Layered mafic-ultramafic massifs remain the main focus of mineral exploration for the platinum group elements (PGEs). The large PGE reserves in the Bushveld, Stillwater, Sudbury and Great Dyke complexes provide the major share of platinum metals production, particularly the Bushveld, in South Africa. However, looking back to the beginning of the 20th century, it is surprising how important PGE lode mining was from unique geological structures like Onverwacht and Mooihoek (South Africa), and Nizhny Tagil (Urals, Russia). The iron-rich platinum pipe bodies found throughout the eastern lobe of the Bushveld Complex were probably discovered during early exploration of this igneous complex. In fact, the first discoveries of economic levels of PGEs were in the Onwerwacht and Mooihoek (South Africa), and Nizhny Tagil (Urals, Russia). The iron-rich platinum pipe bodies found throughout the eastern lobe of the Bushveld Complex were probably discovered during early exploration of this igneous complex. In fact, the first discoveries of economic levels of PGEs were in the Onwerwacht and Mooihoek (South Africa), and Nizhny Tagil (Urals, Russia).
Phoscorite-Carbonatite Pipe (PCP) Complexes

Multistage, phoscorite-carbonatite zoned complexes are found worldwide, but the most interesting are in the Kola Peninsula, at Maymeicha-Kotui in northern Siberia, at the Aldan Shield in the far east of Russia, in Alaska, in the east coast countries of Africa, and in the central-southern region of Brazil.

Phoscorite-carbonatite complexes are small, pipe-like bodies. They may take the form of dikes, sills, small plugs or irregular masses. A typical pipe-like body is of subcircular or elliptical cross-section and 3 to 4 km in diameter. Pipes extend to depths of 3 to 13 km or more (10).

The magmatic mineralisation in pipe-like carbonatite is commonly found in crescent-shaped, steeply dipping zones. Metasomatic mineralisation occurs as irregular forms or veins (11). PCP complexes possess a deep-step structure, and have experienced a prolonged, multistage metasomatic-hydrothermal evolution. Their complex composition and internal structure is clearly indicative of multiple intrusions/injections of molten partially crystallised magmatic masses. Tectonic discontinuities, layering, banding and steep inward concentric dips all indicate episodic diapiric emplacement mechanisms. Phoscorites and carbonatites are present as paired rocks; they occur near the nuclear area of the PCP complexes. Phoscorites are practically always associated with carbonatites, but many carbonatite complexes, especially those of linear structure, do not contain phoscorites.

Phoscorites, by definition, are medium and coarse-grained igneous rocks of magnetite-forsterite-apatite composition (12). Besides typical phoscorites, there are a variety of rock types of
similar mineral composition in the same geological environment. Some of these contain diopside instead of forsterite, while others contain actinolite, with or without relicts of diopside or phlogopite and tetraferriphlogopite (13). In the PCP complexes calcite-carbonatite is the dominant rock type, followed by dolomite-carbonatite.

Carbonatites occur in close spatial and temporal association with phoscorites and often form multiphase phoscorite-carbonatite series. The phoscorite-carbonatite series are mantle-derived rocks, and much discussion centres on whether carbonatite and phoscorites separate by fractional crystallisation and accumulation, by liquid immiscibility, or by both mechanisms. The existence of multistage phoscorite-carbonatite complexes, the similar mineral association and their geochemical peculiarities indicate, without doubt, that both rocks were formed from a parental magma by some method of differentiation. The mantle origin of phoscorite has been confirmed by both radiogenic and stable isotope studies (13, 14). Recently, a growing body of evidence has suggested that such magmas could be derived directly from depths in excess of 70 km by partial melting of the carbonated mantle peridotite (15, 16).

Multiple intrusions are revealed by the lithological and structural arrangement of successive stages of paired phoscorite-carbonatite; there are six at Kovdor (Russia) (14), two at Solki (Finland) (17), at least two in Phalaborwa (South Africa) (18, 19) and five in Tapira (Brazil) (20, 21).

The economic relevance of the PCP complexes is demonstrated by the presence of large hosted mining operations, such as phosphate mining at Phalaborwa, Jacupiranga, Tapira and Catalão (Brazil); Kovdor (Russia); baddeleyite mining at Phalaborwa and Kovdor; copper mining at Phalaborwa; iron mining at Kovdor; niobium mining at Araxá and Catalão (Brazil), see Figures 1 and 2, and uranium mining at Phalaborwa and Araxá.

