Oregeology and Mineral deposit models
Topics of the lecture

• This lecture follows the ch. 2 in Evans.
• Introduces some key features associated with deposits models
  – Terminology concerning the shape
  – Wall-rock alteration
  – Geological models for mineral deposits
Ore classifications

• Mineral deposits/Ore bodies are commonly classified according to
  – Shape and dimensions
  – Mineralogy
  – Genetic origin
  – geodynamic environment, tectonic setting, and fluid/magma involved in mineralisation.
  – Grade tonnage
Terminology associated with shape

- Ore bodies can be **discordant** or **concordant** to lithological banding in the enclosing rocks (bedding or dominant foliation)
  - Same terms used for igneous intrusions
Discordant ore bodies

- Regularly shaped
  - Tabular,
  - Tubular

- Irregular
  - Disseminated
  - Irregular replacement deposits
Tabular ore bodies

- **Veins** are considered to have resulted mainly from the filling of open spaces,
- **Lodes** was due to extensive replacement of preexisting rock.
- Since such a genetic distinction is often ambiguous, nowadays all tabular orebodies are generally referred to as veins.
Tubular ore bodies

- Chimneys and pipes are 1D and more or less vertical
- Mantos are 1D horizontal (but some times flat lying 2d-bodies)
- Both can branch
- Pinch and swell
Irregularly shaped ore bodies

- Disseminated ore deposits
  - “peppered” into host rock
  - Commonly only accessory amounts
    - Gradation to subeconmic levels
  - More or less regular veinlets: stockwork
  - Commonly cut across geological boundaries

- Irregular replacement deposits
  - Mineralization replaces pre-existing rocks
  - Particularly in carbonate rock rocks
  - Skarns, a.k.a. contact metamorphic or pyrometasomatic
Concordant ore bodies

• According the host:
  – Sedimentary,
  – Volcanic
  – Plutonic
  – Metamorphic

• Also following terms are used

  *Stratiform* orebodies are an integral part of the stratigraphic sequence e.g. (Phanerozoic ironstones) or epigenetic infillings of pore spaces or replacement orebodies or syngenetic ores formed due to exhalation of mineralizing solutions at the sediment-water interface.

  *Stratabound* ore deposits are any type of orebodies, concordant or discordant, which are restricted to a particular stratigraphic horizon.
Sedimentary host rocks I

• Limestones
  – Base metal deposits
  Typically restricted to small number of beds with fractures,
  – increased permeability+ reactivity of limestones
  – Can be just “minor” sequences in siliciclastic systems
    • Bingham Pb-Zn (not to be confused with Bingham porphyry copper)
      – Limestones comprise 10 % of the 2300 m thick stratigraphic succession

• Argillaceous host
  – Can be extremely continuous
  – Kupferschiefer in Germany and Poland( subeconomic in NE-England)
  – Lead-Zinc ore (Sullivan)
  – Part of Zambian copper-belt
Sedimentary host rocks II

- Arenaceous host (sandstones)
  - Some of the Zambian copper belt
  - “desert sand” copper deposits in China
  - Many placer deposits (unlithified)

- Rudaceous host
  - Alluvial conglomerates
  - Precambrian quartz-pebble conglomerates
    - Witwaterstrand (gold, U)
    - Blind River Ontario (U)

- Chemical sediments
  - Fe, Mg-formations (BIF)
  - Evaporites
Igneous host rocks

- Volcanic rocks
  - Volcanic associated massive sulfide deposits V(A)MS
    - Major targets of exploration, significant sources of base metal
    - Cu-, Zn-Cu- and Zn-Pb-Cu-deposits
    - Commonly significant amounts of Au and Ag
    - Different types based on ore mineralogy+ host rocks
      - Differences in tectonic setting
      - AMD-potential (to be approached in future course)
  - Ni-Cu-sulfide ores (associated with komatites)
A “basic” model for VMS-deposits

Extensional setting
Magma acts as a thermal pump and source of H$_2$S (and metals)
Fluid is heated sea water plus magmatic fluids
Hot saline and acid waters dissolve metals from (unaltered) host rocks
Plutonic sources

- Layered (mafic) intrusions
  - Cr-deposit Chromium-magnetite-titanite
  - Fe-Ti-V-ores (in anortosites)
  - Ni-Cu-sulfide
  - PGE-ores
- Porfyric granites
Metamorphic host

- Besides irregular replacement deposits and contact metamorphic aureoles (skarns) metamorphosis can play a key role defining the economic value of a mineralization formed in sedimentary and igneous host rocks
  - Grain size effects
  - Mobilization of ore mineral
Residual deposits examples

