

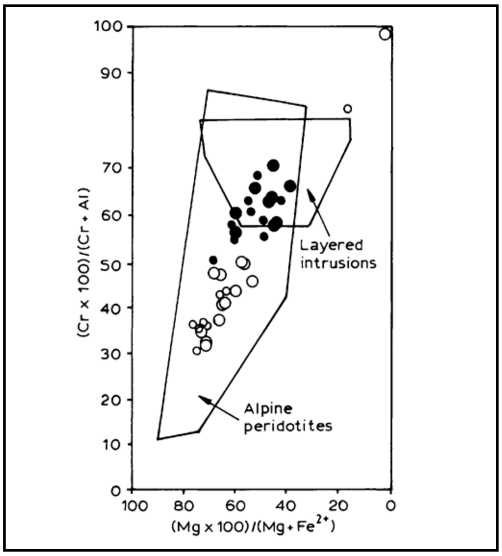

Fig. 4 Data from the Ipanema Complex of compositions of spinel-group minerals from the main chromitite layer, as (Cr × 100)/(Cr + Al) and (Mg × 100)/(Mg + Fe^{2+}). Fields for layered intrusions and alpine peridotites (ophiolites). Filled circles are relict chromite cores; empty circles are chromite margins (10)

Table I Platinum Group Elements and Gold in Chromitite from the Santa Cruz Massif in Eastern Brazil						
Sample	Chromite separate			Chromite whole-rock		SARM7
Metals	Average, ppm	ESD1*	Maximum, ppm	Average, ppm	ESD2*	
Os	45	24.0	57	7.9	5.3	50
Ir	23	7.0	41	19.0	7.8	69
Ru	136	73.0	203	49.0	21.0	334
Rh	19	7.4	27	3.7	1.5	241
Pt	98	131.0	521	29.0	52.0	3792
Pd	63	88.0	157	13.7	20.0	1440
Au	83	87.0	285	6.0	6.6	325

**ESD: element standard deviation; ESD1- separate chromite, based on 13 samples; ESD2- whole-rock chromite, based on 7 samples. Data were obtained first by scanning electron microscopy with energy dispersive spectrometry (SEM-EDS) and then by electron probe microanalysis (EPMA) for whole rock, and by induced neutron activation analysis (INAA) for the grains.*
INAA, for separation of some crystals of chromite, was calibrated against SARM7 (Standard South Africa) for PGE + Au determinations. These crystals were separated by acid treatment and magnetic separation

textures indicate tectonic deformation; they contain inclusions of different minerals. The chromite crystals have narrow rims of ferritchromite. This indicates there was a tectonic and metamorphic event after the intrusion in the differentiated sequence (and in the basement rocks). However, many of the crystals were preserved (11), and they indicate that the layered structure is due to various magma coolings. This contradicts the earlier idea of alpine-type peridotite (Figure 4). The unaltered crystals are found in layered intrusions, see for example, (20, 21).

The grain sizes of the PGE-containing chrome-spinel crystals (in the chromitite layer) range from 1.5 to 4 mm, sometimes reaching 50 mm. Crystals of chrome-spinel with imperfect faces and without faces are also found, with later-formed silicatic minerals. These crystals indicate that the PGE-bearing mineral was concentrated later and dispersed in the interior and in the matrix (Table I). The more preserved parts (of only small volume) appear to have low PGE content, and the PGEs are concentrated in the core of the chromite crystals.

Most of the analysed chromite crystals have a high TiO_2 content (> 0.3%) and a low Al_2O_3 content associated with enrichment in Cr_2O_3. This shows direct correlation with oxygen fugacity: enrichment in Fe_2O_3 and loss of MgO (Figure 5) indicating the action of O_2 in the system. Mining the PGE-bearing chromite in the Ipanema Complex would be uneconomic, as there is little of it and the noble metal content is low.

