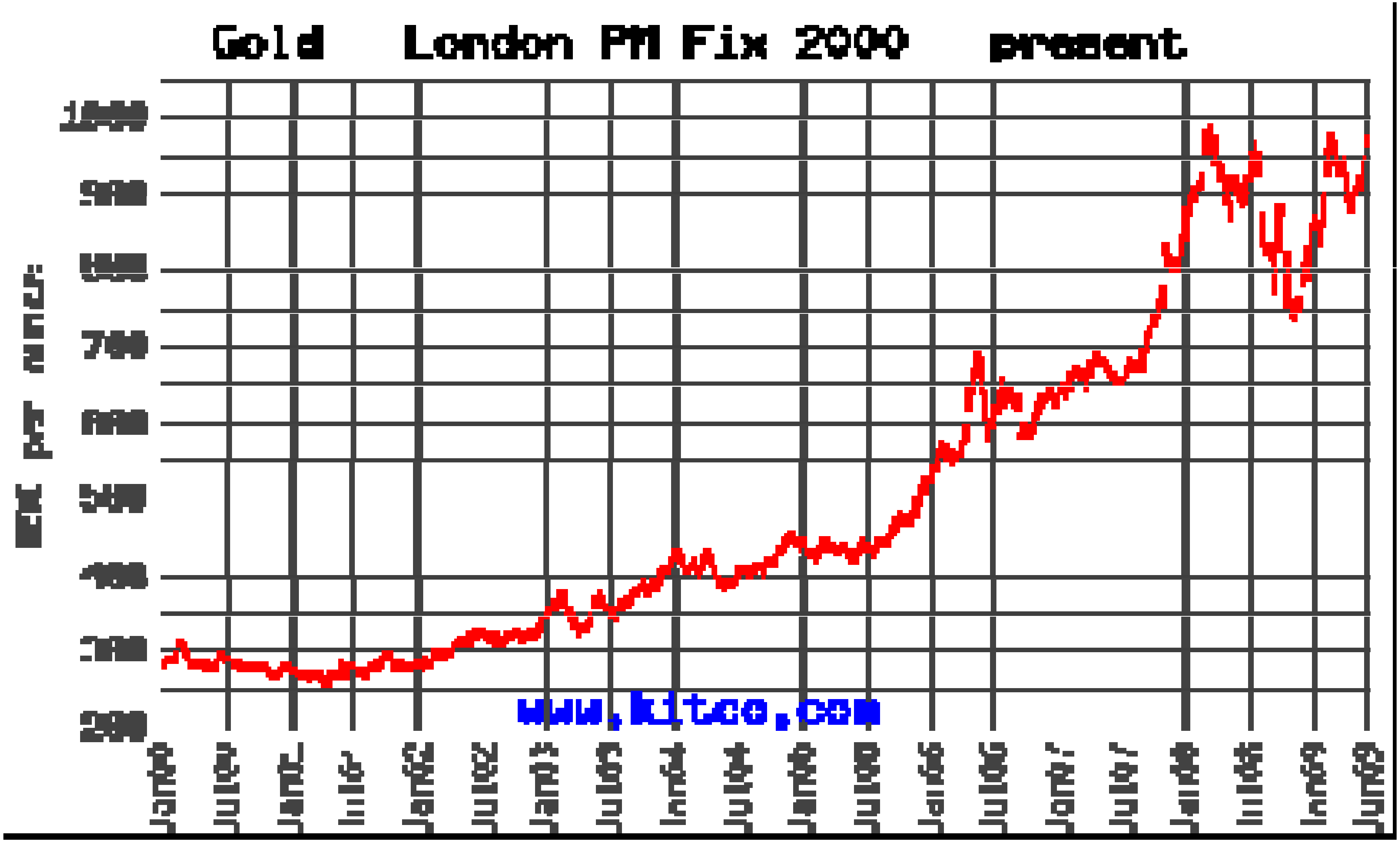
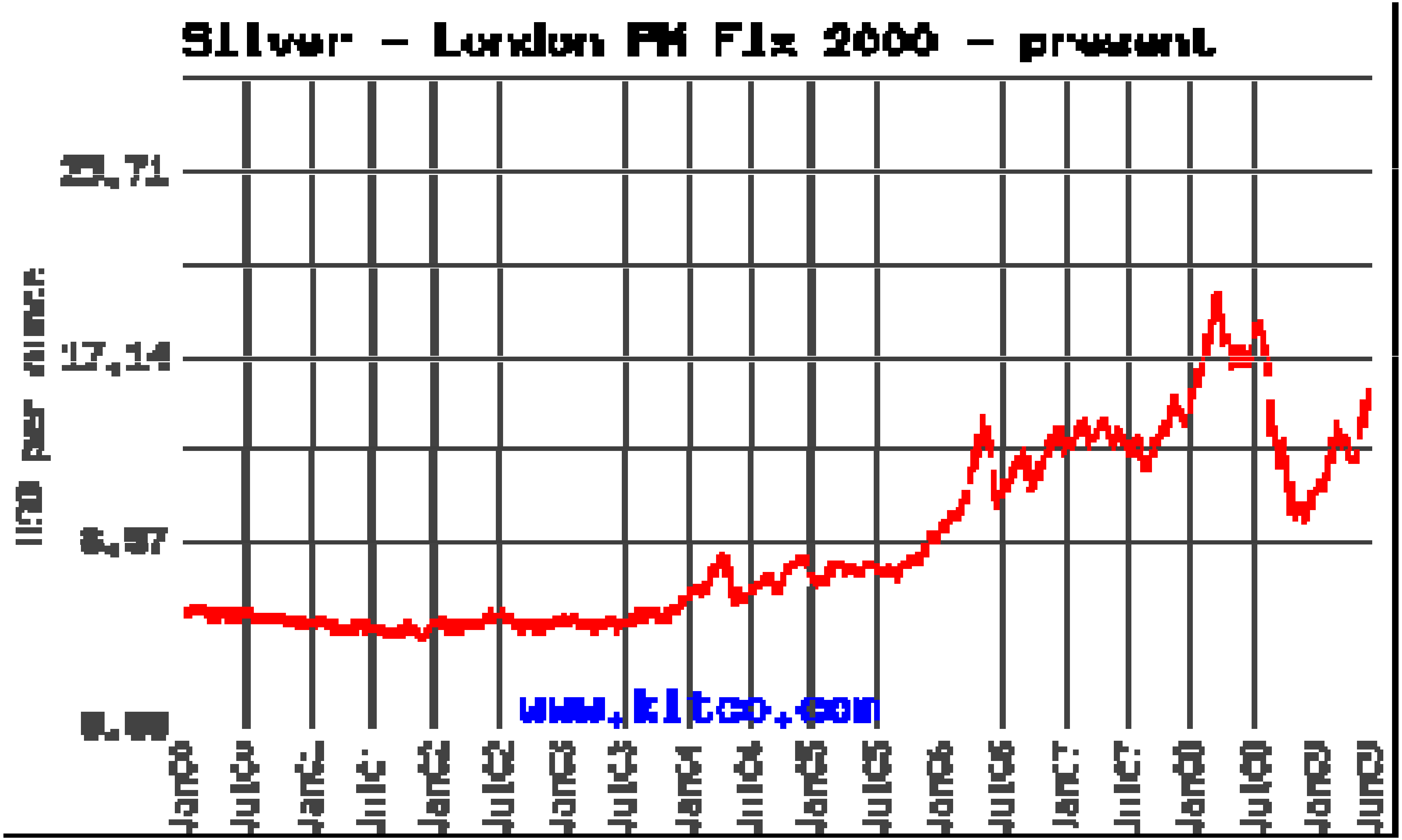
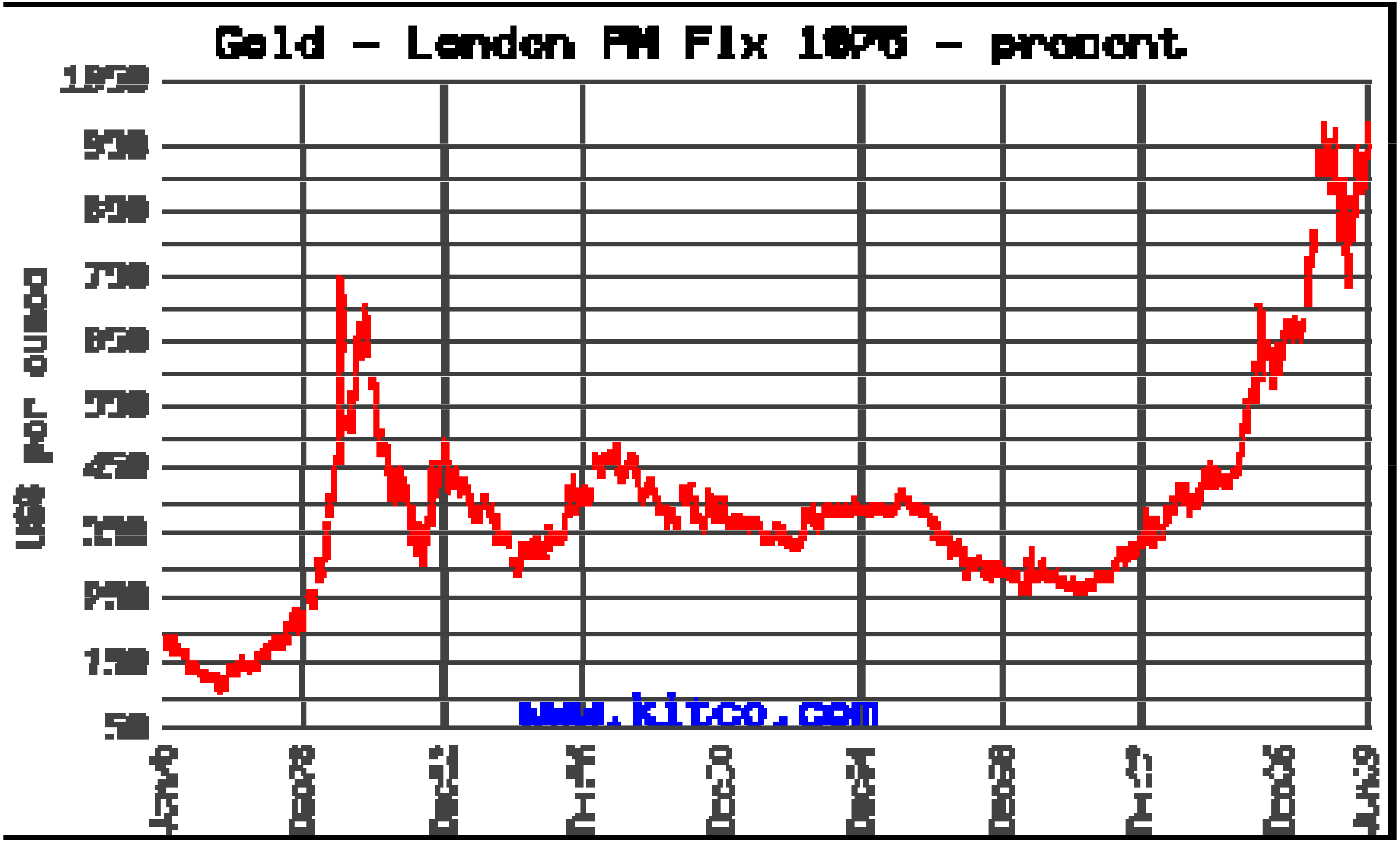
Lehmann:
Gold deposits

