British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Meeting future global demand for minerals

Supply challenges and possible solutions

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Talk Outline

- Introduction and definitions
- Demand for minerals – what are minerals used for and what are the drivers changing demand
- Supply challenges
- Minerals supply – how much is left (what we know, what we don't know)
- Technical supply solutions
- Conclusions

What are minerals?

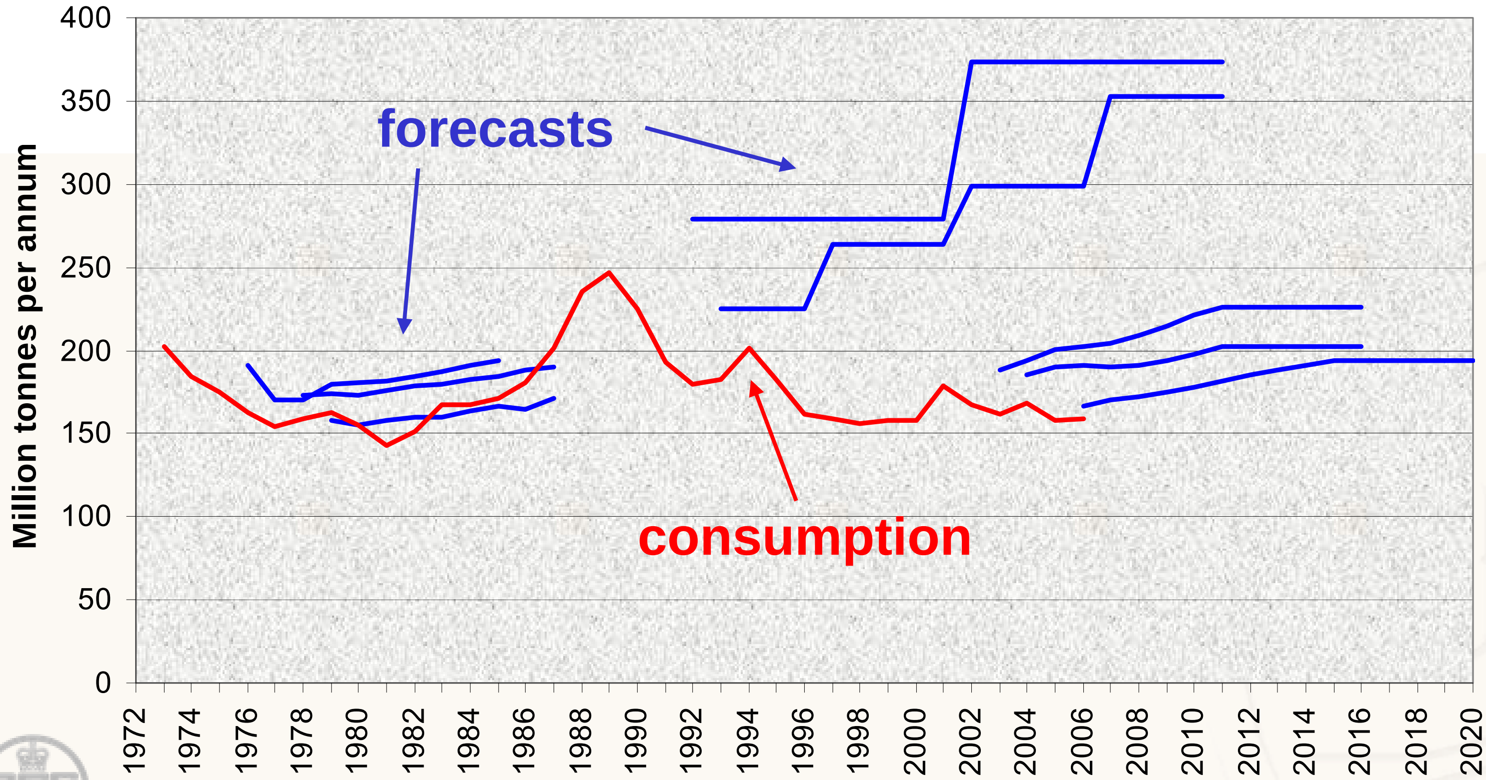
1. Metals - rare, difficult to find, expensive
2. Energy minerals – coal, oil and natural gas
3. Industrial minerals - non-metallic, such as salt, china clay, fluorspar
   - occur in large quantities in a few places
   - require specialised processing and are expensive
4. Construction minerals - sand and gravel, crushed rock, brick clay
   - deposits are extensive and common
   - transportation is economical over short distances only

Minerals are all around us

- Food – fertilisers, drinking water, food preparation and packaging
- Energy – vital for all industries, transport, power generation, heating
- Construction – in the developed world for houses, schools, shops, hospitals, etc
- Transportation – roads, railways, airports, cars, buses, trains, ships and aircraft
- Technology and communications – computers, telecommunications, electronic applications
- Globally we produce approximately:
  - 15.5 million tonnes copper
  - 1.6 billion tonnes iron ore
  - 6 billion tonnes coal

How much will we use in the future?

