Formation of Ores

Q. What is the most profitable mineral commodity that is mined today?

A. Sand and Gravel

It doesn't have to be flashy to make money …

What is an ore?

An ore is an aggregate of minerals from which one or more minerals can be extracted *profitably*.

Less than 15 oxides occur in quantities of > 0.5% in crustal rocks

Constituent	*Rhyolite*	*Dacite*	*Andesite*	*Basalt*
SiO_2	73.66	63.58	54.20	50.83
TiO_2	0.22	0.64	1.31	2.03
Al_2O_3	13.45	16.67	17.17	14.07
Fe_2O_3	1.25	2.24	3.48	2.88
FeO	0.75	3.00	5.49	9.05
MnO	0.03	0.11	0.15	0.18
MgO	0.32	2.12	4.36	6.34
CaO	1.13	5.53	7.92	10.42
Na_2O	2.99	3.98	3.67	2.23
K_2O	5.35	1.40	1.11	0.82
P_2O_5	0.07	0.17	0.28	0.23
H_2O	0.78	0.56	0.86	0.91
Total	100.0	100.0	100.0	100.0

Source: Carmichael, Turner, and Verhoogen 1974.

An ore is a geochemical anomaly.

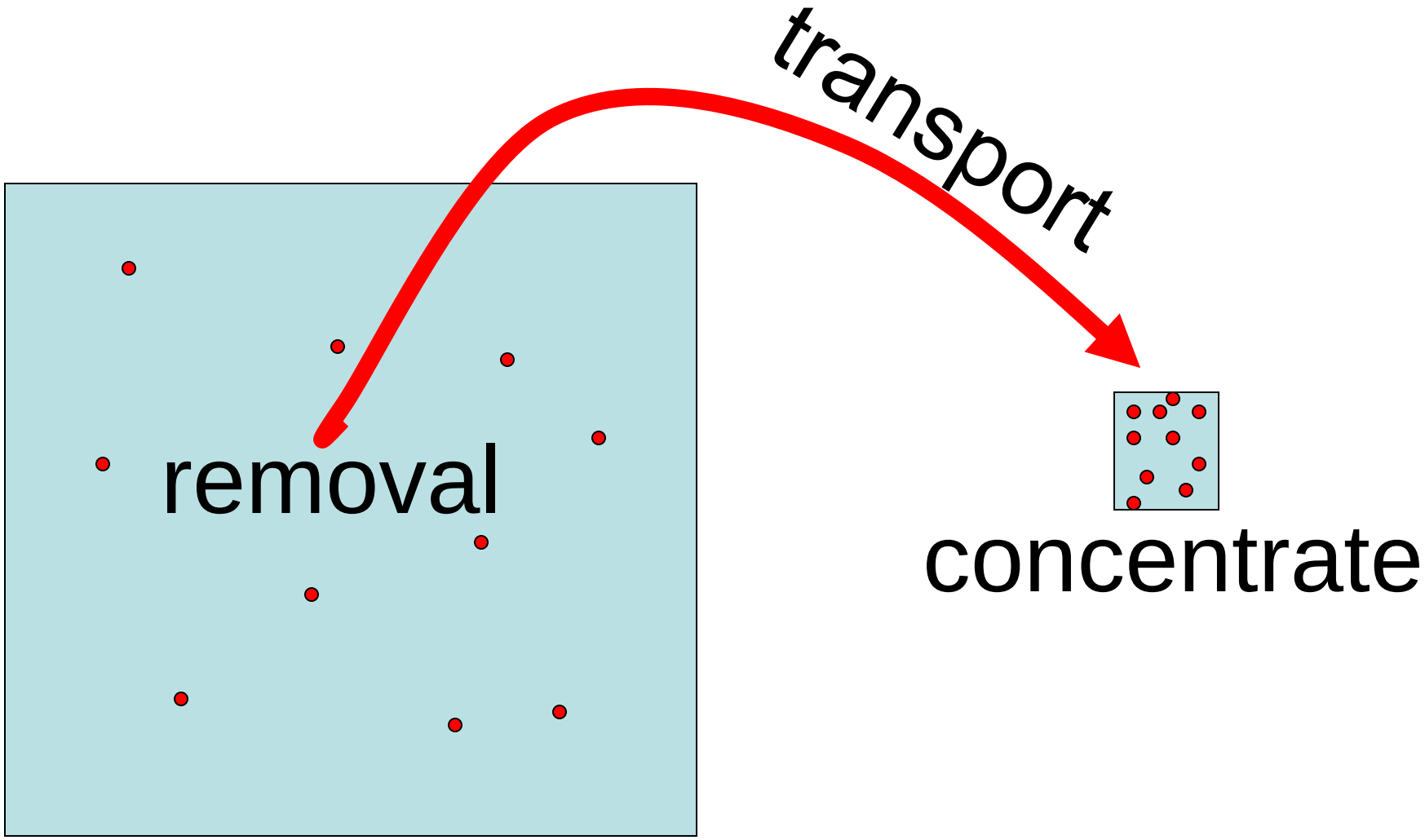
Some unusual process must:

1) **remove** specific elements, compounds or minerals from ordinary rock,

2) **transport** these elements, compounds, or minerals

3) **concentrate** the elements, compounds, or minerals preferentially at one spot or zone where the transport stops.

Formation of ore



the primary mechanisms for concentrating minerals into ores involves either:

sorting by density

sorting by solubility.

Weathering and erosion as a mechanism of separating and concentrating chemical constituents

Mechanical weathering and erosion can concentrate minerals

We’ve already seen examples -

Wave action concentrates sand on a beach

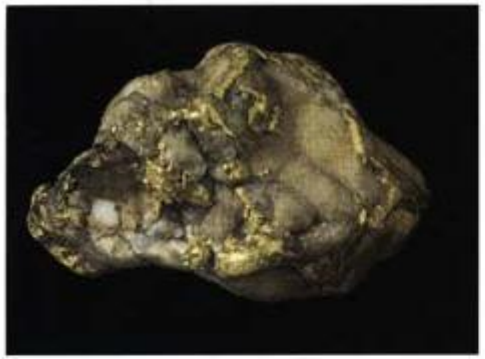
Quartz sand typically mined from ancient beaches, sand bars, etc.

nuggets

lumps of metal

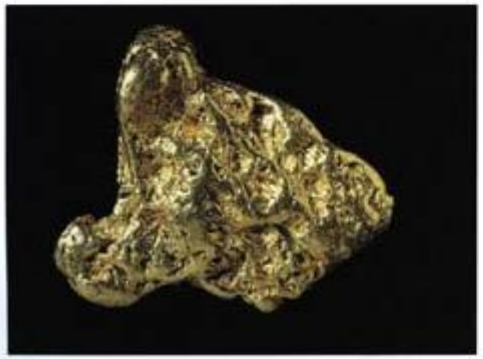
gold nugets: concentration by abrasion
brittle quartz removed by weathering

gold left behind



A.

B.



C.

Formation of a Gold Nugget

A. A vein of metallic gold cutting through a pebble of vein quartz. Stream abrasion causes the brittle quartz to chip and be reduced in size, while the malleable gold deforms but is not reduced.

B. The ratio of gold to quartz increases as the quartz is abraded away. Eventually a nugget of almost solid gold forms.

C. A nugget of metallic gold from California. No quartz remains.

Each of the specimens has a diameter of about 4 cm.

Figure 9.19 from:
Skinner, Brian J. and Stephen C. Porter (1995) The Dynamic Earth, 3rd ed. New York: John Wiley & Sons, Inc., p. 266.

Placer deposits.

placers: deposits of heavy mineral particles in stream bed.

Steps for making a placer

1. weathering removes mineral particles from country rock.

2. kinetic energy of high velocity stream transports mineral particles.

3. where kinetic energy drops suddenly, high density particles stop, lower density particles continue