The evolution of carbonatite and alkaline complexes could be related to crustal evolution dynamics and to continental rifting; carbonatite and alkaline complexes were formed shortly before the continental break-up and the opening of the ocean basins. Continental-type U-ATCs are closely related to PCP complexes; for instance, the large cylindrical platiniferous dunite-pyroxenite/alkaline intrusive complexes at Inagly, Kondyor and Gul platinum province in the Aldan Shield, eastern Siberia. These alkali-ultrabasic complexes are widespread in tectonically stable areas of eastern Russia. These complexes usually exhibit well-formed, concentric zoned structures, and are mainly composed of platinum-bearing chrome-spinel dunites and pyroxenites, which are very similar to those occurring in the Ural Platinum Belt (UPB) (22). However, in contrast to the Uralian ultramafic massifs, the Aldanian massifs occur as isolated, pipe-like bodies intruding the Archean crystalline basement.

The strong similarities between the Uralian and Aldanian platinum-bearing ultramafic rocks is thought to reflect similar melt-rock interaction mechanisms during their individualisation in the shallow mantle, before their emplacement in different geodynamic contexts. The geodynamic
setting was probably subduction-related for the Uralian-Alaskan zoned complexes and it is clearly intra-continental, possibly related to a rift zone for the Aldanian massifs (23).

Could PCP Complexes Generate PGE Ore Deposits?

PCP complexes are assumed to be associated with the continental-type U-ATCs series, similar to the Aldanian massifs, and have been examined as a potential source for research on minerals of the PGEs. The question is, could some highly siderophile mantelic magma, by recurrent and multiphase magmatic-metasomatic-hydrothermal evolution, result in PGE ore deposits? Indications of such a process are isolated, for instance:

- Platinum group metals have been recovered from electrolytic refinery sludge at Phalaborwa for many years (24).
- PGE mineral phases have been reported in some ore concentrates from Phalaborwa and Kovdor (25).

Despite the suggestion that the PGE and gold-silver mineralisation of the Kovdor and Phalaborwa complexes has a close spatial and probably genetic relationship with the multistage magmatic and post-magmatic processes, there is no consistent empirical evidence to support this.

The strategy of the current research was to use geological knowledge accumulated at PCP complexes that have been mined over a number of years. A field and laboratory research programme was drawn up to survey four typical PCP intrusions located in central southern Brazil: Ipanema, Tapira, Salitre I and Catalão II, and also at Phalaborwa in South Africa.

It was assumed that a selective survey of rock geochemistry could define any potential PGE enrichment in the PCP complexes and could provide sufficient data to establish a connection between the evolution of the PCP phases and the PGE concentration. The survey used a mineral exploration approach to look for PGE concentrations at ore standard. Current geological concepts and exploration methodology, known to be effective in this area, were used. However, exploration is not driven by highly specialised models or by using a range of techniques, so a follow-up exploration is necessary in order to establish appropriate techniques that can be adapted for effective exploration.

The Brazilian PCP Complexes

Voluminous flood basalt magmatism occurred in central and southern Brazil from the Early Cretaceous period to the Eocene time. These regions include the extensive Early Cretaceous Paraná continental flood basalt province and a number of Early Cretaceous to Eocene alkaline igneous provinces that surround the Paraná Basin, see Figure 1.

Some quite large (up to 65 km²) intrusive, carbonatite-bearing ultramafic complexes are located in these provinces (21). The main PCP complexes are: Catalão I, Catalão II, in southern Goias State; Serra Negra, Tapira, Salitre I, Salitre II and Araxá in south-west Minas Gerais State; Ipanema, Jacupiranga and Juquíá in east São Paulo State, and Lajes and Anitapolis, the southern intrusions found in Sta Catarina State.

With kamaafugites, lamproites and kimberlites, these complexes are multistage intrusions emplaced into Late-Proterozoic metamorphic terrains (20). The PCP complexes are formed by the amalgamation of multiphase intrusions comprising mainly ultramafic rocks (dunite, wehrlite and clinopyroxenite), see Figure 3, with subordinate calcite-carbonatite, phoscorite and syenite.

