INTRODUCTION

Below is a summary of geological, geochemical and geophysical signatures of ore deposits which are located at the contacts of layered mafic intrusions. Examples are presented from Portimo and Koillismaa (Tornio-Näränkävaara Belt, Finland), Platreef and Sheba's Ridge (Bushveld Complex, South Africa) and East Bull Lake and River Valley (East Bull Lake Intrusive Suite, Canada). The examples included here are PGE-dominated base-metal sulfide deposits where the precious metals are the most important for the economics of the deposit.

It is hoped that listing the features of these deposits will help exploration geologists to recognize critical features when planning and conducting the various phases of exploration. The first and most critical step in all exploration is choosing area for exploration at the province or formation scale. The second step is definition of targeted deposit models. It is hoped that this paper will contribute to this stage of the exploration in particular. The exploration methods are very similar for any type of metal exploration. They include areal and regional geophysical and geochemical tools and preliminary or scout drilling. The exploration model can facilitate the choice of proper sampling or measurement intervals and various pathfinders. The exploration methods used depend on several geographic factors, some of which are listed in Table 4-1.

PORTIMO AND KOILLISMAA MARGINAL SERIES DEPOSITS

Portimo Stratigraphy and Structure

The Portimo Layered Igneous Complex (Portimo Complex) is part of the ca. 2450 Ma old and approximately 300 km long belt of layered intrusions which crosses Finland almost along the Arctic Circle and also extends into Sweden and Russia (Fig. 4-1). This belt, consisting of about 10 intrusions, is known as the Tornio-Näränkävaara Belt (TNB) and it is an example of a major failed rift system. Furthermore, the TNB contains roughly one third of the ca. 2450 Ma layered intrusions of the Fennoscandian Shield.

The Portimo Layered Igneous Complex (Fig. 4-1) is composed of four principal structural units (modified after Iljina 1994):

- the Narkaus intrusion
- the Suhanko intrusion
- the Konttijärvi intrusion
- the Portimo Dykes

Each intrusion contains a marginal series and an overlying layered series. The marginal series of the Suhanko and Konttijärvi intrusions have a different thickness and prevailing rock types from that of the Narkaus intrusion. The Narkaus marginal series varies from about 10 to 20 metres in thickness, whereas the Suhanko and Konttijärvi marginal series is typically several tens of metres in thickness. The Narkaus marginal series is mainly composed of pyroxenite, whereas olivine cumulates generally make up the upper half of the Suhanko and Konttijärvi marginal series (Fig. 4-2). The metamorphic alteration of cumulates is pervasive, which, for example, prevents the study of the mineral chemistry.

The principal difference between the layered series overlying the marginal series of the intrusions is the presence of marked reversals in the Narkaus intrusion, as shown by the thick ultramafic olivine-rich cumulate layers, whereas crystallization in the Suhanko and Konttijärvi intrusions continued without any notable reversals (Fig. 4-2). The major reversals in the Narkaus layered series resemble those of the Penikat intrusion and enable its layered series to be divided into three megacyclic units.
TABLE 4-1. GEOGRAPHIC FACTORS AND RELATED EXPLORATION METHODOLOGY

<table>
<thead>
<tr>
<th>Climate</th>
<th>Landscape</th>
<th>Geochemical</th>
<th>Geophysical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>Deep <em>in situ</em> soil</td>
<td>Soil, rock, soil profile and stream sediment sampling</td>
<td>Magnetics/IP/EM</td>
</tr>
<tr>
<td>Temperate</td>
<td>Residual</td>
<td>As above</td>
<td>As above</td>
</tr>
<tr>
<td>Semi-desert</td>
<td>Residual with lag of heavy mineral</td>
<td>Sampling of magnetic lag, geochemistry of wind-winnowed material</td>
<td>As above</td>
</tr>
<tr>
<td>Temperate to</td>
<td>Till; transported soils, alluvium</td>
<td>Till geochemistry, boulder sampling with transport directions deduced. Bio-geochemistry.</td>
<td>Aeromagnetic and EM mapping for possible source anomalies</td>
</tr>
<tr>
<td>Cold</td>
<td>Dissected</td>
<td>Drainage heavy mineral sampling, rock geochemistry.</td>
<td>As above</td>
</tr>
</tbody>
</table>

Fig. 4-1. Mafic-ultramafic layered intrusions (black) in the Tornio-Näränkävaara Belt. The white areas are mainly Archean gneisses and the grey indicates Proterozoic domains. Insets show the distribution of intrusions and intrusion blocks of the Portimo (left) and Koillismaa Layered Igneous Complexes. The location of the Ahmavaara (A) and Haukiaho (H) deposits are also indicated. The ‘connecting dyke’ in the Koillismaa area refers to a strong magnetic and gravimetric anomaly joining the Näränkävaara intrusion to the Pyhitys and Kuusijärvi blocks of the Western Intrusion.

(MCU, Fig. 4-2). These megacyclic units are a result of major influxes of mafic magma into the chamber. These kinds of sequential magma influxes and the significant differences between subsequent chemical compositions of incoming magmas are features of both the Portimo and Bushveld Complexes. In Portimo the MCU I and MCU II crystallized from Mg-Cr-richer magma whereas Mg-Cr-poorer magma made up MCU III and the entire Suhanko and Konttijärvi intrusions. The Mg-Cr-richer magma type produced the Portimo Dykes in the Ahmavaara and Konttijärvi regions.

Mafic and ultramafic Portimo Dykes can be found in the basement below the Konttijärvi intrusion and in the Ahmavaara area of the Suhanko intrusion. They have also been found as fragments in the marginal series of Konttijärvi (Fig. 4-3). The dykes have not been dated and their link to the same
magmatic event as the main intrusions is based on geochemical observations. The dykes are subparallel to the basal contact of the intrusion and merge with it locally, so that a dyke can actually form the basement of the intrusion. It has also been verified that the marginal series cross-cuts the Portimo Dyke on an outcrop.

