Ore deposits related to mafic igneous rocks – PGE’s

- GLY 361 –
Lecture 2
Ore deposits related to mafic igneous rocks

- Ores commonly associated with mafic rocks include:
  - Platinum Group Elements (PGE’s)
  - Chromite
  - Ilmenite
  - Nickel
  - Copper (Carbonatites)
  - Diamonds (Kimberlites)
Ore deposits related to mafic igneous rocks

- Examples for PGE’s
  - Platinum (Pt)
  - Rhodium (Rh)
  - Palladium (Pd)
  - Rhuthenium (Ru)
  - Osmium (Os)
  - Iridium (Ir)
Platinum Group Minerals

PGE’s are often hosted in sulphides as trace elements, but also form their own sulphide minerals when their concentrations are high enough.

Important minerals:
- Cooperite – PtS
- Laurite – RuS
- Pentlandite – (Ni, Fe)$_9$S$_8$
- Braggite – (Pt, Pd)S
Ore deposits related to mafic igneous rocks

- **Uses**
  - Catalyst for air pollution abatement in both light and heavy duty vehicles.
  - **Chemical sector:**
    - Catalyst for manufacturing of bulk chemicals such as nitric acid
    - Petroleum refining and fabrication of laboratory equipment
  - **Electronics sector:**
    - Used in computer hard disc, multilayer ceramic capacitors and hybridized integrated circuits
  - **Glass manufacturing sector:**
    - Production of fiberglass, liquid crystal displays and flat panel displays
Ore deposits related to mafic igneous rocks

• Uses
  – Platinum alloys
    • Used in jewellery
  – Pt, Pd and variety of complex Ag-Au-Cu alloys are used as dental restorative material
  – Pt is a catalyst used in fuel cells to convert H and O to electricity
## Ore deposits related to mafic igneous rocks

### World Mine production

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>United States</td>
<td>3,700</td>
<td>3,700</td>
<td>12,400</td>
<td>12,200</td>
<td>900,000</td>
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<tr>
<td>Canada</td>
<td>7,000</td>
<td>6,500</td>
<td>14,000</td>
<td>13,000</td>
<td>310,000</td>
</tr>
<tr>
<td>Colombia</td>
<td>1,230</td>
<td>660</td>
<td>NA</td>
<td>NA</td>
<td>(6)</td>
</tr>
<tr>
<td>Russia</td>
<td>25,000</td>
<td>26,000</td>
<td>86,000</td>
<td>82,000</td>
<td>1,100,000</td>
</tr>
<tr>
<td>South Africa</td>
<td>145,000</td>
<td>128,000</td>
<td>82,000</td>
<td>72,000</td>
<td>63,000,000</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>10,600</td>
<td>11,500</td>
<td>8,200</td>
<td>8,900</td>
<td>(9)</td>
</tr>
<tr>
<td>Other countries</td>
<td>2,500</td>
<td>2,500</td>
<td>12,200</td>
<td>12,000</td>
<td>800,000</td>
</tr>
<tr>
<td>World total (rounded)</td>
<td>195,000</td>
<td>179,000</td>
<td>215,000</td>
<td>200,000</td>
<td>66,000,000</td>
</tr>
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</table>

### World Resources

*World Resources:* World resources of PGMs in mineral concentrations that can be mined economically are estimated to total more than 100 million kilograms. The largest reserves are in the Bushveld Complex in South Africa.

Source: USGS, 2013
• Boom starting in late 90s due to emerging marked in BRIC countries and former Yugoslavia.

• Credit crunch and sovereign debt crisis in 2008.
Ore deposits related to mafic igneous rocks

- Range from largest, most extensive igneous petrologic systems in the world (e.g., Bushveld Complex) down to moderate-sized bodies like carbonatites.

- **Magmatic segregation deposits:**
  - formed in intrusive bodies
  - ore deposits formed during fractional crystallisation

- **Exceptions:**
  - pegmatites, porphyry base-metal deposits, and other ores that involve hydrothermal transport.
Ore deposits related to mafic igneous rocks

- **Layered mafic intrusions**

- **Formed of layered mafic-ultramafic cumulates** (chromitite, harzburgite, pyroxenite, norite)
  - Major sources for:
    - PGE’s, Chromium, Nickel, Copper, Titanium, Iron, Vanadium, Tin, Sulfur as by-product