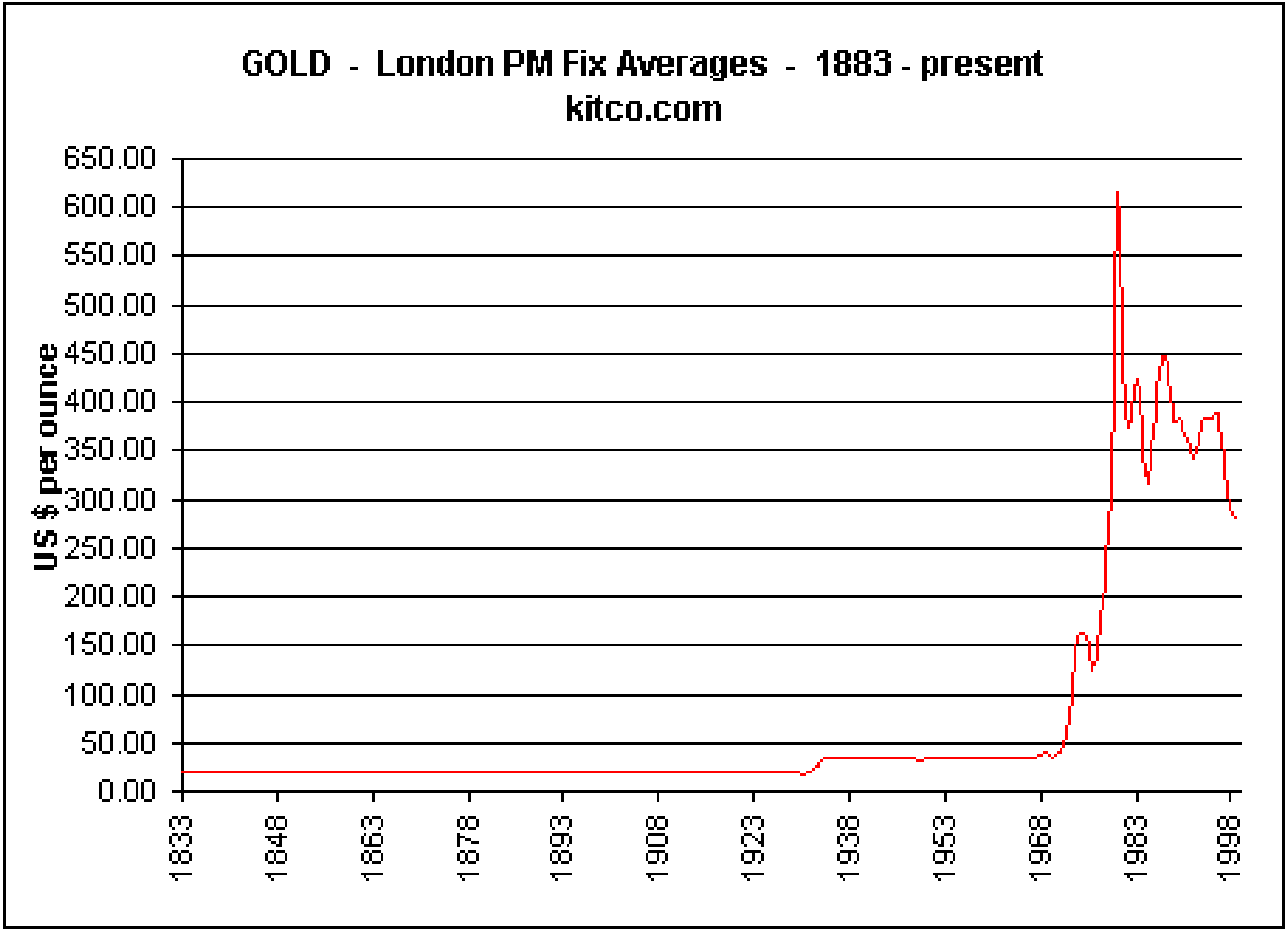
SS 2009



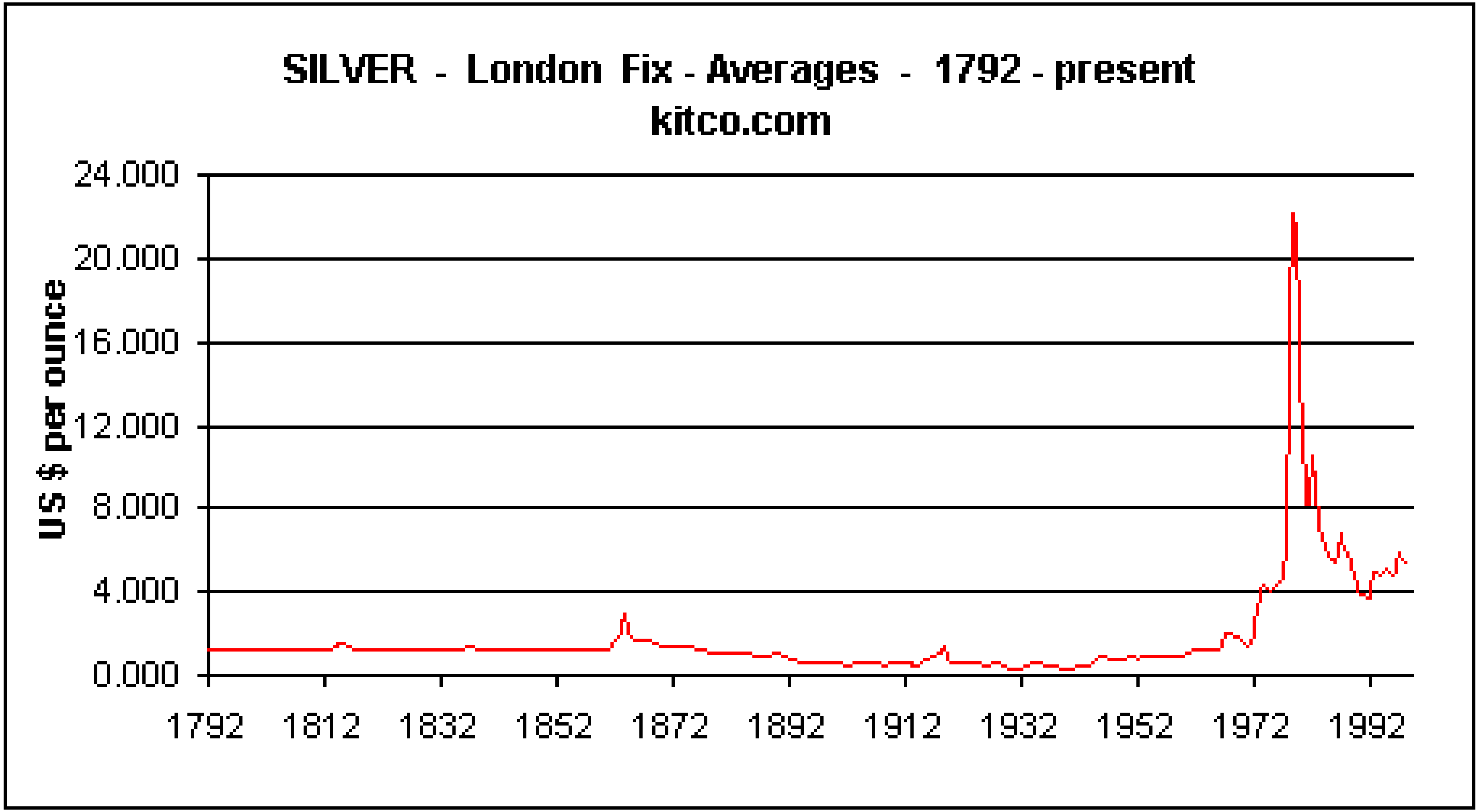
Gold London PM Fix 2000 present
1000
900
800
700
600
500
400
300
200
www.kitco.com


Silver - London PM Fix 2000 - present
USD per ounce
17.14
www.kitco.com

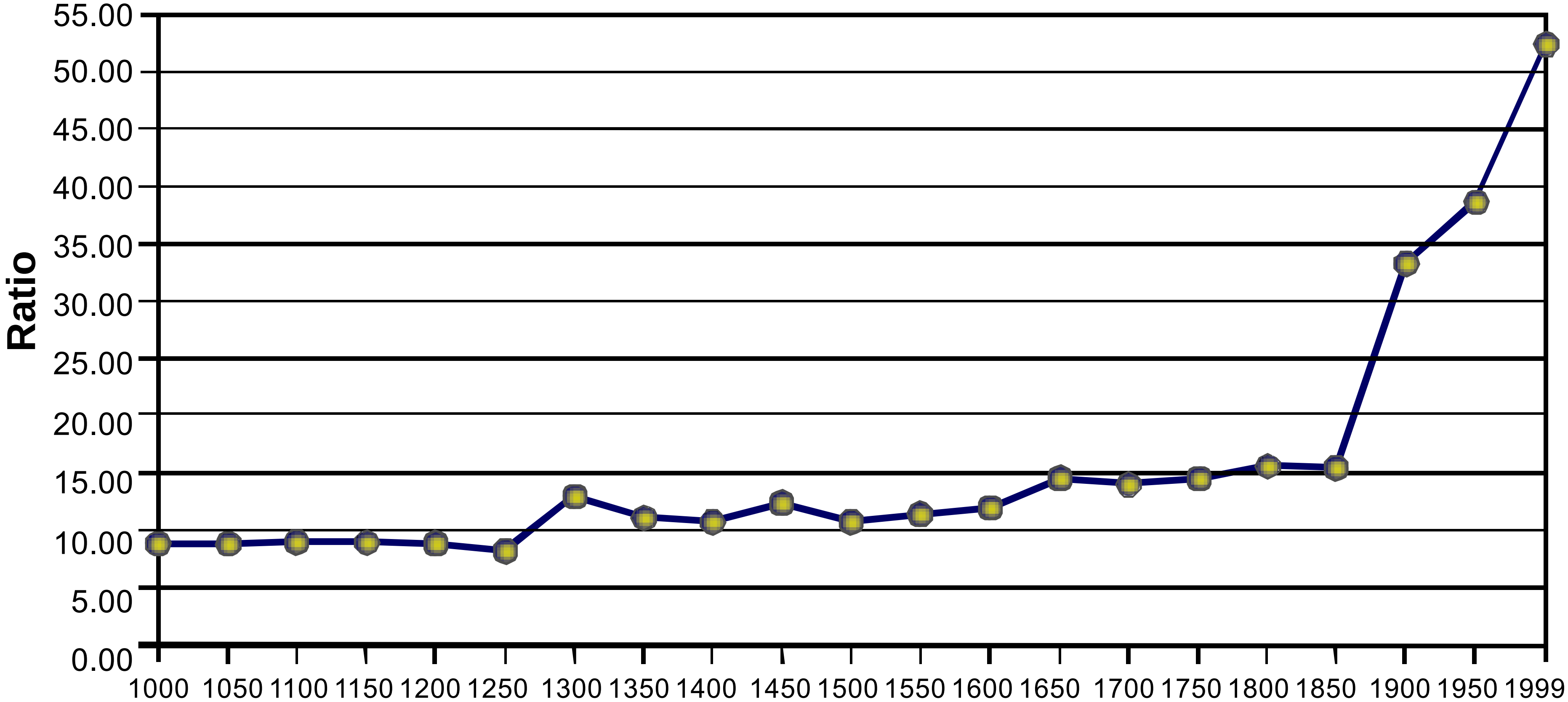

Gold - London PM Fix 1975 - present
USD per ounce
www.kitco.com



GOLD - London PM Fix Averages - 1883 - present
kitco.com
US $ per ounce
650.00
600.00
550.00
500.00
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
1833
1848
1863
1878
1893
1908
1923
1938
1953
1968
1983
1998


SILVER - London Fix - Averages - 1792 - present
kitco.com
US $ per ounce
24.000
20.000
16.000
12.000
8.000
4.000
0.000
1792
1812
1832
1852
1872
1892
1912
1932
1952
1972
1992

Gold/Silver Price Ratio (1000 – 1999)