The layered series cumulus sequences of the small Konttijärvi intrusion and the western end of the Suhanko intrusion (Ahmavaara section) resemble one another. Pyroxenite, which separates the lowermost poikilitic orthocumulate from the overlying gabbroic adcumulate, is over tens of metres thick in both sections and makes up about one fifth of the whole Konttijärvi layered series. The gabbroic rocks of the Konttijärvi marginal
series are, in fact, mostly pyroxene cumulates with variable portions of felsic material introduced by floor rock contamination. This and the thick layered series pyroxenite make the present day Konttijärvi stratigraphy largely ultramafic when cumulus terminology is applied. The lower contact of the Konttijärvi intrusion is also unique in the TNB intrusions. Below the lowermost more homogenous cumulate there is a thick Mixing Zone, which in some places is up to approx. 150 m wide (Fig. 4-4). The combined thickness of the Konttijärvi marginal and layered series is only slightly more (approx. 160 m) than this Mixing Zone.

The Mixing Zone is made up of a rock type termed 'hybrid gabbro' and of banded gabbro (Fig. 4-5). The 'hybrid gabbro' is characterized by grain size variations from fine to medium and also contains an almost assimilated felsic contaminant. Further away from the intrusion the hybrid gabbro turns into the banded gabbro, which according to outcrop evidence, is recrystallized banded Archean quartz dioritic gneiss which still has a primary folded texture but gabbroic mineralogy (Fig. 4-5). Contacts between homogenous gabbro (of marginal series proper), hybrid gabbro and banded gabbro are arbitrary but the hybrid and banded gabbros are included in the basement domain in this paper. This division is due to the pattern that in many drill holes there are several sections of hybrid and banded gabbros (1–20 m in length) right next to each other, so that the two gabbro types together form a distinctive, mappable unit. This unit also contains

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**Fig. 4-4.** Cross-section (A) and longitudinal section (B) of the Konttijärvi body.
basement gneiss blocks which are up to several tens of metres in size. The Mixing Zone 'gabbros' appear to be a result of the mechanical mixing of melted Archean gneiss and mafic magma and also the metasomatic recrystallization of the basement gneiss into mafic gneiss. The Mixing Zone seems to dip to form a depression structure, some tens of metres in diameter (Fig. 4-4) at the center of the Konttijärvi igneous body.

Diverse Portimo sulfide-PGE mineralizations

The Portimo Complex is exceptional among the layered intrusions as it hosts a variety of PGE mineralization styles (Figs. 4-6 – 4-8). The principal mineralization types are (Iljina 1994):

- PGE-bearing Cu–Ni–Fe sulfide disseminations in the marginal series of the Suhanko and Konttijärvi intrusions (Figs. 4-6 to 4-8).
- predominantly massive pyrrhotite deposits located close to the basal contact of the Suhanko intrusion (Figs. 4-6 and 4-8).
- the Rytikangas PGE reef in the Suhanko layered series (Fig. 4-6).
- the Siika-Kämä PGE reef in the Narkaus layered series (Fig. 4-6).
- the offset Cu–PGE mineralization below the Narkaus intrusion (Fig. 4-6).

Fig. 4-6. Schematic presentation of the locations of the various PGE enrichments encountered in the Portimo Layered Igneous Complex. The numbers refer to the figures in this paper.
Fig. 4-7. Stratigraphic sequence of the Konttijärvi marginal series showing variations in bulk Pt+Pd+Au, S, Se, Se/S and Cu. For the structural position, see Fig. 4-6.

Fig. 4-8. Comparison of the Ahmavaara deposit and one low grade, disseminated and massive sulfide deposit of the Suhanko Intrusion. For the structural position, see Fig. 4-6.
The high PGE concentrations in the Konttijärvi marginal series sulfides were first discovered in a mineralogical study by Outokumpu Oy in the late 1970s (Vuorelainen et al. 1982). Because of these findings together with developments in cost-effective automatic analytical instrumentation the entire Portimo Complex was subjected to extensive platinum exploration. Although the pyrrhotite-dominated sulfides in the Suhanko marginal series had already been explored extensively in the 1960s, reassays of the old drill core did not reveal significant platinum contents until in 1986 a new drilling campaign hit the more highly Cu–Ni–PGE-enriched sulfides in the Ahmavaara area. Since then the exploration has produced results indicated in Table 4-2 and the Konttijärvi and Ahmavaara deposits are now considered economically viable.

Disseminated Suhanko and Konttijärvi marginal series sulfides

Disseminated PGE-bearing base metal sulfide mineralizations (Table 4-3; Figs. 4-6 – 4-8) of the contact zone, which are normally 10–30 metres in thickness, occur throughout the entire marginal series of the Suhanko and Konttijärvi intrusions. Their distribution is erratic and their occurrence typically extends from the lower peridotitic layer downwards for some 30 metres into the basement. In Konttijärvi, this mineralization sometimes extends 100 metres below the actual marginal series, hosted in rock types belonging to the Mixing Zone (Fig. 4-7). In places, the mineralization seems to have occurred along the mafic replacement bands, possibly indicating concurrent metasomatism and mineralization in the banded gabbro (Fig. 4-5).

The bulk of the platinum-group minerals (PGM) in the Portimo Complex is composed of various arsenides, bismutotellurides and arsenoantimonides, with some sulfarsenides, sulfides, stannides, selenides and bismuthides, in descending order, whereas native elements and Fe-PGE alloys are totally absent (McElduff & Iljina 1991, Iljina 1994). Of the platinum-group elements, palladium, platinum and rhodium were found to form minerals deficient in the other PGE, whereas traces of osmium, iridium and ruthenium were found to be present in minerals mainly composed of other PGE. The platinum-group minerals are associated with silicates, sulfides and oxides, the silicates being the most common environment (Table 4-4). In base metal mineralogy, a peculiar kind of composite sulfide intergrowth (Fig. 4-9), composed of galena, pentlandite, sphalerite, pyrite and sometimes even platinum-group minerals, is common in the mineralized Konttijärvi basement gneisses. This kind of assemblage is not characteristic of fractionated mss sulfides, but suggests a paragenesis introduced by or re-equilibrated with fluids.

