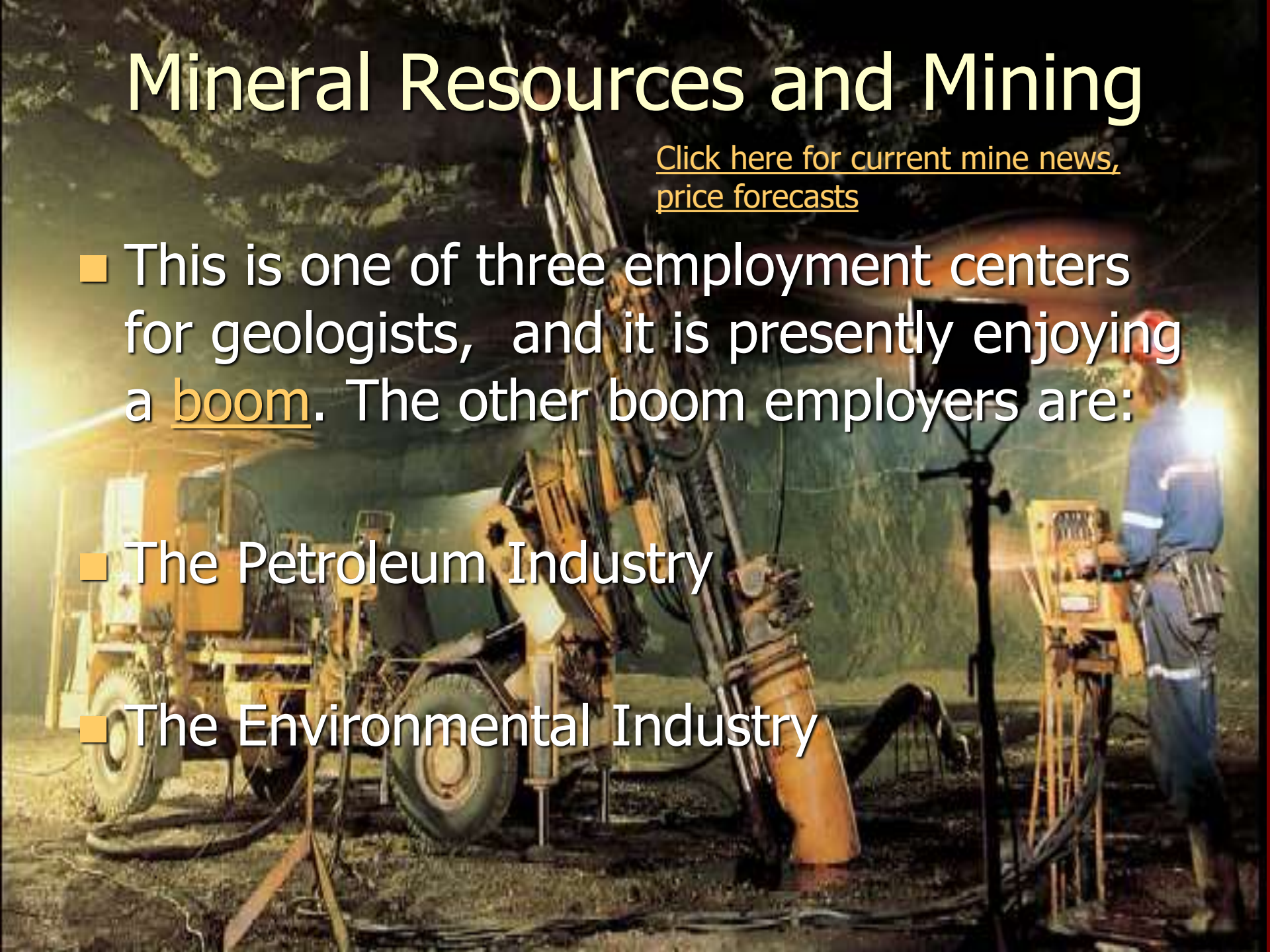


Mineral Resources and Mining

[Click here for current mine news, price forecasts](#)

- This is one of three employment centers for geologists, and it is presently enjoying a boom. The other boom employers are:
 - The Petroleum Industry
 - The Environmental Industry



Mineral Resources and Mining

Some definitions:

- Ore, Ore Mineral, Gangue, Resource < Reserve
- Reserves are profitable and also technically & legally extractable
- Commodities Au, Ag, Al, Coal, crude oil, Iron ore
- Is it profitable, i.e. "economic"? Consider futures price, costs of energy, infrastructure, labor, processing and environmental protection & cleanup. To do that we consider grade, type of deposit and type of processes feasible, special environmental problems, etc.

Prospecting, Exploration & Development, Mining: often different companies. Who should you work for when starting out?

Current conditions: Gold at 30 year high, crude oil futures near record prices

As a geologist, you should keep an eye on Mineweb.com

Units 1 Metric Ton AKA tonne = 10^6 grams therefore a grade of 1 g/T = 1 ppm

Some Important Ores and a deposit

- Native Ores: Gold Au, Copper Cu, Platinum Pt
- Base Metal Ores: Bauxite (mostly Gibbsite $\text{Al}(\text{OH})_3$), Hematite Fe_2O_3 , Magnetite Fe_3O_4
- Sulfide Ores: Silver as Argentite Ag_2S , Copper as Bornite Cu_5FeS_4 , Chalcopyrite CuFeS_2 , or Chalcocite Cu_2S , Mercury as Cinnabar HgS , Lead as Galena PbS , and Zinc as Sphalerite ZnS
- Oxide Ores: Uranium as Uraninite UO_2 , Titanium as Ilmenite FeTiO_3 ,
- Deposit: Kimberlites for Diamond C

Steps in obtaining mineral commodities

1. **Prospecting:** finding places where ores occur.
2. **Mine exploration and development:** learn whether ore can be extracted economically.
3. **Mining:** extract ore from ground.
4. **Beneficiation:** separate ore minerals from other mined rock. (Mill)
5. **Refining:** extract pure commodity from the ore mineral. (Refinery)
6. **Transportation:** carry commodity to market.
7. **Marketing and Sales:** Find buyers and sell the commodity.

Mining is an economic activity.

The decision to mine (or not to mine) a particular ore deposit depends upon:

an analysis of costs, benefits and risks

These considerations are both:

- tangible (i.e. dollar profit)

and

- intangible (i.e. hopes of stimulating the economy, fears of environmental damage)

3. Prospecting: finding where ores occur

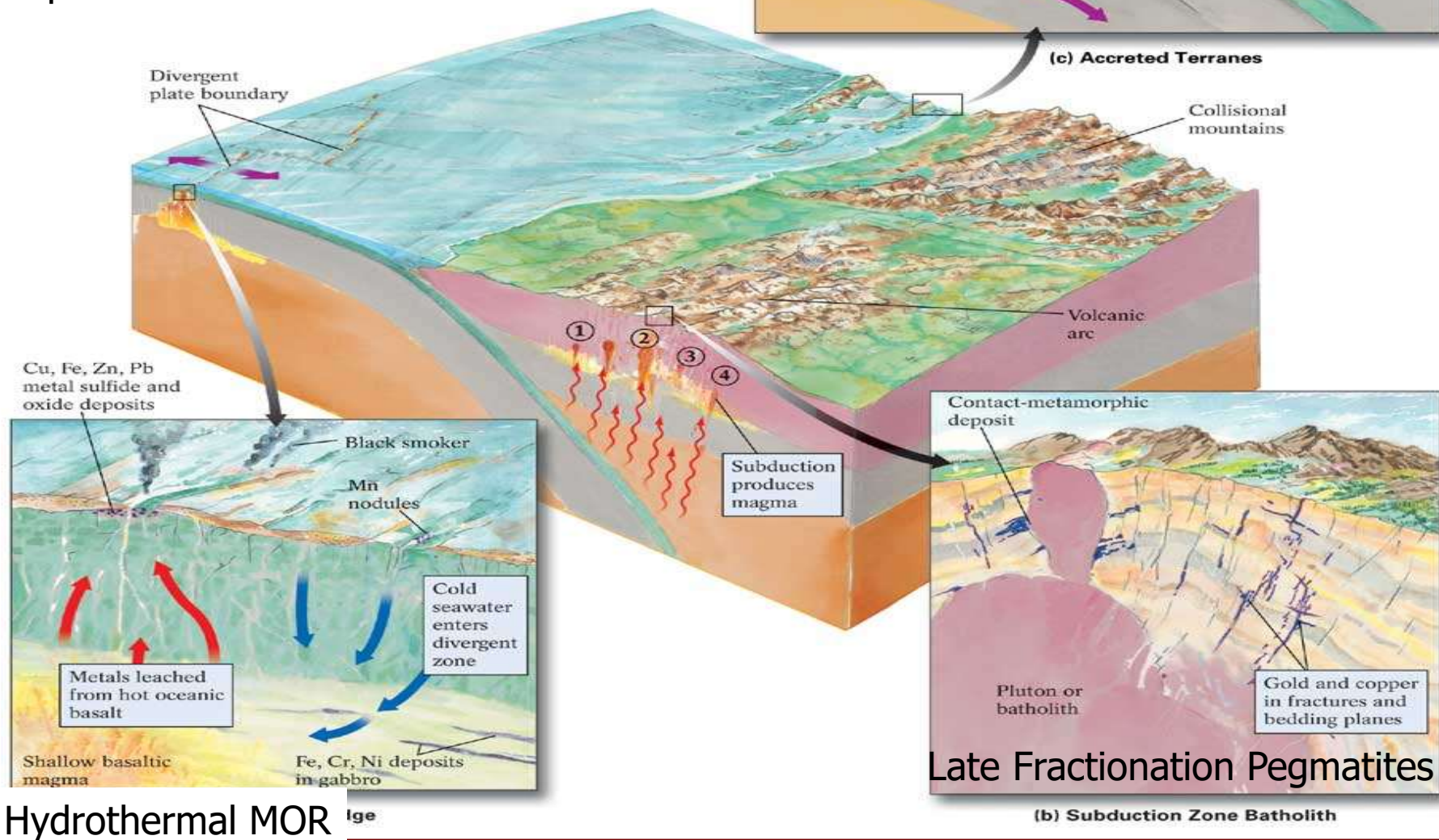
Important Factors:

- **Applying knowledge of association of ores with specific geological settings.**
- using remote sensing techniques such as satellite imagery, seismic reflection profiles, magnetic field intensity, strength of gravity to detect geological structures.
 - photos useful in finding faults.
 - small basaltic intrusions have prominent magnetic anomalies.
 - dense ore bodies can have prominent gravity anomaly.
- developing detailed maps of rock types and geological structures (faults, folds, intrusions).
- developing 3-d picture of geological structures containing ore.
- obtaining samples of ore for chemical analysis.

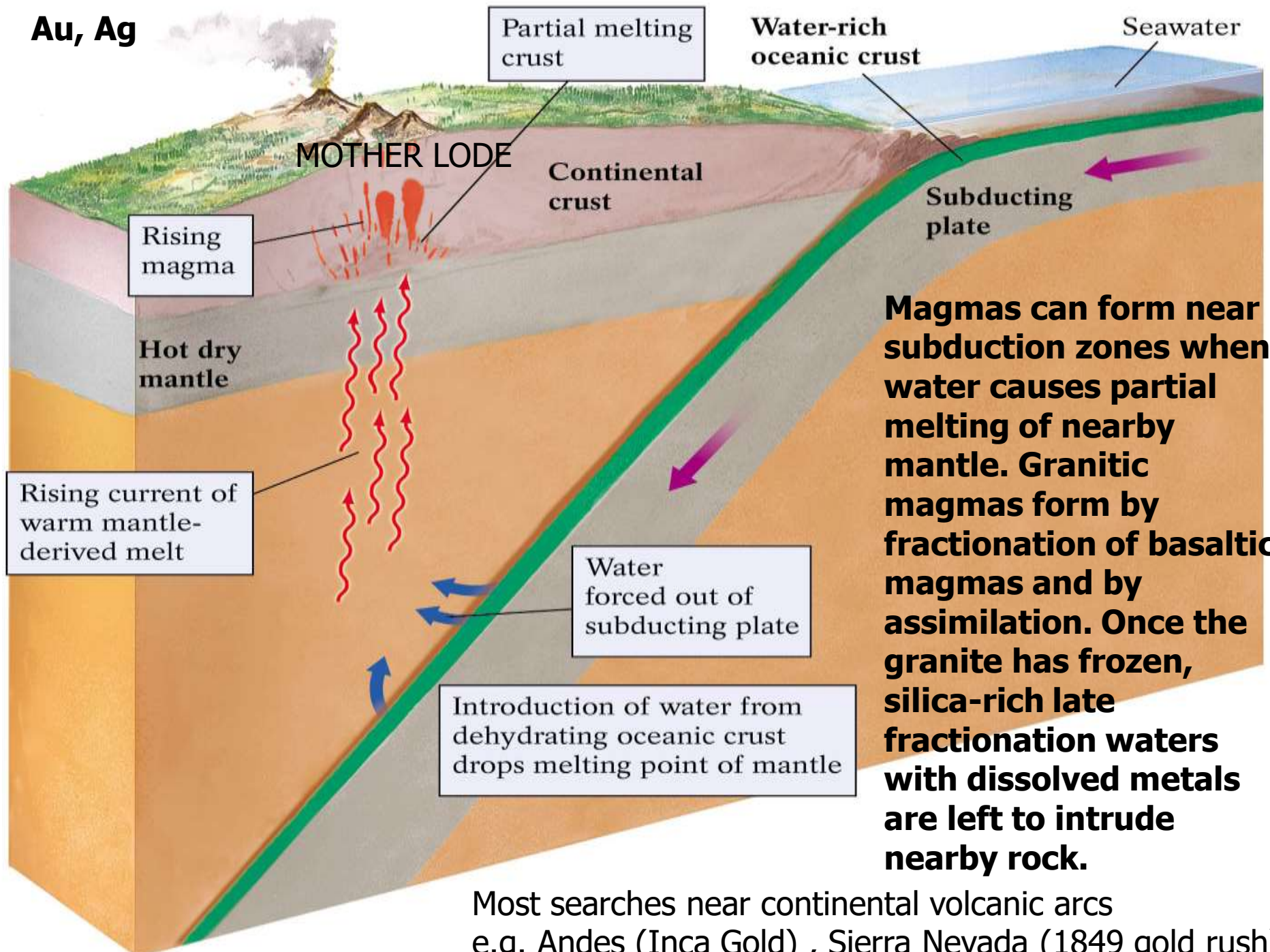
• **WHERE DO WE LOOK?**

A review from your Geology 1200 Course

Recall that several processes can produce magmas. All are initially basaltic in composition. Basalts contain minor amounts of precious metals.



