Introduction to Ore Deposits

- GLY 361 –
Lecture 1
Miners among most productive, happiest workers in the world: study (www.mining.com and iOpener Institute for People and Performance, London)

<table>
<thead>
<tr>
<th>Industry Sector</th>
<th>Time on Task</th>
<th>Time Happy</th>
<th>Time Engaged</th>
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</table>
Mine strike hits South African economy (www.infomine.com)

No talks are scheduled between the two sides to the strike, the Association of Mineworkers and Construction Union (AMCU) and the world's top platinum producers, Anglo American Platinum, Impala Platinum and Lonmin, and they remain poles apart on the issue of wages.

The strike has hit about 40 percent of global production of the precious metal, which is used for catalytic converters in vehicles and is a key source of hard currency for South Africa.

This current account deficit is already a key weakness in South Africa's economy, putting its rand currency under pressure. It grew in 2013 to 5.8 percent of gross domestic product, its widest since 2008.

Miners gather at Wonderkop stadium outside the Lonmin mine in Rustenburg, northwest of Johannesburg, in this Jan 30, 2014 file photo. As South Africa's biggest post-apartheid mine strike marks its eighth week on Thursday, it is already denting growth and export earnings, and many of those affected are having to sell their most prized possessions to make ends meet. [Photo/Agencies]
Introduction to Ore Deposits

• Lecturer: Dr. Nils Lenhardt

• Outcomes:
  – Introduce the student to major ore deposits
    • geodynamics of ore formation processes
    • ore-forming processes in dependence of geotectonic environments
  – Examine and identify overall similarities and to highlight deposit specific characteristics

➢ The knowledge should enable you to compare different deposits and conceptualise exploration and exploitation of such deposits
Introduction to Ore Deposits

• Assessment criteria:
  – Evaluation of the semester/module mark will comprise one oral presentation + short report and one practical test. The calculation of your semester/module mark is weighted as follows: 25% oral presentation + 25% short report + 50% Practical Test = semester/module mark.
  – Note that there is a subminimum of 40% for the semester/module mark for students to pass the course. If you do not reach 40% for your semester/module mark, you will be considered to have failed the course, irrespective of your performance in the final exam. The time and venue will still be announced during the course (and/or on ClickUP).
Introduction to Ore Deposits

- **Assessment criteria:**
  - **IMPORTANT:** There is a subminimum of 40% in the exam. Students who gain less than 40% in the exam will be considered to have failed the course, IRRESPECTIVE of the semester/module mark. Only students with a semester/module mark of more than 50% and an exam mark of more than 35% will be awarded a supplementary exam.
  - The final mark will comprise the semester/module mark (50%) and the exam mark (50%). A final mark of more than 50% is needed to pass the course.
Introduction to Ore Deposits

- Definitions
- Brief introduction to geodynamics of ore formation
- Ore deposits of mafic igneous rocks:
  - PGE’s (Platinum Group Elements)
  - Diamonds
  - Carbonatite-hosted copper
- Ore deposits of intermediate to felsic igneous rocks:
  - Porphyry base metal deposits
- Deposits related to submarine volcanism:
  - VHMS (volcanic-hosted massive sulfides)
Introduction to Ore Deposits

- **Ores related to submarine volcanism and sedimentary processes:**
  - SEDEX

- **Ores related to sedimentary processes:**
  - Sedimentary Iron
  - (Sedimentary Manganese)
  - Gold (Wits)
  - (Laterites)
  - Coal
Introduction to Ore Deposits

• What is an “ore”?  
  – An ore is a naturally occurring material from which a mineral or minerals of economic value can be extracted at a profit (Glossary of Geology, 1974).

Iron Ore, Brazil
Introduction to Ore Deposits

• “Profit” depends on:
  – socio-economic conditions (geography, energy costs, type and degree of dilution, grade, depth in crust, environmental aspects, etc.)
  – prevailing interests

• The definition changes with time: “today’s ore is yesterday’s valueless pile of rock”.
Introduction to Ore Deposits

• What is an “ore deposit”?  
  – natural concentration of ore minerals that formed during a single or spatially related series of geological events and may comprise of one or more ore-bodies.
Introduction to Ore Deposits

• What is an “ore deposit”?
  • A mixture of
    • valuable minerals and
    • gangue minerals
    from which at least one of the minerals are of sufficient
    • concentration,
    • quantity, and
    • value
    to be profitably
    • mined,
    • transported,
    • milled, and
    • processed
    at the current technology.
Introduction to Ore Deposits

• What is an “ore deposit”?  
• An ore deposit is the product of natural, highly selective and efficient, mass transfer processes.

• This can happen in four ways:
  – **Syngenetic**: formed at the same time as their host rocks  
  – **Epigenetic**: formed later than the host rocks
  
  – **Hypogene**: formed by ascending hydrothermal fluids  
  – **Supergene**: formed by descending solutions from alteration of near surface minerals

• **Proto ore** – mineral material in which an initial but uneconomic concentration of metals has occurred that may, by further natural processes, be upgraded to the level of ore.
Introduction to Ore Deposits

• Nowadays an ore deposit must be viable both
  – economically and
  – environmentally.

• At present, few submarine deposits fit both these criteria.

• However, many deposits that form in the submarine environment end up on land.

Therefore, knowing about the **processes of formation and concentration** helps us to find and manage ore deposits!
Introduction to Ore Deposits

• Ore, or mineral deposits are found by means of exploration (search for deposits). The results of exploration need to be correctly reported to satisfy the markets.