The PGE contents vary from only weakly anomalous values to 2 ppm in most places in the marginal series of the Suhanko intrusion but rises to >10 ppm in a number of samples from Konttijärvi and Ahmavaara (Figs. 4-6 and 4-8). Highly PGE-enriched marginal series of this kind are rare in layered intrusions; another well-known occurrence is the Platreef in the Northern Bushveld Complex, described below. In the case of the Suhanko intrusion, the PGE grade and Cu and Ni contents of the sulfide fraction seem to correlate with the presence of the Portimo Dykes underneath the intrusion.

Figure 4-7 shows a lithological log and variation of some elements in one drill core close to the depression structure mentioned earlier (Fig. 4-4). In the drill hole depicted, the precious metals appear in the lower peridotite layer and are present down to the base of the hybrid gabbro of the Mixing Zone with an additional peak at a depth of approximately 200 m. The copper correlates well with the precious metals, but the sulfur does not, indicating variations in the relative amounts of iron and copper sulfides.

Massive Suhanko marginal series sulfides

Massive sulfide deposits are characteristic of the marginal series of the Suhanko intrusion. They are in the form of dykes and obviously also plate-like bodies conformable to layering and generally vary in thickness from 20 cm to 20 m. The deposits are also found in various locations from 30 m below the basal contact of the intrusion to a position 20 m above it and range in size from less than 1 million tonnes to more than 10 million tonnes. The sulfide assemblage is composed almost exclusively of pyrrhotite, except for the Ahmavaara deposit, which also contains chalcopyrite and pentlandite. Outcrop evidence from Ahmavaara shows that massive sulfides occur exclusively as crosscutting dykes.

The PGM are approximately the same as in the disseminated sulfide mineralization. Despite the
### Table 4-2. Comparative Values for Operating and Potential PGE Open Pit Operations on the Platreef, N. Bushveld.

<table>
<thead>
<tr>
<th>Project</th>
<th>Company</th>
<th>Resource Status</th>
<th>PGE+Au g/t</th>
<th>Ni %</th>
<th>Cu %</th>
<th>Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N. BUSHVELD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drenthe</td>
<td>Anooraq – Angloplat</td>
<td>Inferred</td>
<td>1.3 (4E)</td>
<td>0.16</td>
<td>0.1</td>
<td>99.4</td>
</tr>
<tr>
<td></td>
<td>Genmin (now Pan Palladium)</td>
<td></td>
<td>1.19 (3E?)</td>
<td>0.07</td>
<td>0.21</td>
<td>50.4</td>
</tr>
<tr>
<td>Nonnenwerth</td>
<td>Pan Pistol</td>
<td>Inferred?</td>
<td>1.15 (4E)</td>
<td>0.15</td>
<td>0.04</td>
<td>23.8</td>
</tr>
<tr>
<td>(Aurora)</td>
<td>Genmin</td>
<td></td>
<td>1.09 (3E)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Volspruit</td>
<td>Pan PALLADiUM</td>
<td>Inferred</td>
<td>1.2 (4E)</td>
<td>0.16</td>
<td>0.03</td>
<td>17.5</td>
</tr>
<tr>
<td>Volspruit</td>
<td>AIM Resources</td>
<td>Inferred</td>
<td>.55 (2E)</td>
<td>0.085</td>
<td>0.146</td>
<td>39 (?)</td>
</tr>
<tr>
<td>Mokopane</td>
<td>Platinum</td>
<td>Intersection values over 28 metres</td>
<td>2.34 (4E)</td>
<td>–</td>
<td>–</td>
<td>350.8</td>
</tr>
<tr>
<td>Tweespak</td>
<td>Platinum</td>
<td>Measured and indicated</td>
<td>2.44 (4E)</td>
<td>–</td>
<td>–</td>
<td>153.6</td>
</tr>
<tr>
<td>Potgietersrus</td>
<td>Platinum</td>
<td>‘Main zone’ Indicated and Inferred</td>
<td>0.94 (3E)</td>
<td>0.22</td>
<td>0.08</td>
<td>370</td>
</tr>
<tr>
<td>Potgietersrus</td>
<td>Platinum</td>
<td>‘Upper zone’ Indicated and Inferred</td>
<td>0.48 (3E)</td>
<td>0.12</td>
<td>0.03</td>
<td>577</td>
</tr>
<tr>
<td><strong>E. BUSHVELD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheba's Ridge</td>
<td>Ridge Mining</td>
<td>‘Main zone’ Indicated and Inferred</td>
<td>2.46 (3E)</td>
<td>0.07</td>
<td>0.19</td>
<td>35.6</td>
</tr>
<tr>
<td>Sheba’s Ridge</td>
<td>Ridge Mining</td>
<td>‘Upper zone’ Indicated and Inferred</td>
<td>1.88 (3E)</td>
<td>0.11</td>
<td>0.28</td>
<td>61.8</td>
</tr>
<tr>
<td><strong>PORTIMO</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Konntijärvi</td>
<td>Gold Fields–Arctic Platinum</td>
<td>JORC classified resources, 1.0E cut-off</td>
<td>1.54 (3E)</td>
<td>0.08</td>
<td>0.20</td>
<td>16.3</td>
</tr>
<tr>
<td>Ahmavaara</td>
<td>Gold Fields–Arctic Platinum</td>
<td>JORC classified resources, 1.0E cut-off</td>
<td>0.99 (3E)</td>
<td>0.13</td>
<td>0.19</td>
<td>–</td>
</tr>
<tr>
<td>Ahmavaara east</td>
<td>Gold Fields–Arctic Platinum</td>
<td>JORC classified resources, 1.0E cut-off</td>
<td>0.79 (3E)</td>
<td>0.22</td>
<td>0.36</td>
<td>–</td>
</tr>
<tr>
<td><strong>KOILLISMAA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murtolampi</td>
<td>Geological Survey of Finland</td>
<td>cut-off 0.7 g/t 3E, average of 49 1m long drill hole samples</td>
<td>2.2 (3E)</td>
<td>0.02</td>
<td>0.13</td>
<td>4.1</td>
</tr>
<tr>
<td>Haukiaho</td>
<td>Geological Survey of Finland</td>
<td>Intersection values over 51.5 metres</td>
<td>2.44 (4E)</td>
<td>–</td>
<td>–</td>
<td>153.6</td>
</tr>
<tr>
<td><strong>RIVER VALLEY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dana Lake</td>
<td>Pacific North West Capital</td>
<td>Measured</td>
<td>2.2 (3E)</td>
<td>0.02</td>
<td>0.13</td>
<td>4.1</td>
</tr>
</tbody>
</table>