Au, Ag



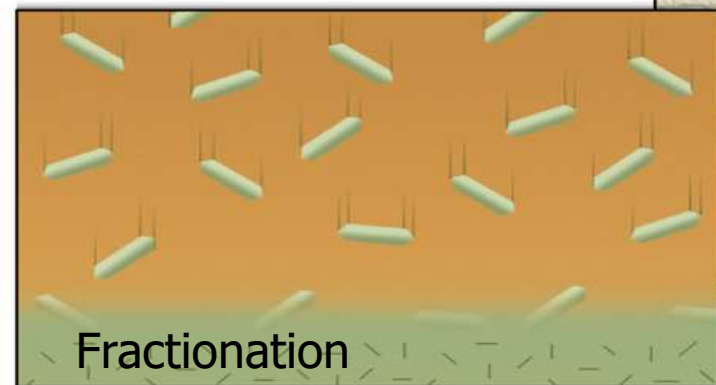
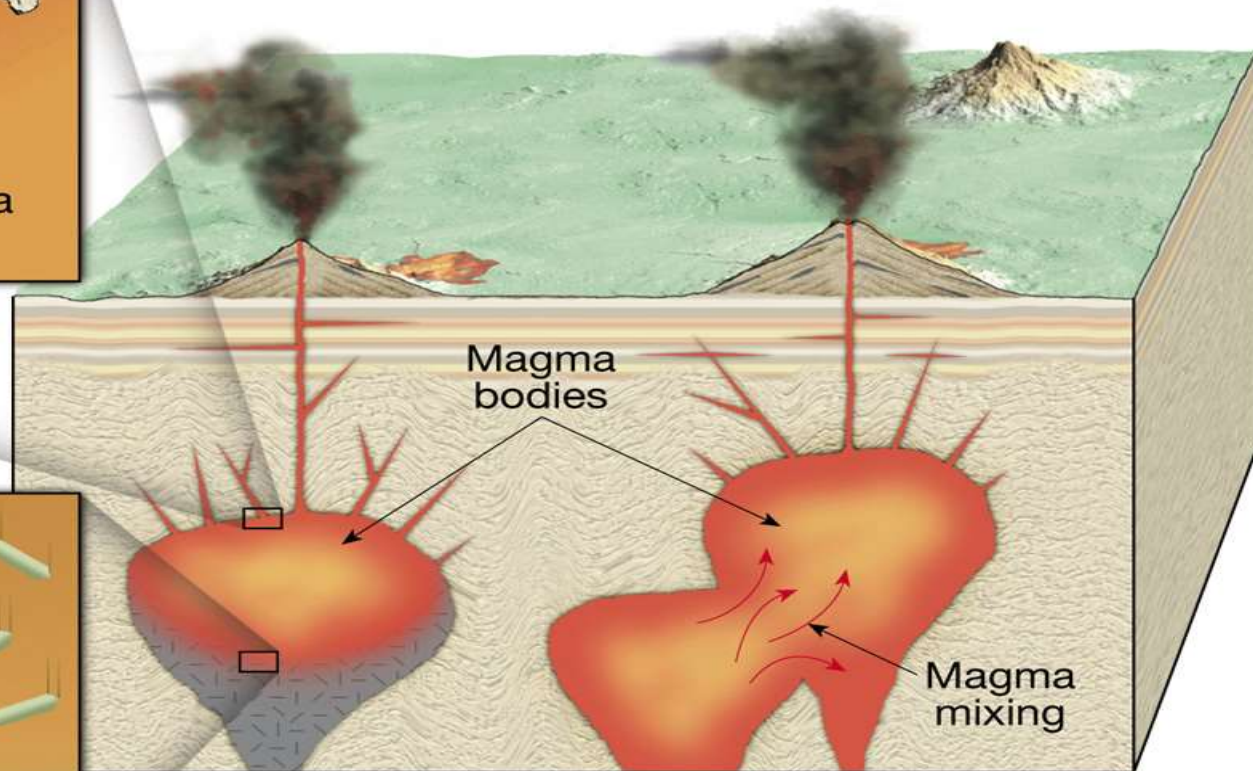
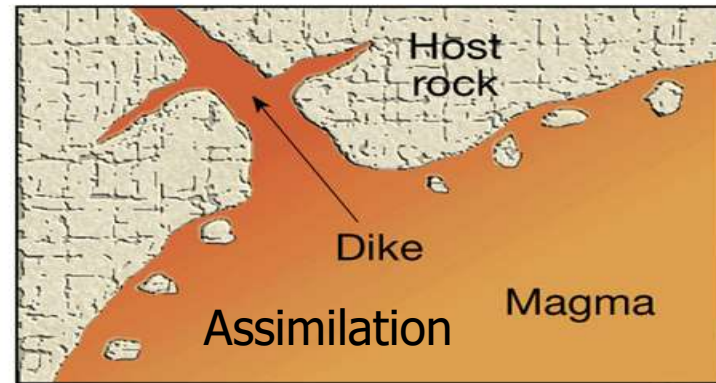
Magmas can form near subduction zones when water causes partial melting of nearby mantle. Granitic magmas form by fractionation of basaltic magmas and by assimilation. Once the granite has frozen, silica-rich late fractionation waters with dissolved metals are left to intrude nearby rock.

Most searches near continental volcanic arcs
e.g. Andes (Inca Gold) , Sierra Nevada (1849 gold rush)

Initially Basaltic, rising magma may become silica-rich through two processes.

Fractionation and Assimilation

Assimilation of country rock



Crystallization and settling

Granitic melt genesis

Metal-rich waters may originate from the magma or groundwater

Au, Ag

Hot spring
or geyser

Strip mine

Cool groundwater
infiltrates downward

Travertine
deposit

Hydrothermal
vein deposits
from magmatic
water

Metal ores precipitate
near surface

Metal-enriched
magmatic water
rising along fractures

Heated
groundwater
dissolves metals

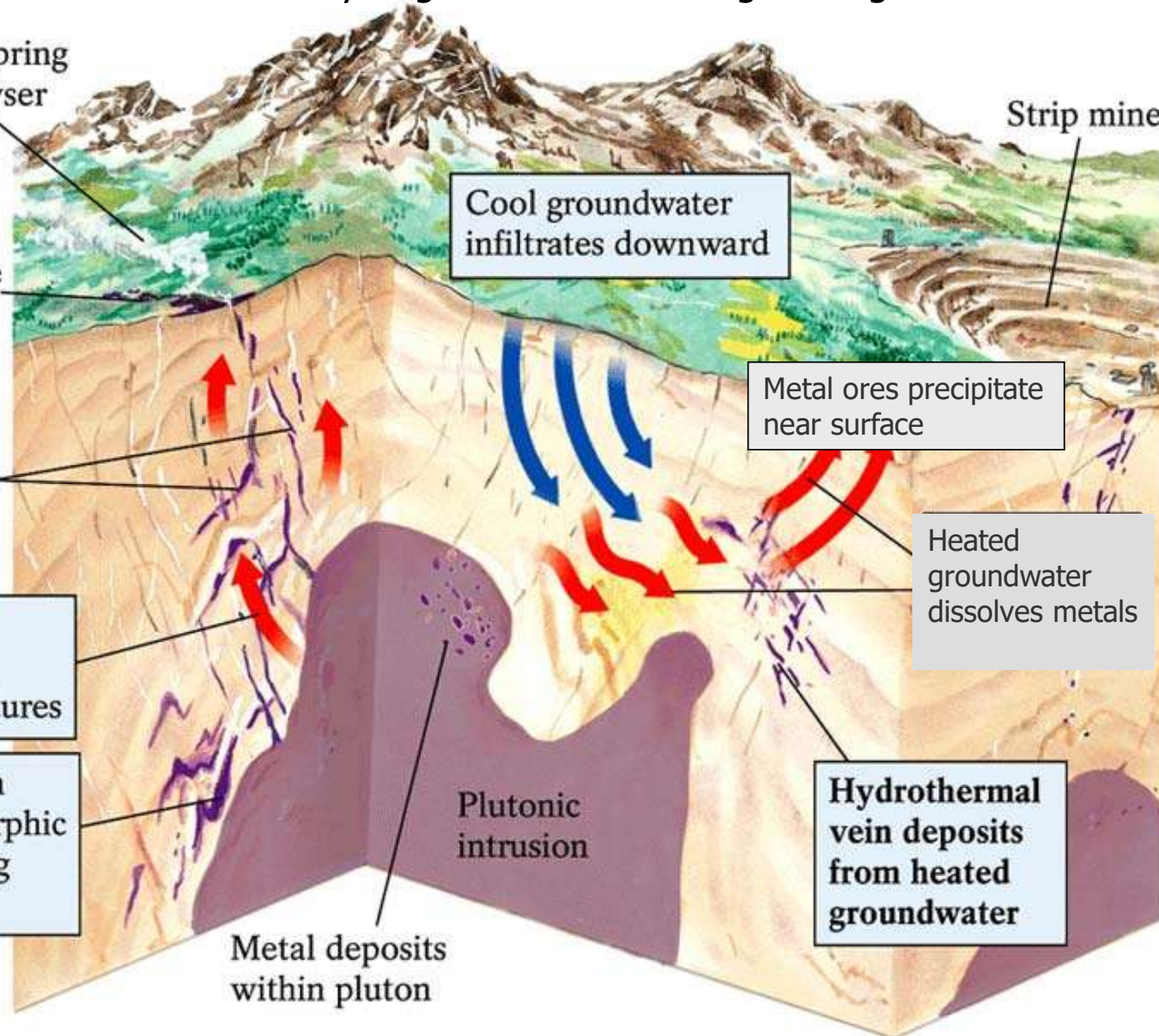
Metal deposits in
contact-metamorphic
zone surrounding
pluton

Plutonic
intrusion

Hydrothermal
vein deposits
from heated
groundwater

Metal deposits
within pluton

Two mechanisms for metals emplacement near granitic intrusions (both occur)



Gold Ore

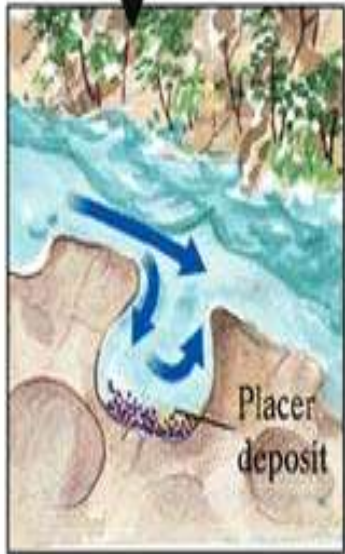
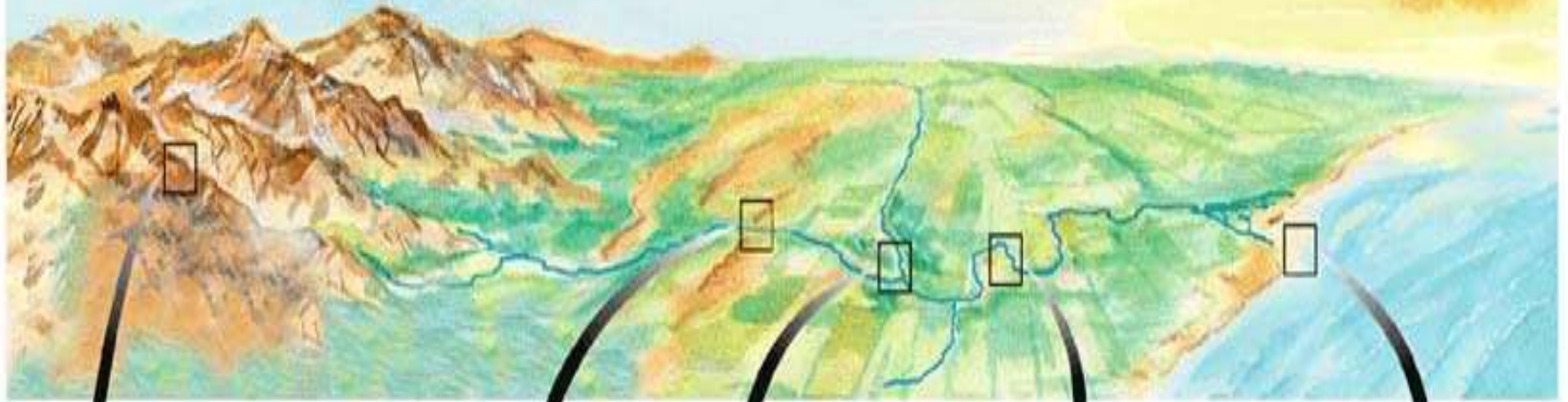
Ore mineral Gold Au