• The degree of confidentiality in prospecting results is standardized. With growing confidence distinction is made between:

  – **Mineral resources**: reasonable prospects of possible exploitation.

  – **Mineral reserves**: economically measured and profitably extractable ore body.
TOTAL RESOURCE

IDENTIFIED
- Measured
- Indicated
- Inferred

UNDISCOVERED
- Hypothetical
- Speculative

RESERVES
- Price fall; restrictions imposed

CONDITIONAL RESOURCES
- Price rise; restrictions lifted; technology

HYPOTHETICAL RESOURCES

Price:Cost Ratio
- Sub-economical (<1)
- Economical (>1)

Increasing degree of economic feasibility

Increasing degree of geological assurance
Introduction to Ore Deposits

• Zoning of mineral commodities

• Zoning:
  – The spatial distribution patterns of major or trace elements, mineral species, mineral assemblages, or textures in ore deposits.

• Three intergradational classes of ore deposits:
  – Orebody zoning
  – District zoning
  – Regional zoning/ metallogenic zoning
Introduction to Ore Deposits

• Orebody zoning

• What is an orebody?
  – A 3-D shape, well-defined mass distribution of material of sufficient ore content to make extraction economically feasible (Glossary of Geology, 1974)
  • i.e., the length, width and thickness must be determined as well as the concentration of the commodity of interest.
  • changes in the character of mineralization within a single orebody from vein to vein
Introduction to Ore Deposits

• District zoning

• What is an ore district?
  – an ore district is a relatively small geographical area in which a group of discrete ore deposits (generally of the same type) occurs.
  – zoning shown by closely grouped mines and occurrences such as Bingham, Utah or Aggeneys-Gamsberg, South Africa
Aggeneys-Gamsberg Cu-Pb-Zn Ore District, central Bushmanland
Introduction to Ore Deposits

• Regional zoning/ metallogenic zoning:

• What is a metallogenic province?
  – Various regions or provinces are associated with a particular assemblage of mineral deposits or by one or more characteristic types of mineralization, such a region is then called a metallogenic province.

  – This term normally refer to a continental region characterized by one or more geological features that indicate the development of the region in a single tectonic environment (often related to orogenies).

  – It is important to note that the geological setting controls the size of the deposits and the minerals that they contain.
Tintina Gold Province, Alaska / Canada
Introduction to Ore Deposits

- In order to become “ores”, elements or minerals need to be significantly enriched in respect to their average abundance in the crust and must be concentrated in the right locality.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Average crustal abundances for selected metals and typical concentration factors that need to be achieved in order to produce a viable ore deposit</th>
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<tbody>
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<td>Average crustal abundance</td>
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<td>5.6%</td>
</tr>
<tr>
<td>Cu</td>
<td>55 ppm</td>
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<tr>
<td>Ni</td>
<td>75 ppm</td>
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<td>Zn</td>
<td>70 ppm</td>
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<tr>
<td>Au</td>
<td>4 ppb</td>
</tr>
<tr>
<td>Pt</td>
<td>5 ppb</td>
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</table>

Note: 1 ppm is the same as 1 g t⁻¹.
Introduction to Ore Deposits

- Classification of the elements
  - cross-section of the Earth

Deepest mine: 3.8 km
Deepest well: 12 km

Crust: 5-40 km
Mantle: 2885 km
Outer core: 2270 km
Inner core: 1216 km
Introduction to Ore Deposits

- Classification of the elements

- Goldschmidt’s classification based on rock association:
  - Lithophiles; associated with silicates and crust
  - Chalcophiles; associated with sulfides
  - Siderophiles; associated with the core forming native metals and alloys
  - Atmophiles; volatiles associated with the atmosphere

- Some elements can belong to more than one group. Fe, equally forms sulfides and oxides and is abundant in the crust, mantle and in the core.
Introduction to Ore Deposits
Introduction to Ore Deposits

• **Classification of ores**
  - **metal ores:**
    - Oxides, sulfides, silicates
    - „native metals“ (copper and gold)
  - **non-metal ores:**
  - **transitionary metalloids:**
    - B, Si, As, Se, Te, At
Introduction to Ore Deposits

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<th>H</th>
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<td>85</td>
<td>At</td>
<td>86</td>
<td>Rn</td>
</tr>
</tbody>
</table>

Figure 4 Periodic table showing the 92 geologically relevant elements classified on the basis of their rock and mineral associations.

At- astatine, Fr- francium; Pa - protactinium


Introduction to Ore Deposits

What is the age of the Universe?

Expansion of the universe: the "Big Bang" is the reason for the expansion.

Proof: The microwave-echo of the Big Bang is present everywhere in the Universe. "Cosmic background noise" at $\lambda = 7 \text{ cm}$. This wavelength equals the radiation of an opaque, non-reflecting object at $3.7 \pm 1 \text{ K}$. The velocity of the expansion of the Universe implies that before c. 13 gyr all galaxies were concentrated in one point. This must have been the point where the Big Bang occurred and formed the Universe and the expanding cosmic matter.

The rate of the expansion of the Universe depends on the Hubble constant. The expansion velocity increases by the Hubble constant, with growing distance of the galaxies from the centre of the Universe (Edwin Hubble, 1929).
**Introduction to Ore Deposits**

**Doppler law:** $S_1$ to $S_4$ are subsequent positions of a moving light source (star). The respective circles delineate the distance the light has travelled from its source. The wavelength $\lambda$ becomes shorter in the direction of movement and longer in the opposite direction.