- Demand forecasting is difficult, but is needed to guide decision/policy making
- Need to look to the past, but also anticipate the future



Forecast demand versus actual consumption for construction aggregates in England

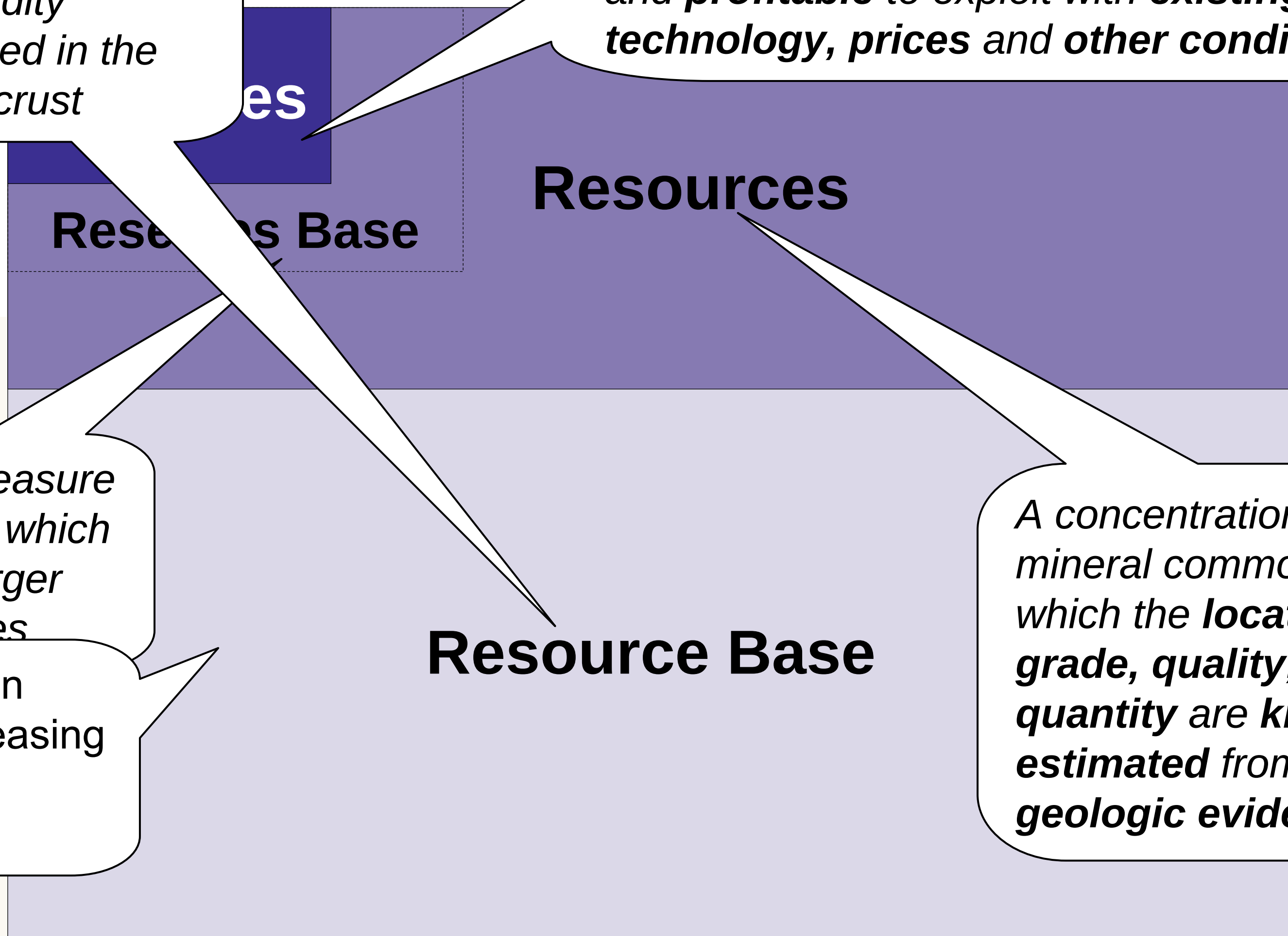
Supply of natural resources – mineral deposits

- “If it can’t be grown it has to be mined”
- Mineral deposits are rare concentrations in a small volume of the earth’s crust of potential economic value
- Uneven global distribution
- Minerals are where you find them – you can’t locate a mine anywhere!