Gangue Mineral Quartz

Popular term "Mother Lode" initial placement
Ore Body

Placers: Gold is concentrated as a detrital sediment



Deposition in potholes



Deposition at channel constriction



Deposition at confluence of two or more streams

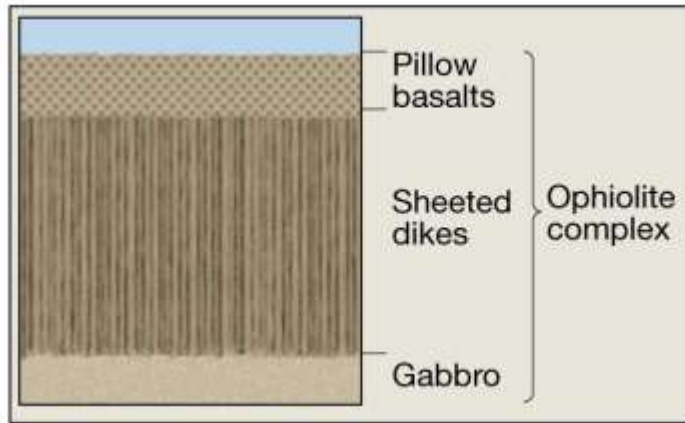


Deposition on inside of meander loops



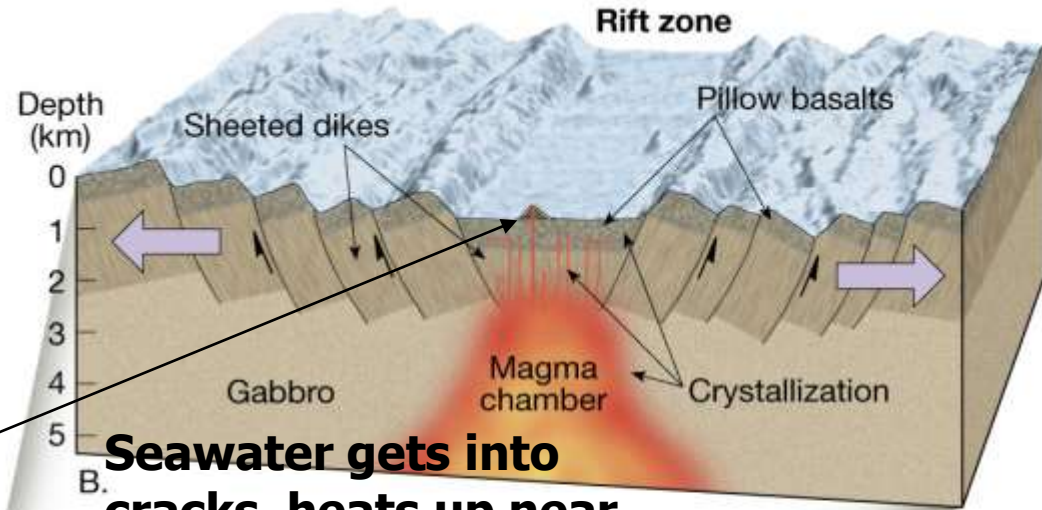
Deposition at coast

Magma 2: formation at divergence zone



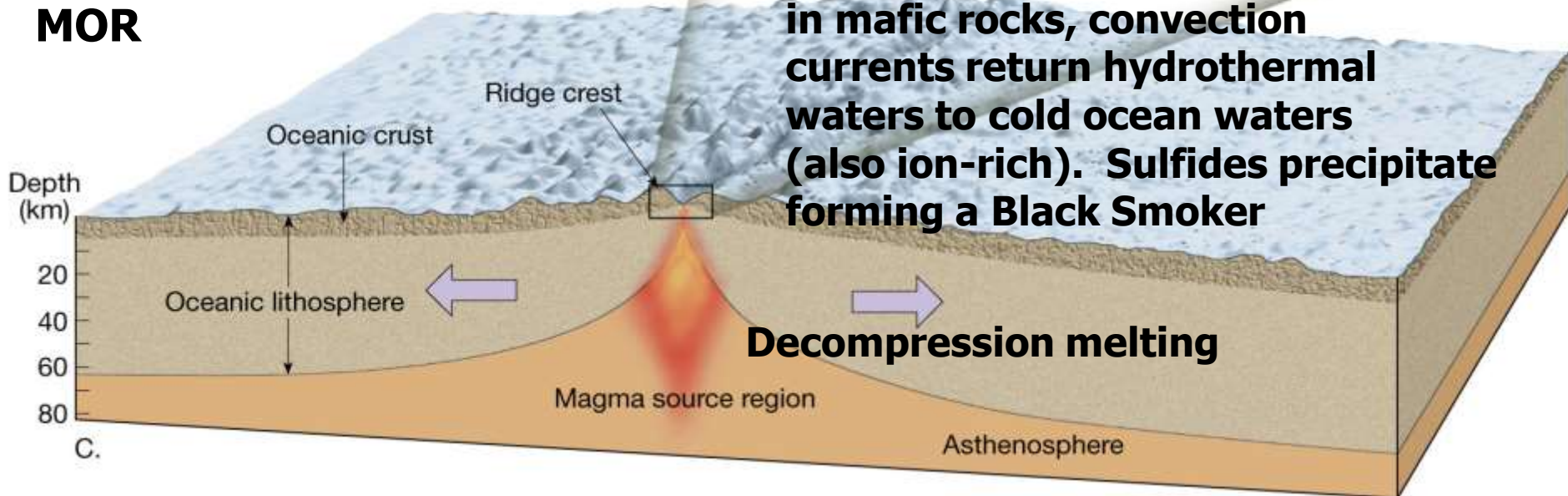
A.

Black Smoker
on cracks near magma



Seawater gets into cracks, heats up near magma, dissolves metals Cu, Fe, etc in mafic rocks, convection currents return hydrothermal waters to cold ocean waters (also ion-rich). Sulfides precipitate forming a Black Smoker

MOR

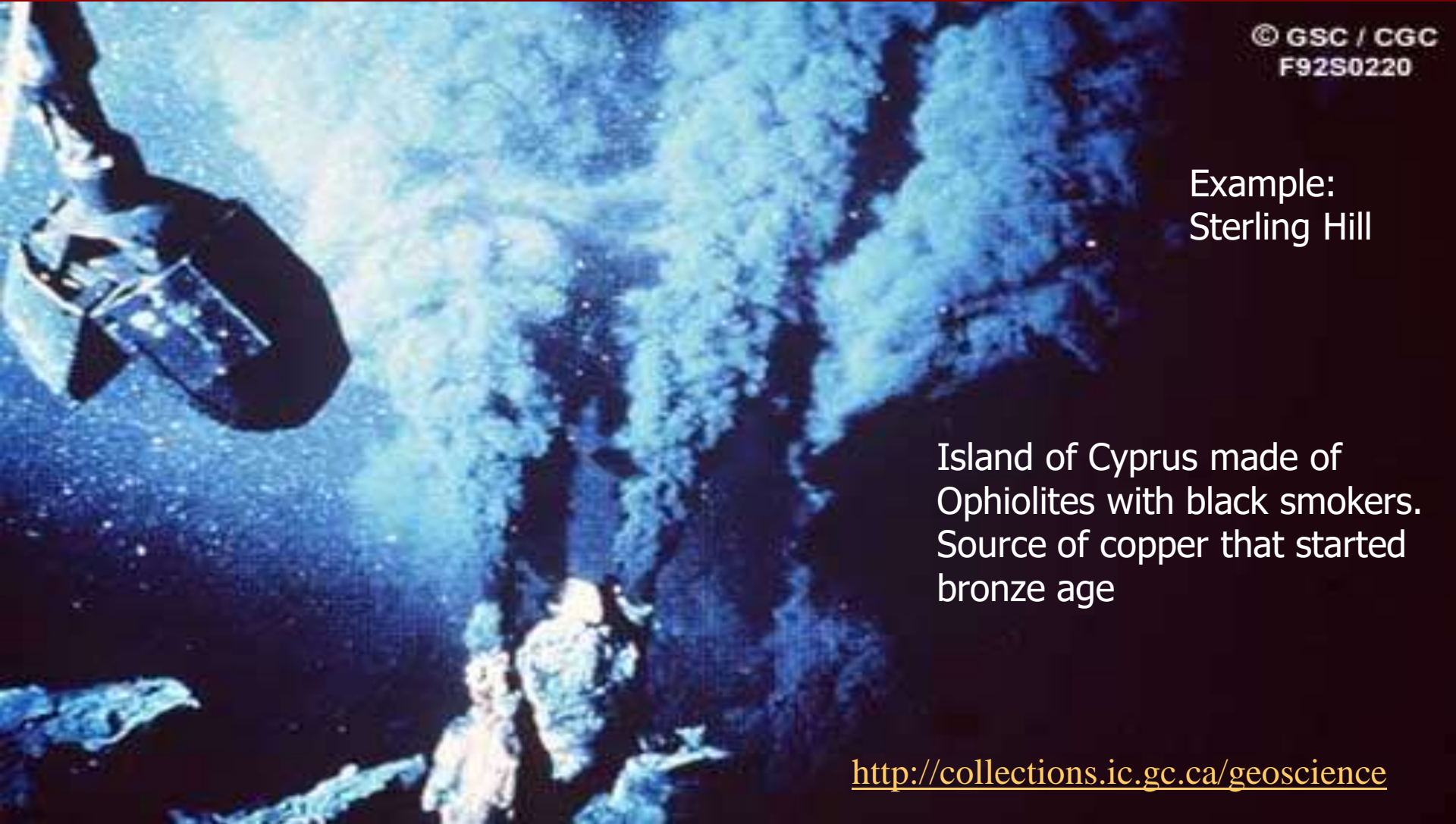


C.

Decompression melting

Cu, Fe

Black Smokers



© GSC / CGC
F92S0220

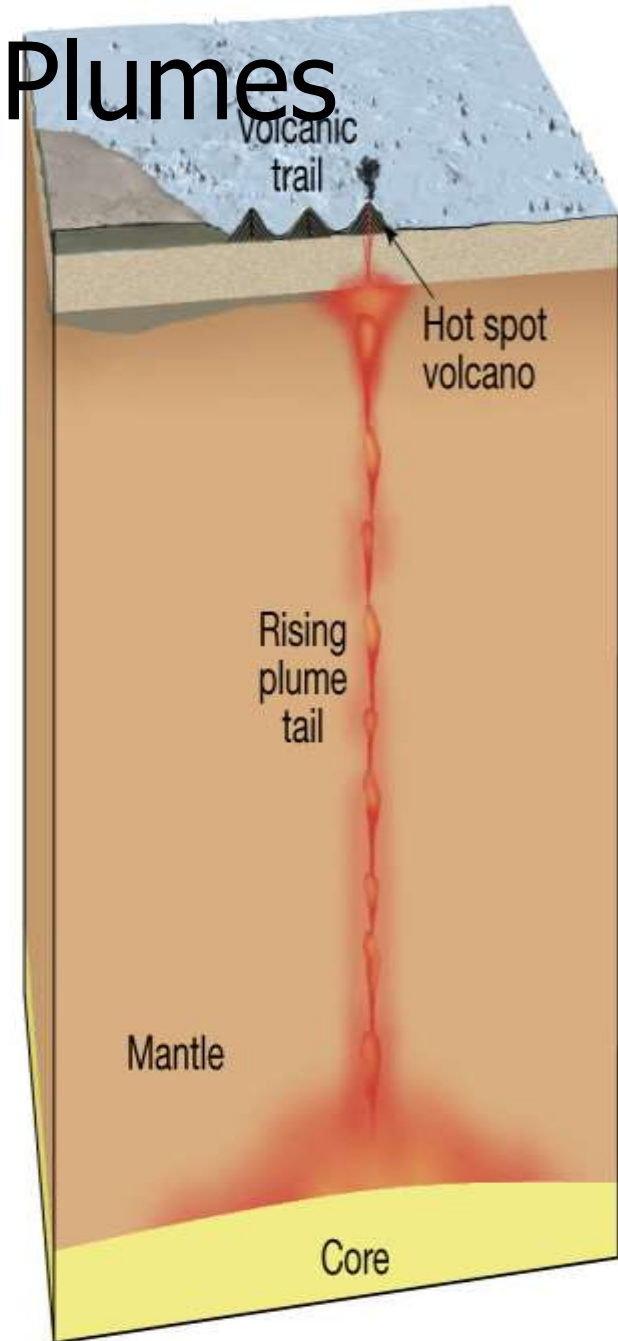
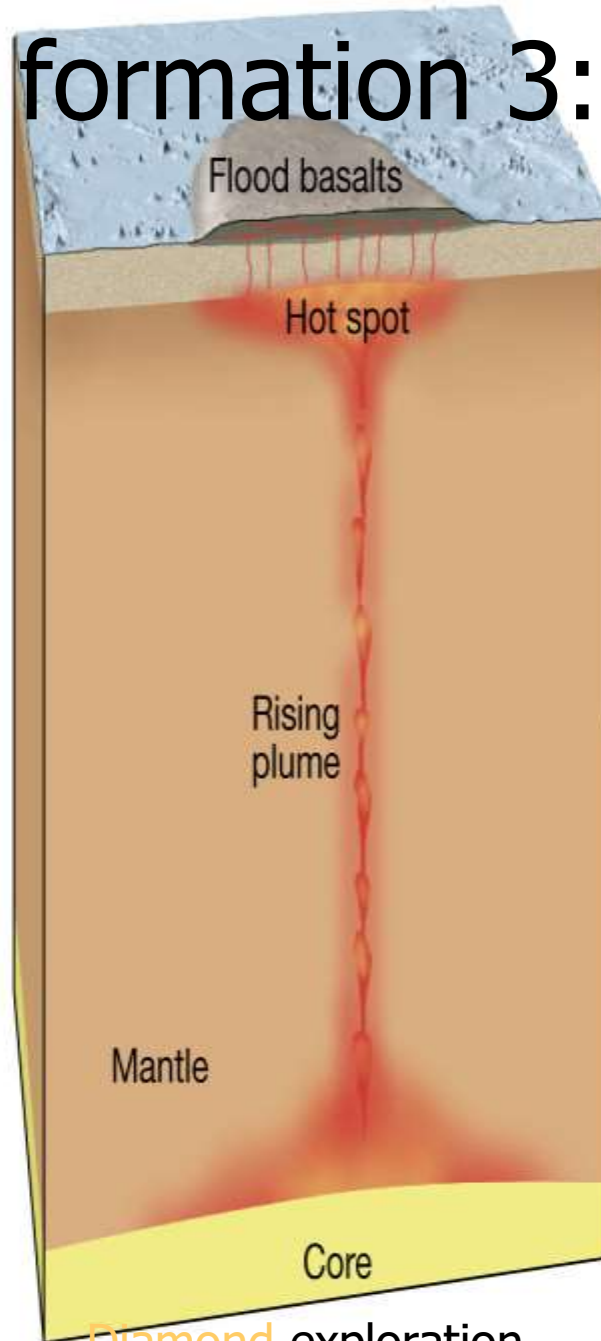
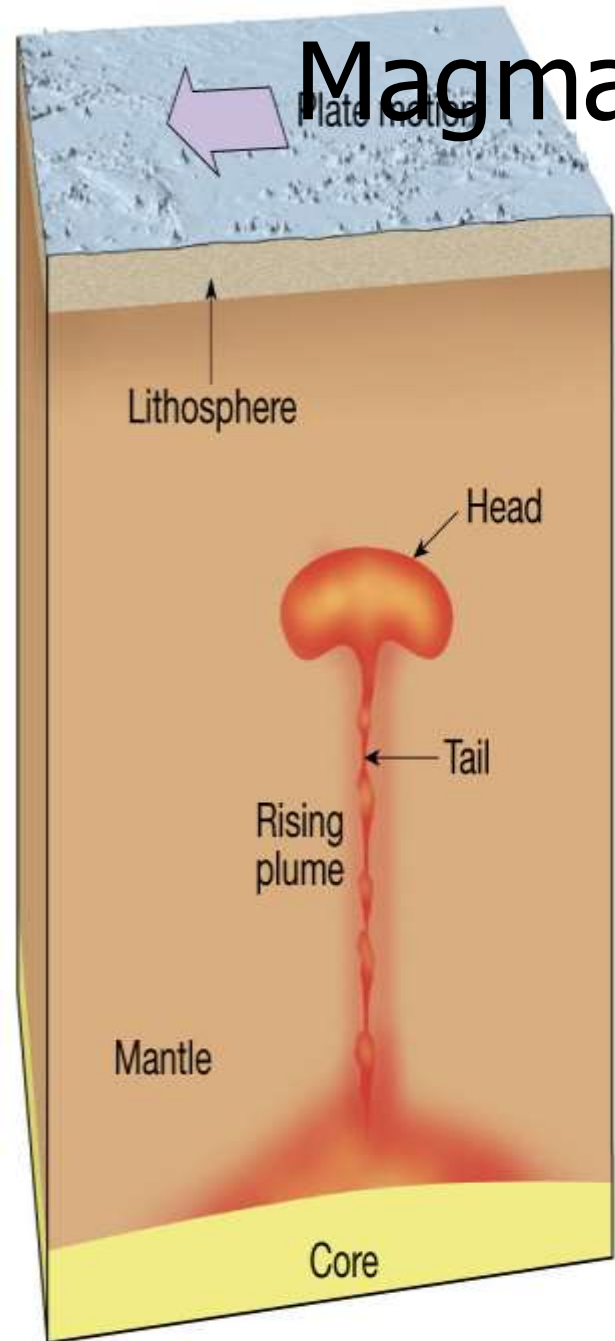
Example:
Sterling Hill