Placer Locales

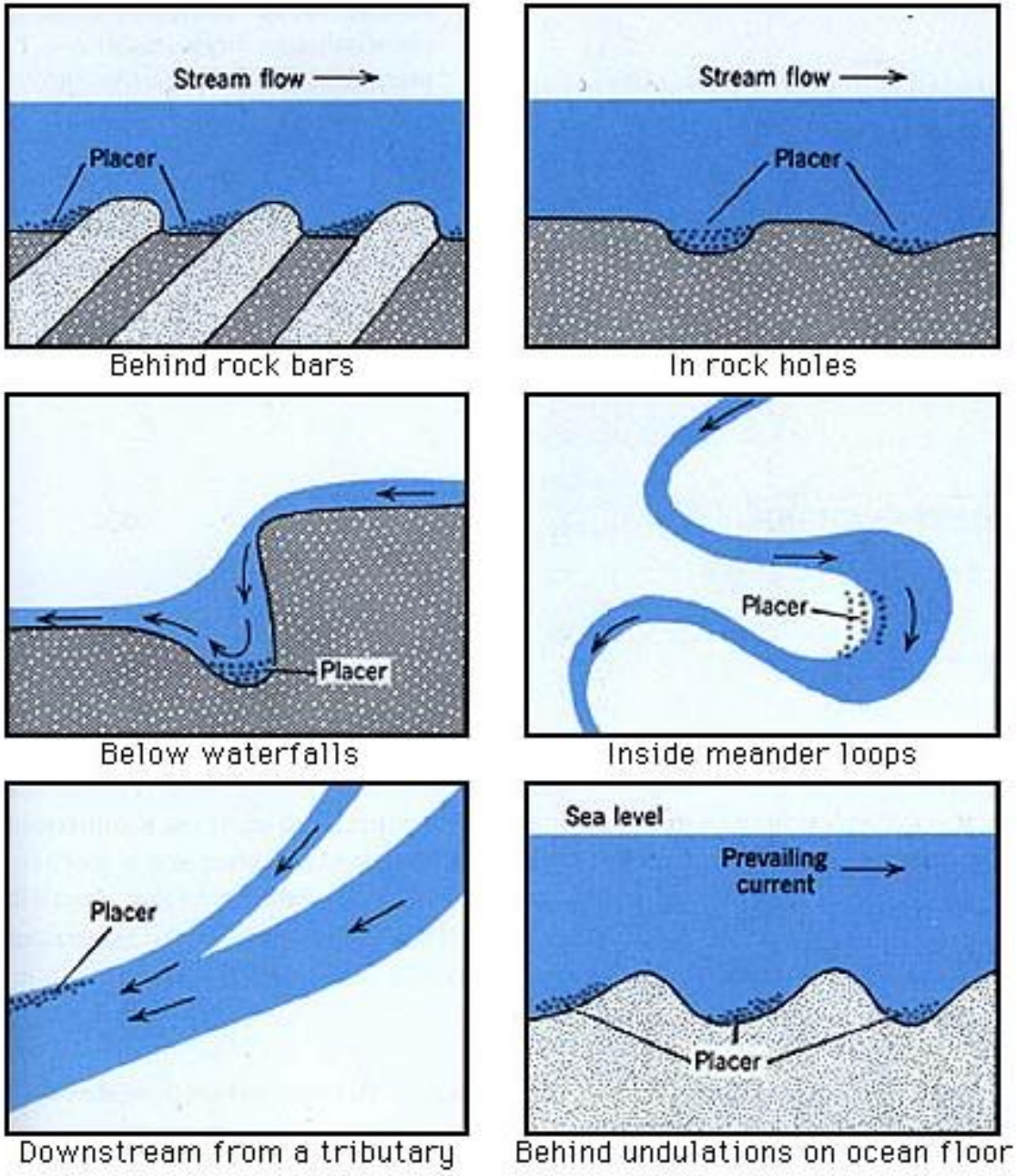
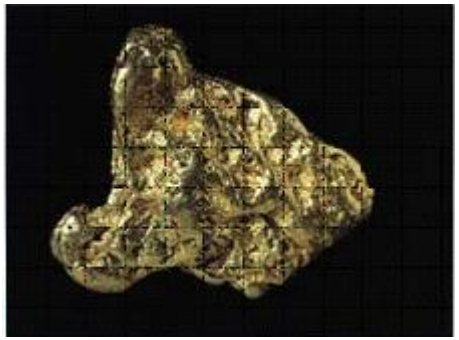


Figure 17.6 from: Skinner, Brian J. and Stephen C. Porter (1995)
The Dynamic Earth, 3rd ed. New York: John Wiley & Sons, Inc., p.507.

density contrasts are substantial:

quartz - 2.65gm/cc.

gold - 19gm/cc.



Panning – same principle as a placer, but in a pan

economically important placers:

gold nuggets
silver nuggets
platinum nuggets.
diamonds (carbon).
zircon (zirconium silicate).
uraninite (uranium oxide).
rutile (titanium oxide).

Chemical weathering and erosion can concentrate minerals

Bauxite – aluminum ore

Progressive dissolution of silica from clays in wet soils will eventually turn the

kaolinite clay $Al_2Si_2O_5(OH)_4$

Into

gibbsite $Al(OH)_3$.

these soils become *bauxite*, a major ore of aluminum.

Bauxite – associated with tropical climates

Settling of crystals in a magma chamber
can concentrate minerals

Spinel Group of Minerals all relatively dense

- spinel: $MgAl_2O_4$

- Fe^{2+}, Mn^{2+}, Zn^{2+} substitute for Mg^{2+}
- Fe^{3+}, Cr^{3+}, Mn^{3+} substitute for Al^{3+}
- Ti^{4+} and V^{3+} can also substitute into the structure.

Basaltic magmas contain about

ten percent Fe

a few percent Ti

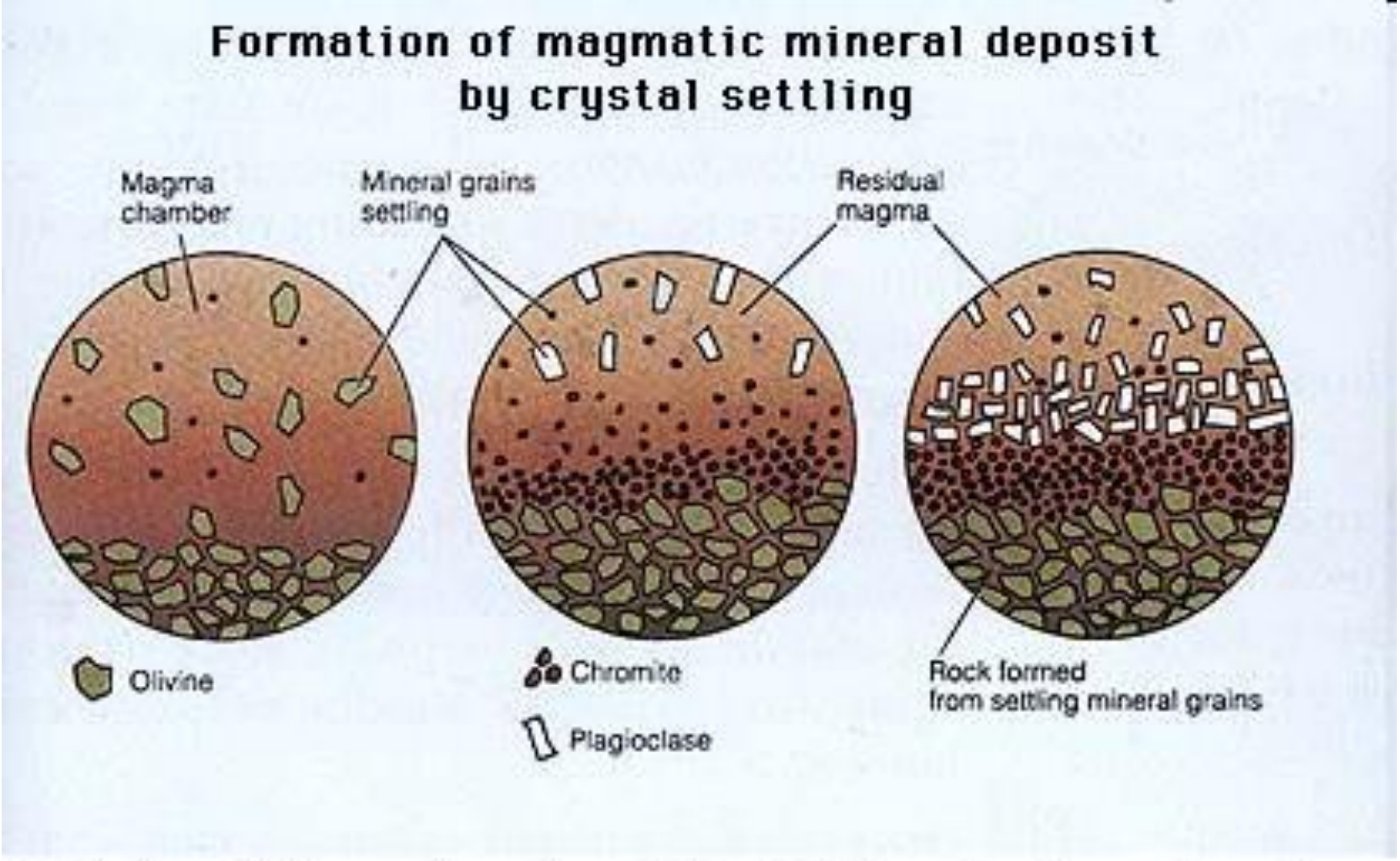
and trace amounts of Cr, Mn, and V

Under favorable circumtances these become concentrated in the spinels.

Since the spinel crystals are dense, they can sink to the bottom of a slowly cooling magma body and make layers of ore