Mineral resources and ore reserves

- Clarity and consistency of definitions amongst:
  - user groups
  - globally (variation in ‘codes’)

Mineral resources



All of a mineral commodity contained in the earths crust

*The quantity of a mineral commodity found in subsurface resources, which are both **known** and **profitable** to exploit with **existing technology, prices** and **other conditions***

*A related measure to **reserves** which is slightly larger than reserves*

Sub-divided in order of increasing **geological confidence**

*A concentration of a mineral commodity of which the **location, grade, quality**, and **quantity** are **known** or **estimated** from specific **geologic evidence***

Drivers of increased demand for minerals

Global population growth

- 6.5 billion in 2005
- UN forecast 9.1 billion by 2050 (40% increase)
- Today 95% of population growth in developing world
- By 2050 population of developing world increasing by 34 million p.a.

Standard of living

- Per capita consumption of most minerals has increased in most countries in the past century
- Rapidly developing BRIC economies require minerals for construction, manufacture, energy, agriculture, etc.
- USA, Japan, Europe use proportionally less
- Unprecedented urbanisation forecast to continue in China
  - 221 cities with > 1 million inhabitants by 2025
  - up to 50 000 tower blocks, and associated infrastructure

New markets for minerals

- new or expanding technologies
  - PGE in autocatalysts and fuel cells
  - indium in flat screen displays
  - tantalum in electronic devices
  - lithium in Li-ion batteries for transportation

Expanded markets for existing applications

- Growing economies
  - minerals for construction, manufacturing, power generation, transportation, etc
- Global warming
  - aggregates and concrete products for flood defences
  - metals and energy minerals for cooling applications, including underground mining
  - limestone for flue gas desulphurisation (FGD)
  - uranium for nuclear power generation
  - fertilisers for agriculture

Drivers of reduced demand (or changing geographic pattern of demand)

- Higher costs leading to higher prices
- Increased recycling
- Pollution controls e.g. lead in petrol; coal; asbestos, etc
- Substitution e.g. plastics and fibre optics for copper
- Increased efficiency and intensity of use – doing more with less
- Economic conditions – global recessions and regional events

Supply challenges

Sustainable development and environmental challenges

- To meet increasing economic demand while maintaining environmental protection and community benefits
  - now and in the future
- Mining deeper, lower grades, larger scales, new ore types, new sources of supply
  - increased carbon footprint
  - pollution and health risks
  - require innovative solutions for mining, processing, transportation and waste management

Resource accessibility and ‘licence to operate’

- Competition for land and sterilisation of resources
- Social acceptability
  - operators need understanding and support of local communities
  - ‘licence to operate’
- Politics, legislation and regulation
  - security and stability are key
  - resource nationalism

Economic issues

- Global economic conditions (cycles and crunches)
- Increasing capital and running costs
- Former exporting countries (BRIC) becoming importers
- Threats to security of supply
  - especially in EU and Japan
  - traditional sources no longer available, no indigenous supplies
- Shortage of labour
  - in Australia – demand for staff forecast to rise from 128,000 in 2008 to 215,000 in 2020 (**68% increase**)

Technical challenges

- New discoveries required to replace depleted deposits
- **Where to explore and how to explore**
- When to explore
- Energy supplies e.g. southern Africa
- Water supplies e.g. Andes; southern Africa; Australia
- Equipment procurement
  - exploration, mining, processing & transport
- **Processing and beneficiation**
- Infrastructure availability
- Artisanal and small-scale mining
  - better regulation and training
  - technical improvements

Minerals – how much is left?

“The Limits to growth”

- *An Essay on Principal of Population* (Malthus, 1798)
- *The Coal Question … and the Probable Exhaustion of our Coal Mines* (Jevons, 1865)
- Presidents Material Policy Commission (1950-1952)
- *The Limits to Growth* (The Club of Rome, Meadows et al. 1972)
  “only 550 billion barrels of oil remained and that they would run out by 1990”!!!

“On borrowed time?”

Metal stocks and sustainability (Gordon et al. 2006)

Countdown – are the Earth’s mineral resources running out? **MEM (2008)**

Perspectives on the ‘Environmental Limits’ concept (Turner et al. 2007)

Peak Minerals (Bardi and Pagani, 2007)

Assessing the long-run availability of copper (Tilton and Lagos, 2007)

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Earth’s natural wealth: an audit (Cohen, 2007)

Metal stocks and sustainability – copper (Gordon et al. 2006)

- Estimate the copper the world will require by 2100 if:
  - population reaches 10 billion
  - average stock copper in use per person reaches 170 kg

    = 1.7 billion tonnes copper
- Determine total copper resource
  - cumulative discovery of copper deposits **= ~1.6 billion tonnes**
- *"virgin stocks of several metals appear inadequate to sustain the modern developed world quality life for all Earth's peoples"*

Earth's natural wealth: an audit (New Scientist)

$$\textit{Number Years left} = \frac{\textit{Reserve base}}{\textit{Annual global consumption}}$$

- Conclude - *antimony "will run out in 15 years, silver in 10 and indium in under five"*

Peak minerals?

