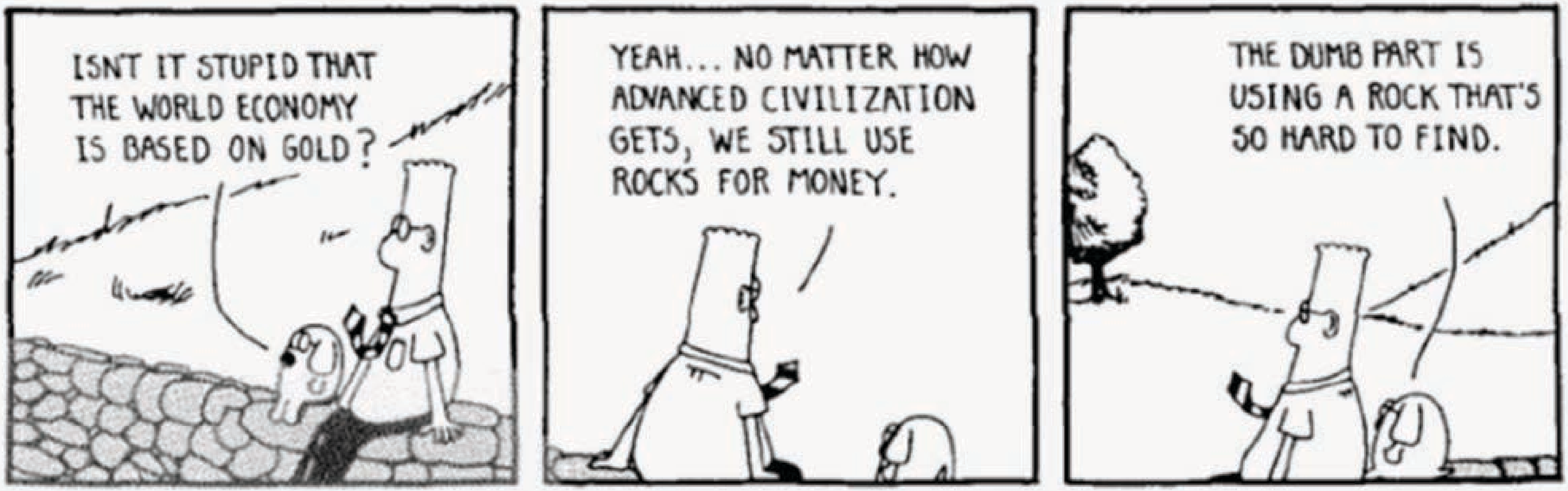
EARTH 471
Mineral Deposits

Hydrothermal Au deposits

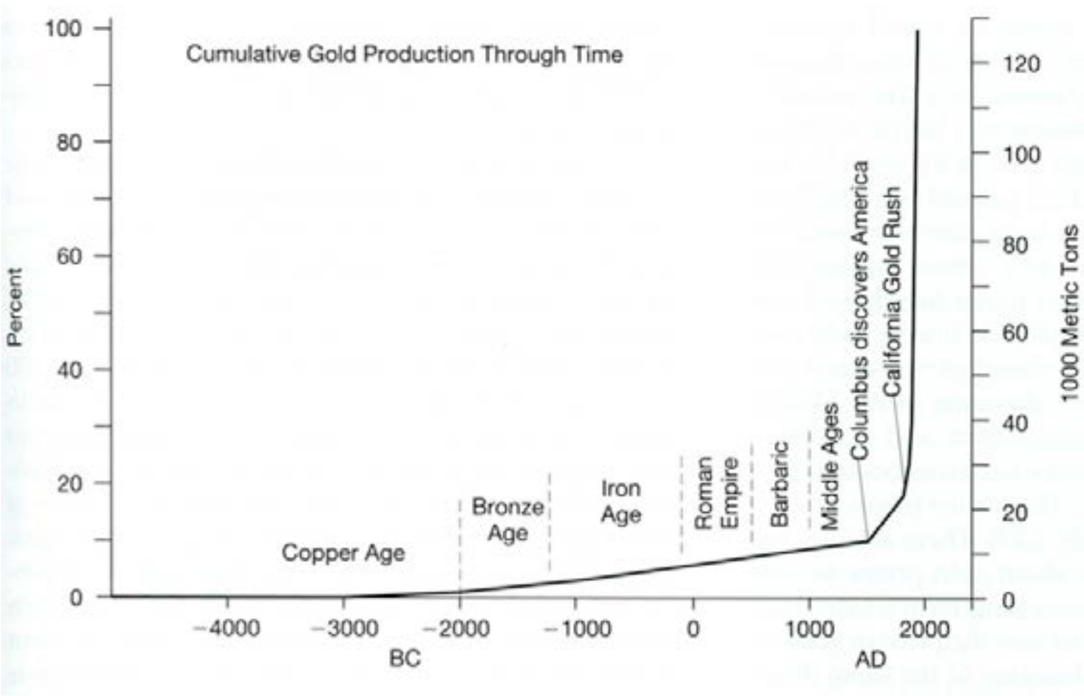

ISN'T IT STUPID THAT THE WORLD ECONOMY IS BASED ON GOLD?
YEAH... NO MATTER HOW ADVANCED CIVILIZATION GETS, WE STILL USE ROCKS FOR MONEY.
THE DUMB PART IS USING A ROCK THAT'S SO HARD TO FIND.

Gold

- Low reactivity
- Does not tarnish
- Ductile
- Conductive
- Rare!!
- Reusable (most gold is recycled over and over again)

Uses:

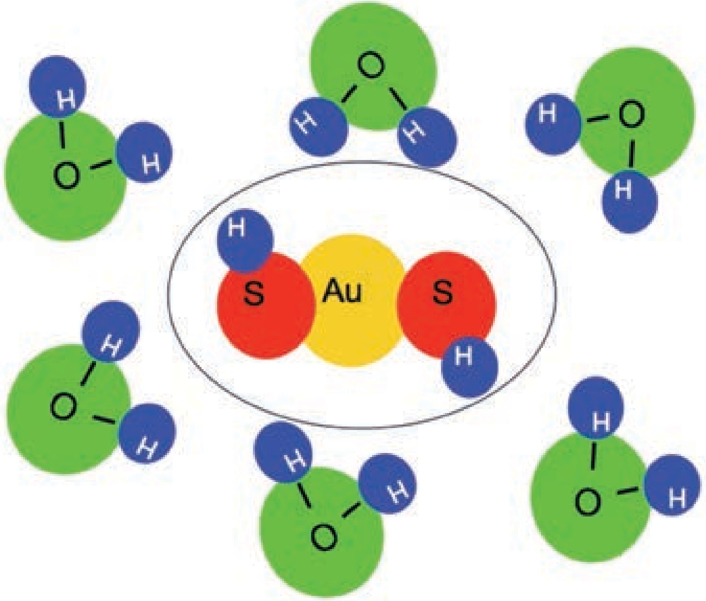
- Jewelry
- Medium of exchange



Craig et al. (2010)

Geochemistry of Au

- Siderophile (iron-loving)
- 1.5 ppb in continental crust (0.00015g/ton)
- ~1 ppb in the mantle
- ~140 ppb in chrondrites
- Most gold is in Earth's core
- Essentially insoluble but… can be soluble if bound to some ligands



From A.E. Williams-Jones

Gold solubility – references

13.15 Geochemistry of Hydrothermal Gold Deposits

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13.15.1 Introduction

The geochemistry of the three most significant hydrothermal gold deposit types, epithermal, Carlin-type, and orogenic, is described in this article. The geologic characteristics of these deposits are discussed in detail elsewhere (Cline et al., 2005; Goldfarb et al., 2005; Simmons et al., 2005), and their general geotectonic settings and relationship to other important deposit types are summarized in Figure 1.

Another important hydrothermal gold deposit type, porphyry copper–gold deposits, is not discussed here. Among the three deposit classes considered, the high-sulfidation epithermal and probably most low-sulfidation epithermal deposits are genetically linked to coeval magmas and magmatic

Treatise on Geochemistry 2nd Edition http://dx.doi.org/10.1016/B978-0-08-095975-7.01117-7 383

Gold in Solution

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1811-5209/09/0005-0281$2.50 DOI: 10.2113/gselements.5.5.281

Although gold is a noble metal and is effectively insoluble even in strong acids, we have known for nearly 500 years that it can be concentrated to mineable levels by being transported as dissolved species in crustal fluids (indeed, most economic gold deposits owe their origin to this mode of transport). From alchemy and later experimental chemistry and geochemistry, we have developed an understanding of the solubility and speciation of gold in aqueous liquids and other crustal fluids. This knowledge informs us about the processes that promote the transport of gold in the Earth's crust, result in exploitable gold deposits and lead to the remobilization of gold in the surficial environment.

Keywords: gold, solubility, hydrothermal fluids, petroleum, supergene

INTRODUCTION

Gold is the most noble of all metals. No other metal is less reactive at its surface when in contact with liquids or gases (this helps explain why in nature gold occurs dominantly in its native form), and no other metal is more valued for its resistance to corrosion. Indeed, gold was accorded the status of noble metal because, unlike other metals, it was not known to tarnish or dissolve in strong acids and was therefore deemed incorruptible. However, as early as the 8[th] century CE, Jabir ibn Hayyan (721–815), an Arab alchemist, discovered that gold dissolves in a mixture of three parts hydrochloric acid and one part nitric acid, a liquid that later became known as *aqua regia* (royal water) because of its capacity to dissolve gold (Russell 1686). This capacity, which even today is used in the analysis of gold, results from the fact that nitric acid, an extremely strong oxidant, is able to convert the gold to Au^{3+}, thereby making it available for complexation with Cl^- ions to form aqueous species such as $AuCl_4^-$.

"Now I will discuss that kind of minerals for which it is not necessary to dig, because the forces of water carries them out of the veins"
– Agricola 1556

During the 17[th] century, the German chemist Georg Stahl (1660–1734), in a quest to explain how Moses was able to turn the golden calf into "bitter water", found that gold dissolves in aqueous solutions prepared by heating a mixture of *sal mirabilis* (Na_2SO_4) and charcoal. He had discovered that gold is soluble in aqueous solutions of NaHS and, as we now know, this occurs because of the complexation of gold to form the species $AuHS^\circ$ and $Au(HS)_2^-$. However, an equally plausible "bitter water" that Stahl could have considered is colloidal gold, which had been used in Roman times to make dichroic glass (Fig. 1) and was later promoted by Paracelsus (1493–1541), under the name *aurum potabile*, as an elixir of life; the colloidal nature of this deep red fluid was eventually deduced by Michael Faraday (1791–1867).

From an industrial perspective, arguably the most important discovery about the solubility of gold came in the 18[th] century when the Swedish chemist Carl Scheele (1742–1786) found that gold is highly soluble in hydrocyanic acid. This finding eventually led to the patenting of the cyanidation process for refining gold by MacArthur and the Forrest brothers in 1887; the process involves dissolving the gold as $Au(CN)_2^-$ and reducing it to the native metal with zinc powder. By the early 20[th] century, cyanidation had become the method of choice for the beneficiation of gold ores and remains so to this day.

The idea that gold could be transported in crustal fluids and concentrated as ore can be traced back to the 16[th]-century writings of Agricola (1546) in *De Ortu et Causis Subterraneorum*. This work describes vapours of heated groundwaters mixing with "earth" to form "juices" that rise into fractures, where they deposit metals including gold. Interestingly, however, Jabir ibn Hayyan had noticed some 800 years earlier that waters flowing from copper mines carried scales of copper, which after drying in the desert "contained amongst them the purest gold". He concluded that the gold was the product of "long washing in water and digestion by the heat of the sun" (Russell 1686), an idea that foreshadows modern thinking about the supergene origin of some of the gold in placer- and regolith-hosted deposits. In the late 17[th] century, the roots of modern hydrothermalism started to take hold, with the proposal by Webster (1671), in his *Metallographia*, that the ore metal is in *principis solutis*, that is, it dissolves in water or steam. This proposal was further developed in the 19[th] century with the observation that dissolution of metals requires "mineralizers" such as B, F, PO_4 and Cl (Daubrée 1841). By the late 19[th] century, hydrothermalism was well established, although opinion continued to be divided well into the 20[th] century over whether the ore-forming fluid is invariably liquid (Graton 1940), or whether, in magmatic-hydrothermal systems, vapour can also play this role (Ingerson and Morey 1940). The issue was finally thought to have been settled when Krauskopf (1957) concluded that the

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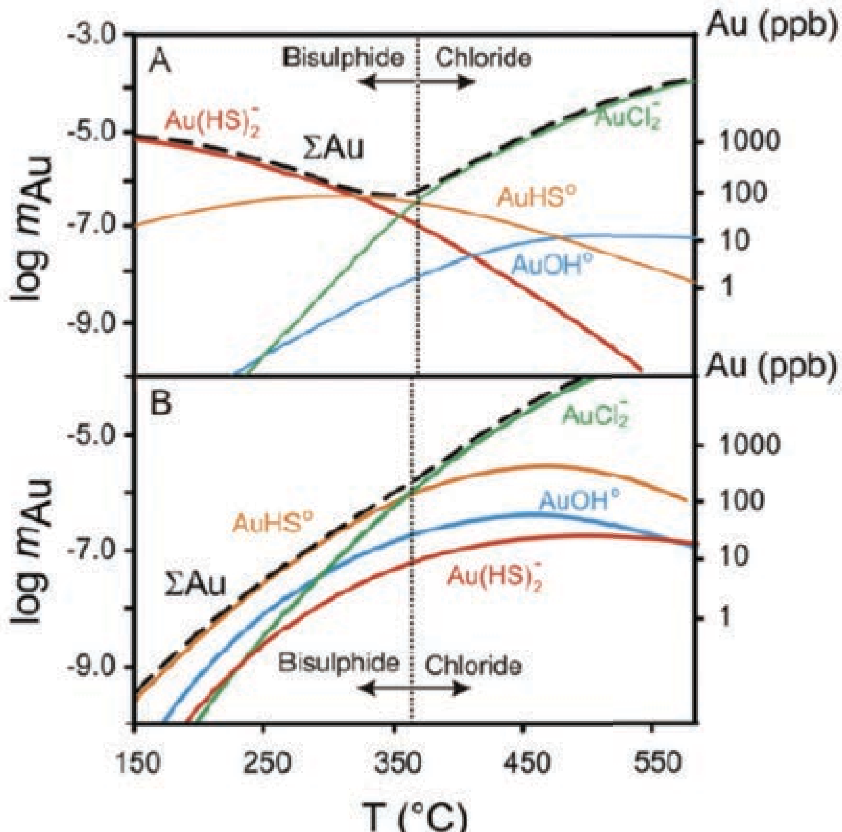
Elements, Vol. 5, pp. 281–287 281 October 2009

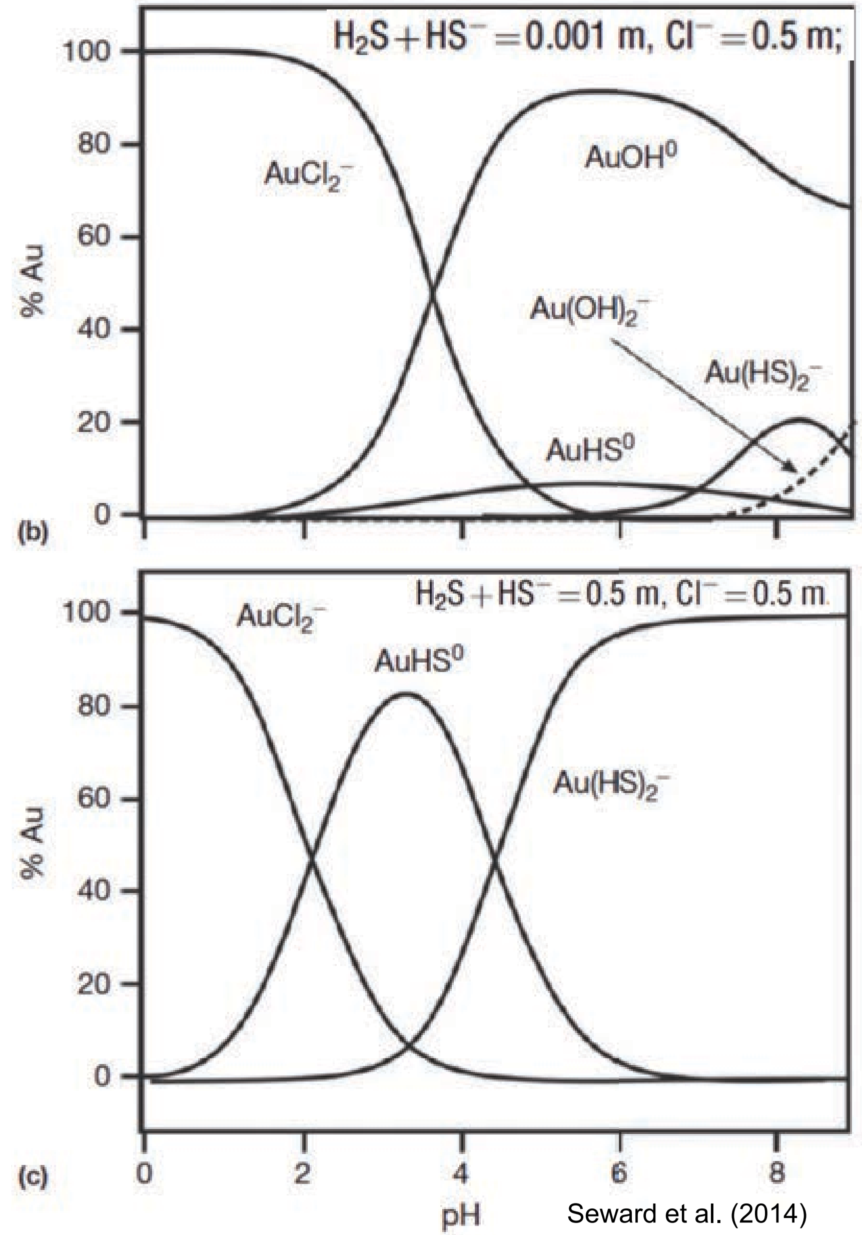
Gold ligands

- **HS^- –** low T and/or high pH
- **Cl^- –** high T and/or low pH



Williams-Jones et al. (2009, Elements)

500°C and 0.5 kbar



Seward et al. (2014)

Gold precipitation from hydrothermal fluids

$$Au_S + HS^- + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)^\circ + 1/2\ H_2O$$

and

$$Au_S + 2HS^- + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)_2^- + 1/2\ H_2O$$

<u>How to precipitate gold:</u>

Decrease HS^-

Decrease O_2

Increase pH

Gold precipitation from hydrothermal fluids

1. **Boiling**
2. Sulfidation
3. Oxidation
4. Cooling

$$Au_S + \boxed{HS^-} + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)^\circ + 1/2\ H_2O$$

and

$$Au_S + \boxed{2HS^-} + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)_2^- + 1/2\ H_2O$$

Boiling would fractionate H_2S into the vapour and lower the activity of HS^- through the reaction:

$$HS^- + H^+ \rightleftharpoons H_2S$$

As a bonus, boiling increases pH, which promotes precipitation of Au

Gold precipitation from hydrothermal fluids

1. Boiling
2. **Sulfidation**
3. Oxidation
4. Cooling

$$Au_S + \boxed{HS^-} + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)^\circ + 1/2\ H_2O$$

and

$$Au_S + \boxed{2HS^-} + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)_2^- + 1/2\ H_2O$$

<u>Sulfidation</u> or replacing iron-bearing minerals with iron sulfides (e.g. pyrite), the fluid becomes depleted in HS^- and precipitates Au with an iron sulfide (can be referred to as pyritization)

Gold precipitation from hydrothermal fluids

1. Boiling
2. Sulfidation
3. **Oxidation**
4. Cooling

H_2S, HS^- and SO_4^{2-} are sensitive to oxidation state (see plot on left)

When gold is as the species $Au(HS)_2^-$ (red field), Oxidation (increasing fO_2) results in a drop in HS- concentration which can precipitate Au

How: Mixing Au fluid with a hematite host rock or oxygenated meteoric water

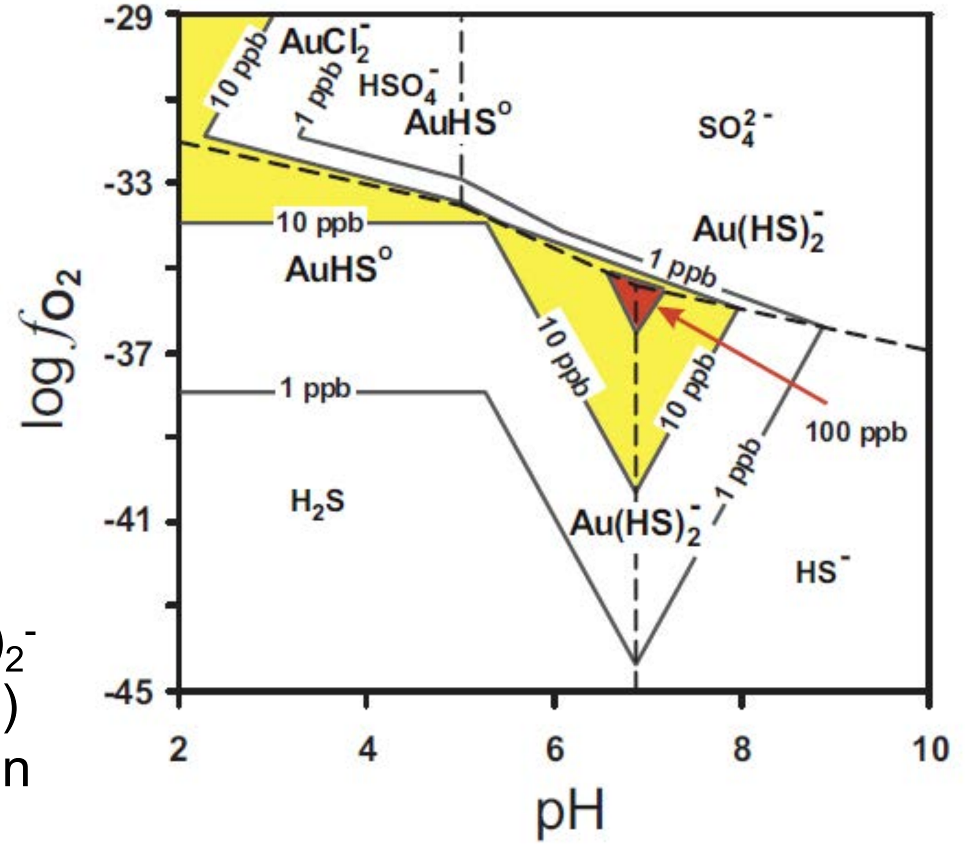
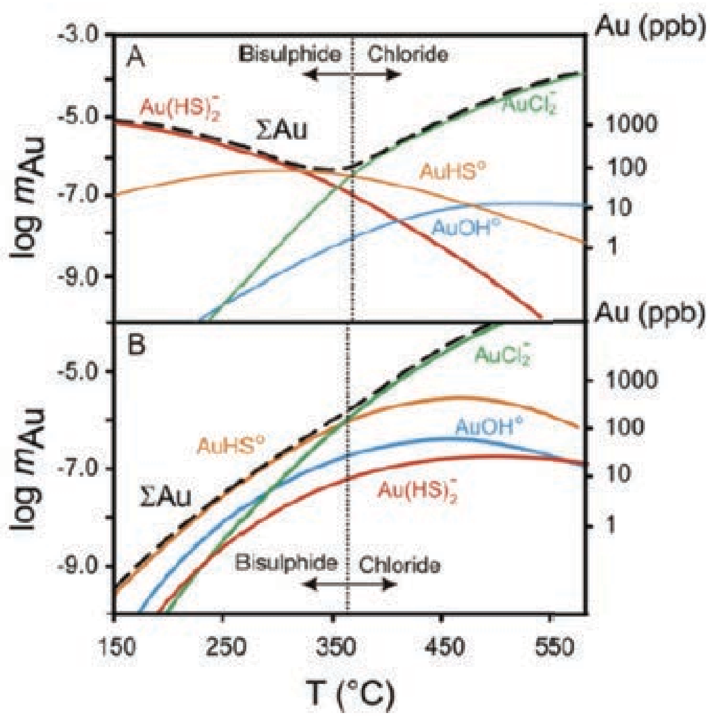


FIGURE 3 Gold solubility (in parts per billion; solid lines) and speciation at 500 bar and 250°C as a function of log fO_2 and pH in a solution containing 1 m NaCl with ΣS = 0.01 m. The dashed lines separate regions of predominance of H_2S, HS^-, SO_4^{2-} and HSO_4^-. Regions of high solubility are highlighted. The stability constants for gold species are from Stefánsson and Seward (2004), and thermodynamic data for other species are from the SUPCRT92 database (Johnson et al. 1992).