Island of Cyprus made of
Ophiolites with black smokers.
Source of copper that started
bronze age

<http://collections.ic.gc.ca/geoscience>

Circulation of hot water in cracks at mid-ocean ridge dissolves metals in Basalt, (Copper, Iron, Zinc, Lead, Barium) which are re-precipitated as various ores, often Sulfides. Accumulate in ocean sediments.

Magma formation 3: Plumes



[Diamond](#) exploration

A.

B.

C.

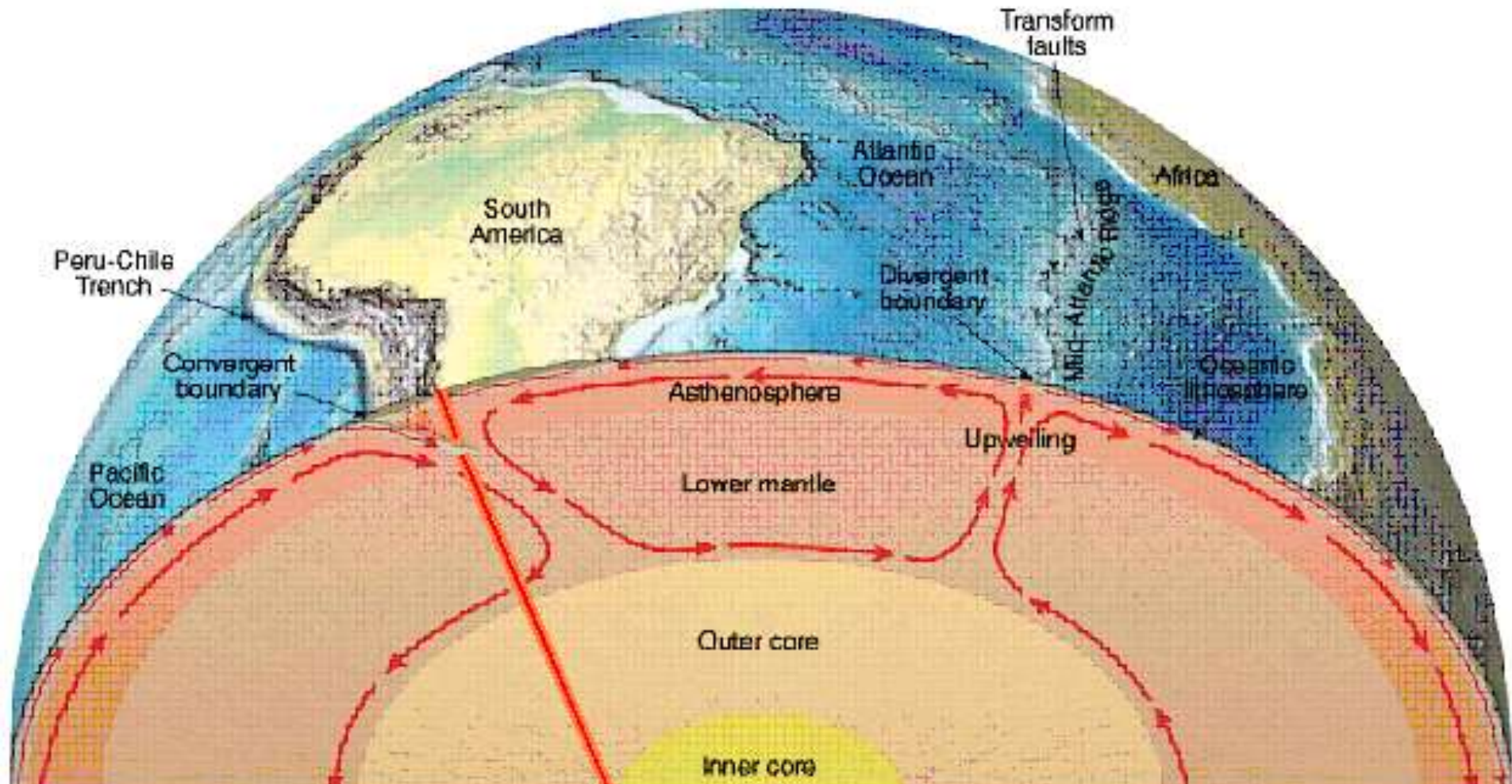
C (diamond)

Subduction zones pull carbon down to depths necessary for Diamond formation. Plumes rise from depths far below diamond formation depths. A plume cutting across subduction zone will lift diamonds to the surface

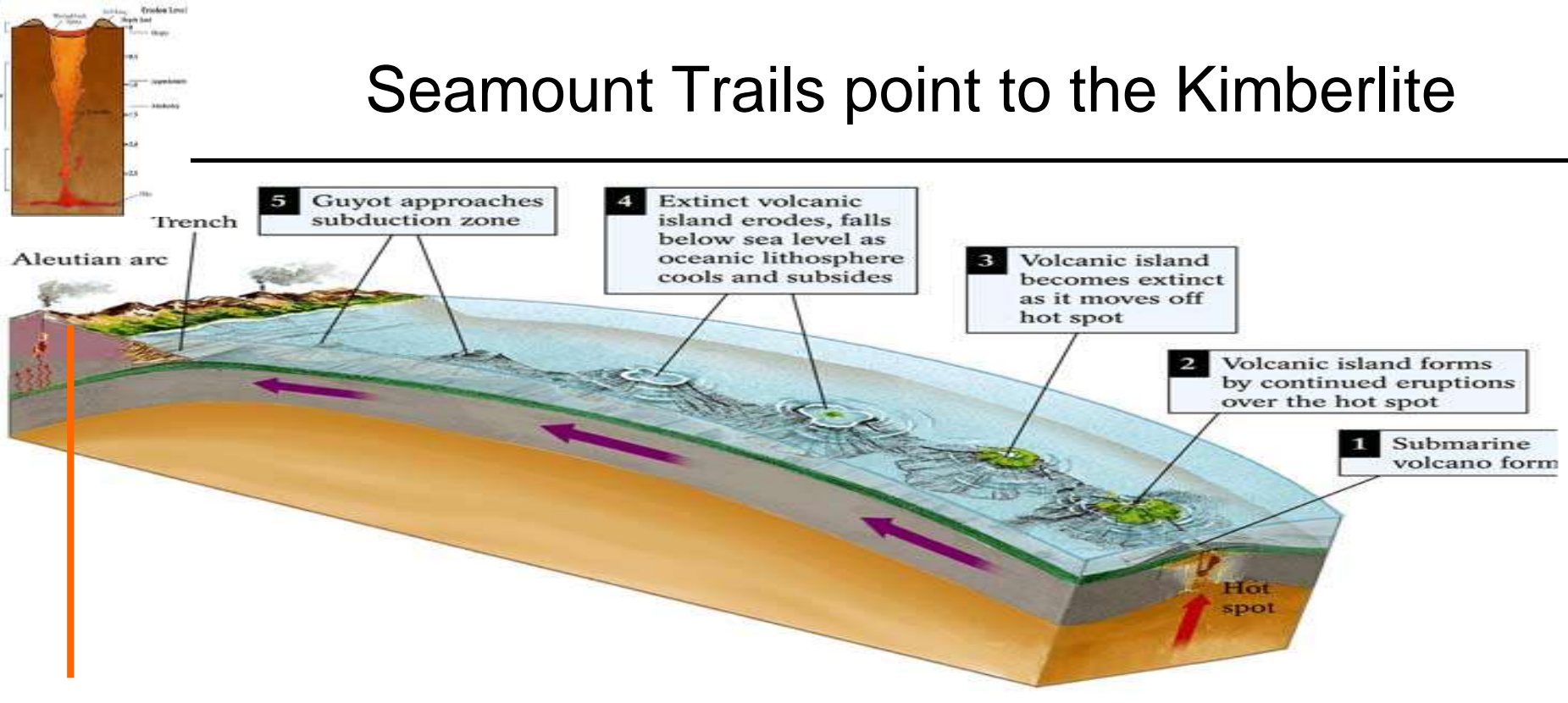
Rising plume cuts through subduction zone, lifting HT HP Carbon to the surface

Diamond Genesis

Diamond exploration

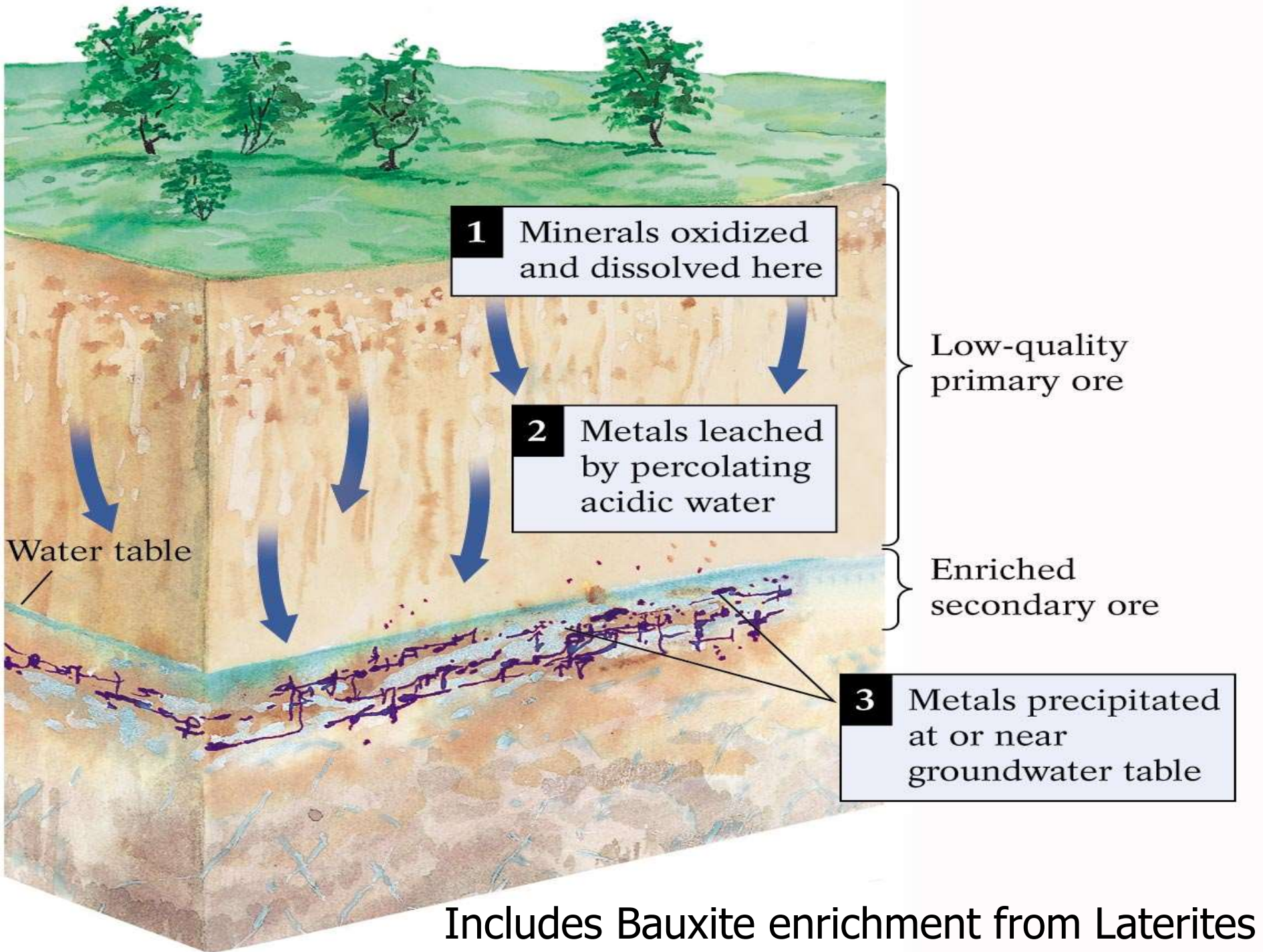


Seamount Trails point to the Kimberlite



Plumes cause straight chains of seamounts on the ocean floor
The Atlantic rift has moved America west of several plumes.
These were once under the continent, sometimes under old subduction zones.
Use chains of seamounts to point to old positions of the plumes' "hot spot".
Extend those lines onto North American continent
Find where those projected lines cross sutures between PreCambrian Cratons
assembling North America. Now use Google Earth to search for [Maars](#)