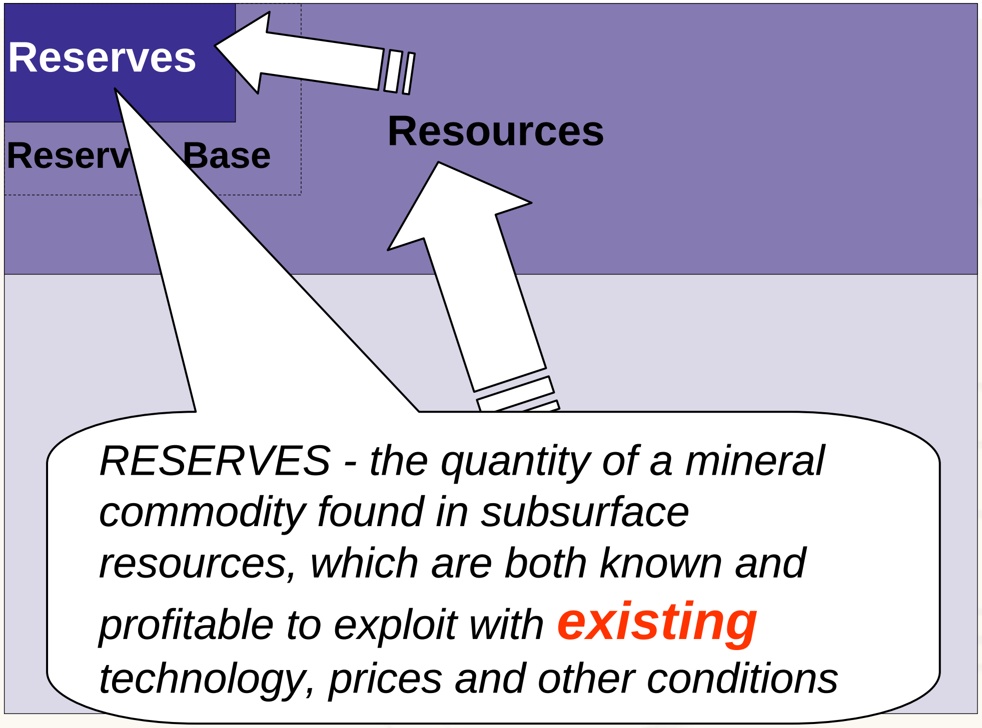
- Hubbert's Peak Theory:
  - production of a commodity peaks when half the extractable resource has been extracted
  - following ‘peaking’ there will be an inevitable decline in production of a depleting resource

- Application to minerals (Bardi and Pagani, 2007):
  - examined 57 mineral commodities
  - *“11 cases where production has clearly peaked and is now declining”* (e.g. Hg,Te, Pb, Cd, phosphate rock)
  - *“most minerals should be peaking in the coming decades”*

Reserves are dynamic

- Fixed stock approach
- Estimates of remaining life expectancies ("how many years left?") based on two critical factors of future uncertainty:
  1. reserve/resource estimates
  2. consumption rate

- Reserves are not static
  - exploration and expansion
  - new deposit types e.g. unconformity related uranium
  - reserves are an "inventory"
  - criteria for resource estimates



The truth about resource scarcity

- Production/consumption rates are unknown
  - do we really envisage a ‘developed’ quality of life for all people on the planet?

- Peak minerals?
  - metals are ‘graded’ resources
  - falling production does not = depletion
  - “Ultimate” global peaks

False assumptions and flawed conclusions

- **Current reserves are unreliable indicators of future availability of minerals**
- **Clear terminology is essential**
- **Falling production is not the same as resource depletion**
- **Investment and policy decisions should be based on high quality data and clear understanding of its meaning**

Company reserves

“Shell to write off half of last year's reserves”

“Pebble mine prospect keeps getting richer”
Anchorage Daily News

“Gold Fields reserves fall on troubled times”

“Tethyan doubles size of Reko Diq”
Mining Journal

“World No.4 gold miner slashes reserves by 11 million oz”

“BHP Billiton ups Olympic Dam resources”

The reality of resource estimations

- So what do we really know?
  - surprisingly little

- USGS – global leaders in the field
  - Mineral Commodity Summaries
    (reserve and reserve base)
  - range of sources
    (inconsistencies)
  - vary widely with time
    (as would be expected)
    e.g. copper

  "recent assessment of U.S. copper resources indicated 550 million tons of copper in identified and undiscovered resources, more than double the previous estimate"

Towards a quantitative global mineral resource assessment

- The Global Mineral Resource Assessment Project (GMRAP) – a major, complex undertaking

  1. Delineating areas for undiscovered resources
  2. Estimating the number of undiscovered deposits
  3. Estimating the amount of resource contained in the undiscovered deposits
     – evaluation of results
     – relies on current geological models
     – snap-shot/how frequently can it be repeated?
     – massive undertaking