Gold precipitation from hydrothermal fluids

1. Boiling
2. Sulfidation
3. Oxidation
4. **Cooling**

$$Au_S + 2Cl^- + H^+ + 1/4\ O_2 \rightleftharpoons AuCl_2^- + 1/2\ H_2O$$



At T > 350°C, $AuCl_2^-$ stability strongly dependent on temperature

A 50°C drop (e.g. 400→350°C) in T can result in 95% precipitation of Au

Au may then be remobilized as $AuHS^-$ and carried up towards the surface (epithermal environment)

Classification of hydrothermal Au deposits

No uniform classification because there are still a lot of unknowns, however we will look at:

1) Epithermal

- Low sulfidation
- High sulfidation

2) Orogenic (or "lode gold")

3) Carlin

4) VMS (we discussed these last week)

5) IOCG (we will discuss this later)

6) Porphyry (we will discuss this later)

Historic Au production

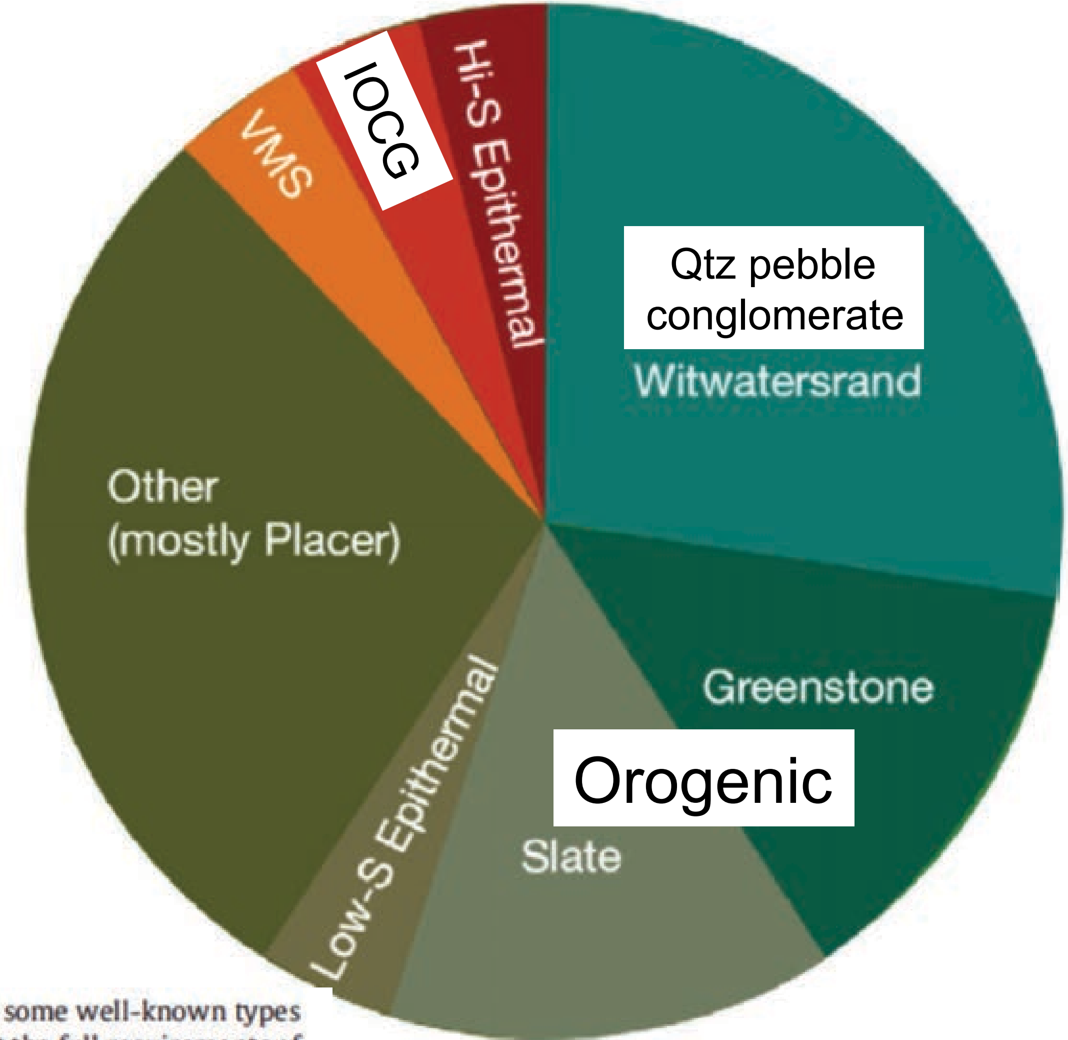
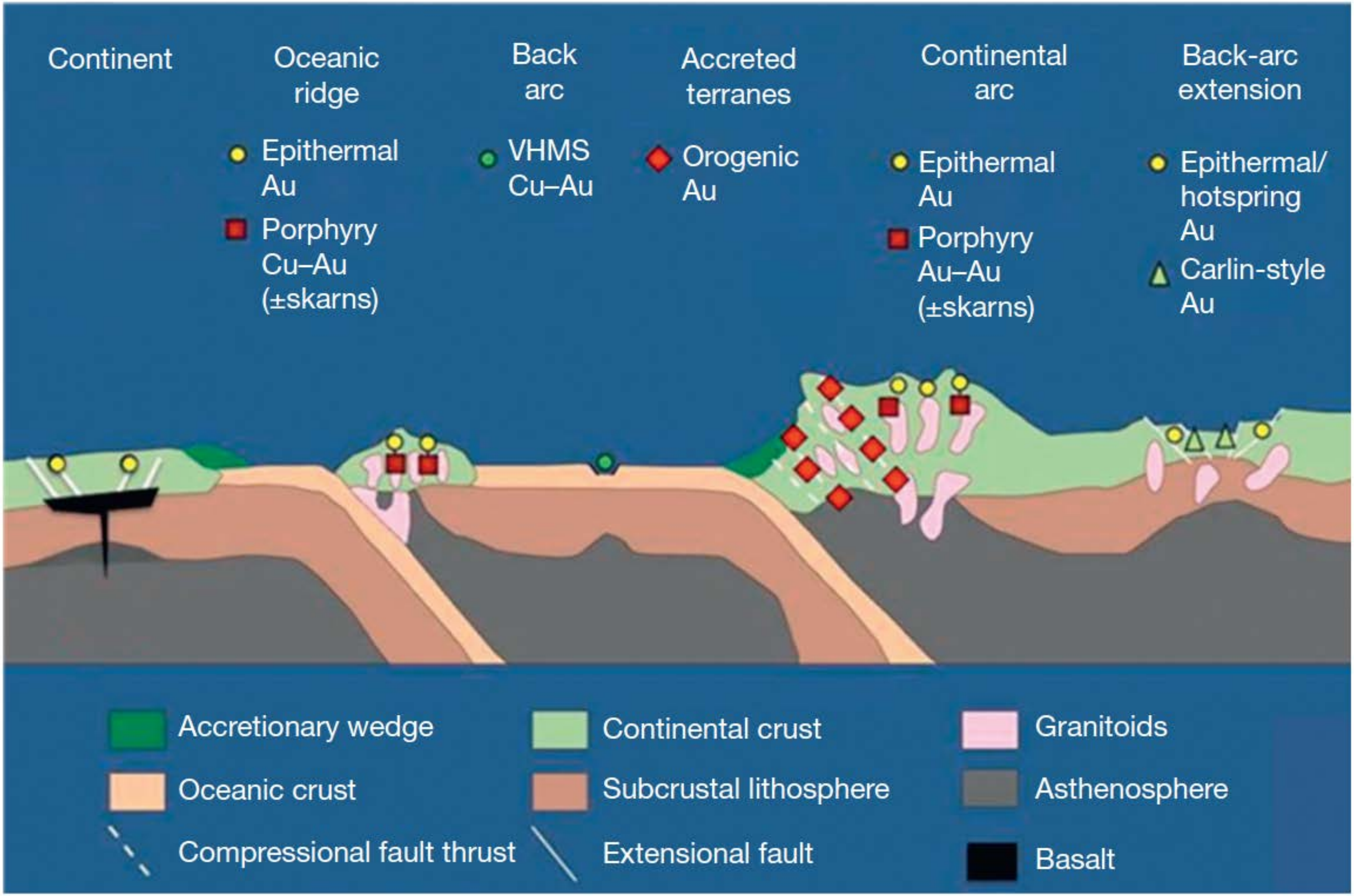


Fig. 2. All-time world gold production with an allocation to some well-known types (although useful and widely used, this scheme does not meet the full requirements of an ideal classification scheme). Eighty percent of production has come from gold-only deposits being those with no economic base metals (shown in the various shades of green); less than a quarter comes from deposits with co-product or by-product base metals (gold-plus deposits, in red and orange colours). This is based upon 175 000 t Au produced to the end of 2013; and has plenty of scope for different interpretations of what should be in each sub-category of gold-only production.

Phillips & Powell (2015)


Continent
Oceanic ridge
Epithermal Au
Porphyry Cu–Au (±skarns)
Back arc
VHMS Cu–Au
Accreted terranes
Orogenic Au
Continental arc
Epithermal Au
Porphyry Au–Au (±skarns)
Back-arc extension
Epithermal/ hotspring Au
Carlin-style Au
Accretionary wedge
Continental crust
Granitoids
Oceanic crust
Subcrustal lithosphere
Asthenosphere
Compressional fault thrust
Extensional fault
Basalt

Another classification scheme of hydrothermal Au deposits

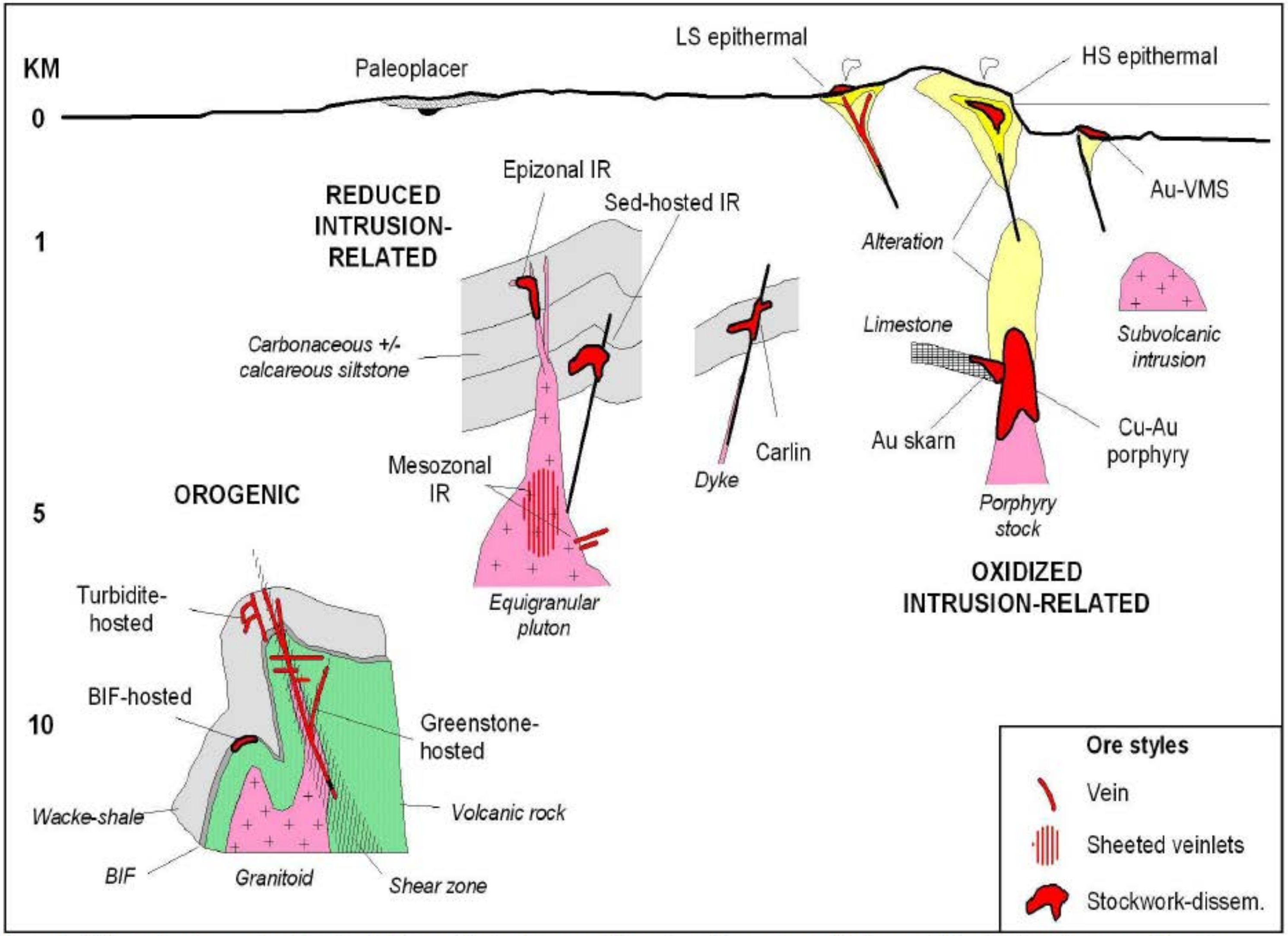


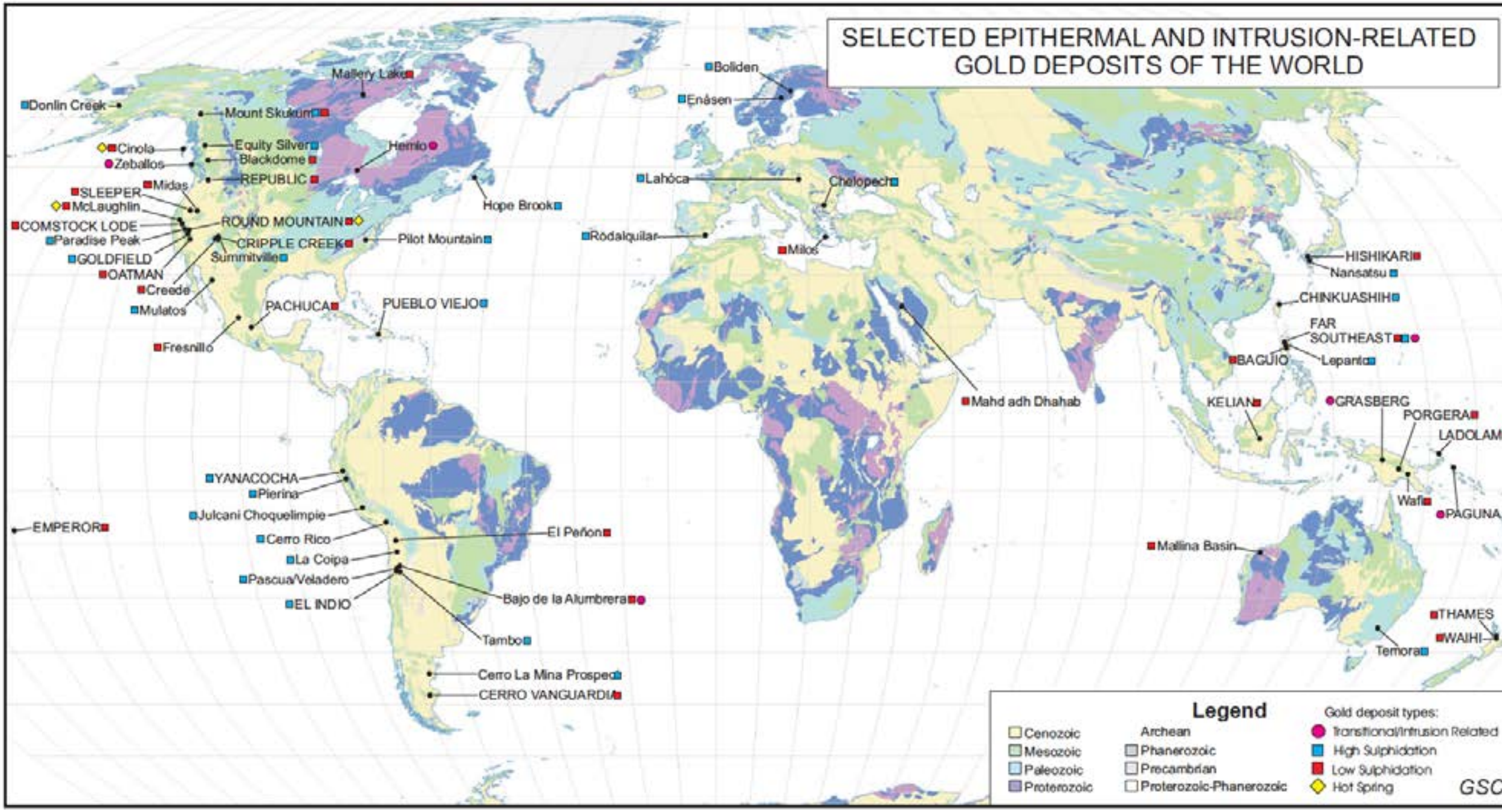
Figure 1: Schematic cross section showing the key geologic elements of the main gold systems and their crustal depths of emplacement. Note the logarithmic depth scale. Modified from Poulsen et al. (2000), and Robert (2004a).

Epithermal Au

Epithermal Au – near surface

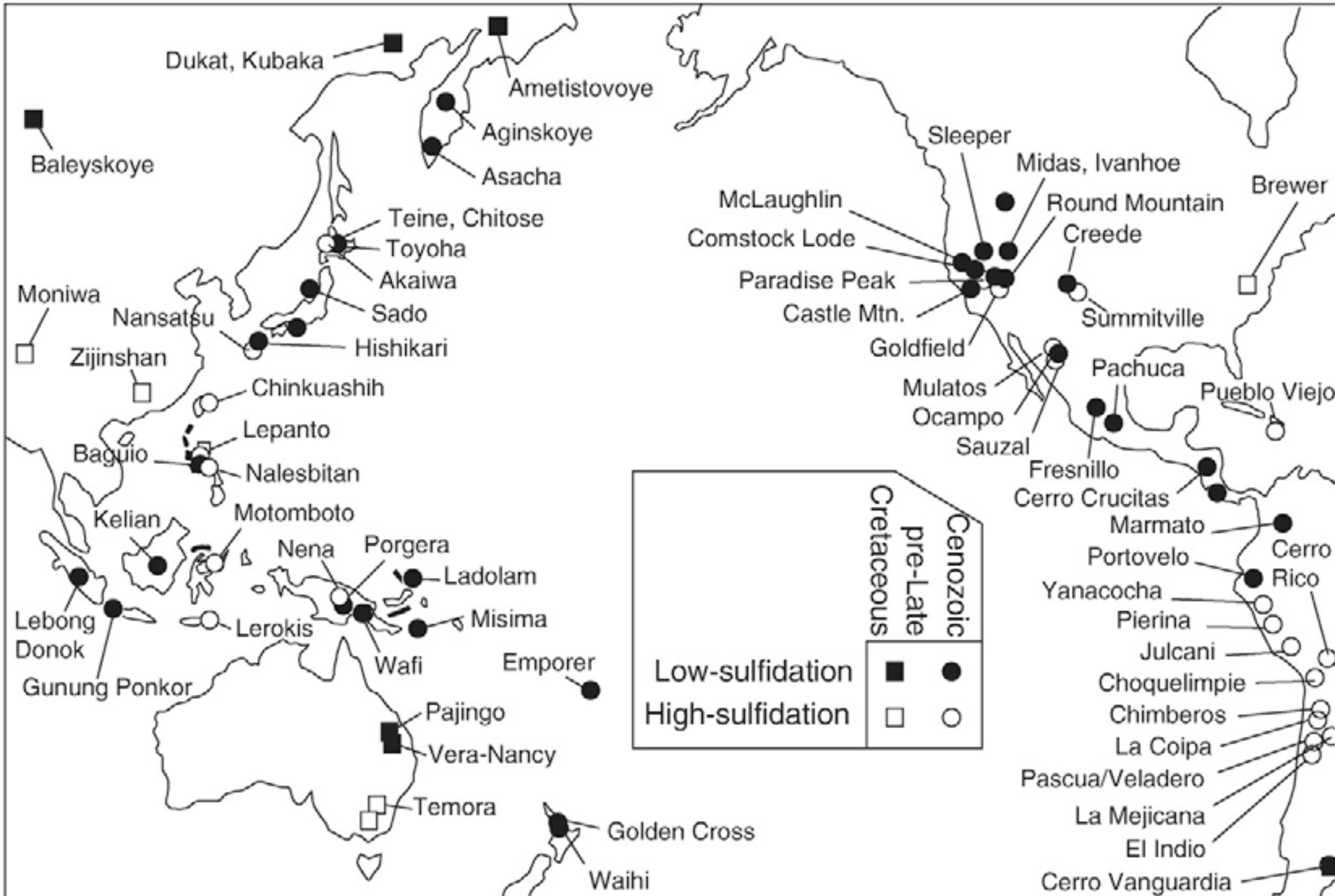
- Generally found in **Tertiary and younger rocks** around the pacific rim (ring of fire)
- Temporally and spatially related with volcanic centres
- Shallow setting of epithermal deposits makes them **<u>highly susceptible to erosion</u>**
- Mined mainly for Au and Ag, but may contain Cu, Pb and Zn
- Generally low *T* (<300°C)

Spatial distribution of epithermal Au deposits



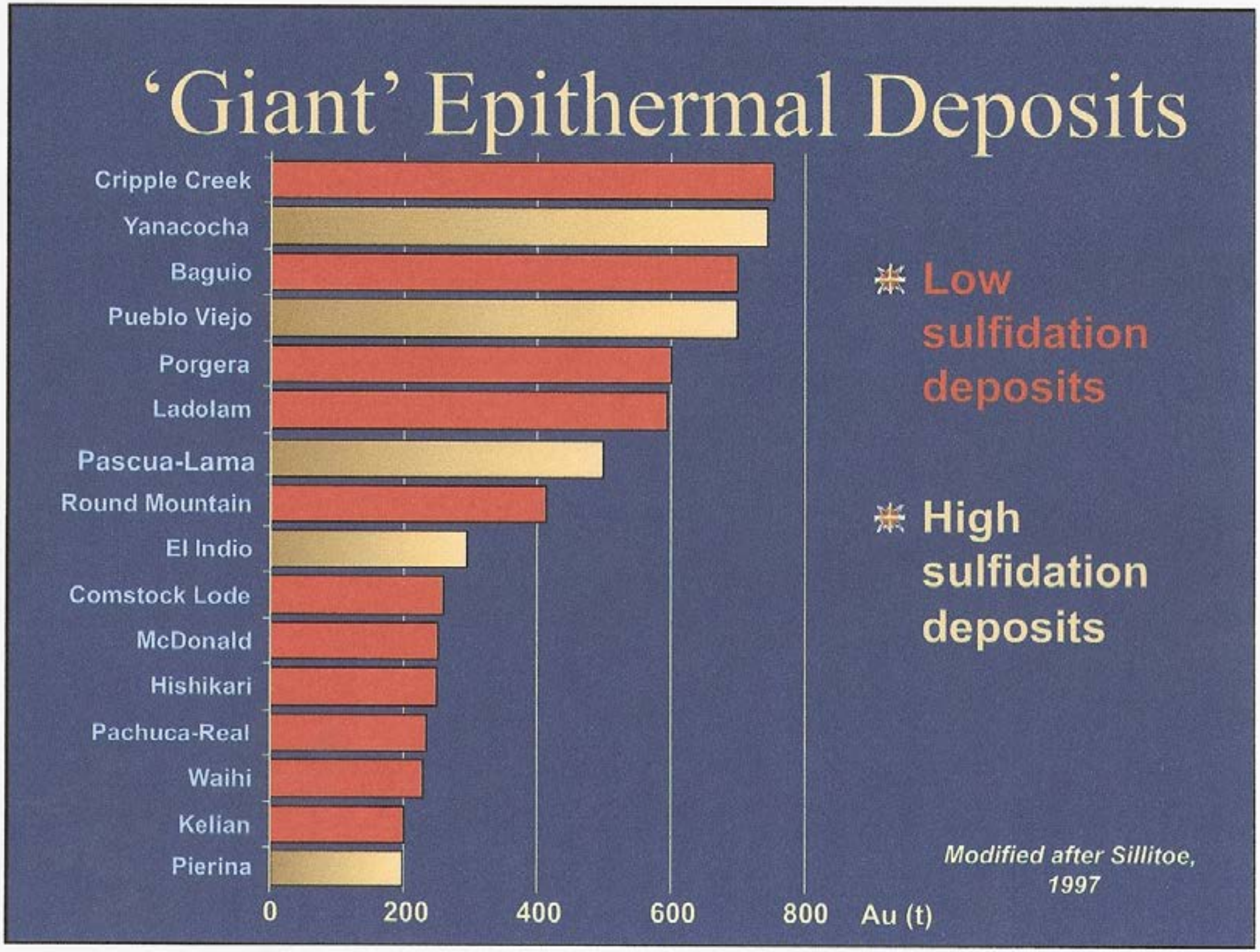
Taylor (2007)