3E = Pt+Pd+Au; 4E = Pt+Pd+Rh+Au

Data here are compared with those from the Sheba's Ridge deposit (E. Bushveld) and Portimo, Koillismaa and River Valley examples. Koillismaa information taken from Iljina (2004) data CD-ROM and the other examples from published company Annual Reports and/or press releases.
TABLE 4-3. Ni, Cu, S, PGE AND Au CONCENTRATIONS OF SOME CONTACT-STYLE PGE DEPOSITS IN THE TORNIO-
NÄRÄNKÄVAARA BELT.

<table>
<thead>
<tr>
<th>Portimo Layered Igneous Complex</th>
<th>Ni (wt.%)</th>
<th>Cu</th>
<th>S</th>
<th>Pt (ppm)</th>
<th>Pd</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Konttijärvi marginal series A (5)</td>
<td>0.056</td>
<td>0.239</td>
<td>0.323</td>
<td>1.3</td>
<td>4.07</td>
<td>0.24</td>
</tr>
<tr>
<td>B</td>
<td>6.1</td>
<td>25.9</td>
<td>35.0</td>
<td>141</td>
<td>441</td>
<td>26</td>
</tr>
<tr>
<td>D</td>
<td>5.4</td>
<td>14.4</td>
<td>36.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ahmavaara, massive B</td>
<td>2.00</td>
<td>0.719</td>
<td>25.8</td>
<td>1.51</td>
<td>11.0</td>
<td>0.104</td>
</tr>
<tr>
<td>sulfides D</td>
<td>2.7</td>
<td>2.4</td>
<td>37</td>
<td>2.12</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>Vaaralampi, massive B</td>
<td>0.284</td>
<td>0.143</td>
<td>23.3</td>
<td>–</td>
<td>0.485</td>
<td>0.005</td>
</tr>
<tr>
<td>sulfides D</td>
<td>0.94</td>
<td>0.63</td>
<td>37</td>
<td></td>
<td>0.820</td>
<td>0.009</td>
</tr>
<tr>
<td>Koillismaa Layered Igneous Complex</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murtolampi marginal series C</td>
<td>0.128</td>
<td>0.193</td>
<td>0.541</td>
<td>0.33</td>
<td>0.60</td>
<td>0.01</td>
</tr>
<tr>
<td>D</td>
<td>10.6</td>
<td>17.0</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haukiaho, massive sulfides C</td>
<td>0.223</td>
<td>0.357</td>
<td>0.819</td>
<td>0.16</td>
<td>0.43</td>
<td>0.19</td>
</tr>
<tr>
<td>D</td>
<td>10.1</td>
<td>16.1</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A, Average of selected type samples (n=number of samples); B, concentrations in the type samples, recalculated to 100% sulfide; C, metal concentrations in a large number of samples and D, metal concentrations in a large number of samples, recalculated to 100% sulfide. Portimo data from Iljina (1994) and Koillismaa calculated from the data CD-ROM Iljina (2004). In Murtolampi cut-off 0.7 ppm 2PGE+Au was used.

TABLE 4-4. PERCENTAGES OF PGM IN VARIOUS HOST MINERALS IN SOME PORTIMO DEPOSITS

<table>
<thead>
<tr>
<th>Deposit</th>
<th>su</th>
<th>su/si</th>
<th>si</th>
<th>ox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Konttijärvi marginal series, n=54</td>
<td>19</td>
<td>8</td>
<td>49</td>
<td>27</td>
</tr>
<tr>
<td>Ahmavaara disseminated sulfides, n=42</td>
<td>39</td>
<td>32</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>Ahmavaara massive sulfides, n=14</td>
<td>50</td>
<td>29</td>
<td>21</td>
<td>0</td>
</tr>
</tbody>
</table>

su: sulfides only; su/si: sulfide/silicate margins; si: silicates only; ox: oxides; n, number of identifications. (from Iljina 1994).

massive nature of base metal sulfides, the proportion of PGM in the interstitial silicate is rather large (21%, Table 4-4).

The massive pyrrhotite deposits show relatively low PGE values with the maximum Pt + Pd normally reaching a few ppm. PGE concentrations are, however, much higher in the Ahmavaara deposit, attaining a level of 20 ppm (Figs. 4-6 and 4-8), which is similar to the disseminated Ahmavaara sulfide mineralization.