In the Ipanema Complex most of the PGEs are associated with disseminated chromite ore, and massive and banded ore has been found. A net-like texture can be seen where the chromite lenses meet and where small quantities of chromite crystallise with pyroxenites (orthopyroxenites), at the

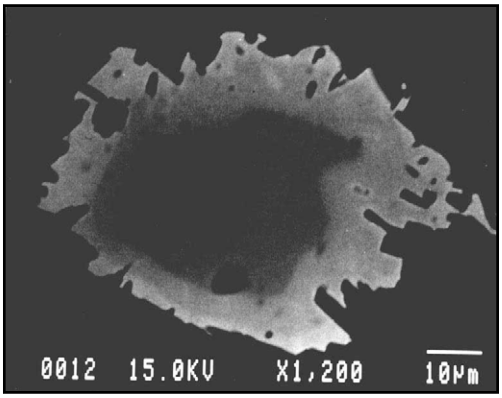

Fig. 5 Photomicrograph of a backscattered electron image of chromite from the Santa Cruz massif showing zoning of the poikiloblastic crystal. The crystal core is rich in chromium and magnesium, and the rim has lost chromium and small quantities of magnesium, but has an enrichment of iron. The matrix is composed mainly of serpentine and chlorite (10)

base of the pyroxenitic/pyroxenite level. Chromitites in the ultramafic sequences show marked lateral variation over short distances and cross-cutting faults have displaced the lens-shaped bodies by up to 0.2 to 0.5 km.

Some areas with PGE values exceeding 1 ppm have been found in the rock geochemistry. The maximum PGE contents recorded are: 209 ppb (156 ppb Pd and 53 ppb Pt). Platinum group minerals are not found in the Santa Cruz massif, but analysis of separate chromite grains shows that the chromites contain PGE + Au values (in ppb): Pt 98, Pd 63, Os 45, Ir 23, Ru 136, Rh 19 and Au 83 (Table I). This is a significant PGE + Au enrichment of approximately 4 times over whole rock. The matrix of the chromitite does not contain PGEs and Au (or they are in such small quantities that they go undetected).

The PGE-containing samples from Ipanema, when compared with other complexes around the world (content of PGE + Au, C_1 chondrite normalised), were most similar to those in the Lower Zone of the Bushveld Complex in South Africa. The rocks of the Santa Cruz massif originate in the Earth's mantle. They show a relative depletion in Ir and an enrichment in Ru, characteristic of stratiform deposits.

São Francisco Structural Province

The São Francisco Province differs from the bordering provinces. It is a cratonic (central stable) area in the neighbouring fold belts. The province has massifs with chromitites and regions with placer deposits.

Serro and the Alvorada de Minas Mafic/Ultramafic Complex/Massifs Chromitite Deposits

Deposits in the Serro and Alvorada de Minas massifs have been examined (Figure 6). Chromium ore was mined here in the 1970s. The Serro (Morro do Cruzeiro body) has country rocks of metasedimentary sequences associated to banded iron formations enclosed in granite-gneissic terranes (Minas Supergroup) (21). The Serro body is formed of metaperidotites and metapyroxenites (metamorphosed peridotites and pyroxenites), with serpentine (mainly antigorite), chlorite, talc, actinolite and anthophyllite (23, 24). Inclusions of sulfides, for instance, pyrite and chalcopyrite, occur in the chromites and in the silicate gangue (minerals associated with the ore), mainly allied with regions rich in carbonates (23).

The Serro and Alvorada de Minas bodies contain chromitite lenses of perfect, as well as imperfect, crystal shapes. The crystals are fine-grained, from 0.5 to 4 mm. In some places the texture is disseminated, but the ore is rich in chromite (75 to 90%). The textures and thicknesses are associated with serpentinisation and deformation of the ultramafic rocks. Cr-spinel crystals of various shapes and thicknesses are found here as remnants of the original peridotites (22).

Some crystals have a preserved core and an altered rim, and the zoning is chemically distinct: the core is rich in Cr and Al and the border is more iron-bearing, showing high values for Cr/(Cr + Al) and $Fe^{2+}/(Fe^{2+} + Mg)$, respectively (23). Crystals of sperrylite are also found as inclusions in chromites and the silicatic matrix.