Supply solutions - developing and utilising the 'resource base'

Technical solutions

- Mineral exploration – where and how to explore
- Mining technology
- Mineral processing technology
- Recycling and resource efficiency
- Substitution

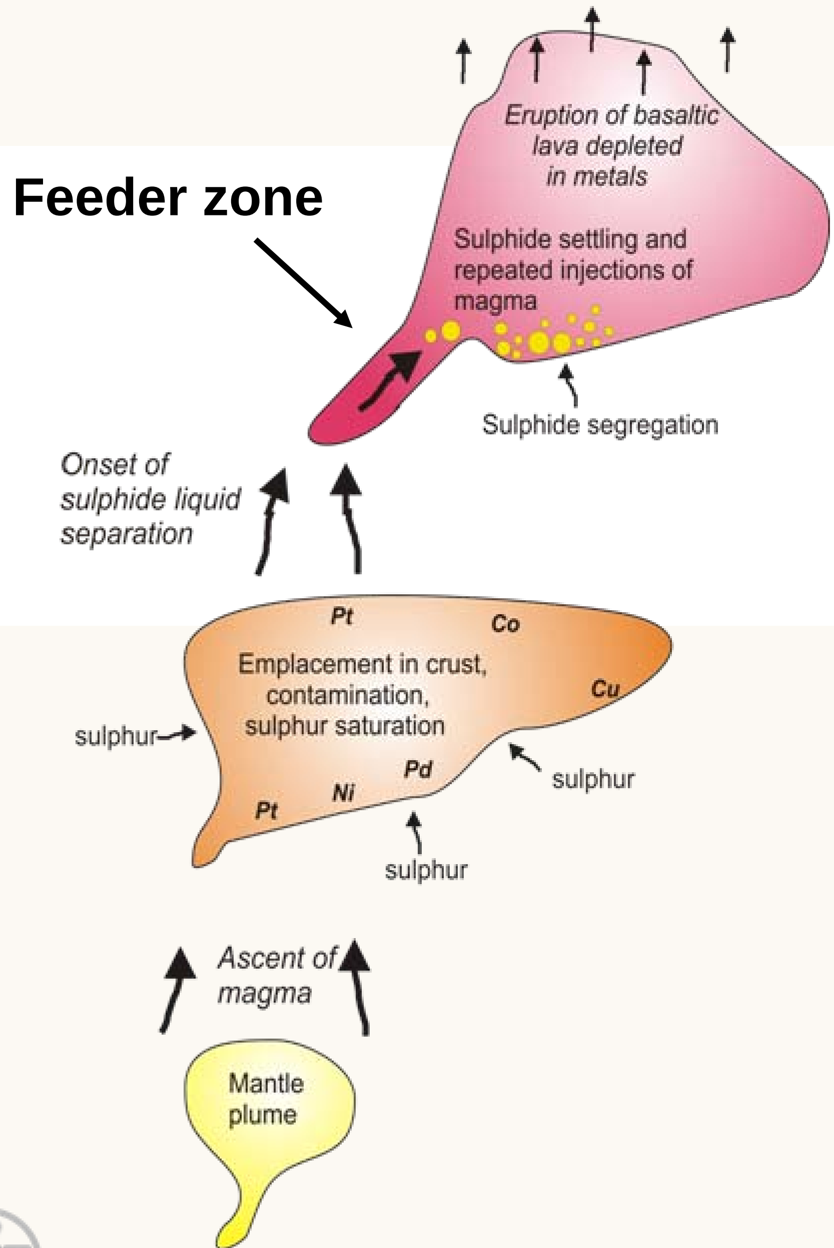
Advances in mineral exploration

- New mineral deposit models
- Where to explore
  - new frontiers
  - new terranes
  - new targets
- How to explore
  - new techniques in data collection, processing, visualisation and interpretation

Mineral deposit models - what are they?

- Systematically arranged information describing the essential attributes of a class of mineral deposits
- Two end-member types:
  - descriptive or empirical
  - genetic or conceptual
- Many commodities and many deposit types

- Deposit type - name, commodities, examples
- Economic characteristics - importance, grade and tonnage
- Geological features - setting, host rocks, morphology, mineralogy, alteration, paragenesis, age of host rocks, age of ore, geochemical and geophysical features
- Genetic aspects - sources of metals, fluids, etc; controls on sites of mineralisation.
- Exploration methodology



Conceptual model nickel – PGE in magmatic sulphides

Mineral deposit models - why are they useful?