The expansion rate of the Universe depends on the **Hubble constant**. The more distant the galaxies are from the centre of the Universe (their common point of origin), the faster is their expansion rate and velocity (Edwin Hubble, 1929).
The reigning FORCE of the Universe is the GRAVITATION!

The pulsating cosmic matter within the galaxies changes constantly it’s inner pressure:

The Sun originated from matter left over from an older star that imploded, producing of heavier elements then H and He.

The subsequent **Supernova** (explosion during which most of the lighter matter is expelled from the system to outer space) left a dense cloud of matter (H, He, C, O, N, Si, Fe....). This cloud has cooled down and condensed to build the **Planetary Nebula** or Stellar Nebula, and eventually condensed further by gravitation to build the Sun and the planets at about 4.6 billion years ago.
Introduction to Ore Deposits

The Sun consists mainly of H and He. The high density concentration of H and the high temperature in the centre of the Sun result in nuclear fusion and in burning of hydrogen and production of helium:
Beginning at c. 1 000 000 K → nuclear fusion: H→He→C......

Acquisition of protons and addition of neutrons

At c. 1 000 000 K → nuclear fusion: H→He→C......Fe
Surface temperature of the Sun = 3000 to 20000 K, the inner temperature is several millions K, Life expectation of the Sun is c. another 5-10 billion years.

<table>
<thead>
<tr>
<th>Elemental concentration (% mass) in the Sun</th>
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<tbody>
<tr>
<td>H</td>
<td>78.5%</td>
</tr>
<tr>
<td>He</td>
<td>19.7%</td>
</tr>
<tr>
<td>O</td>
<td>0.86%</td>
</tr>
<tr>
<td>C</td>
<td>0.40%</td>
</tr>
<tr>
<td>Fe</td>
<td>0.14%</td>
</tr>
<tr>
<td>Si</td>
<td>0.10%</td>
</tr>
<tr>
<td>N</td>
<td>0.09%</td>
</tr>
</tbody>
</table>

Fe is the heaviest element that can originate in a star via nuclear reactions. Heavy elements like Gold, Silver, Titanium, Uranium, originate from addition of neutrons during stellar explosions (Supernovae) at c. 5-10 000 000 K core temperature and formation of Giant Star. "
"Nebula-Hypothesis" (Kant 1724-1804 and Laplace 1749-1827) \(\rightarrow\) the planets are by-products formed from cosmic gas- und dust clouds, left over during the formation of a star:

- Through the angular momentum (rotation) of the gravitationally contracting solar nebula \(\rightarrow\) lighter elements were expelled outwards within the rotation system.
- A disc of proto-planetary dust was formed at a certain rotational velocity and density around the proto-Sun. Through chemical reactions between the elements, mm-large dust particles are formed and collide and bind with each other because of gravitation.
- Discs of varying density, protoplanets (planetesimals) and eventually planets are formed, within few 10‘s of millions of years of accretion.
Introduction to Ore Deposits

Nebula-Hypothesis:
(Kant 1724-1804 and Laplace 1749-1827)

1. The cosmic nebula (cosmic gases) rotates through the rotational momentum...

2. the spin forms a fragmented disc around the primordial, small and faint proto-Sun.

3. mm-size dust particles are formed from the gases through chemical reactions.

4. Dust particles collide and bind with each other through gravitation

5. Within the first few tens million years of initial accretion proto-planets and planetesimals are formed
Introduction to Ore Deposits

Origin of the Planets:

“Nebula-Hypothesis” \(\rightarrow\) Planets = By-products of gas- and dust clouds left over from the birth of the Sun:

- through the rotational momentum of the gravitationally contracting solar nebula \(\rightarrow\) low mass elements are concentrated in the outer rings, around the proto-Sun. At increasing rotational velocity and density the rotating matter forms a rotating disc.
- Discs of different densities (Planetesimals) are formed at different distances from the proto-Sun. From these discs, different planets are formed through gravitation, at different orbits, within the first few tens of millions of years.

The composition of terrestrial planets:
**Heterogeneous Accretion Theory:** Dense, heavy elements accreted first and built the core of the Earth, followed successively by lighter elements.

**Homogeneous Accretion Theory:** Accretion of all terrestrial elements from a homogenous dust cloud and subsequent separation according to density, after melting:

Melting of the terrestrial material through impact and collision energy, pressure and bulk mass rise, and radioactivity. Temperatures over 1200°C led to a **magma ocean** on the surface and thorough melting, down to the core. In the core, temperatures of over 1500°C. Differentiation in the melt, depending on density of the elements. → solid core because of increased pressure

99% of the Earth mass are represented by 8 elements:

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<th>Mass %</th>
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<td>Mg</td>
<td>13%</td>
</tr>
<tr>
<td>Al</td>
<td>1.1%</td>
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HETEROGENEOUS ACCRETION

Accretion of the core
Accretion of the mantle
Final bombardment of silicated material

HOMOGENEOUS ACCRETION

Differentiation of the core and final bombardment of homogeneous material

Figure 10: The two competing scenarios for the formation of the Earth.
The silicate envelope of the Earth is c. 2900 km thick = 70% of the Earth’s mass and 84% of the volume.

The metallic core = c. 3490km radius = 30% of the Earth’s mass.

The silicate envelope of the Earth is subdivided into 5 - 40km thick, Earth Crust (only 0.4% of the mass) and the Earth Mantle (Peridotite, Ol+Px+Gt, Mg-, Fe-Silicates).