In addition, the author has found small crystals of laurite $(Ru,Os,Ir)S_2$, irarsite (Ir,Ru,Rh,Pt)AsS, cooperite (PtS) and more rarely Pt-Pd and Pt-Ir alloys (23). One chromitite sample gave anomalous values for PGEs: 196 ppb Ru; 96 ppb Pt; and 72 ppb Pd.

The Serro Placer Deposits

This region has three known placer deposits, all with similar geological setting (where the crystalline basement rocks meet the 'Espinhaço Supergroup' (in Minas Gerais)). They are:

- Morro do Pilar (Limeira),
- Conceição do Mato Dentro (Salvador), and
- Serro (Bom Sucesso).

The largest and most important PGM concentrations are alluvial deposits from the Bom Sucesso stream. This is being worked by casual prospectors, but to little gain. Pt-rich nuggets and Pt-Pd alloys occur in the Bom Sucesso stream in north Serro, 15 km from the city. In the past PGMs, Au and diamonds were extracted from this placer.

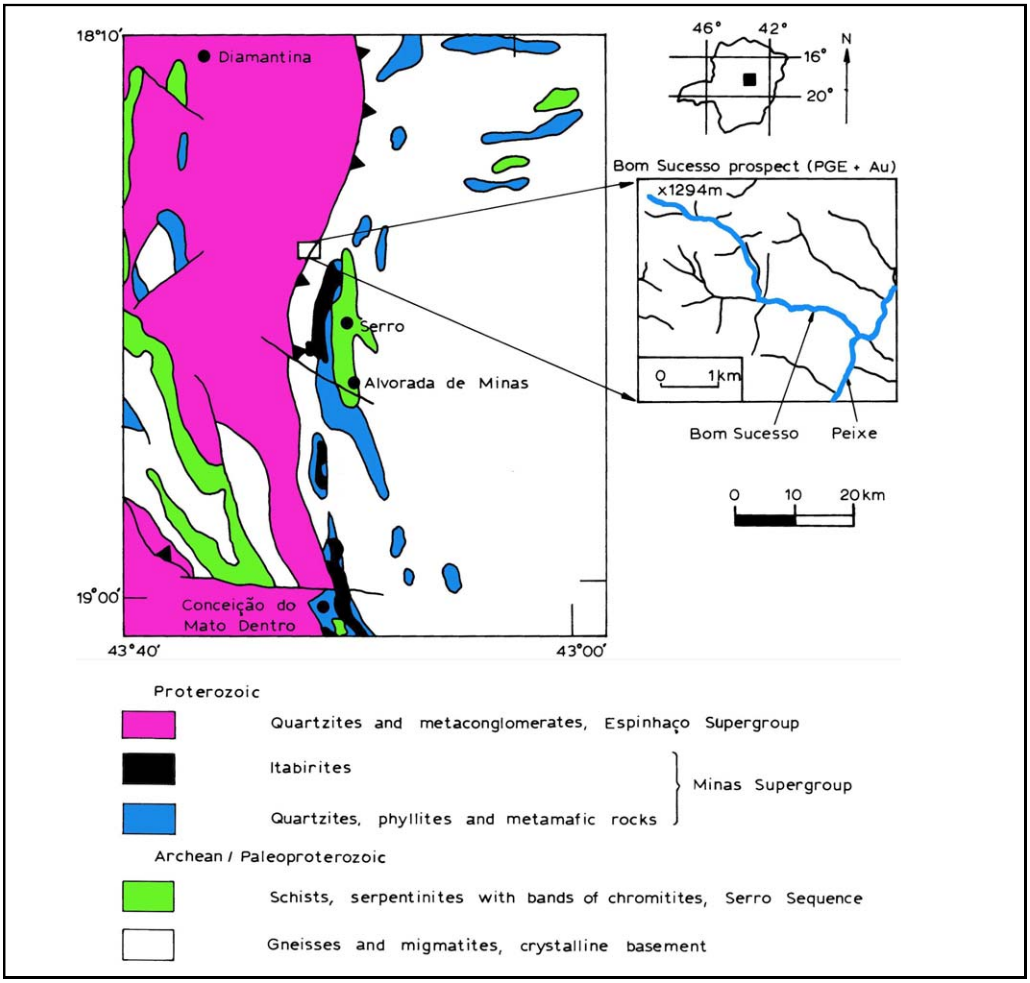

Fig. 6 Geological map of the Serro area in Minas Gerais State, showing the Bom Sucesso stream prospect on the southern flank of Mount Condado (modified from 25)

Glossary

Geological term/mineral	Meaning
Country rocks	Rocks occurring in the region beside a mineral deposit
Differentiated sequence	A layered sequence of rocks (a continuous series of ultramafic-mafic-intermediate rocks). The complete sequence at Santa Cruz is: dunites-peridotites, pyroxenites, gabbros and anorthosites (from bottom to top). It is a common sequence of stratiform complexes present in small quantities in rock.
Accessory minerals	Other minerals present in rocks, but not usually described
Ferritchromite	Ferriferous chromite (chromite enriched in Fe^{3+}, impoverished in Mg and Al)