- Allow comparison between deposits and classification of new discoveries
- Establish a deposit signature or fingerprint, allowing **prediction** of the location of new targets
- Assist in defining exploration methodology and strategy
- They are dynamic: can be continually refined as more data becomes available

New Frontiers

Resources on the seabed

- Cu-Zn-Au-Ag in massive sulphide deposits in SW Pacific
- Nautilus Minerals (Teck and Anglo)
- Mining planned for end 2010

Manganese nodules and cobalt-rich crusts

- Resources of sea-bed Co and Ni are comparable in size to those on land

Polar regions – minerals in the Arctic

- Arctic has offshore resources of hydrocarbons, but also gold, base metals, iron ore and coal
- Sovereignty issues likely to be critical – regulated under the Law of the Sea (not ratified by USA)

Minerals in Antarctica

- Geology not well known, poorly exposed
- Comparisons with South Africa and the Andes indicate potential for copper, gold, platinum, nickel, chrome, diamonds, iron, etc
- Exploration costly and difficult
- Commercial mining banned under the Madrid Protocol in 1998 for a period of 50 years. To be reviewed in 2041.
- 7 countries have made territorial claims on Antarctica

‘New’ terranes

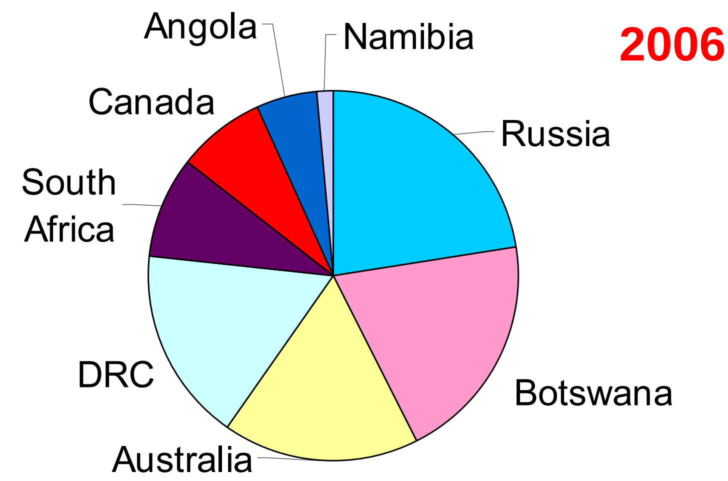
- Application of existing geological models to previously unexplored terranes
  - inaccessibility
  - lack of perceived mineral potential
  - lack of data
  - political restrictions or conflicts

New copper deposits in 'new' terranes

- Aynak, Afghanistan
  - 240 Mt @ 2.3% Cu
  - 10.6 billion pounds Cu
- Oyu Tolgoi, Mongolia (Mar 2007)
  - 2784 Mt @ 1.1% Cu, 0.35 g/t Au
  - 70 billion pounds Cu, 32 million oz Au
- Reko Diq, Pakistan (Mar 2008)
  - 4500 Mt @ ca. 0.5% Cu, 0.29 g/t Au
  - 47 billion lbs Cu, 38 million oz Au

Diamonds in Canada

- Geological setting well understood, but economic deposits rare
- Canada has 4 operational mines, all opened in the last decade



Global production 176,800,000 carat

Tellus Project, Northern Ireland, 2004-7

- New geophysical and geochemical datasets have revived mineral exploration

Magnetics

Electrical conductivity

New data encourages exploration

- Exploration licences in Northern Ireland

‘Old’ targets in ‘old’ terranes

- Lumwana, NW Zambia
  - shear-zone hosted Cu-Co in pre-Katanga basement
  - 6.3 million tonnes Cu
  - 16.6 million lb U_3O_8
  - production 172,000 tpa (37 years from 2009)

- Hemerdon, Devon, UK
  - sheeted veins in granite, SW corner of Dartmoor
  - operated during World War II
  - Amax drilled 24,500 m in late 1970s; permission granted in 1986, valid until 2021
  - inferred resource 81.8 Mt @ 0.172% W and 0.022% Sn
  - contains 17.7 million mtu tungsten trioxide
  - Wolf Minerals updating feasibility, production in 2010

How to look for mineral deposits

- New or improved mineral deposit models
- Developments in exploration technology

New models - Iron oxide-Copper-Gold (IOCG) deposits

- Large, multi-commodity deposits
  - >1000 Mt
  - Fe, Cu, Au (REE, U, P, Ag, F, Ba, Co)
- Type example is Olympic Dam, South Australia
  - discovered in 1975 beneath 600m of cover
  - largest uranium deposit in the world
  - 4th largest remaining copper deposit
  - 5th largest gold deposit
- Other 'IOCG' deposits known but no unifying genetic model
  - Mauritania, Sweden, Chile, China, and Queensland