Table 4-3 shows some representative element contents and ratios for the Portimo mineralizations. Konttijärvi and Ahmavaara are both examples of the higher PGE tenor marginal series and Vaaralampi is taken to represent the lower PGE tenor marginal series. Contrary to the fact that copper generally dominates over nickel, the Ahmavaara massive sulfide dykes are nickel-dominated. Despite this, the disseminated sulfides in Ahmavaara are copper-dominated and the PGE show low correlation with the modal amounts of sulfides (Iljina 1994). In a way, the base metal sulfide and PGE mineralizations superimpose each other.
**Correlation of Portimo and Penikat Complexes**

Figure 4-10 shows the stratigraphic correlation of the Portimo Complex intrusions and the nearby Penikat Intrusion. The correlation was made by taking the boundary between the two parental magmas as a reference height. An interesting observation is that in this interpretation the Sompujärvi Reef of the Penikat Intrusion, the Siika-Kämä Reef of the Narkaus Intrusion, and the high-PGE grade marginal series of the Konttijärvi and Ahmavaara plot on the same stratigraphic level (Lahtinen et al. 1989; Iljina 1994).

**Haukiaho and Murtolampi Sulfide–PGE Deposits, Koillismaa**

The Western Intrusion of the Koillismaa Layered Igneous Complex (KLIC, Fig. 4-1) is the third intrusion of the TNB where the thick border zone is encountered in addition to the Suhanko and Konttijärvi intrusions. The interaction between the felsic footwall gneisses and mafic magma is even more pronounced in the KLIC than in most places below the Konttijärvi or Suhanko Intrusions. In the Koillismaa area, the footwall rocks are pervasively recrystallized into albite–quartz rocks, sometimes up to few hundreds of metres below the basal contact of intrusion, and the marginal series is also thicker on average and attains a few hundreds metres. A full description of the KLIC stratigraphy is given by Alapieti (1982) and the structural development and mineralization are described by Iljina et al. (2001) and Iljina (2004).

The PGE–sulfide precipitation has taken place throughout the entire strike length (>100 km) of the marginal series. However, the northernmost blocks, Kaukua and Murtolampi, have a higher PGE tenor, although with a slightly lower base metal content compared with the other intrusion blocks to the south of them (Iljina 2004). Fig. 4-11 shows a drilling profile through the Murtolampi marginal series, and Tables 4-3 and 4-2 gives metallogenic data on the Haukiaho and Murtolampi marginal series. Compared to Suhanko and Konttijärvi, the Murtolampi PGE concentrations are lower but the base metals are in about the same order. The Haukiaho example (Table 4-3) represents a more base-metal-enriched marginal series. Koillismaa marginal series is also unique in having a Pt/Au ratio close to one, however, this does not include Murtolampi, which has higher PGE/Au ratio and low absolute Au concentrations. The PGM and their distribution within silicates and sulfides resemble those of the Konttijärvi and Ahmavaara sulfide disseminated marginal series (Kojonen & Iljina 2001).

**BUSHVELD COMPLEX**

**Platreef, Northern Bushveld**

The Platreef is probably the largest PGE resource in the world. It extends for over 100 km and ranges in thickness from 50 to 200 m. The dip is variable, around 40° to the west, and has been intersected by drilling at 1400 m below the surface. The sequence is at present the focus of intense exploration (Table 4-2). It is also where the largest one of the three PGE open pit mines in the world is located (Potgietersrus, Lac des Iles, and Ngezi) and operated by Anglo Platinum. Two pits at Potgietersrus, Sandsloot and Zwartfontein, are mined at a rate of 48 million tonnes per annum.
The term Platreef is an informal stratigraphic name for a PGE–sulfide deposit hosted at the margin of the Bushveld Complex, in the northern limb of the complex (Figs. 4-12 and 4-13). The name appears to have originated in the 1960s when the South African mining company Johannesburg Consolidated Investments were exploring the area. Van der Merwe (1976) proposed the use of the term Platreef in analogy with the term Platinum Horizon used by Wagner (1929).

Sedimentary rocks of the 2.2–2.5 Ga Transvaal Sequence and Archean granites comprise the floor rocks of the Platreef. This has a transgressive contact progressively cutting older sedimentary rocks and eventually the granite from south to north. The Platreef is overlain by Main Zone gabbro and Upper Zone ferrogabbro.
The sedimentary rocks are quartzite, shale (carbonaceous in places), iron formation, and dolomite. The thermal metamorphic aureole of the Bushveld Complex was created in two stages, indicating a multiple magma intrusion (Nell 1985). The first event indicates a pressure of about 1.5 kb and temperatures up to 750°C, during which most of the water in the sedimentary rocks was driven off, but the temperature was not high enough to cause partial melting. In the second stage, the estimated pressures were between 4 and 5 kb, and the maximum temperatures attained were 850° to 900°C. Nell (1985) attributed the first event to the intrusion of Lower Zone magma, now preserved as pyroxene-
PGE deposits in the marginal series of layered intrusions

Fig. 4-13. Geological Map of the Potgietersrus limb, Northern Bushveld Complex.

Platreef stratigraphy

Gain & Mostert (1982) demonstrated that the Platreef consists of a complex assemblage of norite, pyroxenite, serpentinite, and xenoliths of floor rock dolomite. The Platreef is about 250 metres thick, between the underlying floor rocks and the overlying Main Zone gabbro and norite.

An informal stratigraphic zoning to the Platreef pyroxenite was devised and has been in use since the 1980s. The sequence is subdivided into three zones (Buchanan 1988) termed, from the base up, 'A reef', 'B reef', and 'C reef'. Broadly these divisions correlate with the metal zoning in the reef, with 'B reef' being the main carrier of economic mineralization. 'A reef' is erratically mineralized and 'C reef' is usually barren. The zoning was originally defined to give datum marks for the application of geostatistical modeling and resource estimation of the deposit. The internal geochemical and mineral compositions also broadly correlate with this zoning, though it is not consistent along the strike, in particular the upper 'C zone' pyroxenite, which is in many places absent.

