PLATINUM-GROUP ELEMENT MINERALIZATION
PIPES OF THE EARLY PROTEROZOIC
KEIVITSA MAFIC-ULTRAMAFIC INTRUSION,
NORTHERN FINLAND

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Talk outline

- Location and geology of the Keivitsa deposit
- Ore types
- Distribution of PGE, Ni, Cu and S
- Host rocks of the ore
- Host rock composition, silicate minerals
- Geochemistry, chondrite normalized PGE
- Sulfide ore minerals
- Platinum Group Element (PGE) minerals
- Mineralization phases and types
- Summary and conclusions
Location of the Keivitsa intrusive
Ore types

- Low grade Cu-Ni sulfide dissemination with PGE and Au

- PGE rich pipes (cut off 1 ppm PGE+Au) with average 0.5% Ni and 0.4 % Cu, 1.8 % S and 2.1 ppm PGE + Au

- Massive sulfide veins, thickness from a few to 30 cm
Preliminary Mineral Resource Estimate is total of 465 Mt (indicated + inferred)

- Indicated 150 Mt have average Ni 0.18%, Cu 0.27%, Co 0.011%, S 1.23 %, Au 0.09 g/t, Pt 0.23 g/t, and Pd 0.15 g/t

- Inferred mineral reserves contain 315 Mt with average Ni 0.18%, Cu 0.29%, Co 0.012%, S 1.26 %, Au 0.08 g/t, Pt 0.20 g/t, and Pd 0.12 g/t

- The Ore Reserve Estimate contains 120 Mt ore with Ni 0.21%, Cu 0.30%, Co 0.012%, S 1.40 %, Au 0.11 g/t, Pt 0.25 g/t, and Pd 0.16 g/t
Disclaimer

Whilst Scandinavian Gold Ltd. has consented to the GTK's use of its proprietary data in the preparation of this paper, Scandinavian Gold Ltd. does not endorse any estimates of dimensions, grade or tonnage contained therein. Any such estimates are purely the personal opinions of the authors.
Conductive blocks after Gefinex (Sampo) surveys, horizontal layered model, line coil separations 300 to 575 m

Keivitsa Intrusive from gravity data

Modeling geophysics

2003

5 km
3-D MODEL
PGE, Ni, Cu and S distribution

PGE > 500 ppb
PGE+Au > 1 ppm

Ni > 0.15%, PGE+Au > 1 ppm.

Cu > 0.2%
PGE+Au > 1 ppm

S > 0.5%, PGE+Au > 1 ppm.
Block and solid modeling

PGE > 0.5 ppm

PGE > 1 ppm

500 m
Modeling geophysics

Conductive

S.G. > 3.15

Conductive

S.G. < 3.05

PGE

KEIVITSA, EW Section 7512500

- Drill holes
- High conductivity blocks (0-100 Ω m)
- High density blocks (S.G.>3.15)
- Low density blocks (S.G.<3.05)
- PGE pipes

200m E
Block and 3 D modeling

Specific gravity
And PGE pipes

< 3.05

> 3.15

200 m
Distribution of Cu and S

Copper

Sulphur
Drilling results of SG Ltd. in 2003 of Central Lens A
compiled by John Pedersen

Surface area and grade intersections of the high-grade nickel-PGE lens

Average for R695 and R801
- 0.80% nickel
- 1.16 g/ton platinum
- 0.86 g/ton palladium
- 0.21% copper

7612.500

Average KV-10 from 24 to 92:
- 0.64% nickel
- 1.12 g/ton platinum
- 0.92 g/ton palladium
- 0.19% copper

2300 m²

Platinum in 2 m section
- 1.00 to 4.39
- 0.50 to 1.00
- 0.25 to 0.50
- 0.10 to 0.25
- 0 to 0.10
Platinum in drillcore along section 7512.500
compiled by John Pedersen

39 m with
0,67 % Ni
1,13 g/ton Pt
0,69 g/ton Pd

52 m with
0,58 % Ni
0,82 g/ton Pt
0,54 g/ton Pd

29 m with
1,01 % Ni
1,49 g/ton Pt
1,39 g/ton Pd

36 m with
0,73 % Ni
1,81 g/ton Pt
1,23 g/ton Pd

Section area to a depth of 100 m: 2100 m²

Platinum in 1 m section
Grains per ton (ppm)
- Red: 1 to 4,54
- Yellow: 0,5 to 1
- Green: 0,25 to 0,5
- Blue: 0,1 to 0,25
- Blue: 0 to 0,1
Central lens A feed PGM distribution vol %