Spatial distribution of epithermal Au deposits

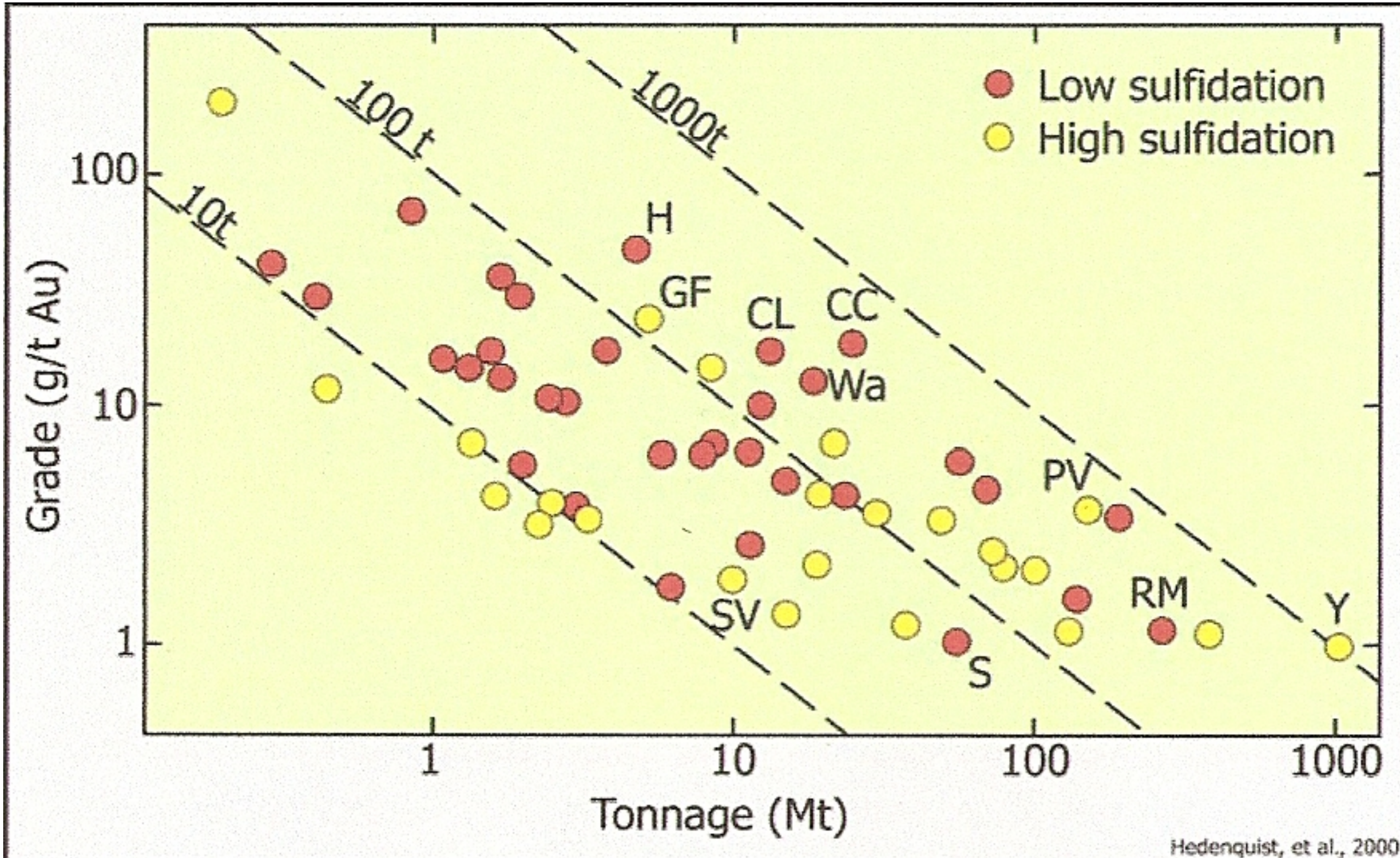


Ridley (2013)

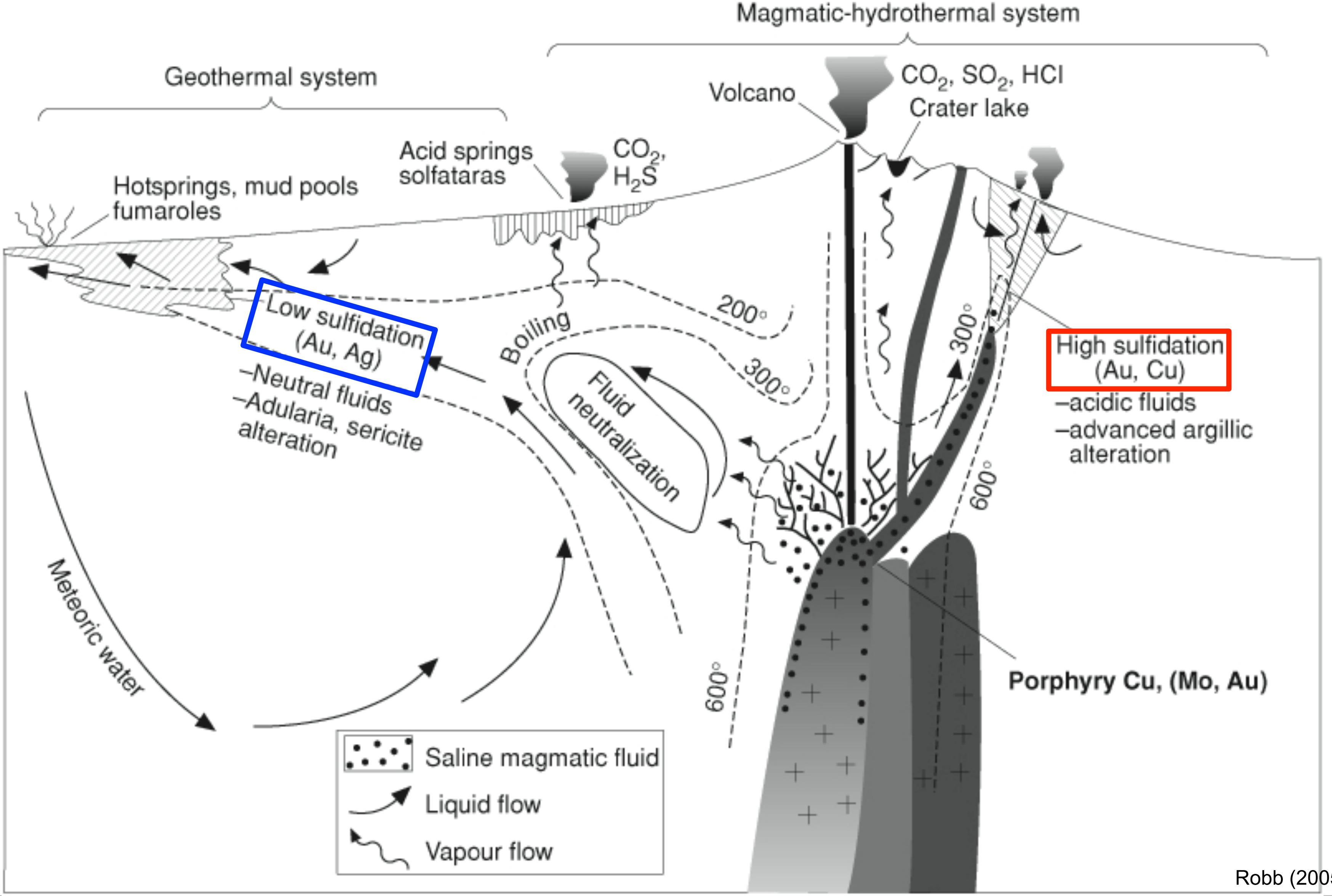
Au tonnage


'Giant' Epithermal Deposits
Cripple Creek
Yanacocha
Baguio
Pueblo Viejo
Porgera
Ladolam
Pascua-Lama
Round Mountain
El Indio
Comstock Lode
McDonald
Hishikari
Pachuca-Real
Waihi
Kelian
Pierina
0
200
400
600
800
Au (t)
Low sulfidation deposits
High sulfidation deposits
Modified after Sillitoe, 1997

Au tonnage


Low sulfidation
High sulfidation
10t
100 t
1000t
H
GF
CL
CC
Wa
PV
SV
S
RM
Y
Grade (g/t Au)
100
10
1
Tonnage (Mt)
1
10
100
1000
Hedenquist, et al., 2000

Low vs high sulfidation epithermal deposits



Robb (2005)

Low v. high sulfidation epithermal deposits

Table 2.2 Characteristics of high- and low-sulfidation epithermal deposits

High-sulfidation	Low-sulfidation
Oxidized sulfur species (SO_2, SO_4^{2-}, HSO_4^-) in ore fluid/vapor S^{4+} or S^{6+} (oxidized)	Reduced sulfur species (HS^-, H_2S) in ore fluid/vapor S^{2+} (reduced)
Also referred to as	
Gold–alunite, acid–sulfate, alunite–kaolinite	Adularia–sericite, hotspring-related
Fluids	
Acidic pH, probably saline initially, dominantly magmatic	Near-neutral pH, low salinity, gas-rich (CO_2, H_2S), dominantly meteoric
Alteration assemblage	
Advanced argillic (zonation: quartz–alunite–kaolinite–illite–montmorillonite–chlorite)	Adularia–sericite (zonation: quartz/chalcedony–calcite–adularia–sericite–chlorite)
Metal associations	
Au–Cu (lesser Ag, Bi, Te)	Au–Ag (lesser As, Sb, Se, Hg)

Robb (2005)

Table II

Field characteristics for distinguishing epithermal types.

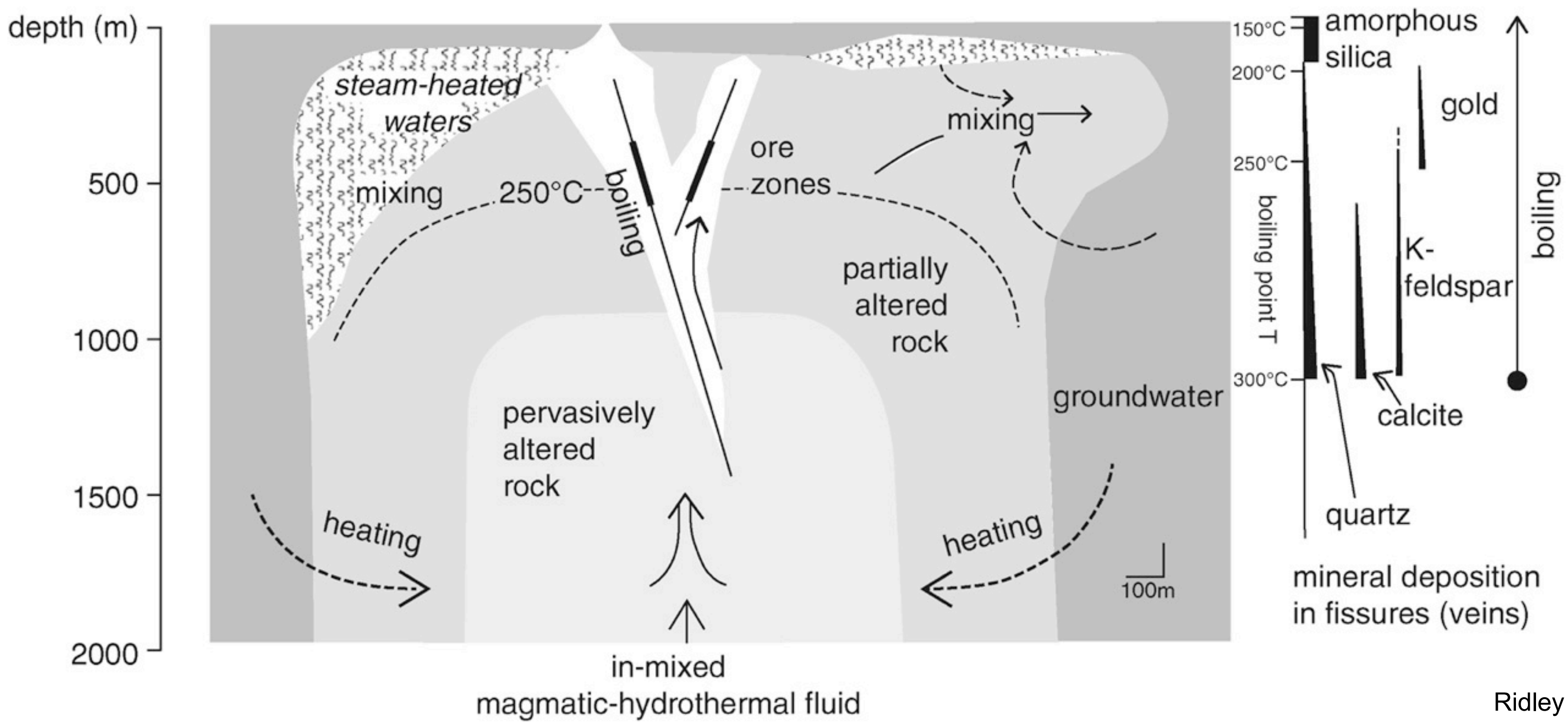
	High sulphidation (HS)	Low sulphidation (LS)
Genetically related volcanic rocks	Mainly andesite-rhyodacite	Andesite-rhyodacite-rhyolite
Alteration zone	Areally extensive (commonly several km^2) and visually prominent	Commonly restricted and visually subtle
Key proximal alteration mineral(s)	Crystalline alunite; pyrophyllite at deeper levels	Sericite or illite ± adularia; roscoelite (V-mica) in deposits associated with alkalic rocks; chlorite in few cases
Quartz gangue	Fine-grained, massive, mainly replacement origin; residual, slaggy ("vuggy") quartz commonly hosts ore	Chalcedony and (or) quartz displaying crustiform, colloform, bladed, cockade and carbonate-replacement textures; open-space filling
Carbonate gangue	Absent	Ubiquitous, commonly manganoan
Other gangue	Barite widespread with ore; native sulphur commonly fills open spaces	Barite and (or) fluorite present locally; barite commonly above ore
Sulphide abundance	10-90 vol.%, mainly fine-grained, partly laminated pyrite	1-20 vol.%, but typically <5 vol.%, predominantly pyrite
Key sulphide species	Cu sulphosalts (enargite, luzonite) and Cu + Cu-Fe sulphides (chalcocite, covellite, bornite) common; generally later than pyrite	Sphalerite, galena and tetrahedrite common. Cu present mainly as chalcopyrite
Metals present	Cu, Au, As (Ag, Pb)	Au and (or) Ag (Zn, Pb, Cu)
Metals present locally	Bi, Sb, Mo, Sn, Zn, Te (Hg)	Mo, Sb, As (Te, Se, Hg)

From R. Morton

Low sulfidation

- Hosted in volcanic units away from the volcanic center
- Strong structural control (e.g. Au in veins)
- Gold transported as a bisulfide complex (low T, neutral pH)
- Au precipitation due to boiling and/or mixing with meteoric H_2O

$$Au_S + 2HS^- + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)_2^- + 1/2\ H_2O$$



Ridley (2013)

Low sulfidation Au precipitation reaction:

Most (>85%) Au transported as $AuHS^-$

$$Au(HS)_2^-{}_{(aq)} + H_2O \leftarrow\rightarrow \underline{Au}^0 + \mathbf{H_2S}_{(aq)} + HSO_4^-{}_{(aq)} + \mathbf{H^+}_{(aq)}$$

- Boil to remove H_2S from the system as a gas
- Increase pH by mixing acidic fluid with meteoric water
- Cooling drives reaction to the right

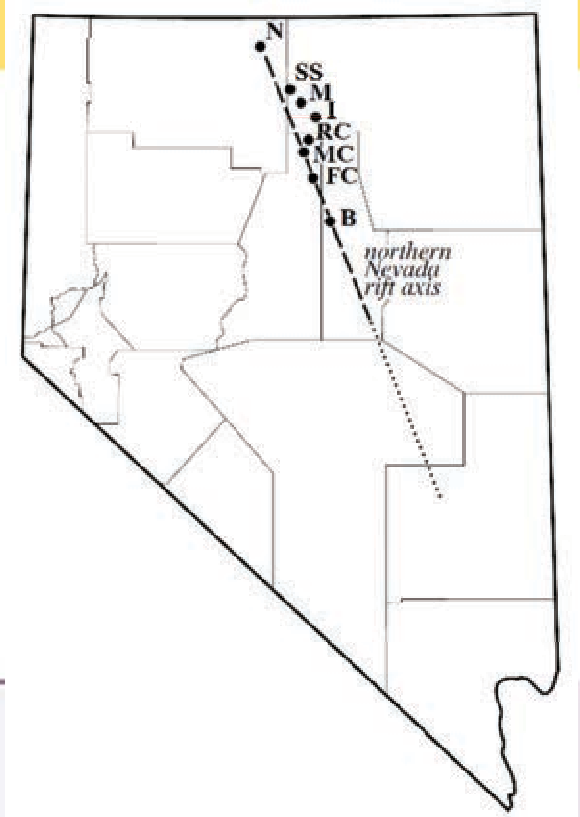
In general, **boiling** is the most important precipitation mechanism in low sulfidation Au deposits

Low sulfidation example – Midas deposit, Nevada

- World-class low sulfidation epithermal vein Au deposit
- ~125 t Au
- Early 1900s: limited exploration
- Early 1990s: large veins discovered
- Underground mine
- ~93% recovery

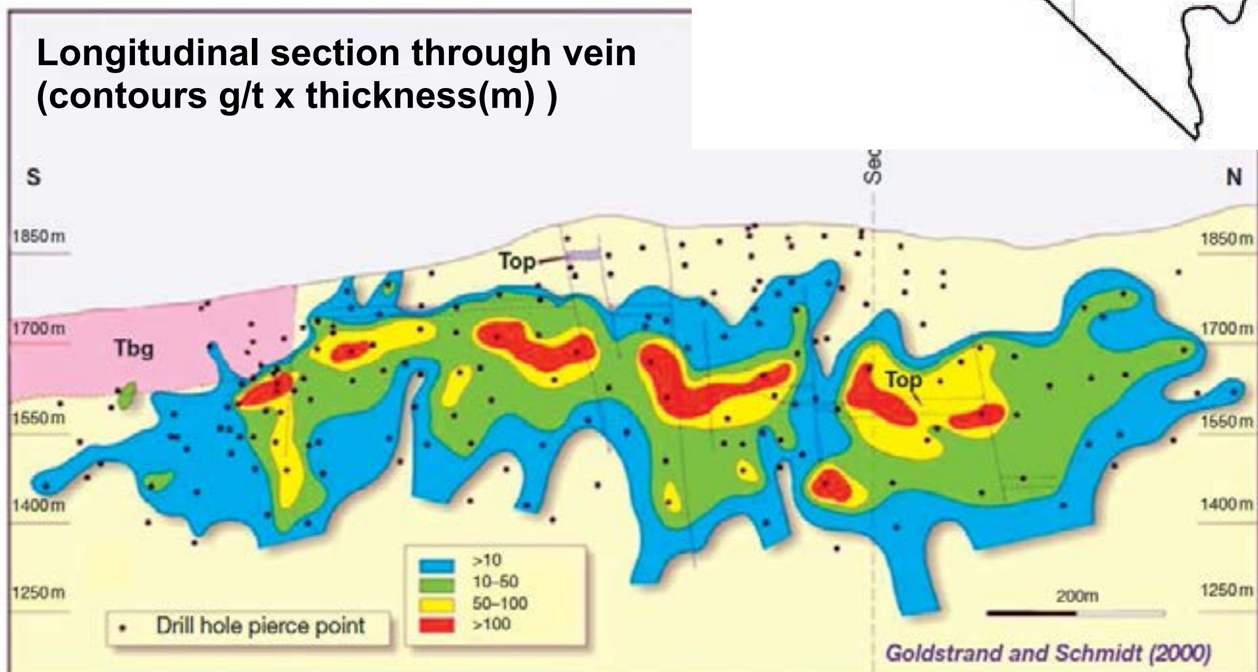
Klondex Mines

Wallace & John (1998) USGS



Midas – geology

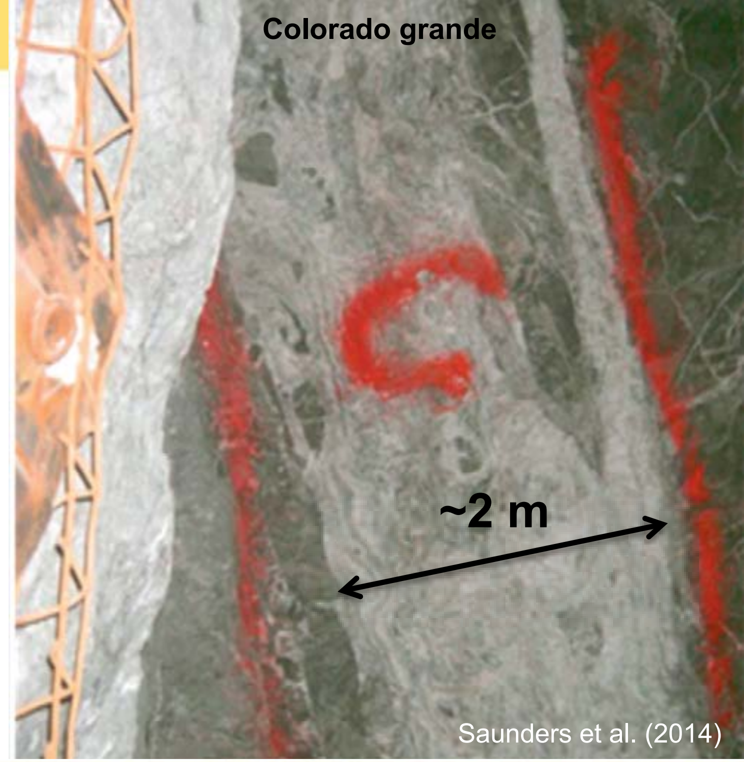
- Located along a large rift system in Nevada
- Bimodal volcanic rocks (~16 Ma) rocks
- Felsic intrusions (15.4 Ma) at depth provided heat for hydrothermal system
- Faulting created dilational zones and pathways for hydrothermal fluids
- Hydrothermal system ceased by 15.2 Ma
- ~200 ka of mineralizing activity

