Ore deposits related to mafic igneous rocks – carbonatite-hosted copper deposits

- GLY 361 – Lecture 6
Carbonatites

• Intrusive or extrusive igneous rocks:
  – Defined by >50% carbonate minerals (calcite, dolomite, siderite), <10% SiO$_2$, crystallising from volatile-rich magma.
  – Plugs, dykes, sills, breccias, and veins.
  – Concentrically zoned plugs associated with alkalic ring complexes (e.g. Palabora, RSA; Magnet Cove, USA).
  – Alkalic complexes not of the ring type (e.g. Mountain Pass, USA).
  – Not associated with alkalic rocks.
  – Lava flows and pyroclastic rocks.
  – Almost exclusively associated with continental rift-related tectonic settings and some spatially related to major faults.
  – Steady increase in carbonatitic activity through the Earth's history, from Archean to present.
### Carbonatites

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**Fig. 1.** Ages of carbonatites, kimberlites and alkaline igneous rocks, modified from Gurney et al. (2010). The oldest examples of each group are labelled: Tu = Tuportalik (Greenland), Do = Dolo (Canada), LS = Lac Shortt (Canada), Si = Siilinjarvi (Finland), GB = Grays Bay (Canada), Ho = Hogernakel (India), Br = Brazil; Al = Algeria, TW = Turkey Wells (Australia), Nb = Nabbeta (Australia), BC = Brockman Creek (Australia), Ku = Kuruman (South Africa); Ki = Kimozero (Baltic Shield), Uk = Ukraine, Pre = Premier (South Africa), Sk = Skjoldungen (Greenland), Kei = Keivy (Baltic Shield), KL = Kirkland Lake (Canada), Wawa = Wawa (Canada); CS = circum-Superior; CP = Churchill Province; Gar = Gardar (Greenland).
Only one carbonatite volcano is known to have erupted in historical time - Ol Doinyo Lengai in Tanzania. It erupts the lowest temperature lava in the world, at 500-600°C (compared with >1100°C for basaltic lavas).

December 1995 - Spectacular bubbling of natrocarbonatite spatter from a small hornito on Oldoinyo Lengai.

March 1999 - Squirting of natrocarbonatite spatter from openings in the wall of a hornito on Oldoinyo Lengai.
Carbonatites

• Three models of their formation exist:
  1. direct generation by very low degree partial melts in the mantle and melt differentiation.
  2. liquid immiscibility between a carbonate melt and a silicate melt.
  3. extensive crystal fractionation from a CO$_2$-rich silicate magma.
Carbonatites

- Geochemical classification:
  - Alkali-rich, ferric iron, and Zr-rich (agpaitic)
  - Alkali-poor, FeO-CaO-MgO-rich, and Zr-poor (miascitic)

- Carbonatites may contain economic or anomalous concentrations of REE’s, P, Nb, U, Th, Cu, Fe, Ti, Ba, F, Zr, etc.

- Vein deposits of Th, fluorite, or REE’s may be associated with carbonatites, and may be hosted internal to or in the aureole of a carbonatite.
The Palabora Carbonatite Complex is unique in that it is the largest open-pit copper mine in Africa and one of only few economically viable carbonatite-hosted copper deposits in the world.
Copper Deposits in South Africa
The Palabora Carbonatite Complex

The Copper deposit

Original Resource:

1156 Mt at 0.5 % Cu

Down to: 1480 m
The Palabora Complex, Limpopo Province

- Proterozoic (2047 Ma) in age
- Concentrically zoned complex of alkaline-igneous rocks (6 x 2.5 km).
- Result of multiple alkaline intrusions in successive stages of pyroxenite, syenite and ultrabasic pegmatoids into Archean gneiss.
The Palabora Complex, Limpopo Province

- Northern pipe:
  - Mafic, pegmatitic rock
  - Composed of serpentine and hydrated phlogopite (vermiculite)
  - Mined since 1946.
The Palabora Complex, Limpopo Province

- Central Pipe (Loolekoop):
- Pipe of greatest economic interest.
- Covering an area of about 1.4 x 0.8 km.
- Pyroxenite, foskorite (magnetite-olivine-apatite rock), banded carbonatite, transgressive carbonatite.
- Contacts between rock types suggest progressive, transitional inward changes:
  - Intrusion in two stages
The Palabora Complex, Limpopo Province