- **Related to anorthosites (monomineralic plagioclase bodies):**
  - contain titanium orebodies as rutile, ilmenite, and titanomagnetite.
Ore deposits related to mafic igneous rocks

- Examples of layered intrusions with PGE’s
  - Bushveld (RSA), 2.06 Ga – 60,388 t at 8.27 ppm
  - Stillwater (USA), 2.7 Ga – 1057 t at 22.3 ppm
  - Great Dyke (Zimbabwe), 2.6 Ga – 7892 t at 4.7 ppm
  - Norilsk-Talnakh (Russia), 0.25 Ga – 6200 t at 3.8 ppm
  - Sudbury (Canada), 1.8 Ga - 217 t at 0.9 ppm
Ore deposits related to mafic igneous rocks

• Bushveld Complex
  – 80% of world’s reserves of Pt.
  – 60% of the world’s reserves of Pd.
  – 80% of world’s production of Pt, and 40% of world’s production of Pd.
  – also world’s biggest supplier of ferrochrome, and a big supplier of V and Ti.
Ore deposits related to mafic igneous rocks

- Bushveld Complex
Ore deposits related to mafic igneous rocks

- Bushveld Complex

Kinnaird, 2005
Ore deposits related to mafic igneous rocks

<table>
<thead>
<tr>
<th>Group</th>
<th>Formation</th>
<th>Main lithologies</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loskop</td>
<td>Red shale, sandstone, conglomerate</td>
<td>0-1000</td>
<td></td>
</tr>
<tr>
<td>Schrikkloef</td>
<td>Rhyolite</td>
<td>200-3000</td>
<td></td>
</tr>
<tr>
<td>Kwaggasnek</td>
<td>Rhyolite, shale</td>
<td>500-2500</td>
<td></td>
</tr>
<tr>
<td>Damwal</td>
<td>Dacite, rhyolite</td>
<td>1000-2500</td>
<td></td>
</tr>
<tr>
<td>Dullstroom</td>
<td>Basalt to rhyolite</td>
<td>Up to 2000</td>
<td></td>
</tr>
<tr>
<td>Rayton</td>
<td>Quartzite, shale</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>Magaliesberg</td>
<td>Orthoquartzite</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Silverton</td>
<td>Black shale</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Dasport</td>
<td>Orthoquartzite</td>
<td>80-95</td>
<td></td>
</tr>
<tr>
<td>Strubenkop</td>
<td>Quartzite, shale</td>
<td>105-120</td>
<td></td>
</tr>
</tbody>
</table>

Lenhardt and Eriksson, 2012
Simplified geological map of the Bushveld Complex showing the location of the major platinum, chromite and vanadium mines.
Ore deposits related to mafic igneous rocks

• RLS forms ~6.5 km thick layers of cumulates of mafic-ultramafic rocks:
  – Magnetite-bearing gabbros and ferro-diorites
  – Gabbronorites
  – Norites
  – Harzburgites
  – Orthopyroxenites

Layering of pyroxenites, harzburgites and norites
Ore deposits related to mafic igneous rocks

"Stratigraphic" units in the Eastern Belt of the BIC. These units are cut by the

<table>
<thead>
<tr>
<th>Lower Zone</th>
<th>Critical Zone</th>
<th>Main Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal Subzone</td>
<td>Transition Zone</td>
<td>Main Norite Zone</td>
</tr>
<tr>
<td>Lower Bronzilite</td>
<td>Lower</td>
<td>1985: Harzburgite or hornblende</td>
</tr>
<tr>
<td>Harzburgite Subzone</td>
<td>Upper</td>
<td>1775: Harzburgite breccia with pyroxenite</td>
</tr>
<tr>
<td>Up. Bz.</td>
<td>Critical Zone</td>
<td>Anorthosite Series</td>
</tr>
<tr>
<td>Pyroxenite Series</td>
<td>Lower</td>
<td>2500</td>
</tr>
<tr>
<td>Anorthosite Series</td>
<td>Upper</td>
<td>850</td>
</tr>
</tbody>
</table>

**Table 9.1: Thicknesses and Lithologies of Zones in the Bushveld Igneous Complex**

<table>
<thead>
<tr>
<th>Older Zone</th>
<th>New Zone</th>
<th>Subzone Designations</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG-1</td>
<td>MG-2</td>
<td>MNP</td>
</tr>
</tbody>
</table>

Notes: m,n, and o: andesitic to dacitic inclusions.
Schematic N-S section through the Bushveld Complex illustrating the “half-graben” geometry and the importance of the Thabazimbi-Murchison Lineament as a structural feature. Note the increasing lateral extent of the different zones from the bottom up (Kruger, 2004).
Floating Felsite and Granophyre

Horizontal Roof contact

Exceptionally large single influx of a Fe-rich gabbroic magma. Rich in S.