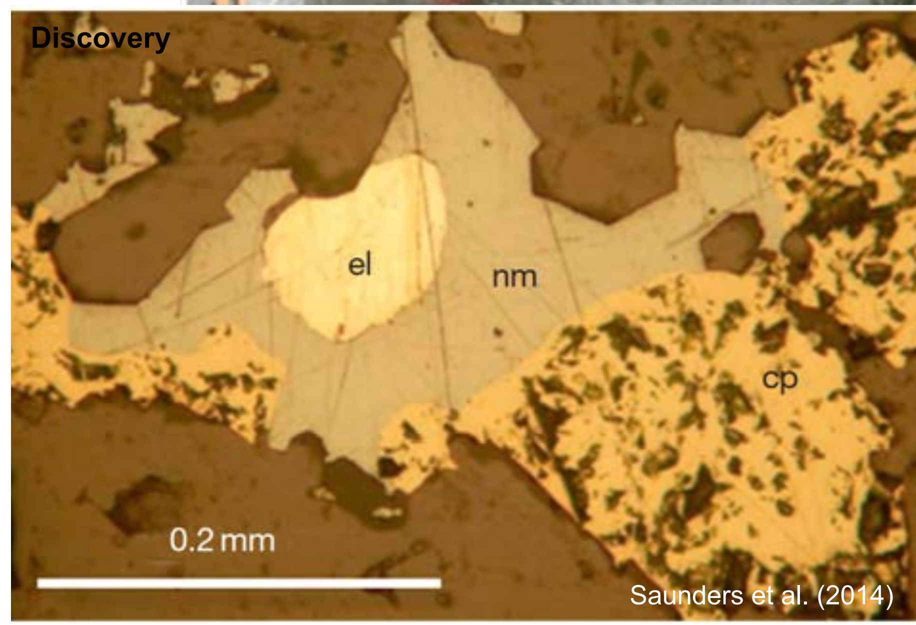


Midas – Ore

- Au hosted in quartz veins
- Major veins: “Colorado Grande” and “Discovery”
- Colorado Grande most important (~1.5 km long and 1–2 m wide)
- Au derived from either nearby rhyolites or mafic rocks at depth (?)
- Au–Ag bearing minerals:
  - Naumannite (Ag_2Se)
  - Chalcopyrite
  - **Electrum** (AuAg)**

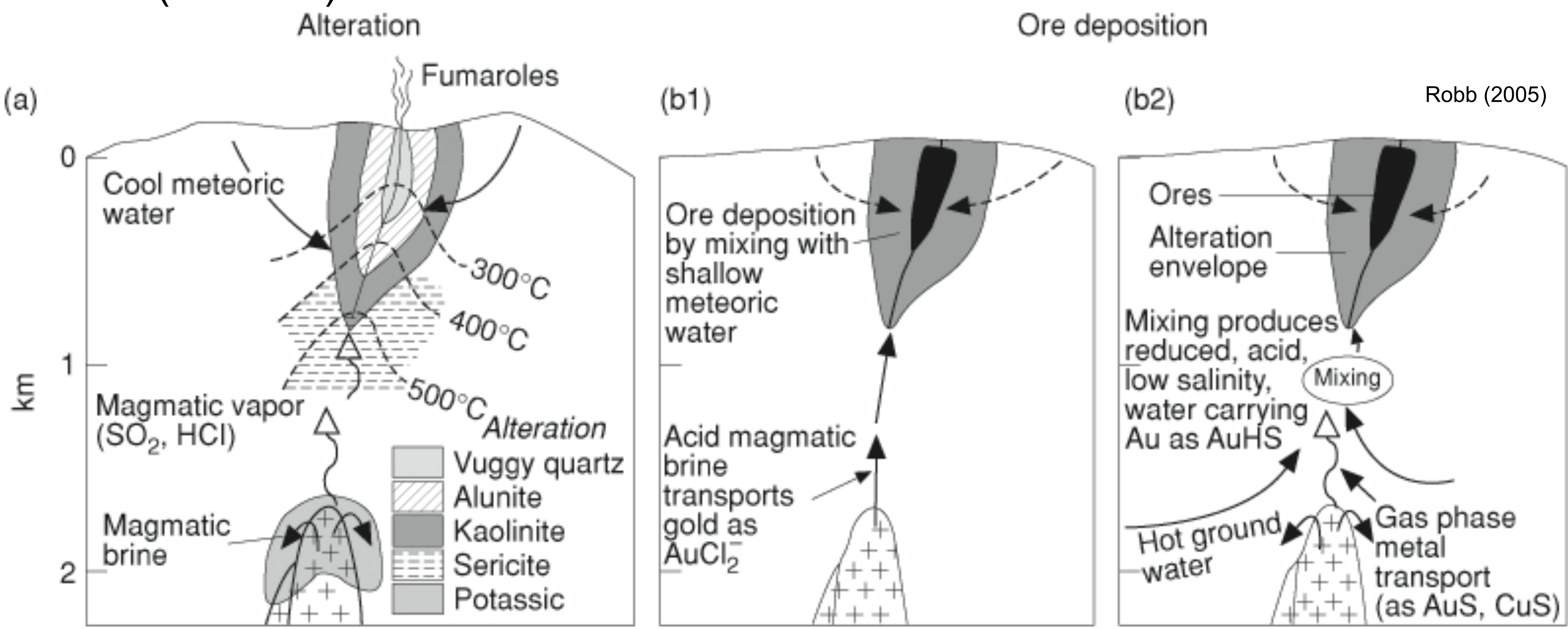
    **generally >20% Ag
  - Fischesserite (Ag_3AuSe_2)





High sulfidation

- Found close to volcanic vents and linked to porphyry deposits at depth
- Boiling produces very acidic fluids that hydrothermally alter the host rock (e.g. **vuggy** textures and argillic alteration)
- Au transported as bisulphide or chloride complexes (low T, pH ~1)
- Au precipitation due to boiling/fluid mixing (bisulphide) or fluid mixing (chloride)



Robb (2005)

High sulfidation Au precipitation reaction:

Most (>85%) Au transported as $AuHS_2^-$

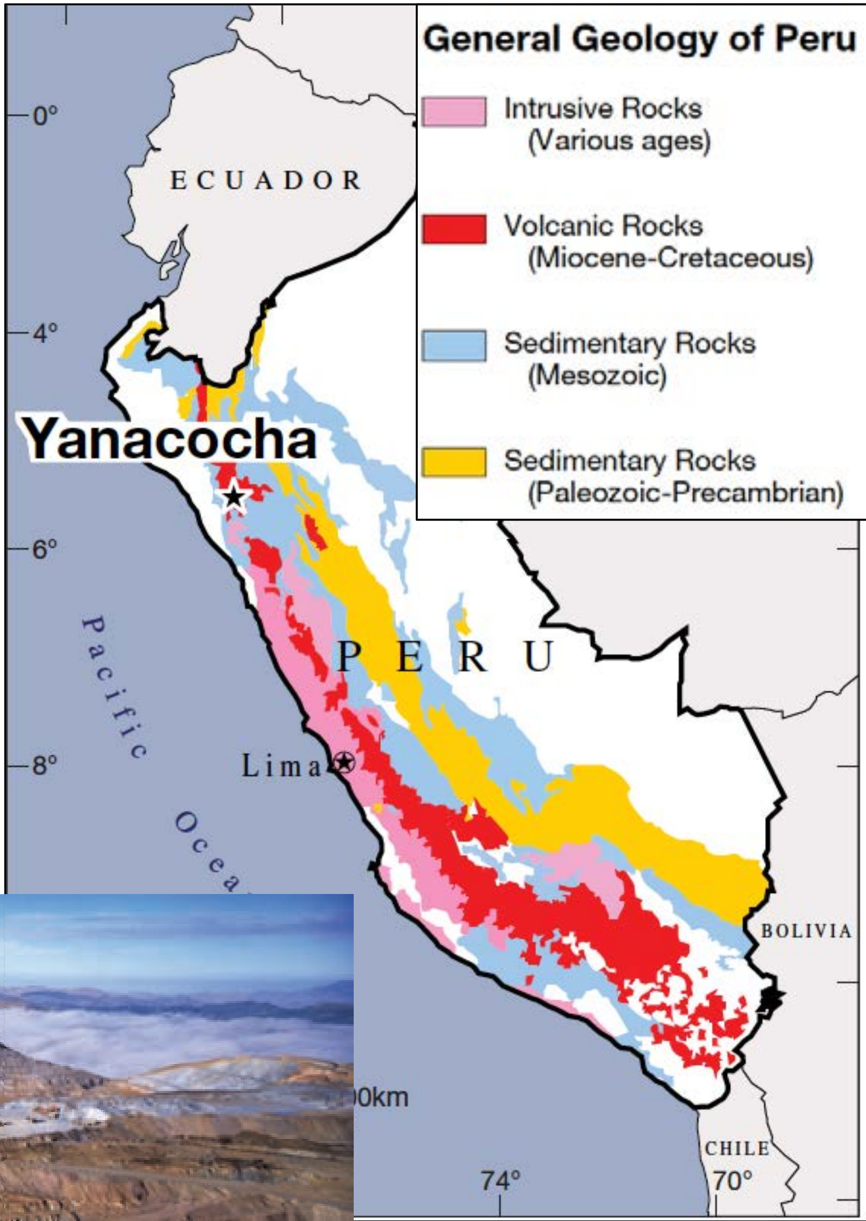
$Au(HS)_2^-{}_{(aq)} + H_2O \leftrightarrow \underline{Au^0} + \mathbf{H_2S}_{(aq)} + HSO_4^-{}_{(aq)} + \mathbf{H^+}_{(aq)}$

- Increase pH by mixing acidic fluid with <u>meteoric water</u>
- <u>Boil</u> to remove H_2S from the system as a gas
- <u>Cooling</u> drives reaction to the right

In general, **<u>mixing</u>** is the most important precipitation mechanism in high sulfidation Au deposits (this is in contrast to *boiling* for low sulfidation deposits).

High sulfidation example Yanacocha, Peru

- Discovered in 1984
- 27.1 Moz Au (1993–2008)
- 1.84–0.65 g/t Au
- Operating costs: $97–358/oz
- Au recovery >70%
- Largest south American gold producer
- 6,800 employees
- 4,100 m above sea level

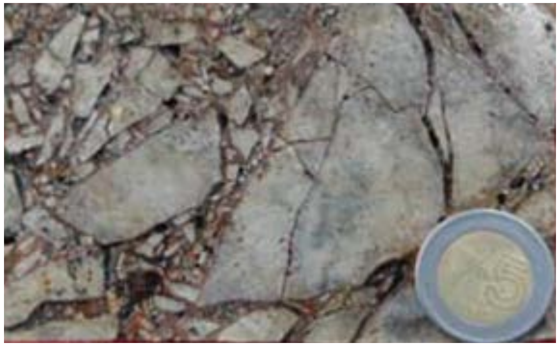


Teal and Benavides (2010)

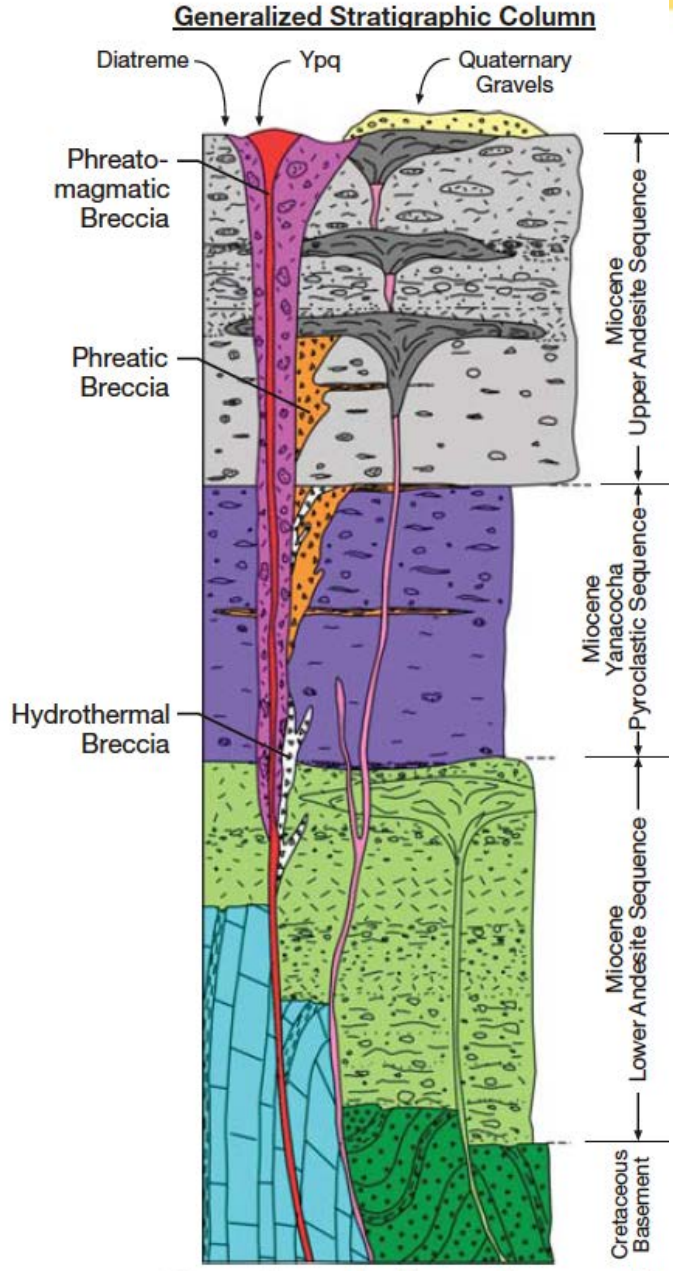
Newmont

Yanacocha – Geology

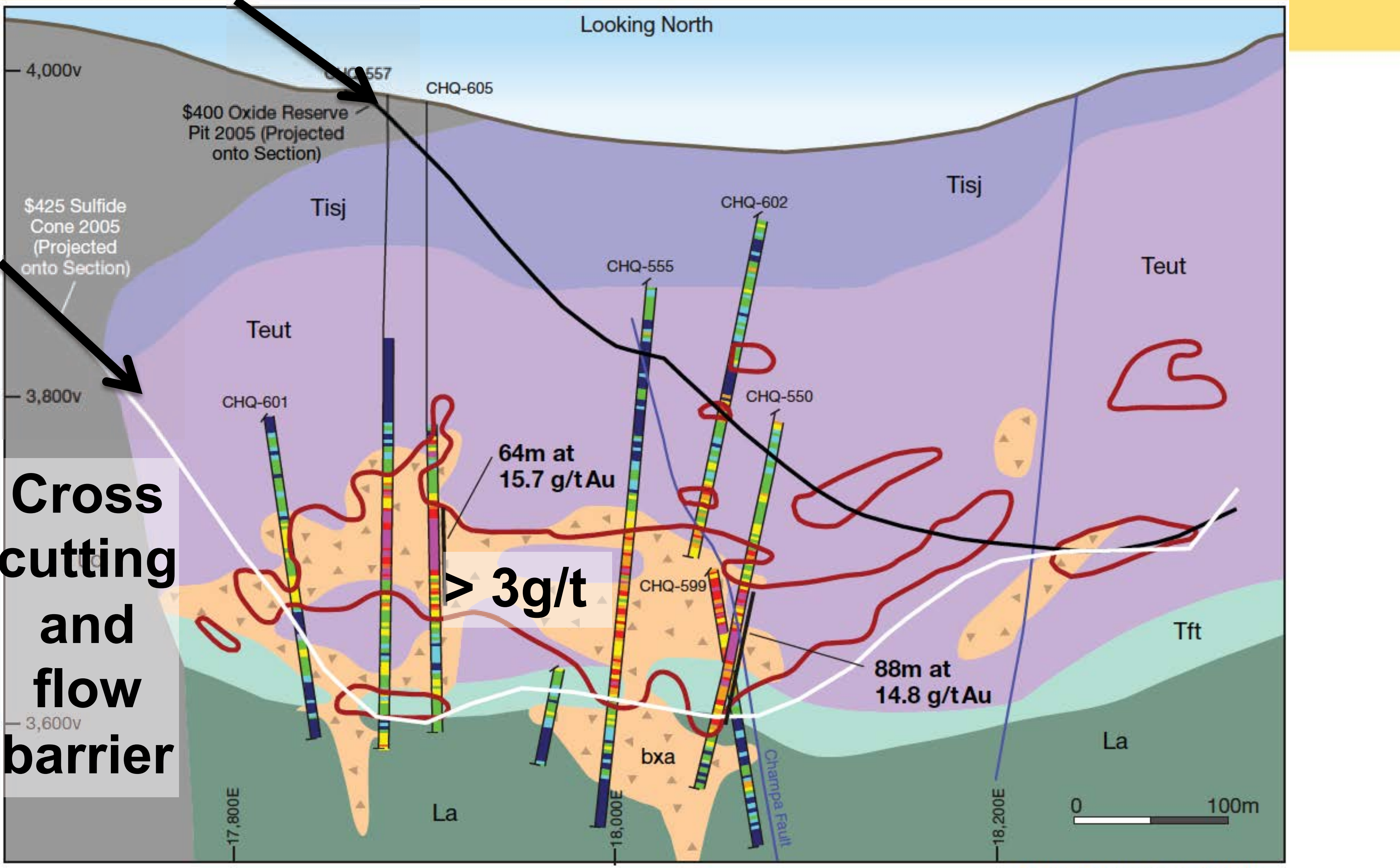
- Erosional remnant of an extensive volcanic field
- Hosted by Miocene–Pliocene volcanic rocks (andesite–rhyolite)
- **Brecciated**



- Late andesite–dacite dykes (10–8 Ma) **Associated with Au–Cu porphyry-style mineralization at depth**
- Advanced argillic alteration



Teal and Benavides (2010)



Teal and Benavides (2010)

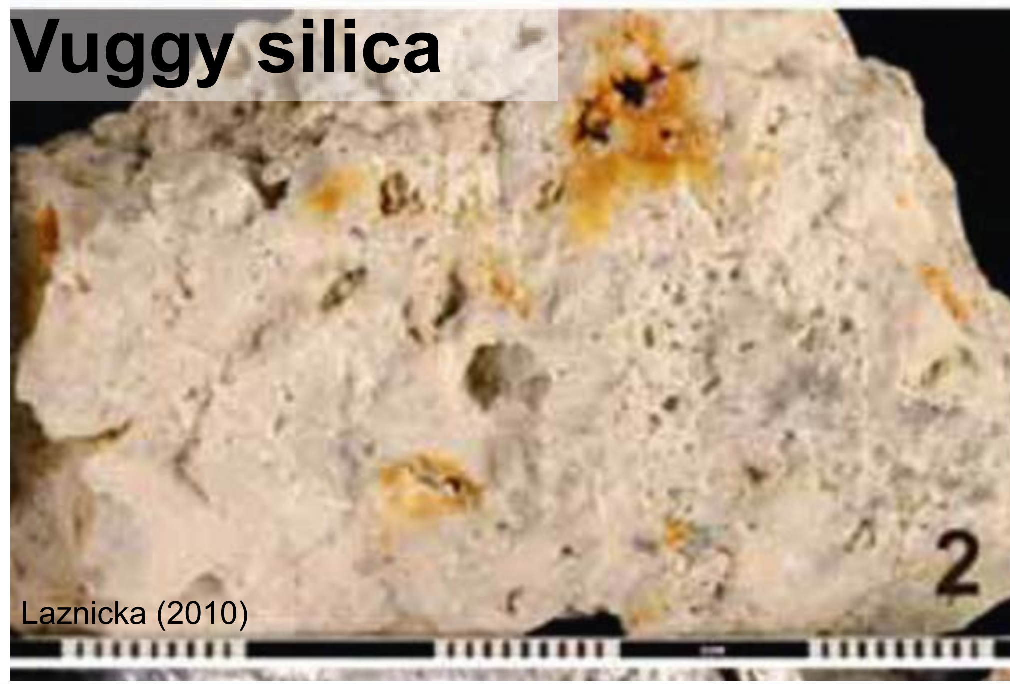
Yanacocha ore

Oxidized ore:
- Fe-hydroxides
- Au occurs as finely dispersed ‘invisible’ particles in limonite

Formed by intense hydrothermal alteration and acidic leaching

Supergene processes were also important

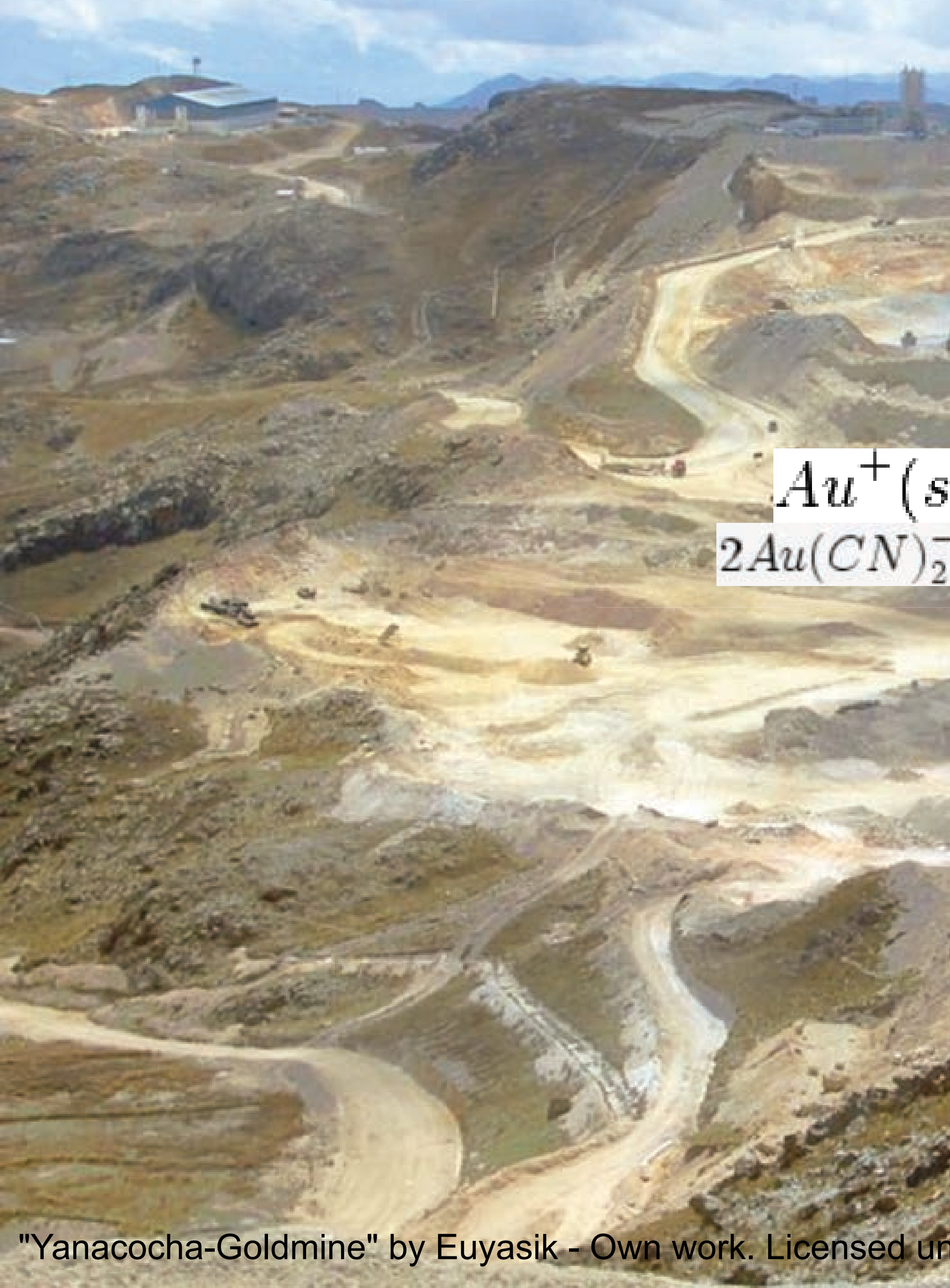
Strong correlation between silicic alteration (quartz) and Au mineralization