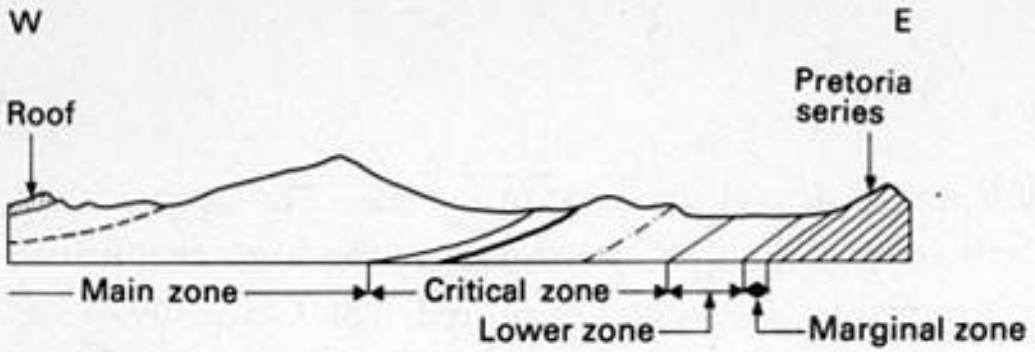
basaltic magma: 2500 kg/m^3

Cr spinel: 4800 kg/m^3

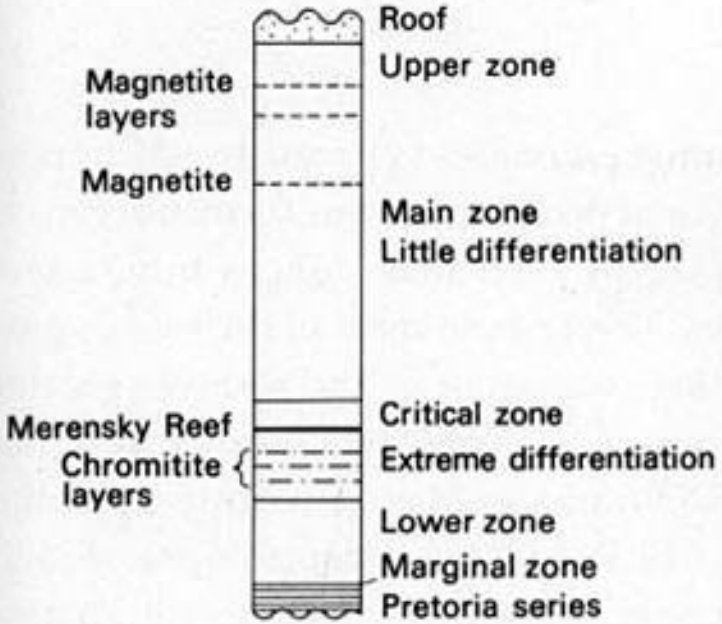


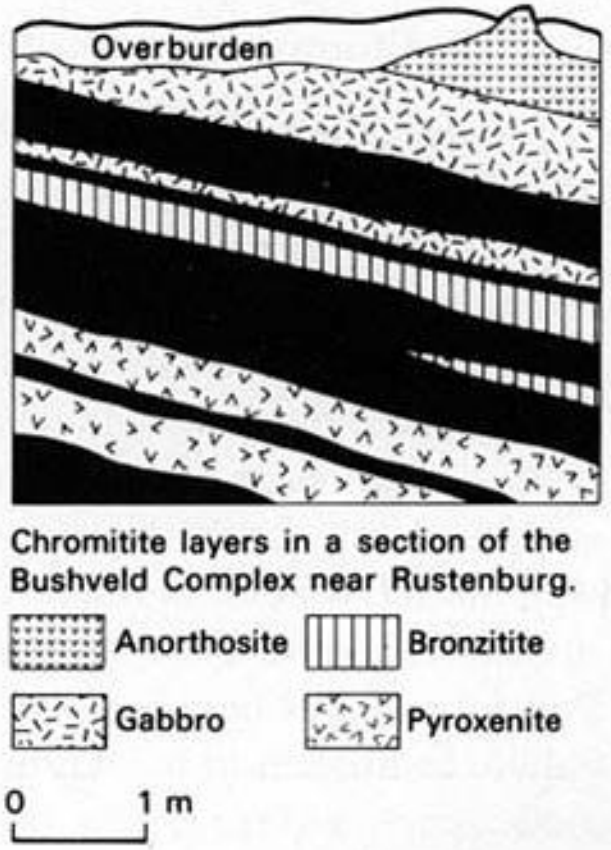
A. Grains of three minerals settle at different rates and produce three rock types of different composition.

Figure 3.38 from: Skinner, Brian J. and Stephen C. Porter (1995) The Dynamic Earth, 3rd ed. New York: John Wiley & Sons, Inc., p.109.



Section showing major zones in the Bushveld Complex, north of Steelport. Length of section, 30.5 km. (After Hall, 1932)

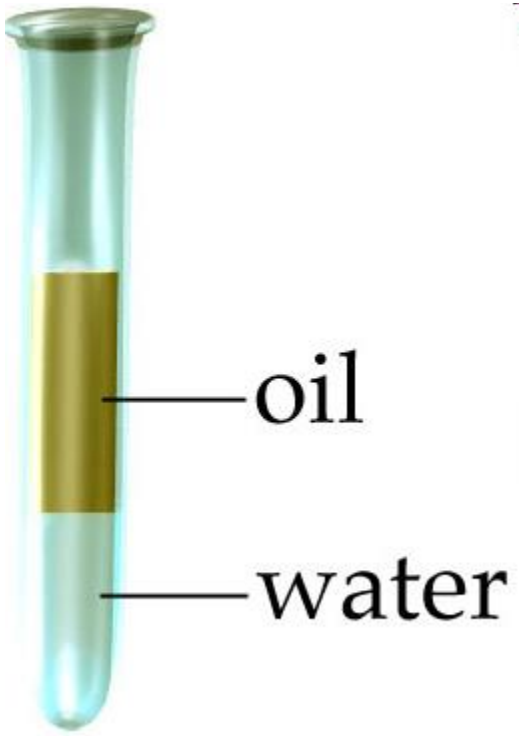




Chromitite layers in a section of the Bushveld Complex near Rustenburg.

Figure 12.2 from:
Evans, Anthony M. An Introduction to Economic Geology and Its Environmental Impact. ©1997 by Blackwell Science Ltd., p. 107.

Liquid Immiscibility

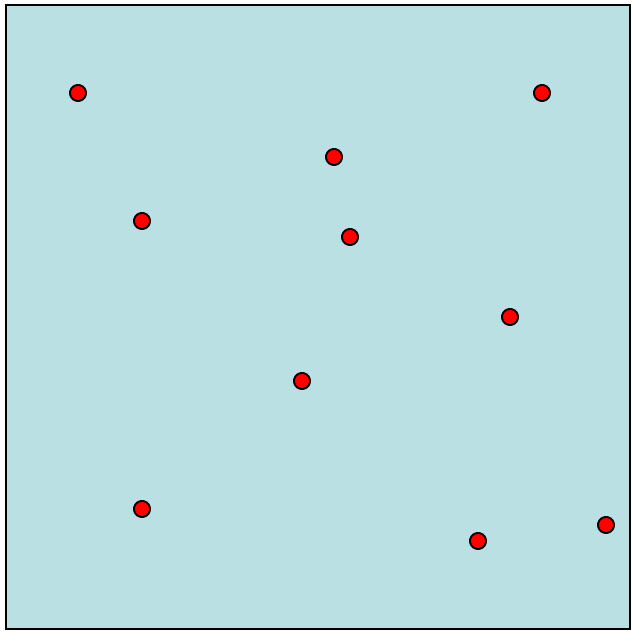


Oil and water don’t mix …

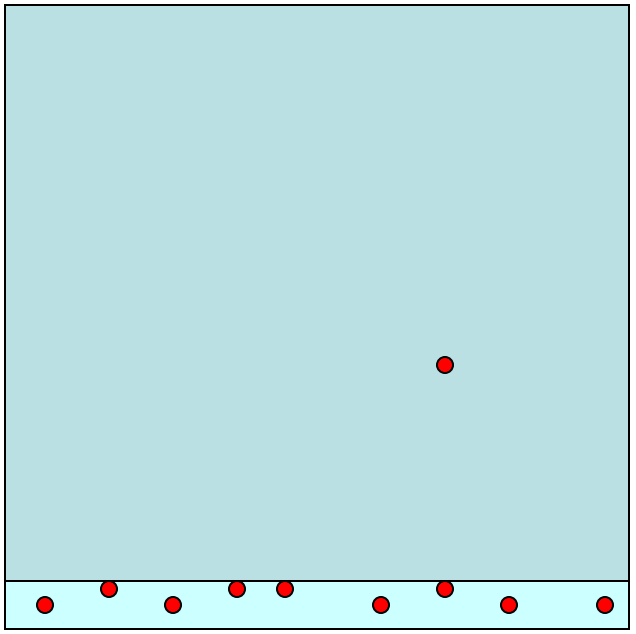
As magmas cool, they can split into two liquids of different composition and density.

- One of these liquids is the silica-rich melt. It has the most volume
- The other, typically much smaller in volume, can be rich in metal oxides, sulfides or carbonates.

High T



Low T



Desirable element • preferentially concentrated into low-volume melt

Types of Immiscible Melts

Oxide melts can be rich in Fe (Fe_2O_3, hematite) and Ti ($FeTiO_3$, ilmanite).

Sulfide melts can be rich in Ni, Cu, and the platinum-group elements, in addition to iron sulfur (FeS, pyrrhotite).

Carbonate melts can be rich in niobium, tantalum, rare earths, copper, thorium, and phosphorous.

Dissolution by water can concentrate chemicals

Aqueous fluids in magma

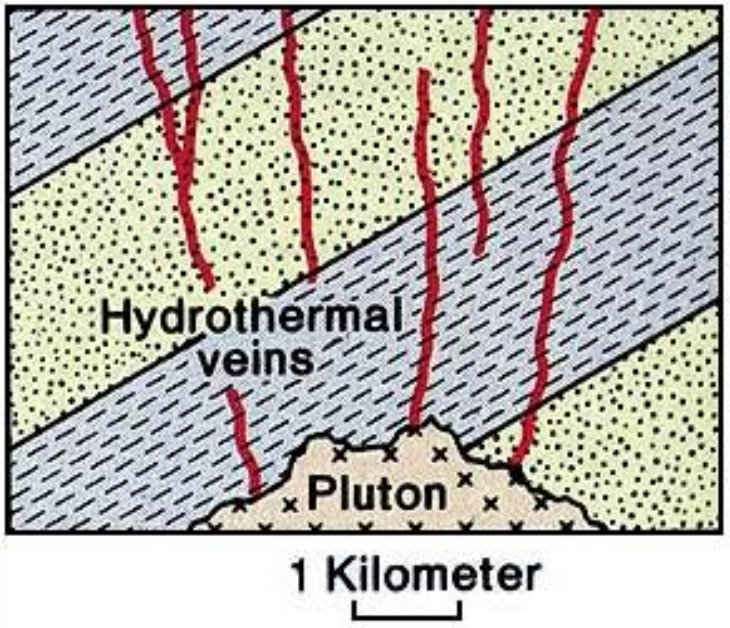
As magma cools, the volatiles (mostly water and carbon dioxide) that they contain can form super-critical fluids.

supercritical fluids are on the verge of making the phase transition from liquid to gas.

because of their extremely high temperature, many elements are soluble.

