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2012 Americas School of Mines

Basics of Mining and Mineral Processing

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Agenda

- Geological Concepts
- Mining Methods
- Mineral Processing Methods
- Mine Waste Management
- Mining and Money
- A Future of Mining

The topics

Elements, minerals, rocks, ore

↓

Formation of ore deposits

↓

Exploration methods

Chemical elements (Let's start at the bottom)

The building blocks of matter
Pure substance consisting of one type of atom

Al – Aluminum	Mo – Molybdenum
Ag – Silver	O – oxygen
Au – gold	Pb – lead
Cu – copper	S – sulfur
Fe – iron	Si – silicon
H – hydrogen	Zn – Zinc

Try to remember the ones in red – useful later

What is a mineral?

A solid, naturally-occurring, inorganic compound having a definite chemical composition (of elements) that may vary within limits

Examples:

quartz: SiO_2 (an oxide sometimes called silica)

hematite: Fe_2O_3 (commonly called rust)

pyrite: FeS_2 (an iron sulfide – "fool's gold")

chalcopyrite: $CuFeS_2$ (common copper sulfide)

Sphalerite: ZnS (zinc sulfide), Galena; PbS (lead sulfide)

Pyrrhotite: $Fe_{1-x}S_x$, $0 \leq x \leq 0.2$ (a magnetic iron sulfide)

Feldspars: $KAlSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$ (comprise 60% of earth's crust – the upper 40 km)

Notes: What is a mineral?

The definition of a mineral used to exclude substances formed by biogeochemical processes. However, recent research has found a close link between the metabolic activities of micro-organisms and mineral formation. In fact, micro-organisms are capable of forming minerals and particular crystal structures which cannot be formed inorganically. Based on this, Skinner (2005) made the following expanded definition of a mineral:

> An element or compound, amorphous or crystalline, formed through biogeochemical processes

to reflect " a greater appreciation, although an incomplete understanding, of the processes of mineral formation by living forms." Skinner views all solids as potential minerals.

References:
See http://en.wikipedia.org/wiki/Mineral (accessed June 2011)
Skinner, HCW, 2005. Biominerals, *Mineralogical Magazine* **69** (5): 621–641

Shiny stuff

pyrite

gold

The samples would easily fit into your hand.

chalcopyrite owl

rose quartz

galena

You likely would not see these kinds of samples in a mine because the concentrations of minerals in a mine are low.

This sample has all of them

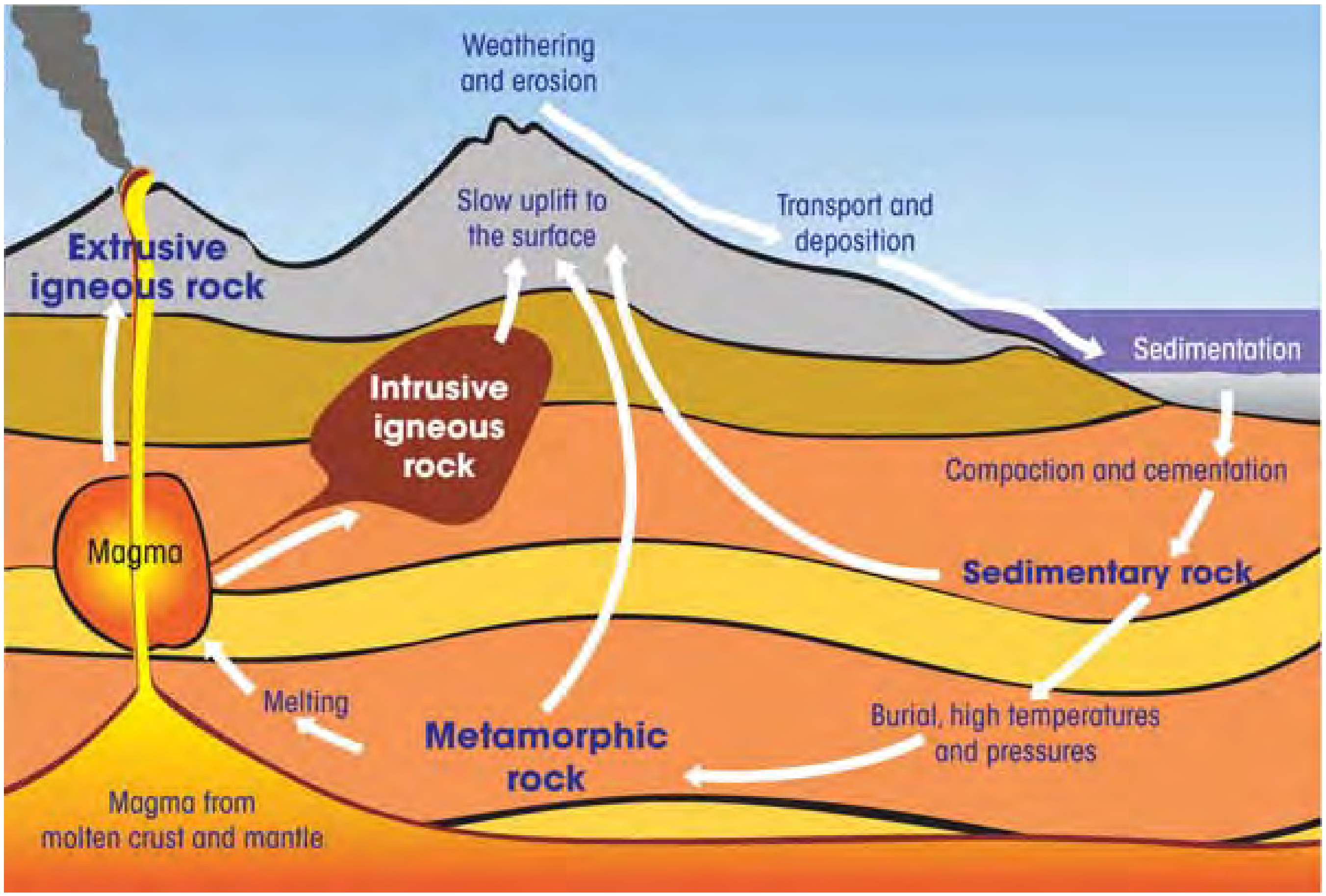
Quartz, gold, pyrite, chalcopyrite, galena, and sphalerite in matrix
Sunnyside Gold Mine, Eureka, San Juan County, Colorado USA

These are rocks

A rock is a solid, naturally occurring assemblage of minerals.

Soils are also a naturally occurring assemblage of minerals, but they are not solid.

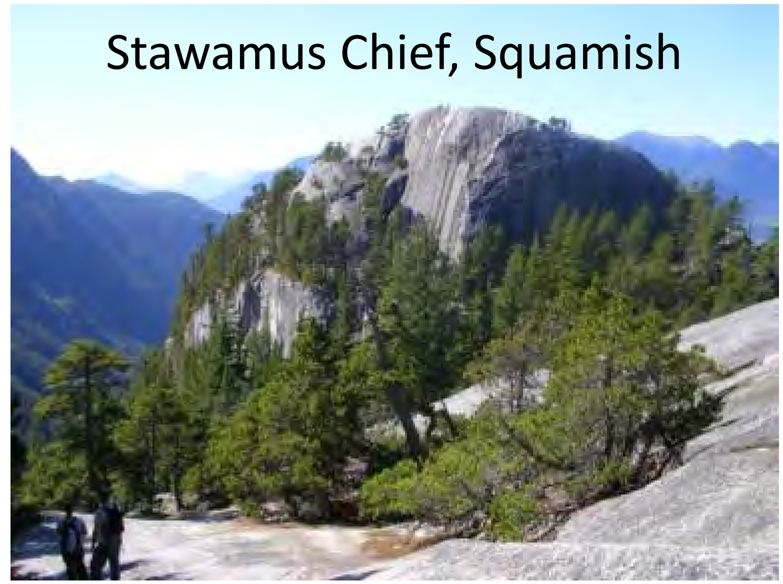
The rock cycle



http://www.thaigem.com/gemopedia/gemstone-formation.asp

Igneous rock – granite, for example

http://z.about.com/d/geology/1/0/c/1/1/stop23granite.jpg



Stawamus Chief, Squamish

http://en.wikipedia.org/wiki/File:Stawamus_Chief_South_Peak_2.JPG

Slow freezing of magma allowing crystals to form

Igneous rock – rhyolite, a volcanic rock

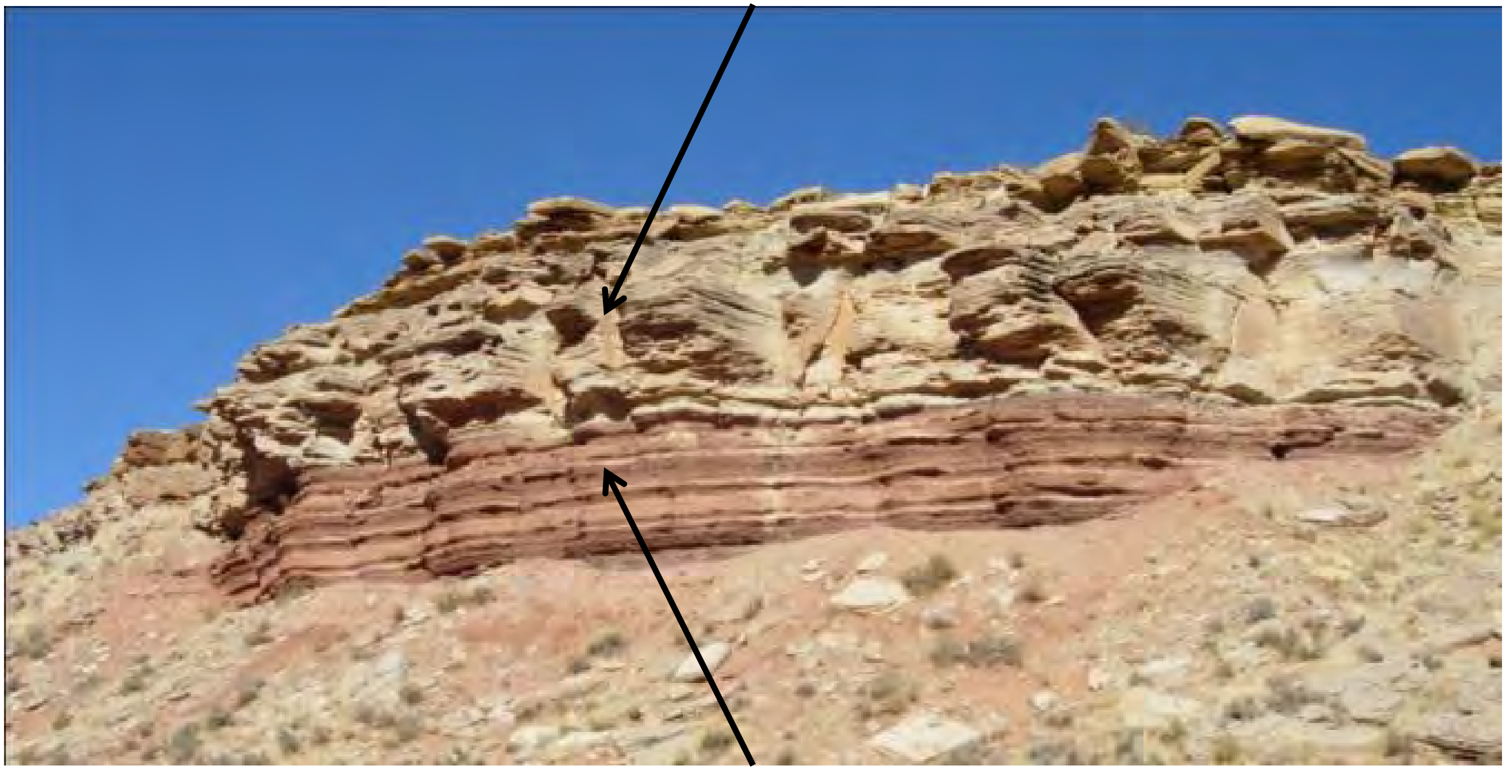
http://z.about.com/d/geology/1/0/7/S/1/rocpicrhyolite.jpg

www.jamesdenyer.co.uk/travel/iceland/iceland.asp

Same composition as granite but smaller crystals as a result of fast freezing of lava

Sedimentary rock

Greenish-grey: low oxygen environment, deep marine in this case



Red: well oxygenated environment (rust forms), shallow marine in this case

Metamorphic rock

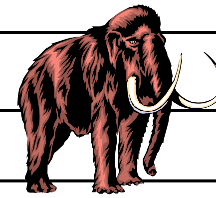
Gneiss

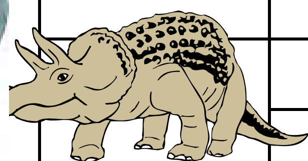
Characteristic alternating clear and dark layers

http://geology.about.com/od/rocks/ig/metrockindex/

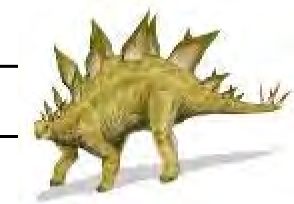
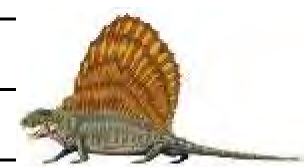
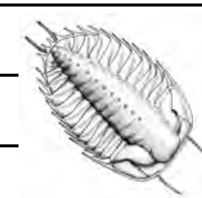
http://sciencealtavista.wordpress.com/2010/02/

Mother Earth is old!



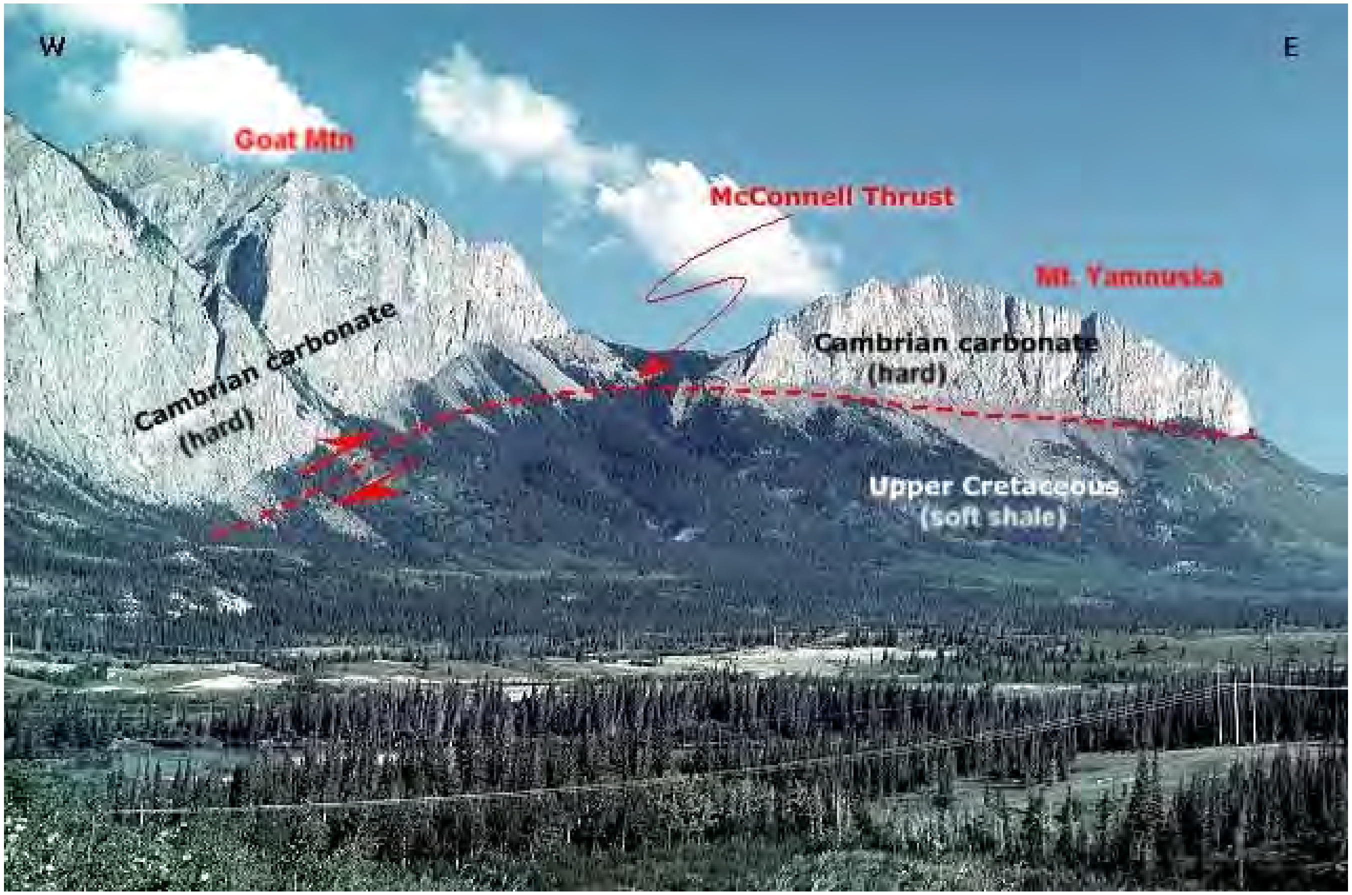



Eon	Era	Period	MYBP	
Phanerozoic	Cenozoic	Quaternary	**0-1.6**	
		Tertiary	**1.6-66**	**Dinosaur extinction 66 MYBP**
	Mesozoic	Cretaceous	**66-144**	**Ore deposits in western NA and SA**
		Jurassic	**144-208**	**Coal deposits in BC**
		Triassic	**208-245**	
	Paleozoic	Permian	**245-286**	
		Pennsylvanian	**286-320**	
		Mississippian	**320-360**	
		Devonian	**360-408**	**Oil forms in Alberta and western US**
		Silurian	**408-438**	
		Ordovician	**438-505**	
		Cambrian	**505-543**	
Proterozoic			**543-2500**	**Sudbury nickel deposits**
Archean			**2500-4600**	

and she has faults

McConnell Thrust, Rocky Mountains, Alberta



and fractures

with mineralization in pit wall in X15 pit, Pine Point mine, NWT

http://gsc.nrcan.gc.ca/mindep/photolib/mvt/pine/index_e.php

What is an ore deposit?

A solid, natural occurring mineral concentration useable as mined or from which one or more valuable constituents may be economically recovered

Implications:

current technology and current economic conditions make economic recovery possible

This is not a legal definition

Base metal?

One meaning

It's basic to industry

aluminum, copper, iron, lead, nickel, tin, zinc

Chemical meaning

It oxidizes easily meaning its atoms readily give up electrons

Precious metal?

Rare, naturally occurring metallic element of high economic value

Gold

Silver

Platinum and the Platinum Group Metals (PGMs):

ruthenium, rhodium, palladium, osmium, iridium

Chemically and physically speaking:

Do not chemically react easily, high lustre, high melting point, soft

Sometimes called noble metals

What is ore grade?

The concentration of economic mineral or metal in an ore deposit

Base metals: weight percentage
Precious metals: grams/tonne (g/t) or ounce/ton (oz/ton)
Diamonds: carats/tonne (cpt)

Examples

Copper at Highland Valley	~**0.43%** = 0.0043×1000 kg/tonne = 4.3 kg/tonne
Gold at Cortez, Nevada	**0.05 oz/ton** = 0.05 × 31.1 g/oz × 1.1 ton/tonne = 1.7 g/t
Gold at Bulyanhulu, Tanzania	**0.32 oz/ton** = 0.32 × 31.1 g/oz × 1.1 ton/tonne = 11 g/t
Diamonds at Diavik, NWT	average 3.9 cpt

tonne = metric ton, ounce = troy ounce , see notes

Notes: What is ore grade?

Tonnage:

There is the US or English ton (2000 lb) and the metric tonne (1000 kg or ~2200 lb).