'A reef' is coarse-grained feldspathic pyroxenite in which pyroxene and feldspar form aggregates that give the drill core a patchy appearance which can also be seen when the rock is exposed in mining operations. Orthopyroxene is iron-rich compared to that in the overlying 'B reef'. This basal compositional reversal could constitute a stratigraphic marker in the initial phases of exploration for margin-hosted sulfide.

'B reef' is medium-grained feldspathic pyroxenite with an even texture. In proximity to metasedimentary xenoliths there is serpentinitization and a coarsening of the rock. This sequence is consistently sulfide-bearing. This is the main ore zone of the Platreef.

'C reef' pyroxenite is fine- to medium-grained feldspathic pyroxenite. Pyroxene composition is similar to that in the B reef, but the whole-rock Cr is higher.
**Platinum-group minerals**

Kinloch (1982) observed the PGM trends in the Platreef. Vertical trends in a 200 m thickness of the Platreef show statistically significant amounts of platinum-group sulfides near the footwall contact, whereas, when present, platinum-group alloys occur towards the hanging wall contact. Pd alloyed with Sn, Sb, Bi, and Te minerals, as well as Pt–Fe alloys, occur in significant quantities in the Zwartfontein area of the Platreef. Platinum-group sulfides are the dominant minerals to the south of Zwartfontein. Armitage *et al.* (2002), however, reported the Platreef to be devoid of PGE sulfides in mineralized footwall lithologies and they found this to be also the case at the Platreef proper at the Sandsloot area. The PGM identified comprise high temperature metal (Pt–Fe, Pt–Sn) and semi-metal alloys (Pt, Pd arsenides), and a dominant assemblage of lower temperature semi-metals and alloys.

**Inter-relationship of metals**

The sulfide distribution is heterogeneous and rarely exceeds 5 per cent of the mode. The sulfides generally occur as droplets within the silicate grains or as irregular blebs up to 30 mm across between the silicates. The lower part of the reef is dominated by pyrite, monoclinic pyrrhotite, pentlandite and chalcopyrite, whereas in the upper Platreef the assemblage is hexagonal pyrrhotite, pentlandite, and chalcopyrite (± cubanite). Variation in the composition of the base metal sulfide minerals indicates a change from a sulfur rich to a sulfur poor (or metal rich) environment during the crystallization of the Platreef. There is an upward decrease in the Ni/Cu ration and the Pt/Pd ratio. Nickel and Cu tend to be strongly correlated. Correlation of PGE and S is only moderate.

The proportions of the precious metals in the Platreef are illustrated in the pie chart (Fig. 4-14), representing 200 data points. Platinum and palladium are generally well correlated but with scatter, possibly brought on by later stage redistribution. There is also a general relationship between the base metals and Pt and Pd, but with considerable scatter (Fig. 4-15). A detailed description of Platreef metal ratios is given by Mostert (1982).

**Isotope studies on the Platreef**

As indicated in the studies summarized below, the Platreef has evidence of crustal contamination. It appears that this has occurred in at least two stages. The sulfide and cumulus mineral component has an overall crustal imprint, possibly due to an interaction with crust in an intermediate staging magma chamber. This is overprinted by the local interaction with floor rocks at the site of emplacement, and with the later circulation of hydrothermal fluids. This last event accounts in part for the de-coupling of sulfur and PGE, noted earlier.

Sulfur isotope data from the Platreef show a range of δ^{34}S values, from 0 to +2 up to as much as +6 to +10 close to or at the contact with dolomite xenoliths. These higher values have led to the suggestion that the sulfide liquation in the Platreef was directly associated with local contamination from floor rocks (Buchanan & Rouse 1984). More recently, δ^{34}S values of 4.8–5.6 have been reported from chalcopyrite and values of 4.5–5.3 from pyrrhotite of the Platreef, suggesting a crustal component within the sulfides (Sharman-Harris & Kinnaird 2004). That magmatic and near magmatic δ^{34}S values (0 – +2) are recorded in the Platreef where the floor rock is granite, and there appears to be little magmatic interaction with floor, suggests contamination was a local imprint, and may not be the cause of sulfide liquation.

Re–Os systematics on sulfides of the Platreef from a single bore hole yield an isochron with a Re–Os age of 2011 ± 50 Ma and an initial $^{187}$Os/$^{188}$Os value of 0.226 ± 0.021, which corresponds to the accepted age of the Bushveld Complex of ~2050 Ma. The initial Os ratio suggests that the source of the Os in the sulfides has a strong crustal component, possibly in an intermediate magma chamber within the crust (Ruiz *et al.* 2004).
Oxygen isotope studies show that the Upper and Main Zones in the Platreef area are crystallized from a well-mixed contaminated magma, and that higher δ^{18}O values in the Platreef indicate the addition of dolomite country rocks (Harris & Chaumba 2001).

Geochemical profiles for Rb and Sr isotope ratios through the Platreef and the overlying Main Zone show differences depending on the footwall composition. Where granite is the floor rock, the initial ^{87}Sr/^ {86}Sr ratio of the Platreef ranges from 0.7107 to 0.7226. For dolomite footwall there is a lower initial ratio of 0.7054 to 0.7147. Orthopyroxene has a much lower initial ratio than the whole-rock, indicating that this cumulus phase formed prior to contamination. It is also inferred that the separation of sulfide liquid predated the main contamination process (Cawthorn et al. 1985 and Barton et al. 1986). Widespread reaction of Platreef intercumulus melt with floor rock-derived fluids and dolomite xenoliths had presented obstacles in determining the nature of “uncontaminated” Platreef. Lee et al. (1989) sampled a sequence from an area of Platreef inferred to be unaffected by xenoliths or close to granite but with floor rock composed of cordierite hornfels. A lower facies of the Platreef gave whole-rock Mg number in the range 0.72–0.75, and an upper facies with an Mg range of 0.77–0.82. Whole-rock Sr isotope ratios (R_{Sr}) range from 0.7069–0.7087; the higher values correlate with higher PGE and higher Mg number in the upper facies. The role of contamination was deemed to be insignificant.