The Earth crust is the result of partial melting of the Earth mantle. The Earth crust is subdivided into the 5-10 km thin, basaltic Oceanic crust and the much thicker, granitic Continental crust. (The Oceanic Crust is basically equal to the extruded Earth mantle)

The core of the Earth is subdivided into the outer, liquid core and the inner, solid, metallic core.
In the first 15 Ma (4.565-4.550 Ga) “Planetary Embryos” and Planetesimals, contributed the vast majority of the matter forming the Earth. Gravitational accretion within the proto-planetary disk of the early Solar System, collisions and amalgamation of matter were the most important processes.

Fig. 1.1-1. Chronology of major events during formation of the solar system and the early Earth (see section 1.2 for further details).
Introduction to Ore Deposits

• The ore-bearing fluids
  – Magma and magmatic fluids
  – Hydrothermal fluids
  – Meteoric waters
  – Seawater
  – Connate waters
  – Metamorphic waters
  – Thermal springs
Introduction to Ore Deposits

- Magma and magmatic fluids

Figure 2-3. Schematic illustration of probable early behavior of a cooling gabbroic liquid. Crystallization and settling out of gabbro silicates moves the composition of the liquid as shown by the arrow. This diagram, as well as those of Figures 2-4 to 2-6, is schematic only and not to scale. Liquid and liquidus paths imply progressively falling temperatures from about 1200 to 800°C.
Introduction to Ore Deposits

- Magma and magmatic fluids

Figure 2-4. The same system as in Figure 2-3, but showing two-liquid fields. The addition of CO₂, for example, may generate three-or-more-liquid fields. The shaded area is described in Figure 2-6.
Figure 2-5. Experimentally determined tie lines within the two-liquid fields describe the compositions of each liquid. For example, at the moment of first separation, the silicate liquid composition is $a$, the sulfide liquid $b$. Had the melt contained more sulfur to start with, the pair $c-d$ might have formed first.
Introduction to Ore Deposits

- Magma and magmatic fluids

Figure 2-6. Two crystallization paths, one of any starting composition in the shaded field that keeps the melts mutually soluble and involves only solid phases in equilibrium with one liquid and vapor, the second involving two liquids. In the former, silicates crystallized, for example, from r to s are joined at p-q on the magnetite-silicate eutectic line by a spinel, with crystallization proceeding to the eutectic e where silicates and oxides are joined by minor late sulfides. From point j a separation of silicates would move the liquid to point k, where a second liquid of composition l would form. The two liquids would evolve with further cooling (and by removal of silicates and sulfur-rich liquid) toward the oxide apex. At m the system would progress as just described, toward q and finally to e. But in this latter case, a sulfide melt of composition l toward m, probably carrying copper and nickel, would be produced and would be transiently available for settling, injection, or both as an ore magma.
The ore-bearing fluids

(Mantle or crustal melting. Mafic magma includes silicate >> oxide, sulfide components. Along subduction zone, under or within continental crust, or in oceanic crust)

Figure 2-1. Schematic of a sequence of early magmatic events leading to ore magmas and their emplacement. The diagram generally extends to perhaps diorite stages of differentiation in the magma portion at the right. See also Figures 2-3 to 2-7. (Adapted from diagrams by A. J. Naldrett.)
The ore-bearing fluids

Timing

(Early)

Liquid immiscibility

Sulfides (Sudbury)
Oxides (Bushveld, Kiruna)
Carbonatites (Palabora)

(Mid)

Rest magma

Early Differentiates
Gravity concentrates
Crystal settling (Skaergaard, Bushveld)
Differential magmatic sedimentation (Bushveld?)
Late liquid gravitational accumulation (Allard Lake)
Filter pressing (Sanford Lake)

(Late)

Hydrothermal systems

Meteoric water

Late stage fluids

Juvenile magmatic water

Porphyries
Copper
Molybdenum

Pegmatites
500-300°C

Geothermal steam,
hotsprings,
fumaroles,
vein fillings,
replacements,
exhalites
350-100°C

Intrusive:

Dunite, peridotite,
gabbro, norite

Diorite, quartz diorite,
monzonite, quartz monzonite

Granite (syenite)

Extrusive:

Komatiites, basalts

Andesite, dacite,
lavite, quartz latite

Rhyolite (trachyte)

Associated metals:

Cr(ox)  Ti, V, Fe(ox)  W, Mo, Sn, Cu, Zn, Pb, Mn, Ag, Au  Sn, U, W, Be, Nb, Ta, Li
The ore-bearing fluids

Hydrothermal ores can be:

**Epithermal:** hydrothermal, formed at shallow depth, < 1500 m and at low temperatures < 200 °C

**Mesothermal:** hydrothermal, formed at intermediate depth of 1500 to 4500 m and at temperatures of 200 to 400 °C

**Hypothermal:** hydrothermal, formed at significant depth, >4500 m and at temperatures of 400 to 600 °C

However, temperature (geothermal) gradients may strongly vary locally!
Introduction to Ore Deposits

• Ore-bearing fluids gradually change as they migrate from its source:
  • Chemical composition
  • Eh (activity of electrons; redox-potential)
  • pH (activity of hydrogen ions; acidity)
  • sulfur fugacity
  • etc., changes due to reaction with the wall rock.

• Temperature and pressure decreases upward.