1 tonne = 1.1 ton

Base metals: iron, copper, lead, zinc, aluminum (basic to industry and society)

For example: Copper grade at Highland Valley mine, BC ~0.43%

$0.0043 \times 1000 = 4.3$ kg/tonne (4.3 kg ~ 9.5 lb)

$0.0043 \times 2000 = 8.6$ lb/ton

Precious metals: gold, silver, platinum

Note: For precious metals, the ounces are **troy oz**

1 troy ounce = 1.097 oz = 31.1 grams

For example: Gold grade at Eskay Creek mine, BC ~0.96 oz/ton

0.96 oz/ton × 31.1 gm/oz × 1.1 ton/tonne = 32.85 gm/tonne

This is very rich ore – more typical is 0.2 oz/ton or less (6.84 gm/tonne)

Sometimes gram/tonne is denoted g/t

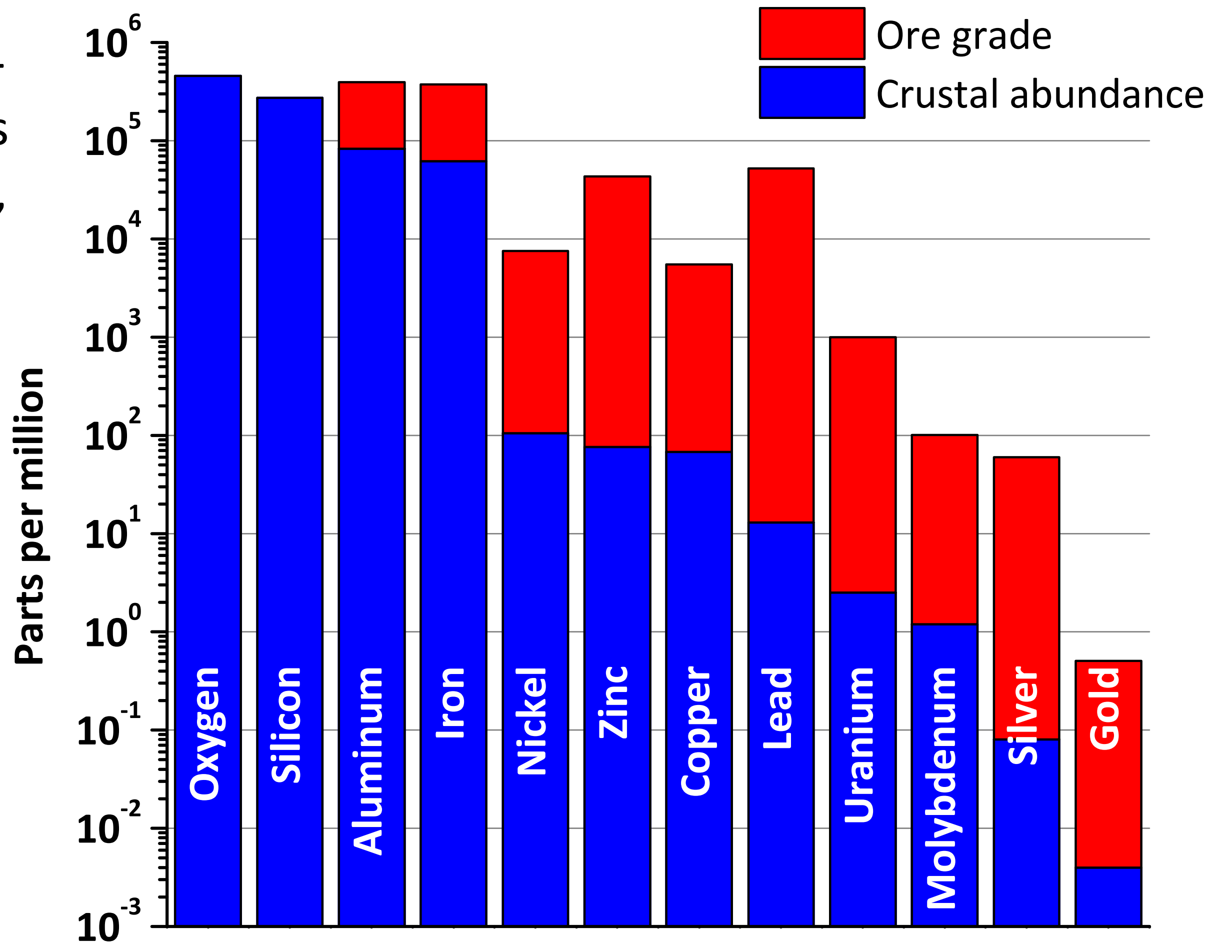
Since there are 1 million grams in a tonne, gold grade given in gm/tonne, then it is in parts per million, e.g., 6 gm/tonne is 6 ppm.

To convert a weight percentage to ppm, multiply the percentage by 10,000. Thus

0.4% is 0.004 = 4000 gm in 1,000,000 gm, i.e., 4000 ppm or 0.4 × 10,000

Concentrations of metals

Note logarithmic scale – one large division equals one order of magnitude, i.e., multiply by 10



Notes: Concentrations of Metals

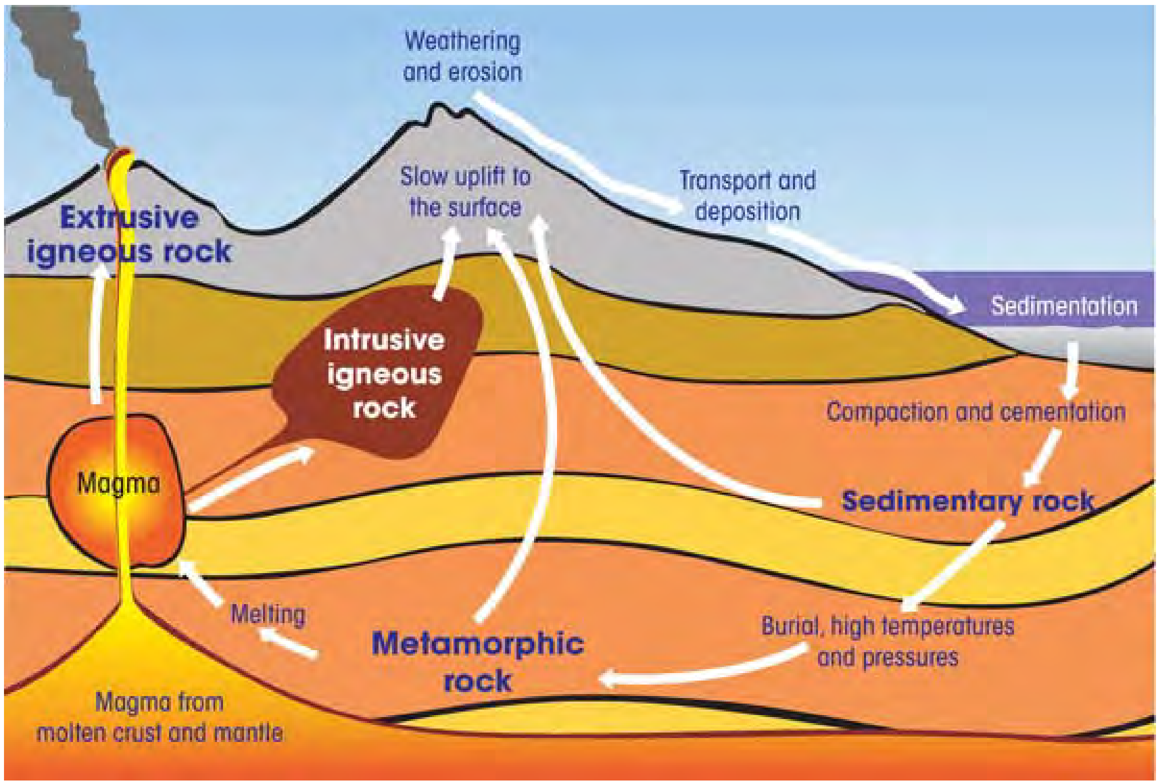
1 ppm = 1 part per million. Note that 1 ppm = 0.0001% = 1 gram/tonne or 1 ppm ~ one drop of water in a 50 liter tank or one second in ~11.5 days. The **crust** is the outer 30-50 km of earth under the continents, 5-10 km under the oceans. The radius of the Earth is about 6500 km.

Since ore is what can be mined under current economic conditions, as metal price increases, the concentration of metal required to make a mineralized mass of rock an ore deposit goes down.

Metal	Crustal abundance (ppm)	Minimum ore grade (ppm)
Oxygen	455,000	
Silicon	272,000	
Aluminum	83,000	311,250
Iron	62,000	310,000
Nickel	105	7,455
Zinc	76	43,396
Copper	68	5,440
Lead	13	52,000
Uranium	2.5	1000
Molybdenum	1.2	100
Silver	0.08	60
Gold	0.004	0.5

Where and how does concentration happen?

At any point in the rock cycle



That means there's a lot of ways concentration could happen.

Mineral chemistry – a clue for one mechanism

Pyrite: FeS_2 Chalcopyrite: $CuFeS_2$

Sphalerite: ZnS Chalcocite: Cu_2S

Molybdenite: MoS_2 Millerite: NiS

Galena: PbS Pentlandite: $(Fe,Ni)_9S_8$

Argentite: Ag_2S Linnaeite: Co_3S_4

And the common element is?

Sulfur which is formed by …

Sulfur hot spring,
Yellowstone National Park

Kawah Idjen Volcano,
Indonesia

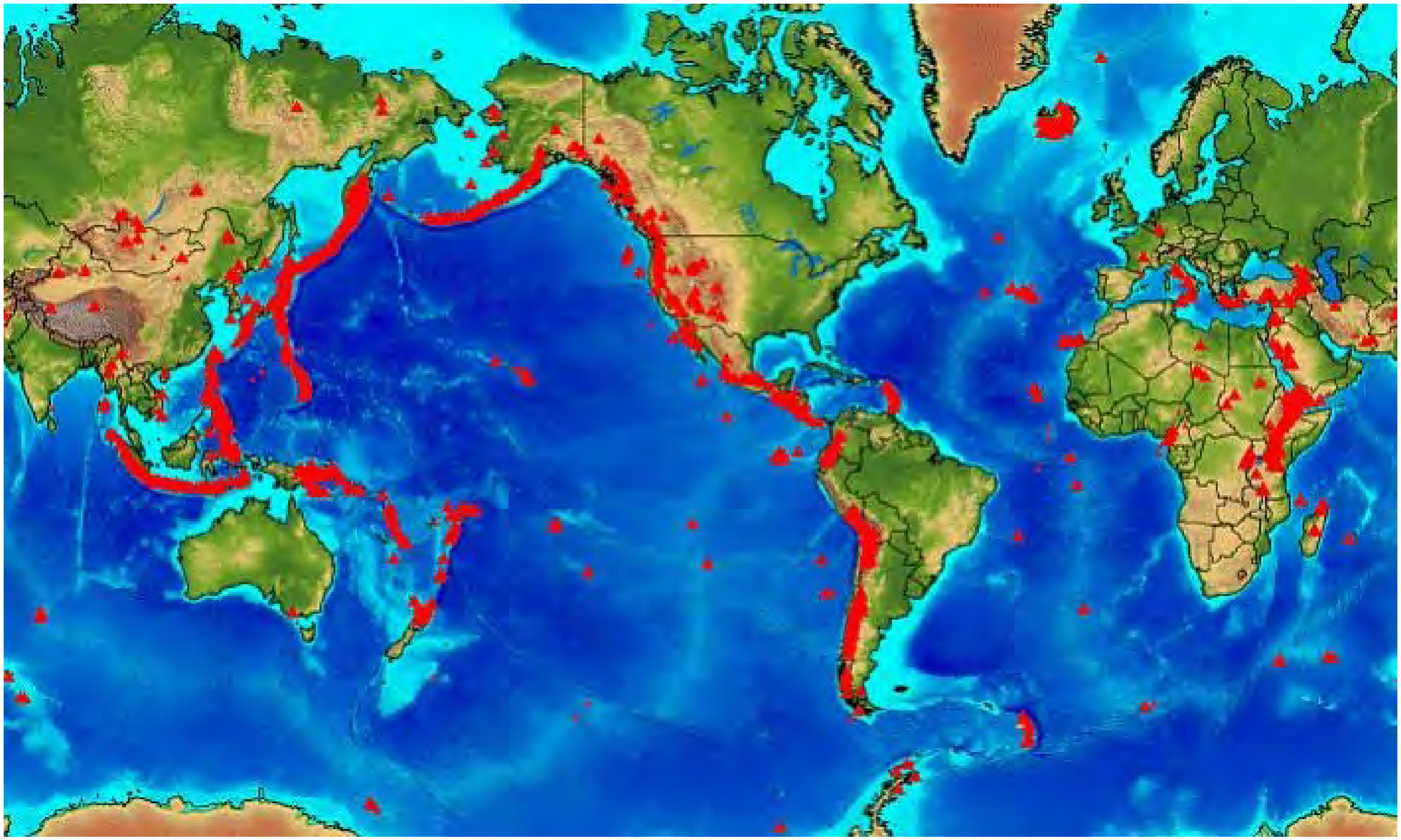
Volcanoes!

Cleveland volcano, Aleutian Islands

Image from www.nasa.gov/multimedia/imagegallery/iotd.html

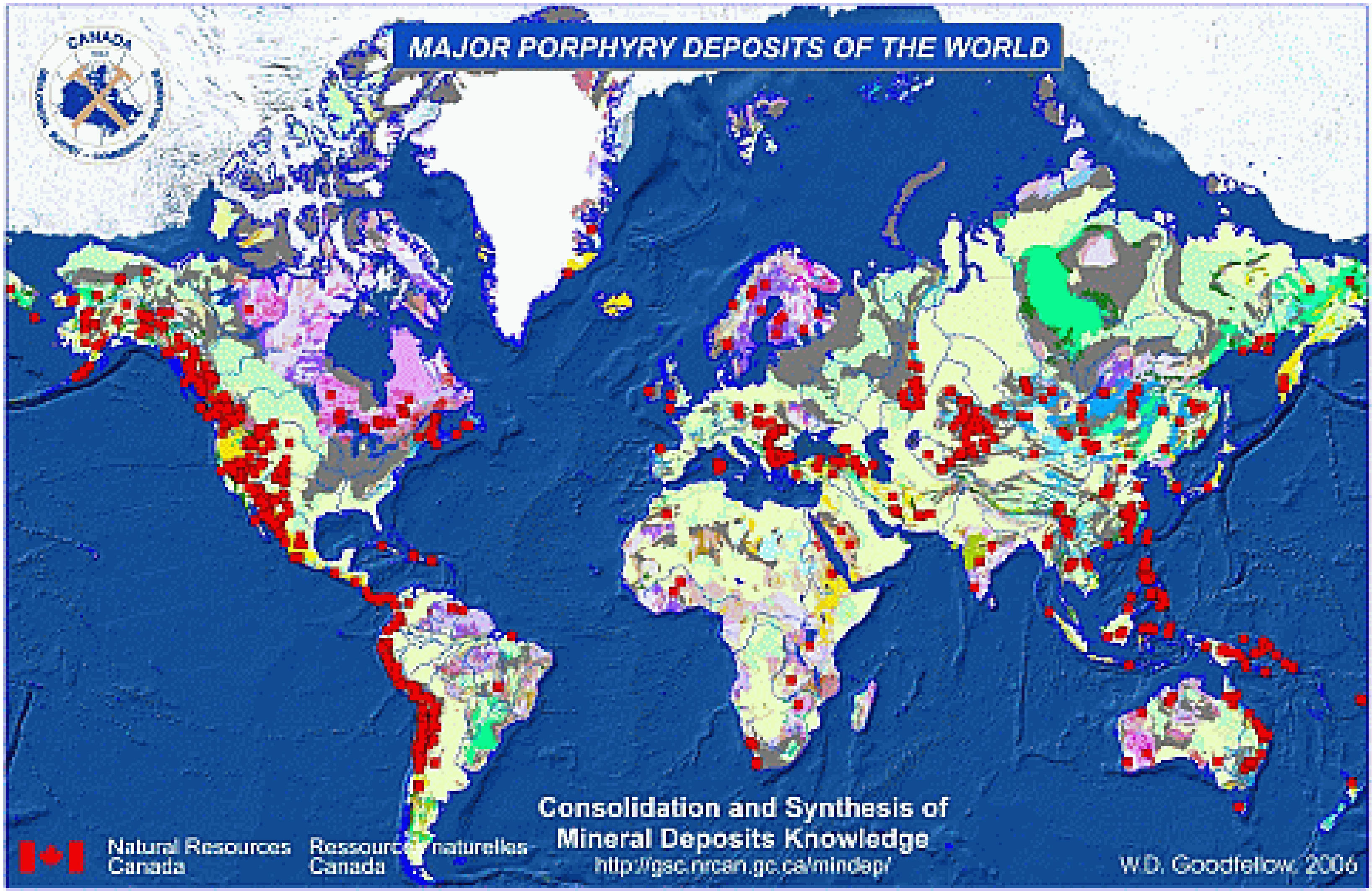
Where do volcanoes occur?

Currently at these red dots



Source: www.volcano.si.edu/world/find_regions.cfm

Major Porphyry Copper Deposits



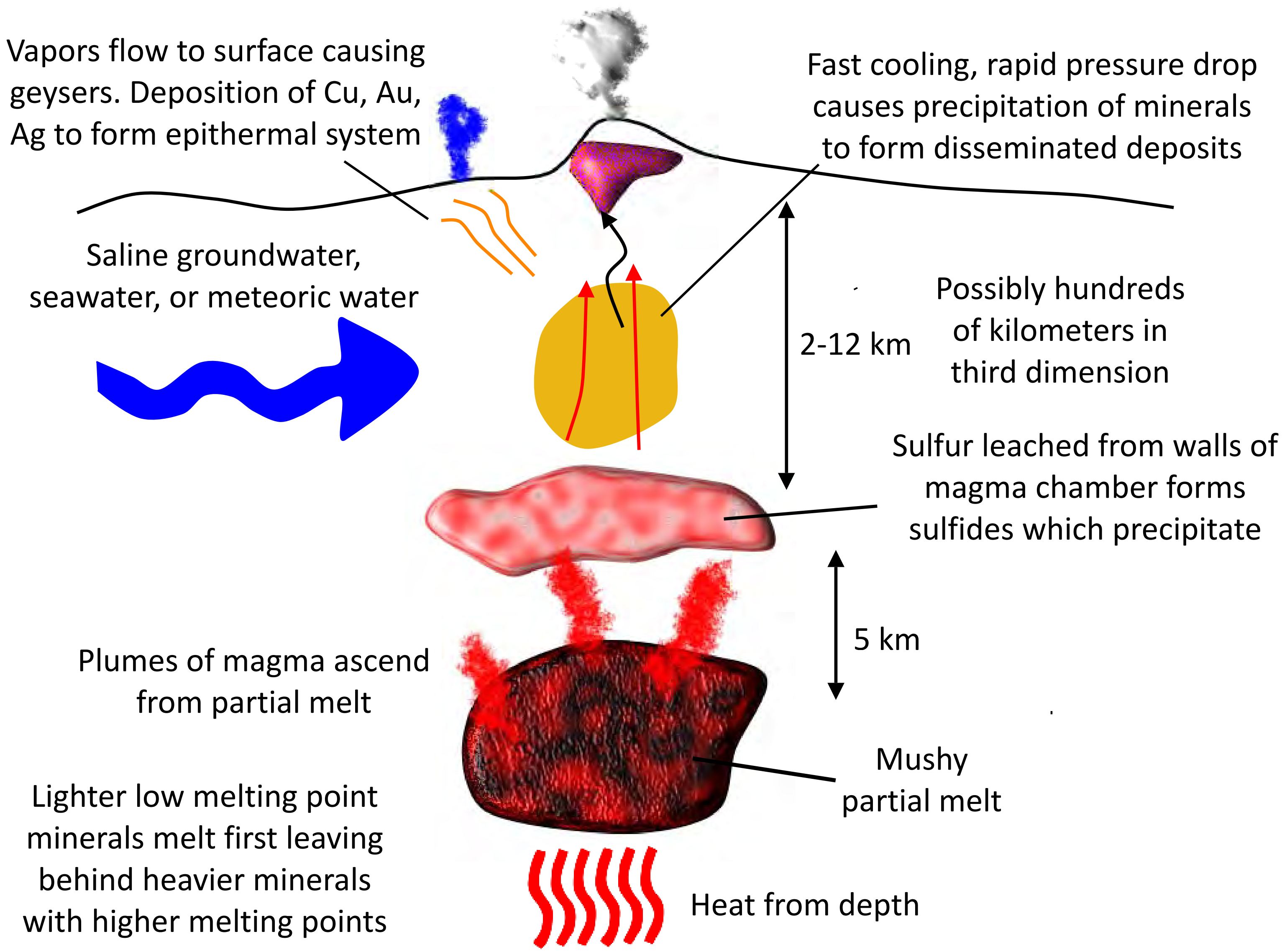
Notes: Major Porphyry Copper Deposits

The term **porphyry** refers to a rock texture in which large crystals that form in early slower stages of magma solidification are surrounded by smaller crystals that form in later faster stages of solidification. (Impress your friends with this knowledge.)

Porphyry copper deposits are associated with intrusive rocks and are formed when large quantities of hydrothermal solutions from underlying magma pass through fractured rock within and around the intrusive and deposit metallic minerals along hairline fractures as well as within larger cracks. Porphyries are disseminated, low grade deposits (0.5% to 2% Cu, commonly as chalcopyrite) with smaller amounts of other metals such as molybdenum, silver and gold.

Porphyry copper deposits occur in subduction zones such as the west coast of South America, or in areas where subduction zones once existed such as in Western Canada, western and southwestern US which have a complicated geological history involving considerable volcanism.

Igneous – hydrothermal ore deposits



Notes: Igneous – hydrothermal ore deposits – 1

This slide shows the many ways in which igneous activity can lead to an ore deposit. Not all of these mechanisms occur in the same region. Note the depths and sizes.

Rock begins to melt at temperatures of 600°C. At locations distant from crustal plate boundaries (see later) the temperature in the earth increases at a rate of about 20°C per kilometer. This means that melting could begin at a depth of 30 km. This is quite deep. Magma is known to form at much shallower depths because water in minerals lowers the melting point of the rock.

The rock does not melt all at once because the minerals in a rock mass have different melting points. Instead a partial melt forms. Feldspars and quartz have the lowest melting points (about 600°C) and are the first to become liquid resulting in a felsic magma that ascends from the rock mass. Left behind are crystals of the minerals olivine and pyroxene which have a higher melting point (about 1000°C). Once that melting point is reached a basaltic magma forms. In this way the less dense felsic minerals, which could contain metals of economic interest, are separated from the heavier minerals in a rock mass.

One kitchen example of a partial melt is frozen orange juice. The sugary juice has the lowest melting point (between -30 and -40°C) and thaws first as the temperature increases. The water in the juice has the highest melting point (0°C) and is the last to thaw.

Notes: Igneous – hydrothermal ore deposits – 2

Magma may melt enough rock to form a chamber where it accumulates. Fractionation continues in the chamber as lighter low melting point minerals remain as fluids and heavier sulfide and oxide minerals precipitate. Sulfur is leached from the walls of the chamber and forms sulfides which precipitate once the solution becomes saturated resulting in a massive sulfide deposit. Nickel deposits such as Voisey's Bay and Norilsk formed this way.