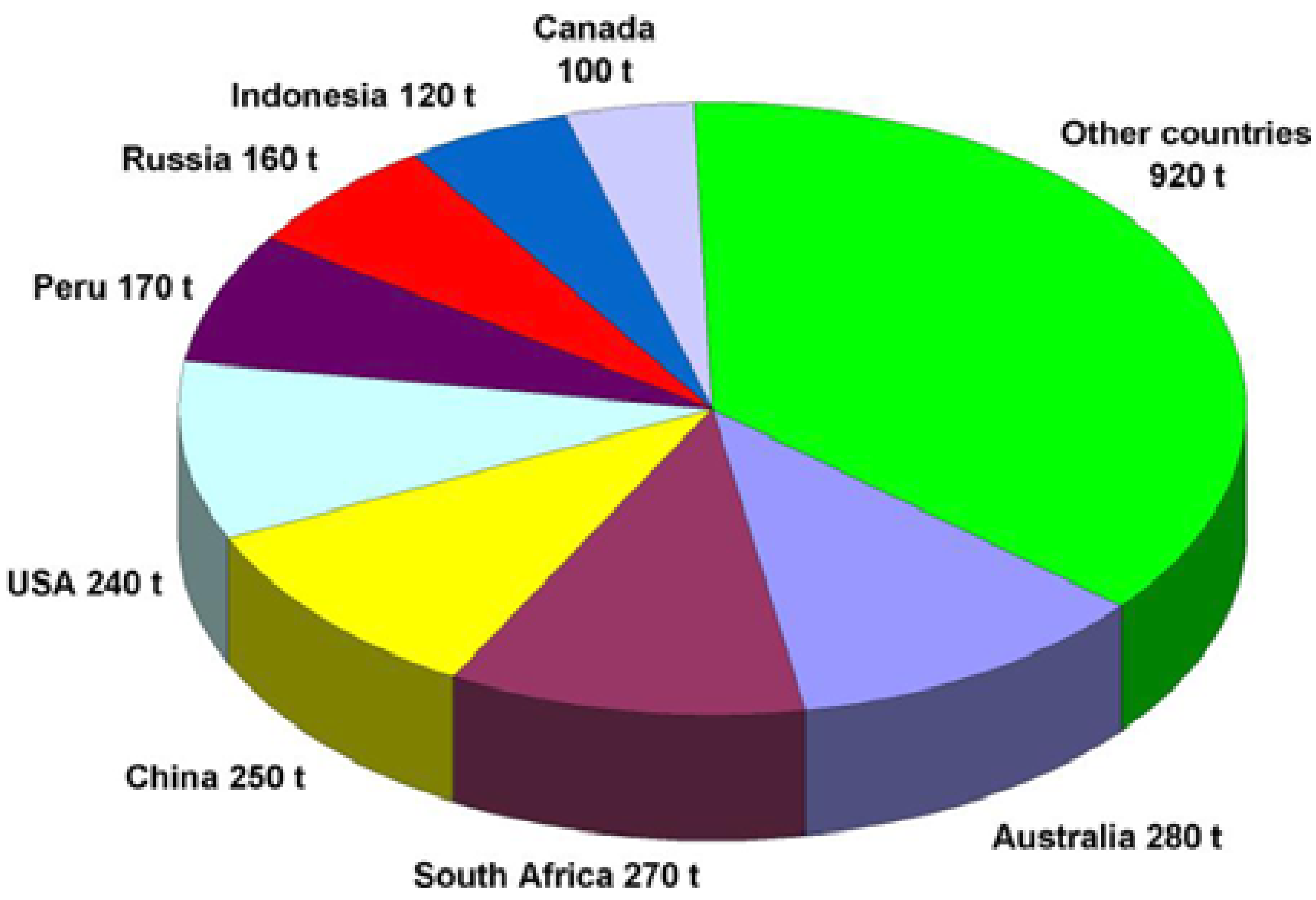


←3500 BC: **2.5**

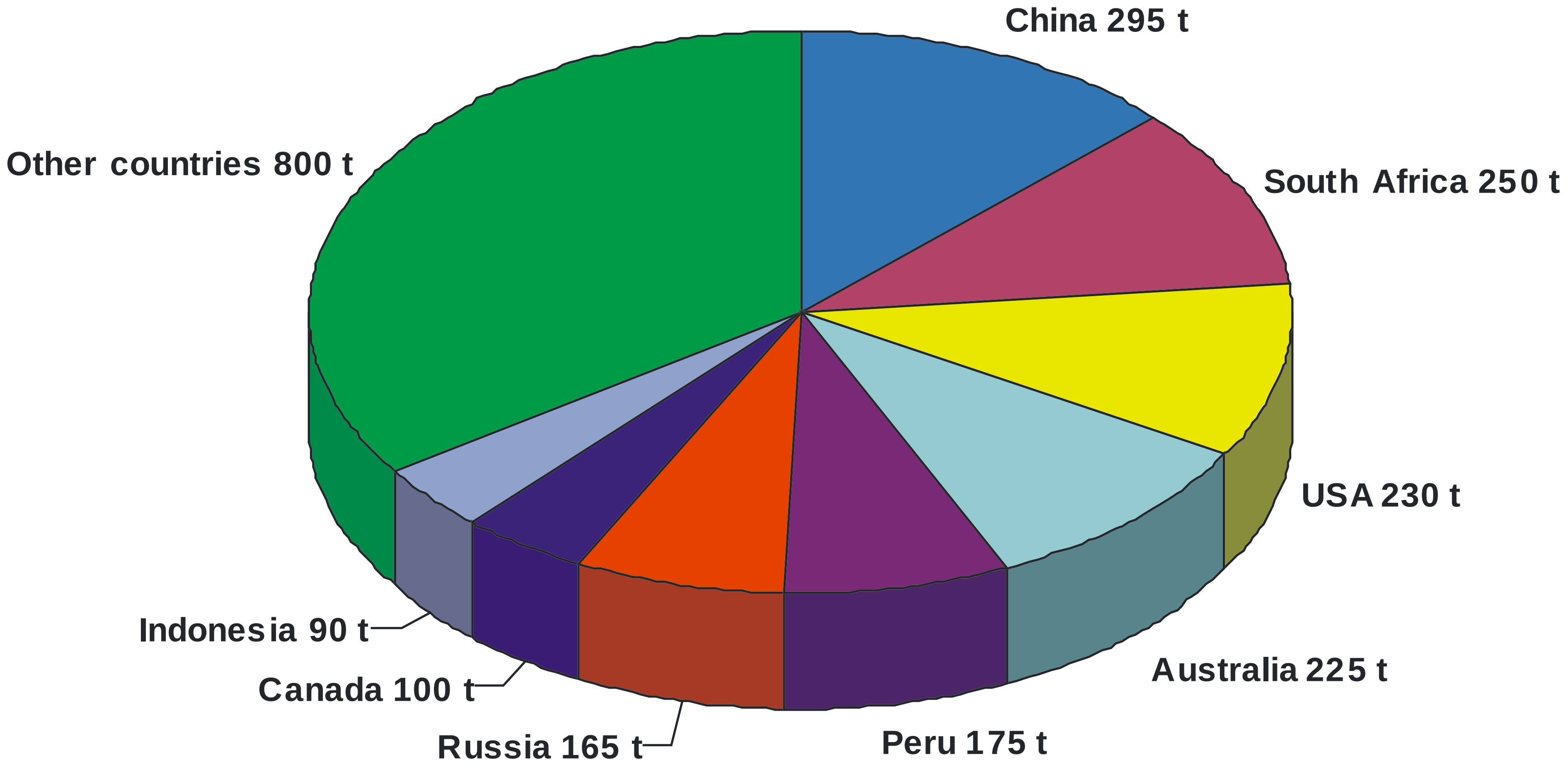
→ 2008: **50**

Quelle: T. Green: The Millenium in Silver 1000-1999, Rosendate Press, London, 1999

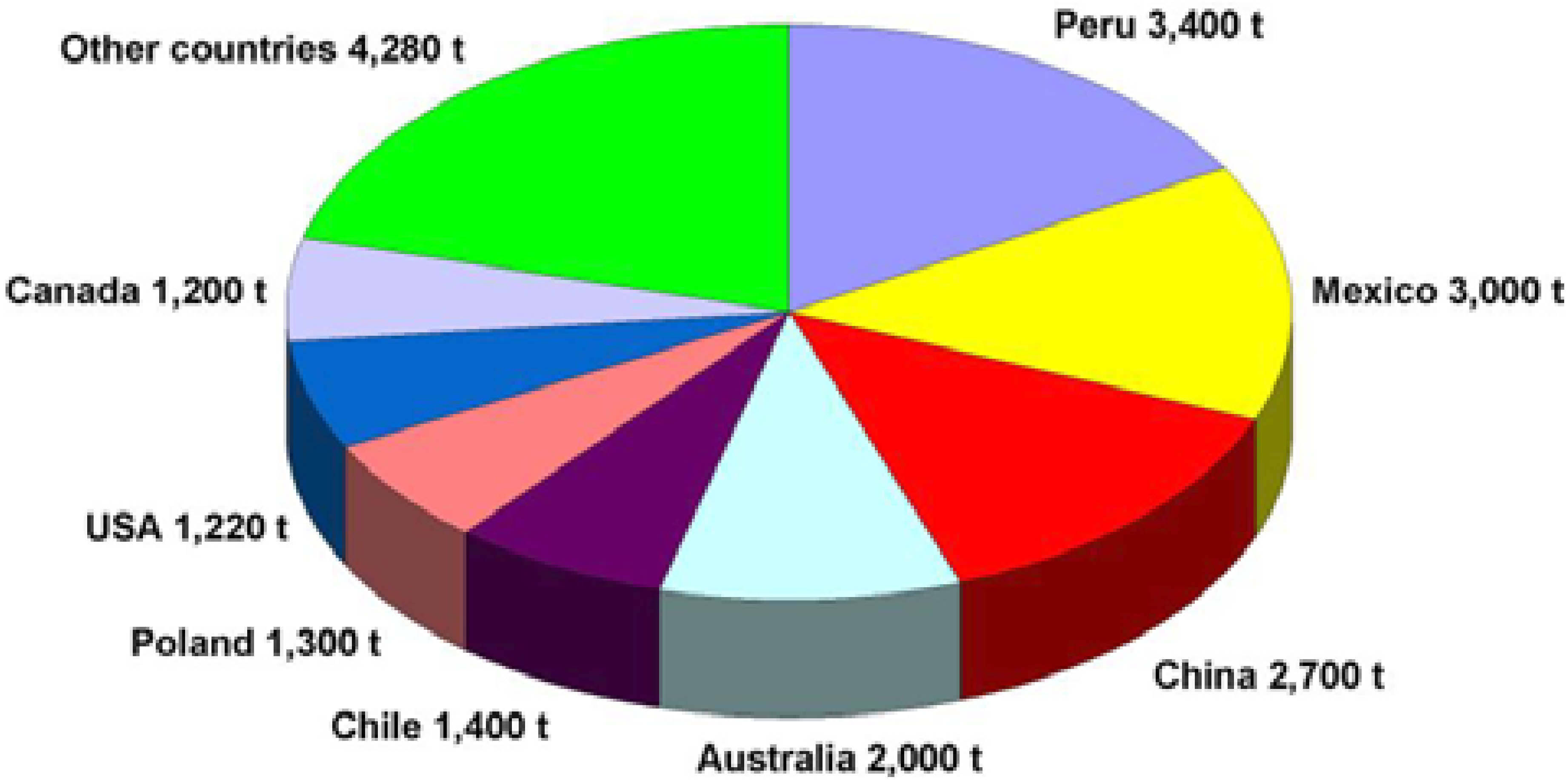
GOLD WORLD MINE PRODUCTION 2007 (2,510 t)



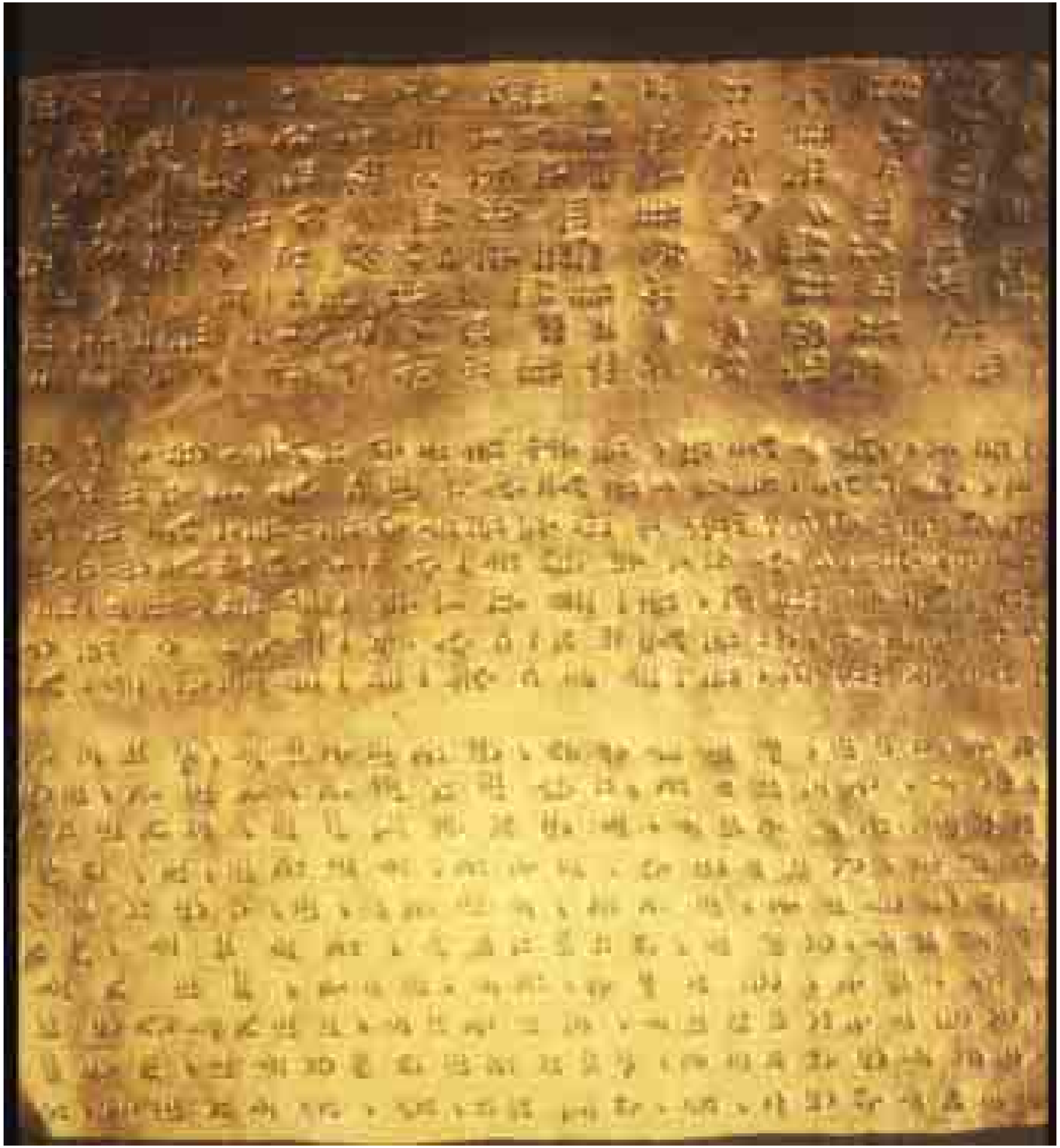
GOLD WORLD MINE PRODUCTION 2008 (2,330 t)



SILVER WORLD MINE PRODUCTION 2007 (20,500 t)