Chondrite rock	Similar in composition to the Earth's mantle and to meteorites; used as a standard in rock analyses
Metasedimentary rock	Sedimentary rocks subjected to metamorphism (transformation by fluid, pressure and temperature)

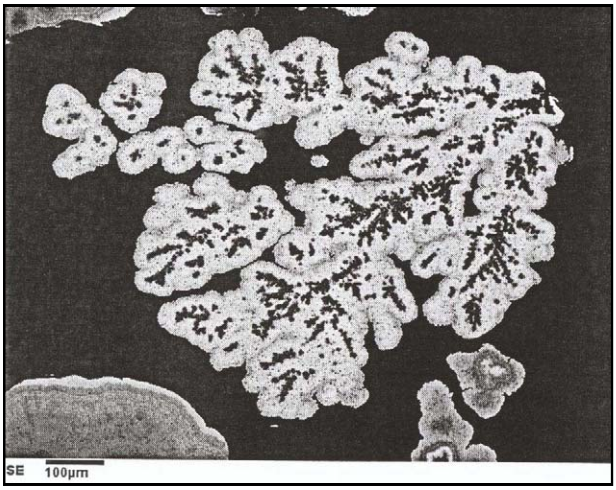

Fig. 7 The backscattered image of a zoned botryoidal Pt-Pd nugget found in the placer deposit in the Bom Sucesso stream. The bright zone is enriched in Pt relative to Pd. This is a typical arborescent nugget with a core of dendritic auriferous potarite and a narrow rim of Pd-Pt (28)

The country rocks here are quartzites and meta-conglomerates with thin intercalations of banded iron formations and metabasic rocks (talc-chlorite schists) (Figure 6). In order to find the source of the PGMs, correlations were attempted between the alluvial PGMs and the chromitite lenses from Serro, but without success. Others have looked at the rocks high above the Bom Sucesso stream (quartzites, conglomerates and weathered rocks), for the source rocks of the placer deposits (25, 26, 27), but no PGMs have yet been identified. Only one sample of soil from on top of a quartzite unit has yielded Pt (two grains) and Au (three grains).

Pt-Pd alloy nuggets found in the Bom Sucesso stream are botryoidal with pronounced zoning, (Figure 7). The zones have a wide range of morphologies of varying thickness (< 1–100 µm). The core region of the nuggets is composed of massive auriferous Pd-Hg alloy (potarite [Pd,Au,Pt]Hg), and a narrow zone or cavity space of platiniferous palladium or alloy of composition near $Pt_{50}Pd_{50}$, and progressively oscillatory zones of Pd-Pt (~ $Pd_{60}Pt_{40}$ to $Pd_{70}Pt_{30}$). Pd occurs in the core of the nuggets and may have been formed by changes in earlier auriferous potarite (10 to 34 wt.% Pd) (28).