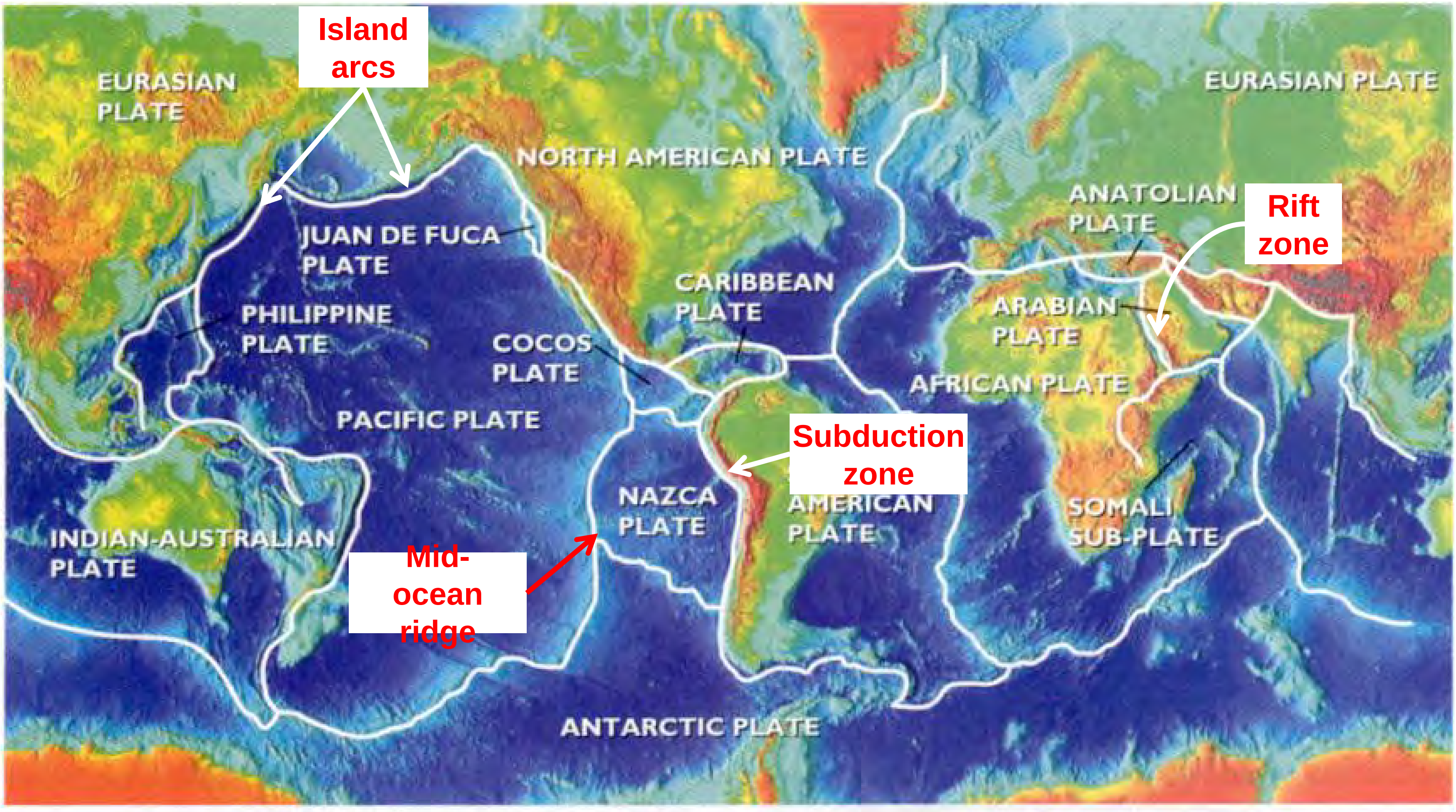
The addition of saline groundwater, seawater, or meteoric water to magma creates a hydrothermal system, essentially a hot (>200°C) brine, which can dissolve and transport large quantities of metals and other elements. As a hydrothermal solution moves upwards, it cools and undergoes a pressure decrease causing the dissolved minerals to precipitate from solution at temperatures between 500 and 50°C. Disseminated mineral deposits form at higher temperatures and epithermal deposits form in veins at lower temperatures. The geysers at Yellowstone National Park are an example of an epithermal system.

To generate sufficient mineralization to form an ore body, the supply of molten rock must be continuous over a long period of time, perhaps a few thousand to a few hundred thousand years. However, there may also be several phases of magmatic activity.

Reference: Tosdal et al, 2009. From source to sinks in auriferous magmatic-hydrothermal porphyry and epithermal deposits, *Elements*, **5**:289-295

And the solid result is …

Plates of the Earth's crust



Notes: Plates of the Earth's crust

The crust of the earth is divided into a number of thick plates. Oceanic crustal plates are about 10 km thick. Continental crustal plates are much thicker.

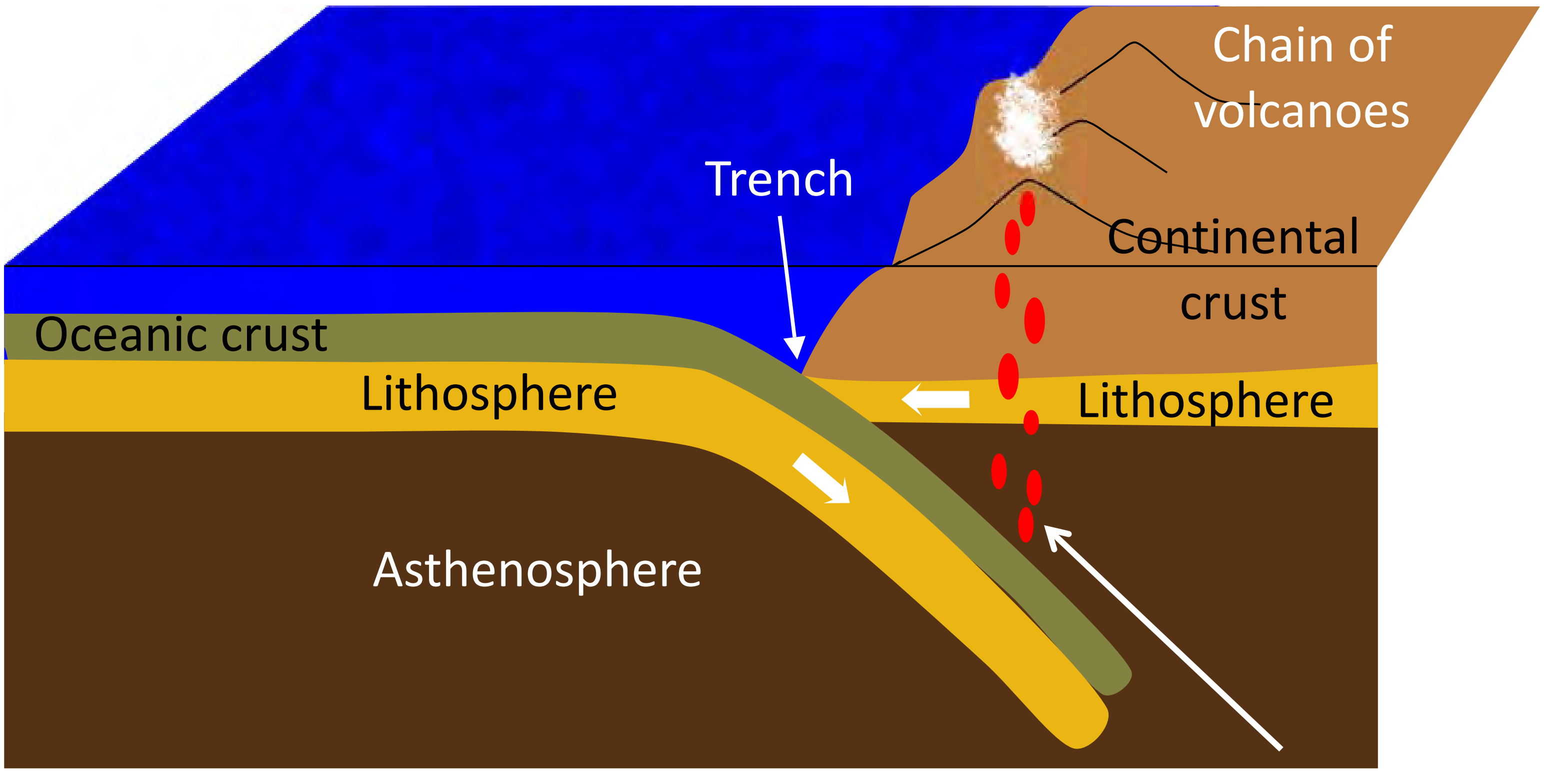
There are a number of different boundaries between the plates (shown as white lines on the map). **Mid-ocean ridges** are large mountain ranges in the ocean and **subduction zones** are where a heavier (iron rich basalt) oceanic plate goes under a lighter (silica rich granite) continental plate. **Island arcs** are also subduction zones but the over-riding continental crust happens to be below sea level. Continental **rift zones** are large openings caused by extensional forces due to upwelling of magma and leading to thinning of the crust. Rift zones occur at mid-ocean ridges and within continents. The Basin and Range province of Nevada and Utah is one example of an old (17 million years) continental rift. The East African rift zone and the Gulf of California are examples of current rift zones.

Types of plate boundary

Plate boundary	Example
Convergent	
Ocean-Ocean	Island arc such as Japan
Ocean-Continent	Andes Mountains
Continent-Continent	Himalayas
Divergent	
Mid-ocean ridge	Mid-Atlantic ridge
Rift zone	East African rift, Benue trough
Transform	San Andreas fault

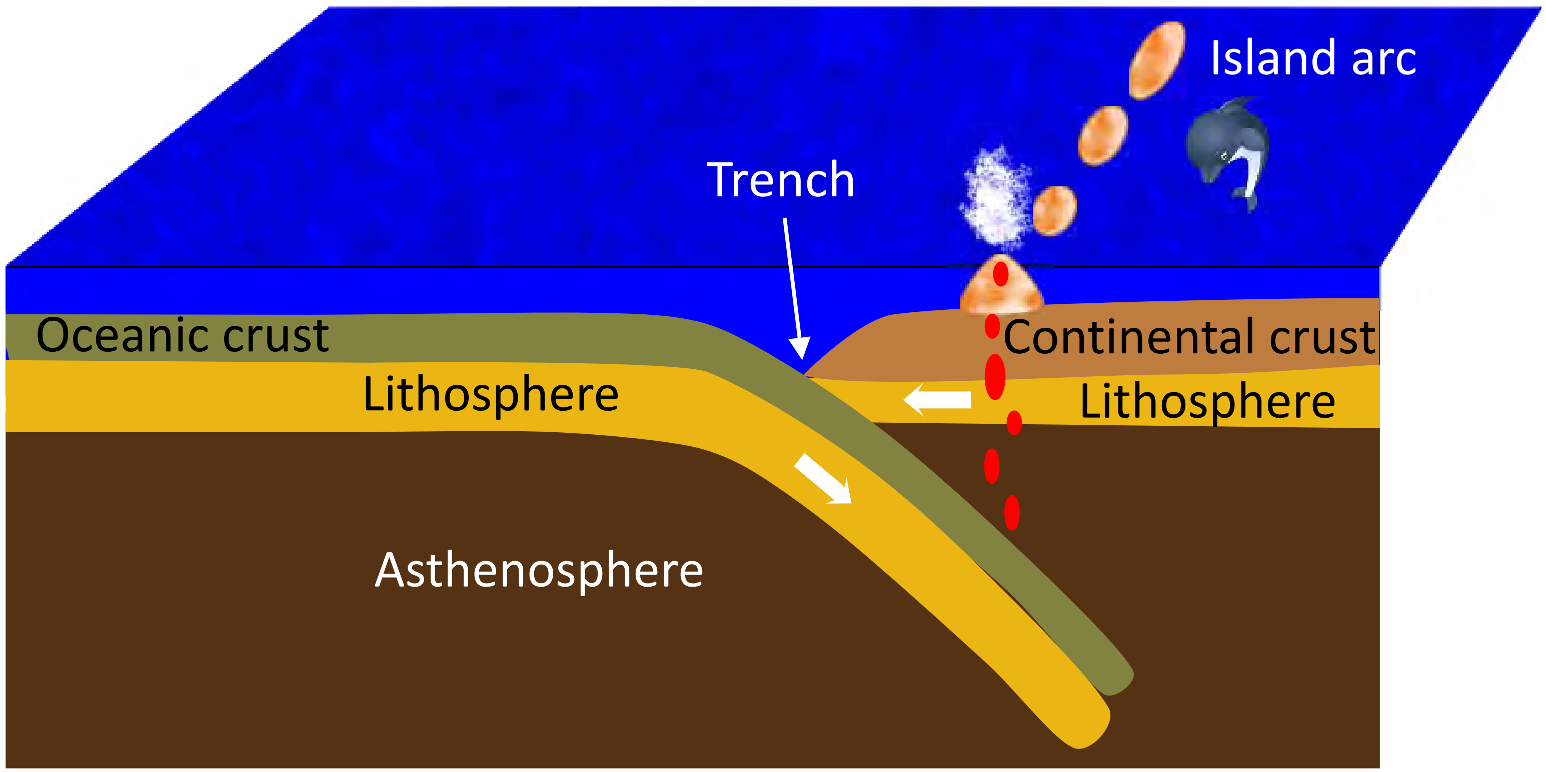
Magma is produced at the boundaries in red

Subduction at a continental boundary



Water-bearing minerals in oceanic crust lower the melting point of the asthenosphere causing partial melt

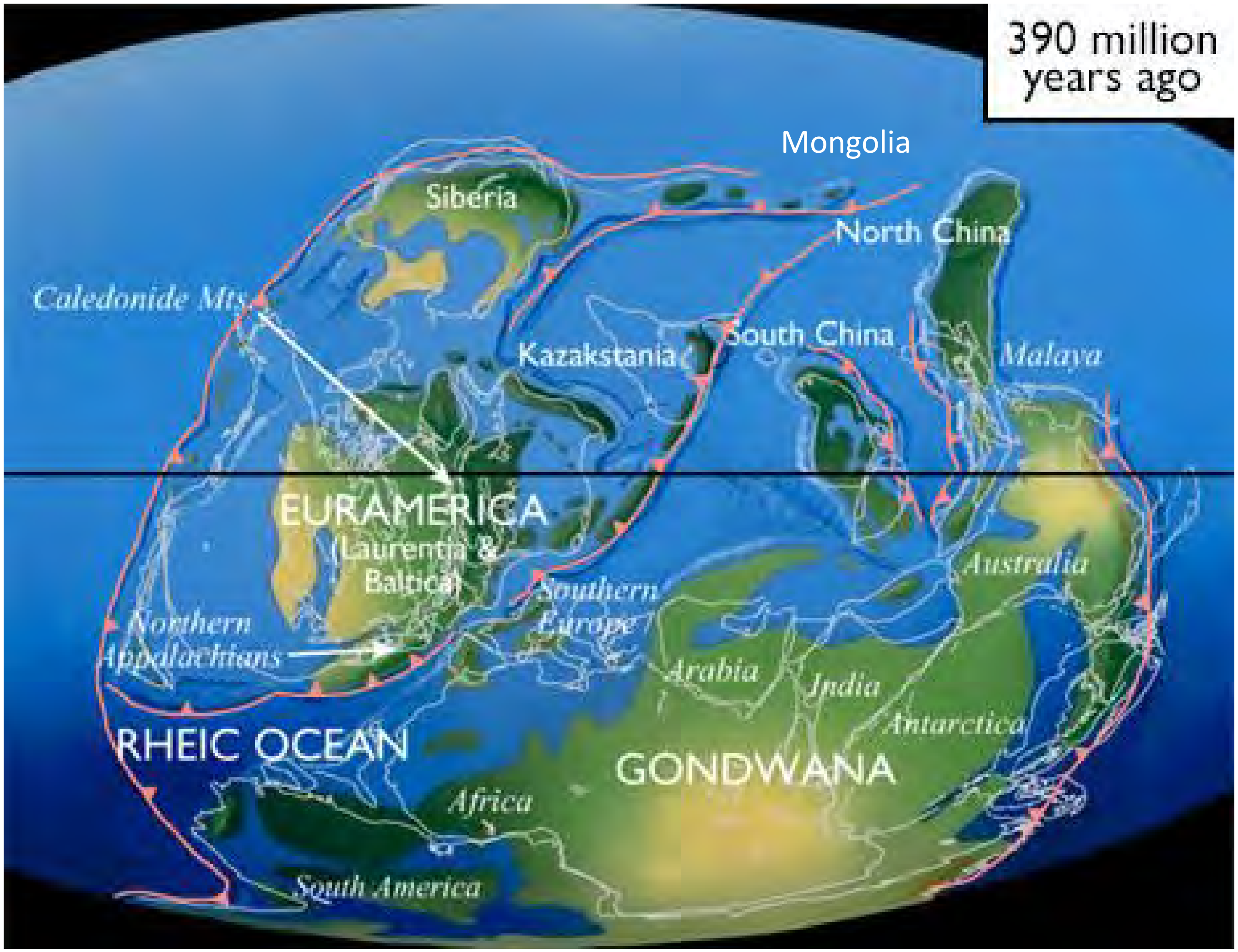
Subduction forming an island arc



Convergence in the Aleutians

Image from
www.nasa.gov/multimedia/imagegallery/iotd.html

Earth geography 390 million years ago

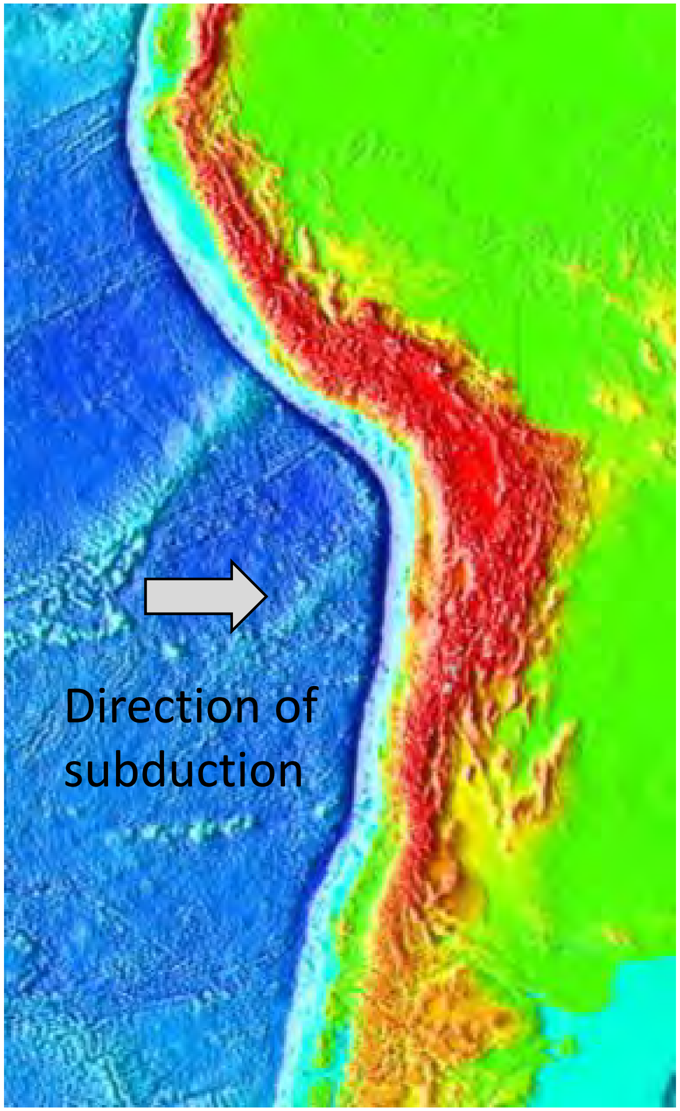


http://www.paleoportal.org/index.php?globalnav=time_space&sectionnav=period&period_id=13

Mineral Resources in Mongolia

Source: Polo resources, Thomson Reuters, China General Administration of Customs. *Estimate **As of 01/02/11

Western South America

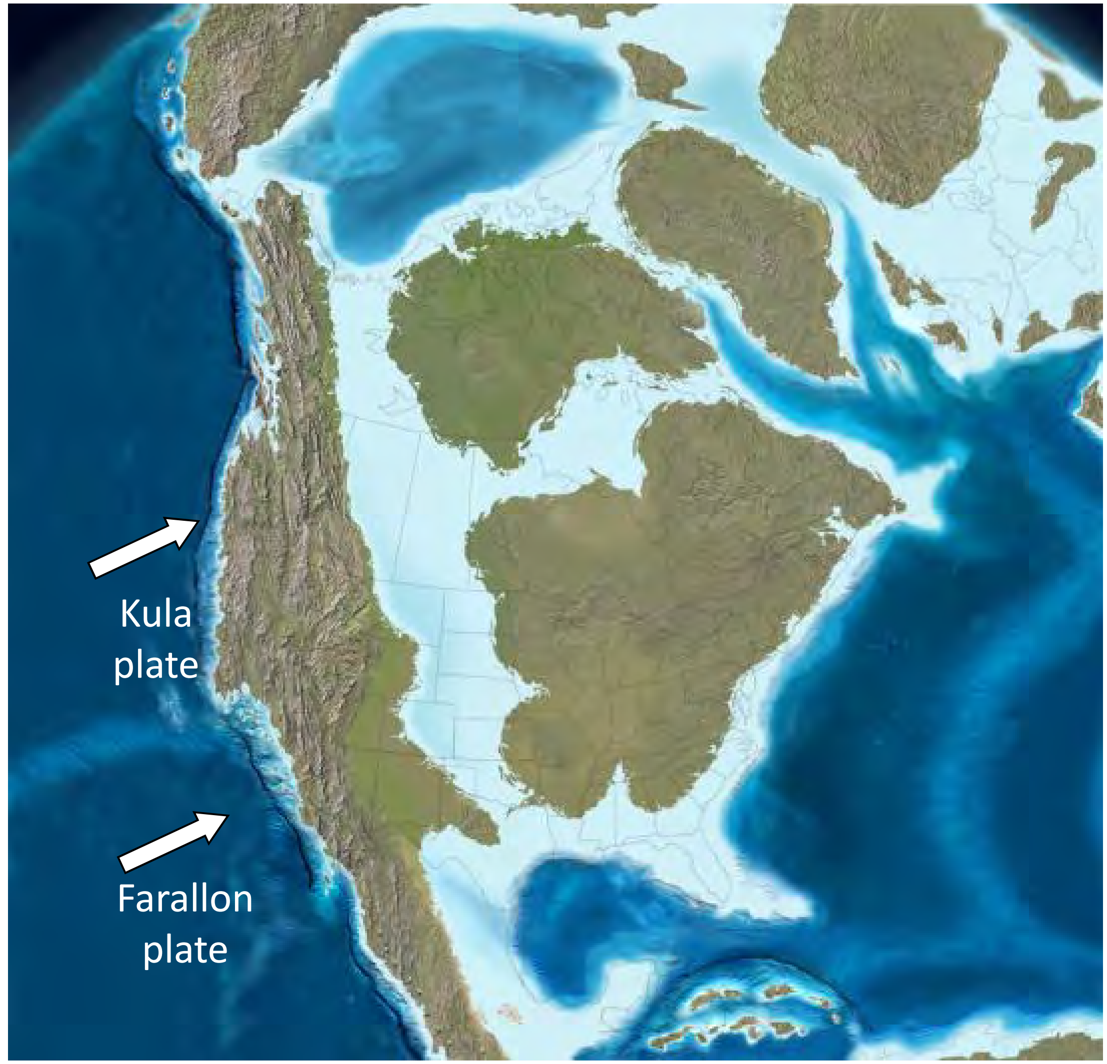


Tungurahua Volcano , Ecuador, December 2010

www.ngdc.noaa.gov/mgg/image/2minrelief.html

Western North America 75 million years ago

Subduction (arrows) and volcanic activity all along coast to form mountain ranges (and ore bodies)



