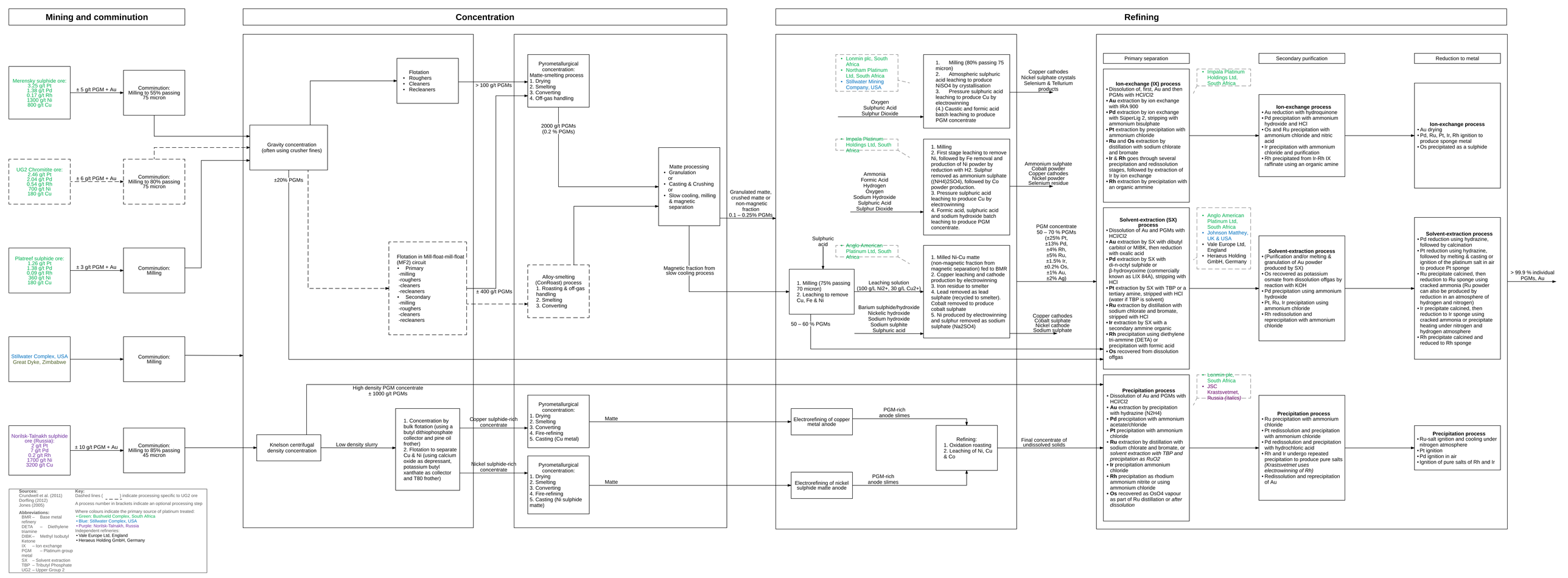
Mining and comminution
Concentration
Refining
Merensky sulphide ore:
3.25 g/t Pt
1.38 g/t Pd
0.17 g/t Rh
1300 g/t Ni
800 g/t Cu
± 5 g/t PGM + Au
Comminution:
Milling to 55% passing
75 micron
UG2 Chromitite ore:
2.46 g/t Pt
2.04 g/t Pd
0.54 g/t Rh
700 g/t Ni
180 g/t Cu
± 6 g/t PGM + Au
Comminution:
Milling to 80% passing
75 micron
Platreef sulphide ore:
1.26 g/t Pt
1.38 g/t Pd
0.09 g/t Rh
360 g/t Ni
180 g/t Cu
± 3 g/t PGM + Au
Comminution:
Milling
Stillwater Complex, USA
Great Dyke, Zimbabwe
Comminution:
Milling
Norilsk-Talnakh sulphide ore (Russia):
2 g/t Pt
7 g/t Pd
0.2 g/t Rh
1700 g/t Ni
3200 g/t Cu
± 10 g/t PGM + Au
Comminution:
Milling to 85% passing
45 micron
Gravity concentration
(often using crusher fines)
±20% PGMs
Flotation
• Roughers
• Cleaners
• Recleaners
> 100 g/t PGMs
Flotation in Mill-float-mill-float (MF2) circuit
• Primary
-milling
-roughers
-cleaners
-recleaners
• Secondary
-milling
-roughers
-cleaners
-recleaners
± 400 g/t PGMs
Pyrometallurgical concentration:
Matte-smelting process
1. Drying
2. Smelting
3. Converting
4. Off-gas handling
2000 g/t PGMs
(0.2 % PGMs)
Alloy-smelting (ConRoast) process
1. Roasting & off-gas handling
2. Smelting
3. Converting
Matte processing
• Granulation
or
• Casting & Crushing
or
• Slow cooling, milling & magnetic separation
Granulated matte, crushed matte or non-magnetic fraction
0.1 – 0.25% PGMs
Magnetic fraction from slow cooling process
High density PGM concentrate
± 1000 g/t PGMs
Knelson centrifugal density concentration
Low density slurry
1. Concentration by bulk flotation (using a butyl dithiophosphate collector and pine oil frother)