The PGMs and PGE alloys in the nuggets have rounded as well as irregular outlines, and are much larger than primary grains. Particle sizes range from 10 to ≤ 500 µm. In general the nuggets comprise, a core of dendritic auriferous Pd-Hg alloy (potarite) surrounded by a narrow zone of platiniferous palladium and an alloy of composition near to $Pt_{50}Pd_{50}$. The Ir level was low and did not form a solid solution with the other PGEs, so the hypothesis of hydrothermal origin (for the primary ore) is not likely in the drainage basins (27). The zoning has been accentuated by chemical leaching processes, mainly by organic complexes, in the drainage basins. Potarite (Pd-Hg) was found in the placer deposits at Morro do Pilar and in the Serro (26).

The nuggets have a range of shapes: kidney (reniform), mamillary, cavernous, stick-shaped,

Glossary	
Geological term/mineral	Meaning
Banded iron formation	Banded rock formed by quartz (SiO_2), and hematite (Fe_2O_3). Sometimes hematite is predominant and constitutes ore.
Laterites	Ferralitic soils associated to mafic/ultramafic rocks, and other rocks rich in Fe. These soils are poor in Si and rich in Fe hydroxides, and in acidic rocks, where they are rich in Al hydroxides.
Metagabbros	Coarse grained igneous rock of basalt composition

Table II

Composition of PGMs Found in Serro (Bom Sucesso) Nuggets by Electron Probe Microanalysis (EPMA)

No.	Pt, wt.%	Pd	Hg	Au	Total*	Pt, at.%	Pd	Hg	Au
Platinum									
1	100.01	0.13	0.00	0.00	100.53	99.76	0.24	0.00	0.00
2	99.31	0.24	0.00	0.00	99.71	99.57	0.43	0.00	0.00
Palladium platinum									
3	95.36	4.41	0.60	0.08	100.46	91.59	7.77	0.56	0.08
4	86.07	13.03	0.46	0.16	99.72	77.84	21.61	0.41	0.15
5	87.60	11.44	0.47	0.26	99.76	80.16	19.19	0.41	0.23
6	78.07	21.39	0.28	0.06	99.80	66.37	33.34	0.23	0.05
7	96.64	3.20	0.09	0.07	100.00	94.13	5.72	0.08	0.07
8	87.86	12.30	0.15	0.02	100.33	79.46	20.40	0.13	0.02
Platiniferous palladium near $Pt_{50}Pd_{50}$									
9	63.71	36.39	0.05	0.00	100.16	48.82	51.13	0.04	0.00
10	62.95	36.21	0.49	0.09	99.75	48.46	51.11	0.37	0.07
11	62.33	36.97	0.37	0.00	99.66	47.77	51.95	0.28	0.00
12	63.60	35.74	0.24	0.00	99.58	49.16	50.66	0.18	0.00
Platiniferous palladium									
13	48.50	49.13	1.56	0.11	99.29	34.59	64.25	1.08	0.08
14	50.93	47.34	1.32	0.07	99.67	36.62	62.41	0.93	0.05
15	54.58	43.16	0.57	0.10	98.40	40.62	58.90	0.41	0.07
16	58.04	40.45	0.45	0.08	99.02	43.73	55.88	0.33	0.06
Pd-Hg alloy (auriferous potarite)									
17	0.48	40.20	53.93	6.32	100.93	0.36	55.46	39.47	4.71
18	0.75	47.48	49.61	2.06	99.91	0.55	63.04	34.94	1.48
19	0.28	42.77	48.35	8.05	99.45	0.21	58.65	35.17	5.96
20	0.00	37.48	44.44	18.04	99.97	0.00	52.94	33.30	13.76
21	0.38	36.73	47.70	15.31	100.12	0.30	52.09	35.88	11.73
22	0.32	36.96	50.82	12.15	100.25	0.24	52.31	38.15	9.29
23	0.48	43.30	47.42	8.29	99.50	0.36	59.16	34.36	6.12
24	1.17	45.09	50.57	3.59	100.41	0.85	60.53	36.01	2.60
25	0.33	43.03	44.60	11.61	99.56	0.25	58.83	32.35	8.57