- Moncheite: 22.0%
- Sperrylite: 51.8%
- Mertieite-II: 6.8%
- Michenerite: 4.4%
- Braggite: 3.3%
- Sobolewskite: 3.0%
- Isoferroplatinum: 2.8%
- Undefined: 2.0%
- Melonite: 0.9%
- Rustenburgite: 0.8%
- Keithconnite: 0.3%
- Geversite: 0.3%
- Merenskyite: 0.1%

Total of 2015 grains – 32 microns, compiled by Mr. Jukka Laukkanen, GTK MinTek 2004
Ore reserve estimate of central lens A
by John Pedersen

• To a depth of 100 meter the central lens A contains 0.4-0.7 Mt ore with ca. 0.7 % Ni, Cu 0.2 %, Co 0.012 %

• 1.1 g/t Pt and 1.0 g/t Pd

• Au and other PGE are ca. 0.3 g/t

• The grade, tonnage and potential are under re-evaluation
Host rock composition

- All oreotypes are hosted by olivine-clino-pyroxenites and websterites with narrow layers of wehrlites, lherzolites and dunites

- The PGE rich zones show hydrothermal alteration with serpentinization, carbonatization, chloritization, and alteration to actinolitic amphibole
The chilled microgabbro representing parental magma

- SiO$_2$ 52.14 %
- TiO$_2$ 0.89 %
- Al$_2$O$_3$ 11.92 %
- MgO 9.15 %
- CaO 9.47 %
- Cr 194 ppm
- Ni 113 ppm
- Cu 261 ppm
Ni-Cu-PGE ORES
Host rocks

GEOCHEMICAL AFFINITY OF THE PARENTAL MAGMAS OF THE KEIVITSA INTRUSION

Diagram showing geochemical affinity with F, Tholeiitic, Calc-alkaline, A, and M axes and data points for Pyroxenites and Chilled Margin.
Ni-Cu-PGE ORES
Host rocks

NORMATIVE (CIPW) COMPOSITION OF PYROXENITES
(Rocks with MgO>12 wt.%)
Correlation of PGE+Au with MgO in the Keivitsa clino-pyroxenites, lherzolites and olivine websterites

Filter: Pd50000 (n= 477)
Ni-Cu-PGE ORES
Host rocks

OLIVINE WEBSTERITE: R695 – 68.45 m
PYROXENITE

Olivine clinopyroxenite – olivine websterite

- CUMULUS MINERALS: olivine and clinopyroxene
- POSTCUMULUS MINERALS: orthopyroxene, plagioclase, hornblende and sulfides.
  Minor: phlogopite, CI-apatite and graphite

METAPYROXENITE

- ALTERATION MINERALS: actinolitic amphibol and serpentine with minor chlorite, talc, epidote and carbonate
TEXTURAL RELATIONS BETWEEN MINERALS OF THE SERPENTINE GROUP:

• Formation of LIZARDITE. Retrograde metamorphism: Sulfide remobilization and reequilibration (↓S & ↑Ni). Dusting of millerite in lizardite

• Formation of ANTIGORITE. Prograde metamorphism: new sulfide remobilization
Ni-Cu-PGE ORES
Host rocks

Cl-apatite serpentine and chlorite associated with fractured sulfides:
R695 – 71.45 m
Ni-Cu-PGE ORES
Whole-rock PGE distribution

- Olivine clinopyroxenite
- Metaclinopyroxenite
- Metaperidotite
- Albite and carbonate rock

Ni-Cu-PGE ORES
Whole-rock PGE distribution

- Olivine clinopyroxenite
- Metaclinopyroxenite
- Metaperidotite
- Albite and carbonate rock
Ni-Cu-PGE ORES
Whole-rock PGE distribution

C1 chondrite-normalized PGE contents of the studied drill-core samples
$Pt_{C1} = 1,020$ ppm y $Pd_{C1} = 0,545$ ppm (Naldrett & Duke, 1981)

- Flood basalt
- Ni_PGE
- regular
- Fe-S
MINERAL ASSEMBLAGE

PENTLANDITE, PYRITE, MILLERITE, PYRRHOTITE AND CHALCOPYRITE

- Minor:
  heazlewoodite, nickeline, maucherite, gersdorffite, cubanite, bornite and mackinawite.