These fluids can concentrate copper, molybdenum, gold, tin, tungsten and lead.

The fluids from a large pluton can invade surrounding rocks, along cracks called hydrothermal veins).



Hydrothermal Ore Deposits

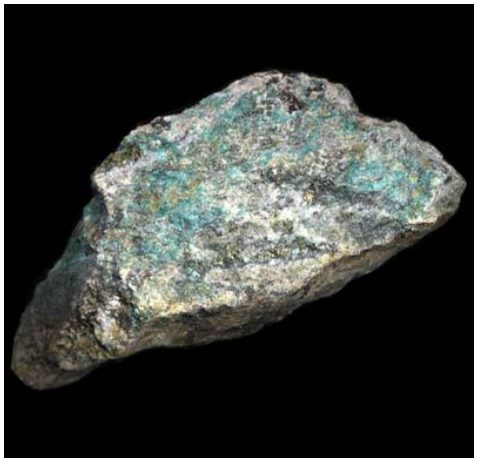
Figure 21.14 from: McGeary, David and Charles C. Plummer (1998) Physical Geology: Earth Revealed, 3rd ed. WCB/McGraw-Hill, p. 486.

These deposits are typically very low grade, but can be huge.

Porphyry copper-molybdenum deposits are one example

native sulphur deposits
volcanic chimney
volcano
breccia
zone of alteration
prevolcanic rocks
ore
cupola
granite batholith

Aqueous fluids from granitic magma have invaded surrounding rock



porphery copper ore

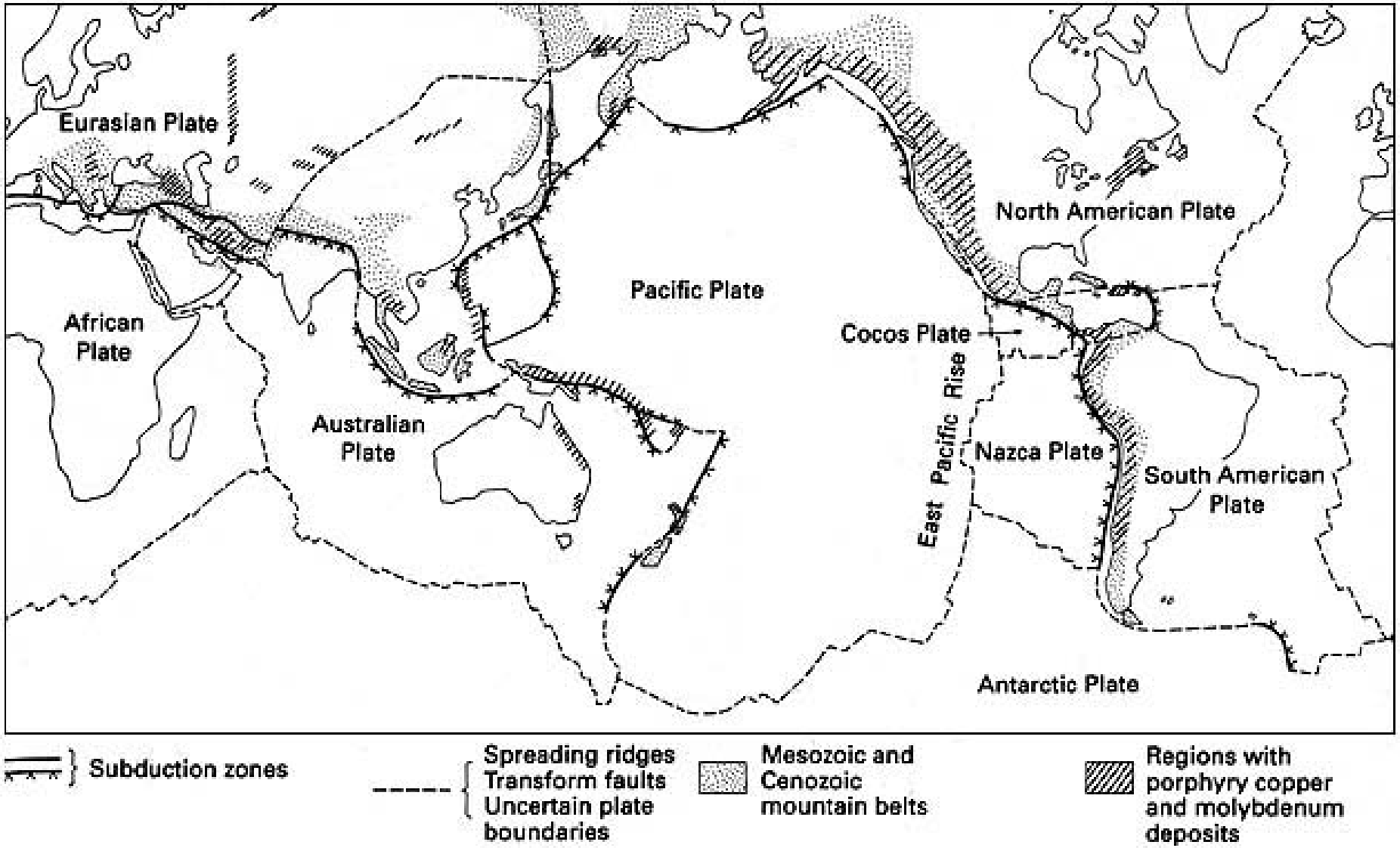


Figure 15.5 from: Evans, Anthony M. An Introduction to Economic Geology and Its Environmental Impact.
, p. 142.

Scarns

acidic fluids from a granitic pluton invade and react with limestones

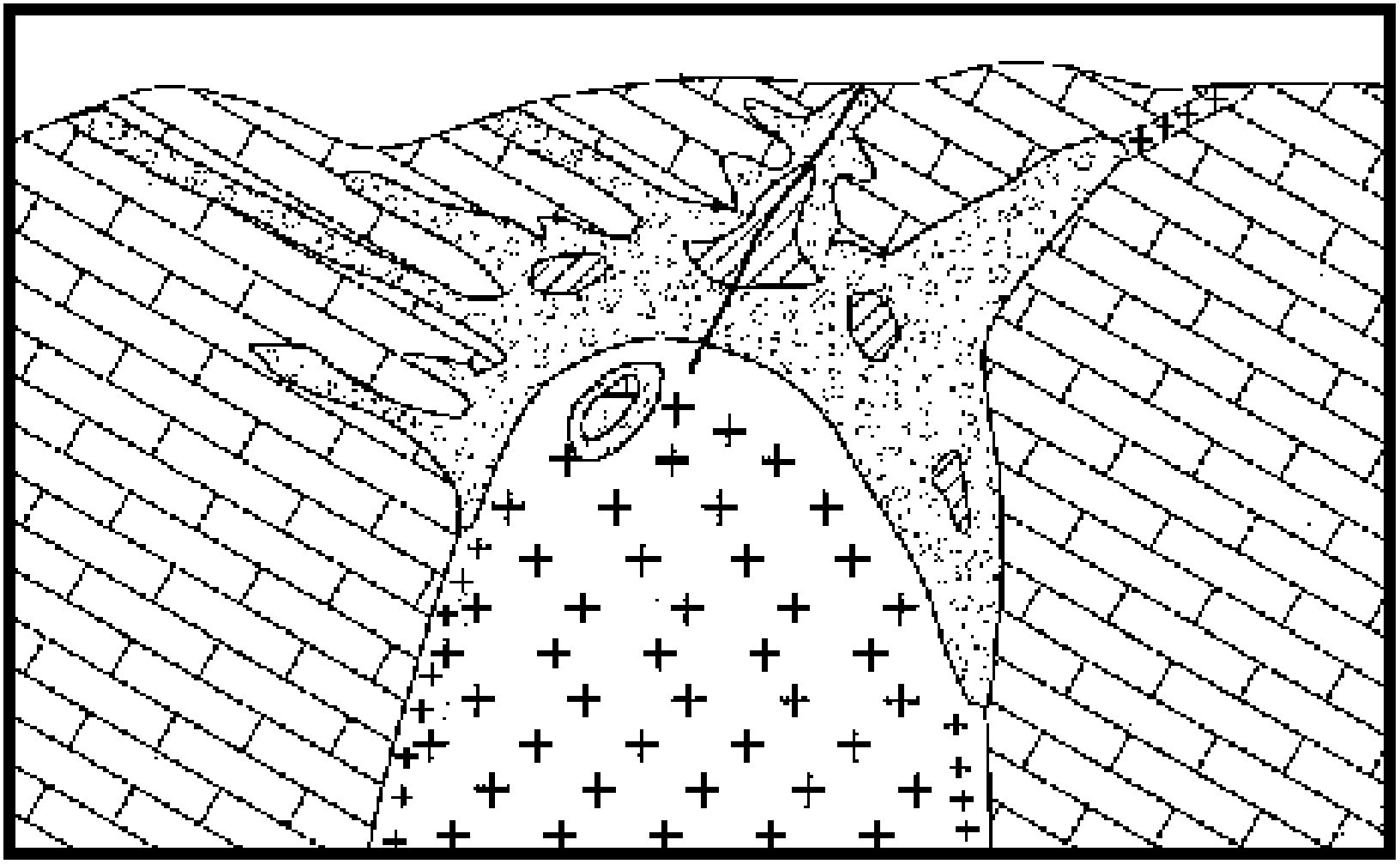
The limestone is dissolved and replaced by:

Silicate minerals,

sulfides of iron, copper, zinc, lead and silver,

oxides of iron, tin, and tungsten

gold



limestone

skarn

granitic intrusion

ore

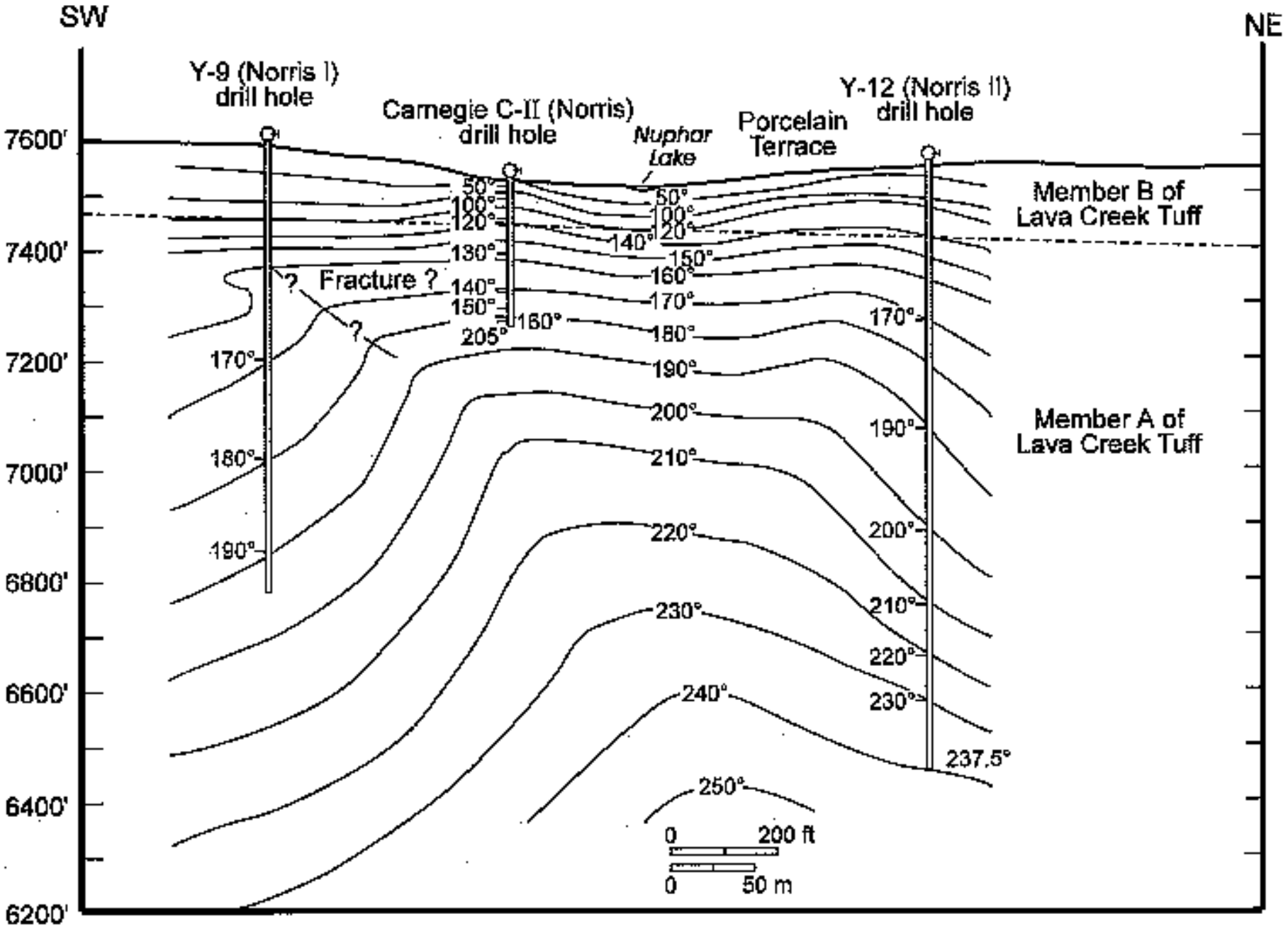
Geothermal systems

magma is the source of heat

but the water is just groundwater, and not derived from the magma

High temperature geothermal systems occur where ground water comes in contact with magma near volcanoes.

Example: Yellowstone


SW
NE
Y-9 (Norris I) drill hole
Carnegie C-II (Norris) drill hole
Nuphar Lake
Porcelain Terrace
Y-12 (Norris II) drill hole
Member B of Lava Creek Tuff
Member A of Lava Creek Tuff
Fracture ?
7600'
7400'
7200'
7000'
6800'
6600'
6400'
6200'
50°
100°
120°
130°
140°
150°
160°
170°
180°
190°
200°
205°
210°
220°
230°
240°
250°
237.5°
0 200 ft
0 50 m