* *The total metal content is sometimes > 100% due to the detection limits of the equipment*

botryoidal, dendritic and arborescent, with the most common being an arborescent-dendritic core of auriferous potarite, with a broad internal zone of either pure Pt or Pd-Pt and a narrow rim of Pt. The origin of the deposits is unclear, but may be weathered rocks, and the PGE source is consistent with precipitation from hydrothermal fluids of mafic rocks, see Table II. The PGE fractionation pattern is similar to that in New Hambler, Wyoming, U.S.A. Pd is observed to be more soluble than Pt in alluvial deposits (29), and in laterites (30). Some placers in Canada and Russia are similar to the Bom Sucesso deposit (26). The bulk Pd content of the alluvial Pt-Pd Bom Sucesso nuggets ranges from 11.7 to 29.3% (28).

Potarite was found in nuggets of Pt and Au in soil on top of quartzites cliffs (Condado Mount) in rocks of the Espinhaço Supergroup in upstream alluvium. The mineralised zones of the quartzite cliffs at Condado Mount are sheared and iron-rich sediments, banded iron formations and mafic rocks in the quartzites is common.

Borborema Structural Province

This province is in the northeast Brazilian fold belt, developed during the Upper Proterozoic time. The Pedra Branca mafic/ultramafic Complex, in Ceará State, 310 km from Fortaleza, comprises five bodies, (Figure 8) (dark green colour); Esbarro is the largest. Prospecting for chromium ore occurred here before 1978.

Pedra Branca Mafic/Ultramafic Complex

This belongs to the Tróia Median massif, bordered by the youngest fold systems (Lower Proterozoic). Pedra Branca Complex is composed of mafic/ultramafic associations: metagabbros, metapyroxenites, pillowed metabasalts, amphibolites, quartzites, metasediments (with sulfides and manganese), marbles and graphitic schists (30).

Esbarro Massif

The Esbarro massif has stratiform characteristics in spite of its small differentiation, and with few and incomplete layers (31, 32). The Esbarro massif presents three units and has been interpreted as the sequential product of magmatic differentiation, starting with dunite-peridotite through pyroxenite and hornblende gabbro (32). These units were metamorphosed into chlorite schist, talc-tremolite-actinolite schist, talc-serpentine schist, serpentinite and anthophyllite schist. Relict grains of olivine and orthopyroxene are occasionally observed (32).

Chromitites occur as lenses in the dunite-peridotite, and those with most potential are ~ 30 m long, 1.4 m wide and 1 m thick. The lenses can be traced for 1.2 km along the strike, and average 55 to 65% chromite of cumulate texture. They comprise chromium ore in which PGMs are found. The chromite grains are octahedral and 0.3 to 0.8 mm long, but some grains are very irregular: thought to be due to hydrothermal changes during low-grade metamorphism. High levels of PGMs, up to 4 ppm, were found in the chromites, and also disseminated in the silicatic matrix, where $PtAs_2$ (sperrylite) occurs, forming small inclusions (15 to 40 μm) in chromite and the chlorite-rich matrix (Cr chlorites), see Figure 9. The crystals are almost spherical, and are composite grains.

Kammererite (Cr chlorite) was found in the margins of the altered grains, and in the silicatic matrix. The kammererite is associated with a preferred crystallographic orientation of the ferritchromite matrix, oriented parallel to {111} planes (15).