TEXTURE:

- SULPHIDES.
  - Aggregates interstitial to the primary cumulus silicates.
  - In metapyroxenites, intergrown with hydrous silicates and filling fractures
  - Graphic textures between pentlandite, pyrite and/or chalcopyrite
  - Partial replacement of pentlandite by millerite, heazlewoodite & mackinawite
Pentlandite altered to millerite with an inclusion of PdCu
Ni-Cu-PGE ORE

PGM intergrowth distribution

DISTRIBUTION OF PLATINUM-GROUP MINERALS

- Included in sulfides: 38%
- Filling fractures in sulfides: 54%
- Attached to sulfide grains: 6%
- Included in hydrous silicates: 2%
Ni-Cu-PGE ORES
PGE distribution: Platinum-group minerals

Heavy minerals concentrate
Ø < 40 µm. Drill core R713

sperrylite & geversite
sperrylite, merenskyite, gersdorffite, & pentlandite
DISTRIBUTION OF PLATINUM-GROUP MINERALS

(818 grains analyzed)

- Braggite (Pt,Pd)S 30%
- Geversite (PtSb$_2$) 26%
- Sperrylite (PtAs$_2$) 26%
- Moncheite (Pt,Pd)Te$_2$ 20%
- Michenerite PdBiTe
- Melonite (Ni,Pd)Te$_2$
- Kotulskite-Sobolevskite PdTe-PdBi
- Merenskyite (Pd,Pt)Te$_2$ 12%
- Keitconnite Pd$_2$Te
- Irarsite IrAsS
- Others

Ni-Cu-PGE ORES

PGE distribution: Platinum-group minerals

Distribution of Platinum-group minerals: 818 grains analyzed.
Vol. % of PGM in drill core samples, compiled by J. Laukkanen
GTK MinTeK 2004

R 824 <37 um 462 grains
- Braggite: 84.0%
- Sperrylite: 1.5%
- Sobolewskite: 0.1%
- unknown: 2.7%
- Mertieite II: 0.1%
- Merenskyite: 0.6%
- unknown: 0.9%
- Gold: 1.0%
- Isoferrplatin: 0.3%

R695 <37 um 606 grains
- Moncheite: 87.0%
- Sperrylite: 52.2%
- Sobolewskite: 3.7%
- unknown: 0.2%
- Mertieite II: 6.9%
- Michenerite: 0.5%
- Moncheite: 0.4%
- Rustenburgite: 0.5%
- Gold: 1.0%
- Isoferrplatin: 0.3%

R713 <37 um 2659 grains
- Moncheite: 87.0%
- Geversite: 31.6%
- Mertieite II: 6.9%
- Sperrylite: 5.1%
- Michenerite: 0.5%
- Moncheite: 0.4%
- unknown: 0.2%
- Braggite: 1.6%
- Sobolewskite: 5.1%

Vol. % of PGM in drill core samples, compiled by J. Laukkanen
GTK MinTeK 2004
Keivitsa Pt-minerals

- Braggite (Pt, Pd)S, cooperite PtS,
- Undefined (Pt,Pd)\(_2\)(Cu, Ni, Fe)\(_5\)S\(_3\)
- Sperrylite PtAs\(_2\)
- Moncheite PtTe\(_2\)
- Geversite PtSb\(_2\)
- Rustenburgite (Pt, Pd)\(_3\)Sn
- Pt-Fe alloy
- Hongshiite PtCu
Braggite in pentlandite
Backscattered electron image

Altered braggite in pn  R824/64.40 FM924

Braggite
Braggite intergrown with pentlandite and silicate
Ni-Cu-PGE ORES

PGE distribution: Platinum-group minerals

Hydrothermal alteration of braggite (Pt,Pd)S

Irarsite (IrAsS)

Vysotskite (PdS)

Partially altered braggite
Ni-Cu-PGE ORES
Vysotskite PdS-Braggite-Cooperite PtS
GENETIC MODEL
Thermal stability of PGM

Chemical composition of Pt and Pd sulfides compared with their compositional limits at 700°C in the system PdS-PtS-NiS (Verryn y Merkle, 2002)
Sperrylite in Ca,Mg silicate
Backscattered electron image

PtAs$_2$ in CaMg silicate, R813/310.90 FM2962
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All results in Atomic Percent; Moncheite (Pt,Pd)Te2
Ni-Cu-PGE ORES
PGE distribution: Platinum-group minerals

Pt, Pd & Ni Bismuthotellurides
Moncheite
in silicate and intergrown with pentlandite
Pt bismuthotellurides

Ni-Cu-PGE ORES

PGE distribution: Platinum-group minerals
Michenerite within Ca-Mg silicate
Backscattered electron image

PdBiTe in CaMg silicate  R824/61.45
Michenerite within Ca-Mg-Fe silicate and pentlandite (pn)

Backscattered electron image
Ni-Cu-PGE ORES

PGE distribution: Platinum-group minerals

Pd bismuthotellurides

Diagram showing the distribution of Pd bismuthotellurides with various minerals and compositions.
Keivitsa Pd- minerals