- Can comprise concordant layers

  Kaolinite deposits weathering of granitic rocks/felsic volcanics
  (K-feldspars and micas weather to kaolinite)

  Bauxites: originating from Al-rich (alkaline) plutonic rocks
  (nepheline-syenites, syenites)

  Lateritic Ni-ores (weathering of mafic/ultramafic rocks)
Wall rock alteration

- Intensive alteration haloes
  - Variable thickness, can be hundreds of meters wide
- Important targets for exploration (geochemical and geophysical anomalies)
- Alteration mineralogy can also help drilling targeting
- Alteration can substantially effect the rock engineering conditions
  - Also the metamorphic equivalents of mineral can have substantially different mining technical properties compared to unaltered host rocks
Hydrothermal alteration

- K-alteration (K-silicates), in hot (magmatic-hydrothermal) systems 500-600 °C
  - E.g. Porphyre- copper.
- "Phyllic alteration" = phyllosilicate formation, example serisitisation
- Propylitic alteration
  - In practice same mineral assemblage as in low-grade metamorphosis
    - greenschist facies (chlorite-epidote)
  - E.g. common around VMS
- Argillic alteration
  - Epithermal ores
  - Difficult to distinguish from weathering (clay mineralogy, isotopes)
- Silicic alteration,
  - Amorphic silica, quartz
Drilling targeting

- Athabasca case
  - Unconformity-type U-deposit
- Alteration
  - a large area footprint for exploration
  - Electromagnetic anomalies of fault zones
IMPLICATIONS OF GEOLOGY TO EXPLORATION AND EXPLOITATION

see Evans, Chapter 22 as a background
Kutema

KUTEMAJÄRVI (ORIVESI MINE), in Tampere Schist Belt, is a deposit presently (September 2006) under feasibility study by Polar Mining Oy. It was mined in 1994-2003 when it produced 13 t gold from 1.4 Mt of ore, and was reopened in June 2007. The current resource estimate is 9500 kg gold. It is a Palaeoproterozoic epithermal high-sulphidation deposit hosted by intermediate metavolcanic rock metamorphosed to lower-amphibolite facies. It comprises at least eight vertical pipes, of which the Pipe V and Sarvisuo are the largest. Proximal alteration (including the ore bodies) is characterised by intense leaching of major elements, intense silicification, and pyrophyllite formation to a variable degree. Locally, phosphates and F minerals (eg. topaz, lazulite) in the alteration assemblage. Chiefly native free gold associated with quartz, also native gold as inclusions in quartz, pyrite and arsenopyrite, and in symplectites with tellurides; in addition, gold tellurides are present.

http://en.gtk.fi/ExplorationFinland/ Commodities/Gold/kutemajarvi.html
Can we ”translate” terminology to engineers?

- **Syngenetic**
  - Ore formed with the host rock
- **Epigenetic**
  - Ore formed later than the host rock
- **Hypogene**
  - Ore formed by up-rising fluids
- **Supergene**
  - Descending fluid

**For hydrothermal ores**
- Epithermal 50-200 °C, < 1500 m
- Mesothermal 200-400 °C, 1500-4500 m
- Hypothermal 400-600 °C, >4500 m
- Metamorphic facies
  - Greenschist facies: lowest T and P conditions characteristic to regional metamorphism T-range 300-450 °C and P 1-4 kbar.
- **Epidote-amphibolite facies**, moderate T and P conditions 250°–400° C and up to 4 kbars
- Amphibolite facies: moderate to high temperatures (500° C) and pressures.
- Granulite facies: Temperatures of 650–1,100 °C and pressures of 3 to 10 kilobars
Epithermal Au-Ag-(Cu) formations

• (Young) basic to -intermediate volcanites
• Also in older formation: e.g. Kutema in Tampere schist belt (about 1980-1900 Ma)
• Based on valence of S:
  – Low –sulfidation
  – High-sulfidation
• Represent end members of geochemical evolution of hydrothermal fluids
• High-sulfidation: near volcanic centers, very acidic pH 1-3, oxidized S4+ ja S6+ ions and components, boiling removes CO2 ja SO2 => pH can drop below 1
Figure 2.22 The geological setting and characteristics of high-sulfidation and low-sulfidation epithermal deposits. A genetic link between high-sulfidation epithermal Au-Cu and sub-volcanic porphyry type Cu-Au deposits is also suggested (after Hedenquist et al., 2000).
Figure 2.23 Two stage model for the formation of high-sulfidation epithermal deposits [after Arribas et al., 1995].
(a) Initial stage where a dominantly magmatic vapor phase is responsible for leaching of the country rock and development of an advanced argillic alteration halo around the main fumarolic conduit. (b1) Ore deposition stage, in this case where gold is transported as a chloride complex; and (b2) ore deposition stage where gold is transported as a bisulfide complex.
“epithermal high-sulphidation deposit hosted by intermediate metavolcanic rock metamorphosed to lower-amphibolite facies”