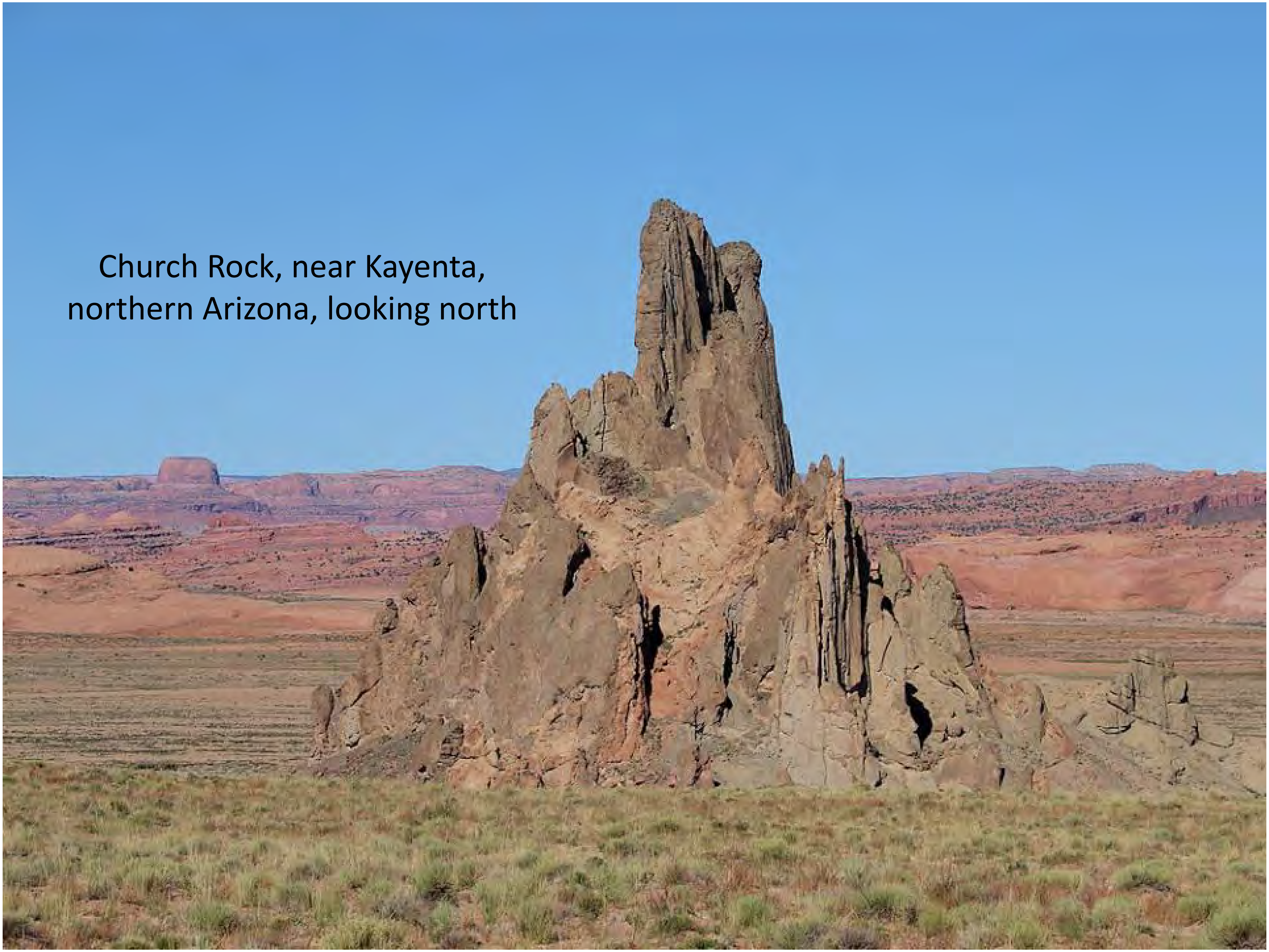
Weaver's needle, remnant volcano east of Phoenix

Notes: Western North America 80-85 million years ago

The geological history of the west coast of North America is quite complex. However, 80-85 million years ago, the western coast of North America was a subduction zone, much like the west coast of Chile is now. Two plates, the Kula to the north and the Farallon to the south were subducting under North America. Mountains formed by volcanic activity and also by accretion of rocks as the Kula and Farallon crashed into the North American plate.

Several intrusions of magma occurred, bringing with them the mineralization that formed the orebodies in the region. Several volcanoes also formed – the eroded remnants of these are all around the province of BC and many western states, including Arizona.

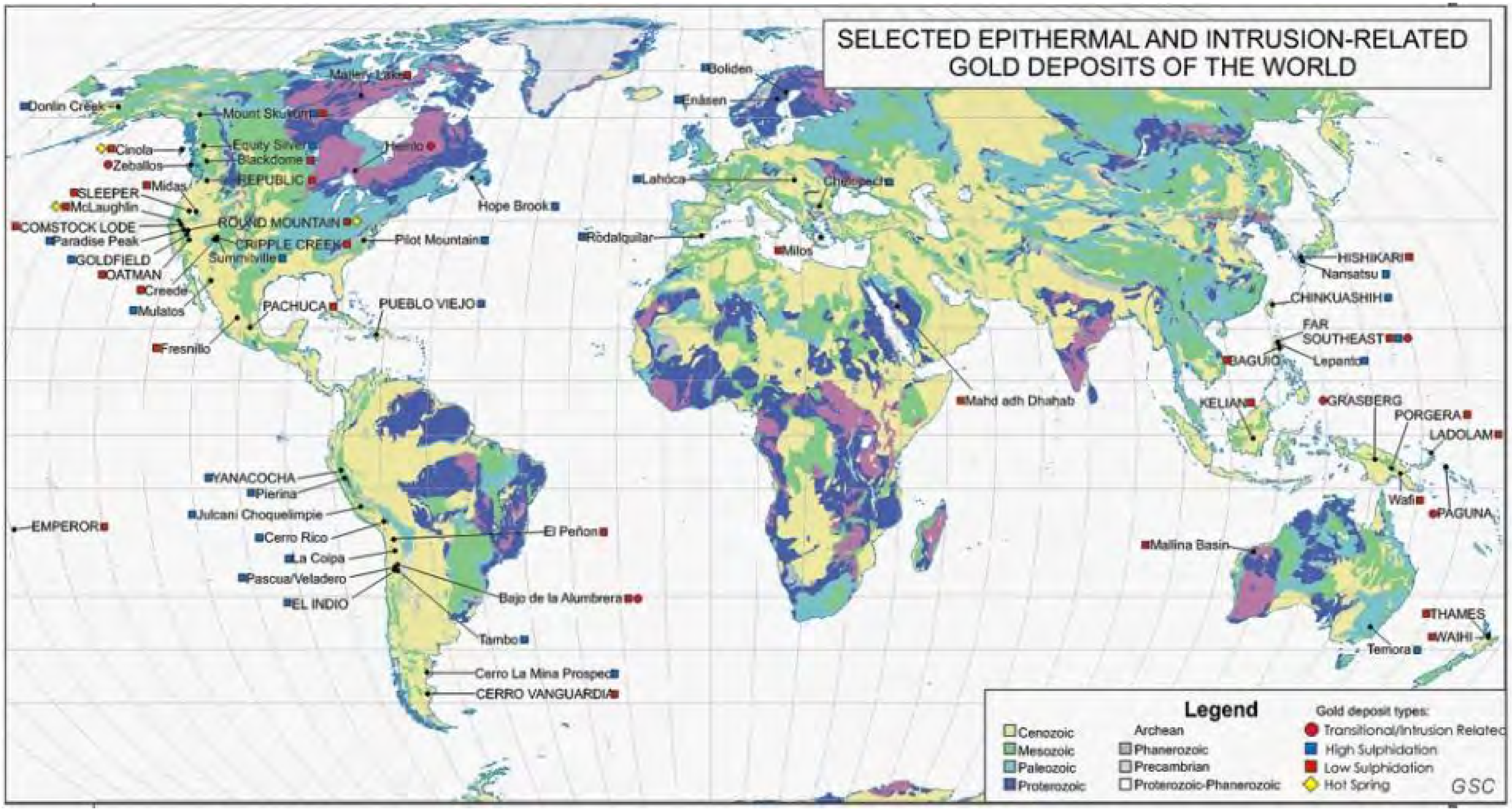
See http://www.washington.edu/burkemuseum/geo_history_wa/



Church Rock, near Kayenta,
northern Arizona, looking north

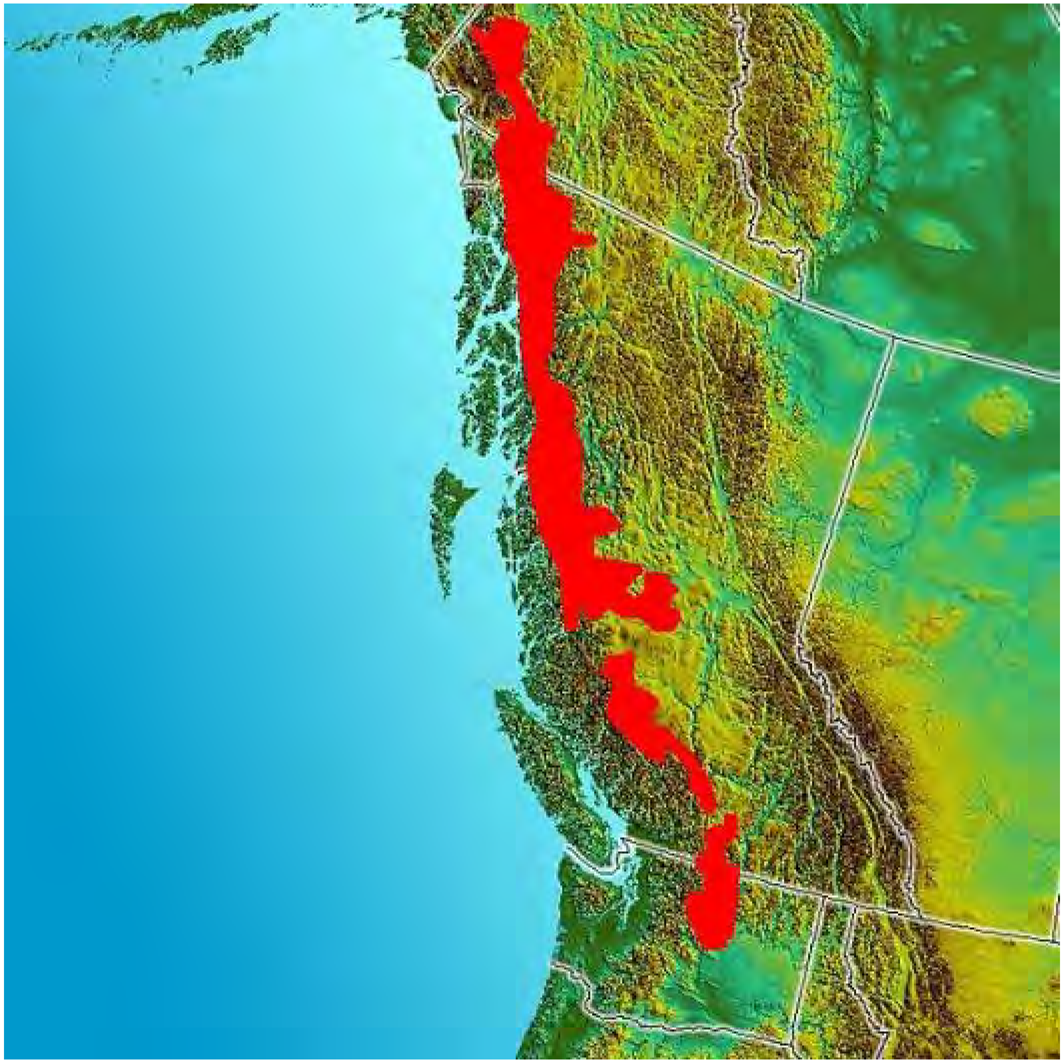
Epithermal deposits of the world

Associated with but far away from a magma source



http://gsc.nrcan.gc.ca/mindep/synth_dep/gold/epithermal/index_e.php

Coast Range in British Columbia



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

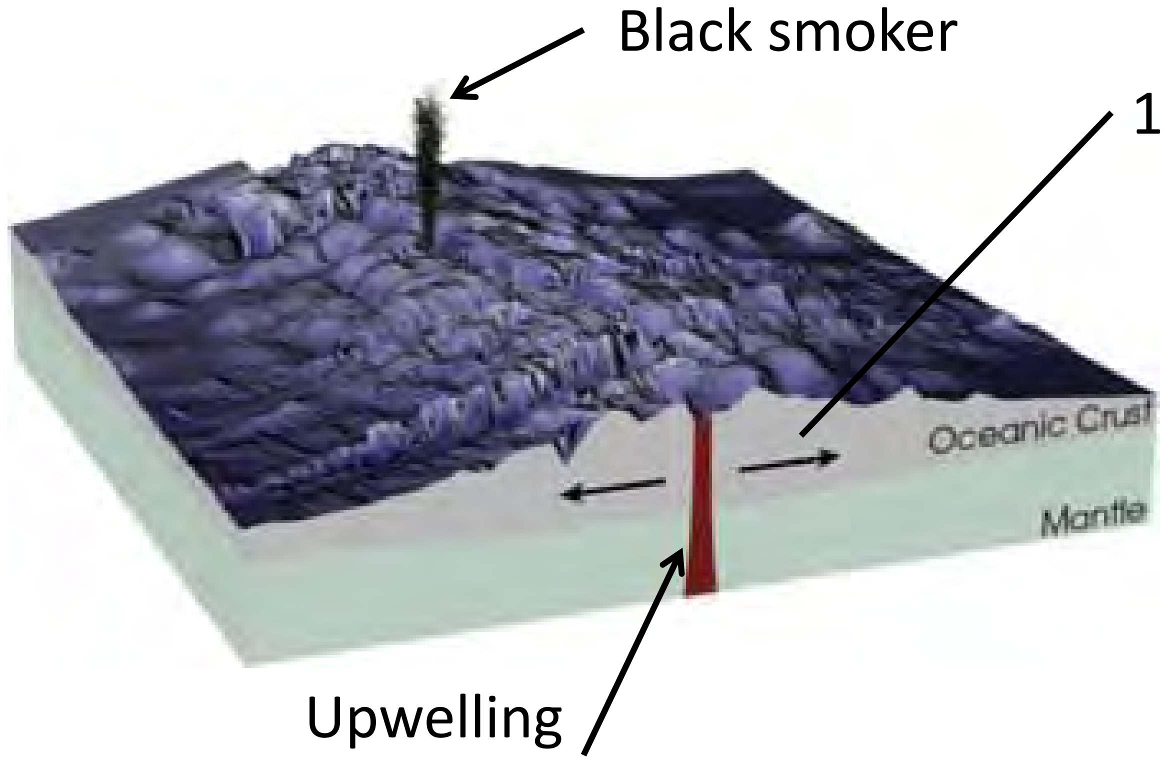
Magma intrusions at subduction zones are enormous!

Several hundred kilometers long
Hundreds of meters thick

Chilean Andes

http://whatonearth.olehnielsen.dk/Tectonics.asp

Mid-ocean ridge (divergent boundary)

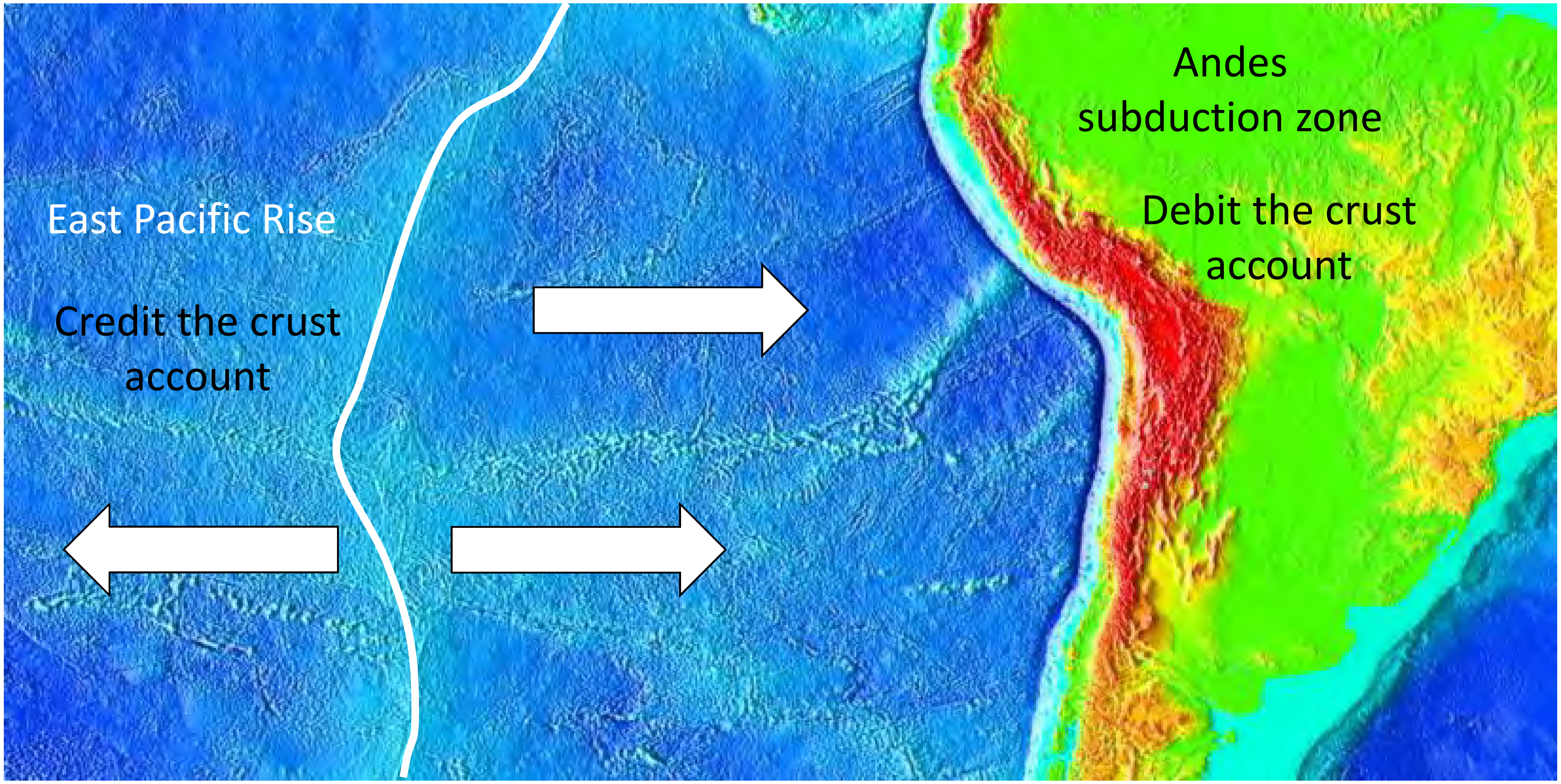


http://earthobservatory.nasa.gov/Features/Tectonics/tectonics_3.php

Black smoker on East Pacific Rise

www.whoi.edu

Divergent to Convergent (credit and debit of the crust account)