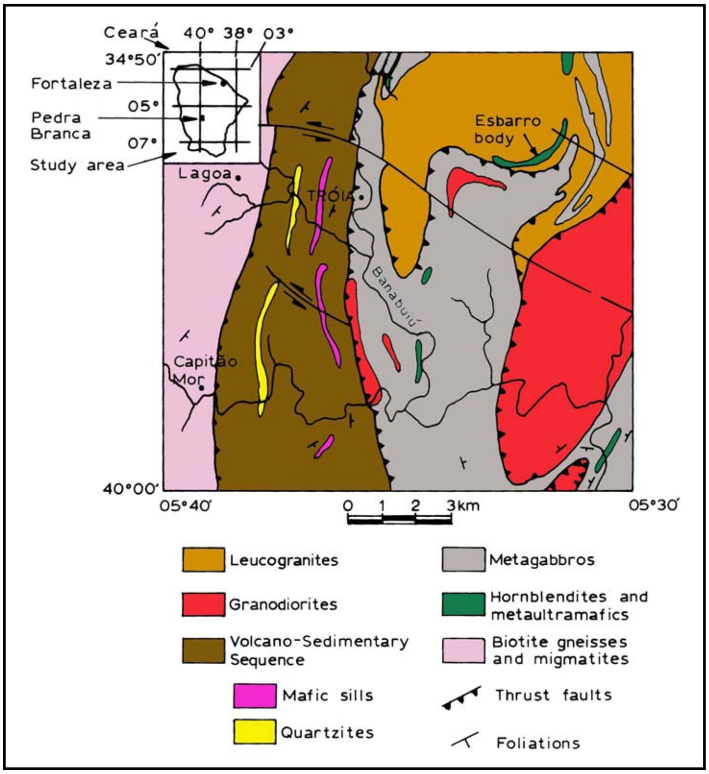

Fig. 8 Geological sketch of Tróia region (Ceará) and the Esbarro body, showing the location of the study area (modified from (30))

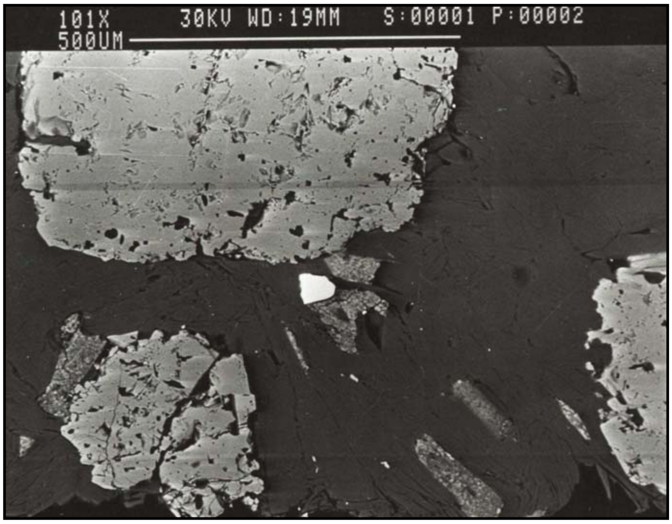

Fig. 9 An electron microprobe image of a sperrylite crystal associated with kammererites (matrix) near large crystals of chromites

Sperrylite is the most important mineral found. Locally the crystals contain, in at.%, up to 1.5 Ir, 2 Fe and 3 S, consistent with substitution of (Ir,Fe)AsS for $PtAs_2$. A single grain of hollingworthite (Rh,Pd,Pt,Ru)AsS was identified in the matrix and was shown to contain, in at.%, up to 9 Pd, 4 Pt, and 2 Ru, with zoning with a Pt-rich rim consistent with a substitution of $PtAs_2$ for (Rh,Pd)AsS (16), see Figure 9.