Marine hydrothermal fields

common on mid-ocean ridges

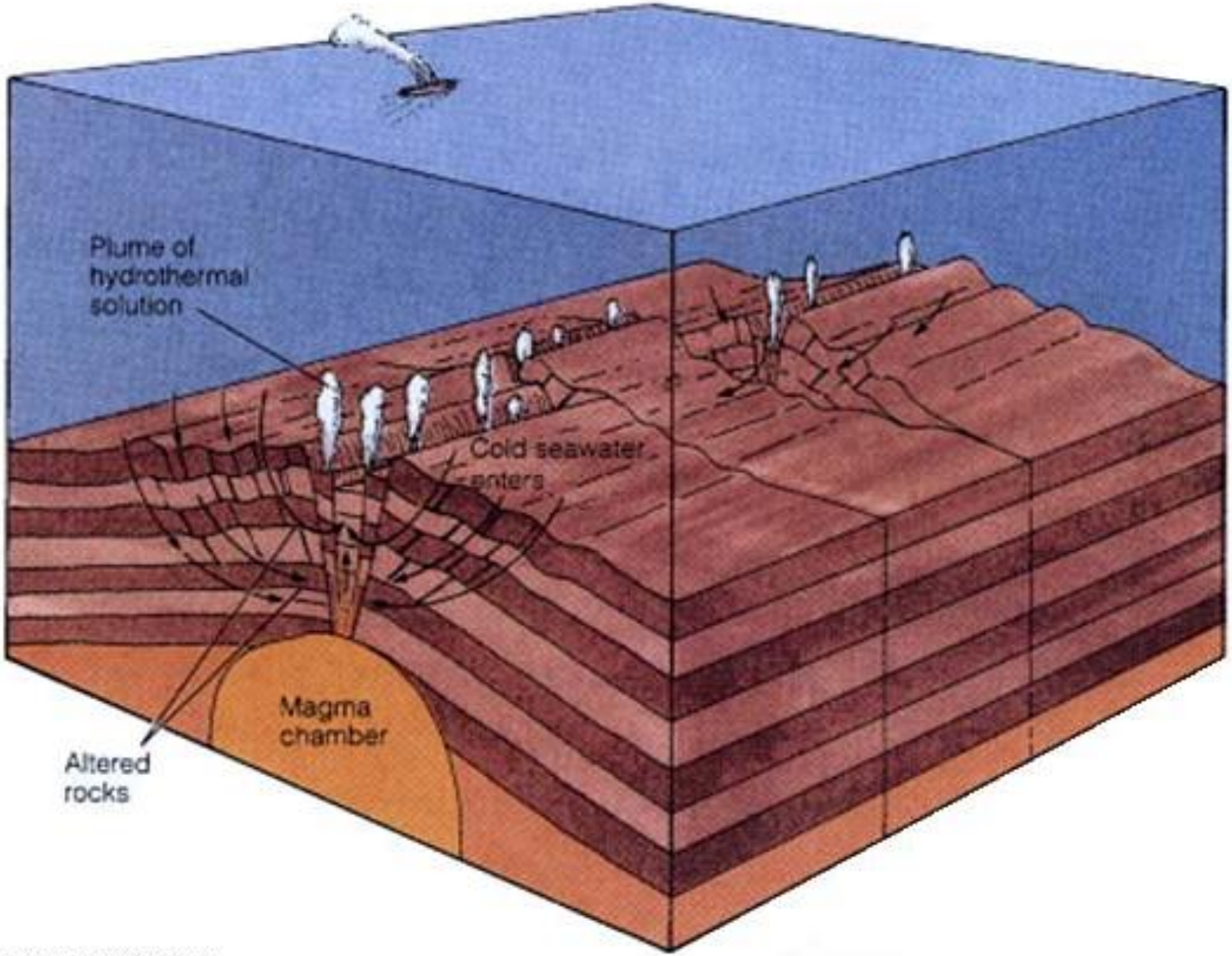
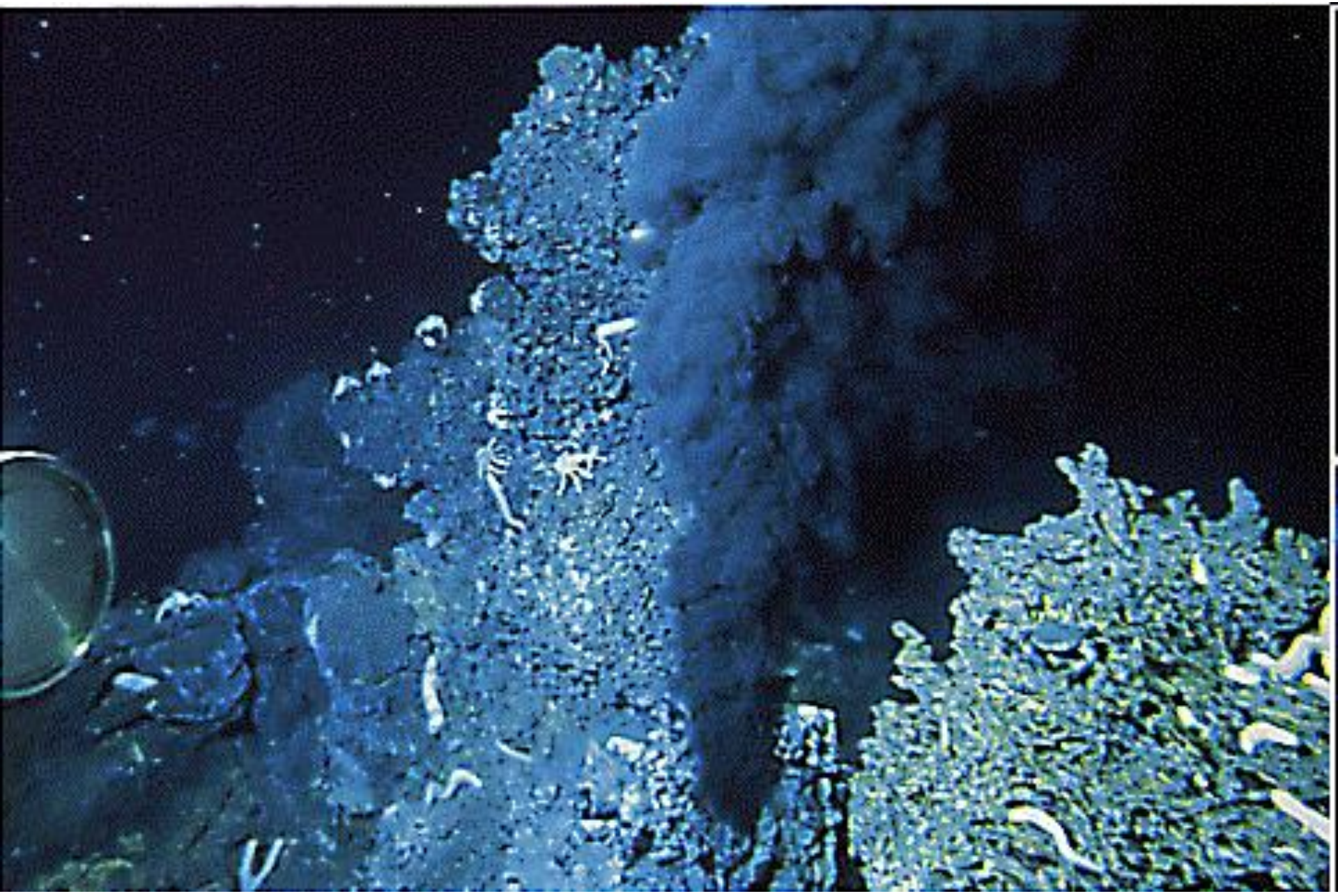
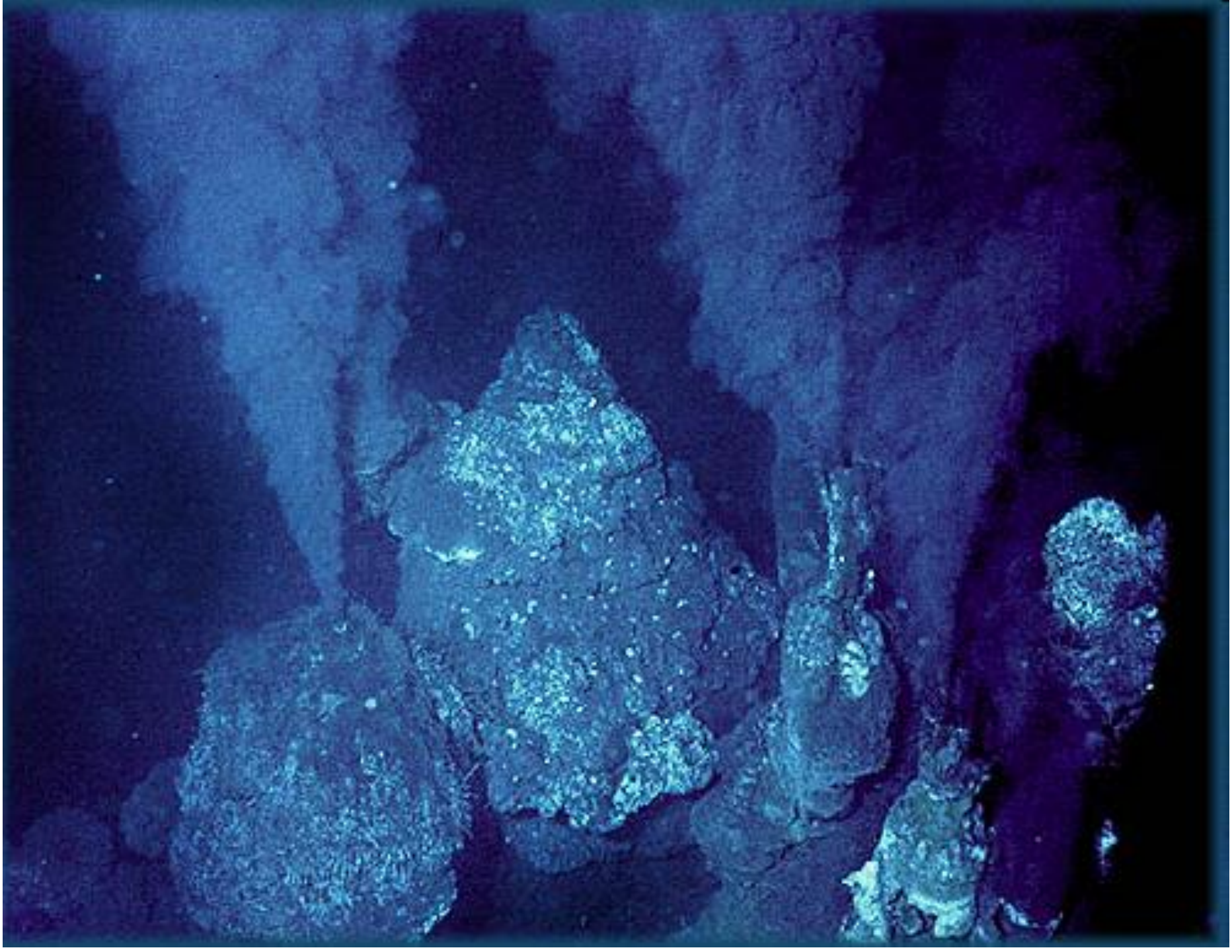
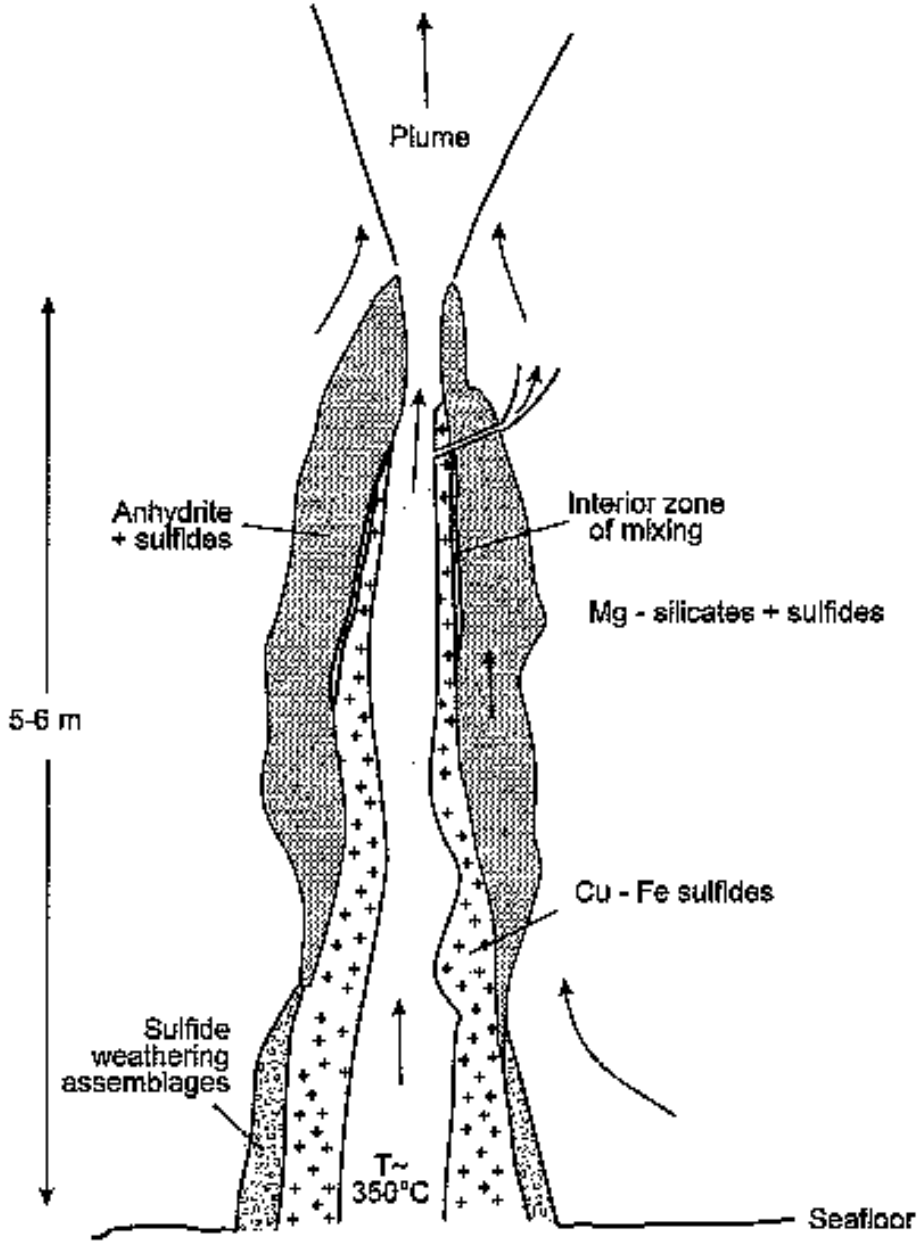


Figure B5.4 from:
Skinner, Brian J. and Stephen C. Porter (1995) The Dynamic Earth, 3rd ed.
New York: John Wiley & Sons, Inc., p. 159.