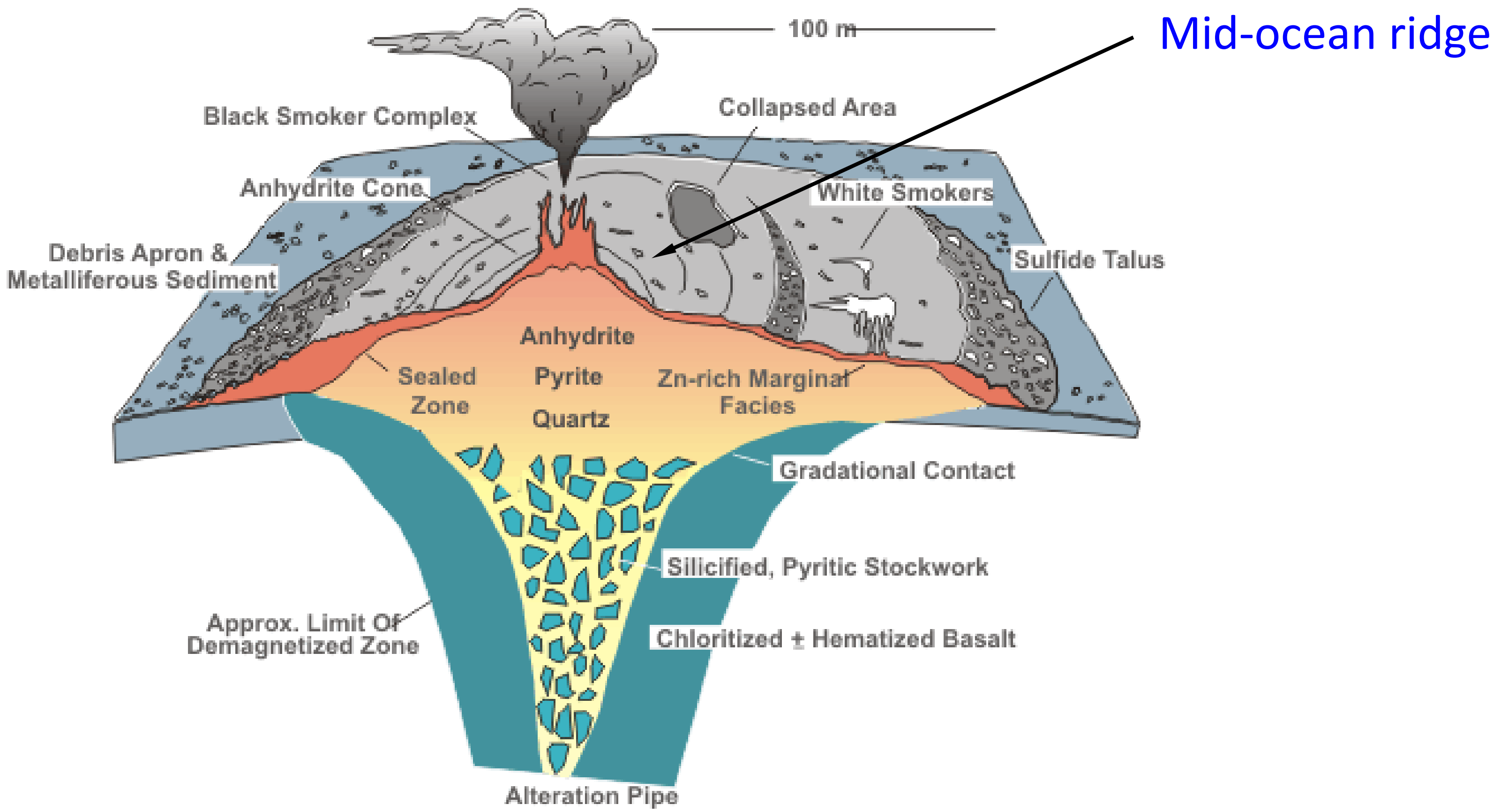


www.ngdc.noaa.gov/mgg/image/2minrelief.html

Iceland – the ridge emerges from the ocean

Eyjafjallajokull, April 17, 2010

Volcanic Massive Sulfide (VMS) Deposits



Source:
http://gsc.nrcan.gc.ca/mindep/synth_dep/vms/index_e.php

Notes: Volcanic Massive Sulfide (VMS) Deposits - 1

Volcanic massive sulfide deposits originate from the rifts along mid-ocean ridges. Seawater circulates through fractures in the rift, comes into contact with the underlying magma or hot rocks deep in the oceanic crust, and is heated to several hundred degrees. The heated seawater leaches metals out of the hot rocks and rises to the sea floor as a very focused discharge of hot, metal-rich fluids – a black smoker. Very high concentrations of minerals precipitate from the hydrothermal solution as lenses of polymetallic massive sulfides.

VMS deposits are major sources of Zn, Cu, Pb, Ag and Au, and significant sources for Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga and Ge. Some also contain significant amounts of As, Sb and Hg. Historically, they account for 27% of Canada's Cu production, 49% of its Zn, 20% of its Pb, 40% of its Ag and 3% of its Au. Because of their polymetallic content, VMS deposits provide "product-switching options" in the event of fluctuating prices of the different metals.

Notes: Volcanic Massive Sulfide (VMS) Deposits - 2

Volcanic massive sulfide deposits originate from the rifts along mid-ocean ridges. Seawater circulates through fractures in the rift, comes into contact with the underlying magma or hot rocks deep in the oceanic crust, and is heated to several hundred degrees. The heated seawater leaches metals out of the hot rocks and rises to the sea floor as a very focused discharge of hot, metal-rich fluids – a black smoker. Very high concentrations of minerals precipitate from the hydrothermal solution as lenses of polymetallic massive sulfides. VMS deposits are major sources of Zn, Cu, Pb, Ag and Au, and significant sources for Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga and Ge. Some also contain significant amounts of As, Sb and Hg. Historically, they account for 27% of Canada's Cu production, 49% of its Zn, 20% of its Pb, 40% of its Ag and 3% of its Au. Because of their polymetallic content, VMS deposits provide "product-switching options" in the event of fluctuating prices of the different metals.

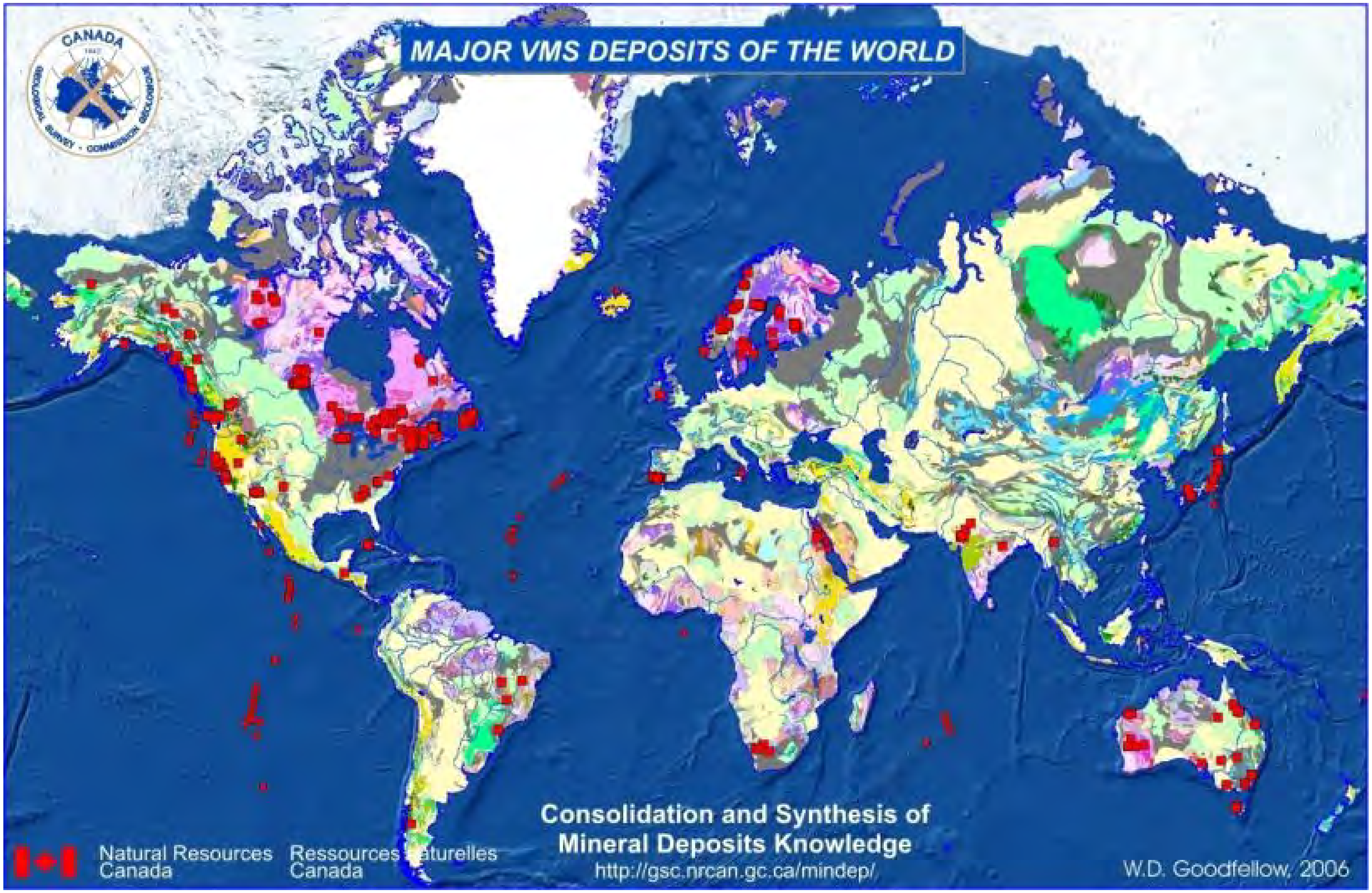
Some examples of VMS deposits are shown in the table below.

Mine	Reserves (Mt)	Cu (%)	Zn (%)	Pb (%)	Ag (g/t)	Au (g/t)
Neves Corvo, Portugal	270	1.6	1.4	0.3	30	-
Rio Tinto, Spain	250	1.0	2.0	1.0	30	0.22
Kidd Creek, Ontario	149.3	2.89	6.36	0.26	92	0.05
Mt. Lyell, Tasmania	106.8	1.19	0.04	0.01	7	0.41
Crandon, Wisconsin	61	1.1	5.6	0.5	37	1.0
United Verde, Arizona	30	4.8	0.2	-	50	1.37
Eskay Creek, BC	4	0.33	5.4	2.2	998	26.4

How did a VMS deposit form in the middle of Arizona? The answer is that more than 500 million years ago, Arizona was under water and a mid-ocean ridge was present. Over time, the ridge was consumed by subduction activity which resulted in the copper deposits that are in southern Arizona. Similar explanation for the VMS deposit in Ontario but a much older mid-ocean ridge.

Adapted from http://gsc.nrcan.gc.ca/mindep/synth_dep/vms/index_e.php

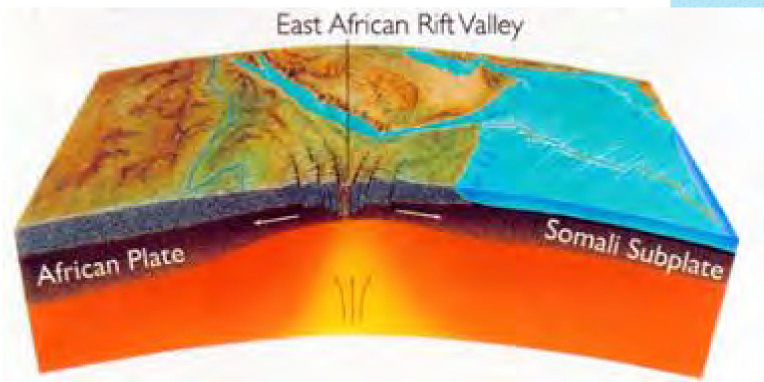
Major VMS Deposits of the World

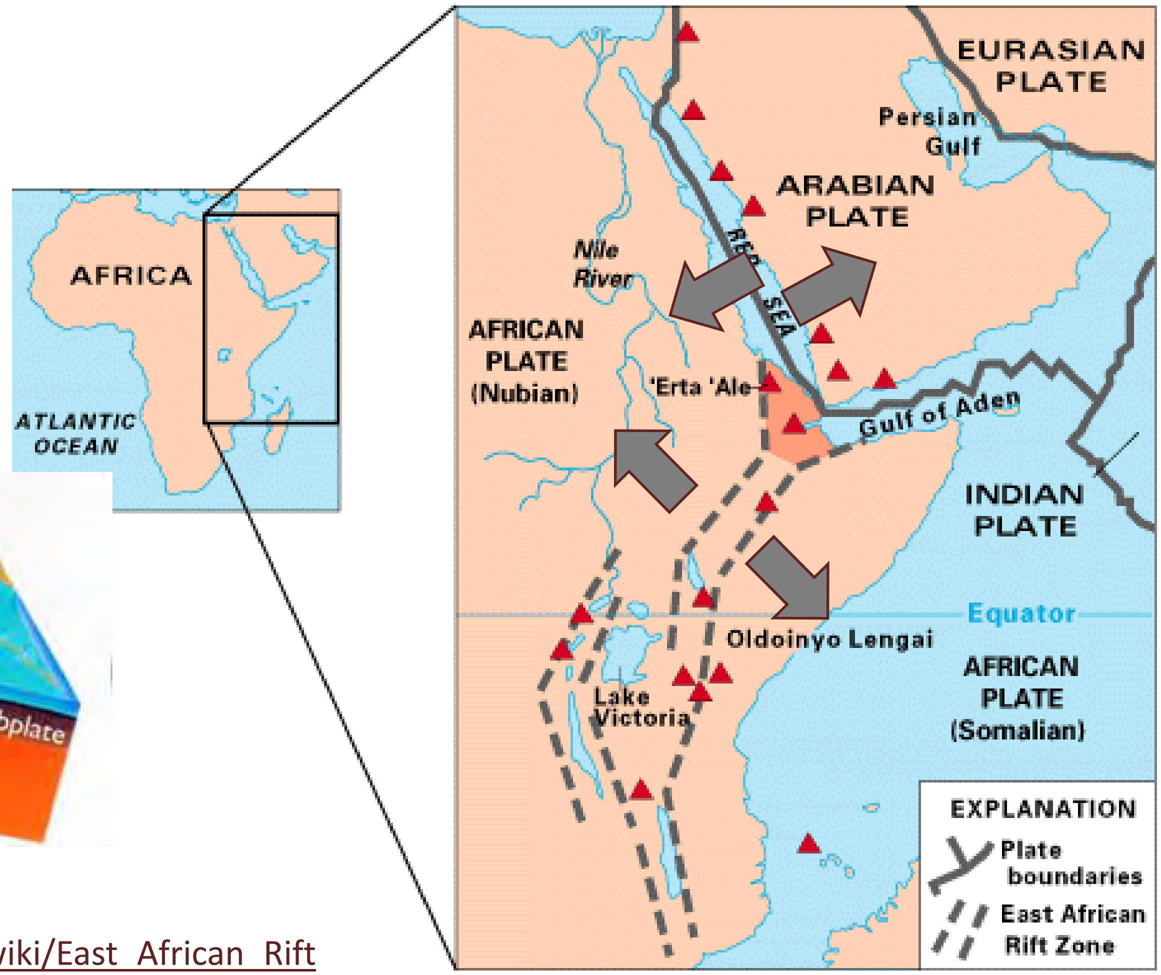


East African rift (divergent boundary)

Three plates meet at a triple junction

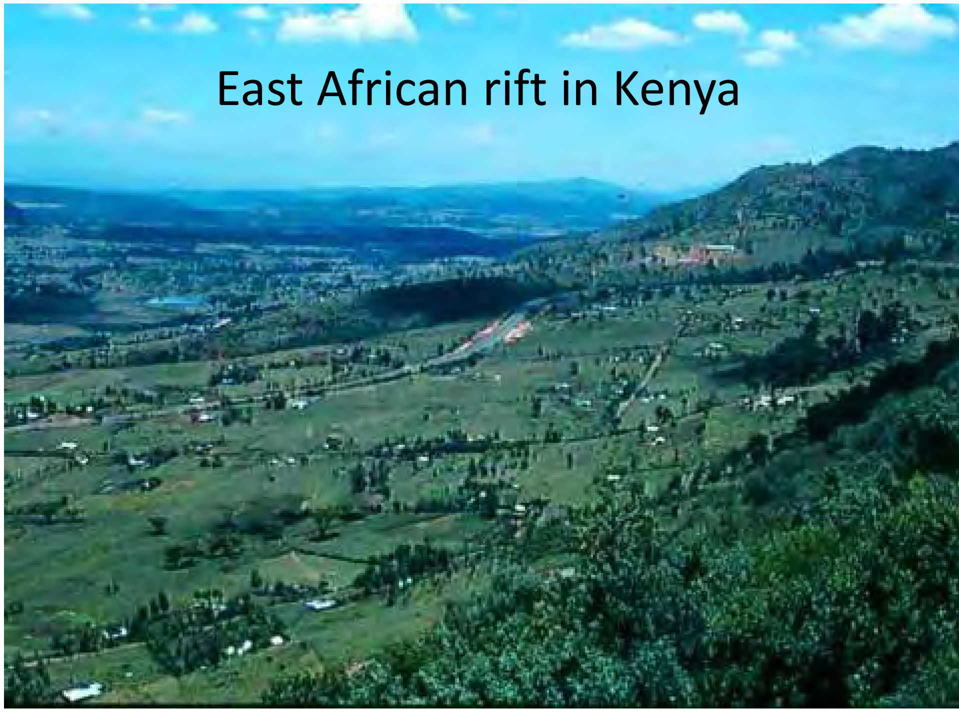
Arabian, Nubian and Somalian plates splitting along rifts





Map: http://en.wikipedia.org/wiki/East_African_Rift

Topography in the rift



www.calstatela.edu/dept/geology/G351.htm

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

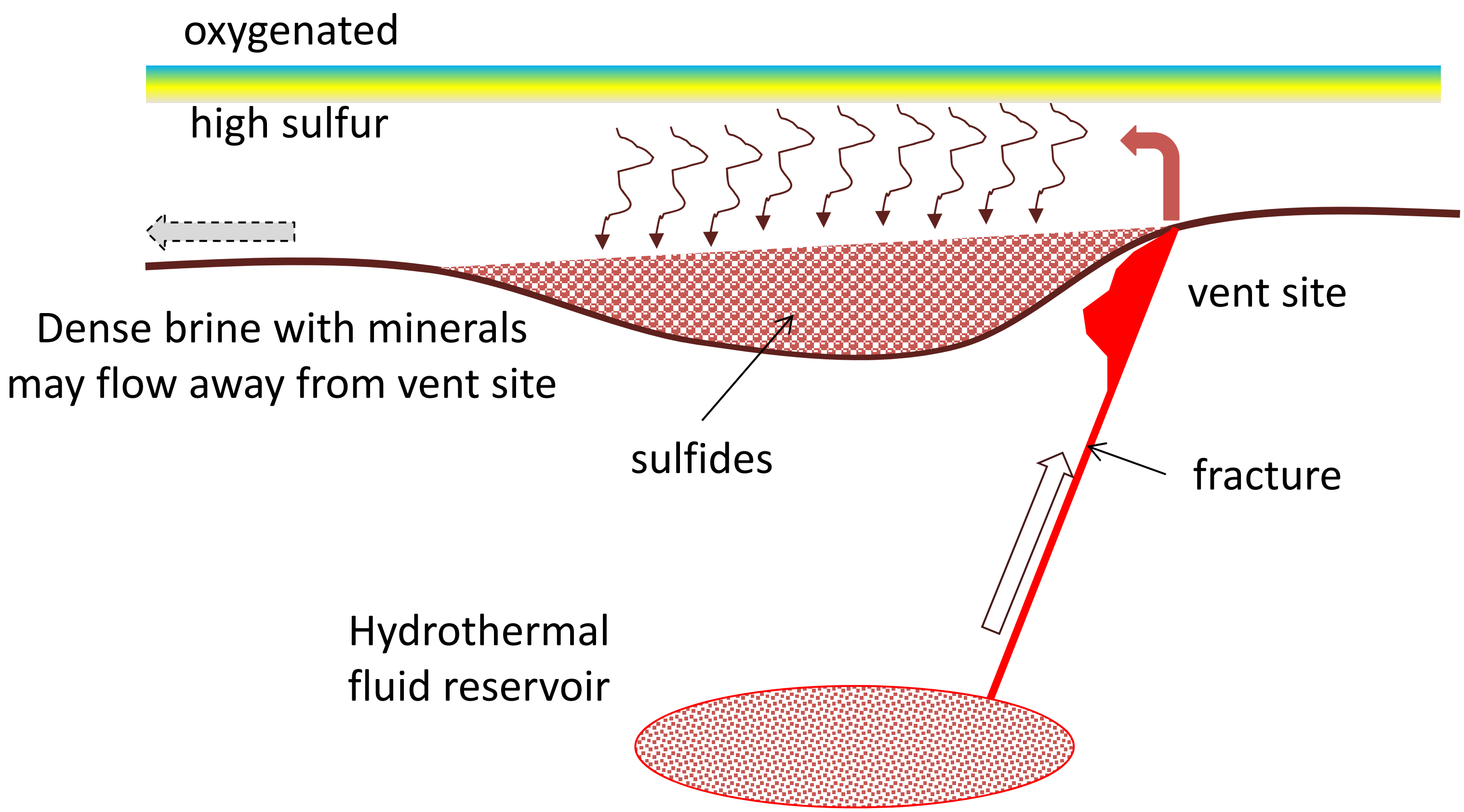
Gulf of California – a flooded rift zone

www.space.com

Formation of a sedimentary exhalative deposit

Abbreviated SEDEX

Massive sulfides precipitate from hydrothermal fluids vented on to the seafloor of a rift basin. Subsequently buried by sediments.