Laznicka (2010)

Yanacocha Mine

Heap leaching – cyanide



$$Au^{+}(s) + 2CN^{-}(aq) \rightarrow Au(CN)_2^{-}(aq$$

$$2Au(CN)_2^{-}(aq) + Zn(s) \rightarrow Zn(CN)_4^{-}(aq) + 2Au(s$$

PBS

"Yanacocha-Goldmine" by Euyasik - Own work. Licensed under GFDL via Wikimedia Commons

Epithermal Au Summary

- Two types:
  1) **High sulfidation** (acidic, oxidized, near volcanic centre, vuggy Qtz!)
  2) **Low sulfidation** (neutral, reduced, away from volcanic centre)
- Near-surface mineralization
- Tertiary and younger rocks (**why?**)
- Associated with volcanic or intrusive rocks
- Au and Ag are main commodities
- Veins, breccias, open-space filling

Fluid: magmatic or meteoric (HS^- or Cl^- ligands)

Source of metals: magmas, underlying volcanic rocks

Transport: fault systems, permeable rocks/sediments

Trap: boiling, fluid mixing, oxidation

Orogenic Au

Orogenic Au deposits

- Accounts for 1/3 of Au mined worldwide
- Host is deformed metamorphic rocks
- Au forms 200–20 m.y. after deposition
- Ag is very rare!
- Archean to 50 Ma old (reflects time required to erode crust)

Setting: syn-tectonic, brittle–ductile transition zone (low grade metamorphic rocks)

Mineralization: Au in quartz–carbonate veins

Alteration: carbonate–sericite–pyrite (variable)

Many workers refer to these as "<u>Lode gold deposits</u>", although strictly speaking, other deposit types can have 'lode' ore

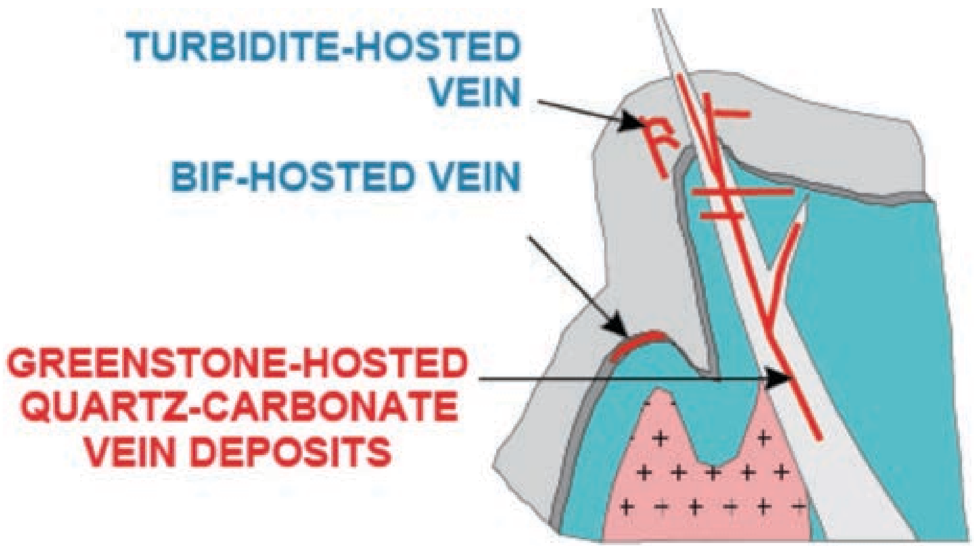
Orogenic Au deposits – general concept

Gold is redistributed during orogenic-related regional metamorphism from amphibolite grade rocks to cooler greenschist facies rocks where it is preferentially deposited near large scale faults (often shear zones), either in quartz veins in greenstones or as tabular replacement bodies in banded iron formations

.

Orogenic Au: 3 types

1) Greenstone hosted
2) Slate hosted
3) BIF hosted



Greenstone belts

Greenstones are belts of dominantly mafic volcanic rocks found in Archean and Proterozoic cratons Worldwide

(what minerals are green and found in metamorphosed mafic rocks?)

Most Greenstone Belts contain one or more major faults that are the focus of gold mineralization – for example the Porcupine–Destor and Larder Lake–Cadillac Faults in the Archean Superior Province of Ontario and Quebec

Gold Mineralization is often accompanied by pyritization and carbonatitization of host greenstones

(1) Greenstone gold

<u>Archean</u> in age

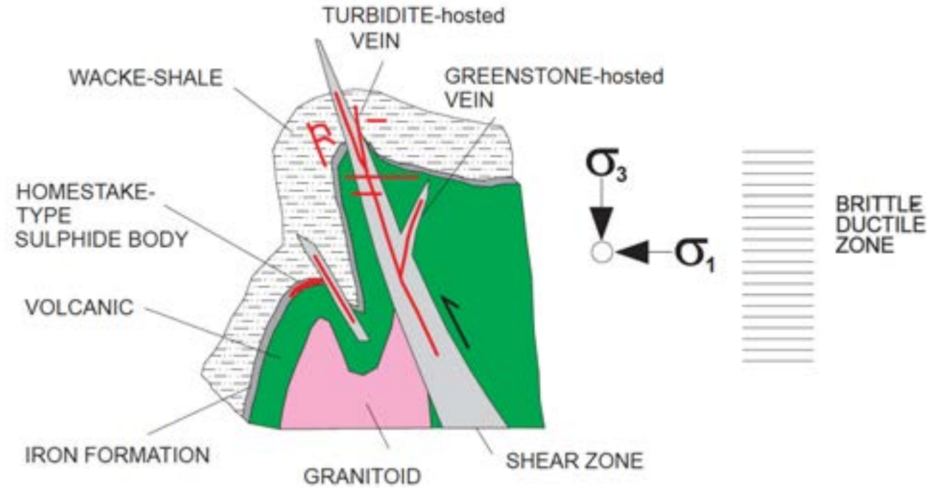
Au in **<u>Qtz–Carbonate veins</u>**:
- Steeply dipping
- Emplaced during compression

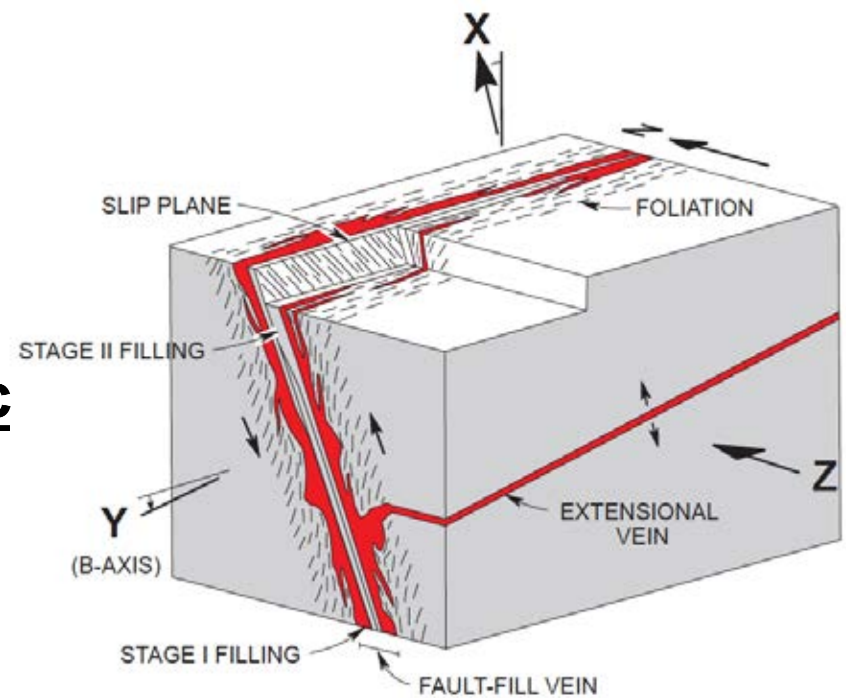
Fluids are **<u>metamorphic</u>** in origin and reducing [$Au(HS)_2^-$]

Fluids focused along **<u>shear zones</u>**

Mineralization is **<u>syn-metamorphic</u>** resulting from interaction with Fe-rich host rocks (mafic/ultramafic)

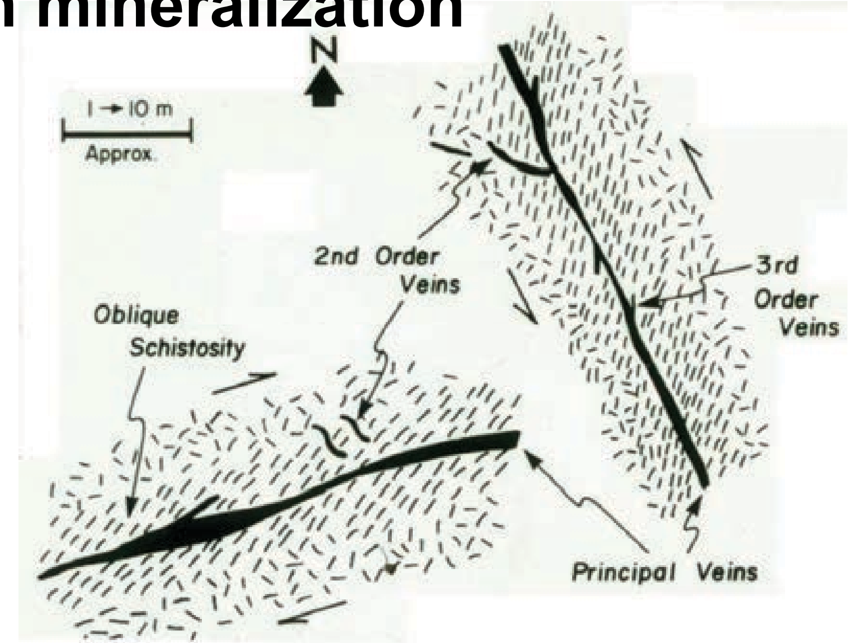
*Sidenote: the Archean was a major gold <u>metallogenic epoch</u>

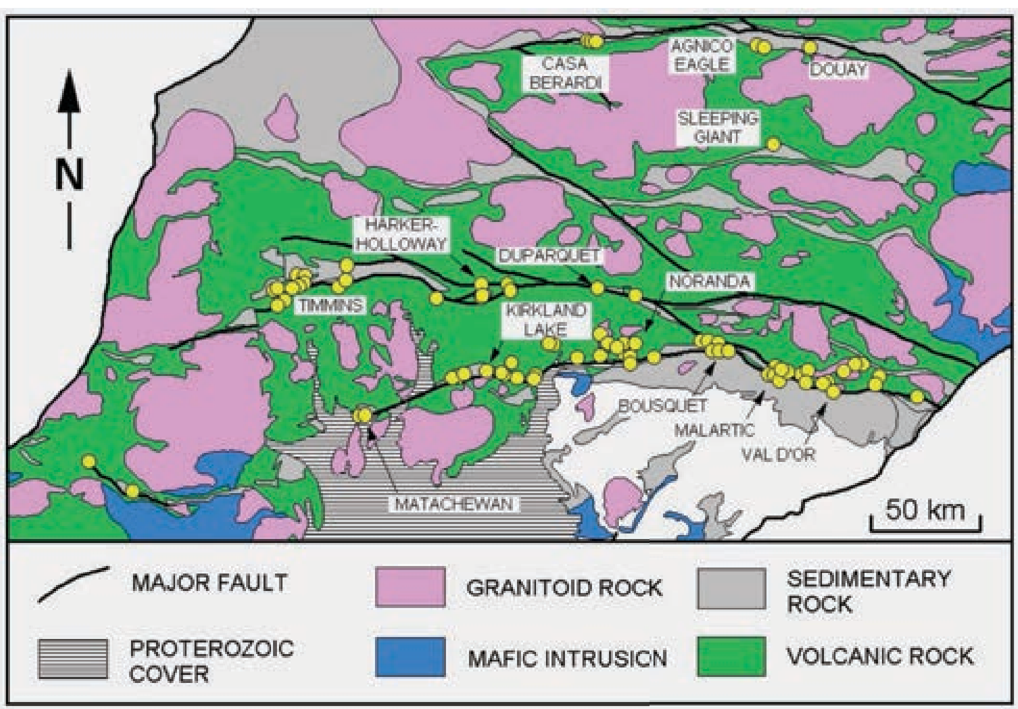




Strong structural control on mineralization

Mineralization is commonly associated with 2nd and 3rd order structures





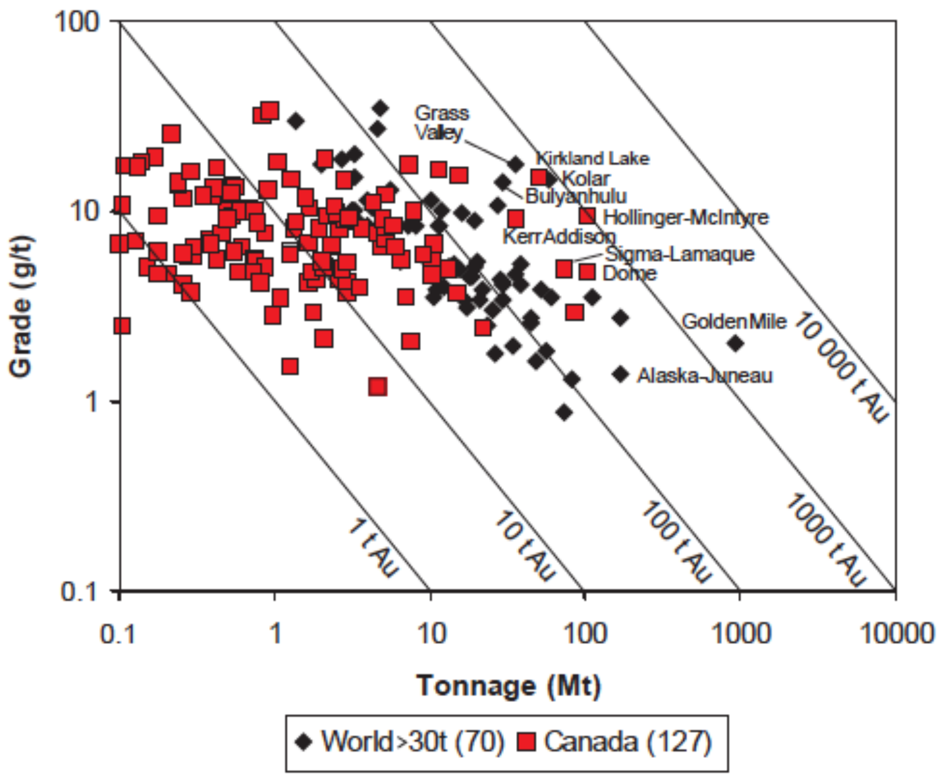


FIGURE 5. Tonnage versus grade relationship of Canadian and world Au deposits containing at least 30 tonnes of Au in combined production and reserves.

Dubé & Gosselin (2007)

TABLE 1. Most productive Canadian districts for greenstone-hosted quartz-carbonate vein deposits.

District	Geological Province	Production & Reserves (tonnes Au)*	Resources (tonnes Au)*
Timmins	Superior/Abitibi	2,072.9	78.5
Kirkland Lake	Superior/Abitibi	794.8	72.6
Val d'Or	Superior/Abitibi	638.9	171.6
Rouyn-Noranda	Superior/Abitibi	519.6	66.5
Larder Lake	Superior/Abitibi	378.7	14.5
Malartic	Superior/Abitibi	278.7	23.2
Red Lake**	Superior/Uchi	128.0	17.2
Joutel	Superior/Abitibi	61.4	27.5
Matheson	Superior/Abitibi	60.4	9.7
Cadillac	Superior/Abitibi	22.1	25.1
Pickle Lake	Superior/Uchi	90.4	8.1
Rice Lake	Superior/Uchi	51.6	25.2
Beardmore-Geraldton	Superior/Wabigoon	123.5	35.1
Michipicoten	Superior/Wawa	41.1	2.8
Mishibishu	Superior/Wawa	26.7	16.8
Goudreau-Lolshcach	Superior/Wawa	8.8	19.6
Flin Flon	Churchill	62.2	12.7
Lynn Lake	Churchill	19.5	14.6
La Ronge	Churchill	3.4	5.6
Keewatin	Churchill-Hearne	7.2	252.4
Yellowknife	Slave	432.8	16.6
MacKenzie	Slave	38.1	286.6
Cassiar	Cordillera	14.9	55.4
Baie Verte	Appalachian/Dunnage	10.3	8.9

*as of December 31, 2002
**does not include the Campbell-Red Lake, Cochenour, and MacKenzie Red Lake deposits as they are not considered typical greenstone-hosted quartz-carbonate deposits

Dubé & Gosselin (2007)

Abitibi greenstone belt

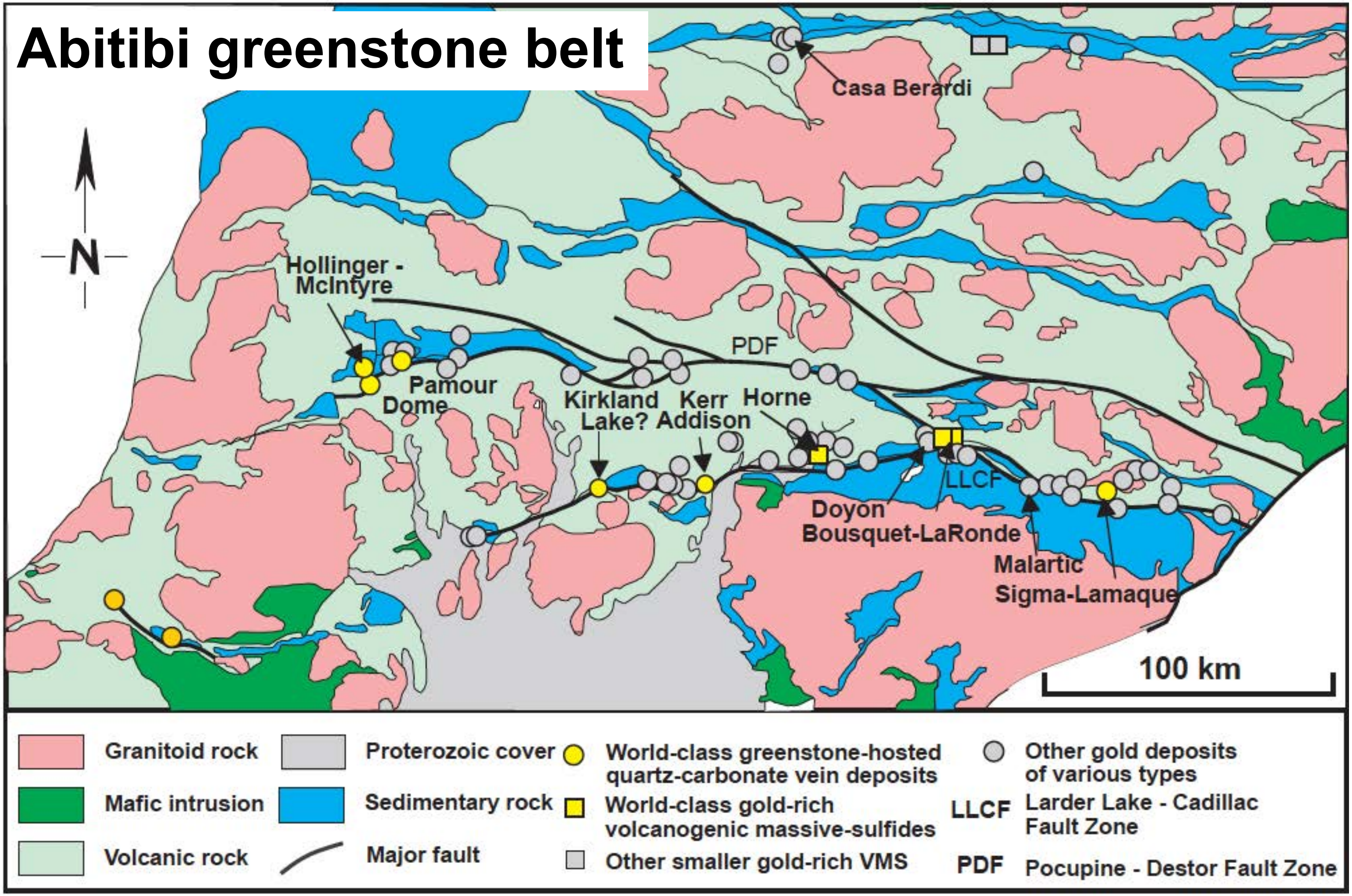
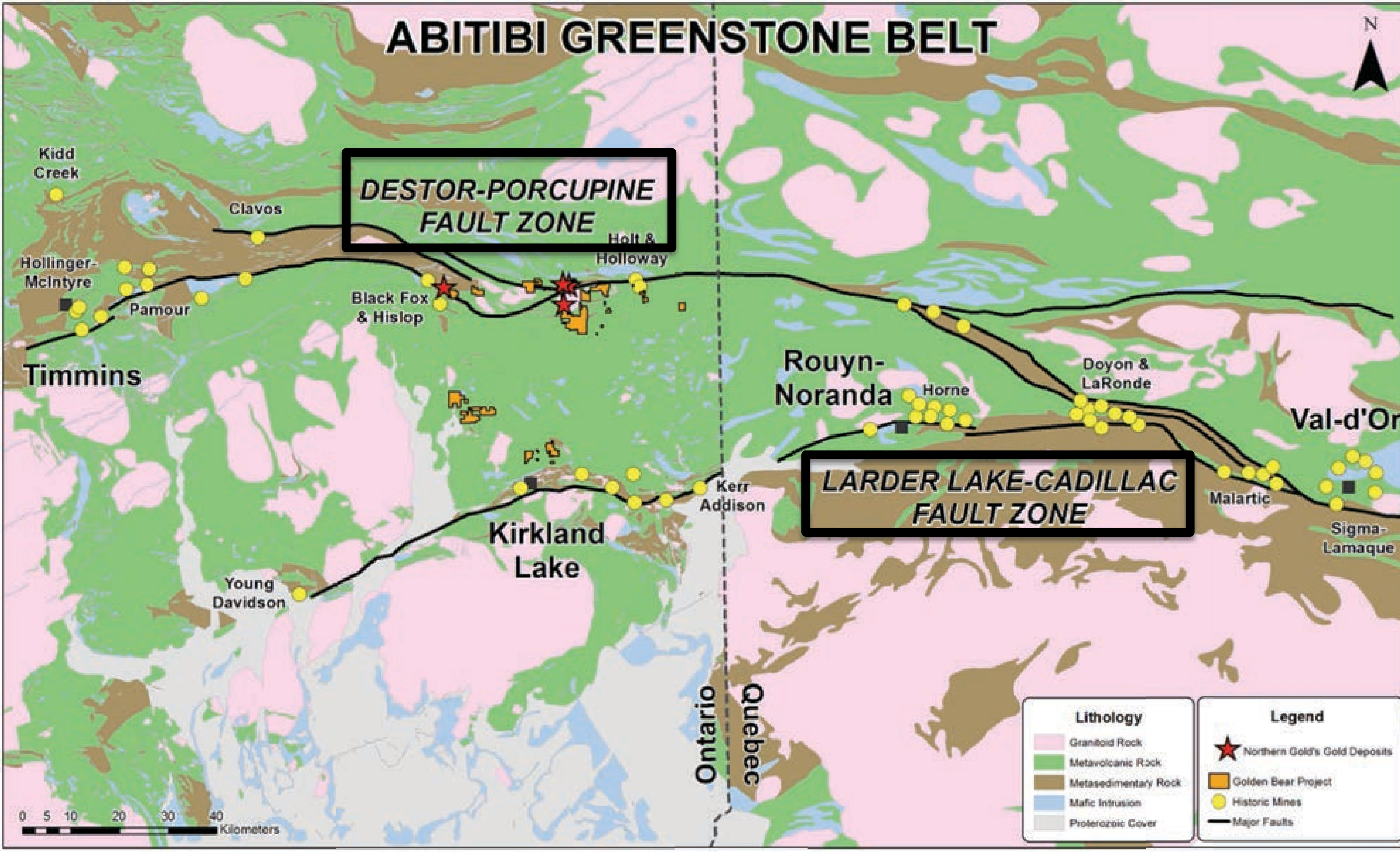


FIGURE 3. Simplified geological map of the Abitibi greenstone belt showing the distribution of major fault zones and gold deposits. Modified from Poulsen et al. (2000). See Appendix 1 for deposit details.