- Braggite (Pt, Pd)S - vysotskite PdS and undefined alteration product (Pt,Pd)\(_2\)(Cu, Ni, Fe)\(_5\)S\(_3\)
- Merenskyite PdTe\(_2\)
- Kotulskite PdTe
- Sobolevskite PdBi
- Palladian melonite (Ni,Pd)Te\(_2\)
- Michenerite PdBiTe
- Sudburyite PdSb
- Stibiopalladinite Pd\(_5\)Sb\(_2\)
- Keithconnite Pd\(_{2.6}\)Te
- Mertieite I and II Pd\(_{5+x}\)(SbAs)\(_{2-x}\)
- Undefined PdCu
Kotulskite PdTe in silicate
### Processing option: All elements analyzed (Normalised)

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All results in Atomic Percent; keithconnite Pd 2.6Te, hongshiite Cu(Pt, Pd)
Keivitsa Ir, Os, Rh, Ru- minerals

- Erlichmannite (Os, Rh, Ir)S2
- Laurite (Ru, Os, Ir)S2
- Irarsite (Ir, Ru, Rh, Pt)AsS
**GENETIC MODEL**

*Previous remarks*

- **THE HOST IGNEOUS ROCKS** are partially altered
- **PENTLANDITE** is partially transformed to MILLERITE or HEAZLEWOODITE
- **PGM** are mostly included in secondary silicates
- **THE DISTRIBUTION AND CHEMICAL COMPOSITION OF PGM** is very irregular
- **HIGH CONCENTRATIONS OF** PGE+Au **ARE LOCALIZED IN PIPE-LIKE, VERTICAL ZONES**
  - Aligned along a N-S vertical zone, strongest alteration
  - Maximum chlorine content in the host rocks
  - Perpendicular to the compositional layering
  - Uncorrelated with the distribution of S, Cu and (Ni)
GENETIC MODEL
Silicate mineral assemblages

STAGES OF ALTERATION-METAMORPHISM

- Subsolidus cooling
  - Pyroxenites
- Serpentinization
  - Lizardite (pseudomorphic texture)
- Hydrothermal alteration-green-schist facies metamorphism (T<550ºC)
  - Antigorite
  - Actinolite
  - Chlorite
  - Epidote
  - Carbonate
  - Talc
Phase relations in the system Ni-Fe-S at 450°C

**GENETIC MODEL**

*Evolution of the magmatic sulfide assemblages*

Nickel enrichment during serpentinization
GENETIC MODEL

Evolution of the magmatic sulfide assemblages

Phase relations in the system Ni-Fe-S at temperatures below 135ºC
Thermal stability of some PGM and PGM-containing assemblages

- Moncheite (PtTe2) stable below 1150°C (decrease with Bi content)
- Kotulskite (PdTe) stable below 720°C (decrease with Bi content)
- Braggite stable below 700°C, altered even lower temperatures
- Geversite (PtSb2) becomes stable at 600°C (Makovicky, 2002)
- PdCu alloy stable at 550-400°C
- Merenskyite+kotulskite+miclenerite coexist at 489°C (Hoffman & MacLean, 1976)
- Sperrylite + PtS + py stable at 470°C (Mackovicki et al. 1992)
- Geversite+merenskyite stable at 400°C (El-Boragy & Schubert, 1971)
- At 400°C vysotskite (PdS) is stable with millerite
- Maximum solubility of Ni is 11.4 at% in PdS at 400°C
Compositional variations of merenskyite \([\text{PdTe}_2]\) with reference to the experimental results in the system Pd-Te-Bi according to Hoffman y MacLean (1976).
HALIDES CONTENT OF SOME HYDROUS SILICATES AND APATITE FROM THE PGE-RICH PIPES

- ACTINOLITE: up to 2.43 wt.% Cl and 2.50 wt.% Br
- CHLORITE: up to 0.23 wt.% F and 2.40 wt.% Br
- MICA (Flogopite): up to 0.44 wt.% Cl and 3.67 wt.% Br
- APATITE: up to 1.22 wt.% F and 2.36 wt.% Cl

TRANSPORT OF Pt AND Pd AS CHLORIDE COMPLEXES: $\text{PtCl}_3^-$ and $\text{PdCl}_4^{2-}$
CONCLUSIONS

Stages in the formation of the PGE-rich ores

1ª FORMATION OF A DISSEMINATED Ni-Cu-PGE MAGMATIC MINERALIZATION

2ª COOLING, SUBSOLIDUS EVOLUTION AND RETROGRADE ALTERATION

3ª HYDROTHERMAL ALTERATION-GREEN SCHISTS FACIES METAMORPHISM:

PGE+Au REMOBILIZATION ($\text{PtCl}_3^-$ y $\text{PdCl}_4^{2-}$) AND CONCENTRACIÓN IN VERTICAL PIPE-LIKE BODIES ALONG A “FAULT ZONE”
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