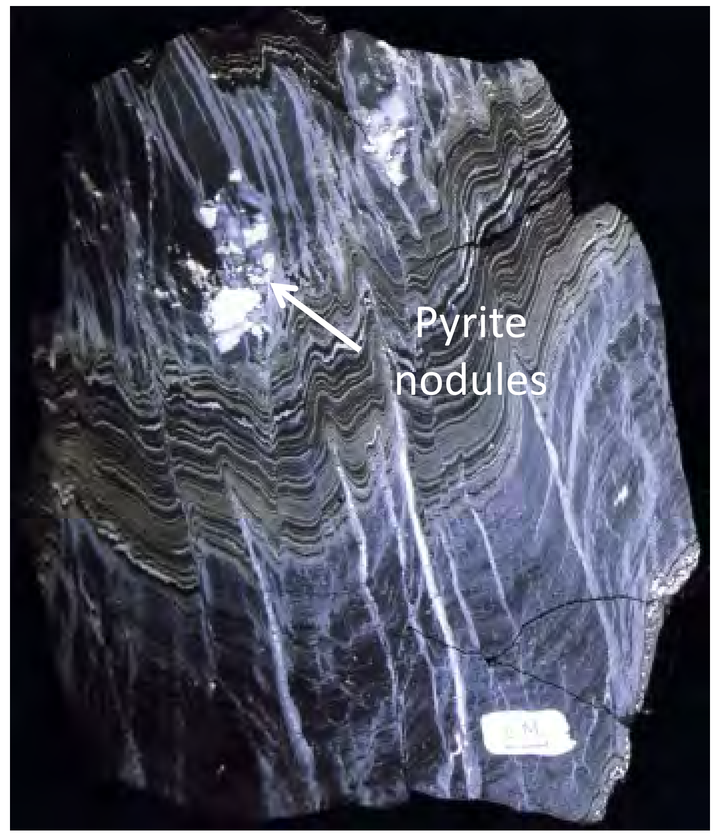


SEDEX lead-zinc deposits

132 deposits known worldwide, 35 in Canada
Also sources of copper and silver

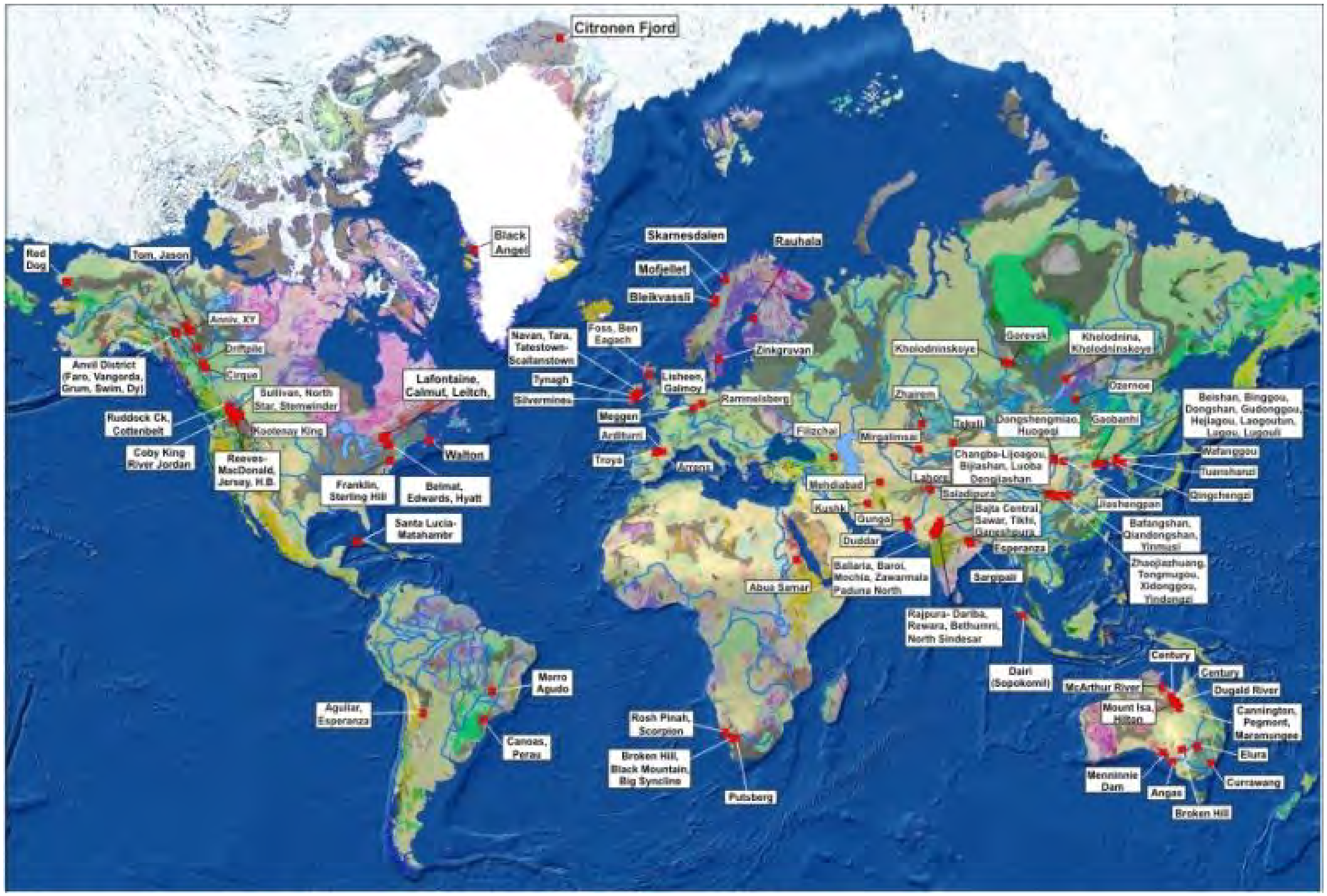
Examples:

Sullivan Mine, BC
Red Dog, Alaska
Mount Isa, Australia
Lisheen, Ireland

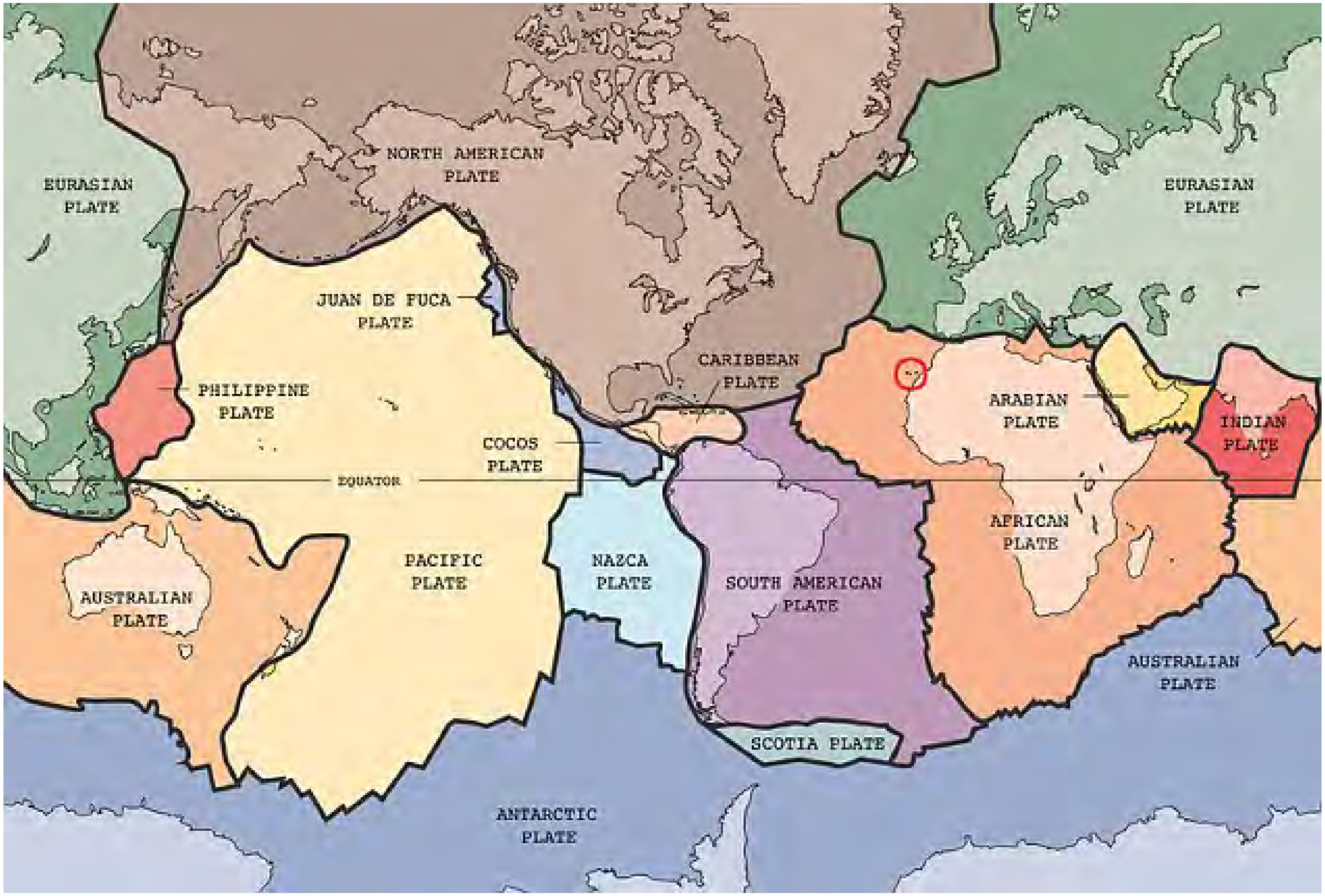


Sample from Howard's Pass, Yukon, NWT
Sphalerite and galena in mudstone

Sedimentary exhalative (SEDEX) deposits



Canary Islands volcano, October 15, 2011



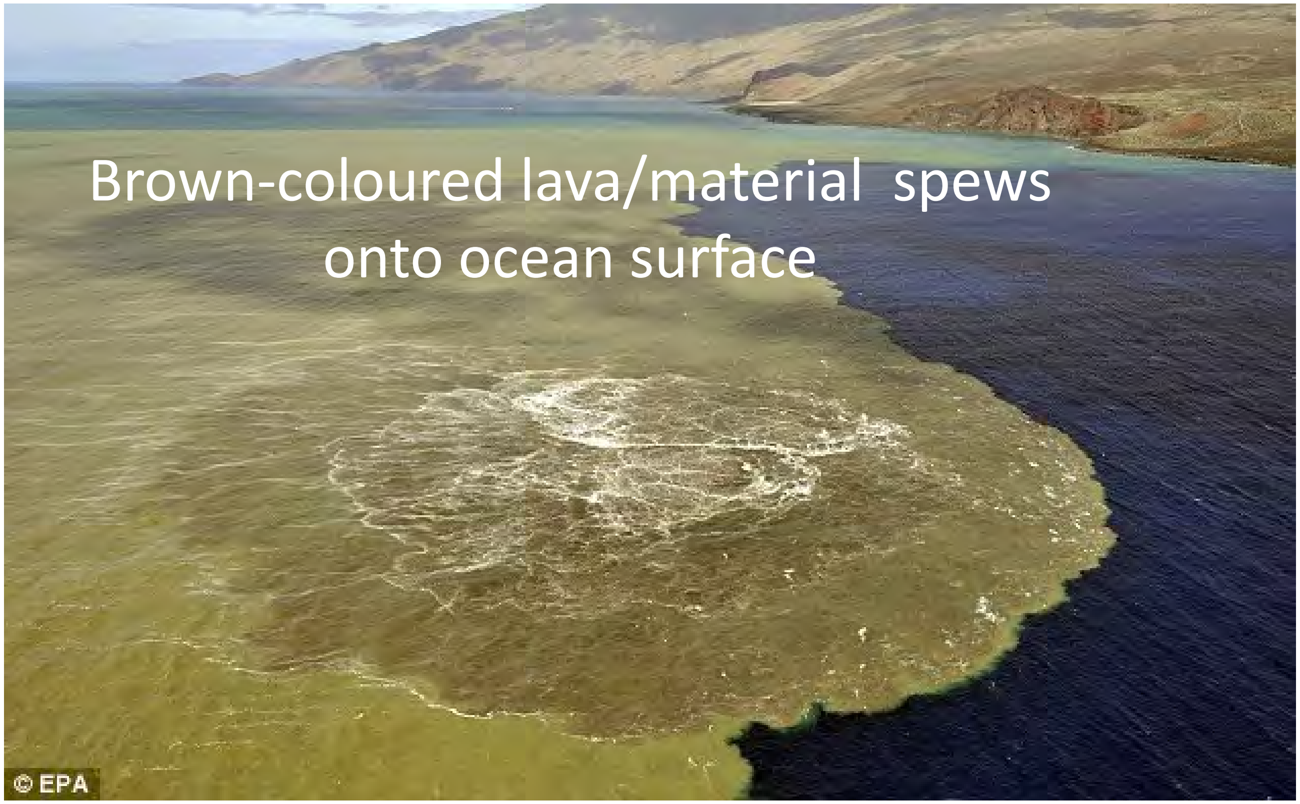
Notes: Canary Islands – a hotspot

The Canary Islands were formed as a result of volcanic activity caused by a hotspot. Hotspots are volcanic regions on, near to, or far from tectonic plate boundaries where volcanic activity usually occurs. If they are far from a plate boundary, there are two hypotheses to explain their occurrence. One suggests that they are due to hot mantle plumes that rise from the core-mantle boundary causing an anomalously hot zone. The other hypothesis suggests that it is localized thinning of the lithosphere that allows melted rock to rise from shallow depths, i.e., the mantle source beneath the hotspot is not anomalously hot.

Other well known examples of hotspots include Hawaii or Yellowstone.


Molten rock
from volcano
© Canarias7


Town of
La Restinga
© EPA


Brown-coloured lava/material spews
onto ocean surface
© EPA

Sedimentary Ore Deposits

Deposition of dense minerals in streams

e.g., placer gold

Placer gold mining
Fortymile River, Yukon
www.fortymilegold.ca

Mineral precipitation from ancient oceans

e.g., potash or salt deposits

Badwater Basin Salt Flats, CA

Sediments containing minerals are always precipitating out of water bodies. Initially these sediments are saturated with water, but when buried by more sediments or when the water body evaporates, a process that may take millions of years, they lose water. Some of the most interesting mineral crystal structures form in sedimentary environments.

North America 385 million years ago

http://www2.nau.edu/rcb7/nam.html

Potash contains sylvite (KCl) and halite (NaCl or salt)

Minerals such as anhydrite, salt and sylvite precipitated from ocean

North America 325 million years ago

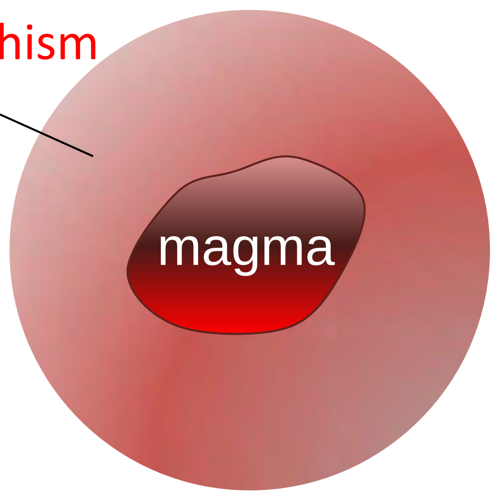
http://www2.nau.edu/rcb7/nam.html

Metamorphism and ore deposits

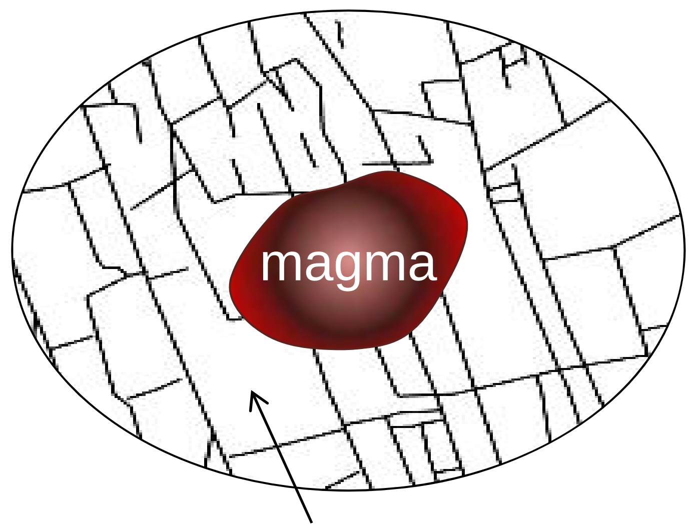
Metamorphism occurs when

Temperatures are above 200°C, below 800°C
Pressures are higher than 300 megapascals (MPa)
(Car tire pressure is about 50 psi or 0.35 MPa)

Zone of contact metamorphism



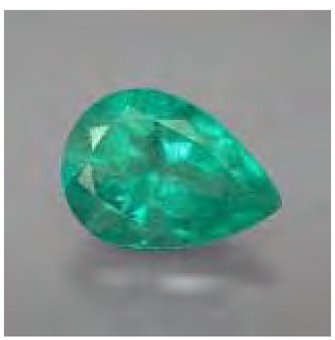
← ~10 km →



Zone of hydrothermal metamorphism
Hot fluids leach metals from fractures in rock and transport them to deposition zone

Ore deposits formed by metamorphism

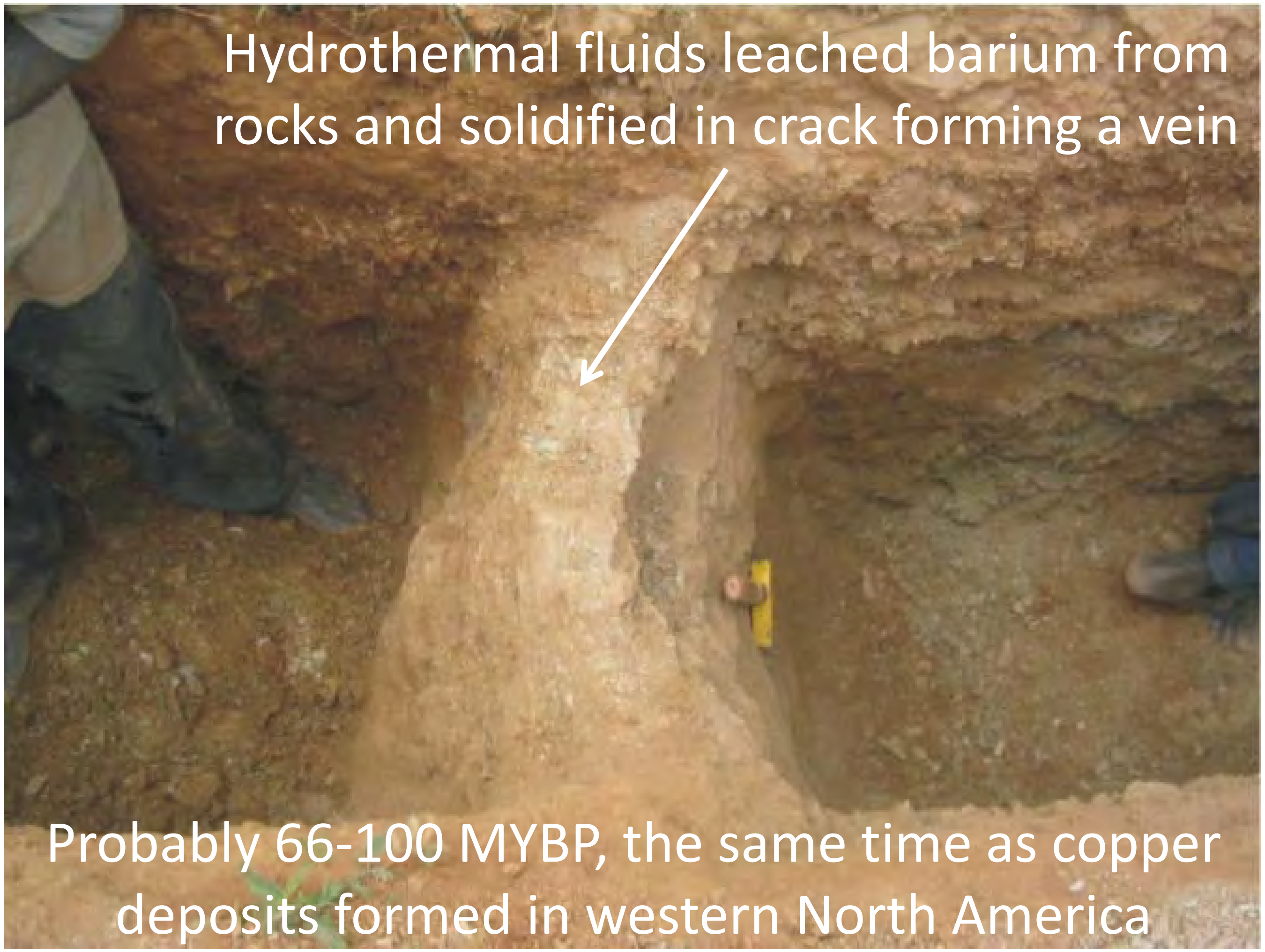
Asbestos	formed by hydration of ultrabasic (<45% silica) igneous rock
Gems	jade, garnet, emeralds, beryls formed by high pressure contact metamorphism of igneous or sedimentary rocks
Talc & Soapstone	formed by hydrothermal metamorphism of limestone (calcium carbonate)
Barite	formed by hydrothermal fluids leaching barium from silicates of sedimentary rocks (hydrothermal metamorphism)
Uranium	in Athabasca Basin of Saskatchewan – formed by hydrothermal fluids leaching uranium from underlying rocks