Concordant
Disconcordant
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Tubular

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Discordant ore bodies

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Example

• In the case of Kutema, distinction of ore/ganque was challenging
  – Substantial nugget effect
    • Sample size independent variation/uncertainty
  – Visual distinction of ore/wall rock difficult
    • Required an experienced eye

• Altered (metamorphosed) rocks had also
  – Differences in rock mechanical competence
  – Included hard minerals increasing costs

http://en.gtk.fi/ExplorationFinland/Commodities/Gold/kutemajarvi.html
At some operations, as at the **Kutema gold mine** in Southern Finland, **gold** is recovered by flotation to produce a sulfide concentrate that can be smelted to recover the **gold**. The **Kutema gold** ore consists of disseminated, banded to massive pyrite with various tellurides and minor base metal sulfides, arsenides and sulphosalts in a sericite-quartz schist. The **gold** occurs as inclusions in the pyrite, arsenopyrite and quartz, intergrown with tellurides and as free grains. About 82 to 87% of the **gold** is recovered (Kojonen et al., 1999).
Mineral deposit models

• Mineral deposit models that describe the characteristics that are considered (by the author(s) of the model) to represent key aspects of the type of mineral deposit that is sought within a particular setting.
  – deposit models allow to know from observed geologic environments the possible mineral deposit types that may exist in the region
  – allow economists to determine the possible economic viability of these resources.
  – transforming geoscience information to a form useful to policymakers.
Deposit Models and Their Application in Mineral Resource Assessments

• Donald A. Singer and Vladimir I. Berger

• (1) possible mineralized environments from barren environments, (2) types of known deposits from each other, and (3) mineral deposits from mineral occurrences.
Most published quantitative mineral resource assessments rely on two kinds of models
  - (1) descriptive models
  - (2) grade tonnage models

These models are applied in producing
  - Deposit density models
  - Economic models
Example of descriptive model

DESCRIPTIVE MODEL OF PORPHYRY Cu-Mo

MODEL 21a
By Dennis P. Cox

DESCRIPTION Stockwork veinlets of quartz, chalcopyrite, and molybdenite in or near a porphyritic intrusion. Ratio of Au (in ppm [parts per million]) to Mo (in percent) less than 3.

GENERAL REFERENCE Titley (1982).

GEological ENVIRONMENT

Rock Types Tonalite to monzogranite stocks
Textures Intrusions contemporaneous with or pre-dating host rocks; fractures may be restricted to small dikes in some cases
Age Range Mainly Mesozoic to Tertiary, but also Cretaceous
Depositional Environment High-level intrusions in continental batholiths
Tectonic Setting(s) Numerous faults in subduction-related volcanic plutonic arcs. Mainly along continental margins but also in oceanic convergent plate boundaries
Associated Deposit Types Cu, Zn, or Fe skarns may be rich in gold, gold + base-metal sulfosalts in veins, gold placers. Volcanic-hosted massive replacement and polymetallic replacement

DEPOSIT DESCRIPTION

Mineralogy Chalcopyrite + pyrite + molybdenite. Peripheral vein or replacement deposits with chalcopyrite + sphalerite + galena ± gold. Outermost zone may have veins of Cu-Ag-Sb-sulfides, barite, and gold.
Texture/Structure Veinlets and disseminations
Alteration Quartz + K-feldspar + biotite (chlorite). Heterogeneous (phylic) alteration may form capping or outer zone of high-alumina alteration assemblages may be present in upper levels of the system.
Ore Controls Ore grade is, in general, positively correlated with spacing of veinlets and mineralized fractures. Country rocks favorable for mineralization are calcareous sediments; diabase, tonalite, or diorite.
Weathering Intense leaching of surface; wide areas of iron oxide stain. Fractures coated with hematitic limonite. Supergene copper as chalcocite may form blanket below leached zone. Residual soils may contain anomalous amounts of rutil.
Geochemical Signature Cu + Mo + Ag ± W + B + Te ± Sr center; Pb, Zn, Au, As, Sb, Se, Te, Mn, Co, Ba, and Rb in outer zone. Locally Bi and Sn form distal anomalies. High S in all zones. Ratio of Au (ppm): Mo (percent) less than 3. Magnetic low.