Plume
Anhydrite
+ sulfides
Interior zone
of mixing
Mg - silicates + sulfides
5-6 m
Cu - Fe sulfides
Sulfide
weathering
assemblages
T~
350°C
Seafloor

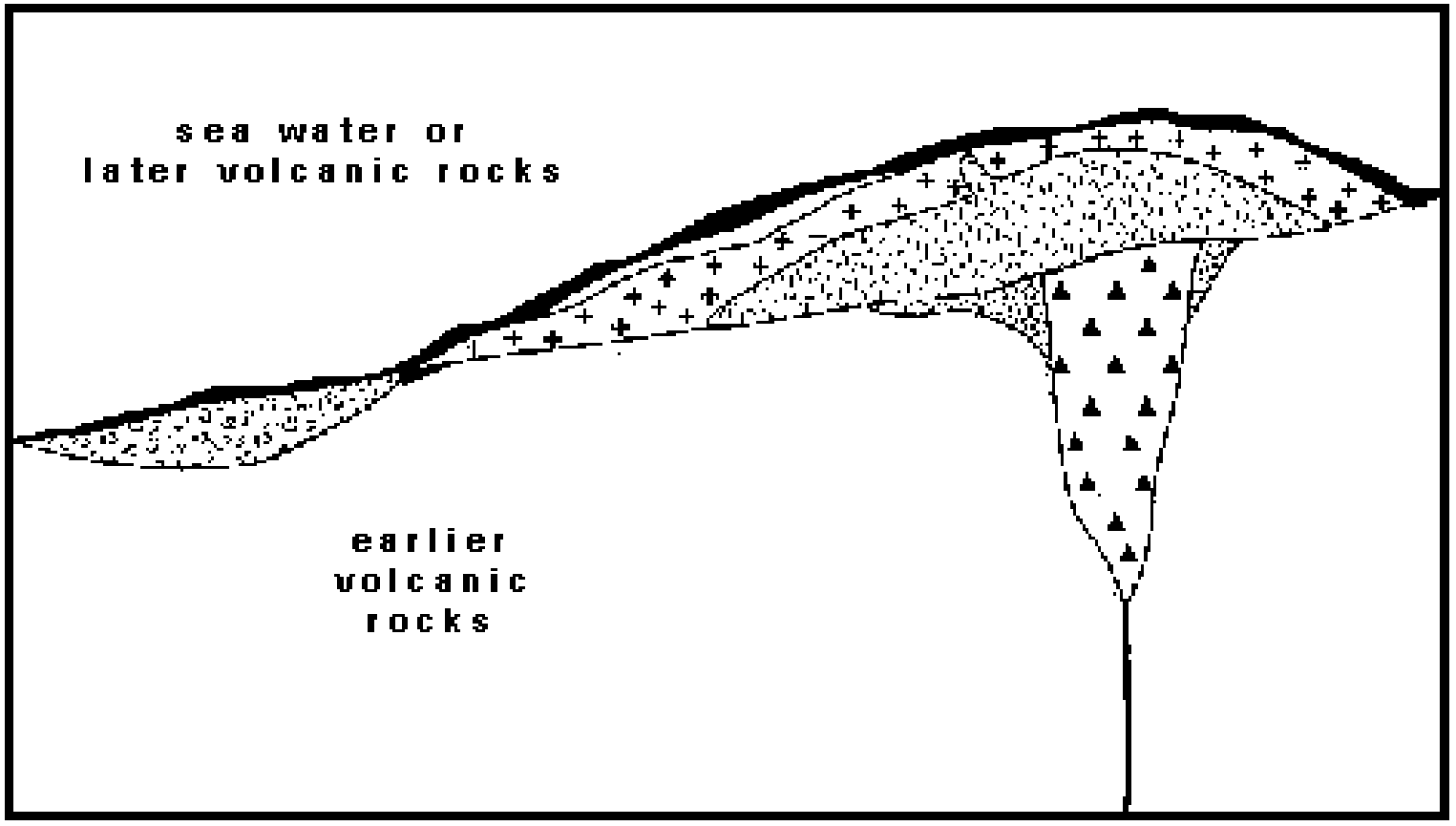
Mechanism for producing the ore

- 1. Sea water percolates thought the hot (>300C) basaltic crust, preferentially dissolving oxides and sulfides from the rock

  2. Water discharges into ocean, minerals precipitate as soon as the water cools.

  3. This process can concentrate copper, lead, zinc and silver as volcanogenic massive sulfide deposits.

  4. The minerals precipitate at different places in the system, since they precipitate at different temperatures.



chert-hematite layer

transported fragmented ore

barite ore

massive sphalerite + pyrite + galena ore

massive pyrite + chalcopyrite ore

siliceous sphalerite + pyrite + galena ore

pyrite + quartz

Mechanisms that involve oxidation state of the water

Ground water can carry dissolved materials. These can precipitate out of solution if the water becomes more or less oxidizing.

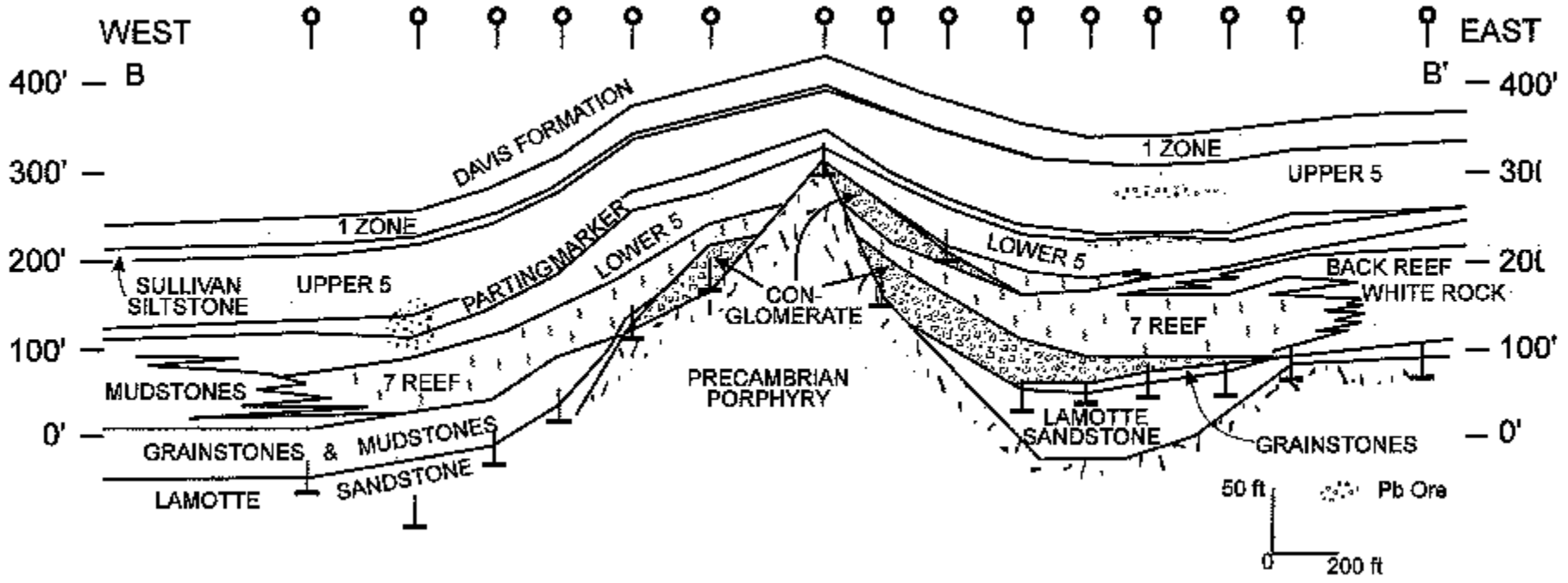
Example: Mississippi Valley Type lead-zinc deposits

ore minerals occur as veins in limestone that overlie a sandstone.

Ores include: lead as PbS, zinc as ZnS, copper as $CuFeS_2$, and flourine as CaF_2.

very saline brines containing sulfate ions (SO_4^{2-}). These brines transported the metals in solution through the sandstone.