➢ causes the precipitation of different minerals
Geologic occurrence and sources of mineral commodities by broad genetic class

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<th>Commodity</th>
<th>Mafic</th>
<th>Intermediate-Felsic</th>
<th>Pegmatitic</th>
<th>Hydrothermal</th>
<th>Volcanogenic</th>
<th>Chemical Sedimentation</th>
<th>Mechanical Sedimentation</th>
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How is plate tectonics related to the formation of ore deposits?
Igneous Ores:

Different magma types produce different metal enrichments:

As magma is generated at two major settings, oceanic crust and continental crust, both being characterised by mafic or felsic magmatism respectively, different ore deposits must be expected in continental and in oceanic crust setting.

Chalcophile and siderophile elements like Ni; Co; Pt; Pd; Au, are more likely to be associated with mafic rock types. Their greatest concentration is situated within the core and the mantle and not accessible for mining. On the other hand, c. 75% of the crustal rocks are mafic, oceanic crust rocks.

Figure 1.1 Oceanic crustal architecture showing the main types of ore deposits characteristic of this environment. Only chromite and related deposits (Cr–Ni–Pt) are related to igneous ore-forming processes; VMS (Cu, Co, Zn) and sediment-hosted deposits (Mn, Co, Ni) are discussed in Chapters 3 and 5 respectively.
Continental crust magmatism:

Lithophile elements as Li; Sn; Zr; W; U are typically found within felsic or alkaline magmatic rocks.

Continental crust is typically 35-40 km thick but pinches out to c. 20 km at rift zones, and swells to >80 km beneath young orogens.

Continental crust is subdivided into upper, largely granitic zone and a lower, more mafic zone, separated by the Conrad discontinuity at c. 6-10 km depths. The upper, granitic zone is less dense (slow seismic velocities) and the lower zone is of higher density layer (fast seismic velocities) below. However, the situation is more complex and continental crust may include in its upper zone various parts of continental and oceanic fragments amalgamated and obducted during 3.8Ga of Earth history. Furthermore, continental deep drilling did not reveal significant material differences across the Conrad discontinuity.

The lower continental crust between the Conrad and Mohorovicic discontinuities is variable in composition and can be similar to the upper crust, but is typically hotter and denser because of geothermal gradients of pressure and temperature at amphibolite facies and above it. It is thus, also anhydrous and residual in the sense of fractional crystallisation, containing gabbro, anorthosite, amphibolite and granulite.

Typical continental crust deposits are: Kimberlites (diamonds); anorthosite hosted Ti deposits; layered mafic intrusions with Cr-V-Pt-Cu-Ni ores; granitic and alkaline intrusions with Sn-W-F-Nb-REE-P-U enrichment.
Melts within the continental crust can descend from various sources:

• mantle,
• subducted oceanic crust and sediments,
• deep rift systems behind subduction zones (back arc basins),
• crustal melting itself.
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<th>Alkaline magma</th>
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If no average is available, a range of values is provided. *Clarke is a term that refers to the average crustal abundance.
†Values as ppb, all other values as ppm.
Ore deposits associated with mafic igneous rocks are typically of siderophile and chalcophile elements such as: Ni; Co; Cr; V; Cu; Pt; Au...

These elements are enriched in basaltic magma.

Felsic magmas vary in composition and can have a complicated differentiation history but also assimilate large parts of crustal and sedimentary rocks, thus enriching lithophile elements such as: Li; Be; F; Sn; W; U; Th....
Most significantly granitoid magmas control the associated mineralization according to magma origin as the mineral wealth is inherited from the molten rock protolith: Magmas descending from sedimentary rocks (*S-type granites*) are associated with concentration of Sn; W; U and Th.

Magmas derived from melting of igneous rocks (*I-type granites*) are associated with metals rather concentrated in basalts, such as Cu; Mo; Pb; Zn; Au.

Magmas that are depleted in SiO₂ but highly enriched in alkalies (K; Na; Ca) like nephelinitic, kimberlitic - lamproitic, calc-alkaline magmas, are enriched in Cu; Fe; P; Zr; Nb; REE; F; U; Th. Such magmas are usually mantle derived (mantle plumes) but may display strong crustal assimilation. They occur in continental crust settings, but e.g. nephelinites can also be found in oceanic settings like Hawaii or Cap Verde islands.
I-type and S-type granites formed in orogenic belts exhibit pronounced provinciality:

I-type granites are generally metaluminous and of tonalitic - quartz-dioritic - granodioritic composition. They are more oxidised (higher magmatic fO₂, measured as Fe₂O₃/FeO ratio). I-type granites are usually located closer to the oceanic side of the magmatic arc.

S-type granites are often peraluminous and of adamellitic - quartz-monzonitic - granitic composition. They are lower oxidised than I-type (low magmatic fO₂, measured as Fe₂O₃/FeO ratio). S-type granites are usually located on the continental side of the magmatic arc.

The reduced, ilmenite granites are associated with Sn-W deposits while the more oxidised magnetite granites are associated with porphyry Cu-Mo (Pb-Zn-Au) mineralisation.

Alkaline, anorogenic, post-tectonic granites, however, can be polymetallic and contain both, base metal and Sn-W mineralisation.
Figure 1.11 Generalized scheme that links granite compositions and magmatic oxidation state to metal associations and intrusion-related ore deposit types (modified after Barton, 1996). Ore deposit types referred to are “alkalic,” “porphyry,” and “lithophile” and are discussed in more detail in Chapter 2. Metals shown in bold reflect the more important associations.
Mantle metasomatism:

The enrichment of metals in calc-alkaline magmas can occur via mantle metasomatism, whereby volatiles and incompatible elements with large ionic radii are enriched in peridotites. This can be seen in some mantle xenoliths, in basalts, where secondary infiltration of fluids into peridotites occurred.