**SHEBA’S RIDGE, EASTERN BUSHVELD COMPLEX**

In the Western and Eastern Bushveld Complex, the cumulate rocks of the Lower and Critical Zones are isolated from the floor rocks by the marginal zone. This zone is norite in composition; pyroxene is around En_{80}, compared to the En_{80} of the overlying cumulates. In places, the texture resembles that of the ’A reef’ of the Platreef. Despite several exploration endeavors, no margin-hosted sulfide or sulfide-PGE sequence has been identified in the Eastern or Western Bushveld Complex, except for Sheba’s Ridge, which is located in an enclave of Bushveld rocks close to the town of Groblersdal (Fig. 4-12).
The Sheba's Ridge occurrence was first explored about 25 years ago, as a result of soil geochemical surveys in the vicinity of a vein-hosted Cu occurrence. The margin-hosted sulfide deposit of Sheba’s Ridge is presently being evaluated as a potential open pit Ni mine with PGE credits (Sharpe et al. 2002). It is a stratabound mineralized sequence and analogies with the Platreef proper have been made.

The base metal sulfide is blebby to disseminated in texture within a medium-grained feldspathic pyroxenite. The sulfide occurs as irregular blebs 1 to 5 mm in size. The major sulfides are pyrrhotite (10 to 20%), pentlandite (5 to 30 %), and chalcopyrite (60 to 70%). The pentlandite also occurs as an exsolution product of pyrrhotite. Occasional small blebs of covellite were also noted. Chalcopyrite and pentlandite tend to occur as the large dominant grains, with pyrrhotite locked in pentlandite. Most of the fine-grained, interstitial sulfide is chalcopyrite. The PGM are dominantly semi-metal alloys.

The mineralization is located close to, but not at, the contact with hornfelsed metasedimentary rocks. A chilled margin is present. The Sheba's Ridge sulfide envelope is defined on grade and continuity into a lower grade sulfide zone, bounding the contiguous sulfide 'Main Sulfide Zone' (Fig. 4-16). For a Main zone modelled thickness of 45 metres, the average whole-rock Ni is 0.22% and Cu is 0.08%. Pt+Pd+Au is on average 0.94 g.t⁻¹, and ranges up to contiguous blocks of 1–4 g.t⁻¹ (see Table 4-2) The Pt/Pd ratio is 0.5, making the sequence the most Pd-dominant in the Bushveld Complex. Preliminary S isotope results give δ³⁴S values of 1–2 for sulfide in the pyroxenite, and around 12 for sulfide in the floor rock metasedimentary rock. This appears to preclude significant floor rock contamination and sulfur addition as a control on the sulfide mineralization.

**EAST BULL LAKE INTRUSIVE SUITE**

Intrusions of the ca. 2480 Ma East Bull Lake Intrusive Suite (EBLIS) occur as an east-west-trending belt along the boundary (Fig. 4-17) of Archean and the Proterozoic provinces (Vaillancourt et al. 2002; Easton et al. 2004), Ontario, Canada, similar to the TNB intrusions in Fennoscandia. Common features of EBLIS and TNB also include the geotectonic location within the intracontinental rift zone, bimodal magmatism and crystallization from low-Ti, moderate to high-MgO, possibly PGE-enriched parental magmas. Intrusions of EBLIS are characteristically gabbroic,
PGE DEPOSITS IN THE MARGINAL SERIES OF LAYERED INTRUSIONS

Fig. 4-17. Location of Palaeoproterozoic East Bull Lake Intrusive Suite (EBLIS) complexes. Modified after Peck et al. (1995) and James et al. (2002).

even rather leucocratic, and ultramafic portions are insignificant, in contrast to the Fennoscandian intrusions as well as the Bushveld Complex. Sulfide–PGE mineralization has been documented to have taken place in many of the EBLIS intrusions and we present two examples in this paper, namely the East Bull Lake and River Valley contact-style enrichments.

Figure 4-18 compares the igneous stratigraphy of five EBLIS intrusive bodies, and it also shows the positions of the mineralized zones. The lower portions of each intrusion are made up of a heterogeneous zone of breccias that is several tens of metres thick and other structures indicative of extensive interaction between mafic magma and the footwall gneisses (Fig. 4-19). In its lower part this so-called inclusion-bearing zone, also called marginal zone or border zone, contains higher amounts of footwall xenoliths, whereas the proportion of mafic xenoliths increases upwards as the footwall material disappears. All this suggest a vigorous intrusion event in which successive magma injections disrupted previously crystallized material from the intrusion margins and prevented the preservation of chilled margins.

The ferromagnesian silicate minerals become more magnesian upwards within the marginal series as the Fo of olivine rises from 68 to 72–76 and the En of orthopyroxene from 44–69 to 55–69 (James et al. 2002), which corresponds with the pattern of Sheba's Ridge in the Bushveld Complex.

PGE–sulfide mineralization is erratically distributed within the lowermost, ca 100 m, rock units. The most favorable rock unit for the sulfide–PGE precipitation has been the inclusion-bearing or breccia zone. Fig. 4-20a demonstrates the lithological interpretation and precious metal concentrations in drill holes through the mineralized lower part of the East Bull Lake Intrusion. The Cu+Ni concentrations in the intersections shown are <0.5 wt.%, with variable Cu/Ni ratios. Fig. 4-20b gives corresponding information from the River Valley Intrusion/Dana Lake prospect, which shows a higher concentration tenor compared with East Bull Lake. The individual intersections of East Bull Lake and River Valley are comparable to many of the Konttijärvi and Ahmavaara ones, but the tonnages are much below those of the Finnish examples (Table 4-2).