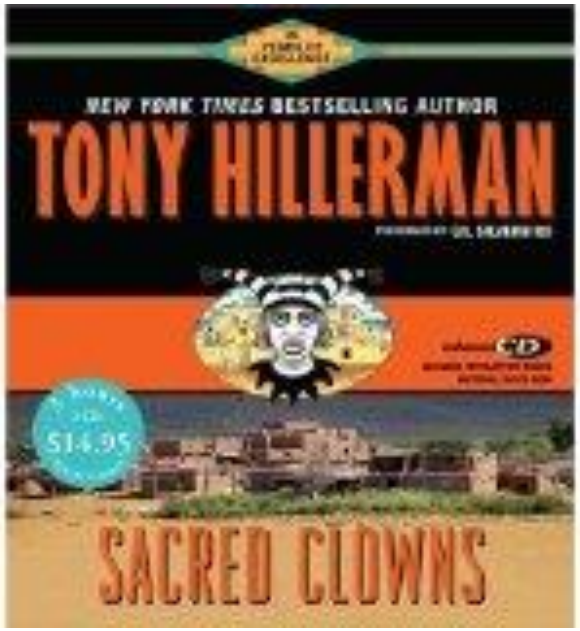
The sulfate was reduced to S^{2-}, perhaps by reaction with methane, and the minerals then precipitated out.


WEST
EAST
B
B'
400'
300'
200'
100'
0'
DAVIS FORMATION
1 ZONE
UPPER 5
PARTING MARKER
LOWER 5
SULLIVAN SILTSTONE
MUDSTONES
7 REEF
GRAINSTONES & MUDSTONES
LAMOTTE SANDSTONE
CON-GLOMERATE
PRECAMBRIAN PORPHYRY
1 ZONE
UPPER 5
LOWER 5
BACK REEF
WHITE ROCK
7 REEF
LAMOTTE SANDSTONE
GRAINSTONES
50 ft
Pb Ore
0
200 ft

Example: uranium ore

soluable U^{6+} is produced during the weathering of igneous rocks.

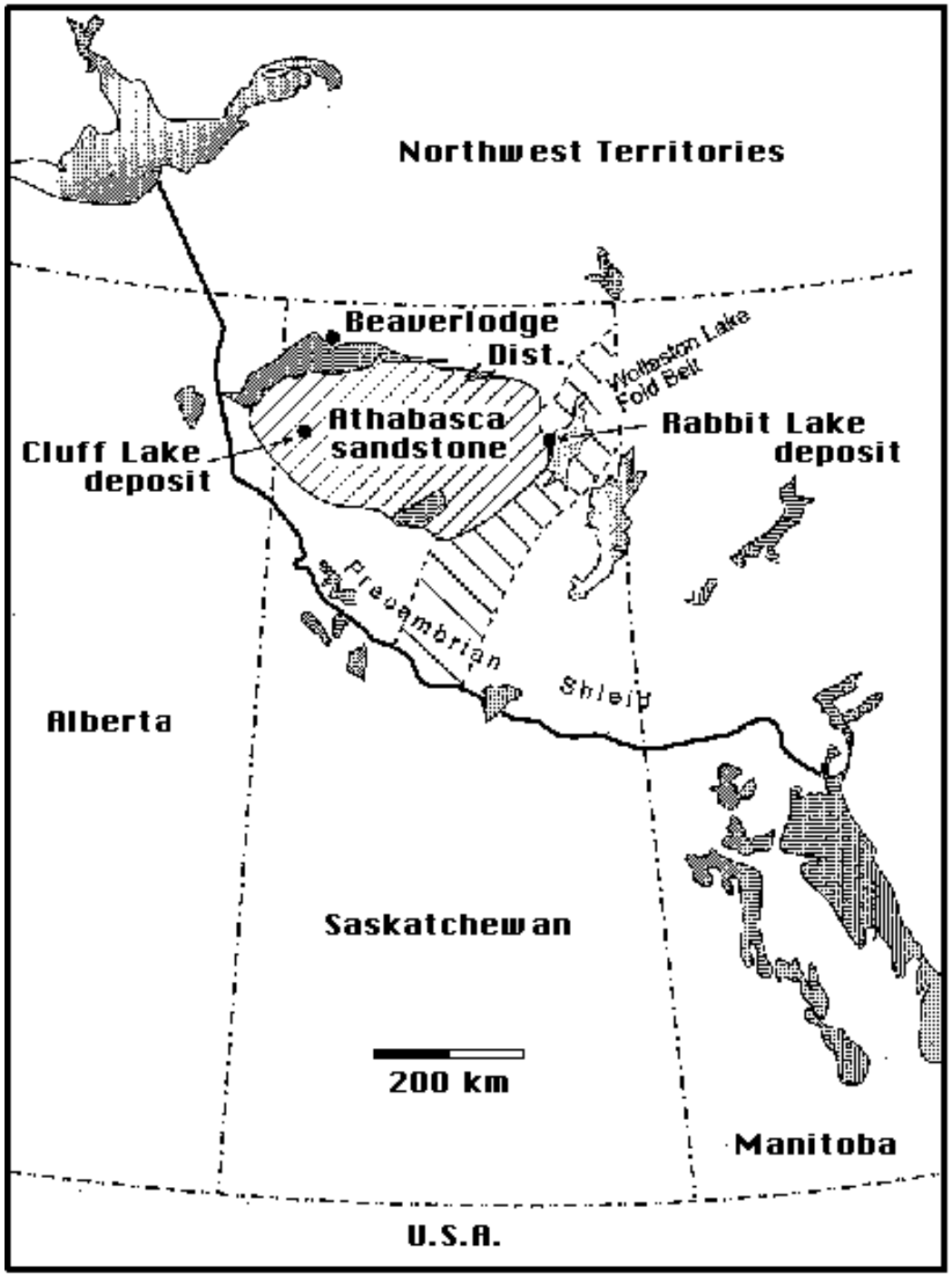
U^{6+} was transported by groundwater until it encounters reducing conditions. It is reduced to U^{4+} and precipitates as uranium oxide.

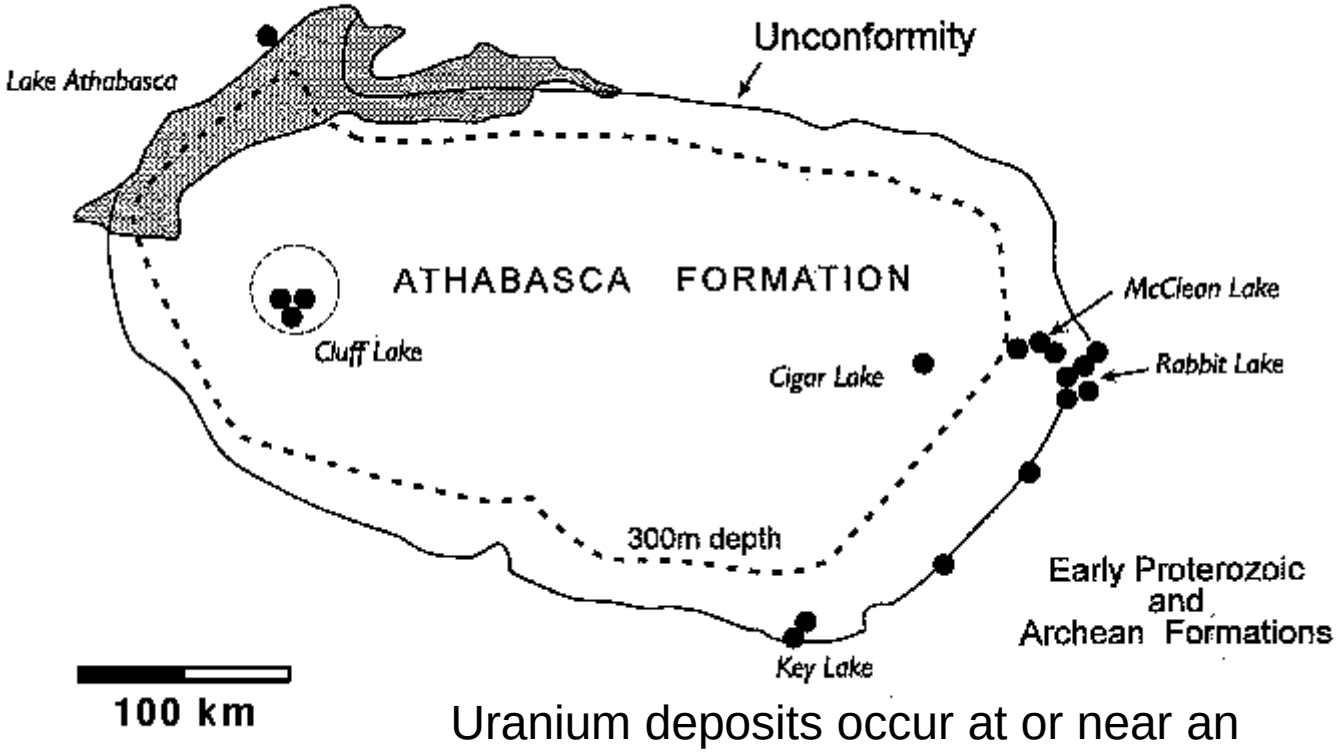


Buried wood makes ground water more reducing, caused uranium to drop out of solution

Uranium oxide (yellow) replacing petrified wood

Large deposit in Canada formed this way


Northwest Territories
Beaverlodge Dist.
Wollaston Lake Fold Belt
Athabasca sandstone
Cluff Lake deposit
Rabbit Lake deposit
Precambrian Shield
Alberta
Saskatchewan
200 km
Manitoba
U.S.A.



Uranium deposits occur at or near an unconformity between a sandstone (upper unit) and a graphite (carbon) bearing gneiss (lower unit). The sandstone provides the conduit for hydrothermal fluids. The gneiss provides the reducing conditions.