Here is a set of links related to this topic: [Diamond](#) exploration





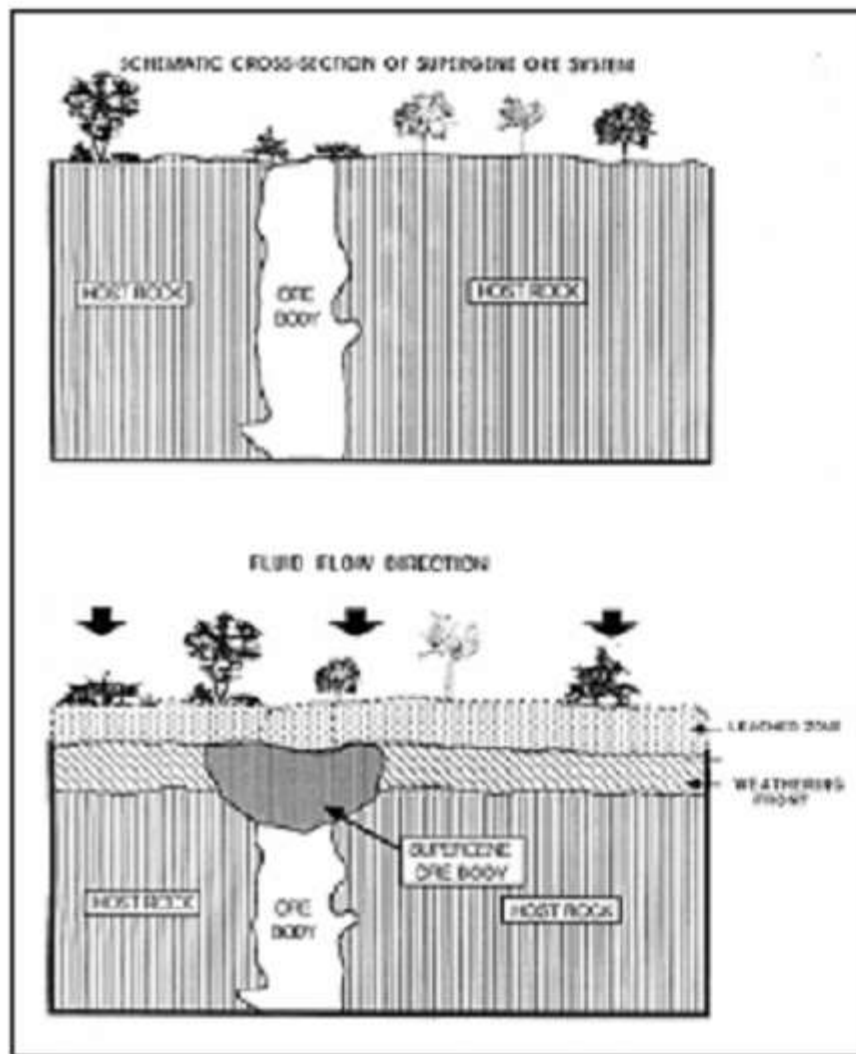
Concentration of Aluminum as Bauxite Ore

From a Laterite similar to the one outside

Gibbsite $\text{Al}(\text{OH})_3$ is the main mineral in Bauxite ore

Weathering processes and supergene ore deposits

Petrology Field Trip to Bemco Mining District



- Sulfide minerals are not stable at the earth's surface and breakdown during weathering liberating metallic ions (e.g., Cu^{++} , Pb^{++} , Zn^{++}).
- These ions may precipitate as oxides, carbonates and sulfates above the water table to form secondary copper, lead and zinc deposits.
- Where copper ions reach the water table and react with primary sulfides, supergene copper deposits form that are dominated by copper sulfides.

2. Mine exploration and development: learn whether ore can be extracted economically

- Define size, shape and grade of ore body.

Grade, G: mass of commodity per mass of ore.

Gold: 5 grams of Au per metric ton (10^6 grams of ore)

Grade = 5×10^{-6} .

Aluminum: 400 kg of Al per metric ton of ore, $G=0.4$

- Drill cores, though expensive, can be used to determine underground extent of ore

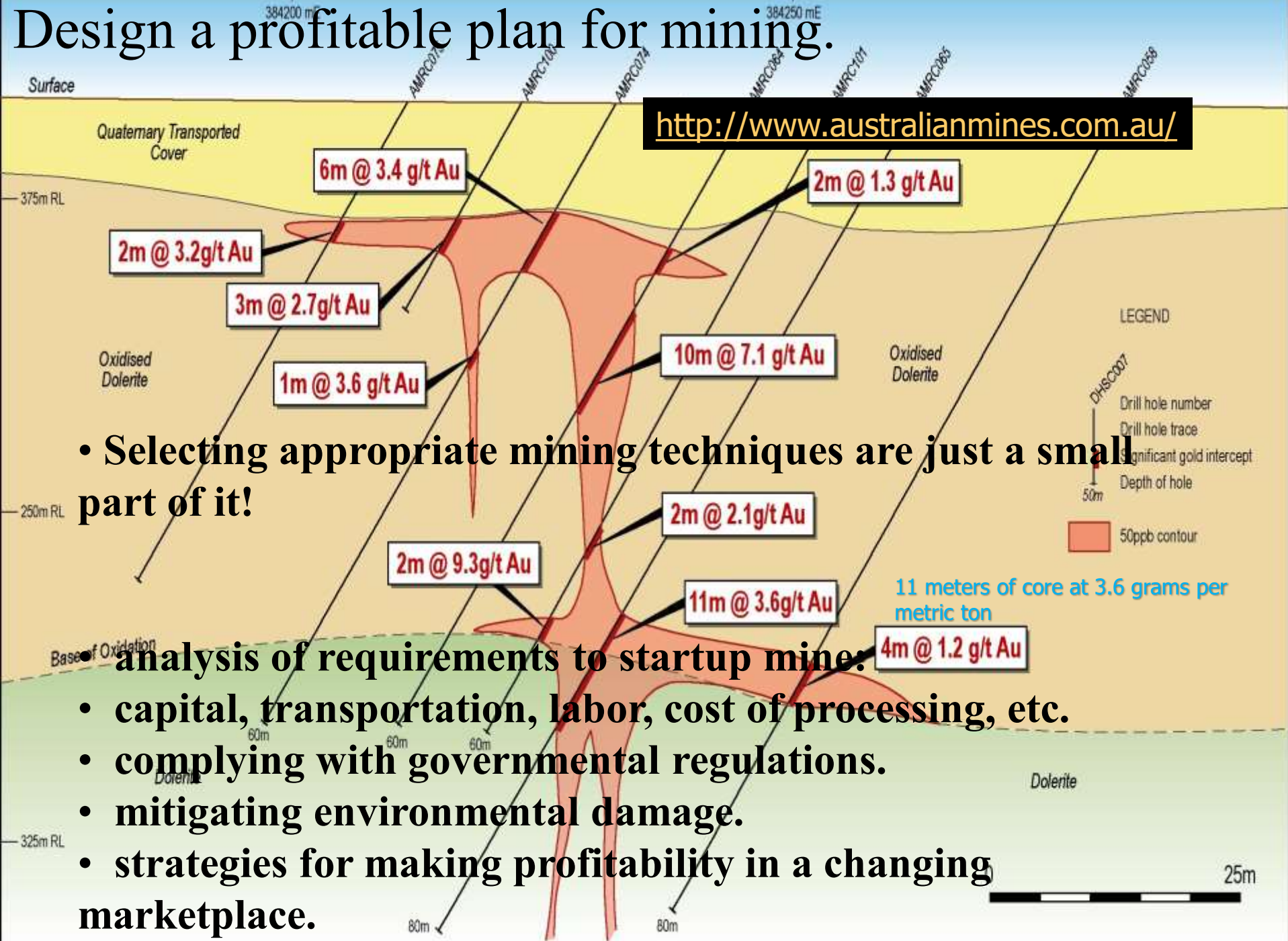
Estimate the mass of the commodity:

= volume of ore body x density of ore body x grade).

1 metric ton = "tonne" is 1000 kilograms



Design a profitable plan for mining.



<http://www.australianmines.com.au/>

• Selecting appropriate mining techniques are just a small part of it!

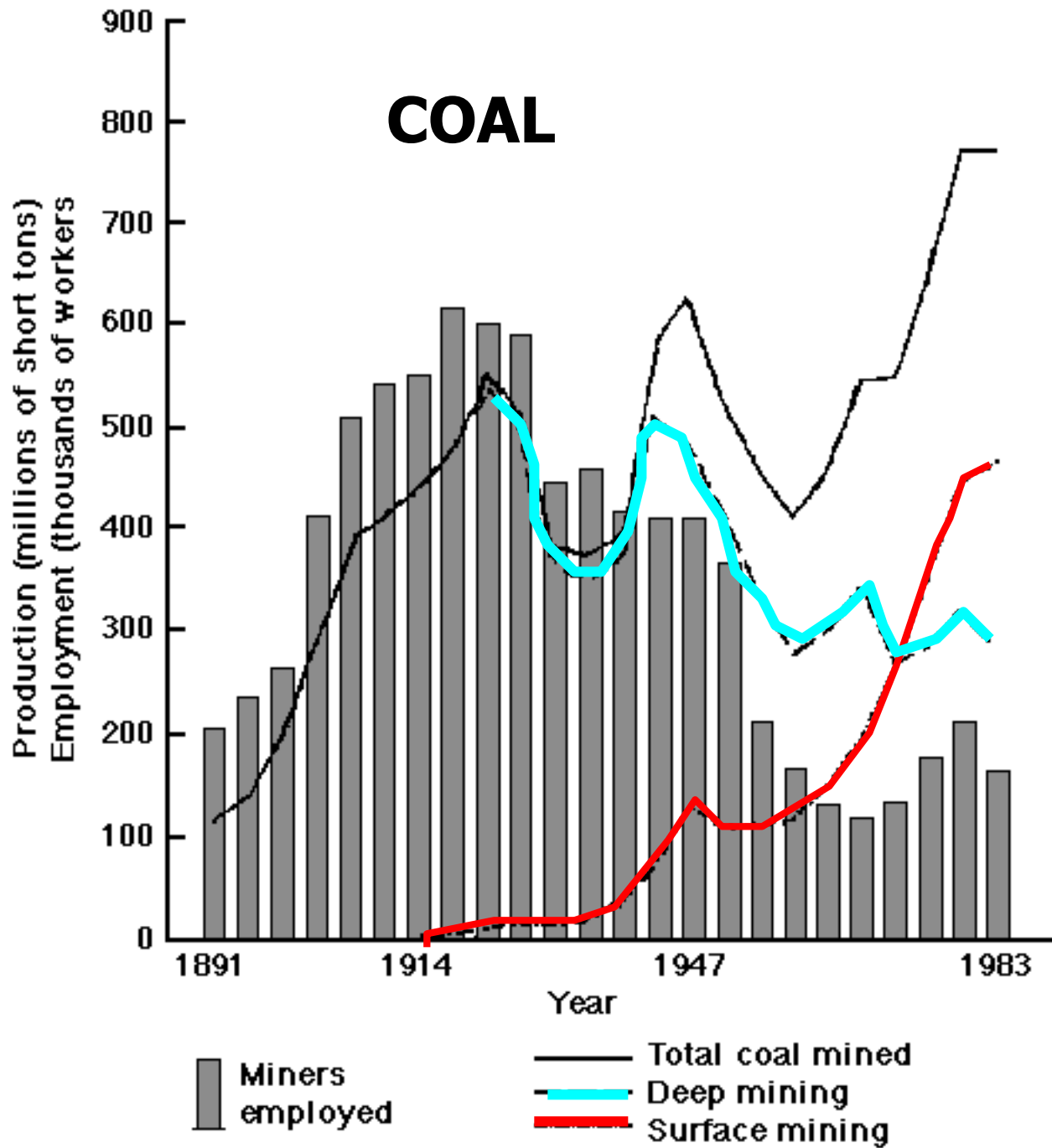
- analysis of requirements to startup mine:
- capital, transportation, labor, cost of processing, etc.
 - complying with governmental regulations.
 - mitigating environmental damage.
 - strategies for making profitability in a changing marketplace.

3. Mining: extract ore from ground

- Types of Mining:

- Surface Mining: Scoop ore off surface of earth.
 - cheap.
 - safe for miners.
 - large environmental destruction.
- Underground Mining: Use of adits and shafts to reach deeply buried ores.
 - expensive.
 - hazardous for miners.
 - usually less environmental damage.

COAL



Surface mining: two types

open pit mining:

- funnel shaped hole in ground, with ramp spiraling down along sides, allows moderately deep ore to be reached.

Initial mining for zinc at Franklin and Ogdensburg, New Jersey.