The phoscorite-carbonatite rock pair in the Brazilian PCP complexes is represented mainly by apatite, magnetite, diopside (minor phlogopite)

Fig. 3 A specimen of magnetite-biotite-perovskite-pyroxenite from the Tapira phosphate mine in Brazil
phoscorite rock associated with calcite-carbonatite, see Figure 4.

The surface shape expression of all PCP complexes is almost rounded or oval, internally concentrically zoned, with diameters varying from 1 to 7 km, depending on the level of erosion. However, the size of the actual phoscorite-carbonatite bodies is even smaller (27). Rock identification at the surface is quite difficult, as chemical weathering results in deep soil formation and a poor fresh rock exposure, see Figure 5.

The Phalaborwa PCP Complex

The Phalaborwa complex intruded the Archean basement at the edge of the Kapvaal Craton in Early Proterozoic times (2.06 million years ago) and consists of concentrically zoned, multiple intrusions, which decrease in age from the margin to the core. The core is an elliptically-shaped vertical intrusion known as the Loolekop pipe (18, 19). The host Phalaborwa complex is mainly composed of ultramafic rocks (dunite and pyroxenite) with a core of carbonatite and phoscorite. Minor rock types include glimmerite, syenite and fenite. The core of the composite intrusion shows a concentric arrangement of phoscorite around the margin and a core of banded carbonatite. Both these rock types were intruded by the central transgressive carbonatite, see Figure 6.

Field and Laboratory Surveys

The present research was oriented to identify possible PGE concentrations (at ore standard) and to establish if there was a relationship between the PGE concentration and individual rock types from the selected PCP complexes. To avoid the weathered upper zone, sampling was done on fresh rock
exposures from the lower benches of the open pit phosphate mines.

In order to avoid the “nugget effect”, large volume chip rock samples (15 kg on average) were collected from every kind of rock type at the Ipanema, Tapira, Salitre I, Catalão II and Phalaborwa PCP intrusions. In all 70 samples were collected, amounting to 1500 kg (Table I).

Rock sampling was planned after consideration of all geological data available from the selected PCP complexes. Representative samples were collected from the main rock types, represented by:

- Tapira: pyroxenite (Figure 3) and phoscorite;
- Salitre: pyroxenite, phoscorite and carbonatite;
- Catalão: phoscorite and carbonatite (Figure 4);
- Ipanema: phoscorite and magnetitite; and
- Phalaborwa: pyroxenite, phoscorite, banded carbonatite (Figure 6) and transgressive carbonatite.

Each rock sample was crushed, homogenised, cross-split and finally pulverised in an oscillating mill to less than 0.044 mm particle size, before being taken for chemical assay. The first round of chemical analyses (54 samples), was performed by the Analytical Science Division of Mintek (South Africa), using the fire assay technique with NiS collection and ICP-OES for the final PGE notation. The laboratory procedures were certified; SARM7 (Standard South Africa) was the reference sample and every sample was assayed twice.

The results from Mintek at the beginning of 2005 were conclusive in indicating that PCP complexes are, in fact, very suitable for the enrichment of PGEs at ore level standards. Three PCP intrusions (Ipanema, Catalão and Phalaborwa) gave very consistent data indicating a high concentration of PGE:

- Ipanema: up to 5.15 ppm in total of Pt, Pd, Rh, Ru, Os;
- Catalão: 4.47 ppm in total of Pt, Pd, Rh, Os;
- Phalaborwa: 16.67 ppm in total of Ir, Os.

The other two (Salitre and Tapira) show no PGE enrichment at all.

It should be noted that the rock samples from Salitre and Tapira were taken from available drill cores, so were not as representative as the samples from Catalão, Ipanema and Phalaborwa collected from the mining pit benches. The negative result obtained for these areas must take the sampling constraints into account, and consequently should not be taken as a definitive statement.

On comparing the data, it can be seen that the relative abundance of PGE in Brazilian PCP complexes shows a distinct enrichment in rhodium (up to 0.60 ppm), with no indication of iridium concentration, whereas the rocks from Phalaborwa do not register rhodium enrichment, but show a very significant iridium concentration (up to 13.5 ppm).