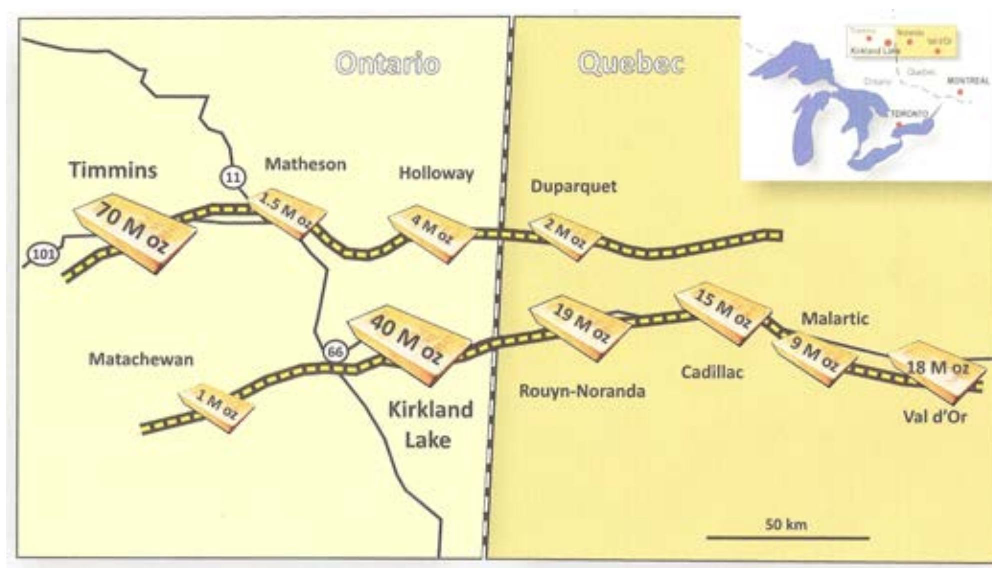
Dubé & Gosselin (2007)



http://www.northerngold.ca/golden-bear-project/garrison-gold-property

Porcupine–Destor Fault

- “One of the great gold camps of the world!”
- Gold discovered in 1910 in Duparquet Lake
- 450 km long
- Extends from Timmins past Duparquet
- 70 gold showings (>1 g/t)
- Gold mineralization associated with carbonate alteration
- **Deposits associated with curvatures, flexures and <u>dilational jogs</u>**

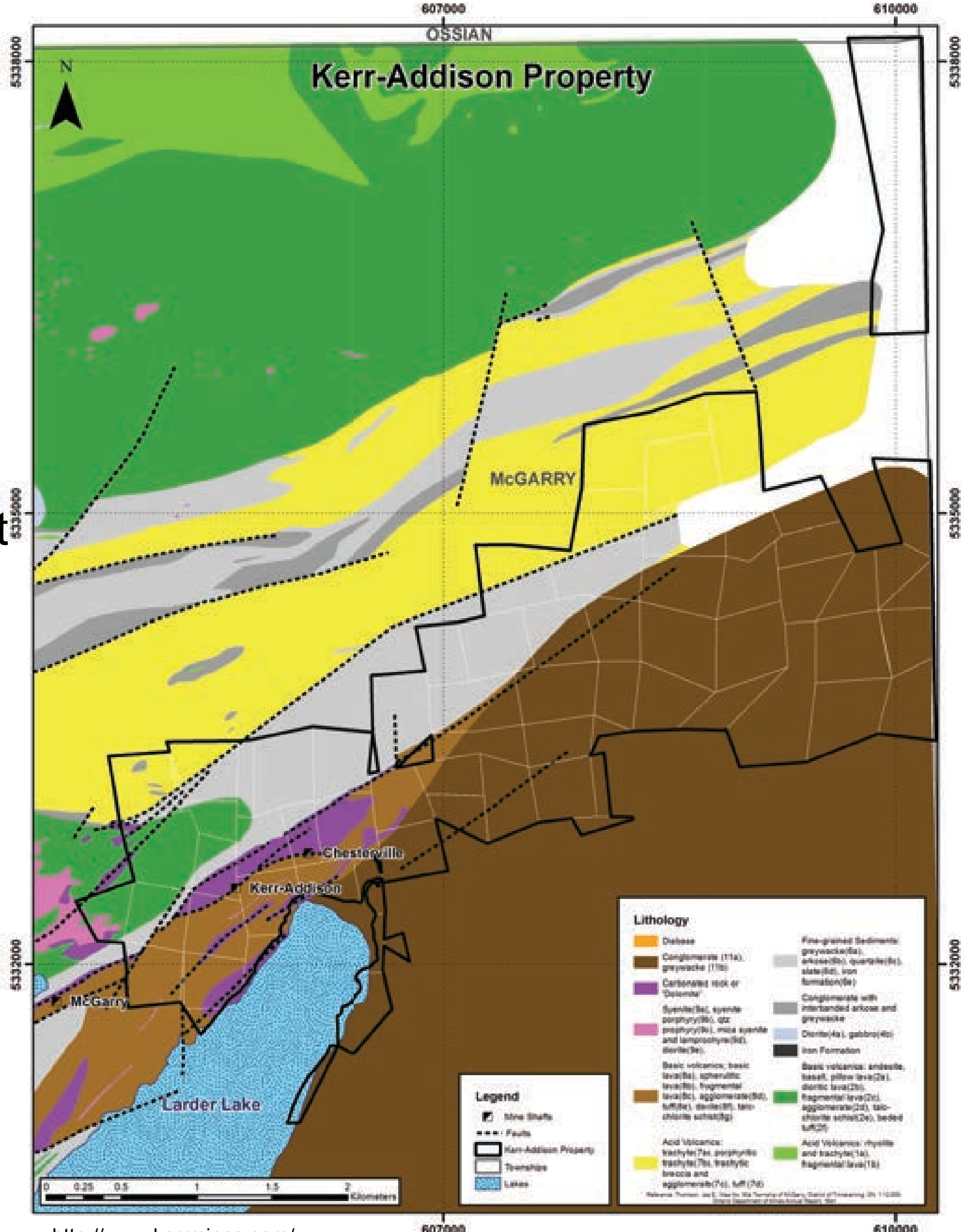


Kerr–Addison historic property

- NOT in production
- Owned by Kerr Mines Inc.
- On the Larder Lake–Cadillac fault zone
- 10M oz Au extracted (as of 1989)
- Proven reserves*: 771,000 t @ 3.1g/t
- Possible reserves*: 1.3 Mt @ 3.5 g/t

*Calculated before NI 43-101

http://www.northerngold.ca/golden-bear-project/garrison-gold-property



http://www.kerrmines.com/

Kerr–Addison geology

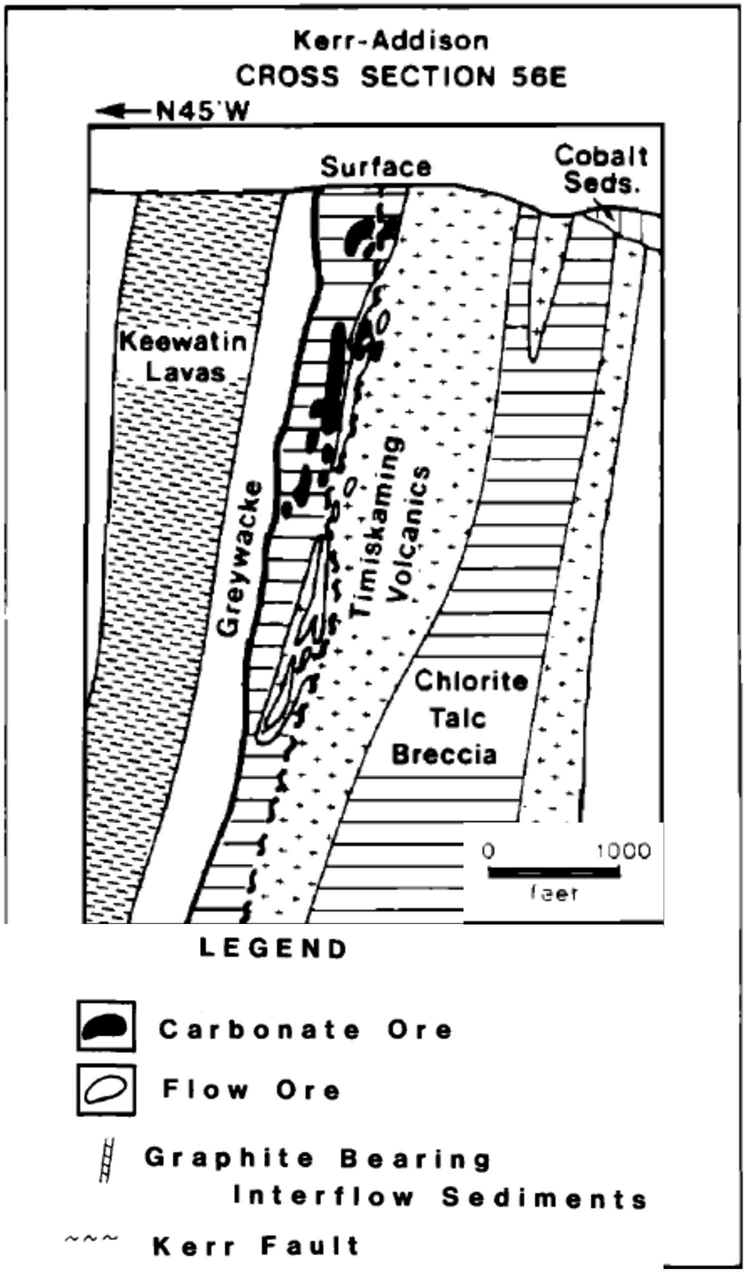
- Host rocks komatiites, tholeiitic and calc-alkaline volcanic rocks, metasedimentary rocks
- Greenschist facies metamorphism
- Alteration minerals: carbonate, pyrite, talc chlorite

Two ore types:

1) “Carbonate”: green **Cr muscovite***-bearing quartz–carbonate rock (with v.g.)

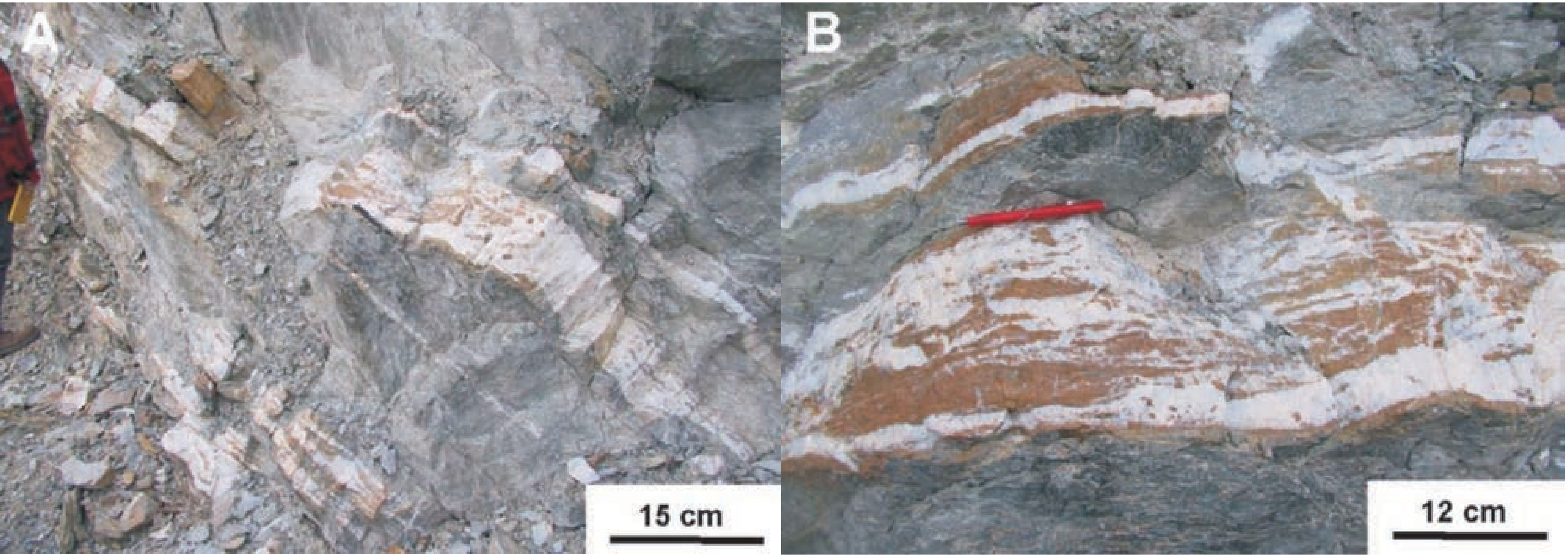
2) “Flow”: quartz, chlorite and carbonate (gold is associated with fine grained pyrite)

***Fuchsite:** Cr-rich muscovite



Quartz–carbonate veins in the Abitibi

Dube & Gosslin (2007)

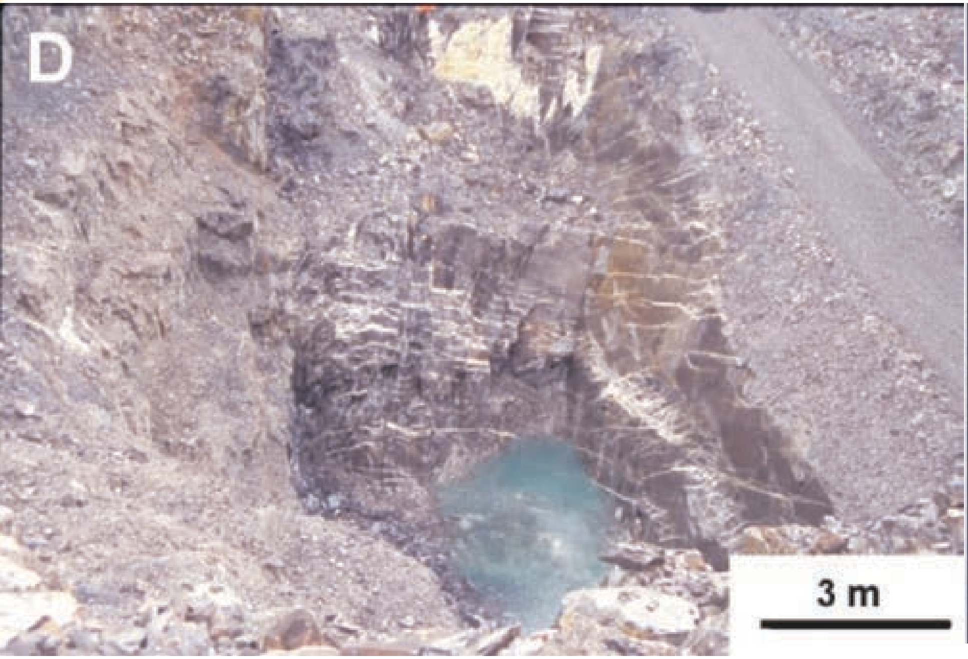


A. Laminated fault fill veins, Pamour mine, Timmins

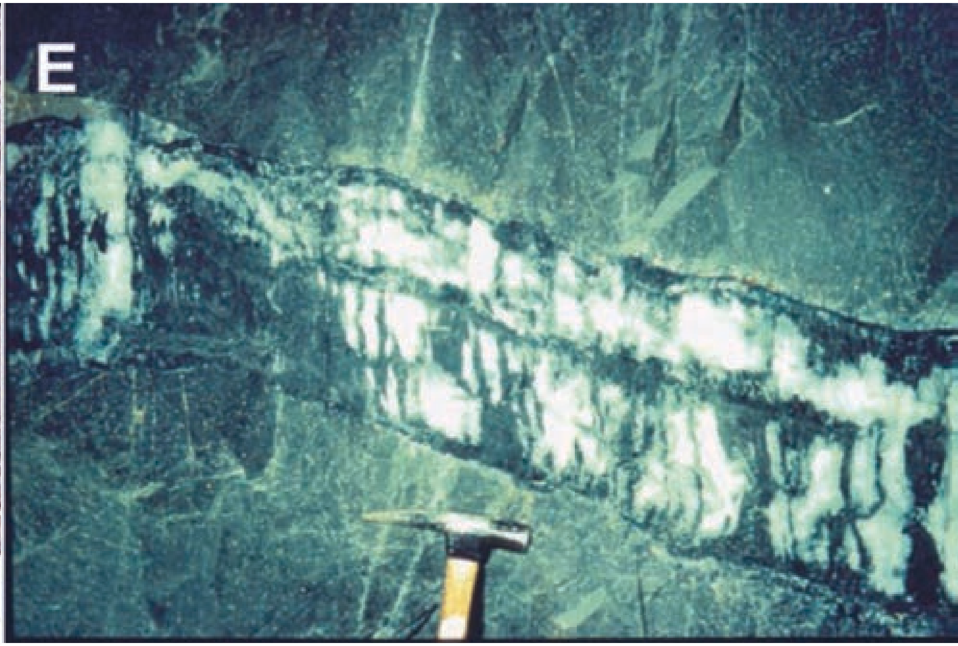
B. Closed up laminated fault fill veins showing iron-carbonatized wall rock clasts.

Extensional veins in the Abitibi

Dube & Gosslin (2007)



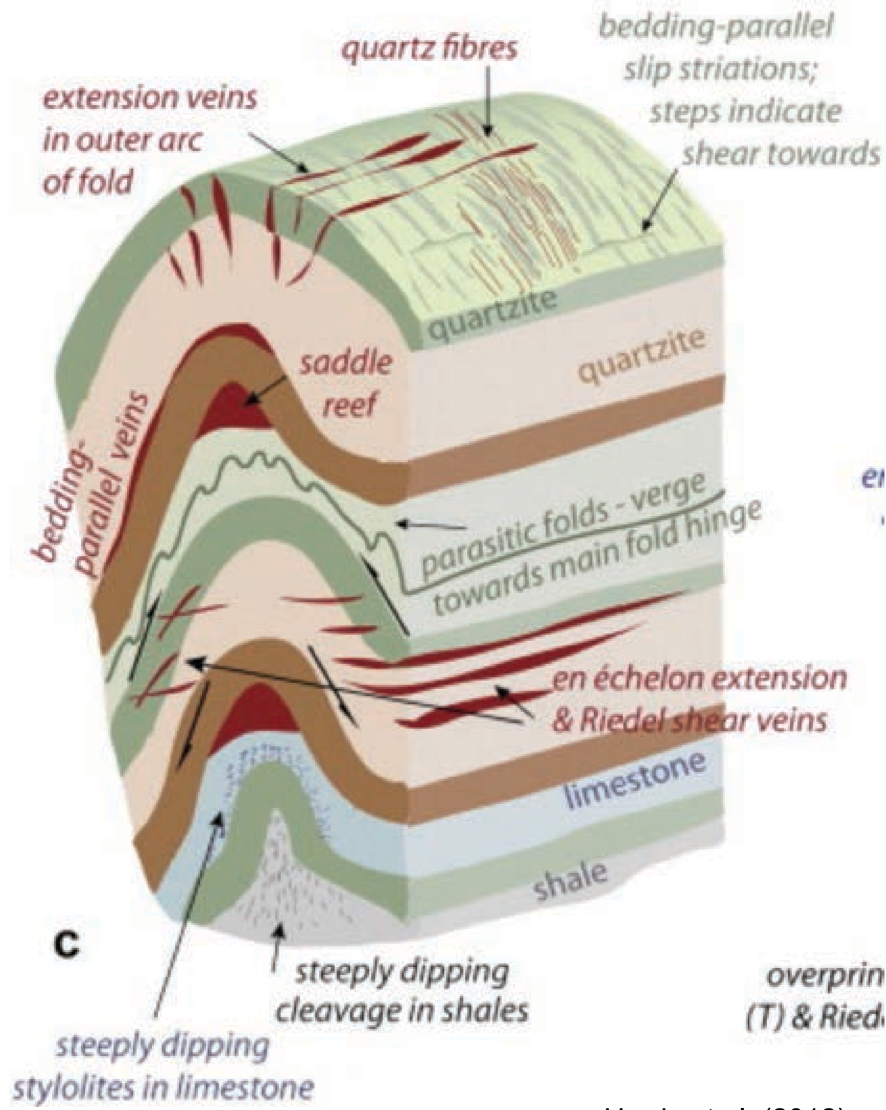
D. Arrays of extensional quartz vein , Pamour mine



E. Extensional quartz-tourmaline "flat vein" showing multiple stages of mineral growth perpendicular to vein walls, Sigma mine (from Poulsen et al., 2000)

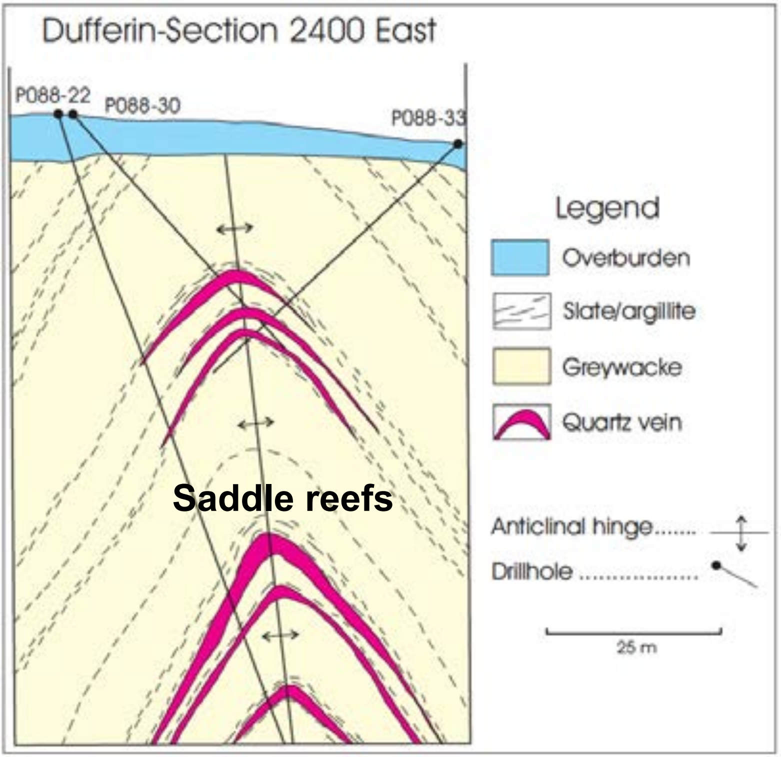
(2) Slate hosted Au

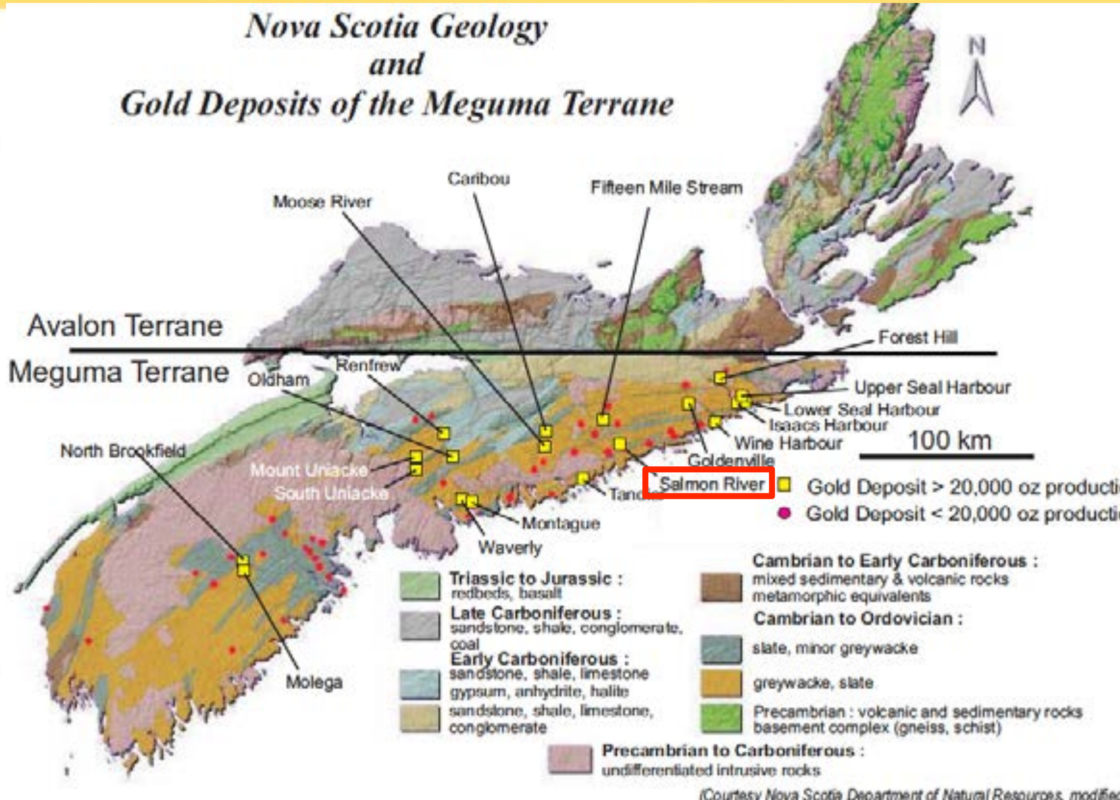
- Also known as "turbidite-hosted"
- Hosted mostly in greenschist-facies metatubidite sequences
- Granite intrusion followed by mineralization
- Strong structural control:
  - Saddle reefs
  - Fold hinges
  - Shear zones
- Look for ankerite <u>haloes</u> and sericitic alteration