It is assumed, that the fertile lower mantle transfers its constituents into the depleted upper mantle, by rising plumes enriched in H$_2$O, C and LIL elements (mantle fertilisation).

Mantle fertilisation with base and precious metals can lead to enrichment of these metals in calc-alkaline magmas produced in subduction zones, in the mantle wedge below oceanic island arcs. The mantle wedge in such case consists of metasomatised peridotite with concentrations in base and precious metals, of up to two orders of magnitude higher relatively to unaltered depleted mantle.

Calc-alkaline basaltic volcanism brings these metals to high crustal levels, where they can form epithermal deposits.
Figure 1.9 Schematic diagram illustrating the concept of mantle metasomatism and metal enrichment associated with subduction, and the subsequent inheritance of an enhanced metal budget by magmas derived from melting of metasomatized mantle. Metal abundances of the relevant rock types (in ppm) are from McInnes et al. (1999); the two analyses showing metal abundances for the magmatic products of subduction refer to basalt (b) and syenite (s).
Ore deposits in global tectonic context

Proterozoic

1000

Giant radiating dikes: the Mackenzie swarm
Partial breakup of supercontinent Nuna & reorganization towards Rodinia

First redox sensitive "unconformity-type" U deposits

Progressive amalgamation of Earth's first "modern" supercontinent: Nuna

Gunflint microfossils
Oldest sedimentary exhalative (SEDEX) Pb-Zn deposits
Oldest phosphatic stromatolites (Aravalli, India)
Bushveld layered intrusion
First widespread evaporite deposits and continental red beds (ca. 2300-2200 Ma)
Sediment-dominated passive margin sequences, abundant Stromatolites worldwide
Extension, progressive rifting and break-up of late Archean supercratons & dispersal of numerous Archean continental microplates
Paleoproterozoic glaciations, at least three cycles (e.g. Huronian and Snowy Pass supergroups)
Matachewan giant radiating dyke swarm and correlative swarms on other cratons
Great BIFs (banded iron formations), e.g. Hamersley & Transvaal Basins
Archean-Proterozoic boundary (defined)

Neoarchean

-2575

2575-2580 Ma: widespread (global?) flood basalt volcanism & komatiites
2775-2700 Ma: widespread (global?) flood basalt volcanism & komatiites
Ca. 2600-3100 Ma: widespread transient stability of early Archean continental nuclei, as indicated by numerous quartzite-BIF-komatiite cover sequences on basement e.g. Central Slave Cover Group (Slave craton), Manjeni Fm. (Zimbabwe craton)
Steep Rock succession: well-developed stromatolitic carbonate platform

Mesoarchean

-2680-2580 Ma: widespread strike-slip faults: rigid plate behavior
Oldest recorded eukaryotic biomarkers

Archean

Fig Tree & Moodles Groups, Barberton greenstone belt

Barberton greenstone & metavolcanic rocks
Ore deposits in global tectonic context

Core crystallization: ±6% complete (by mass)
- Plutonic igneous rocks
- North Atlantic Igneous Province, Paleocene-Eocene thermal maximum
- Chicxulub impact & major extinction
- Deccan flood basalts
- Ontong-Java flood basalts & onset of Cretaceous normal polarity interval (124-83 Ma)
- Central Atlantic large igneous province & initiation of rifting of supercontinent Pangaea
- Siberian flood basalts & Major extinction
- Permo-Carboniferous glaciations

Progressive amalgamation of supercontinent Pangaea

Late Ordovician glaciations
- Amalgamation of supercontinent Gondwana
- Cambrian radiation & first shelly metazoan fossils
- Ediacaran faunas

- Neoproterozoic glaciations ("Snowball Earth states")
  - possibly four discrete cycles

- Progressive rifting of supercontinent Rodinia
- Major period of atmospheric oxygenation (ca. 850-500 Ma)
- Worldwide stromatolites

Progressive amalgamation of supercontinent Rodinia

Abundant phosphorites
- (ca. 580-500 Ma)

Mineral Evolution: Stages 1 to 10

Stage 10
Stage 9
Stage 8
Stage 7
Stage 6
Stage 5
Stage 4
Stage 3
Stage 2
Stage 1
Ore deposits in global tectonic context

One of the most important observations in metallogeny of ore deposits is that there is a clear relationship of the variety of ore deposits to Earth history and to global (plate) tectonic context.

The first, rough subdivision is that of “orogenic” and “anorogenic” deposits:

Orogenic deposits including orogenic Au, volcanogenic massive base metal sulphides (VMS) are concentrated in the Archean and in the Phanerozoic.

Anorogenic deposits including different continental magmatic deposits, SEDEX, MVT or SSC deposits are dominantly Proterozoic and Phanerozoic and coincide with periods of crustal stability and supercontinents such as Nuna; Rodinia or Pangea.

The reason for these rough patterns is manifold, including orogenic cycles (Wilson cycles), the degree of exposure of continents and orogens (denudation and preservation factor) and exogenic factors.