Small fragments of braggite of composition (Pt,Pd,Ni)S were also identified. Most PGMs are dispersed in the silicatic matrix, associated to

Mineralogical Composition of Cited Rocks	
Dunite	Olivine (≥ 90%) and pyroxenes-orthopyroxene (≤ 10%)
Peridotite	A series of rocks composed of olivine (90–40%) and pyroxenes (≤ 60%) (predominantly orthopyroxene), and the more important rock is harzburgite
Pyroxenite	Olivine (≤ 40%) and pyroxenes (≥ 60%) (predominantly clinopyroxene)
Gabbros	Plagioclase (mainly calcic) + pyroxenes (predominantly clinopyroxene) + olivine (in order of importance, for example, olivine ≤ 10%)
Anorthosites	This rock is on top of the layered sequence and is rich in plagioclase (≥ 90%)
Minerals Cited by Abbreviation (19) and General Formula	
Olivine (Ol)	Mg_2SiO_4
Orthopyroxene (Opx)	$(Mg,Fe)SiO_3$
Clinopyroxene (Cpx)	$Ca(Mg,Fe)Si_2O_6$
Plagioclase (Pl)	Mineral from feldspars series, where the component calcic is more common in the mafic/ultramafic sequence: $Ca(Al_2Si_2O_8)$
Metamorphic Minerals Cited by Abbreviation (19) and General Formula	
Serpentine (Srp)	$Mg_3(Si_2O_5)(OH)_4$
Chlorite (Chl)	$(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$
Talc (Tlc)	$Mg_6(Si_8O_{20})(OH)_4$
Actinolite (Ac)	$Ca_2(Mg,Fe)_5(Si_8O_{22})(OH)_2$
Tremolite (Tr)	$Ca_2Mg_5(Si_8O_{22})(OH)_2$
Anthophylite (Ath)	$(Mg,Fe)_7(Si_8O_{22})(OH)_2$

prominent chlorite cleavage; a few crystals appear as inclusions in the chromite grains. The chondrite-normalised signature is similar to those of the Ipanema Complex.

Conclusions

The associations and arrangements of rocks and minerals in the Santa Cruz massif (Ipanema Complex) with chromitite levels on top of metaperidotites is the first evidence for an intrusive origin of the body. The cumulate texture in the metaultramafic parts (metamorphosed peridotites) and the Cr-spinel crystals are typically encountered in stratiform complexes. The gradation of massive and disseminated ore, and the variation in the granulation of the chromites associated to a low Cr/Fe ratio (~ 2.0) support this conclusion.

A large number of chromite crystals with low Mg/Fe^{2+} values changed during serpentinisation, and this is thought to be related to the PGM/(PGE + Au) content. As these bodies, have PGM inclusions, more examination is required at the Ipanema Complex, Pedra Branca (Ceará) and Alvorada de Minas (Minas Gerais), and further work is planned.

Alluvial placers are less important because of their limited distribution and much smaller volumes, but further work will be undertaken. The origins of the PGE seem to be associated to mafic lenses along the Bom Sucesso stream, where the bulk composition yield (Pt, Pd) >> (Os, Ir, Ru, Rh). Another hypothesis concerns their relationship with metasediments (quartzites and conglomerates), due to the constant presence of Au (in quantities similar to the PGMs) and diamonds. This hypothesis links these minerals to the Espinhaço Supergroup, but again, more studies are necessary, and there is always the possibility of finding other deposits.

Acknowledgments

The author wishes to thank D. H. Verdugo for helping in the composition of Figures and Tables. The author is also grateful to the referee for helpful suggestions, and to E. C. Daitx for his help in simplification of the final text.

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The Author

Nelson Angeli graduated from the University of São Paulo (USP-São Paulo) in 1973. In the 1970s he worked in prospecting and exploration of mineral deposits. Since 1981 he has been a Professor at the University of São Paulo State (UNESP–Rio Claro). From 1991 to 1992 he was a Post-Doctoral Fellow at the University of Western Ontario, Canada. Much of his research has been on magmatic ores and their country rocks and lateritic ore deposits (Ni, Mn, and Al). Since 1992 he has worked with PGM/PGE + Au associated to mafic-ultramafic rocks and chromitites.
He is currently a member of the Commission on Ore Mineralogy of the International Mineralogical Association.
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