EXAMPLES
Brenda, CNBC (Soregaroli and Whitford, 1976)
Sierrita Esperanza, USAZ (West and Aiken, 1982)
Grade and Tonnage Models

- Frequency distributions of tonnages and average grades
- More than 60 mineral deposit types based on more than 2,500 deposits from around the world (e.g. USGS)
- A proximity rule is commonly to construct the grade and tonnage model
  - workings within 1.6 kilometers of each other were treated as part of the same deposit.
**Figure 1.** Example of tonnage part of model for porphyry Cu-Au deposits (modified from Singer and Cox, 1986, fig. 78). Each dot represents an individual deposit. Deposits are cumulated in ascending grade or tonnage. Smoothed curves, representing percentiles of a lognormal distribution having the same mean and standard deviation as observed data, are plotted through the points. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distributions are constructed.

**Figure 2.** Example of gold grade part of model for porphyry Cu-Au deposits (modified from Singer and Cox, 1986, fig. 80). Each dot represents an individual deposit. Deposits are cumulated in ascending grade or tonnage. Smoothed curves, representing percentiles of a lognormal distribution having the same mean and standard deviation as observed data, are plotted through the points. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distributions are constructed.
Deposit Density Models

- A key function of many quantitative mineral resource assessments is estimation of the number of undiscovered deposits.
- Several methods e.g.
  - the three-part methods by (Singer 1994) USGS
  - the numbers of deposits per unit area from well-explored regions are counted (Bliss and Menzie, 1993)
    - Proportion of the area explored "completely" must be estimated
    - Similar proximity rules as for grade-tonnage models should be applied when estimating the number of deposits
The three-part method

- Selection or development of a deposit model

- Delineation of permissive tracts

- Estimation of number of undiscovered deposits
Figure 3. Graph of numbers of deposits per unit area by deposit type from well-explored regions, as reported by Singer and others (2001). MB, Manitoba; NS, Nova Scotia; TAS, Tasmania; VIC, Victoria.
Economic Models

• Simplified cost models/prefeasibility cost models are applied
• In the early stages of exploration and planning
• In resource assessments of undiscovered mineral deposits
• Separate economic from uneconomic deposits,
  – help to focus on targets that can benefit the exploration enterprise
  – can be used to eliminate deposits that would probably be uneconomic even if discovered.
• Examples of models applied are based on USBM-models presented by Camm, 1991
  – Estimates of operating and capital expenditure for given mining method, tonnage, grade and depth
Figure 4. Graph showing relation between value per metric ton and deposit size (in millions of metric tons of ore) for some U.S. open-pit, heap-leach gold-silver deposits when prices and the rate of return are as shown.

Figure 5. Graph showing relation between value per metric ton and deposit size (in millions of metric tons of ore) for some zinc-lead skarn deposits. All deposits are assumed to be mined at a depth of 800 feet, with half of each mined by cut-and-fill methods and half by shrinkage stope methods. Prices and the rate of return are shown in the graph.
Quantitative models

- Descriptive models by expert knowledge
- Quantitative statistics based on well investigated deposits

**Figure 6.** Graph showing the proportion of subtypes of porphyry copper deposits reporting the presence of several mineral species.

**Figure 7.** Graph showing the proportion of subtypes of porphyry copper deposits reporting the presence of different deposit types occurring within 10 kilometers.
Linking Mineral Deposit Models to Quantitative Risk Analysis and Decision-Making in Exploration

- Kreuzer et al
- Translating mineral deposit models into flexible probabilistic structures based on
  - Extraction of ore components (fluids, metals, and ligands) from crustal or mantle sources or both,
  - fluid- or melt-assisted transport of ore components from source to trap zones,
  - formation of trap zones (i.e., effective melt or fluid channels)
  - operation of the physicochemical processes that promote and sustain the deposition of metal from fluids or melts passing through a particular trap site.

- An approach to integrate critical mineralization processes and conditions with concepts of probability theory, decision analysis, and financial modeling.
- To make mineral deposit models amenable to financial risk and value analysis
- communication of value-creating geologic concepts to financial stakeholders in economic terms
Ore classifications (genetic process-based)

- Robb L:
  - Magmatic
  - Magmatic-hydrothermal
  - Hydrothermal
  - Sedimentary
  - Surficial and supergene processes
  - Gradational, e.g. Magmatic and magmatic-hydrothermal or hydrothermal
  - Incomplete: does not consider metamorphism as an ore forming process
  - "metamorphism does not represent a fundamental process whereby ore deposits are formed"
  - Other opinions can be justified as well!
THANK YOU!