Pyroxenite Marker

Unconformity

Very large influx of a significantly different magma with an evolved norite-gabbronite composition. Magma was cool & dense. Low in Cr and S.

Merensky Reef

Unconformity

Repeated influxes of a harzburgitic to noritic magma. Assimilation of roof-rocks causes chromitite precipitation. High in Cr & low in S.

Basal Intrusive Contact

Sills and minor harzburgitic to noritic intrusions. Dullstroom/Rooiberg age?

Differentiation stage

Fractional crystallization of initially homogenous magmas

Integration Stage

Multiple magma influxes

(a) Plot of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio vs. height in the stratigraphy from the western limb of the Bushveld Complex (from Kruger, 1994). (b) Plot of En and An of the layered rocks from De Wit & Kruger (1990). The same general trends are present in the eastern and western lobes of the Bushveld Complex.
PGE deposits in the RLS

- Primarily hosted in two horizons:
  - **UG2 chromitite layer** in the Upper Critical Zone
  - **Merensky Reef** between the Upper Critical Zone and the Main Zone
  - **Platreef** (Northern limb)

- Subeconomic concentrations in the Bastard Reef above the Merensky, and in the UG1 chromitite.

Simplified map of the Bushveld Complex showing generalized PGE grades for the Merensky Reef UG2 chromitite layer and Platreef.
The Merensky Reef (MR)

- The world’s most important source of platinum since exploitation commenced in 1928.
- Thickness: ca. 0.04-4 m (1 m average thickness)
- Extending along strike for > 280 km

- Generally composed of:
  - a pegmatoidal feldspathic pyroxenite
  - a thin basal chromitite stringer
  - anorthosite to norite footwall
  - mineralisation decreases from the basal chromitite stringer into the hangingwall and footwall.
The formation of the Merensky Reef

- MR has a mixed isotopic signature – the isotopic signatures from its pyroxenes and plagioclases do not match. Why?
- Three ideas:
  - Mixing of magmas – The reef represents a mixing zone between two different magmas.
  - Mixing of minerals – The Merensky is a cumulus rock in which minerals from different portions of the chamber have accumulated.
  - Metasomatic deposit – The mineralogy has been modified by metamorphism after formation.
Magma Mixing

• **Theory 1:**
  • Mixing of two magmas:
    – One primitive magma, high in MgO, FeO and with low isotopic ratios of Nd/Nd and Sr/Sr
    – One evolved magma, high in SiO$_2$ and with higher isotopic ratios
  • Evolved magma injected into a chamber with a residual primitive magma.
Magma Mixing

Figure 7.7. Behaviour of new magma influxes entering the magma chamber. The density ($\rho$) contrast between Resident magma (R) and the New magma (N) determines whether N settles at the top of the cumulates (case A), mixes with R (case B), settles on top of R (case D) or in the middle levels of R (case D). After Mathison (1991).
Schematic diagram of chromitite formation resulting from a fountain of magma into the chamber that partially melts roof rocks causing contamination and mixing (Kinnaird et al., 2002)
Model illustrating the introduction of a new Main Zone liquid which reacts with and erodes the Critical Zone crystal pile to form an unconformity. The new liquid precipitates the Merensky pegmatoid and pyroxenite (reef) on the unconformity.
Mixing of Minerals

• **Theory 2:**
  • Uniform magma mixing is difficult to achieve:
  • Differences in co-existing mineral populations.
  • The Reef therefore represents the injection of Main Zone magma into a Critical Zone mush, with no mixing.
  • Sulphides are then a product of the Main Zone magma.
Metasomatic Emplacement

• **Theory 3:**
  • Trace elements radically higher in pyroxenes of the MR than in the underlying footwall.
  • Major element compositions of minerals are identical.
  • Postulated that the trace elements (including PGE’s) were transferred to the MR by metasomatism.
Latest theory: Pressure variations in the MR (Cawthorn et al., 2004)