James et al. (2002) reported that the PGM assemblage is made up of six Pd-Te(-Bi), Pd-Bi, Pd-As(-Sb) mineral species and two platinum mineral species, sperrylite (Pt-As) and platarsite (Pt-As-S). This mineralogy closely resembles that of Konttijärvi and Ahmavaara.
Se/S RATIO

Selenium is a chalcophile element, which geochemically tends to follow sulfur and frequently occurs in sulfides, replacing sulfur. The estimated $(\text{Se}/\text{S}) \times 10^6$ ratios in the mantle are in the range of 230 to 350 and a typical ratio in crustal rocks is lower, and generally less than 100 in clastic sedimentary rocks. Selenium is also thought to be less soluble and mobile than sulfur, especially in oxidizing environments. The partitioning coefficient for selenium between sulfide and silicate melts is of the order of $10^3$ (Peach et al. 1990). The Se/S ratio has also been used alongside the sulfur isotope composition as a guide when estimating the source of the sulfur in magmatic Cu–Ni–Fe deposits.

The sulfides in the PGE-rich reefs within the Bushveld and Stillwater Complexes turned out to have Se/S ratios well above the mantle range, and Paktunc et al. (1990) concluded that the pentlandite, chalcopyrite and pyrrhotite in the Merensky and UG2 Reefs and the Platreef tended to have higher Se/S ratios than are found in the reefs of lower grade PGE elsewhere in the Bushveld intrusion or in many other massive to disseminated sulfide deposits low in PGE. Hattori et al. (2002) concluded that high Se/S ratios are characteristic features of boninitic high-MgO second stage melts; the magma type proposed for the Bushveld and Portimo Complexes, for example.
Within the Portimo Complex, mineralization types with higher PGE tenor tend to have higher Se/S ratios at a given S content (Iljina 1994). Figure 4-21 depicts Se/S versus whole-rock sulfur of the various mineralization types of the Portimo Complex. It is worth mentioning that high Se/S versus S describes the likelihood of a particular mineralization type to have a higher PGE tenor, i.e., the results suggest that the high Se/S versus S value is an indication of a higher tenor PGE and points to the higher economic potential of the mineralization encountered in the exploration. Within the Portimo Complex, economically more viable PGE mineralization types seem to have a Se/S*10^6 ratio 300–1,500 at low whole-rock sulfur (disseminated sulfides) content. In more massive sulfides the ratio drops to ca 200. Correspondingly mineralization types of lower economic potential have lower Se/S ratios and the ratio seems to drop more steeply with increasing sulfide content.

Figure 4-7 depicts the variation of copper, precious metals and Se/S ratio in one representative drill hole of the Konttijärvi marginal series. Whole-rock PGE seems to have a good correlation with...
copper, Se and Se/S. At the depth of approximately 170 m, PGE drops and so do the elements and the ratio mentioned. The copper-deficient sulfide mineralization seems to continue further away from the intrusion. Further downhole, the PGE kick associated with the high alkali dyke is accompanied by elevated Cu, Se and Se/S, but these components do not correspond to the higher S peak closer to the end of the hole.

Reported Se/S*10^6 values for East Bull Lake and River Valley are within the range of mantle-derived sulfides of 350–800 (Easton et al. 2004) for the former and 470–2,000 (James et al. 2002) for the latter. In the case of East Bull Lake, the whole-rock PGE, Se and Se/S ratio have a strong positive correlation resembling the situation of the Portimo Complex.

CONCLUSIONS

The following concluding remarks can be made on the basis of the features described above.

- The marginal series hosted, 'contact-style' PGE deposits are generally zones which are tens of metres wide and have developed at the base or sides of mafic layered intrusions. They are also erratic in nature and in individual drill holes the highest PGE values can be found tens of metres above or below the contact of the intrusion; they are also variable along the strike.
- The contact-type mineralizations are typically base metal sulfide bearing, often enriched in copper, but Ni is dominant in the case of the Platreef and Sheba’s Ridge.
- The PGE concentrations are lower than in the reef-type deposits and the exploitability is based on the huge tonnages. These features lead to a broad geophysical signature and the possibility of using elements like copper, nickel and sulfur as pathfinders in geochemical exploration.
- The PGM assemblage is dominated by the low temperature assemblages of Pd–As, Pd–As–Sb, Pd–Bi–Te and Pt–As minerals, with the sulfides and Fe-alloys being rarer. This mineralogy differs from that of the UG2 and Merensky Reefs of the Bushveld Complex. However, the mineral paragenesis is metamorphic in most cases and may not necessarily correspond to the primary assemblage.

Contact-style PGE enrichments seem to be related to an areally larger igneous event, but the size of the hosting intrusion is not necessarily the unambiguous requirement. Sheba’s Ridge is hosted by a pyroxenitic to melanoritic ‘marginal zone’, which is probably a separate intrusion phase, which predates the Lower, Critical and Main Zone phases of the Bushveld Complex. Although elsewhere in the Bushveld Complex it is unmineralized, the body has Ni–Cu–PGE-enriched sulfides at Sheba’s Ridge; the genesis of the sulfide formation is unclear, but the local structures of the igneous body may have played a role in the genesis.

The key conclusion is that the host rocks of contact-style PGE deposits are characterized by extensive and prolonged interaction of mafic magma with the surrounding host rock. This results in thick marginal zones, which also show compositional reversals in modal mineralogy and mineral chemistry. The absolute PGE contents and relative PGE content over the base metals vary in the examples described of which the Platreef and Portimo stand as more highly and particularly more pervasively mineralized. The involvement of more than one magma type and/or sequential magma pulses may favor Platreef and Portimo-grade PGE-enriched base metal sulfide mineralization.

The applicability of Se/S ratios have not been widely enough tested and the results quoted here are tentative. The results, however, suggest selenium should be included in the rock geochemical exploration package and the Se/S
ratios ought to be considered when the significance of the first findings is evaluated.

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