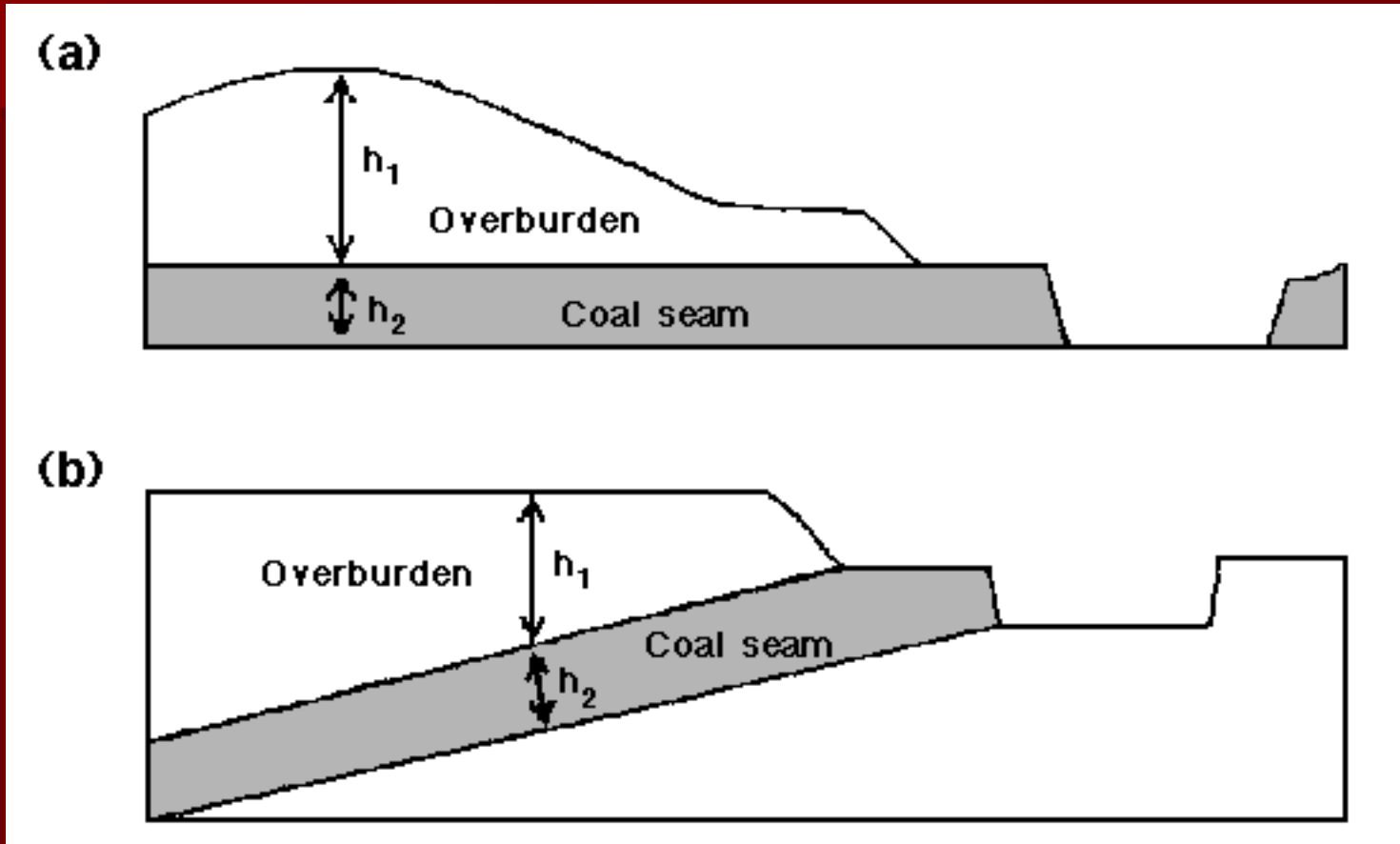
Strip mining.

- **Strip-mining:** Blast, scoop off rock overburden, and then scoop out ore material. Fairly shallow.
- Economics of strip mining depend on stripping ratio
- Large land area can be involved, especially for coal and bauxite.

Example: Alcoa's
Sierra de Bahoruco
Aluminum mining
in D.R. Southern
Peninsula until 1985



Economics of strip mining depend on stripping ratio



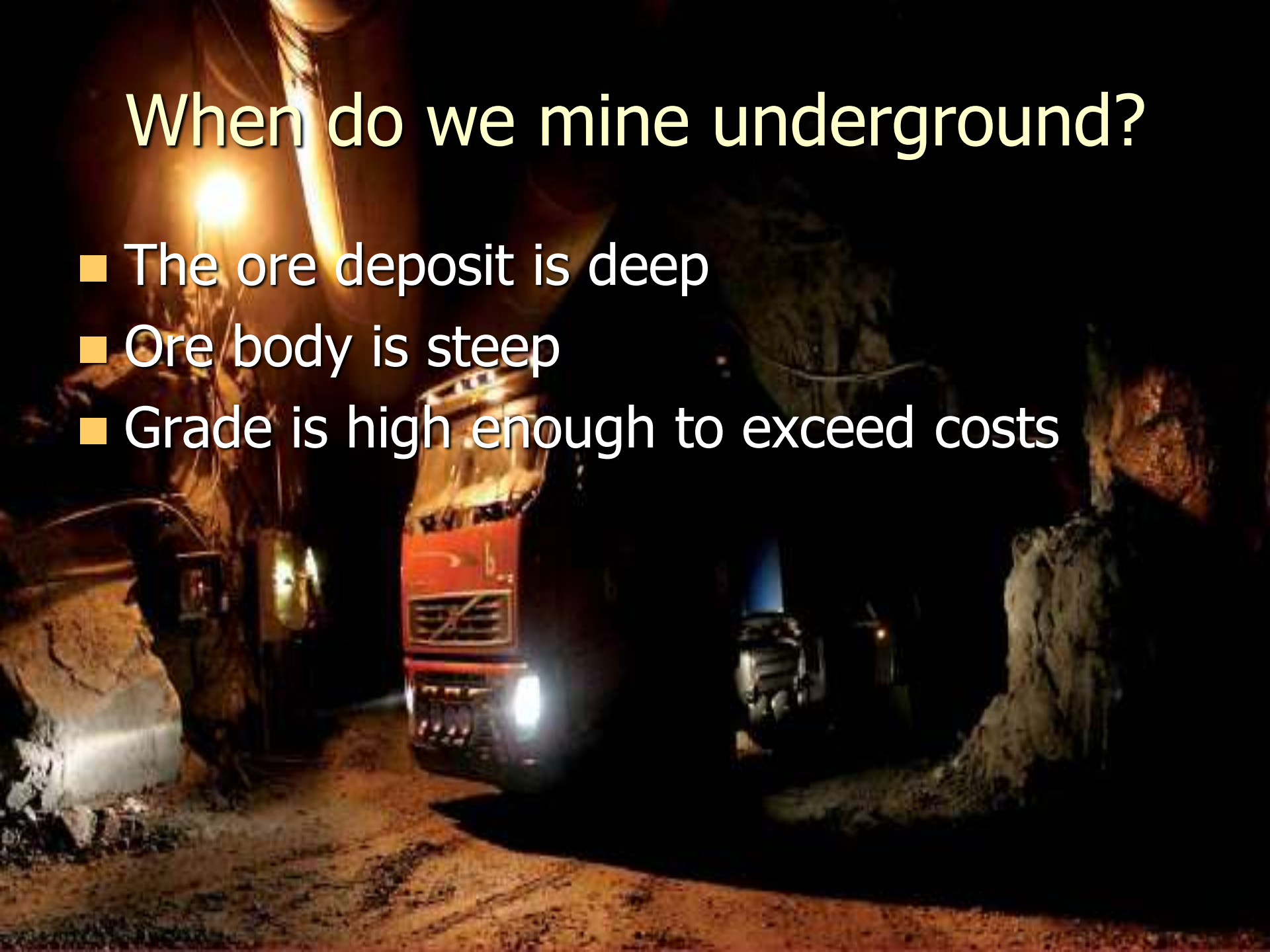
stripping ratio = h_1/h_2

Versus Underground Mining



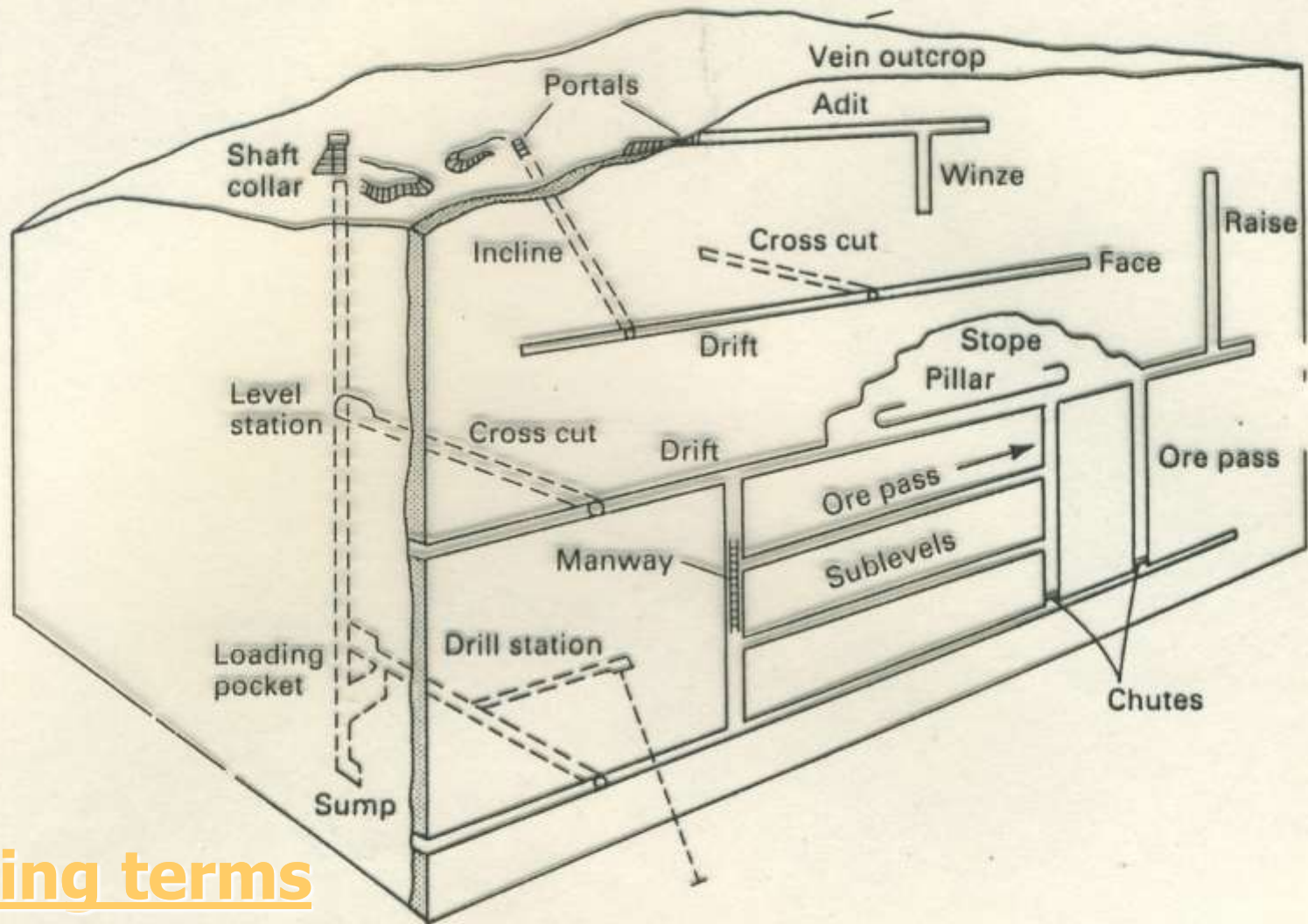
When do we mine underground?

- The ore deposit is deep
- Ore body is steep
- Grade is high enough to exceed costs



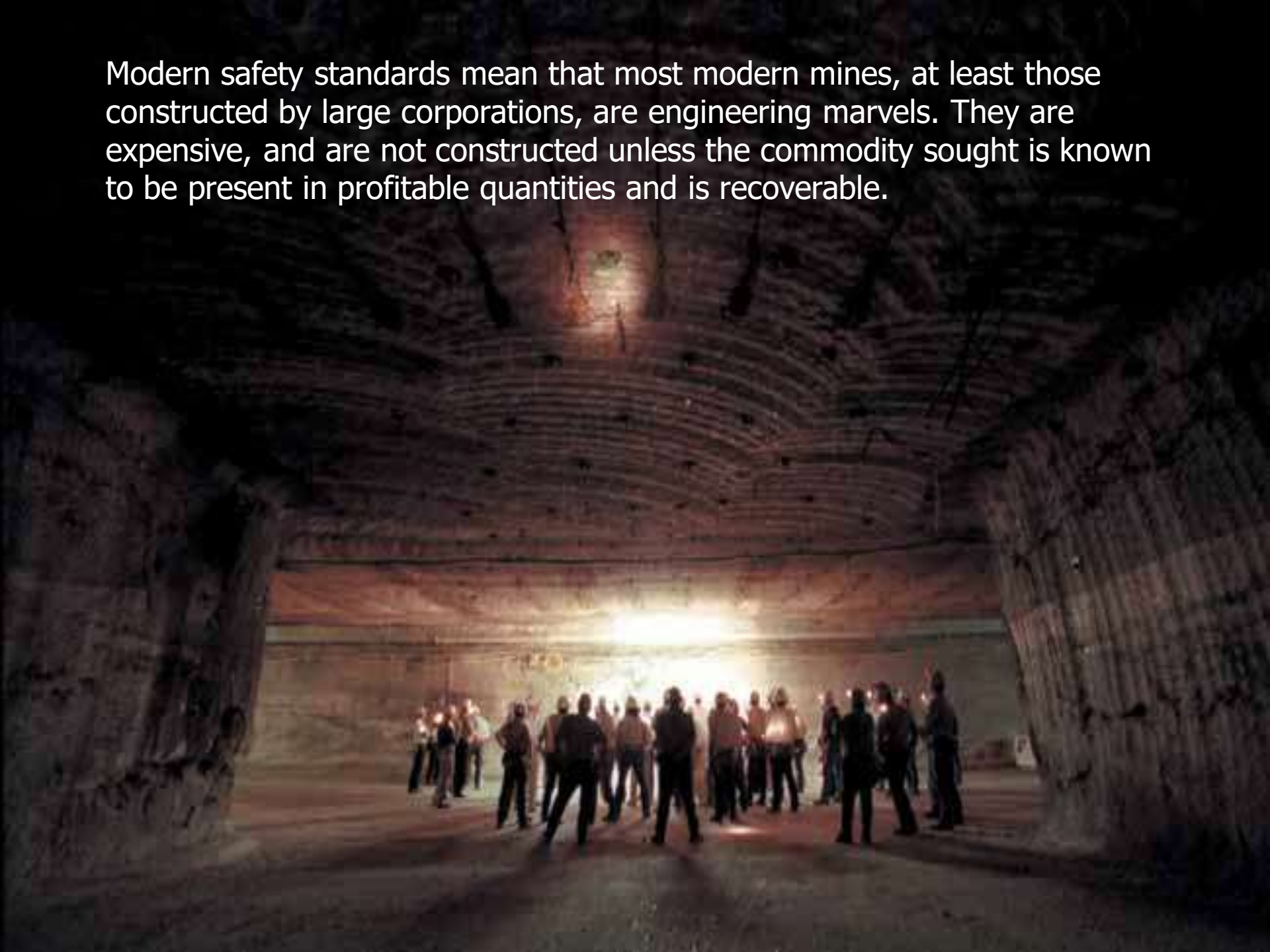
Underground mining

A variety of configurations, depending upon conditions



Mining terms

Modern safety standards mean that most modern mines, at least those constructed by large corporations, are engineering marvels. They are expensive, and are not constructed unless the commodity sought is known to be present in profitable quantities and is recoverable.