- Modification to Mineral Mixing model:
  - Magmas do not mix, Main Zone is injected into Critical Zone.
  - Merensky cyclic unit formed as the result of the introduction of 3 pulses of Main Zone magma (MZm) which displaced the resident Critical Zone magma.
  - Plagioclase was deposited from the new MZm, chromite and pyroxene settled from the displaced Critical Zone magma (Czm).
  - In different areas, cumulates from the earlier 2 pulses were either partially or completely eroded by the final pulse.
  - Localised pressure increases in the mixture lead to the formation of sulphide melt
  - PGE-enriched sulphides settled through the underlying cumulates from the overlying CZm to form the principal mineralisation.
The UG2 Layer

- UG2 (Upper Group 2) chromitite layer in the upper Critical Zone is probably the largest PGE resource on Earth.
- Thickness: ca. 0.5-1 m
- PGE's (as laurite) are interstitial to the chromite grains
- Formation like Merensky Reef?
- 3 sequences of mineralisation (A, B, C).
- Grade decreases upward in each cycle.

Data for Pt, Pd, and Pt/Pd in a very detailed profile through the UG2 chromitite from Western Platinum Mine (Cawthorn, 2004)
The Platreef

- Only in the northern limb.
- Thickness: 400 m thick in the S to <50 m in the N.
- Predominantly pyroxenitic (PGE-Cu-Ni-bearing package)
- Peridotites+norite cycles with anorthosite in the mid to upper portion.
The Platreef

- Complex zone of inter-fingered lithologies (no well-developed chromitite layering). Formation by several pulses of magma.
- Earliest intrusive phase (into Transvaal sediments) equivalent to Lower or Lower Critical Zone magmas (similar Cr/MgO ratios).
- Later pulses intruded into metasediments and earlier Platreef pulses.
- Primary sulphides and PGE’s were re-distributed by several later processes.

Anglo Platinum’s Sandsloot pit. The Platreef is being exploited for PGE, Cu and Ni. Transvaal metasedimentary rocks form the footwakk while Main Zone forms the hanging wall.
The Platreef

A. Excess liquid to lavas and intrusives, mostly eroded

- Early magma
- Accumulation of sulfides within intermediate chamber scavenging PGE

B. Lower Zone cumulates

- Major pulse of magma injects Platreef magma with pre-formed sulfides entrained within it

C. Platreef

- Lower Zone cumulates
- Main zone magma injected

Diagram notes:

- Main Zone
- Platreef
- Lower Zone
- Timeball Hill Fm
- Deutschland Fm
- Penge Fm
- Malmani Subgroup

- Archaean granite/gneiss basement

- Bushveld Complex
- Transvaal Supergroup

- Assimilation of footwall sulfide into Platreef magma
- Leaching of footwall sulfate by hydrothermal fluids

- Upgraded sulfide content in Turfspruit area
- Calc-silicate and hornfels xenoliths incorporated into Main Zone magma

Farm abbreviations:

- TL - Townlands, MC - Macalacaskop, TS - Turfspruit,
- TN - Tweefontein, SS - Sandsloot, ZN - Zwartfontein,
- OY - Overyssel, WR - Witrivier
Concluding remarks

- No consensus on key issues regarding:
  - The number, nature, volume and source of the different magma types
  - Tectonic setting for magmatism

- Three theories for formation:
  - Impact of a comet or asteroid (Rhodes, 1975; Elston, 1992), similar to Sudbury Complex, Canada.
  - Subduction associated with a nearby plate margin along the northern Kaapvaal edge Hatton (1988).
  - Interaction of a mantle-plume with the lithosphere (Sharpe et al., 1981).
Concluding remarks: The mantle plume theory

Figure 8.14. A mantle plume model (not to scale) for the emplacement of the Bushveld Complex. In stage 1, a mantle plume causes updoming of the crust and rifting, between 2.5 and 2.2 Ga; in stage 2, the plume's head spreads out at the lithosphere-crust boundary resulting in melting of the lower crust, continuing rifting and emplacement of the Bushveld felsic phase (Rooinberg felsite); in stage 3, between 2.1 and 2.05 Ga, mafic melts rise through the crust, resulting in two phases, first the intrusions of sills and then a series of magma influxes form the Rustenburg Layered Suite; finally in stage 4, perhaps around 1.9, the mafic melts of the Suite induce further melting of the crustal rocks, producing the Lebowa granite suite. Domal uplift follows, with renewed rifting and deposition of rocks of the Waterberg Group and associated continental flood basalts (see chapter 3, for details of the Waterberg Group). Modified from D. P. McKenzie in Coward and White (1988).