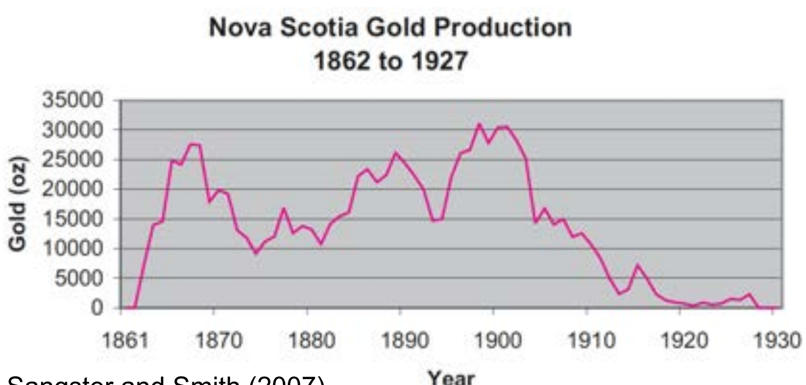


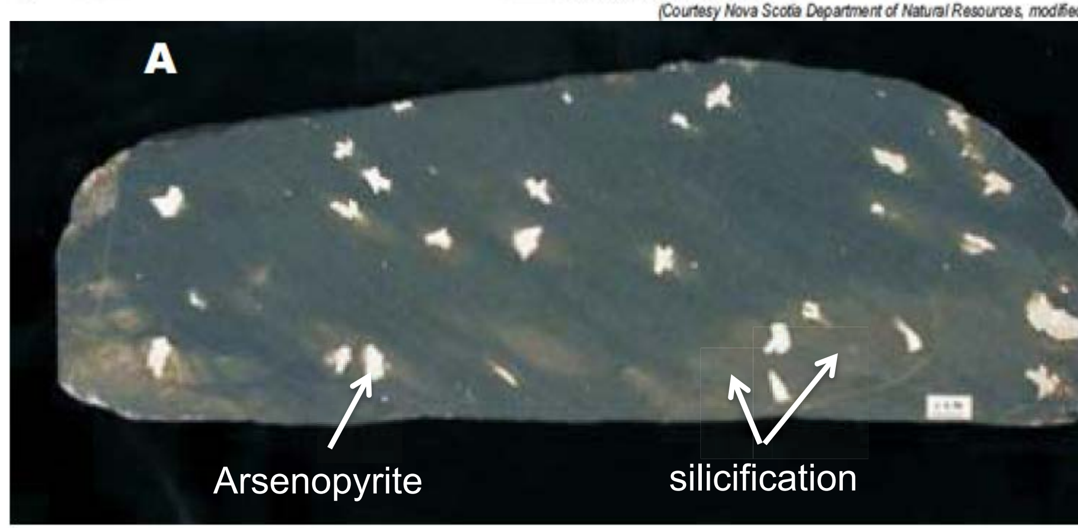
Harris et al. (2012)

Slate Au example









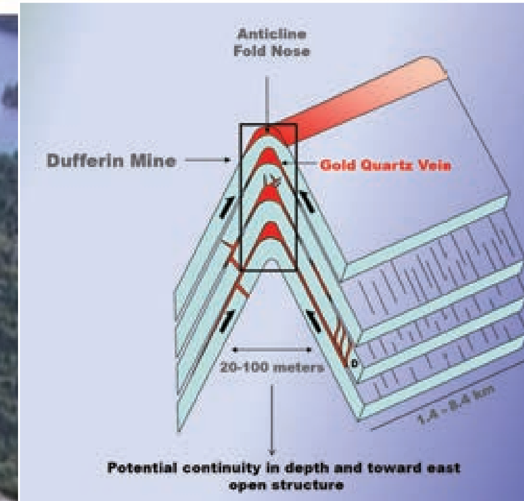
Sangster and Smith (2007)

RESSOURCES APPALACHES

Dufferin Mine Infrastructures

Existing mining infrastructure on site:

- Mining lease in good standing
- Fully permitted by Governments
- 300 tonnes per day plant
- Gravity and flotation process
- Underground access by decline
- All surface infrastructure in place
- Accessible by national road



PORTAL AND DECLINE

PLANT

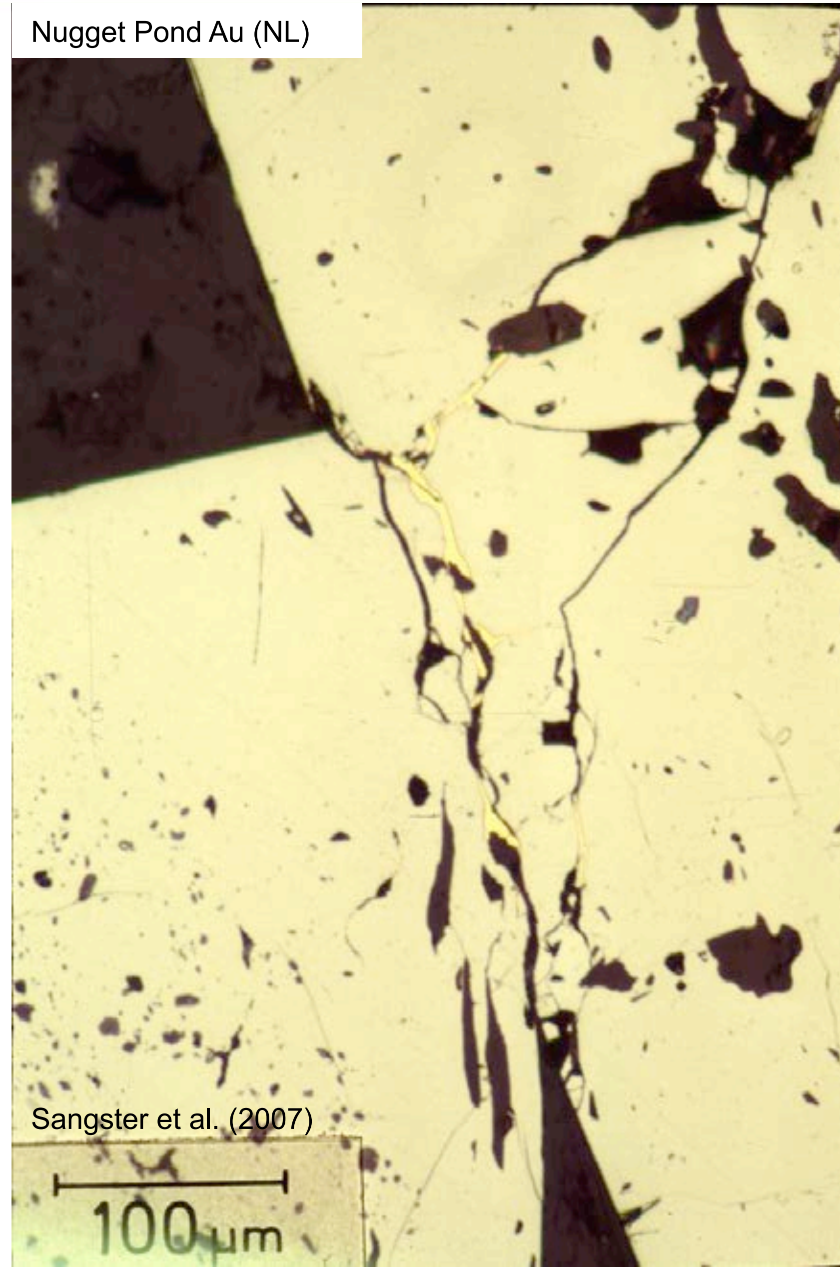
MILLING

(3) Banded Iron Formation (BIF) Au

- Host is BIF (Fe rich!)
- Fe-oxides -> Pyrite <u>or</u>
- Fe-carbonates -> pyrite
- Loss of HS^- from fluid

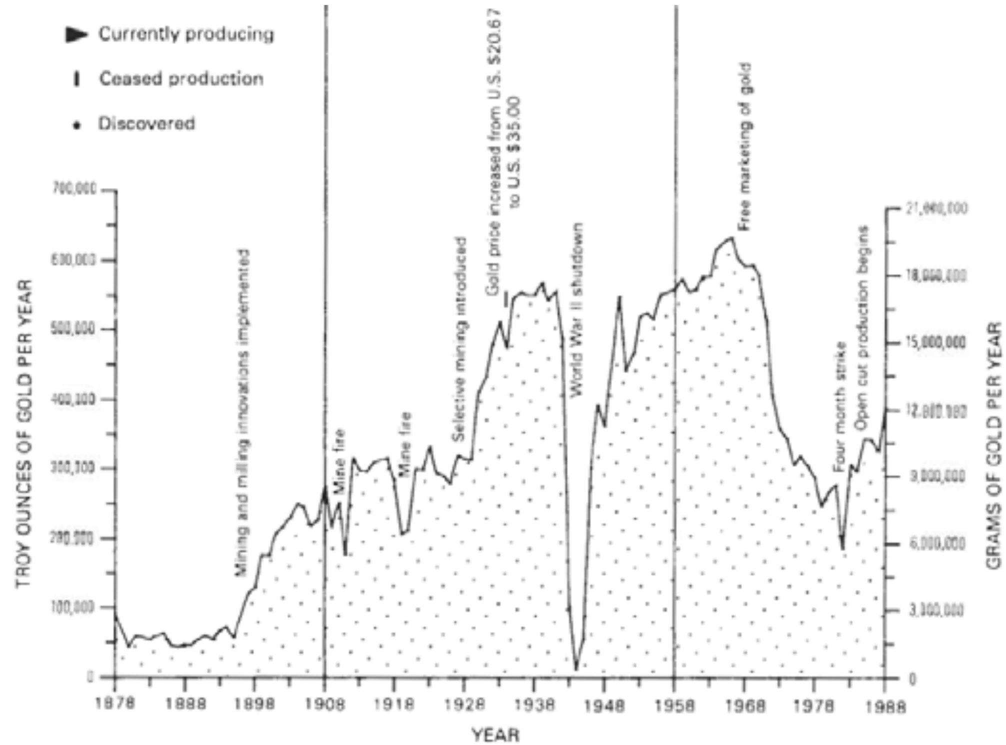
$$Au_S + 2HS^- + H^+ + 1/4\ O_2 \rightleftharpoons Au(HS)_2^- + 1/2\ H_2O$$

- Au precipitation!!



Homestake BIF Au

- Black Hills, SD, USA
- Mined from 1876–2001
- Total of 1,237 t Au
- Ore averaged 8.3 g/t

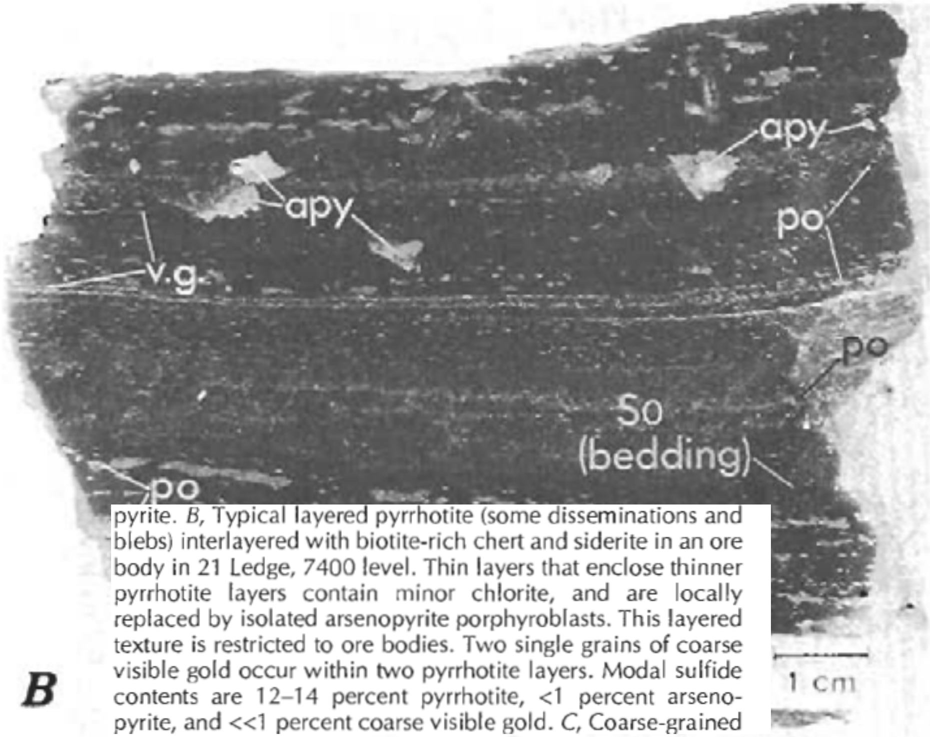


In 1874, the Custer expedition discovered placer gold in French Creek, near the present village of Custer, in the southern Black Hills. When word of the presence of gold in the Black Hills reached the outside world, the gold rush was on. In 1875, placer gold was discovered in Deadwood Creek, about 5 km east of what was to become the city of Lead. The Homestake lode, source area of placer gold, was discovered in 1876, at what is now referred to as Main Ledge (Open Cut surface mine) and Caledonia ore zones.

Caddy et al. (1991, USGS Report)

Homestake BIF Au

- Host: intracratonic rift sediments; Homestake Formation: <125m thick carbonate–silicate–sulfide iron formation
- Upper greenschist to lower amphibolite-facies
- Ore zone contains: pyrrhotite and arsenopyrite
- Re–Os age of ~1740 Ma for mineralization (arsenopyrite)
- T ~400–450°C (fluid inclusion thermometry)
- Gangue: quartz, carbonates
- Alteration: carbonitization and sulfidization
- Stockwork mineralization



Orogenic Au Summary

- Epigenetic and mesozonal
- Three main types:
  1) Greenstone hosted
  2) Slate hosted
  3) BIF hosted
- Structurally hosted, found in deformed metamorphic rocks
- Mineralization related to regional fluid flow during orogeny
- Archean greenstone terranes important in Ontario/Quebec
- Lode, stockwork, (± disseminated) mineralization

Fluid: metamorphic (H_2O and CO_2)

Source of metals: volcanic–sedimentary rocks??

Transport: shear zones and faults

Trap: fluid–rock interactions, *P*, *T*

Carlin type

Carlin – Where in the world?

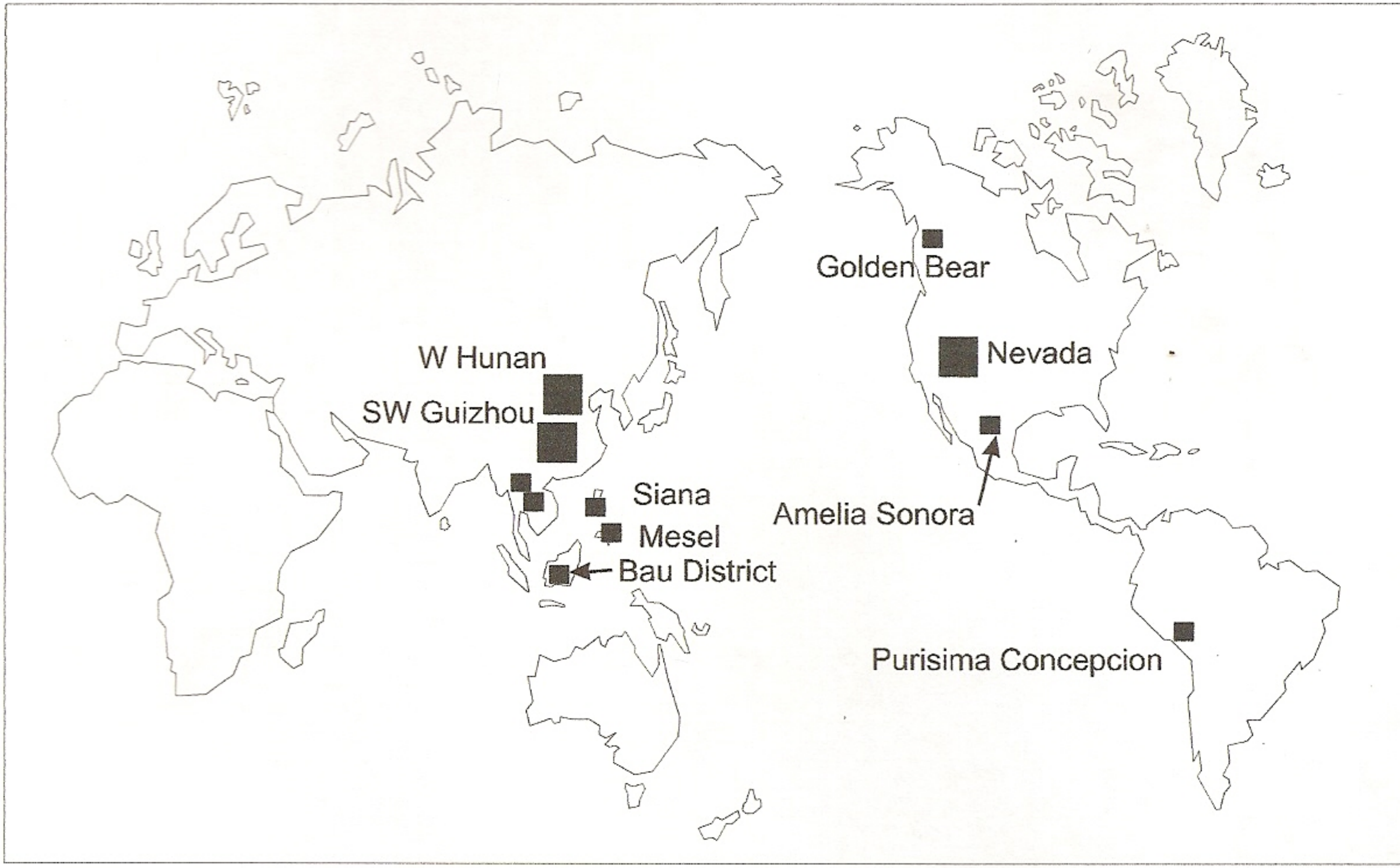
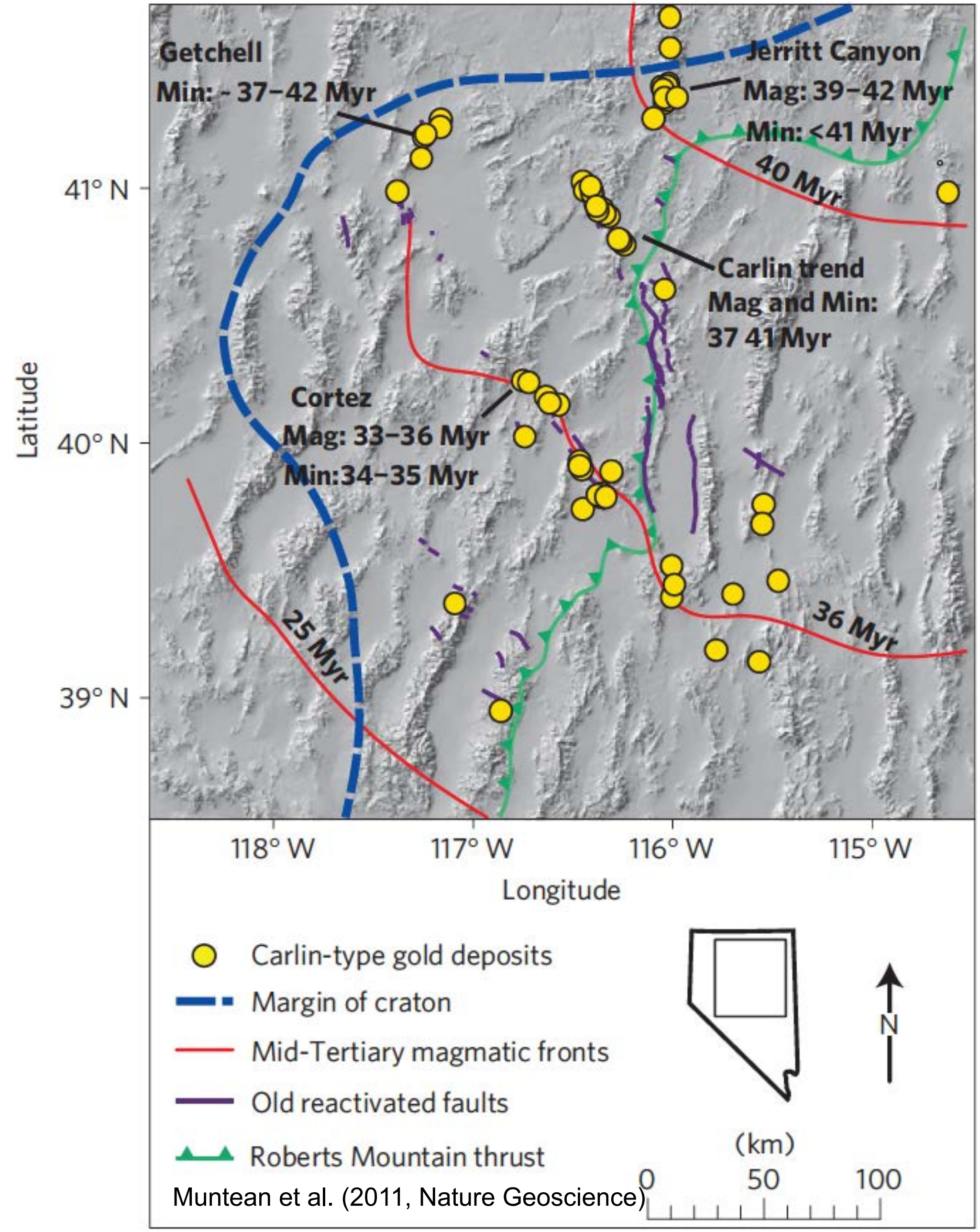


Figure 4. Global distribution of Carlin-type deposits (modified from Christensen *et al.*, 1996).