A general statement of PGE concentration is:

Catalão: \( \text{Pt} > \text{Pd} > \text{Ru} > \text{Rh} > \text{Os} \)
Ipanema: \( \text{Pt} > \text{Pd} > \text{Os} > \text{Rh} > \text{Ru} \)
Phalaborwa: \( \text{Pt} > \text{Pd} > \text{Ru} > \text{Ir} > \text{Os} \)

All the rock samples were graded for particle size distribution by wet screening, followed by

<table>
<thead>
<tr>
<th>Table I</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Characteristics of Samples from the Brazilian and Phalaborwa PCP Complexes</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main characteristics</th>
<th>Tapira*</th>
<th>Salitre I*</th>
<th>Catalão II*</th>
<th>Ipanema*</th>
<th>Phalaborwa†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>70 Ma.</td>
<td>80 Ma.</td>
<td>83 Ma.</td>
<td>123 Ma.</td>
<td>2060 Ma.</td>
</tr>
<tr>
<td>Surface, km²</td>
<td>33.0</td>
<td>15.0</td>
<td>14.5</td>
<td>9.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Shape</td>
<td>Oval</td>
<td>Oval</td>
<td>Circular</td>
<td>Circular</td>
<td>Kidney-shaped</td>
</tr>
<tr>
<td>Main rocks</td>
<td>Peridotite</td>
<td>Peridotite</td>
<td>Peridotite</td>
<td>Peridotite</td>
<td>Clinopyroxenite</td>
</tr>
<tr>
<td></td>
<td>Clinopyroxenite</td>
<td>Clinopyroxenite</td>
<td>Clinopyroxenite</td>
<td>Clinopyroxenite</td>
<td>Clinopyroxenite</td>
</tr>
<tr>
<td></td>
<td>Calcite-carbonatite</td>
<td>Calcite-carbonatite</td>
<td>Calcite-carbonatite</td>
<td>Calcite-carbonatite</td>
<td>Calcite-carbonatite</td>
</tr>
<tr>
<td></td>
<td>Phoscorite</td>
<td>Phoscorite</td>
<td>Phoscorite</td>
<td>Phoscorite</td>
<td>Phoscorite</td>
</tr>
<tr>
<td></td>
<td>Syenite</td>
<td>Alkalic-syenite</td>
<td>—</td>
<td>Syenite</td>
<td>—</td>
</tr>
</tbody>
</table>

* Ref. (27) CBMM
† Ref. (18) Vielreicher et al.
chemical and mineralogical analyses as well as magnetic separation studies.

The research, which is still in progress, will be followed by systematic chemical and mineralogical studies. At present, total rock geochemical analysis, including major and minor trace elements, including the rare earths, is being determined by AAS and/or ICP spectroscopy. The rock samples will be surveyed for process mineralogy studies, and thin-polished samples will be prepared for optical and scanning electron microscopy analyses. Mineralogical analyses will be performed by X-ray diffraction, optical mineralogy and scanning electron microscopy with energy dispersive X-ray spectrometer (SEM-EDS). Gravitational concentration and heavy minerals extraction for a sensitive mineralogical (microprobe) study will also be undertaken.

The author is aware that the following mineralogical study will be much more difficult and time consuming, and is of higher risk. The Brazilian laboratory expertise and technical apparatus may not be sufficient. So it is further intended to ask for the collaboration of Russian mineralogists, especially those linked with St. Petersburg University or with NATI Research JSC, St. Petersburg.

The main aim will be to identify the PGE mineralogical phases and to establish their relationship with associated silicate and oxide minerals, looking for a probable genetic connection between the PGE concentration process and the evolution of the phoscorite-carbonatite complexes. The laboratory procedures will be performed at the University of São Paulo, and other international academic and commercial research facilities.

**Discussion and Conclusions**

The PGEs, rhenium and gold comprise the so-called highly siderophile elements (HSE), the abundances of which in the upper mantle are often