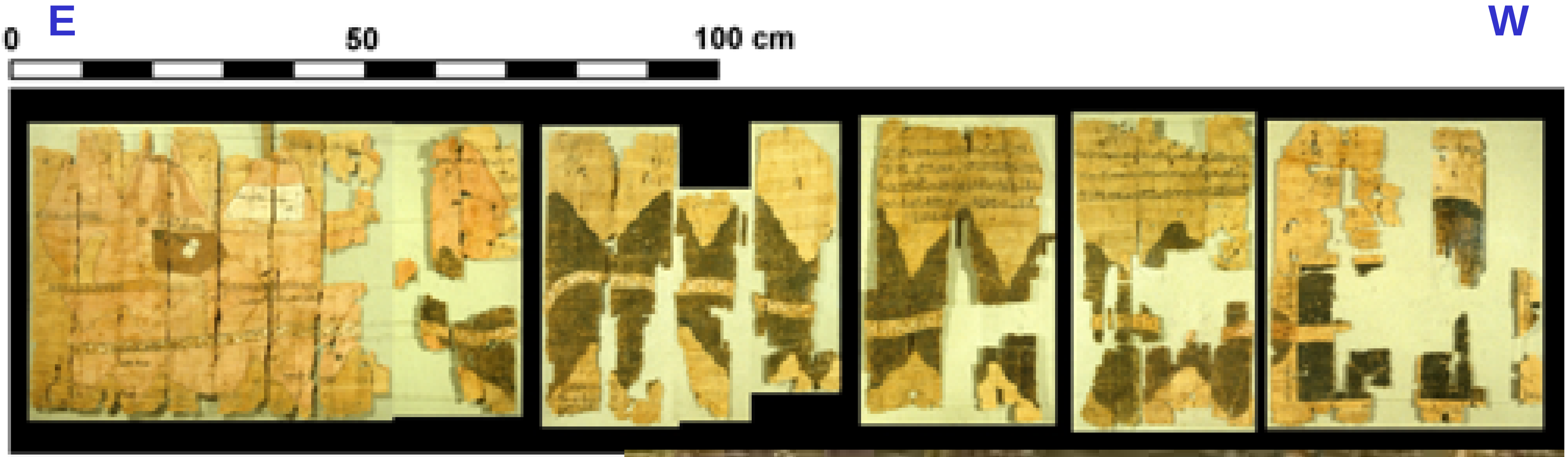


Gold coin with image of Justin II (c. 520 – 578 AC), 4.49 g



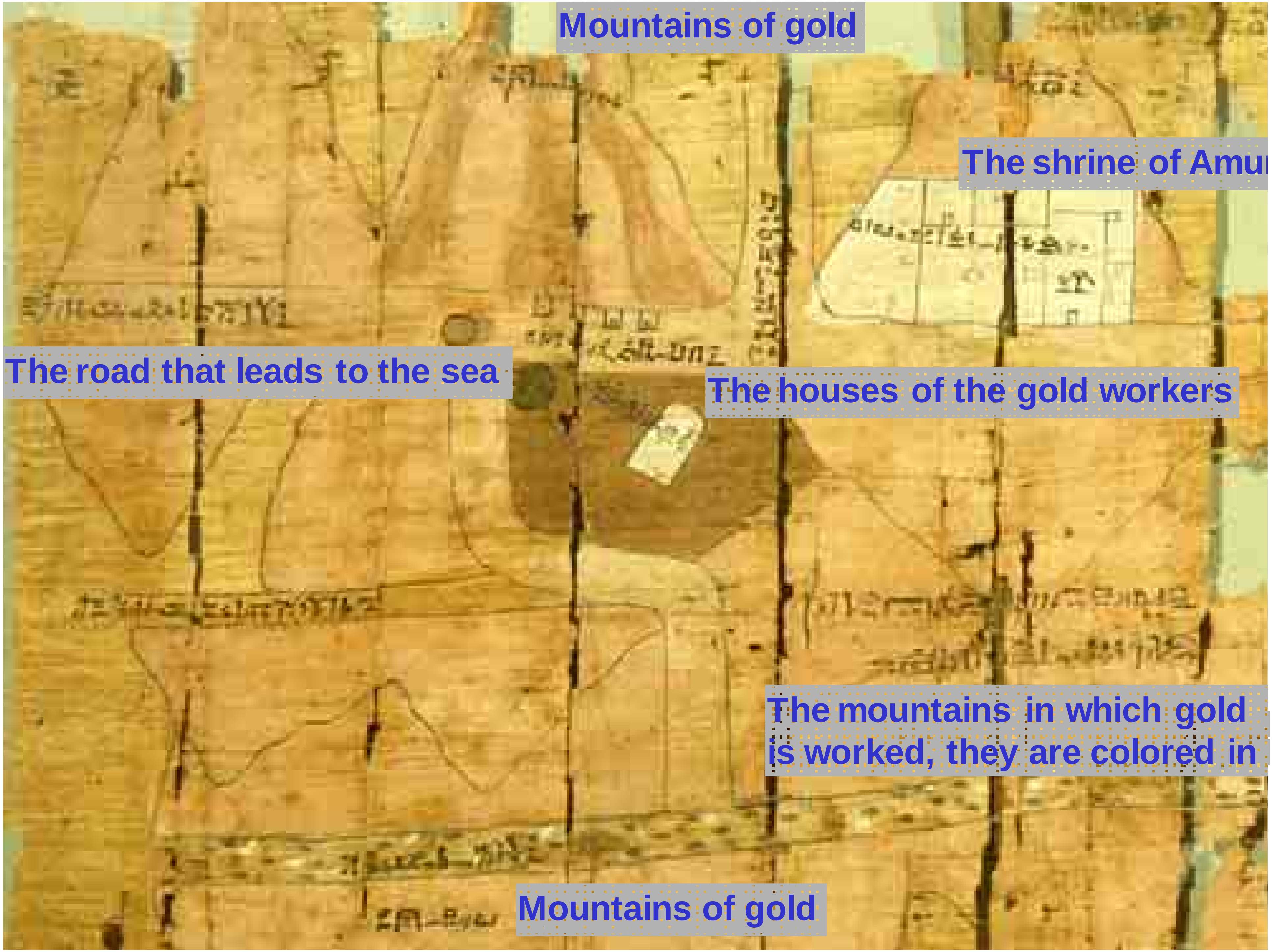
Darius I, Persia
6th century A.D.

Mediterranean Sea
ISRAEL
JORDAN
Cairo
Sinai
EGYPT
Nile
River
SAUDI
ARABIA
El-Minya
EASTERN
Assiut
Wadi Hammamat
Red Sea
Deir el-Medina and
the Valley of Kings
Luxor
DESERT
LIBYA
N
Edfu
Aswan
Lake
Nasser
0 50 100 150 200 250 KM
SUDAN

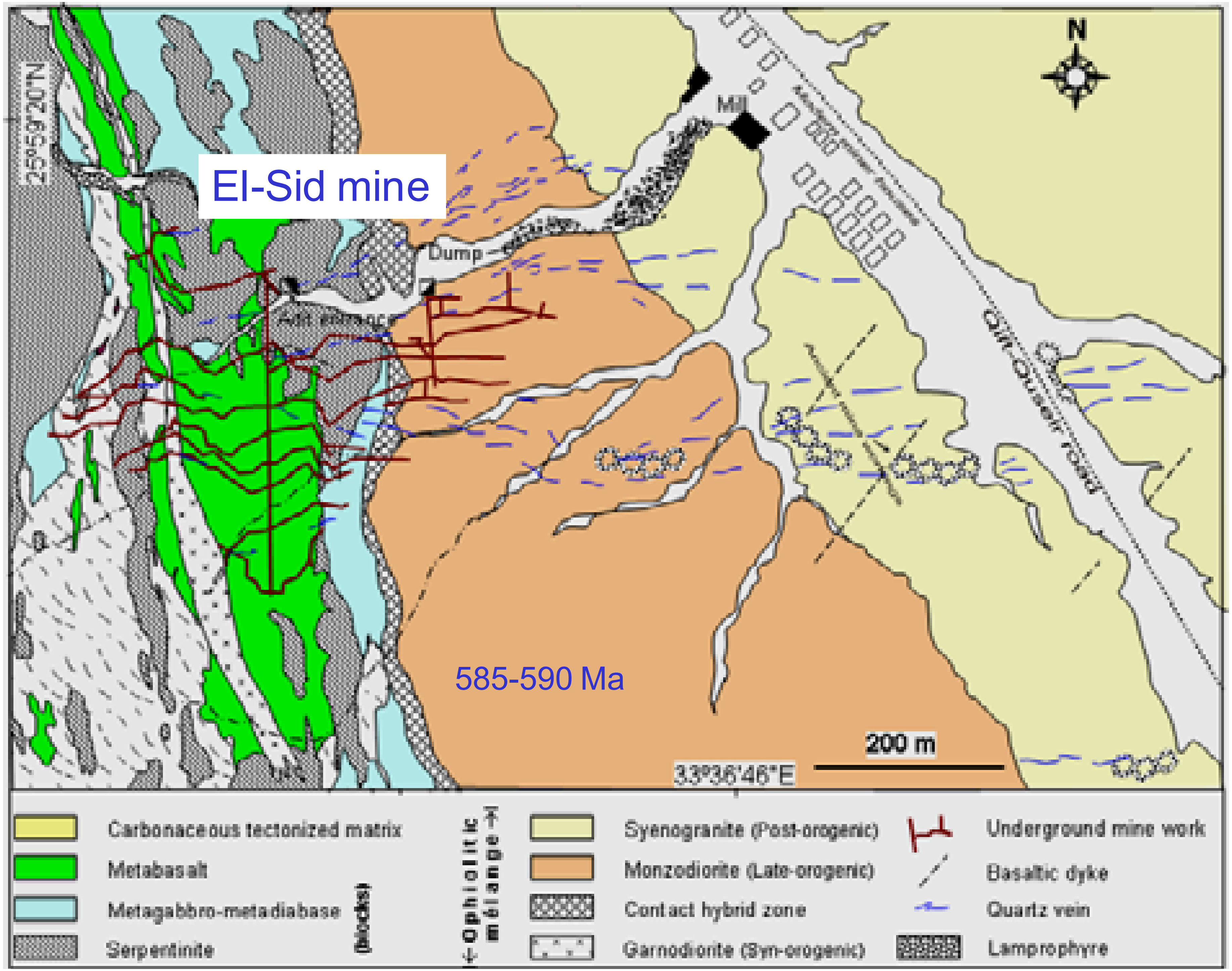


„Turin papyrus map“
Museo Egizio, Turin

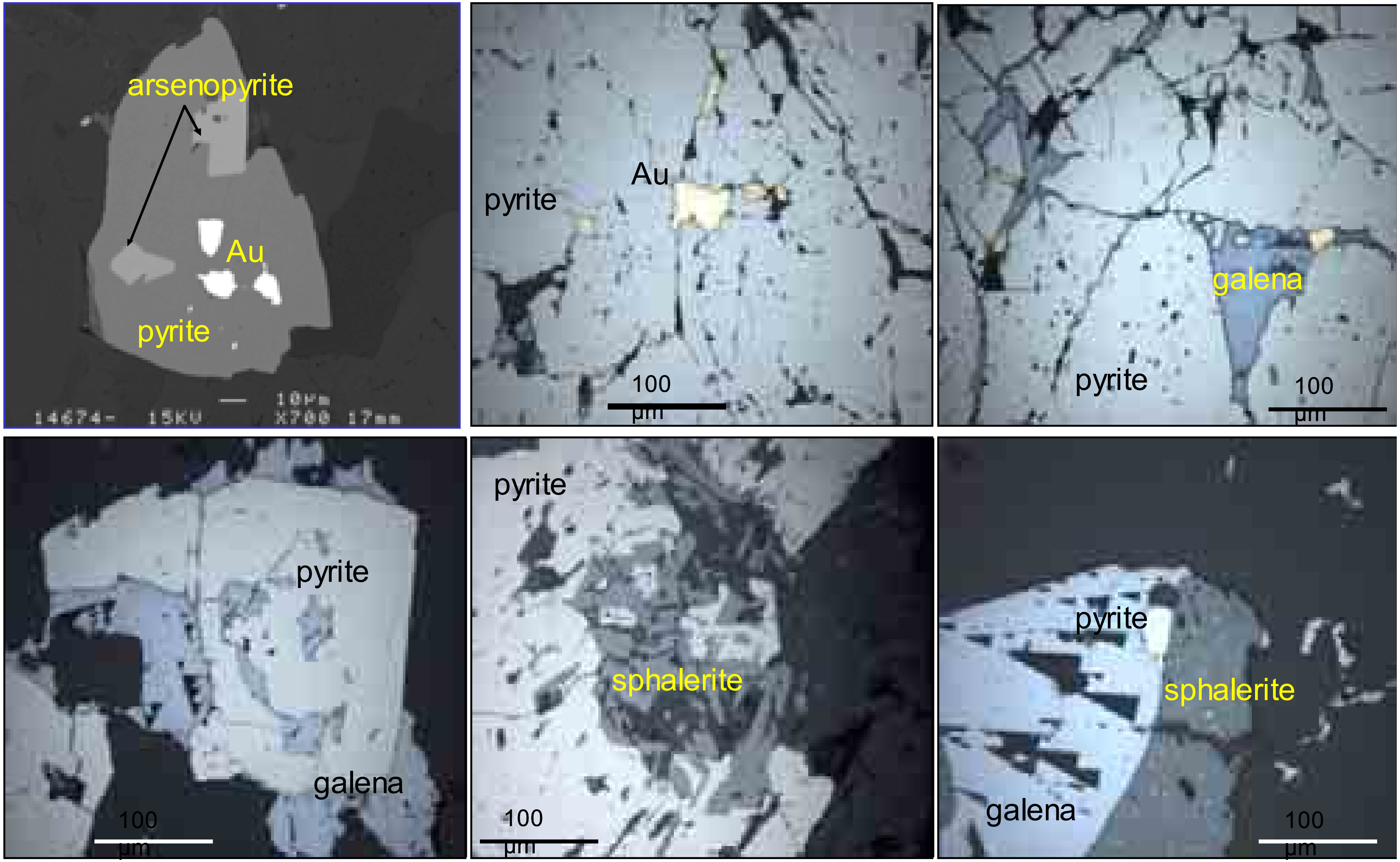
Length of Wadi Hammamat (Valley of the Many Baths) shown is ~15 km.
Made by the well-known ‘Scribe of the Tomb‘ Amennakhte in 1150 BC
First topographic and geologic map


Mountains of gold
The shrine of Amu
The road that leads to the sea
The houses of the gold workers
The mountains in which gold
is worked, they are colored in
Mountains of gold


Old settlements


El-Sid mine
N
25°59'20"N
Mill
Dump
Adit entrance
Qift-Quseir Road
585-590 Ma
200 m
33°36'46"E
Carbonaceous tectonized matrix
Metabasalt
Metagabbro-metadiabase
Serpentinite
(blocks)
Ophiolitic mélange
Syenogranite (Post-orogenic)
Monzodiorite (Late-orogenic)
Contact hybrid zone
Granodiorite (Syn-orogenic)
Underground mine work
Basaltic dyke
Quartz vein
Lamprophyre

El-Sid mine in 1950
(produced 3 t Au from 1940-1955, with an ore grade of 28 g/t Au)