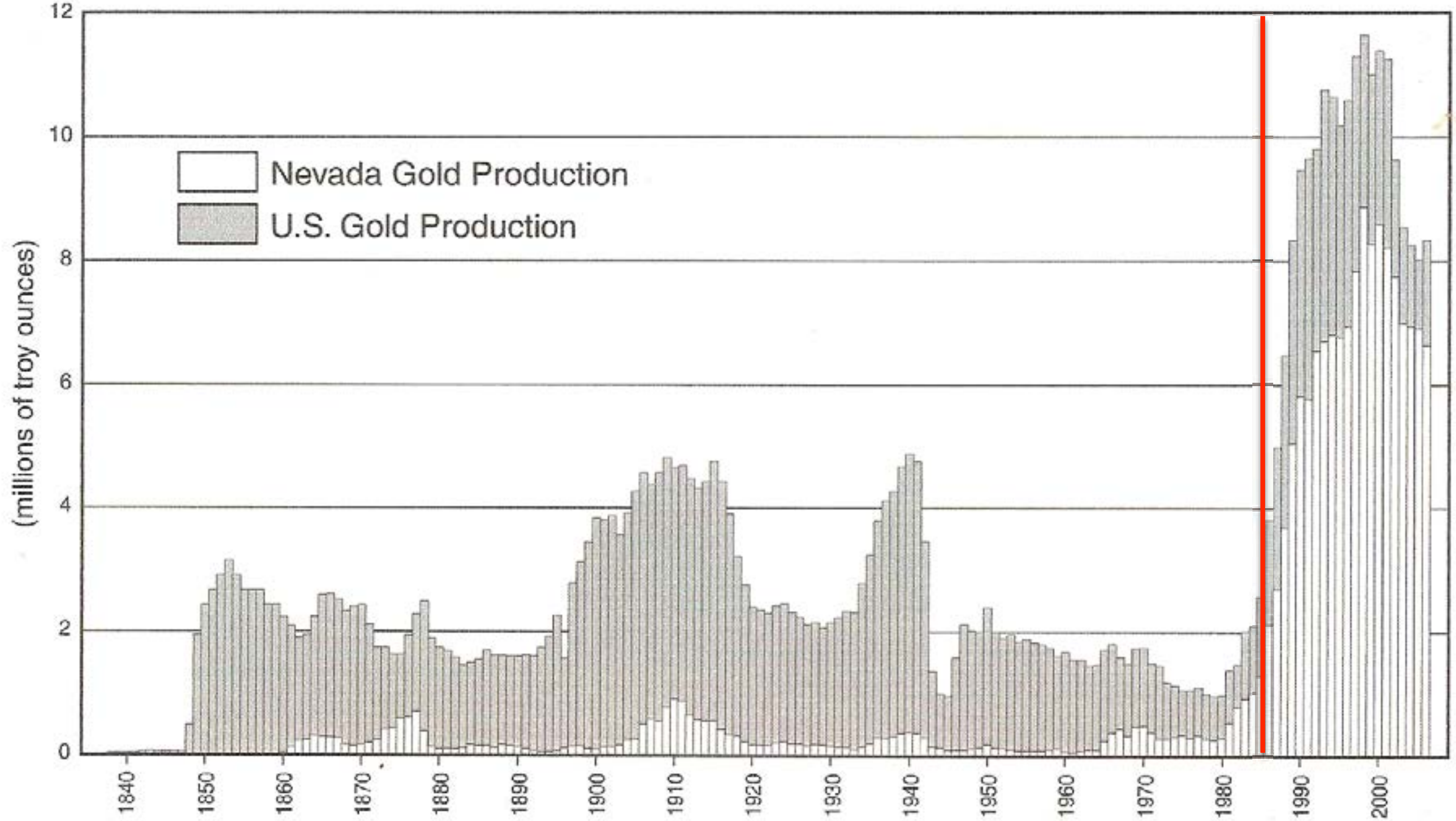
Carlin type

- Type location is Carlin (Nevada, USA)
- Some deposits in SW China
- First recognized in 1985
- Low T hydrothermal epigenetic
- Cenozoic mineralization (43-35 Ma)
- Extensional tectonic setting (basin and range province, SW USA)
- Deposits found in clusters along old, reactivated basement rift structures



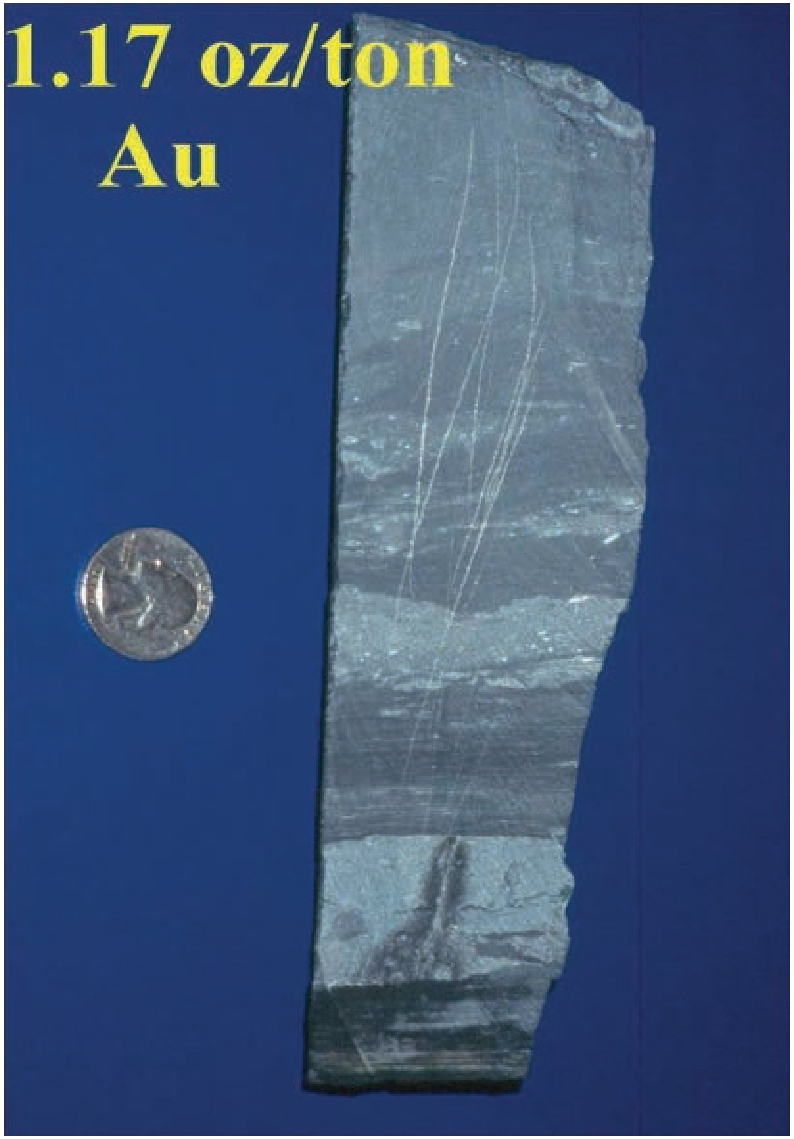
Muntean et al. (2011, Nature Geoscience)

Most USA gold comes from Nevada (much of it Carlin)



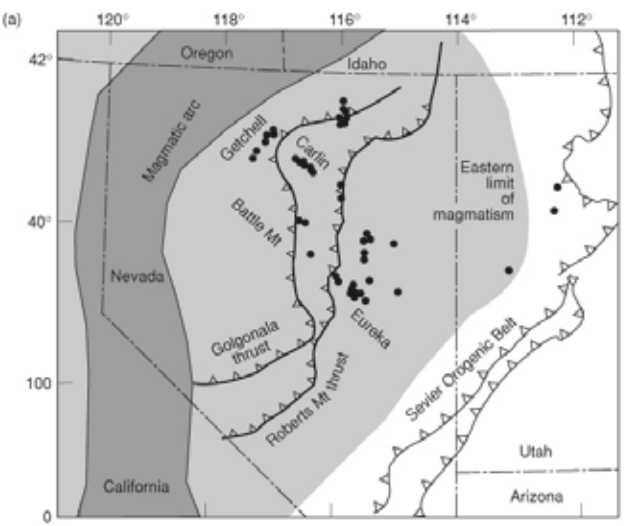
United States and Nevada gold production from 1835 through 2006. Data from U.S. Gold Industry 1998 (NBMG Special Publication 25) by J.L. Dobra and from the U.S. Geological Survey.

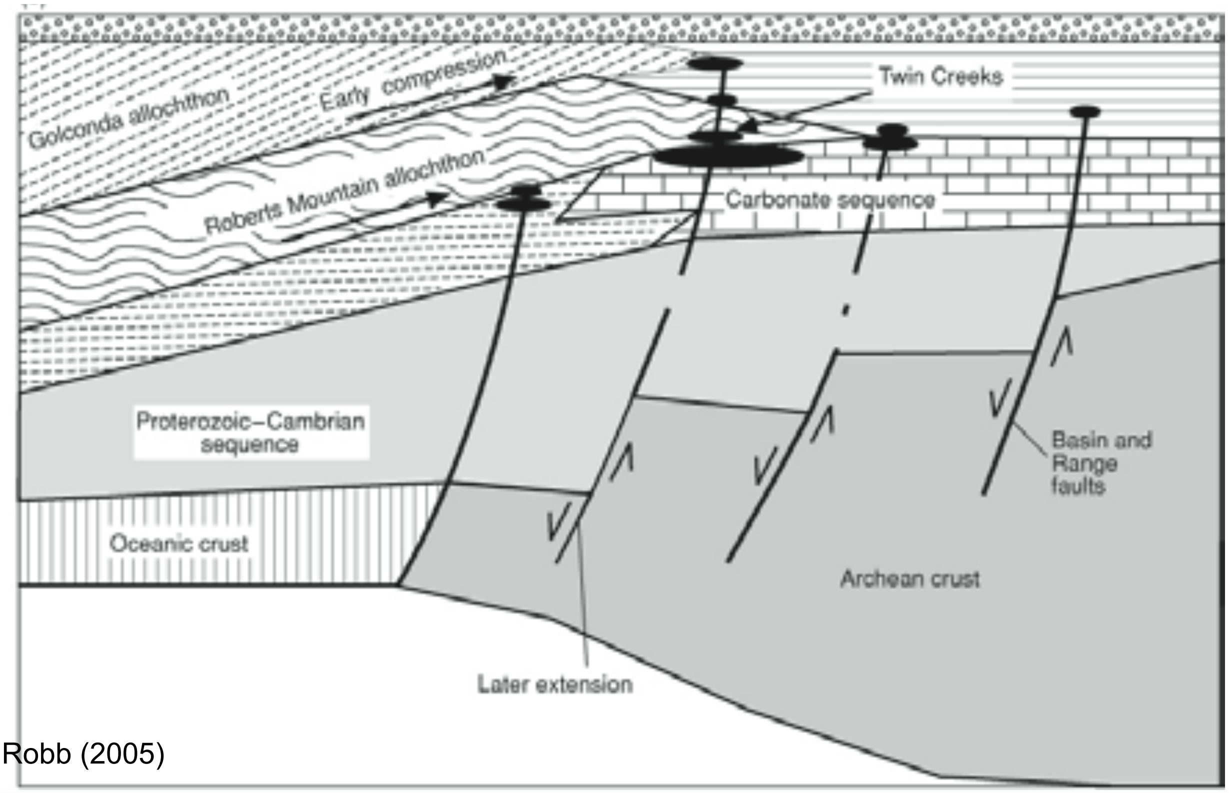
What does the ore look like?



Carlin geology

- Hosted in carbonate-bearing unmetamorphosed sedimentary rocks (stratabound)
- Mineralization associated with deep-seated ancient faults with no surface expression
- Mineralization associated with **extension**

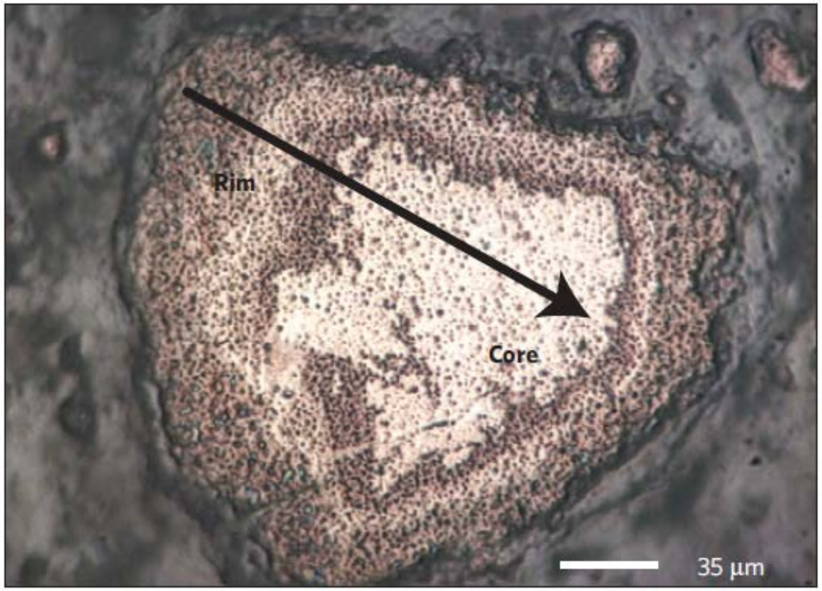


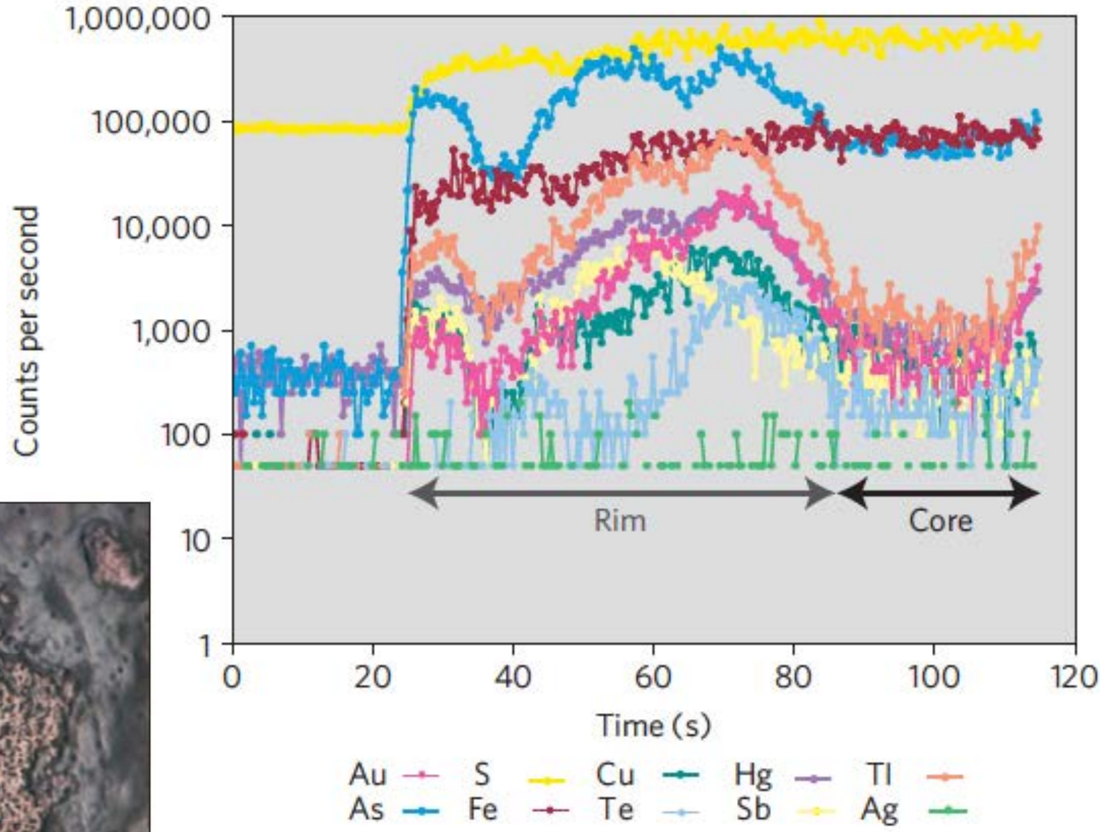


Robb (2005)

Carlin ore

- Disseminated Au
- Au is ‘**invisible**’
- Sub-microscopic grains of Au within pyrite/ arsenopyrite or substituted into their crystal lattices

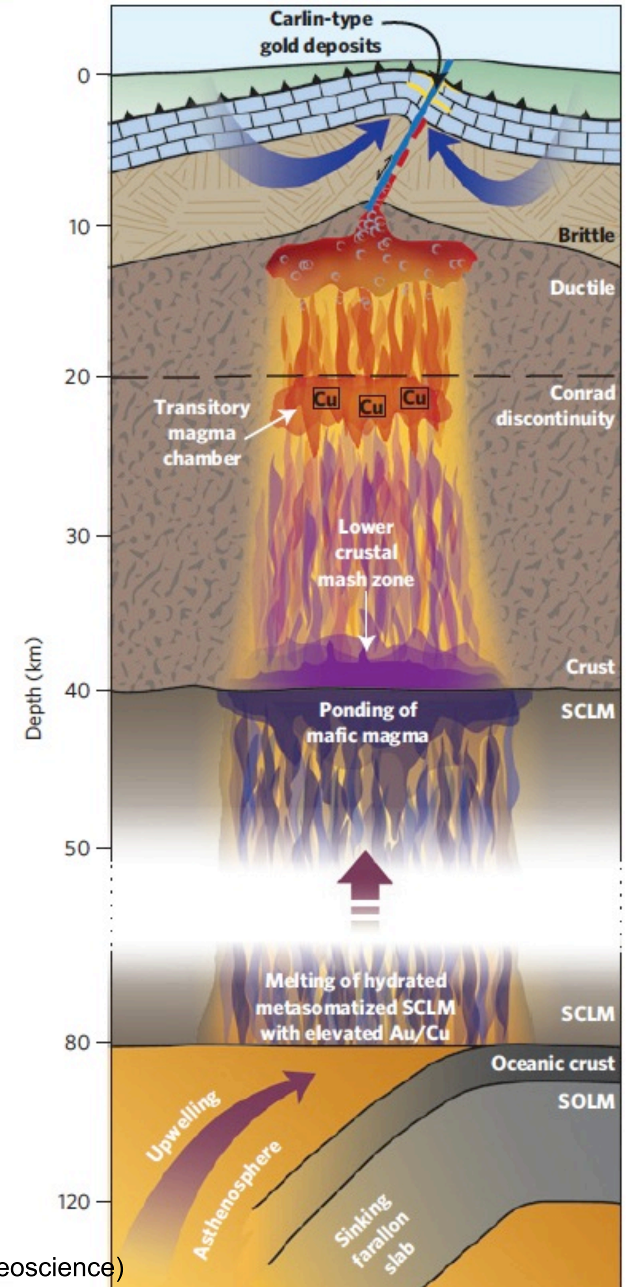




Muntean et al. (2011, Nature Geoscience)

Carlin genesis (one model)

- Melting of sub-continenal lithospheric mantle producing basaltic magma with high Au/Cu
- Basalt underplated and melted crust, producing hydrous S- and Au-bearing granites
- Granites ponded at 20 km, development of MSS (monosulfide solution) increased Au/Cu
- Boiling released Au-rich acidic supercritical fluid along old faults
- Fluid–rock interaction: Carbonate (Fe dolomite) dissolution and silicification
- Reaction of Au-sulfide fluid with Fe^{2+} in host rock producing pyrite
- Au^{+} adsorbed onto growing pyrite
- Ore also contains Tl–As–Hg–Sb–(Se)



**For an alternative (sedimentary origin) model see Large et al. (2011, Econ. Geol.)

Muntean et al. (2011, Nature Geoscience)

Carlin photos

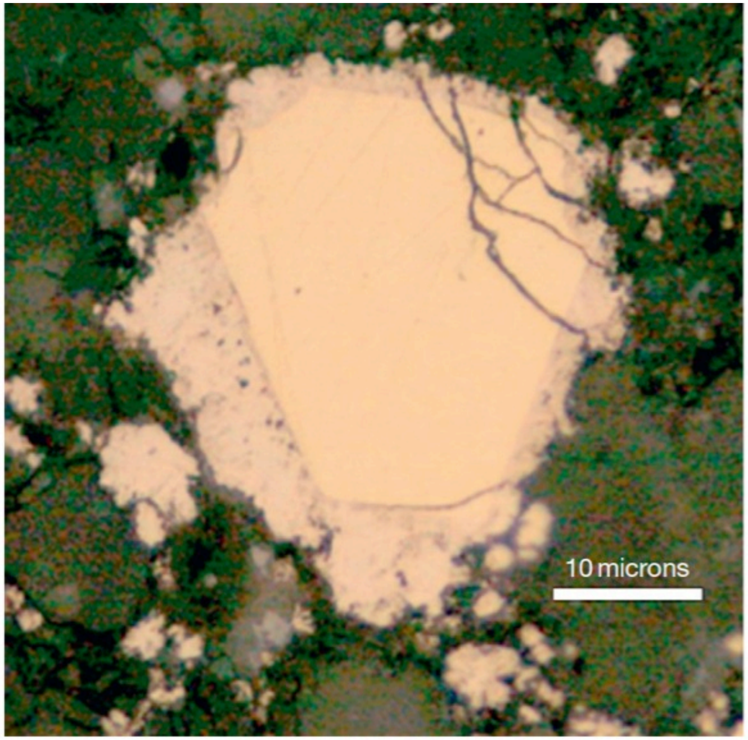


Figure 16 Reflected light photomicrograph of zoned euhedral pre-ore-stage pyrite with rim of ore-stage pyrite, Deep Star deposit, Carlin Trend. Ore-stage pyrite is more fine grained, anhedral, and darker than pre-ore pyrite.

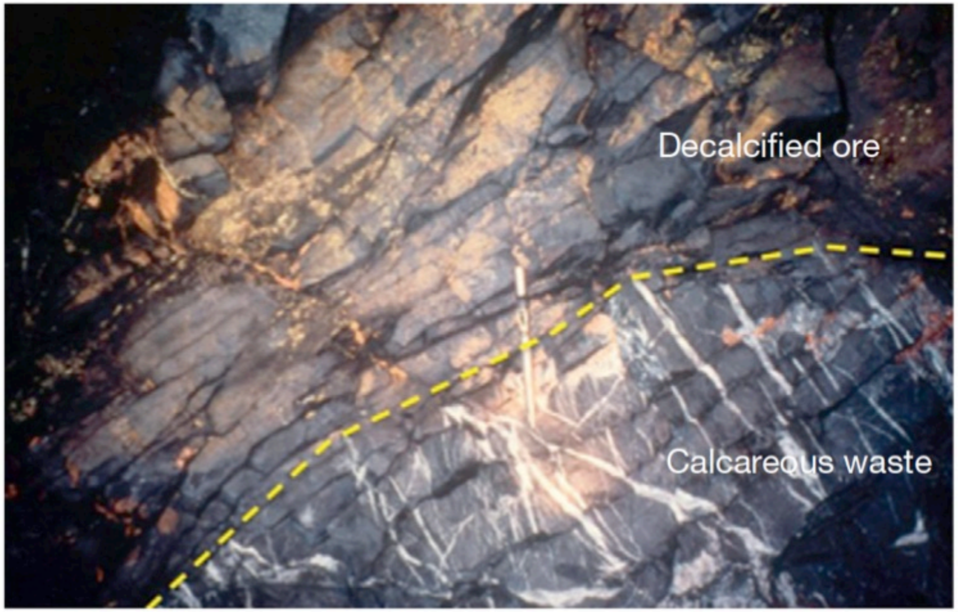


Figure 15 Photograph of decalcification front in Ordovician–Silurian Hanson Creek Limestone, Jerritt Canyon. Pre-ore calcite veins in limestone are absent in decalcified limestone. Fractures in ore are filled with orpiment and realgar. Pen for scale.

Goldstrike Complex, Nevada (courtesy of Barrick)

Carlin Au Summary

- Stratabound (carbonate rocks)
- Epigenetic
- Disseminated: “Invisible” gold in pyrite
- Great Basin (Nevada) hosts most Carlin mineralization

Fluid: multiple sources: magmatic, meteoric and/or metamorphic (HS^- transport)

Source of metals: magmatic or sedimentary?

Transport: old basement rift structures

Trap: fluid–rock (carbonates) interaction