4. Beneficiation

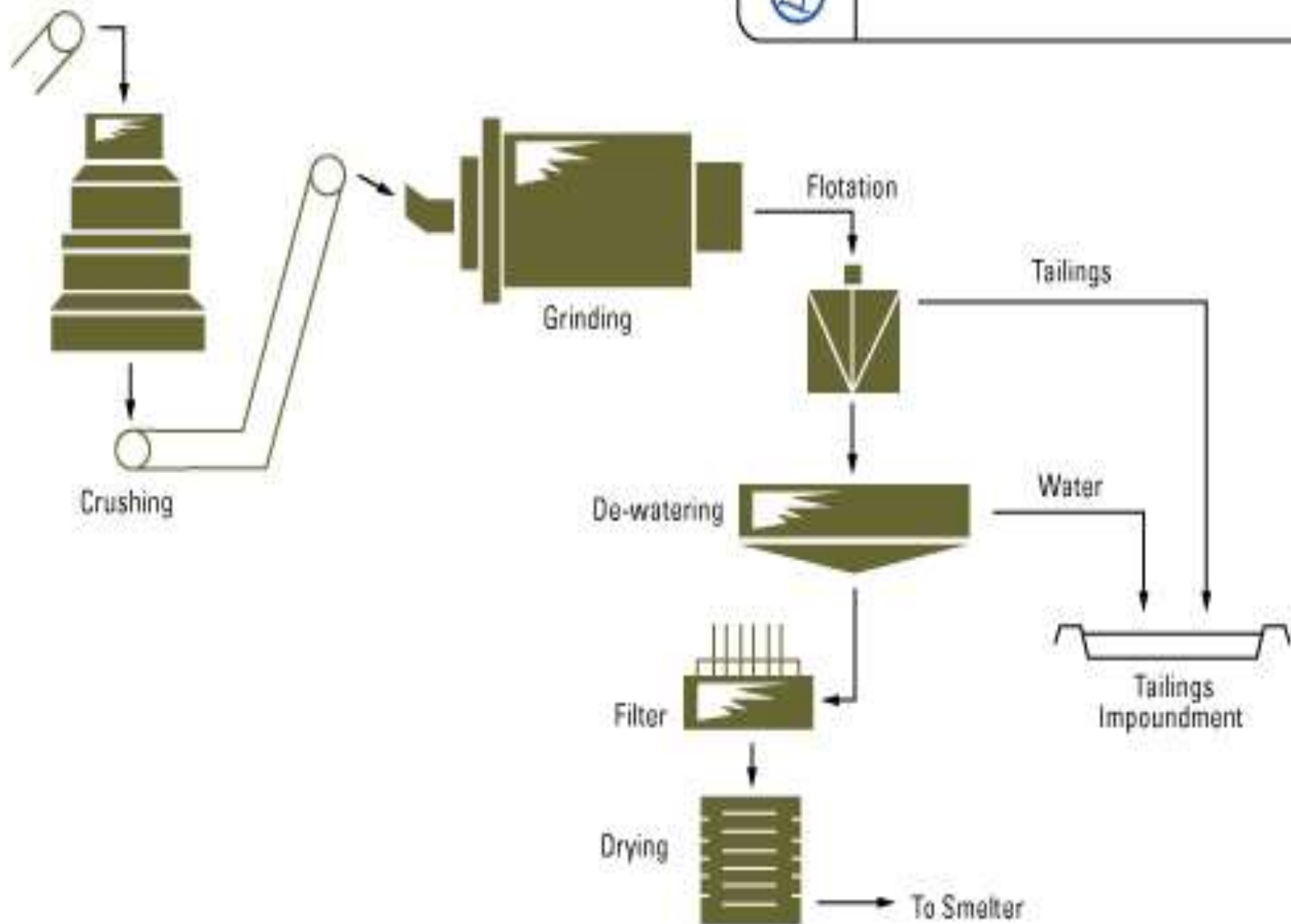
Means of separation of ore mineral from waste material (AKA gangue minerals)

A great deal of bench testing using planned treatment processes avoids nasty surprises later

e.g. Barrick's huge Acanthite reserves in tailings at Veladero

4. Beneficiation: separate ore minerals from other mined rock. Cont'd

- Ore rarely contains enough ore minerals to be refined as is.
- milling is required to separate pure ore minerals from useless "gangue" (**pronounced** "gang") minerals.
- **Milling** techniques:
 - Grinding ore to fine powder.
 - Separation using flotation techniques: powdered ores mixed with water and organic compounds "collectors" and "frothers". The collectors are heteropolar molecules with one end that adheres to ore minerals, the other that adheres to frother-coated air bubbles. Air forced through water then produces a foamy layer of concentrated ore mineral.
- environmental problems associated with mill tailings are similar to mine tailings.



Loading Ore in the Pit



Crushing



Grinding



Ball Mill

Flotation



Dewatering and Impoundment



5. Refining

Smelting

Removes the metal from the ore mineral by heating the ore with a flux, reducing the metal ion to its elemental form

Heap Leaching

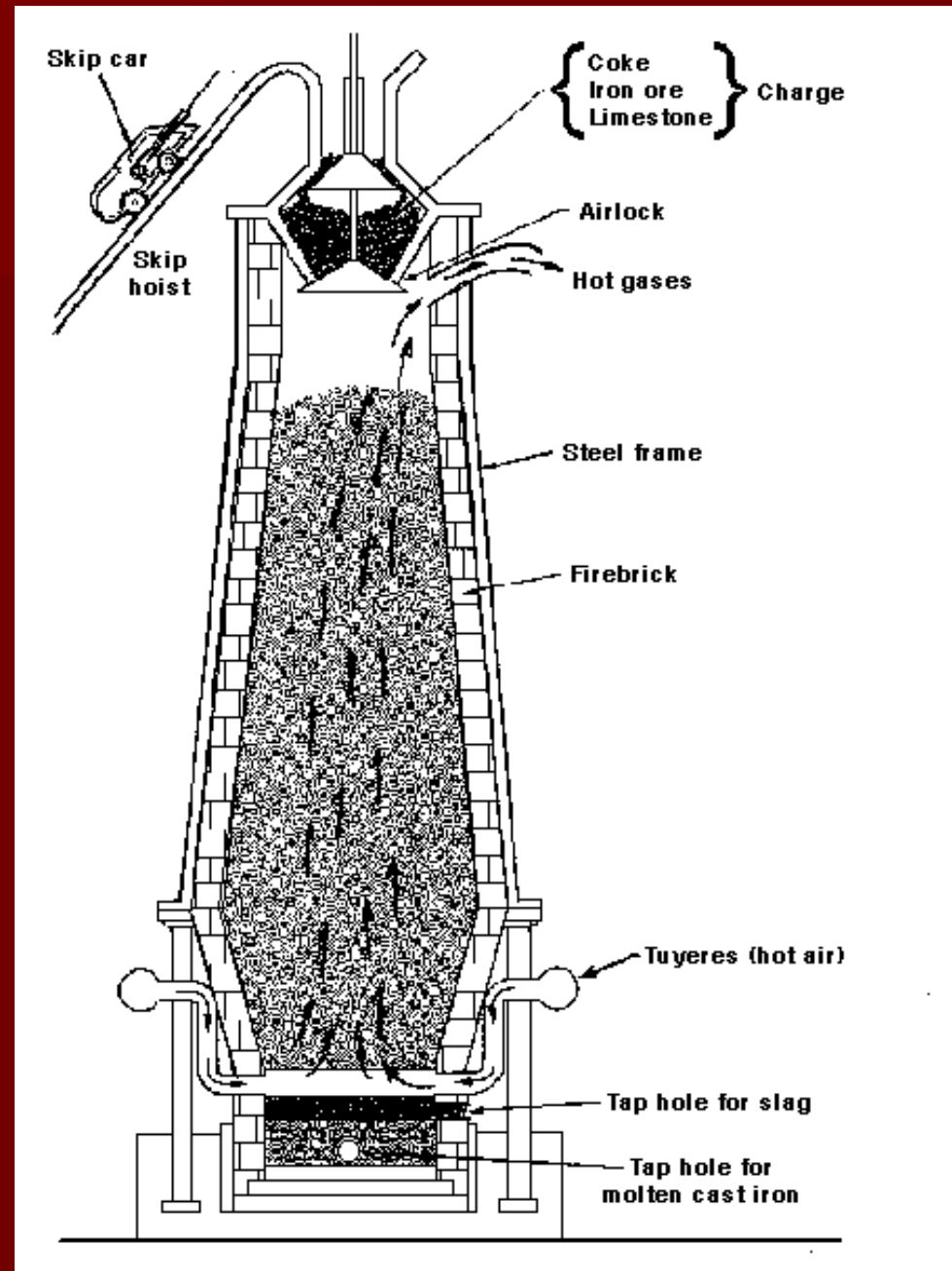
Removes metal from the ore by reaction with a solution, often using cyanide CN^- ion

Smelt refining: extract pure commodity from ore mineral.

- **Iron**, from an iron oxide (Fe_2O_3 , hematite) rich ore (such as a banded-iron formation, which also contains quartz).
- coke (carbon from coal), ore, air, and limestone mixed in blast furnace.



- Very expensive energy costs



smelting reactions:

coke + oxygen = carbon monoxide.

hematite + carbon monoxide = iron (melt) + carbon dioxide.

quartz + calcium carbonate = calcium silicate (melt) + carbon dioxide.

- iron melt and silicate melt are immiscible, with the iron being denser.
 - The iron is drawn off from the bottom of the furnace ("pig iron").
 - The silicate melt is drawn off the top ("slag").

Ex. 1: Iron reactions in Smelter

- Above 800 °C, CO is the predominant carbon combustion product:



- $3\text{CO} + \text{Fe}_2\text{O}_3$ (hematite) \longrightarrow $2 \text{Fe} + 3\text{CO}_2$ (g)
- $4\text{CO} + \text{Fe}_3\text{O}_4$ (magnetite) \longrightarrow $3\text{Fe} + 4\text{CO}_2$ (g)

Smelt Refining Example 2: Aluminum from Bauxite

Mix bauxite with water, Ca(OH)_2 & NaOH at high temperature, dissolving the aluminum (e.g. the ion Al(OH)_4^-). Gangue left behind.

- Cool solution, Al(OH)_3 gibbsite precipitates out.
- Al(OH)_3 is oxidized in a furnace to alumina Al_2O_3
- Alumina is dissolved in molten Na_3AlF_6 flux, (manufactured Cryolite from Fluorite CaF_2) in a container ("pot") made of an electrically-conducting material (typically carbon).
- Carbon anodes are suspended in the solution, and high-amperage, low voltage electricity is used to drive the reaction:
 - **alumina + carbon = aluminum (melt) + carbon monoxide.**
 - $\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 2\text{Al} + 3\text{CO}$
- The aluminum melt is immiscible in the Cryolite melt, and collects at the bottom of the pot.



Smelt Refining Example 3: a sulfide

Copper, from copper-iron sulfide (CuFeS_2 , chalcopyrite).

- the chalcopyrite is melted in a furnace with a fluxing agent that facilitates melting.
- air is added to produce Chalcocite. The process also separates the iron

Chalcocite + oxygen \rightarrow copper + sulfur dioxide



- The resulting copper is very impure, and needs to be further purified in an anode furnace (see above for Al)
- Chalcopyrite occurs with pyrite FeS_2 , a low-value ore and a source of acid pollution from slag.

Smelting (continued):

Environmental problems particular to smelting.

- Production of huge piles of slag.
- Emission of CO_2 , a greenhouse gas, into the atmosphere.
- Pollution associated with the generation of electricity needed in anode furnaces (especially aluminum).
- Sulfur dioxide emissions from the refining of sulfide ores are a major source of air pollution. The sulfur dioxide combines with water to produce sulfuric acid, H_2SO_4 http://en.wikipedia.org/wiki/Sulfuric_Acid#Wet_sulfuric_acid_process .28WSA.29
- Release of heavy metals (As, Cd, Hg), present in trace quantities in sulfide ores, into the environment.