Ore microscopic features of the El-Sid deposit

Small-scale placer mining, Karen State, Burma

Karen State, Burma

Woxi,
Hunan,
China

Pongkor, Java, Indonesia

Pongkor, Java, Indonesia

5 Mt @ 12 g/t Au + 137 g/t Ag
(cut-off 4 g/t Au)

Annual production:
3-4 t Au, 21-28 t Ag

Epithermal quartz vein system
(quartz-carbonate-adularia),
2 Ma old

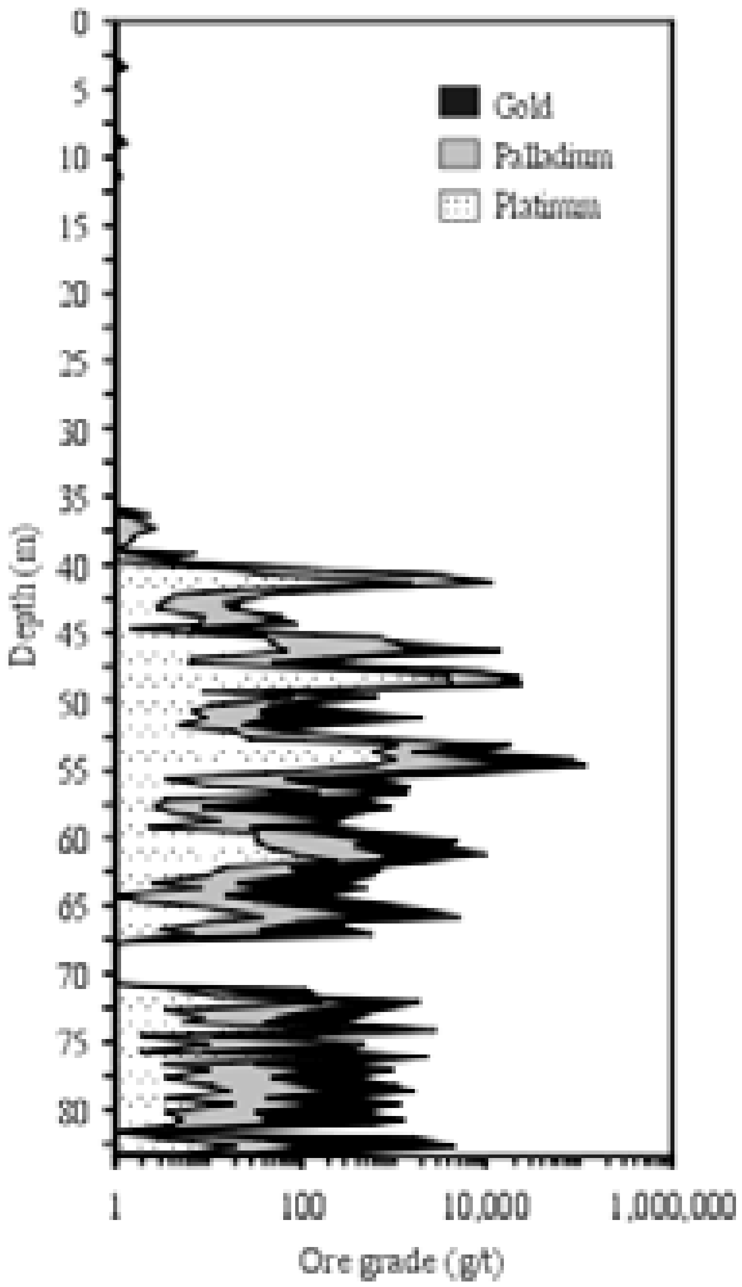
Pongkor,
Java,
Indonesia


Gold rush in Mongolia in 2005

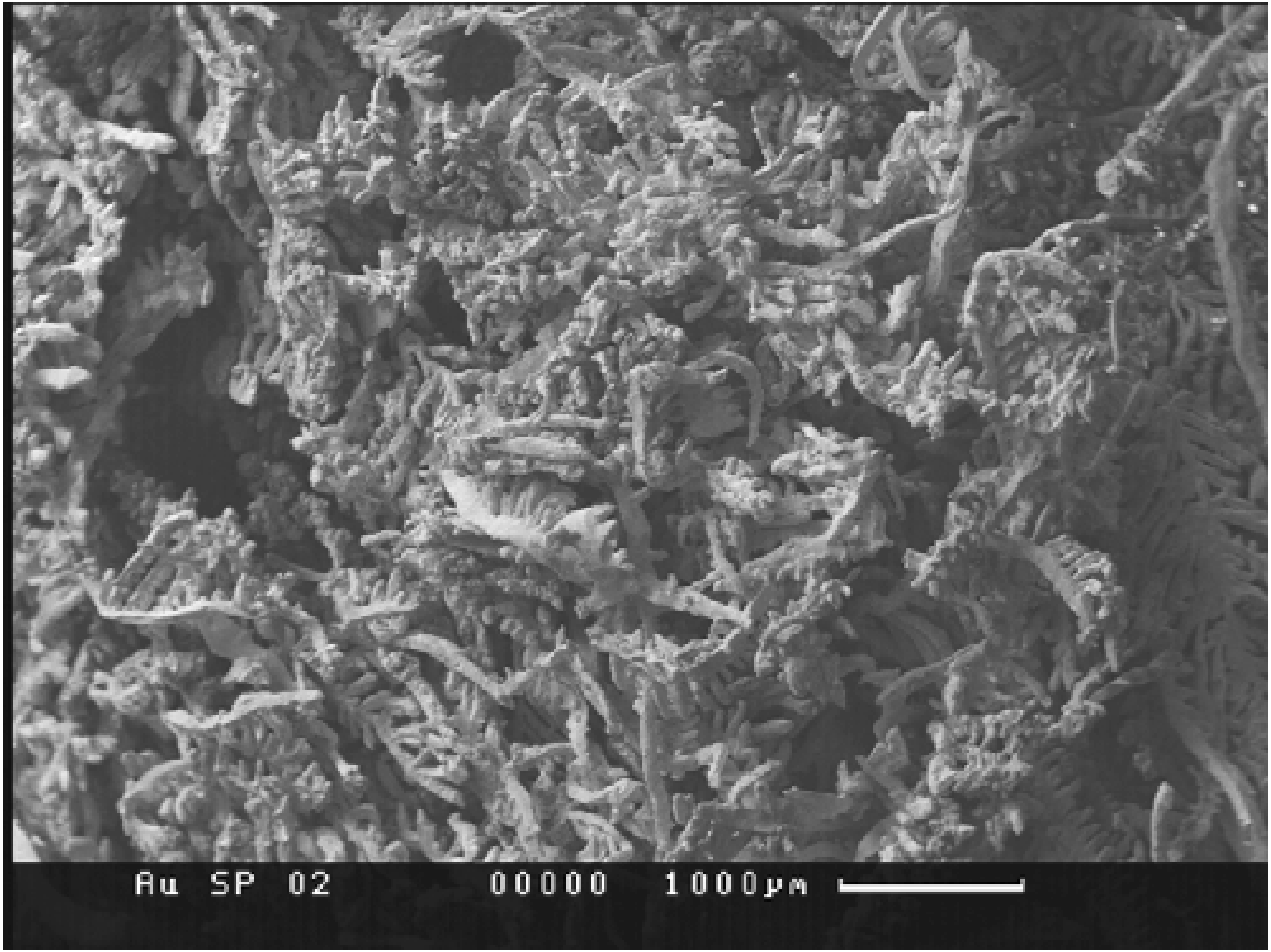
Serra Pelada garimpo, Carajas, Brazil: 60-70 t gold (1980-1984)

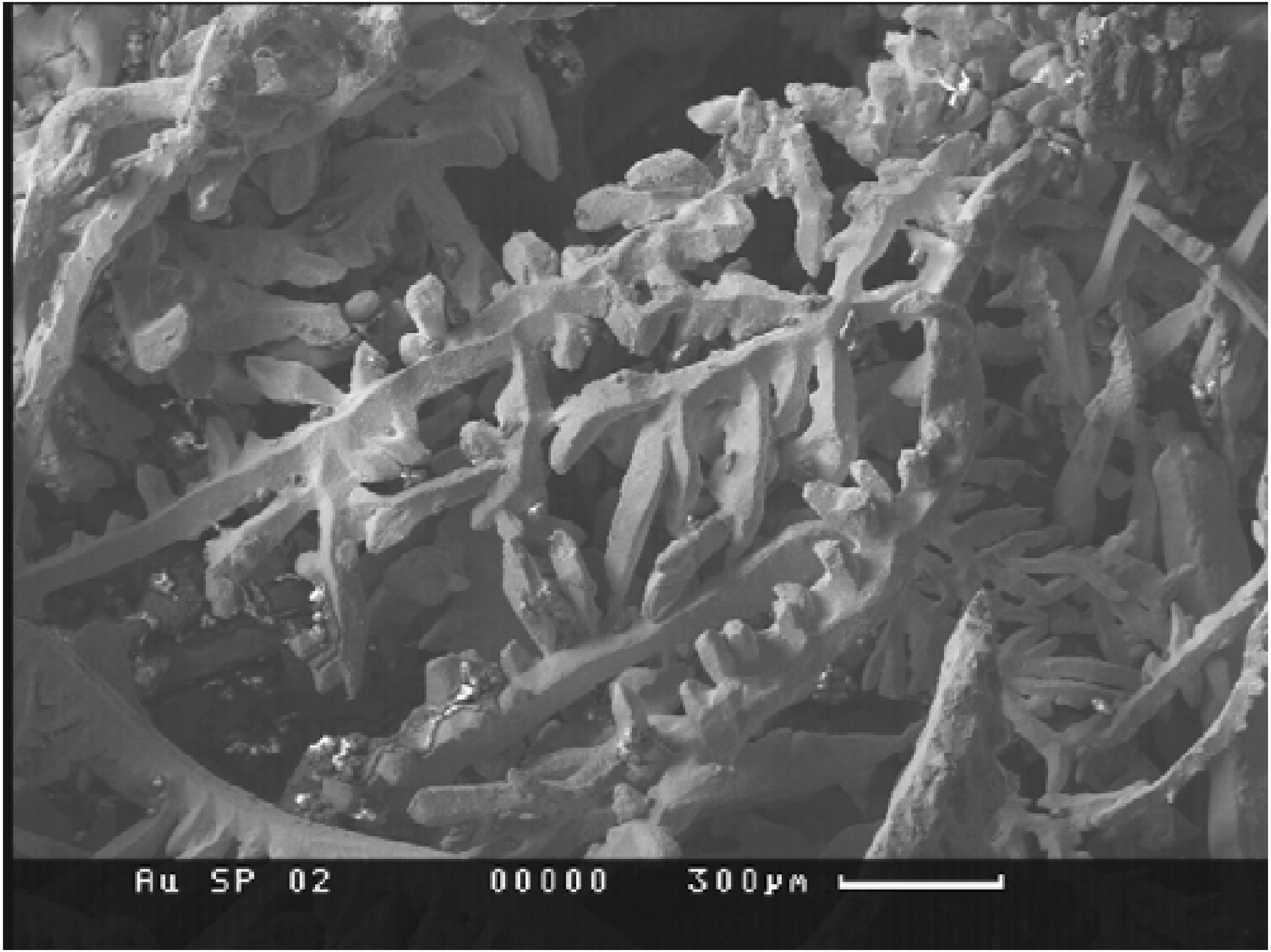
Serra Pelada
(1983)
Carajás, Brazil

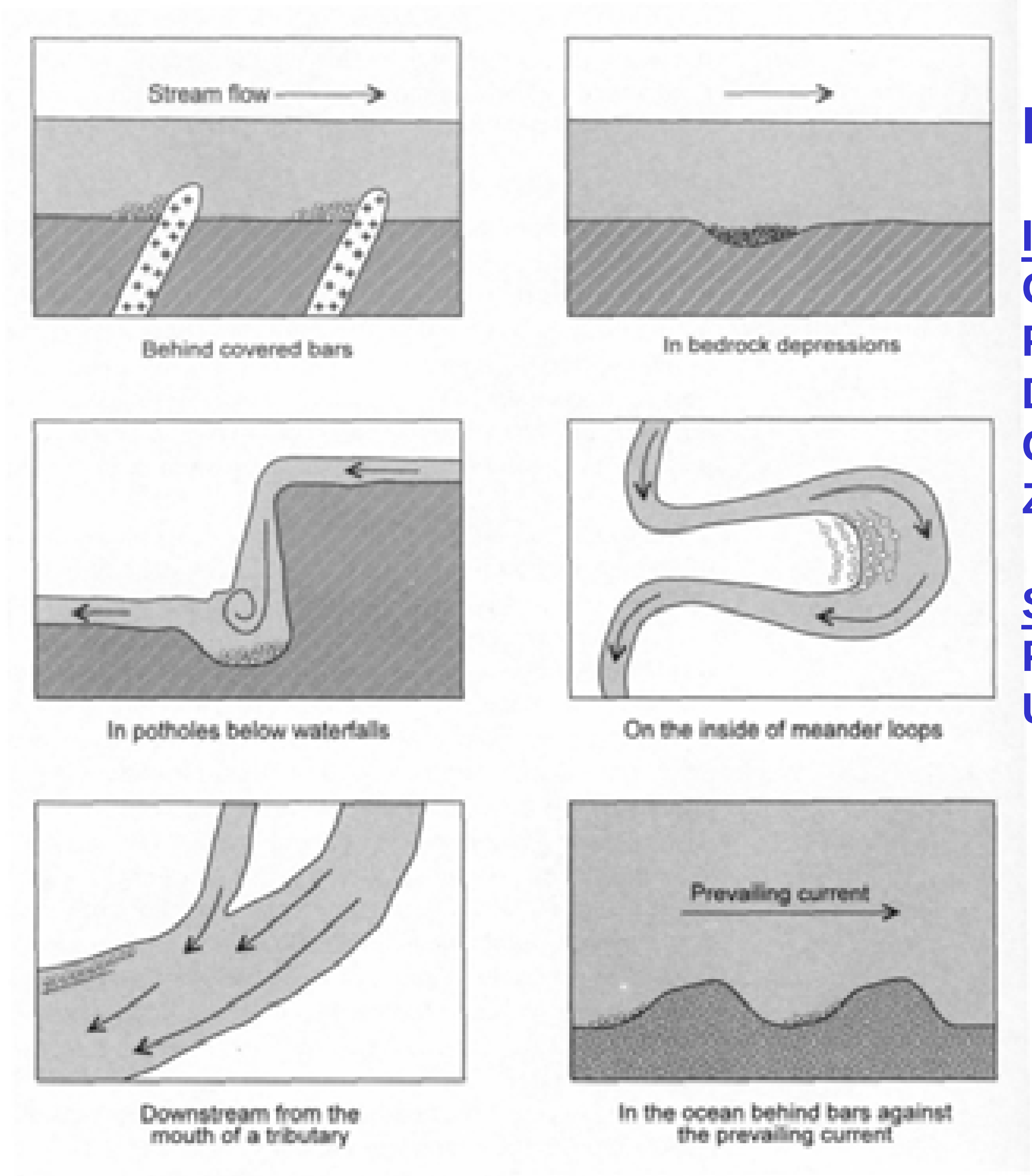
Serra Pelada bonanza gold, drillcore SP-32, sampled over 50 cm intervals



Cabral et al., Econ Geol 97: 1132 (2002)