2. Flotation to separate Cu & Ni (using calcium oxide as depressant, potassium butyl xanthate as collector and T80 frother)
Copper sulphide-rich concentrate
Nickel sulphide-rich concentrate
Pyrometallurgical concentration:
1. Drying
2. Smelting
3. Converting
4. Fire-refining
5. Casting (Cu metal)
Matte
Pyrometallurgical concentration:
1. Drying
2. Smelting
3. Converting
4. Fire-refining
5. Casting (Ni sulphide matte)
Matte
Lonmin plc, South Africa
Northam Platinum Ltd, South Africa
Stillwater Mining Company, USA
Oxygen
Sulphuric Acid
Sulphur Dioxide
1. Milling (80% passing 75 micron)
2. Atmospheric sulphuric acid leaching to produce NiSO4 by crystallisation
3. Pressure sulphuric acid leaching to produce Cu by electrowinning
(4.) Caustic and formic acid batch leaching to produce PGM concentrate
Copper cathodes
Nickel sulphate crystals
Selenium & Tellurium products
Impala Platinum Holdings Ltd, South Africa
Ammonia
Formic Acid
Hydrogen
Oxygen
Sodium Hydroxide
Sulphuric Acid
Sulphur Dioxide
1. Milling
2. First stage leaching to remove Ni, followed by Fe removal and production of Ni powder by reduction with H2. Sulphur removed as ammonium sulphate ((NH4)2SO4), followed by Co powder production.
3. Pressure sulphuric acid leaching to produce Cu by electrowinning
4. Formic acid, sulphuric acid and sodium hydroxide batch leaching to produce PGM concentrate.
Ammonium sulphate
Cobalt powder
Copper cathodes
Nickel powder
Selenium residue
Sulphuric acid
Anglo American Platinum Ltd, South Africa
1. Milling (75% passing 70 micron)
2. Leaching to remove Cu, Fe & Ni
Leaching solution
(100 g/L Ni2+, 30 g/L Cu2+)