Unconformity-related uranium deposits

- Major class of large, high grade deposits unknown before 1970

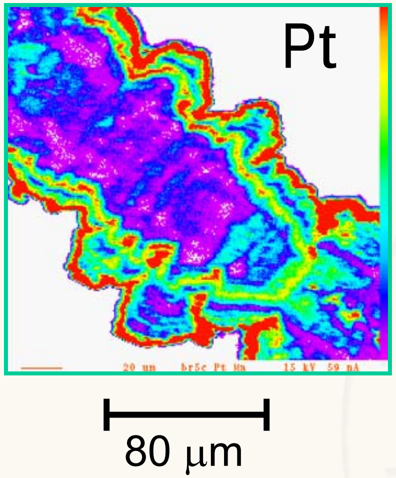
- Alligator Rivers, NT, Australia
  - Jabiluka - 138,000 tonnes U_3O_8
  - Ranger - 79,000 tonnes U_3O_8

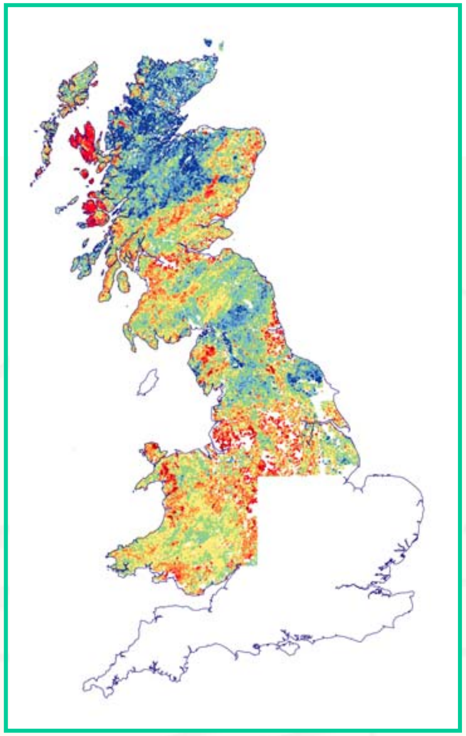
- Athabasca Basin, Saskatchewan, Canada
  - Cigar Lake - 76,000 tonnes U_3O_8, >24% U_3O_8

- Some examples enriched in gold and PGE (e.g. Coronation Hill, Qld)

Data collection

- More types of data, more data points, quickly and cheaply
- High quality data for more effective exploration, fewer false anomalies and missed targets
- Improved deposit models provide better definition of target signatures and aid better design of exploration
- Geochemical data
  - more elements, high sensitivity
  - rocks, waters, mineral grains
- Isotopic data
- Geophysical data
  - airborne gravimetry
  - deep EM (1-2 km)
- Remote sensing
- Mineralogical data





Cu in stream sediments

New methods of data processing, visualisation, modelling and analysis

- Routine use of GIS for integration and visualisation of spatial datasets
- Prospectivity analysis - optimises the use of multiple datasets
- Application-specific software for specific data types
- 3D modelling – Aynak example below

Mining technology

Increasing productivity and lowering costs

- 1960-2000 truck size increased >10 times
- haulage costs reduced by 70% over last 40 years

The porphyry copper revolution

- Relatively low-grade, disseminated ores
- Initial suggestions *"It would be impossible to mine and treat ores carrying 3% or less of copper at a profit"* Engineering and Mining Journal c.1900
- Economies of scale
- Account for ~70% global Cu production, grades 0.4% Cu

Importance of bulk global transportation

- Revolutionised transport of bulk commodities
- Historically uneconomic deposits now the mainstay global supply
  - ocean freight market driven by iron ore, coking coal and steel trade (>95% iron ore is shipped by sea)

- New capacity e.g.
  - RioTinto's automated mine-to-port Pilbara railway
  - Vale orders new iron ore carriers
    "to reduce the cost of long-haul maritime transportation of iron ore to steel makers"

Advances - energy efficiency

- Advances in conventional mining – energy efficiency key driver
  - significant energy is wasted (heat & noise) in grinding
  - breaking rock in tension, microwave-assisted grinding

Industrial energy intensity vs. energy consumption

Mines of the future

- In-situ mining (leaching)
  - in-situ recovery via boreholes
  - **uranium**: low-grade deposits (~0.1% U_3O_8)
  - **base metals**: Mufulira Mine, Zambia; Florence Mine, Arizona (oxide resource)
  - massive economic/social benefits

- Underground bulk mining

- Deeper high-grade deposits
  - costs currently prohibitive
  - deep drilling (>1000 m), automated technology
  - core drilling reached >5800 m

Development and expansion

- Trend towards brownfield exploration
- Expansion of existing operations
  - Bingham Canyon (628 million tonnes @ 0.48% Cu)
  - Chuquicamata underground (test development and engineering studies)
  - Olympic Dam expansion project (eventual open-pit operation)