E.g. the deep erosive level of greenstone belts on Archean continents makes deposits originated at deep crustal levels available. The deeply eroded Proterozoic collisional orogens might have lost their mineral deposits through erosion, but less eroded Phanerozoic orogens preserve such deposits.
Beware! The above diagrams are not universally valid but just present a conceptual model depending on the uncertain interpretation and classification of various ore deposits. Nevertheless they roughly depict a clear relationship between the metallogeny and plate tectonic - Wilson cycles even if not all mineral deposits are included in this diagram (e.g. Archean MVT) deposits and not all are unequivocally classified.
Other factors influencing global mineral deposit distribution in time and space are:

- **Long term global tectonic trends such as:**
  - Continental growth rates
  - Nature of mantle convection
  - Eustatic sea level changes and continental freeboard

- **Evolution of the hydrosphere and atmosphere**

- **Evolution of the biosphere**

- **Secular decrease in global heat production**
Continental growth rates are reconstructed from Sm-Nd models, U-Pb-Zircon ages of continental crust and models of crustal recycling and crustal production. Three main models exist, in which the continental crust grew rapidly in the early Archean (A), or exponentially in time (B), or episodically but roughly linear, during Earth’s history (M&B; McCulloch & Bennett, 1994).

Yet another model, suggests that c. 50-60% of the continental crust was produced during the Archean in 2 major episodes at 3.6 to 3.5 Ga and 2.8 to 2.6 Ga. and the rest in the Proterozoic at 2.0 to 1.8 Ga and 1.1-1.0 Ga and only a small proportion was added in the Phanerozoic.

These episodes however, correspond to major orogenic (Wilson) cycles. The latest supercycle producing large crustal volumes and Pangaea.
Continental growth rates:

As most of the accessible mineral deposits are located on continents, production of new continental crust directly affects the rates and episodes of ore deposit generation through magmatic and hydrothermal processes. Periods of rapid continental growth are periods of intense magmatic activity. Orogenic mineral deposits will be formed during orogenically active times while anorogenic deposits in times of continental stability during supercontinental cycles.

Figure 6.7 Schematic diagram showing the approximate timing of amalgamation and dispersal of the major continents through time (after Rogers, 1996).
Nature of mantle convection:

Basically two models for mantle convection exist:

One suggests overturn of mantle material in two discrete layers with almost no exchange between these layers. In such overturn, continental growth occurs mainly by ocean crust subduction, volcanic arc development and accretion in Wilson cycles.

The second model suggests rapid mantle overturn of the entire mantle mass, due to a major downwelling of a cold lithospheric slab and simultaneous uprise of large mantle plumes. Such overturns coincide with major orogenic events, such as at 2.8, 2.0, 1.0 or 0.3 -0.2 Ga (MOMO model - Mantle Overturn and Major Orogeny) and with alkaline magmatism and related ore deposits.
Eustatic sea level changes and continental freeboard:

Eustatic sea level changes and continental freeboard are invariably connected to mid ocean ridge magmatism and orogenies and periods of stability of oceanic and continental crust. Continental freeboard is reduced when average ocean depth increase. Large shelf or epeiric seas preserve sedimentary environments and associated mineral deposits.

At shallow average ocean depth continental freeboard is increased and shelf areas are emerged and free to erosion. Related shelf deposits, such as SEDEX or MVT have no chance to build up or to be preserved.

**Figure 6.6** Pattern of Wilson cycles, reflecting Pangean assembly and fragmentation during the Phanerozoic Eon (and into the future), and showing water depth of the continental shelf (after Nance et al., 1986).
Hydrosphere and Atmosphere:

The evolution of the atmosphere and hydrosphere concerns mainly the $O_2$ and $CO_2$ content, that rules the precipitation patterns of Fe, the mobility of Fe$^{2+}$ and U, and the weathering patterns and thus supergene enrichment of minerals. Mineral deposits and rocks like BIF, Mn-BIF, placer deposits of Au and U are affected by the evolution of the atmosphere and hydrosphere.

Evolution of the biosphere:

The biosphere has a two fold effect on mineral deposits formation:

Firstly, through changes to oxidation state of the hydrosphere and atmosphere (comp. above). Secondly, in active oxidation and reduction and precipitation processes of metals as carbonates, oxides or sulphides, by various bacteria like cyanobacteria, SRB, Fe-oxidising bacteria etc... In many sulphide and supergene deposits the importance of bacterial activity is still not well understood.
Decrease in global heat production:
The production of heat from the Earth by radioactive decay of long lived isotopes (U, Th; K..) was 2 or 3 times greater during the Archean than today. The mantle therefore, must have been hotter by 200-300°C than today. This led to high Mg-komatiites and related Ni-Cu deposits. In general, volcanism and plutonism must have been more voluminous (compare crustal growth).

The convective overturn of the mantle and the plate tectonic movement were faster and the Archean oceanic crust might have been significantly thicker, and consequently the oceans shallower. As a result, the continents were flooded and wide shelf seas developed with BIF, carbonates and related mineral deposits.

Because of the foregoing considerations metallogeny of mineral deposits is strongly related to the evolution of the Earth and its different time-stratigraphic periods.
**Archean ore deposits:**

In terms of crust formation the Archean can be subdivided into two periods, the earlier period of shield formation (3600-3100 Ma) and the subsequent period of cratonisation (3100-2500 Ma).

The oldest VMS deposits and Algoma-type BIF belong to this stage of amalgamation of oceanic crust and volcanic arcs, and of incipient continental crust formation by emplacement of tonalite-trondhjemite-granodiorite (TTG) plutons.

The oldest subeconomic ores are located in the Isua greenstone belt, Greenland. Metavolcanics and metasediments at 3.8 Ga contain BIFs in amphibolite facies but also minor Cu-Fe sulphides and scheelite in calc-silicate rocks, suggesting submarine exhalative origin. The “Big Stubby” VMS in the Warrawoona Group metavolcanics at 3.46 Ga, represents probably the oldest known mined ore.
The time of cratonisation between 3.1 and 2.5 Ga is also the time of enhanced crust formation and major global mineralisation.