Au SP 02
00000 1000μm


Au SP 02
00000
300µm

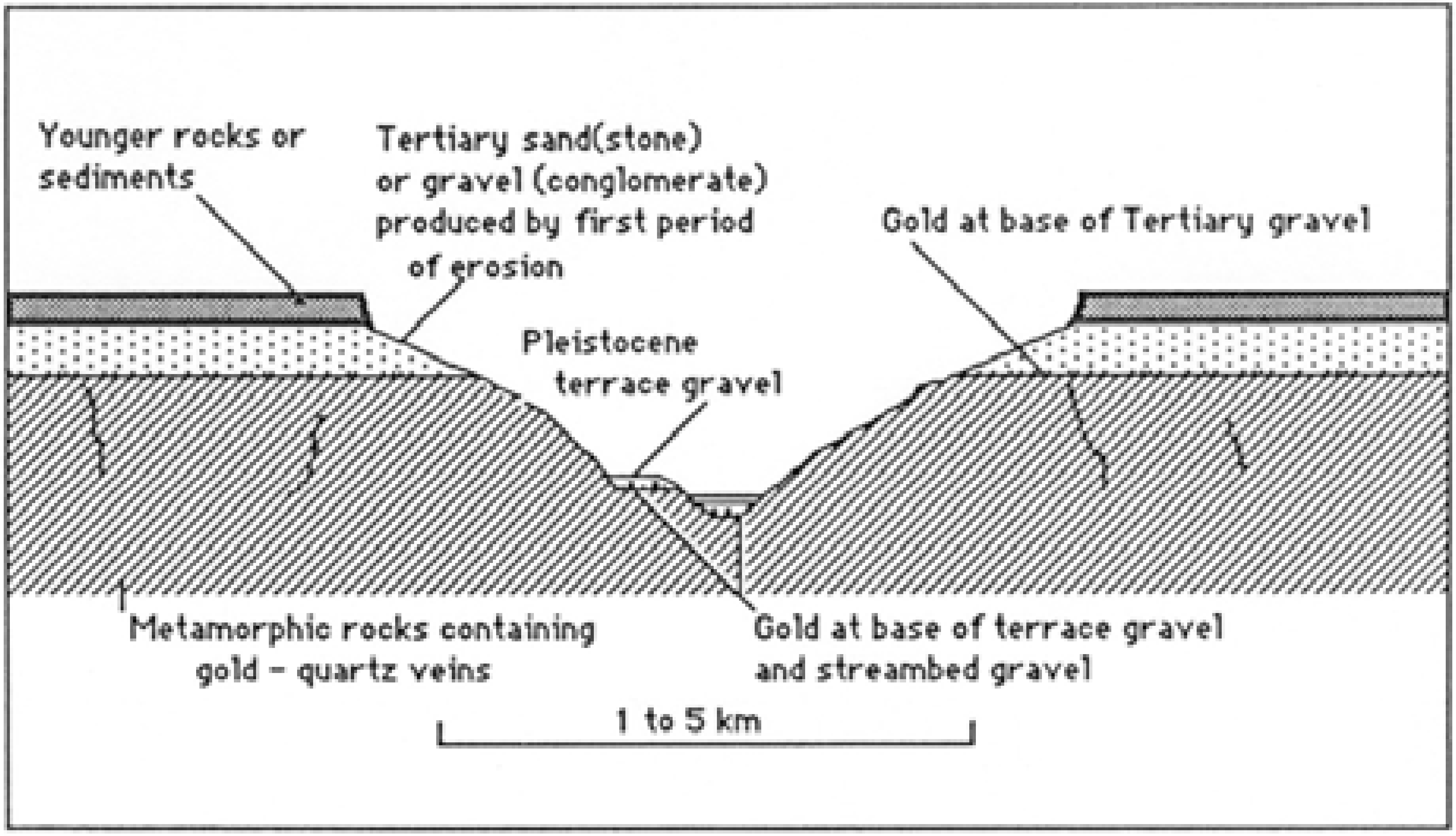


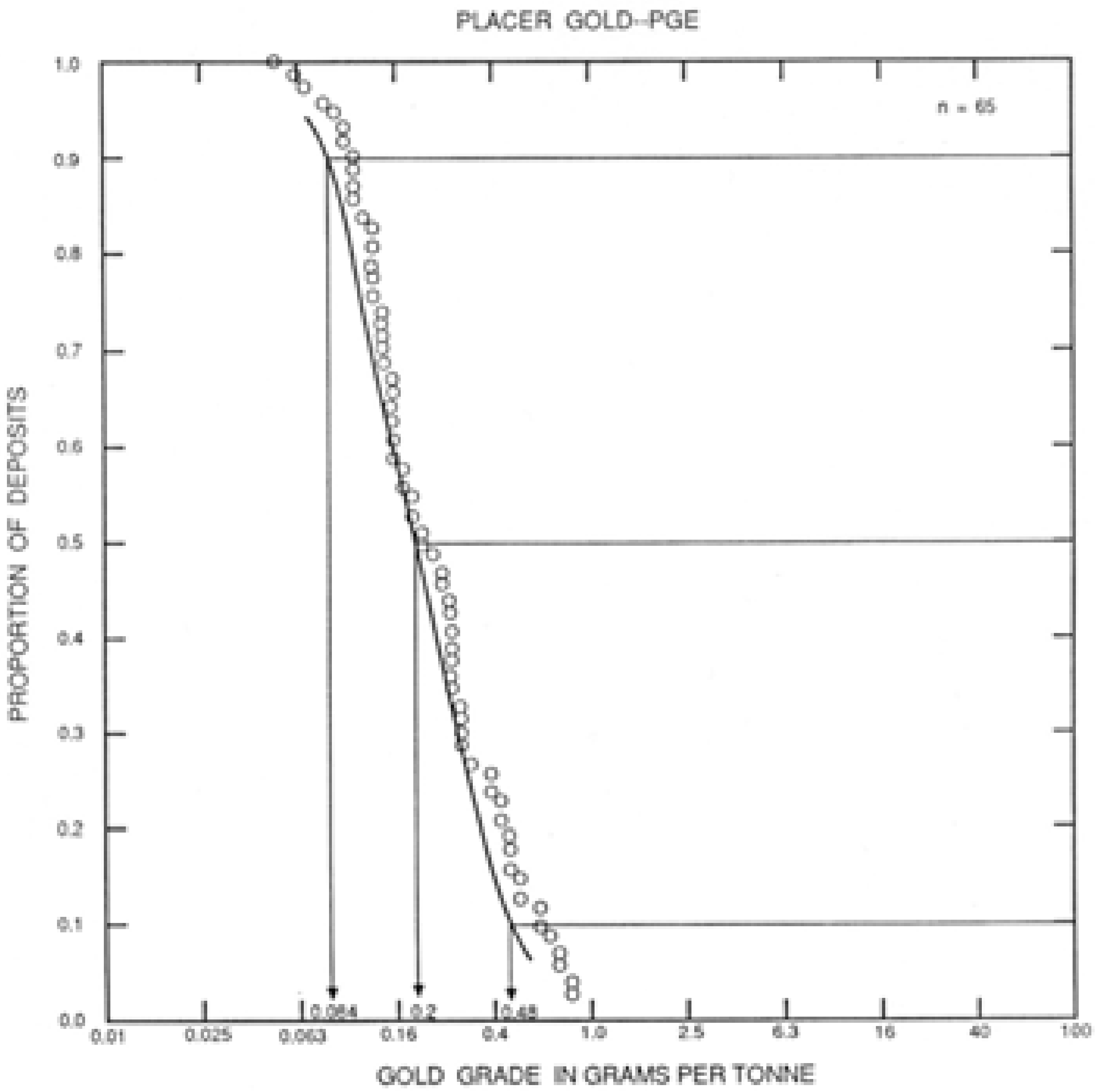
Heavy minerals:

Insoluble:
Gold (17-19 g/cm^3)
Pt-Fe alloy (18-21 g/cm^3)
Diamond (3.5 g/cm^3)
Cassiterite (7.0 g/cm^3)
Zircon (4.7 g/cm^3)

Soluble:
Pyrite (5.0 g/cm^3)
Uraninite (11 g/cm^3)

Placer deposits

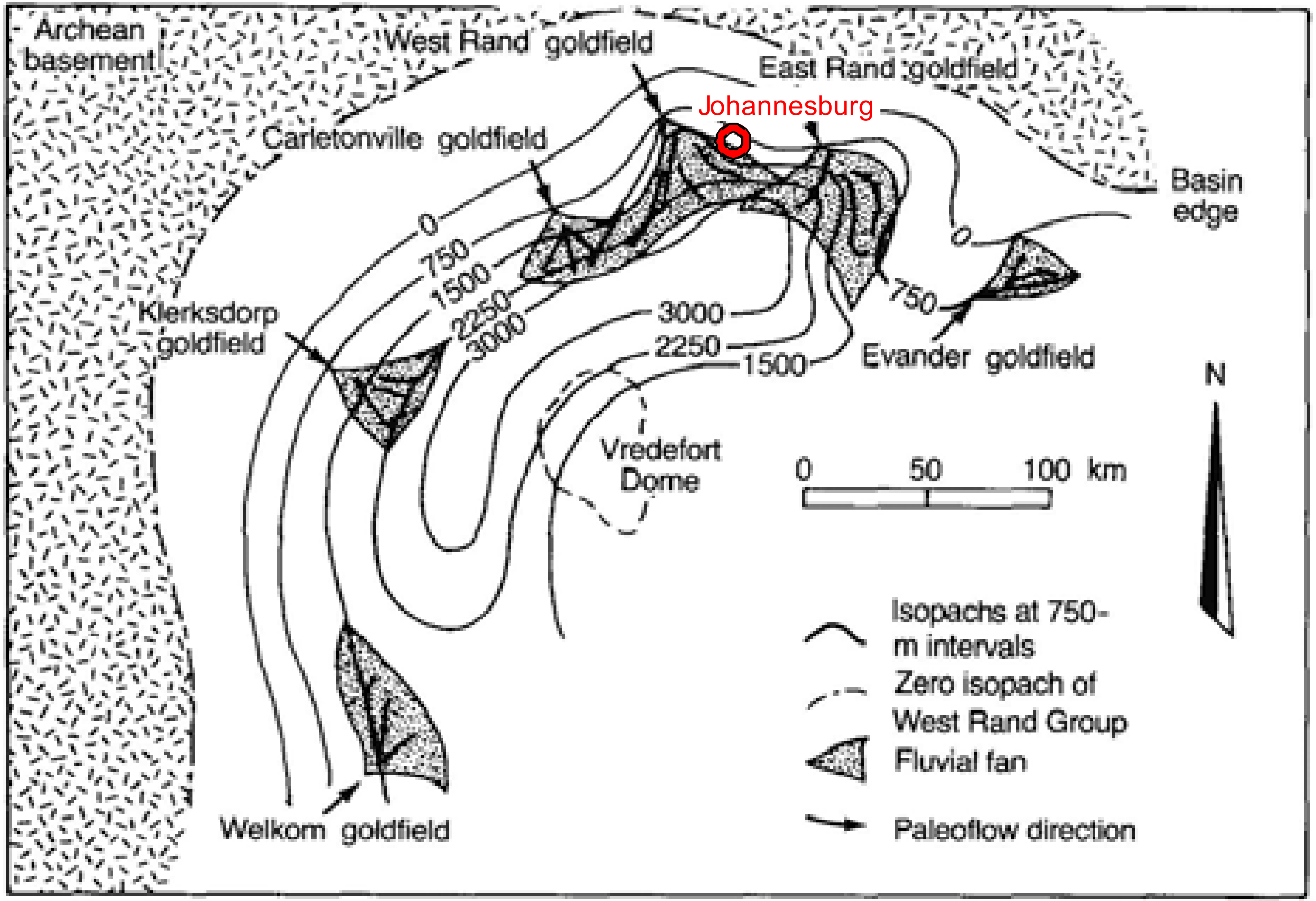




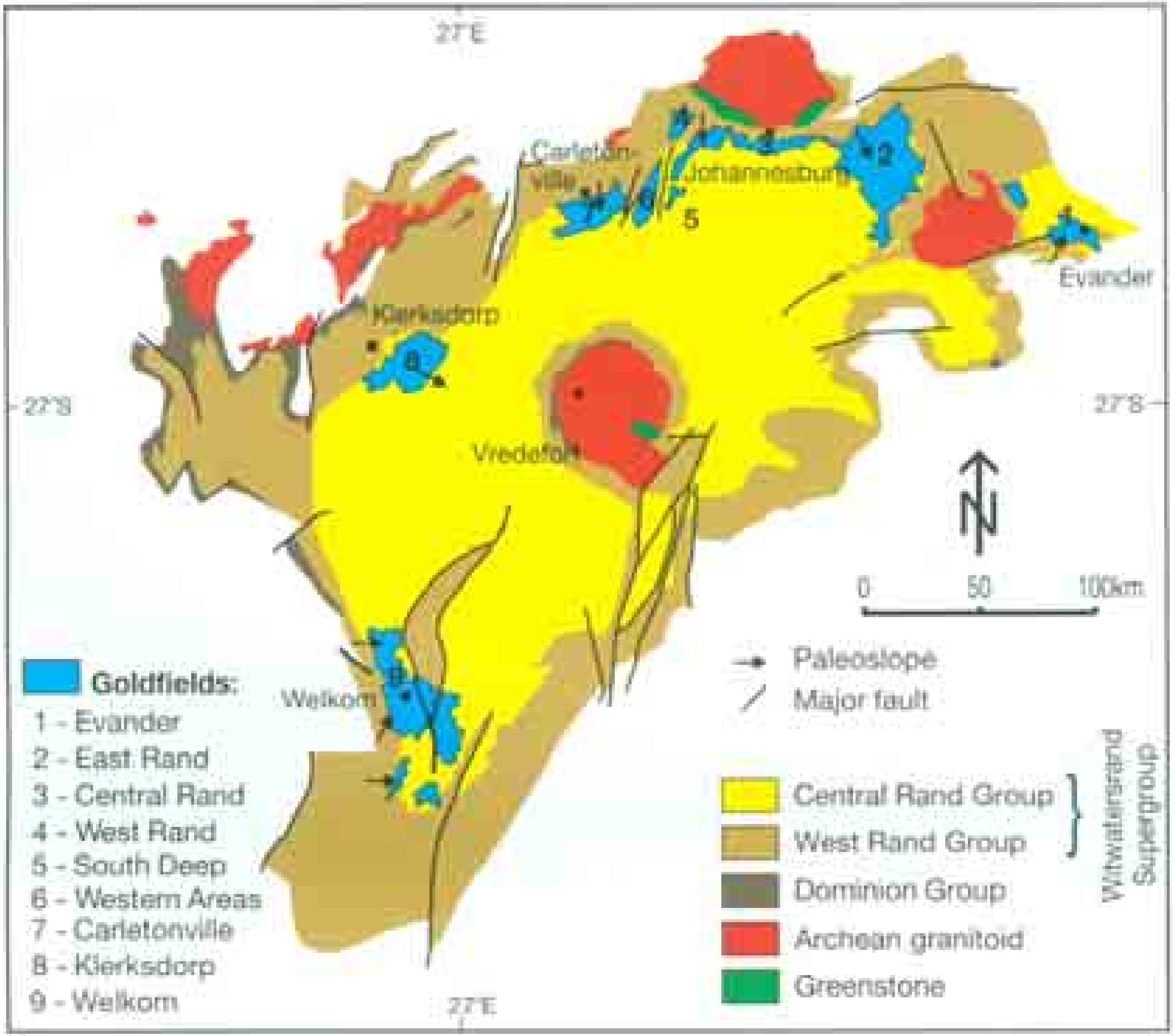
Distribution of ore grade:

80 % of all deposits are in the range of 0.1-0.4 g/t Au

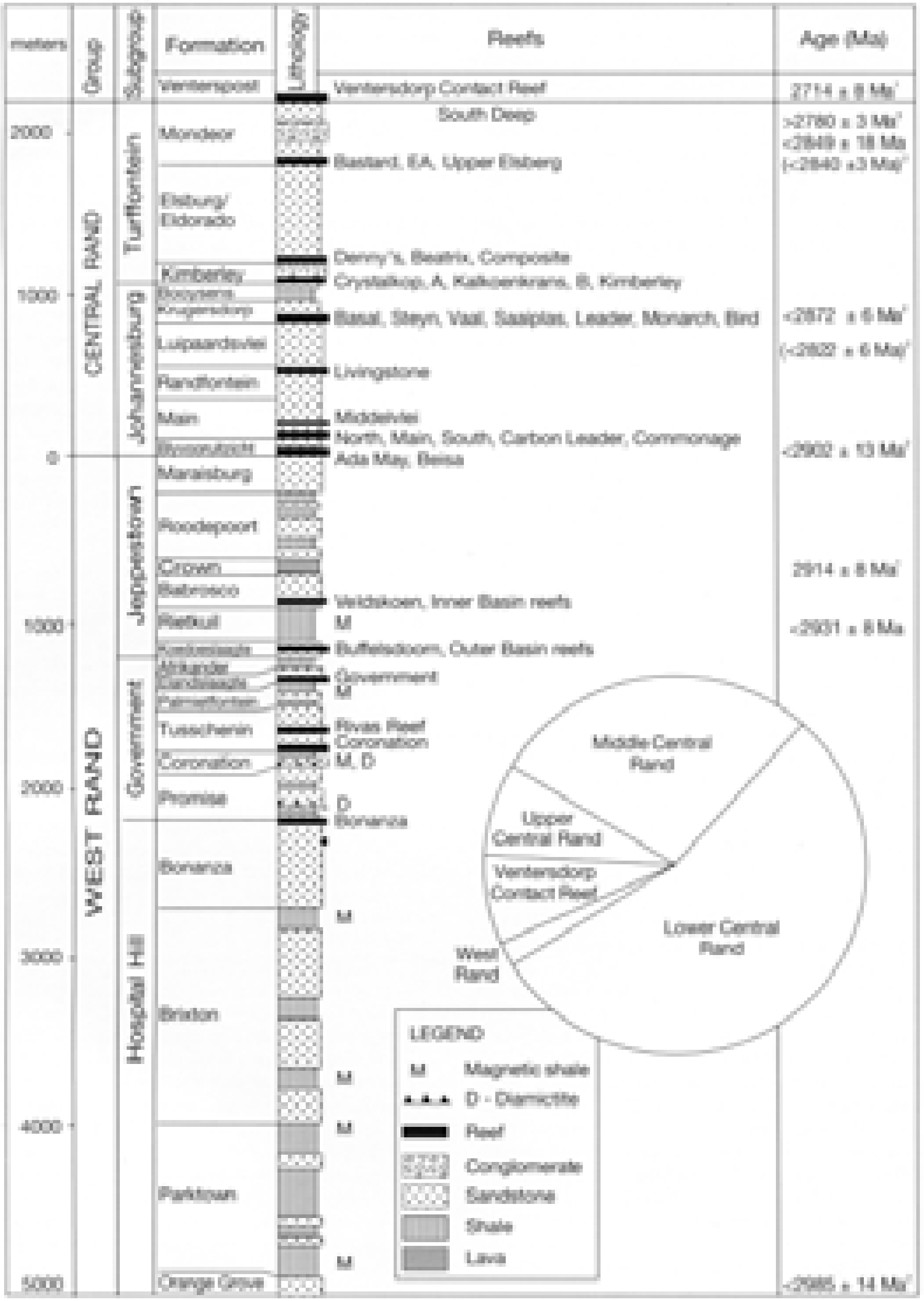
But Witwatersrand: 8 g/t Au!



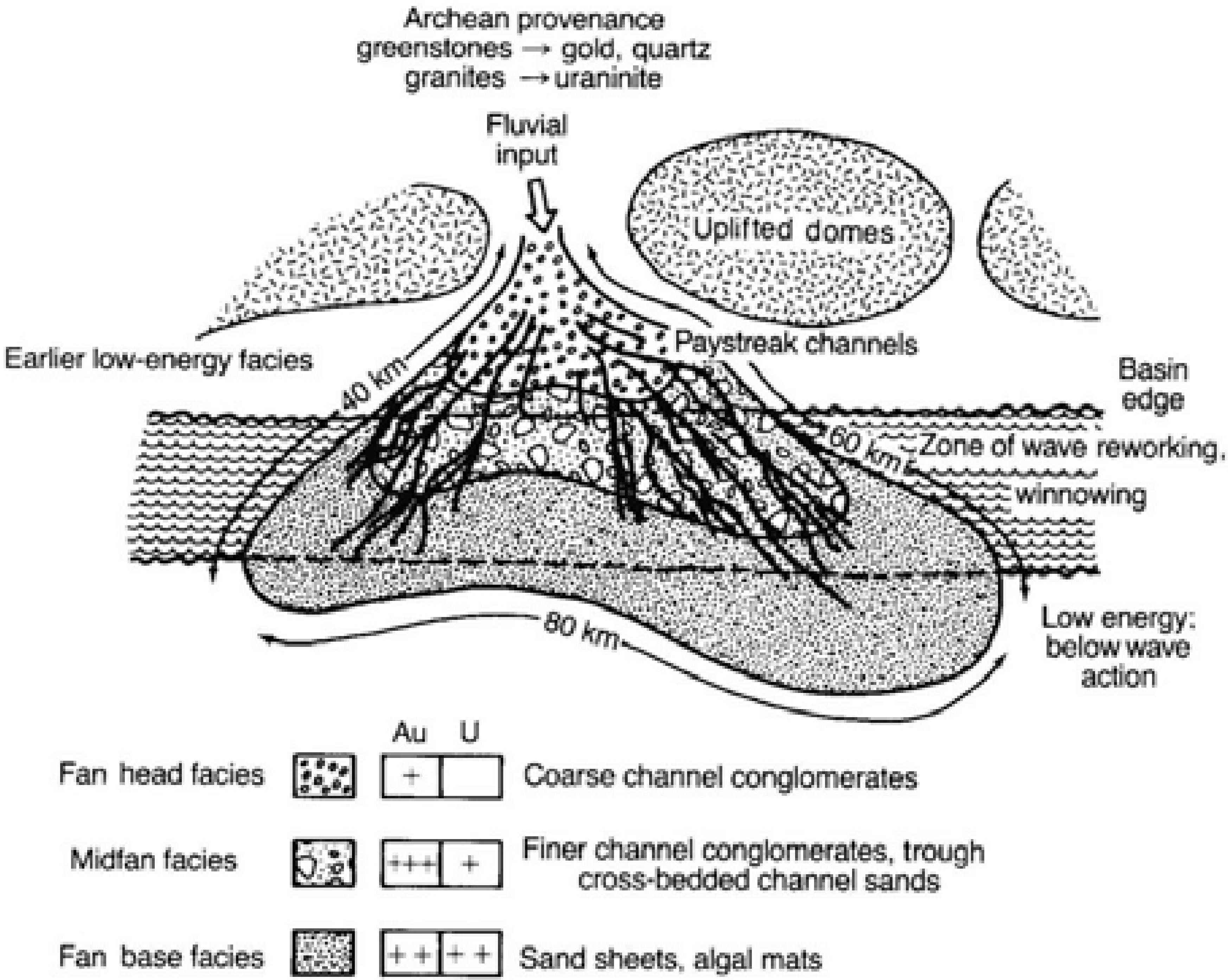
Archean basement
West Rand goldfield
East Rand goldfield
Johannesburg
Carletonville goldfield
Basin edge
0
750
1500
2250
3000
Klerksdorp goldfield
3000
2250
1500
750
0
Evander goldfield
N
Vredefort Dome
0 50 100 km
Isopachs at 750-m intervals
Zero isopach of West Rand Group
Fluvial fan
Paleoflow direction
Welkom goldfield


27°E
Carleton-ville
Johannesburg
5
2
Evander
Klerksdorp
8
27°S
27°S
Vredefort
0
50
100km
Paleoslope
Major fault
Goldfields:
1 - Evander
2 - East Rand
3 - Central Rand
4 - West Rand
5 - South Deep
6 - Western Areas
7 - Carletonville
8 - Klerksdorp
9 - Welkom
Welkom
27°E
Central Rand Group
West Rand Group
Dominion Group
Archean granitoid
Greenstone
Witwatersrand Supergroup

Witwatersrand Supergroup




1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 cm
http://www.e-sga.org



Archean provenance
greenstones → gold, quartz
granites → uraninite
Fluvial
input
Uplifted domes
Paystreak channels
Earlier low-energy facies
Basin
edge
40 km
60 km
Zone of wave reworking,
winnowing
80 km
Low energy:
below wave
action
Au
U
Fan head facies
+
Coarse channel conglomerates
Midfan facies
+++
+
Finer channel conglomerates, trough
cross-bedded channel sands
Fan base facies
++
++
Sand sheets, algal mats

Witwatersrand Basin:

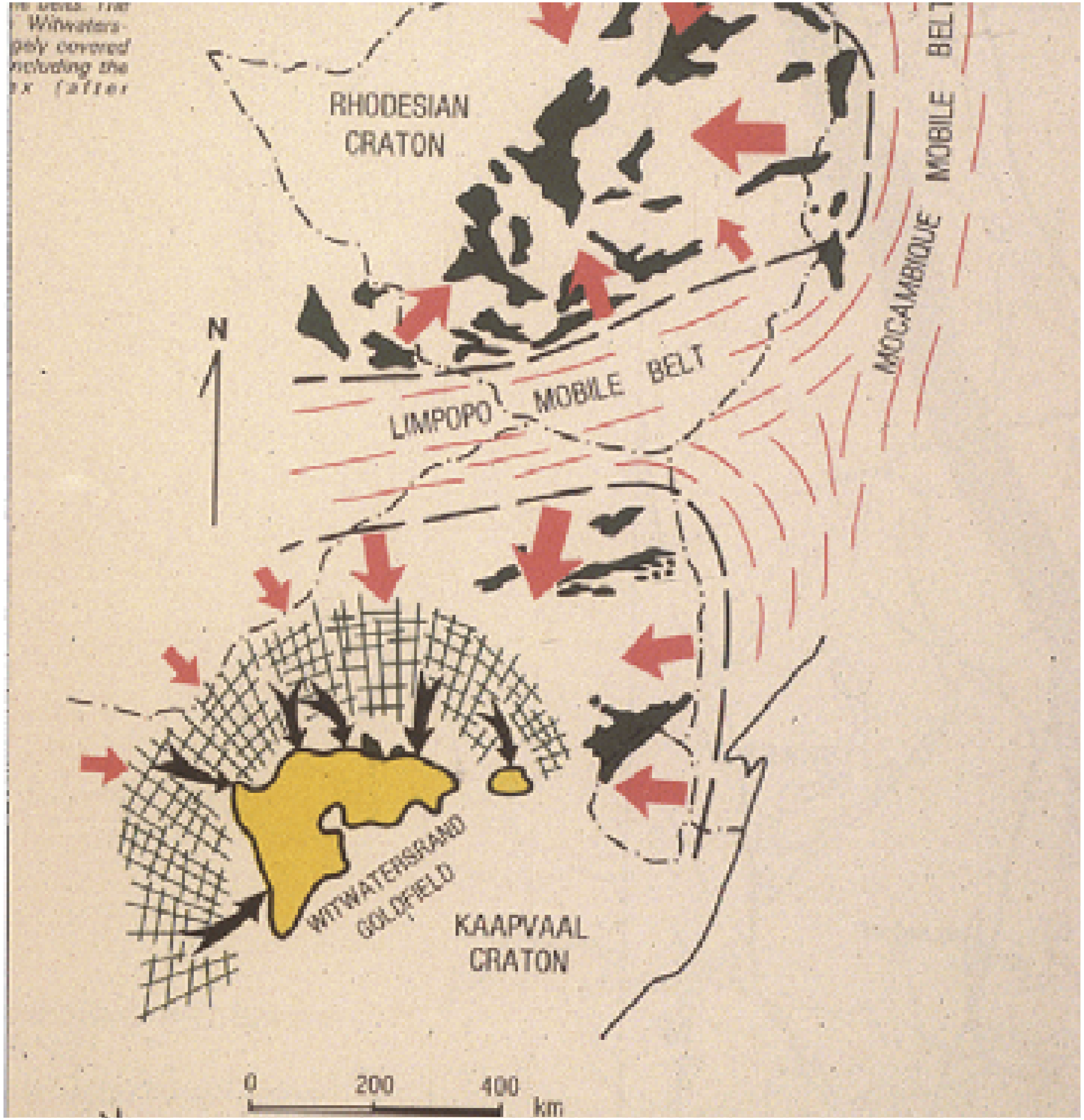
40 % of all gold mined, and 35 % of global gold resources

Gold-uranium bearing meta-conglomerate (2.89-2.76 Ga)
~8 g/t Au, 200 g/t U

Re-Os age of gold: 3.03 Ga

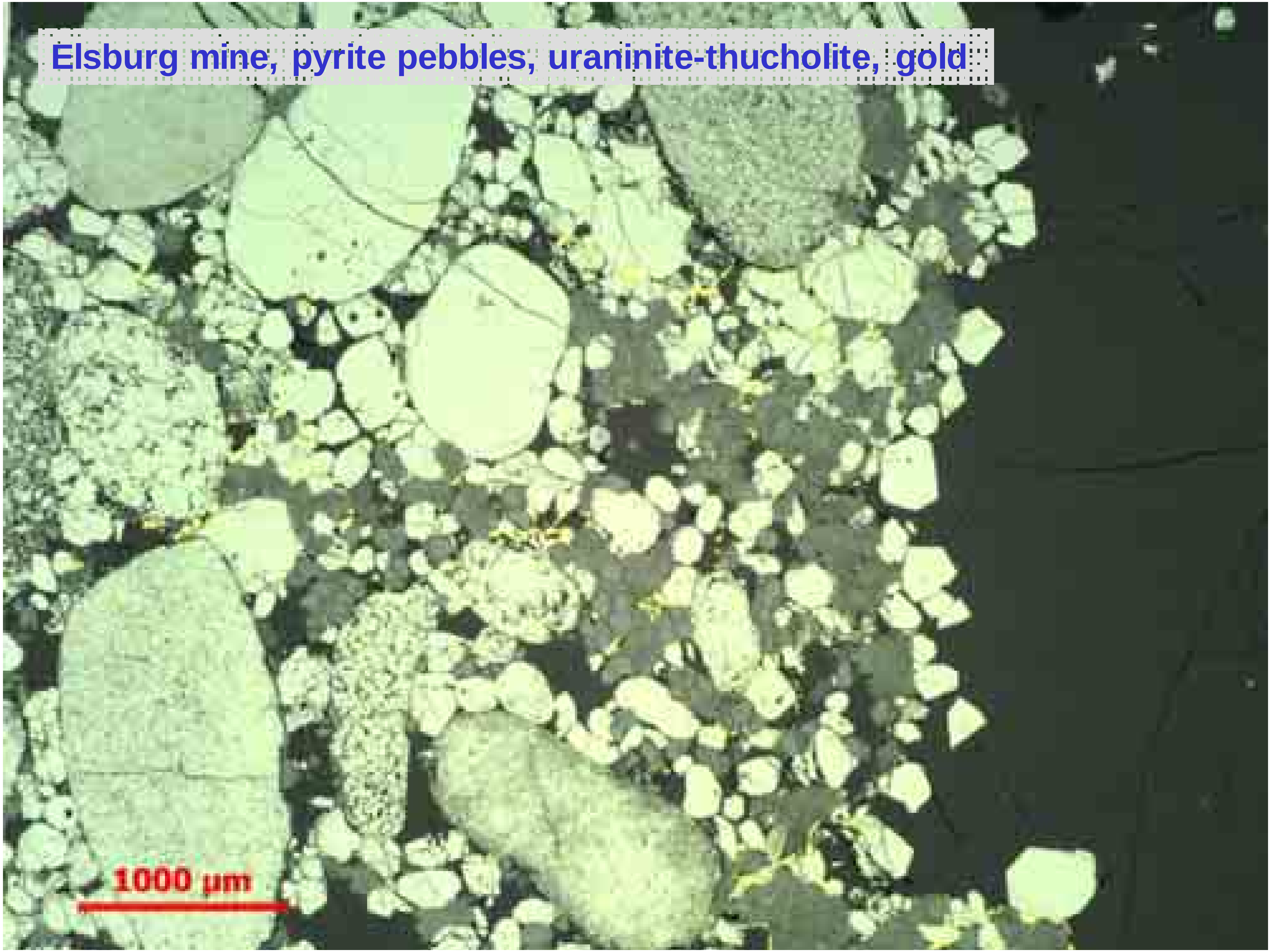
Kirk et al., Science 297: 1856 (2002)