An emerald
Cost: $2,465

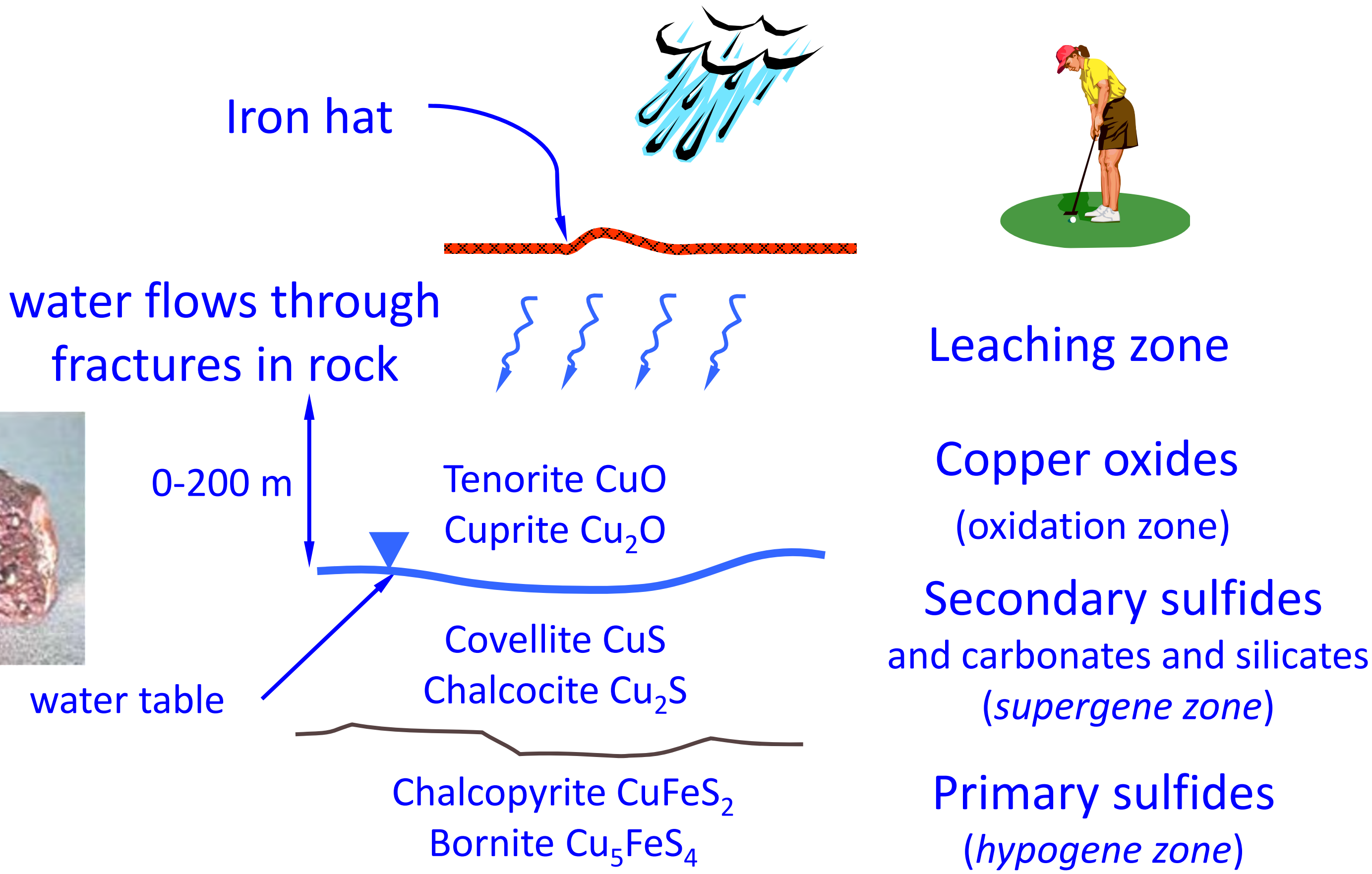
www.gemselect.com/emerald/emerald.php

Baryte vein exposed in trench



Source: Barytes, Exploration Opportunities in Nigeria, MMSD

Formation of copper oxides



Notes: Formation of copper oxides – 1

Porphyry copper ore bodies in the southwestern US and elsewhere (eg Chile) have been subjected to weathering at or near the surface of the Earth after eons of erosion removed overlying rocks. Oxygenated groundwater, derived from rainwater, trickles through fractures in the rock and forms a **leaching zone** where chalcopyrite, a primary sulfide mineral, is dissolved and oxidized:

$4CuFeS_2$	+	$17O_2$	+	$12H_2O$	+	$2CO_2$	→	$4Fe(OH)_3$	+	$4CuSO_4$	+	$4H_2SO_4$	+	$2H_2CO_3$
chalcopyrite	+	oxygen	+	water	+	carbon dioxide	→	iron hydroxide	+	copper sulphate	+	sulphuric acid	+	carbonic acid

The iron hydroxide (called limonite) is forms a residual deposit known as a **gossan** or **iron hat**, typically rust-red in color, used by prospectors as indicators of underlying mineralization.

Notes: Formation of copper oxides – 2

The copper sulfate and carbonic acid continue trickling through the fractures and react with the chalcopyrite to form copper oxides. An example reaction is:

$2CuFeS_2$	+	$5O_2$	+	$2H_2CO_3$	→	$2CuO$	+	$2FeCO_3$	+	$2H_2SO_4$
chalcopyrite	+	oxygen	+	carbonic acid	→	tenorite	+	iron carbonate	+	sulphuric acid

These oxides form an **oxidation zone**, 0-200 m in thickness above the water table.

Below the water table is a zone of **supergene enrichment** in which secondary sulfide minerals such as covellite and chalcocite form from chalcopyrite and copper sulfate in solution:

$CuFeS_2$	+	$CuSO_4$	→	$2CuS$	+	$FeSO_4$
chalcopyrite	+	copper sulphate	→	covellit e	+	iron sulphate

These kinds of reactions in the supergene zone greatly increase the concentration of copper. Native copper might also occur in this zone.

Copper oxides are the source of about 25% of the world's copper supply. (www.icsg.org)

Copper carbonates and silicates and an oxidized pit

Chrysocolla, a copper silicate

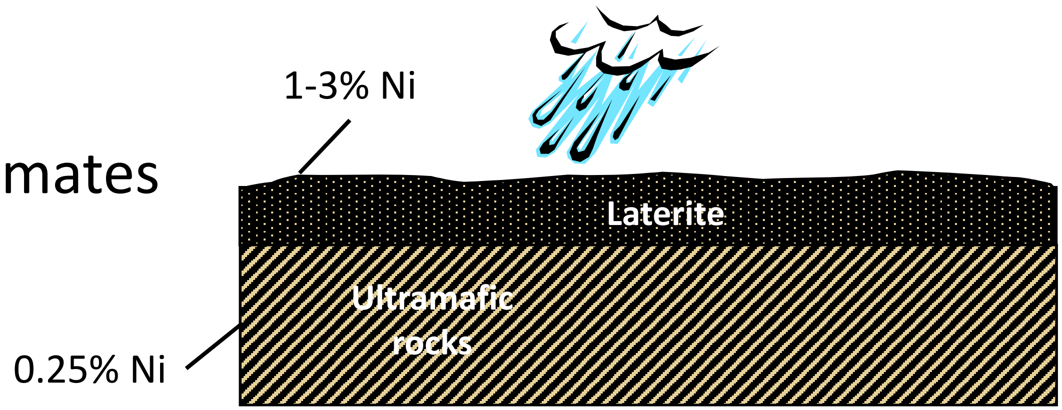
www.ccrlimited.com.au

Malachite, a copper carbonate

Mineral pictures:
www.mindat.org
http://webmineral.com

Residual Deposits: Nickel Laterites

Very common in tropical climates with high rainfall



Rocks are broken down by intense weathering to form a soil layer

Water flowing through the soil layer leaches nickel and other metals from the soil

Nickel, iron and magnesium oxides and silicates precipitate from water into the soil layer, the **laterite**.

Goro nickel project, New Caledonia

Mine Exploration: Basic principles

A mine is located where you find it

Closeology:
If you want to find a mine, look near other mines

Exploration Methods

In increasing order of cost/km^2

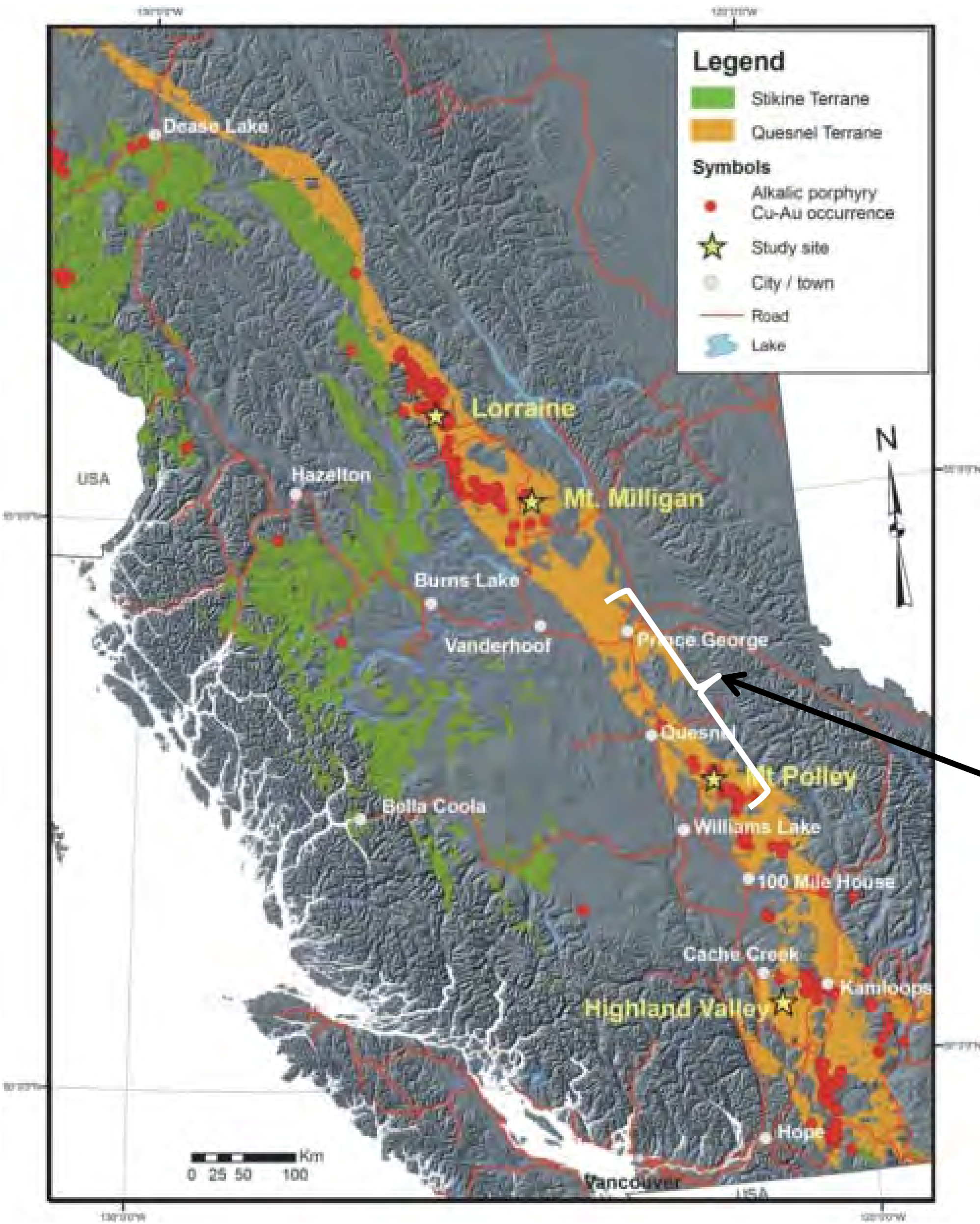
- Remote sensing (satellite imagery)
- Geological mapping
- Geophysical surveys
- Geochemical surveys
- Bulk sampling, drilling

www.geology.com

The role of exploration:

- The alternative to exploration is acquisition of mining properties.
- Exploration has a high failure rate, but this should not affect a diversified mining company.
- Exploration costs are tax-deductible.

An example of "big picture" geological thinking

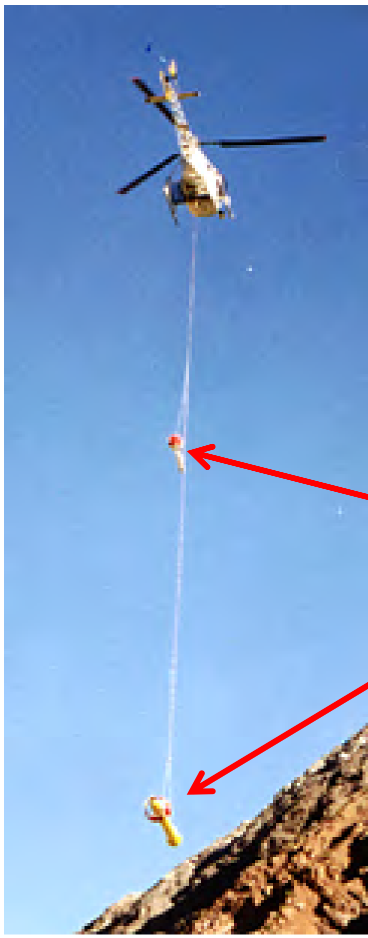


- Porphyry copper gold occurrence

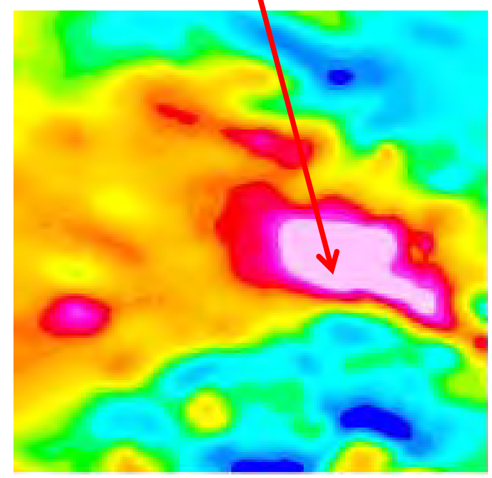
Why the gap?

Source: Bouzari, F, et al, 2010. Porphyry indicator minerals (PIMs): exploration for concealed deposits in south central British Columbia (NTS 092I/06, 093A/12, 093N/01, /14); *in* Geoscience BC Summary of Activities 2009, Geoscience BC, Report 2010-1: 25–32.

Airborne Geophysics



Anomaly
(something different)



Sensors and/or
transmitters

Measure a property of the earth
(such as its magnetic field) or
measure the response to a signal

Magnetic, electromagnetic, visible, infra-red spectral fields, GPS navigation system

Notes: Airborne Geophysics

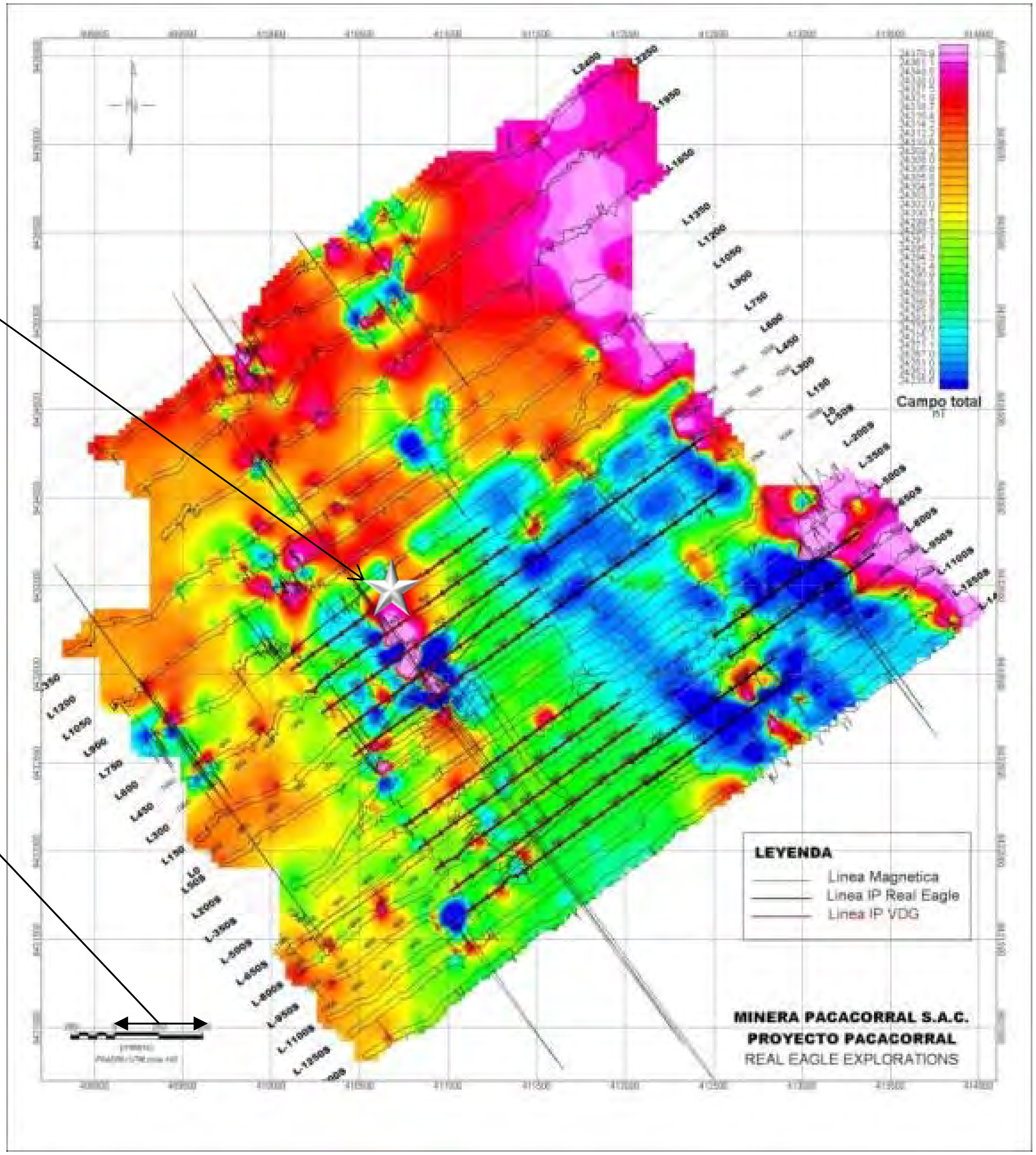
These instruments measure the interaction between underlying metallic deposits and magnetic or electromagnetic fields. Visible and infra-red emissions from land surfaces may also indicate the presence of metals at depth.

The goal of geophysical (or geochemical exploration) is to find an anomaly – something different from the normal or expected.

From a mineral deposit point of view, the earth is generally boring and barren - sometimes it produces anomalies. Therefore anomalies could indicate the presence of minerals and could be a target for drilling.