Problems with Smelting/Roasting

- Air Pollution: SO_2 and CO_2 and particulate matter
- Noranda Quebec used to have the highest single point source of SO_2 in the world.
- Presently removed with scrubbers

http://en.wikipedia.org/wiki/Noranda_%28mining_company%29

Sulfide Minerals

- Are sometimes roasted
 - Heated in air without melting to transform sulfides to oxides
 - Gives off H_2S and SO_2
 - Then oxides processed like Fe in smelters

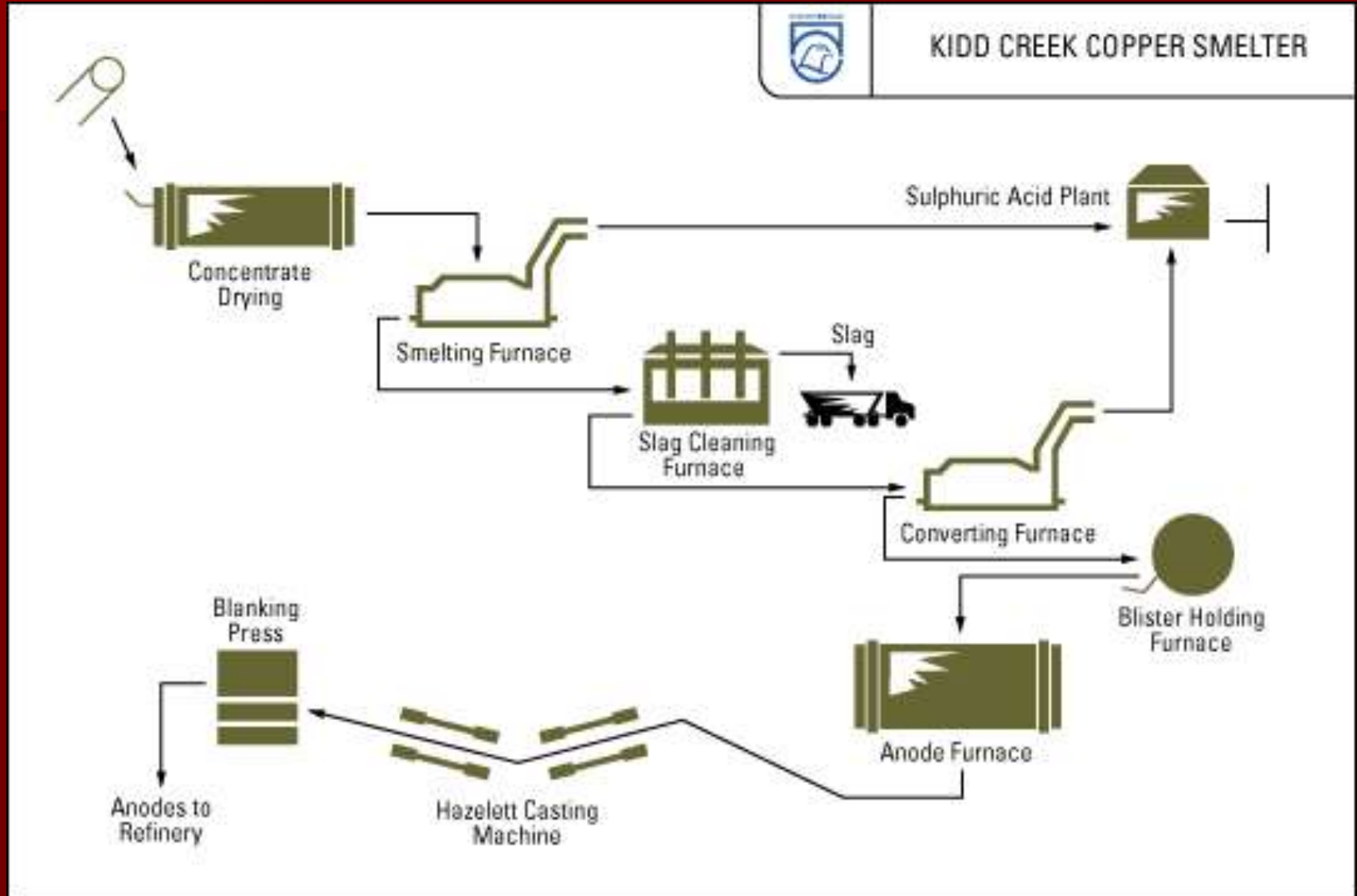
Sulfides cont'd

- Process of roasting and smelting together creates a matte
 - Sulfides are melted into a matte and air is blown through. S is converted to sulfur dioxide and Fe to iron oxide, and Cu and Ni stay in melt

Industries are getting clever at recycling pollutants such as SO₂

In this example they are manufacturing sulfuric acid for sale.

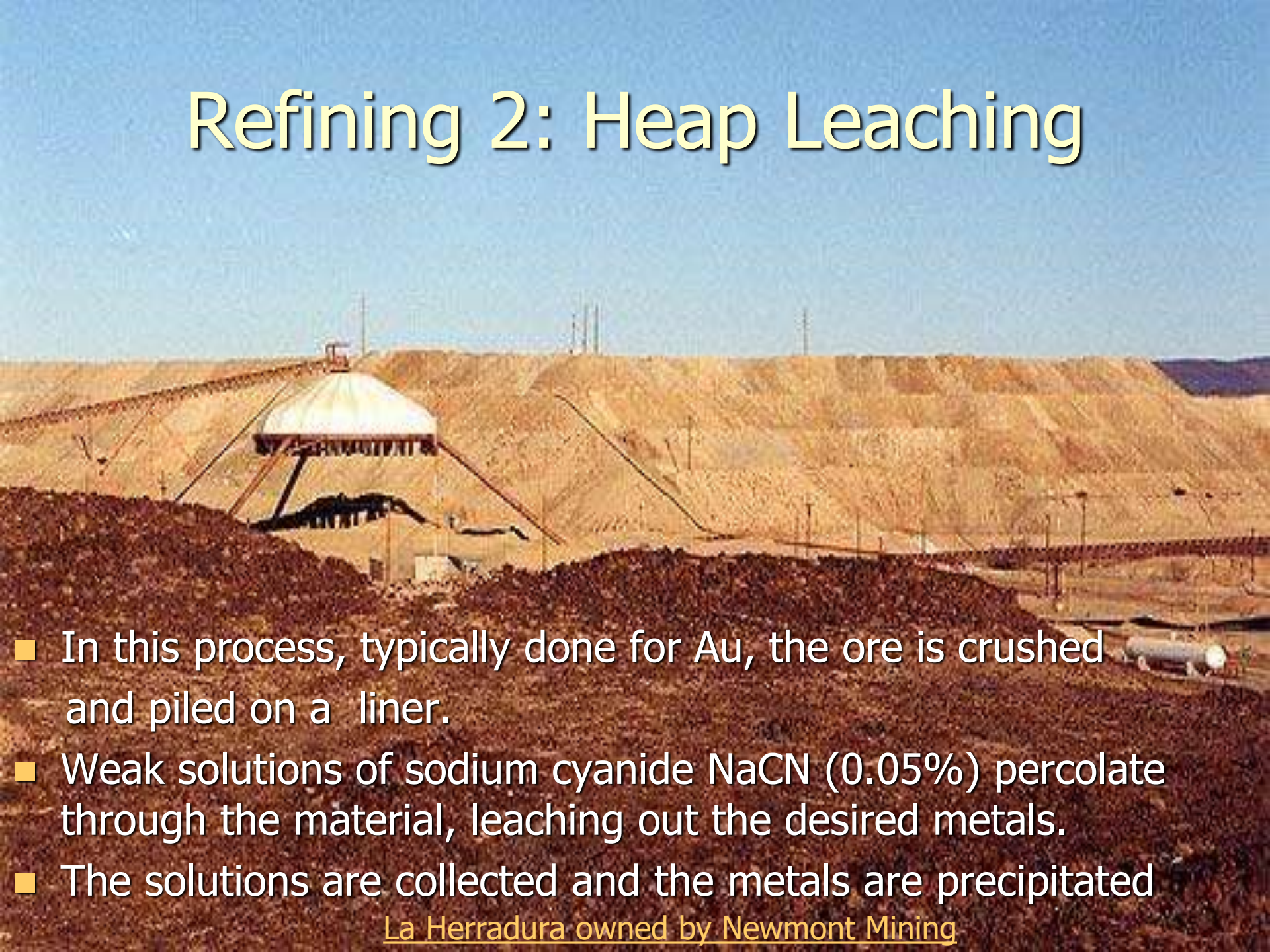
Copper Sulfide Smelting Example



Sulfides cont'd

- Electroplating
 - Used where rock contains Cu but in too little amounts to be recovered by classical methods
 - Expensive energy costs, but voltage forces reluctant reactions

Refining 2: Heap Leaching

- 
- In this process, typically done for Au, the ore is crushed and piled on a liner.
 - Weak solutions of sodium cyanide NaCN (0.05%) percolate through the material, leaching out the desired metals.
 - The solutions are collected and the metals are precipitated

La Herradura owned by Newmont Mining

Heap Leaching 2

- During the extraction phase, the gold ions form complex ions with the cyanide:



- Recuperation of the gold is readily achieved with an oxidation-reduction reaction:



DANGEROUS if cyanide is not carefully recovered.

Discussion: Pete Feigley and [Coeur D'Alene](#)

More Environmental Problems

- Mining operation itself
 - Disposal of a large amount of rock and waste
 - Noise
 - Dust

Subsidence



Newcrest Ltd Cadia Operations, image shows the result of collapse of the Ridgeway underground mine after removal of stope material.



Acidified water

■ Acid Mine Drainage

- Sulfide deposits react with groundwater to make acid
- Acidic streams can pick up heavy elements and transport them.

POISON

Image © 2007 DigitalGlobe

© 2007 Europa Technologies

© 2007 Google

Problems with open pits

- Very large holes
- Pit slopes steep and not stable. Cannot be maintained
- May fill with water
- Strip coal mines – loss of top soil in past
 - Modern fix - Now filled, smoothed out and top soil added

An aerial photograph of a large open-pit mine. The mine is characterized by numerous terraced levels, creating a stepped appearance. In the center, there is a large, circular waste rock pile. The surrounding landscape is arid and hilly. The sky is clear and blue.

Disposal of Waste Rock

- More problematic for open pit than underground
- Waste rock piles have steep angle of repose and thus may not be stable
- Bingham in its hay day produced 400,000 tons of waste rock per DAY.

http://en.wikipedia.org/wiki/Bingham_Canyon_Mine

Tailings pond: problems and solutions

- From concentrating usually have high pH (alkaline = basic)
- So modern Fix:
 - At Bingham **acid** waters mixed with **alkaline** tailings water to neutralize
- Different metals have different problems

Tailings Pond: any collection of wastewater separated out during the processing of mineral ores.

8. Cost of production.

- Costs that scale with grade of ore. The lower the grade,
 - the more ore must be mined.
 - the more ore must be shipped to the mill.
 - the more ore must be milled.
 - the more tailings must be disposed of.
- Fixed costs.
 - building a transportation infrastructure.
 - refining ore minerals, once it has been milled.

9. Cost trends in the future

The price of mineral commodities passes through three stages that depend on changes in costs:

1st: Technical improvements in mining and/or metallurgy

2nd: These improvements become balanced by effects of decreasing ore grades

3rd: cost rises because improvements in technology can not keep up with increasing scarcity.

All metals are now in stages 1 (aluminum) or 2 (copper and iron).

When reserves are too costly to exploit, an “Economic Barrier” exists and production is stopped.

10. Mine Safety

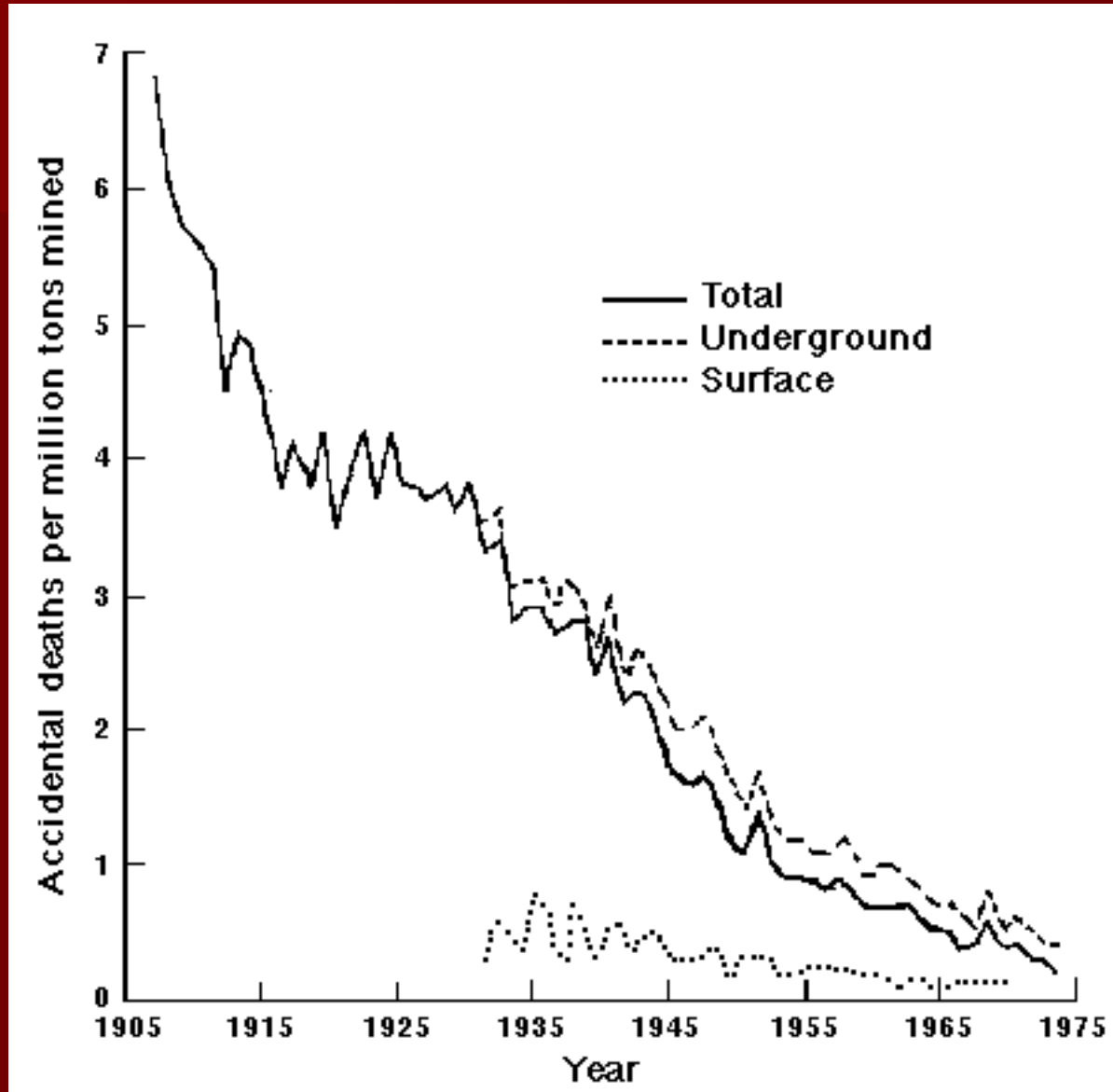
Health problems experienced by miners.

- collapse of mine.
- fire (methane, coal dust, etc.).
- asphyxiation (methane, carbon monoxide, etc.).
- pneumoconiosis (from inhaling coal dust).
- asbestosis (from inhaling asbestos fibers).
- silicosis (from inhaling silicate dust).
- heavy metal poisoning (e.g. mercury).
- radiation exposure (in uranium mining).



Mine Safety

Mine safety: In U.S., stringent mining regulations have led to a reduction in fatalities, both in terms of total deaths per year, deaths per person-hour worked, and deaths per ton mined.



Surface Mining was always safe; underground mining reached comparable safety in 1980

End of Mineral Resources and Mining Lecture

Photos courtesy of Lundin



A FAST GROWING PRODUCER OF BASE METALS
A GLOBAL PORTFOLIO OF WORLD CLASS ASSETS