The early stage of this period involves accretion of island arcs onto the previously formed shield and stabilisation of the shield by intrusion of large granite batholithes. The later stage develops cratonic terranes including major suture zones - the greenstone belts, and development of passive and active (continental) margins flanking these cratonic terranes, on which intracratonic sedimentary basins develop.
The later stage of Archean crustal evolution introduced a wide variety of ore forming processes within the granite-greenstone terranes and sedimentary basins:

- VMS deposits in caldera settings and MOR related settings
- Algoma BIF
- Komatiite related Ni-Cu-Fe deposits
- Orogenic gold deposits
- Serpentine-asbestos deposits within greenstone belts
- Carbonate deposits on stable shelves
- Lake Superior BIF
- MVT deposits on carbonate platforms
- Heavy mineral placers in intracratonic basins.

Plate tectonic reconstructions for the Archean are entirely unreliable and need to be treated with care!
The Proterozoic Eon is regarded as the period of continental stabilisation. However, orogenetic processes were active during the long period of the Proterozoic (e.g. Eburnean-Barramundi at ~1.8 Ga; Grenvillian at ~1.0 Ga; late Pan African 0.8-0.6 Ga). On the other hand, the oxidation of the atmosphere has influenced the sedimentary ore deposits significantly eliminating one type of deposits (e.g. BIF; Uranium) and facilitating supergene oxidation of weathering horizons and providing oxygenated meteoric waters for mixing processes with hydrothermal fluids.

The first Supercontinent Rodinia was formed and dispersed during the Proterozoic.

- Deposition of Lake Superior BIF
- Large layered intrusions in to continental crust (Bushveld, Great Dyke, Cr; PGE; Fe, Ti, V; Sn; W;...)  
- Alkaline complexes as Phalaborwa (Cu; Fe; P; REE)  
- MVT and hydrothermal Pb-Zn-F  
- Porphyry copper  
- Giant SEDEX deposits (Mt. Isa, H.Y.C.) Broken Hill; Aggeneys; Gamsberg; Sullivan)  
- Hydrothermal Fe-Cu-Au deposits (Olympic Dam)  
- Snowball Earth BIF and Mn deposits

~ 750 Ma
The Phanerozoic Eon:
The Phanerozoic is characterised by the assembly and dispersal of the Permian supercontinent Pangea, a process much better understood than Precambrian paleogeographic reconstructions. Pangea was surrounded by active, Andean-type subduction zones, consuming the Panthalassa oceanic crust and by narrow shelves.

The E-W stretching embayment of the Tethys ocean was an active marginal oceanic basin with wide shallow platforms and movement of terranes towards the north.

All modern type of mineral deposits, continental and oceanic, orogenic and anorogenic and sediment hosted or sedimentary formed during the Phanerozoic:

Volcanogenic, hydrothermal, magmatic... VMS; SEDEX; MVT; Evaporites.... black shales, carbonates... Porphyry, Skarn, Au..., Kupferschiefer...., Supergene; Lateritic, Placer...
Relative abundance of different deposits with time and respectively of Phanerozoic Wilson cycles.
Initial rifting of continental crust:

may be related to hotspots and mantle diapirs/upwelling. Magmatism will then be alkaline or ultrapotassic (kimberlites, lamproites).

Anorogenic granites are differentiates of mafic intrusions such as Bushveld (Sn; W; Mo; Cu; F; P; REE; U; diamonds; etc.)
Developed intracontinental rifts:

SEDEX - Pb-Zn-Ba-Ag deposits, Kupferschiefer and black shales related deposition; SSC - deposits, carbonate platforms at the margins. VMS type brines along the spreading ridge at more evolved stages and MVT deposits at carbonate platforms.
Mid Ocean Ridge and oceanic hot spots:

VMS deposits; black smokers (Cyprus-Troodos type); Archean Algoma BIF; and manganiferous sediments. When MOR basalts undergo fractional crystallisation sub-volcanic, magmatic lenticular (podiform) Cr deposits and Cu-Ni-PGE sulphides may form.
**OROGENIC - COLLISIONAL SETTINGS**

**Andean type subduction**

I-type granite intrusions on the subduction trench side of the arc, with porphyry Cu deposits and eiptehrmal Au deposition in the volcanic arc. S-type granites with Sn-W mineralisation and related polymetallic skarn deposits on the continental side.
Oceanic island arc subduction:

Porphyry Cu-Au deposits in initial stages, evolving to calcalkaline bimodal Kuroko type VMS deposits. In the back arc, extensional regime prevails and fractional crystallisation of basaltic magmas can form lenticular (podiform) Cr deposits and Cu-Ni-PGE sulphides and VMS deposits (similar to MOR setting). The back arc can develop MOR activity giving rise to an island arc setting with oceanic crust - ophiolite formation. Closure of the back arc and obduction can form orogenic gold deposits.
Continent-Continent collision (Himalayan-Alpine-type)

S-type granites and related deposits, stratabound scheelite, orogenic gold and thrust related (MVT) Zn-Pb deposits. Fe-Ti-anorthosite through thrusting and crustal underplating and crust thickening.
Figure 1.8 Schematic diagram illustrating features pertinent to the formation of diamond and the fertilization of the Earth’s mantle by plume-related magmas and their associated aqueo-carbonic fluids (after Haggerty, 1999). LILE refers to the large ion lithophile elements; FMQ refers to the fayalite–magnetite–quartz oxygen buffer.