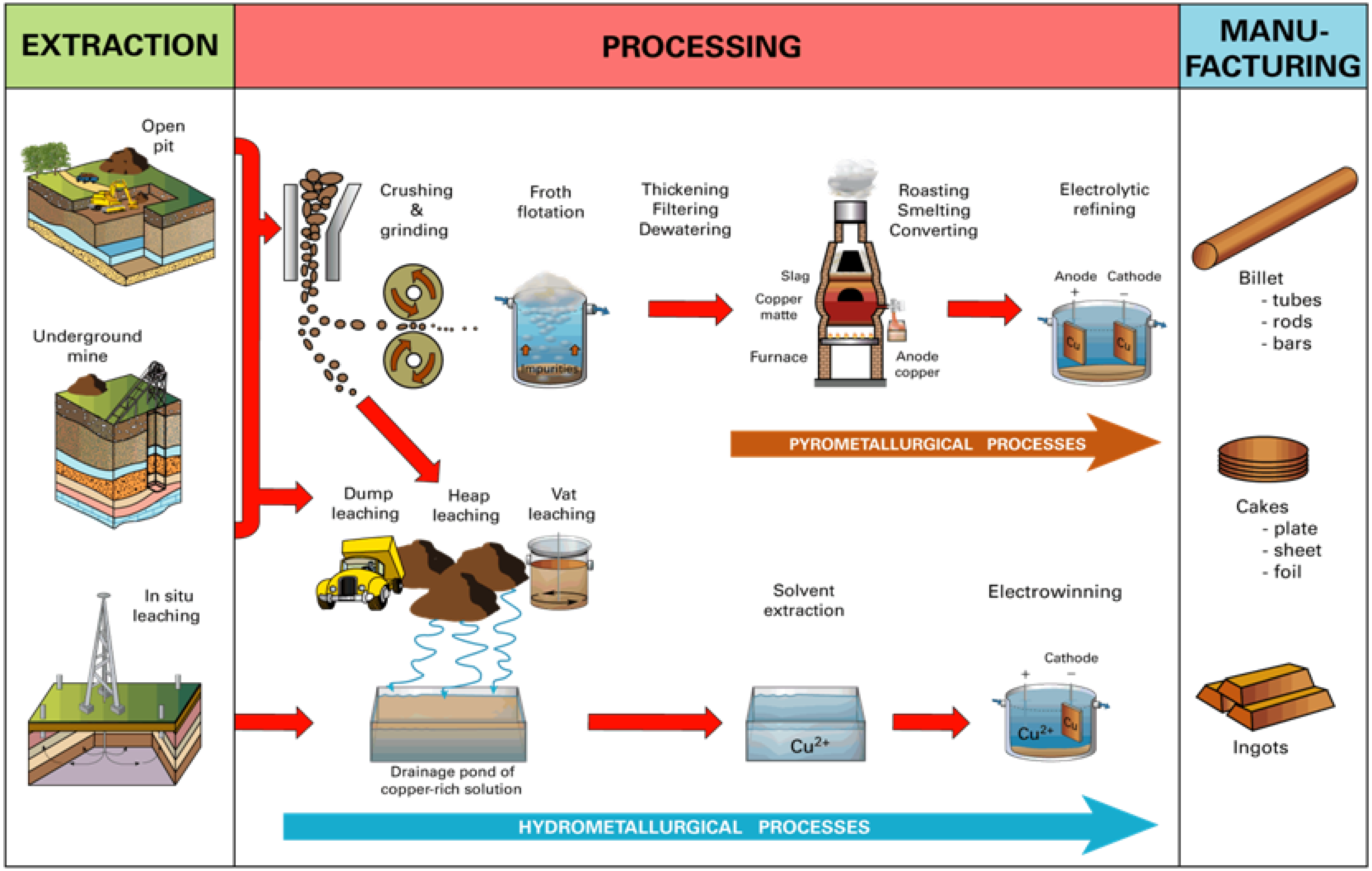
Mineral processing technology

The processing revolution

- Last century – revolutionary advances in extractive metallurgy
- New processing techniques allow exploitation of new resource types

- **Leach processing:**
  - **gold (low-grade, oxidised ores) → expanded global gold reserves**
  - **nickel laterites – a shift towards heap leaching**

Solvent extraction-electrowinning (SX-EW)



Application SX-EW to other metals

- Skorpion zinc mine (Namibia)
  - oxidised silicate ore (not amenable to conventional treatment)
  - first commercial application of SX for zinc processing
  - produces high-grade zinc cathode (>99.99% purity) at mine
  - one of the world's lowest cost zinc producers

Conclusions

- Minerals are essential and demand is likely to continue to increase
- Major challenges exist for the maintenance of adequate supplies, many related to sustainable development and 'licence to operate'
- There is a fundamental misunderstanding about reserves and resources
- Led to unjustified, sometimes alarmist, conclusions
- We believe that adequate mineral supplies can be maintained into the foreseeable future
- Science and technology have major roles to play
- Man will continue to find new materials, new technologies and new applications

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