- Southern Pipe:
- Pyroxene pegmatoid
- 7-10% PO₄ as apatite and minor vermiculite.
- Not currently mined.
1) Fracturing of the entire infilling of the pipe and renewed igneous activity led to the intrusion of a dyke-like body of transgressive carbonatite at the intersection of two prominent zones of weakness.
   - a divergent stockwork of transgressive veins cutting across all the older rocks was also developed
     ➢ bulk of the Cu-mineralization

2) Intensive post-carbonatite fracturing provided further channels for residual sulphide-rich fluids to permeate the transgressive carbonatite and, to a lesser extent, the older rocks

3) Shearing, brecciation, plastic flow and recrystallisation occurred as the mass cooled
   - some sulphides were remobilised and redeposited as valleriite at low temperatures

4) Much later, the entire complex was invaded by barren dolerite dykes
Mineralogy

- **Chalcopyrite** (with minor cubanite) is the predominant Cu mineral in the core, especially in the transgressive carbonatite, containing ca. 1% Cu.

- **Bornite** is dominant in the low grade banded carbonatite and foskorite (olivine, magnetite, apatite and phlogopite in variable proportions).

- **Magnetite** (up 4 wt.% TiO$_2$) makes up 20-25% of the foskorite.

- **Apatite** (phosphor mineral) is present in economic amounts in foskorite.

- **Baddeleyite** (zirconium and hafnium) is recovered from both foskorite and carbonatite.
Sulphide Mineralization

- Low grade – average 0.68% Cu.

- The magnetite precedes the sulphides and its formation probably reduced the oxygen fugacity of the system, triggering sulphide precipitation.

- The sulphide deposition is estimated to have started at a temperature of 600°C, falling to 200°C for the valleriite.
• Earlier workers in the Complex suggested that sulphide mineralisation was a late stage hydrothermal event perhaps not related to magmatism.

• However, sulphur isotopes and fluid inclusions indicate that Cu sulphide liquid was present very early in the crystallisation sequence and even before olivine crystallisation.

• sulphide mineralisation may be a fundamental part of carbonatite magmatism.

• Cu-rich carbonatites at Palabora could have arisen from the pyroxenites by liquid immiscibility.
Carbonatite veins in fenitised granite gneiss country rock to the Palabora alkaline igneous complex.
Banded carbonatite (white rock) and phlogopite magnetite foscorite (dark rock) from the Foskor phosphate mine in Palabora.
Archaean granite country rock to the Palabora Carbonatite Complex. Numerous vertical green veins are fenite, later pale brown veins are carbonatite.
White carbonate matrix has a thin surface coat of calcite with bronze gold coloured phlogopite or biotite and dispersed green single iowaite crystals and magnetite.
A flat parallel-terminated growth of magnetite has a surface dusting of fine crystals of valleriite, calcite and green clinochlore.
A piece of massive baddeleyite with calcite that has several baddeleyite crystals grown through.
Crystallised valleriite on a matrix with magnetite, minor chondrodite and clinochlore.
Products

• **Primary product**: copper.

• **By-products**: magnetite, nickel sulphate, sulphuric acid, *vermiculite*, silver, gold, phosphate, iron ore, zirconia and uranium.
Products

Copper Price
3.01 USD/lb
17 Apr '14

[Graph showing the copper price from 1989 to 2014, with a significant increase around 2009]
Products

- **Use of copper:**
  - electrical wires (60%)
  - roofing and plumbing (20%)
  - industrial machinery (15%)
  - alloys (5%), i.e. brass, bronze
Products

- **Vermiculite** $(\text{MgFe,Al})_3(\text{Al,Si})_4\text{O}_{10}(\text{OH})_2\cdot4\text{H}_2\text{O}$:
  - Phyllosilicate formed by weathering or hydrothermal alteration of biotite or phlogopite.
  - South Africa, USA and China are top producers
Products

- Vermiculite:
  - > 94% of output is exported. Palabora produces 80% of the world’s total vermiculite production at 200,000 tons per year saleable product.
  - Currently mining in the PP&V (Phalaborwa Phosphate & Vermiculite area, the ore body is owned by Foskor but the mica mineral rights are owned by Phalaborwa Mining Company).
  - The PP&V ore body contains large reserves of phosphate and it also contains the world’s largest known reserves of vermiculite.