<table>
<thead>
<tr>
<th>Material</th>
<th>Platinum, ppt*</th>
<th>Palladium, ppt</th>
<th>Rhodium, ppt</th>
<th>Osmium, ppt</th>
<th>Iridium, ppt</th>
<th>Ruthenium, ppt</th>
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<tr>
<td>Crustal average</td>
<td>400</td>
<td>400</td>
<td>60</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>PGE abundance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper mantle (peridotite)‡</td>
<td>Average abundance</td>
<td>6500</td>
<td>5700</td>
<td>n.a.</td>
<td>3500</td>
<td>3500</td>
</tr>
<tr>
<td>Catalão PCP</td>
<td>300,000</td>
<td>300,000</td>
<td>140,000</td>
<td>120,000</td>
<td>n.a.</td>
<td>120,000</td>
</tr>
<tr>
<td></td>
<td>2,860,000</td>
<td>810,000</td>
<td>600,000</td>
<td>200,000</td>
<td>up to</td>
<td>200,000</td>
</tr>
<tr>
<td>Ipanema PCP</td>
<td>300,000</td>
<td>200,000</td>
<td>400,000</td>
<td>400,000</td>
<td>n.a.</td>
<td>150,000</td>
</tr>
<tr>
<td></td>
<td>3,200,000</td>
<td>1,330,000</td>
<td>540,000</td>
<td>up to</td>
<td>up to</td>
<td>490,000</td>
</tr>
<tr>
<td>Phalaborwa PCP</td>
<td>150,000</td>
<td>260,000</td>
<td>n.a.</td>
<td>300,000</td>
<td>1,100,000</td>
<td>120,000</td>
</tr>
<tr>
<td></td>
<td>580,000</td>
<td></td>
<td></td>
<td>up to</td>
<td>up to</td>
<td>up to</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,280,000</td>
<td>13,500,000</td>
<td>160,000</td>
</tr>
<tr>
<td>Ore concentration, g t⁻¹</td>
<td>0.15</td>
<td>0.26</td>
<td>0.14</td>
<td>0.12</td>
<td>1.10</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>3.20</td>
<td>1.33</td>
<td>0.60</td>
<td>3.28</td>
<td>13.50</td>
<td>0.49</td>
</tr>
<tr>
<td>Concentration rate:</td>
<td>89</td>
<td>45</td>
<td>n.a.</td>
<td>57</td>
<td>315</td>
<td>27</td>
</tr>
<tr>
<td>PCP composition/ mantle abundance</td>
<td>492 times</td>
<td>233 times</td>
<td></td>
<td>937 times</td>
<td>3857 times</td>
<td>85 times</td>
</tr>
</tbody>
</table>

* ppt = parts per trillion
‡ Upper Mantle, Ref. (28) Morgan et al.
in the parts per trillion (ppt) range, and, which in the undepleted primitive upper mantle, are in approximately chondritic proportions (28, 29).

Phoscorite-carbonatite pipes (PCP) are generated in a geodynamic environment which provides appropriate structural control to enable the vertical migration of dense iron-rich melts, over thousands of metres, and, equally important, their concentration into relatively small core zones. There is a limited understanding of the role of the magma mixing, assimilation, crustal metasomatism and other subsolidus processes in the origin and evolution of PCP complexes. However, the role of metasomatism, including late-stage alteration is also important in the ultimate understanding of the PGE enrichment processes.

PGE mineralisation has a close spatial and probably genetic relationship with the multistage magmatic and post-magmatic evolution of PCP complexes. The PGE enriched zones, in the core zones of PCP complexes, represent the final product of a series of superimposed events like the progressive PGE fractionation during the evolution of mantle magma and the recurrence of magmatic pulse events.

The parental sulfur-poor/oxygen-rich melt system tends to result in a PGE ore mineralogy assemblage similar to those from classical ultramafic platiniferous pipes. These pipes are commercially very attractive because of the low capital cost of establishing ore dressing facilities, that is, the bulk of the PGEs could be recovered by conventional gravity and magnetic separation technologies.

The PGE concentrations in Catalão, Ipanema and Phalaborwa provide solid evidence of the PGE potential of PCP complexes, particularly in regarde to their ore concentration level. The PGE occurrence in Ipanema shows the need to pay attention to the detection of Fe-Cr and PGE-rich vein-type varieties of spinels. The wide development of such Fe-spinel veins is indicative of a low erosion level at the PCP complex cupola, and consequently, a better PGE potential (22).

The theoretical and factual data encourage the assumption that PCP intrusions are a very promising target for PGE mineralisation. It is proposed that the platiniferous pipe conceptual model should be extended to take into account PCP complexes as a promising new member. For systematic mineral exploration, the PGE exploration strategy for PCP complexes must be directed mainly to a selective structural and geochemistry survey, instead of to conventional saturation rock sampling geochemistry.

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The Author
Dr Juarez Fontana is professor and a mineral exploration expert at the University of São Paulo, Brazil. He is interested in both academic (geological models) and commercial projects, connected with PGE mineralisation and metallogenic processes, especially those related to the alkaline phoscorite-carbonatite intrusive complexes.