Barium sulphide/hydroxide
Nickelic hydroxide
Sodium hydroxide
Sodium sulphite
Sulphuric acid
50 – 60 % PGMs
1. Milled Ni-Cu matte (non-magnetic fraction from magnetic separation) fed to BMR
2. Copper leaching and cathode production by electrowinning
3. Iron residue to smelter
4. Lead removed as lead sulphate (recycled to smelter).
Cobalt removed to produce cobalt sulphate
5. Ni produced by electrowinning and sulphur removed as sodium sulphate (Na2SO4)
PGM concentrate
50 – 70 % PGMs
(±25% Pt,
±13% Pd,
±4% Rh,
±5% Ru,
±1.5% Ir,
±0.2% Os,
±1% Au,
±2% Ag)
Copper cathodes
Cobalt sulphate
Nickel cathode
Sodium sulphate
Electrorefining of copper metal anode
PGM-rich anode slimes
Electrorefining of nickel sulphide matte anode
PGM-rich anode slimes
Refining:
1. Oxidation roasting
2. Leaching of Ni, Cu & Co
Final concentrate of undissolved solids
Primary separation
Secondary purification
Reduction to metal
Ion-exchange (IX) process
• Dissolution of, first, Au and then PGMs with HCl/Cl2
• Au extraction by ion exchange with IRA 900
• Pd extraction by ion exchange with SuperLig 2, stripping with ammonium bisulphate
• Pt extraction by precipitation with ammonium chloride
• Ru and Os extraction by distillation with sodium chlorate and bromate
• Ir & Rh goes through several precipitation and redissolution stages, followed by extraction of Ir by ion exchange
• Rh extraction by precipitation with an organic ammine
Impala Platinum Holdings Ltd, South Africa
Ion-exchange process
• Au reduction with hydroquinone with ammonium chloride and nitric acid
• Os and Ru precipitation with ammonium chloride and nitric acid
• Ir precipitation with ammonium chloride and purification
• Rh precipitated from Ir-Rh IX raffinate using an organic amine
Ion-exchange process
• Au drying
• Pd, Ru, Pt, Ir, Rh ignition to produce sponge metal
• Os precipitated as a sulphide
Solvent-extraction (SX) process
• Dissolution of Au and PGMs with HCl/Cl2
• Au extraction by SX with dibutyl carbitol or MIBK, then reduction with oxalic acid
• Pd extraction by SX with di-n-octyl sulphide or β-hydroxyoxime (commercially known as LIX 84A), stripping with HCl
• Pt extraction by SX with TBP or a tertiary amine, stripped with HCl (water if TBP is solvent)
• Ru extraction by distillation with sodium chlorate and bromate, stripped with HCl
• Ir extraction by SX with a secondary ammine organic
• Rh precipitation using diethylene tri-ammine (DETA) or precipitation with formic acid
• Os recovered from dissolution offgas
Anglo American Platinum Ltd, South Africa
Johnson Matthey, UK & USA
Vale Europe Ltd, England
Heraeus Holding GmbH, Germany
Solvent-extraction process
• (Purification and/or melting & granulation of Au powder produced by SX)
• Os recovered as potassium osmate from dissolution offgas by reaction with KOH
• Pd precipitation using ammonium hydroxide
• Pt, Ru, Ir precipitation using ammonium chloride
• Rh redissolution and reprecipitation with ammonium chloride
Solvent-extraction process
• Pd reduction using hydrazine, followed by calcination
• Pt reduction using hydrazine, followed by melting & casting or ignition of the platinum salt in air to produce Pt sponge
• Ru precipitate calcined, then reduction to Ru sponge using cracked ammonia (Ru powder can also be produced by reduction in an atmosphere of hydrogen and nitrogen)
• Ir precipitate calcined, then reduction to Ir sponge using cracked ammonia or precipitate heating under nitrogen and hydrogen atmosphere
• Rh precipitate calcined and reduced to Rh sponge
Precipitation process
• Dissolution of Au and PGMs with HCl/Cl2
• Au extraction by precipitation with hydrazine (N2H4)
• Pd precipitation with ammonium acetate/chloride
• Pt precipitation with ammonium chloride
• Ru extraction by distillation with sodium chlorate and bromate, or solvent extraction with TBP and precipitation as RuO2
• Ir precipitation ammonium chloride
• Rh precipitation as rhodium ammonium nitrite or using ammonium chloride
• Os recovered as OsO4 vapour as part of Ru distillation or after dissolution
Lonmin plc, South Africa
JSC Krastsvetmet, Russia (italics)
Precipitation process
• Ru precipitation with ammonium chloride
• Pt redissolution and precipitation with ammonium chloride
• Pd redissolution and precipitation with hydrochloric acid
• Rh and Ir undergo repeated precipitation to produce pure salts (Krastsvetmet uses electrowinning of Rh)
• Redissolution and reprecipitation of Au
Precipitation process
• Ru-salt ignition and cooling under nitrogen atmosphere
• Pt ignition
• Pd ignition in air
• Ignition of pure salts of Rh and Ir
> 99.9 % individual PGMs, Au
Sources:
Crundwell et al. (2011)
Dorfling (2012)
Jones (2005)
Abbreviations:
BMR – Base metal refinery
DETA – Diethylene triamine
DIBK – Methyl Isobutyl Ketone
IX – Ion exchange
PGM – Platinum group metal
SX – Solvent extraction
TBP – Tributyl Phosphate
UG2 – Upper Group 2
Key:
Dashed lines (_ _ _) indicate processing specific to UG2 ore
A process number in brackets indicate an optional processing step
Where colours indicate the primary source of platinum treated:
• Green: Bushveld Complex, South Africa
• Blue: Stillwater Complex, USA
• Purple: Norilsk-Talnakh, Russia
Independent refineries:
• Vale Europe Ltd, England
• Heraeus Holding GmbH, Germany