Drillhole DDH-01 Directed NW at 45° angle

500 m



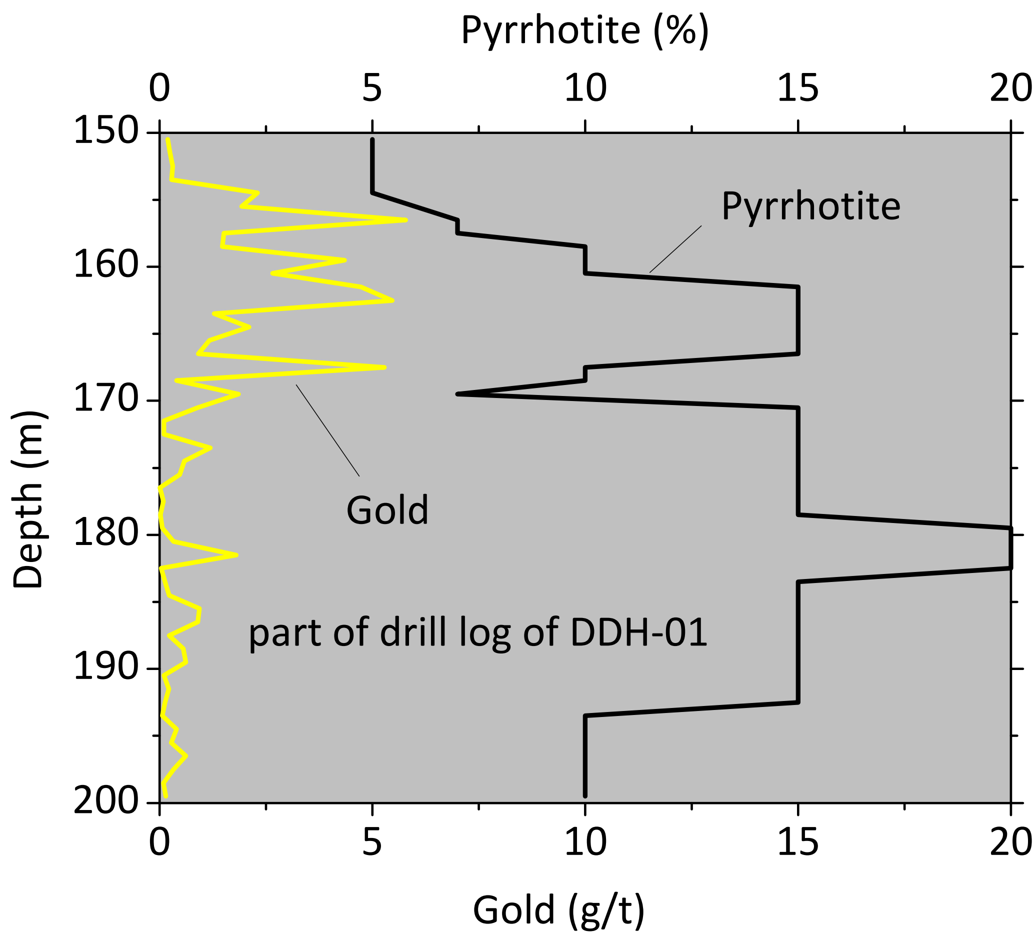
EXPLORATION PROJECT IN PERU MAGNETIC MAP

Red high

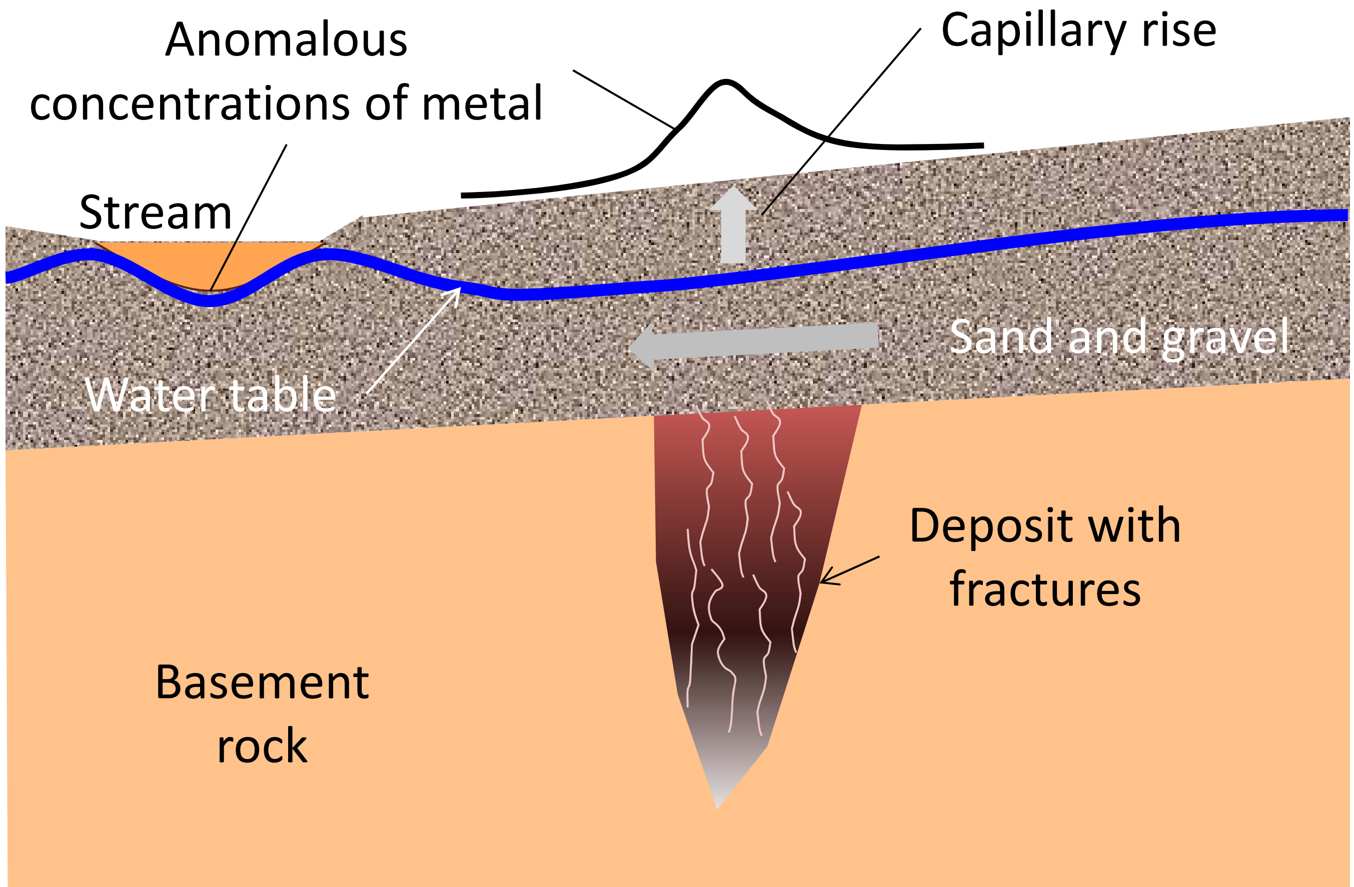
Green low

Where there's pyrrhotite, there's gold

in this case!



Geochemical Anomalies



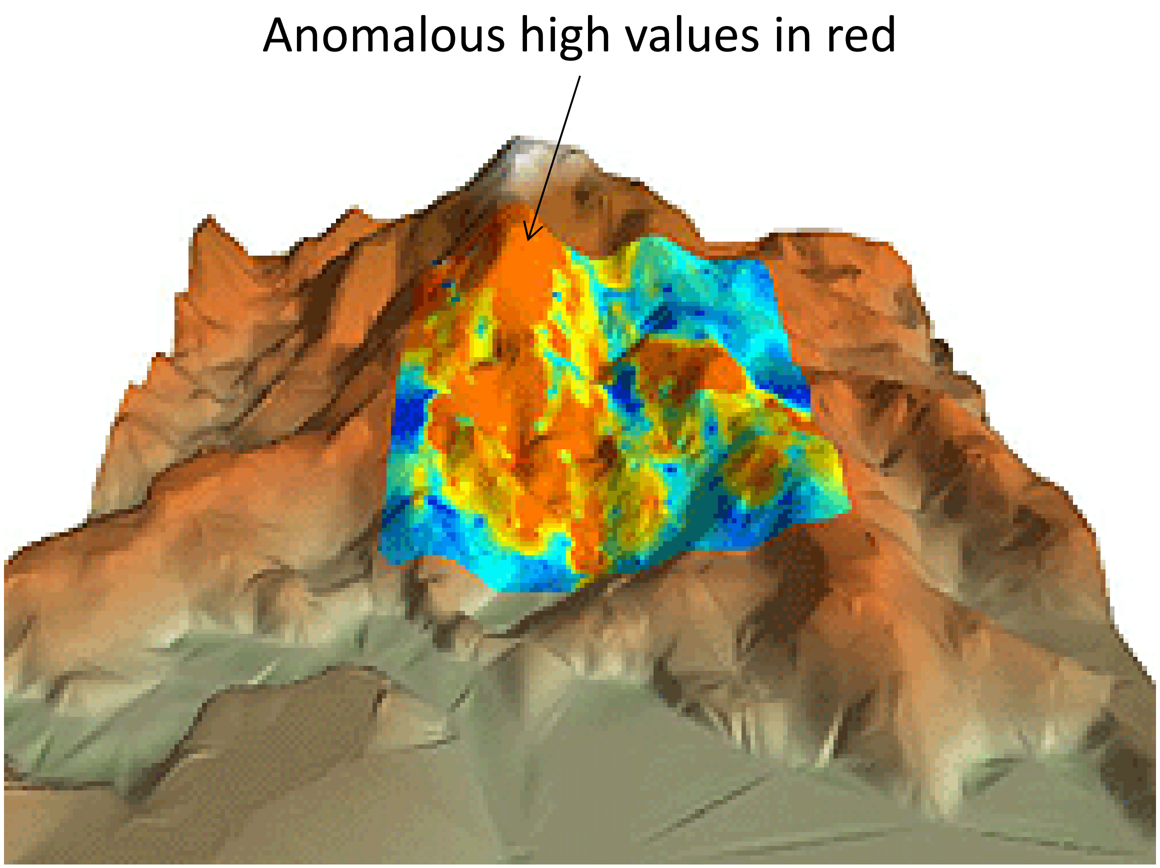
Notes: Geochemical Anomalies

Groundwater in contact with an orebody will leach out minerals and deposit them in the soil or streams. Trees may also take up the water. The closer an orebody is to the surface, the more likely there will be concentrations of metals in soils, water and trees. These concentrations, measured in parts per million and sometimes parts per billion, may form a geochemical anomaly.

On the next slide is an image of a 2 by 3 km soil auger geochemical survey at Mt Kasi, Vanua Levu, Fiji which shows gold concentrations on an image of the topography. Anomalous high values of gold concentration (red) indicate a possible extension of gold mineralization toward the top of the central hill.

Source: www.pathfinderexploration.com.au/mining_exploration.html

Gold concentrations in soil at Mt Kasi

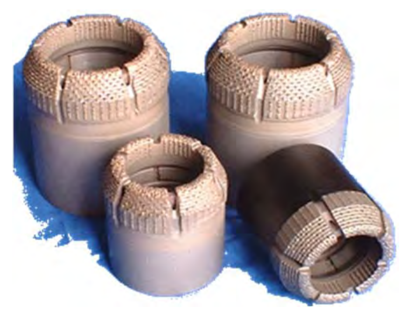


www.pathfinderexploration.com.au/mining_exploration.html

Drilling rigs, Core barrel, Diamond drill bits

Angle hole
~1000 m depth

Poor core recovery can lead to loss of values
⇒ lower measured grades



Drill core

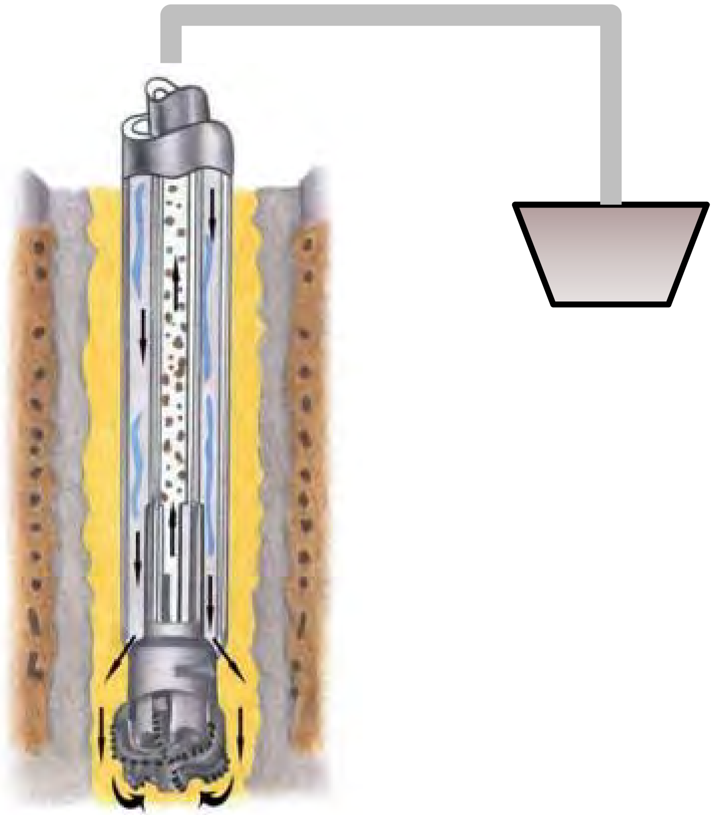
Drill core with grey molybdenite

www.stockinterview.com/News/07262006/molybdenum-energy.html

Boxes of drill core

www.levon.com/s/ProjectPhotos.asp

Reverse circulation drilling



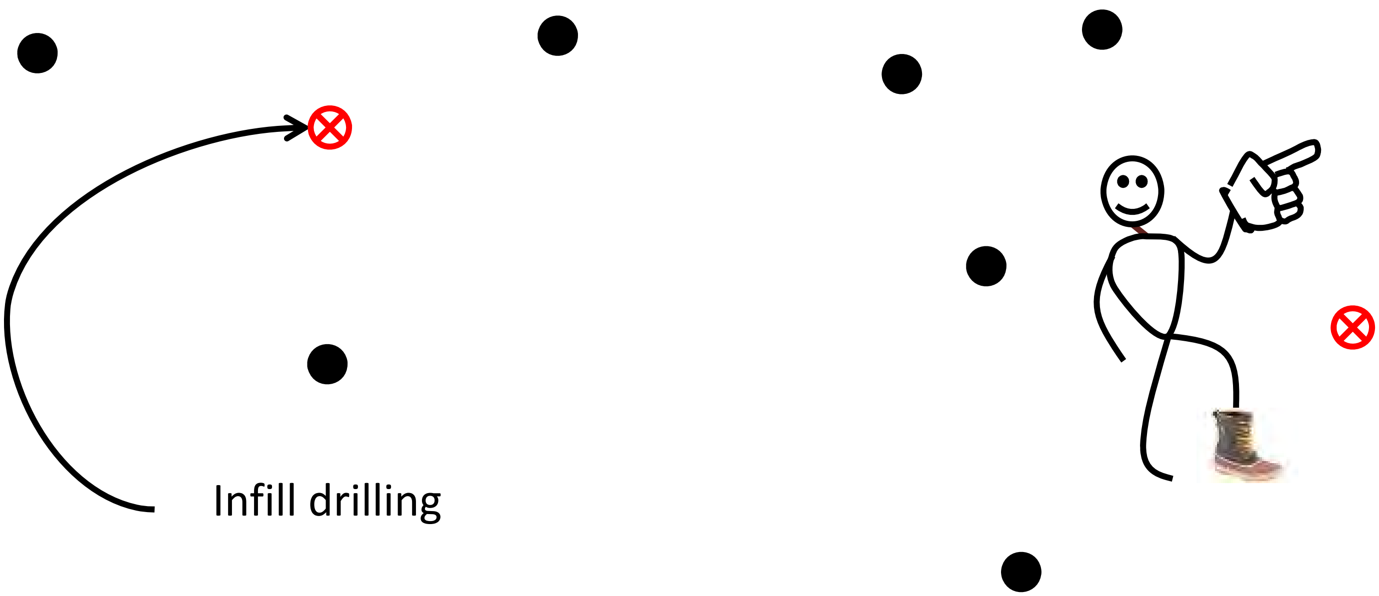
Air forces the cuttings from the drill bit up the pipe into a bin

Results from RC drilling can help corroborate results from core samples in a relative sense, but sample contamination is likely.

Notes: Drilling costs

Reverse circulation drilling may cost $8 to $20 per foot ($18 to $60/metre); and diamond drilling may cost $12 to $40 per foot ($35 to $120/metre). These are the basic drilling costs. There are additional costs for the mobilization and demobilization of the equipment, camp construction and supply, support vehicles, communications, site preparation and drill moves, and supervision. Depending on the contract terms, property location, time of year, etc. the additional costs might double the cost per metre.

Infill and step-out drilling

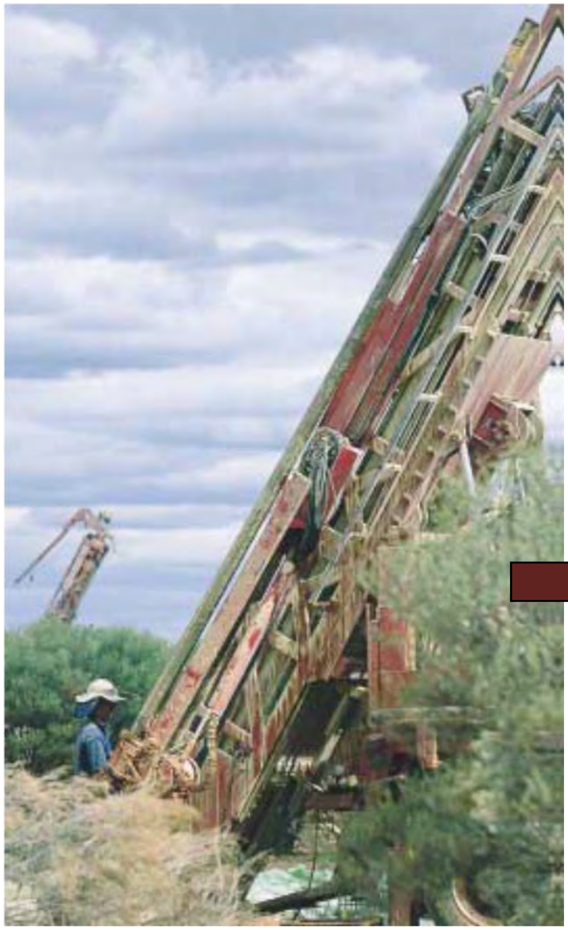


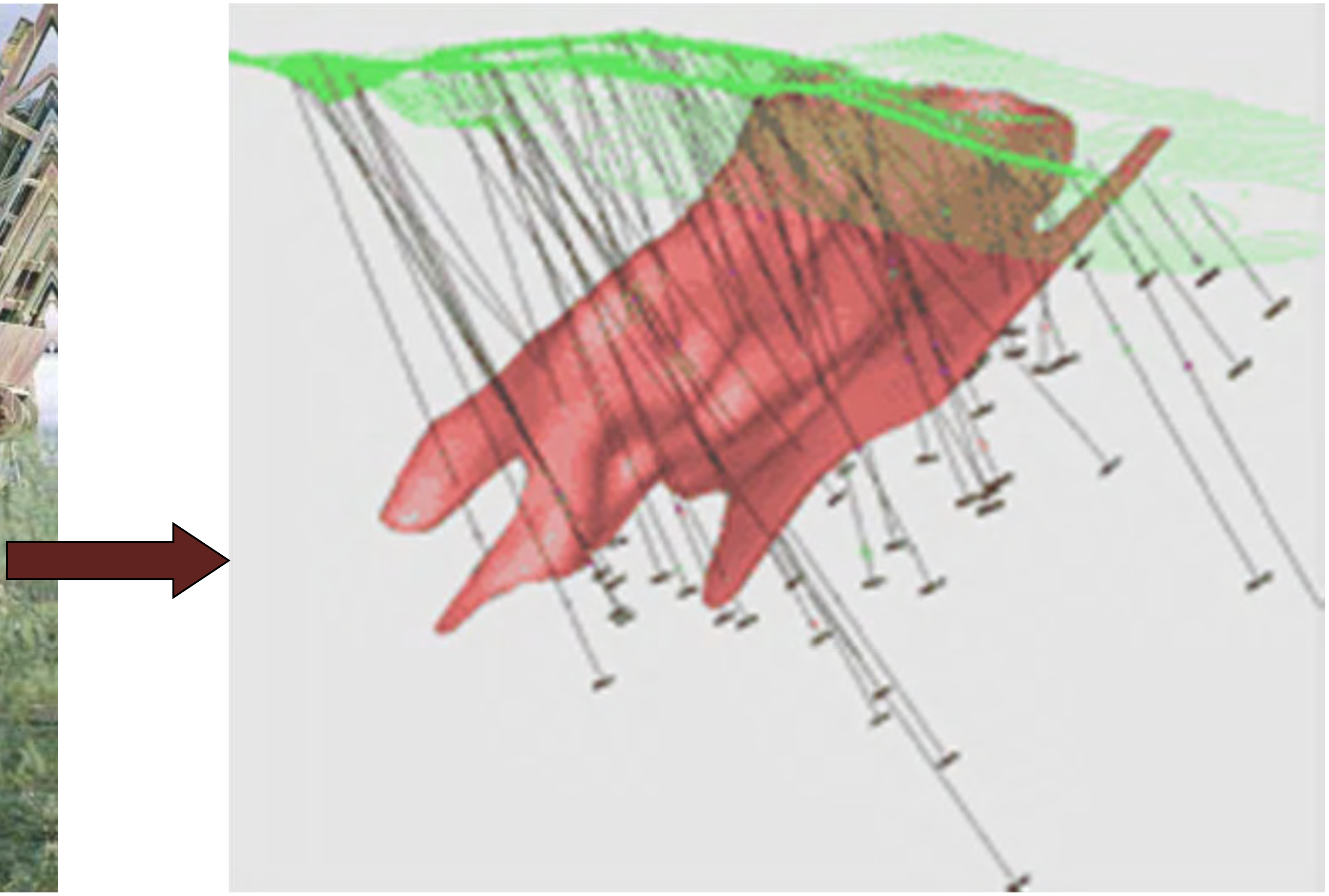
Infill drilling is usually done by a cheaper method of drilling such as reverse circulation

Step-out or expansion drilling

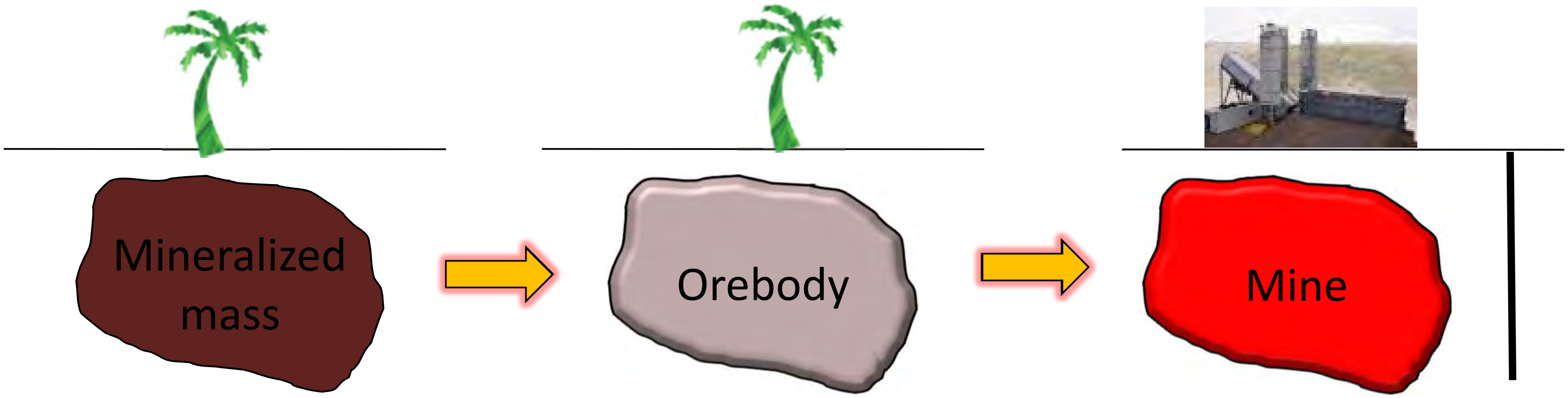
Drilling to orebody models

Thunderbox gold project
Lionore Mining International





How long does it take?



More than 10 years typical

Less than 10 years typical

Remember – it has to be economic and feasible to mine it
Technical and financial issues can delay construction of a mine

END OF PART 1