Historical production 1887-today:
~55,000 t Au
[value 1600 billion USD in 2008]
60,000 fatal accidents

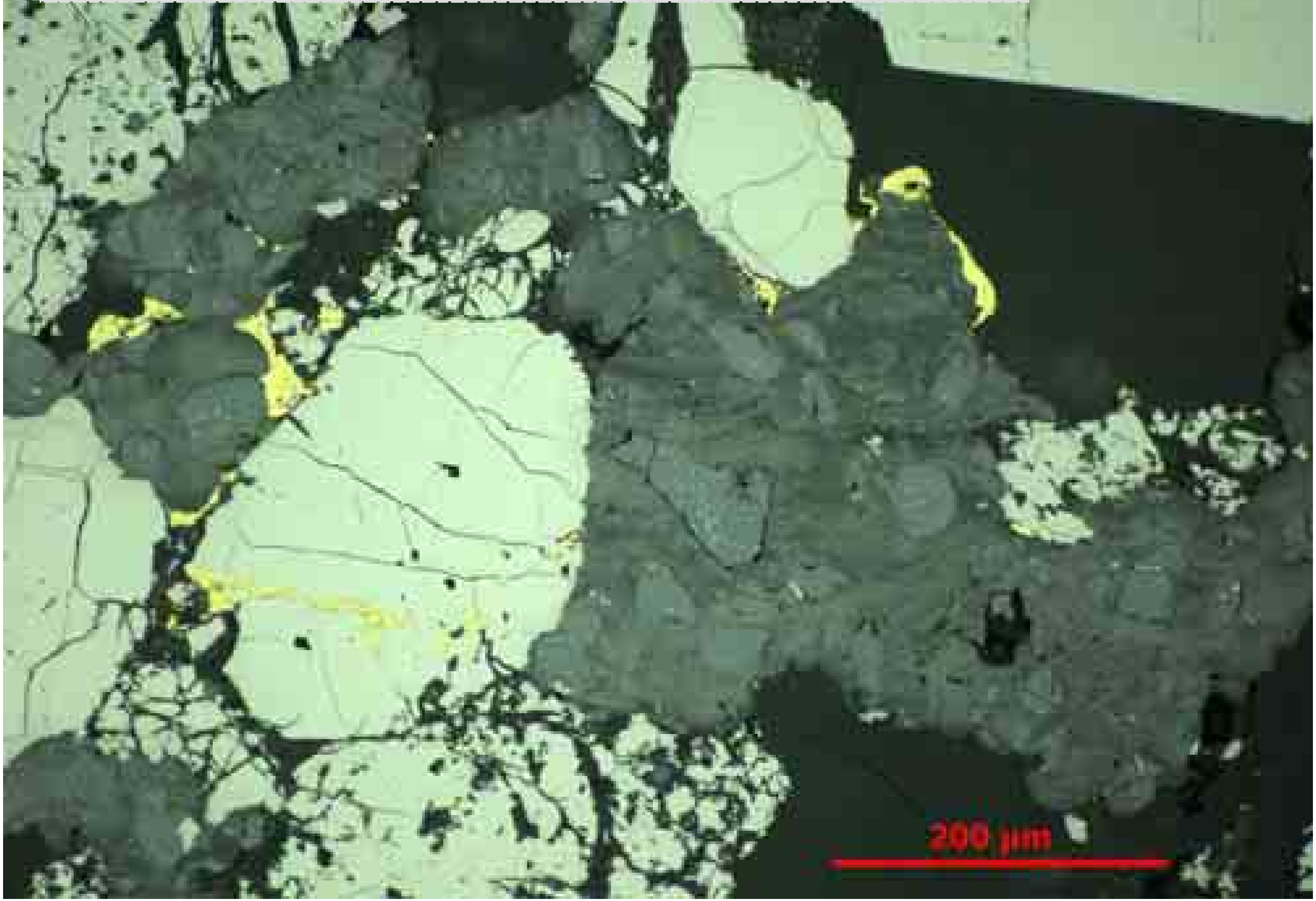



Amazon mine

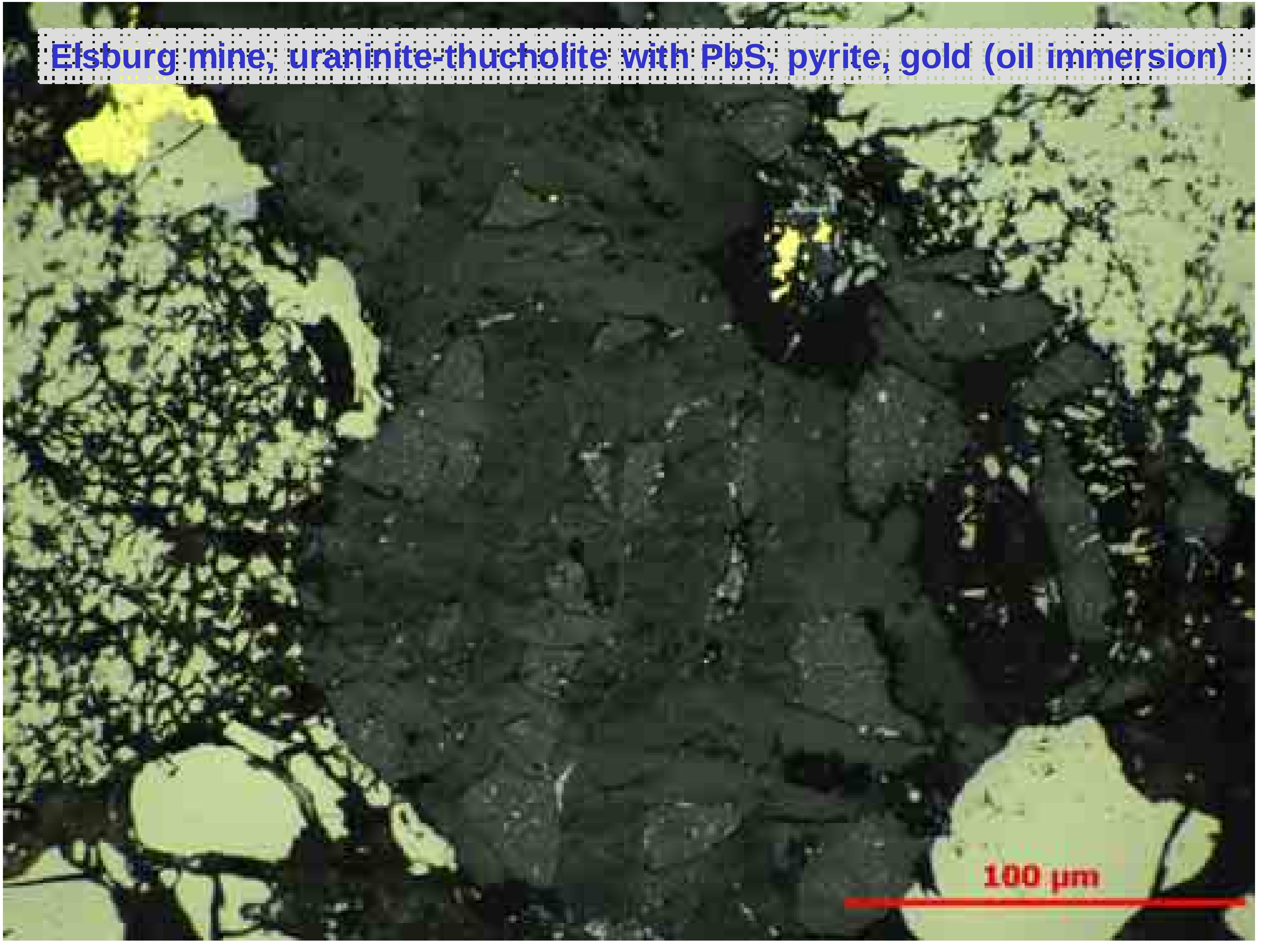
Mponeng mine: Ventersdorp Contact Reef (-3200 m), cut-off at 1000 g/t x cm
Overlying meta-basalt: 2714 ±8 Ma (SHRIMP U-Pb on zircon)


Elsburg mine, pyrite pebbles, uraninite-thucholite, gold
1000 µm

Elsburg mine, pyrite pebbles, uraninite-thucholite, gold

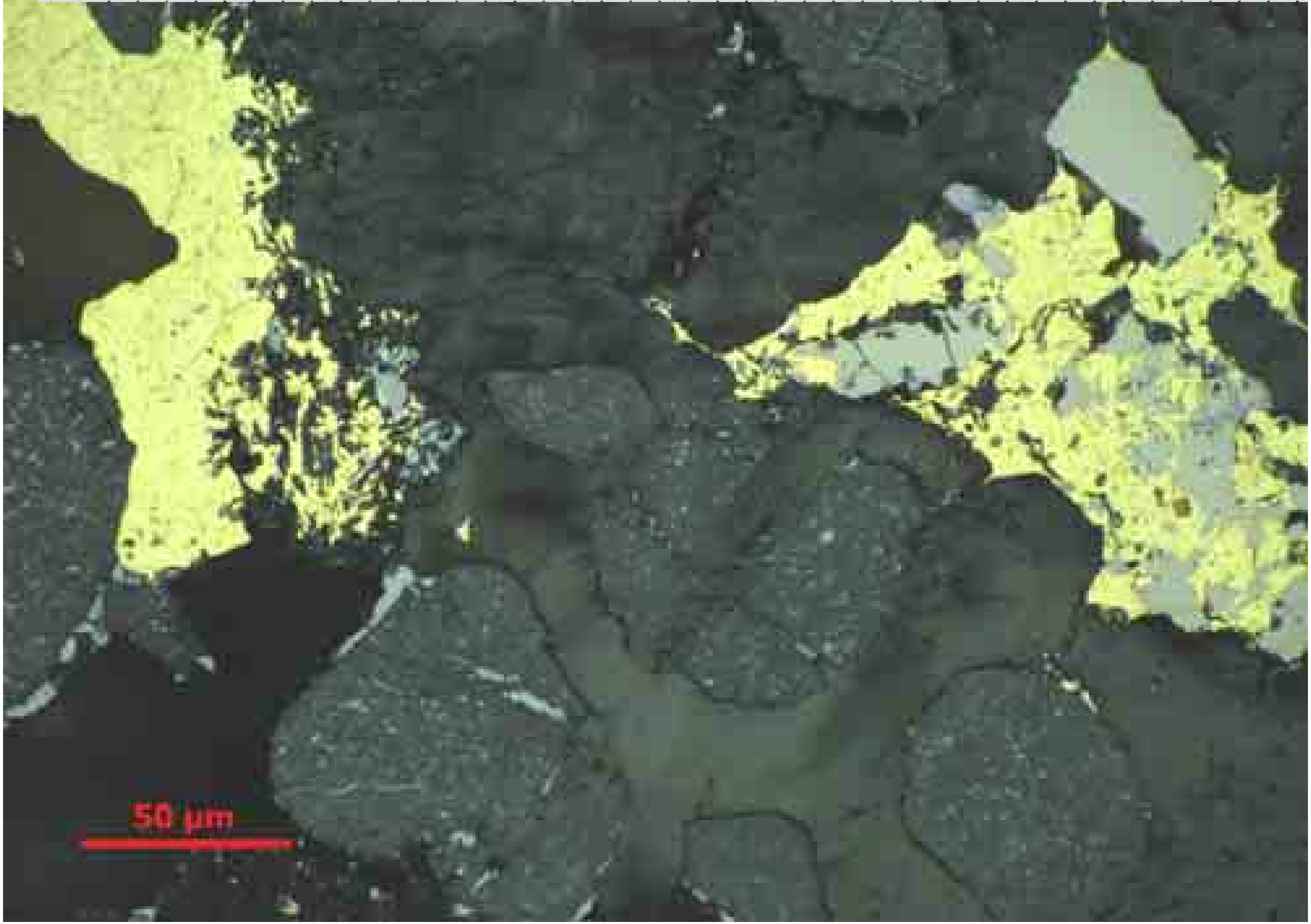


Elsburg mine, uraninite-thucholite with PbS, pyrite, gold (oil immersion)




Elsburg mine, pyrite, uraninite-thucholite with PbS, gold (oil immersion)
100 µm

Elsburg mine, pyrite, uraninite-thucholite with PbS, gold (oil immersion)



The Great Oxidation Event (GOE): 2.4-2.0 Ga

Oxygen from photosynthesis is essentially fixed in Fe-oxides and gypsum. Free oxygen in the atmosphere (>10^{-5} PAL) only after the GOE.

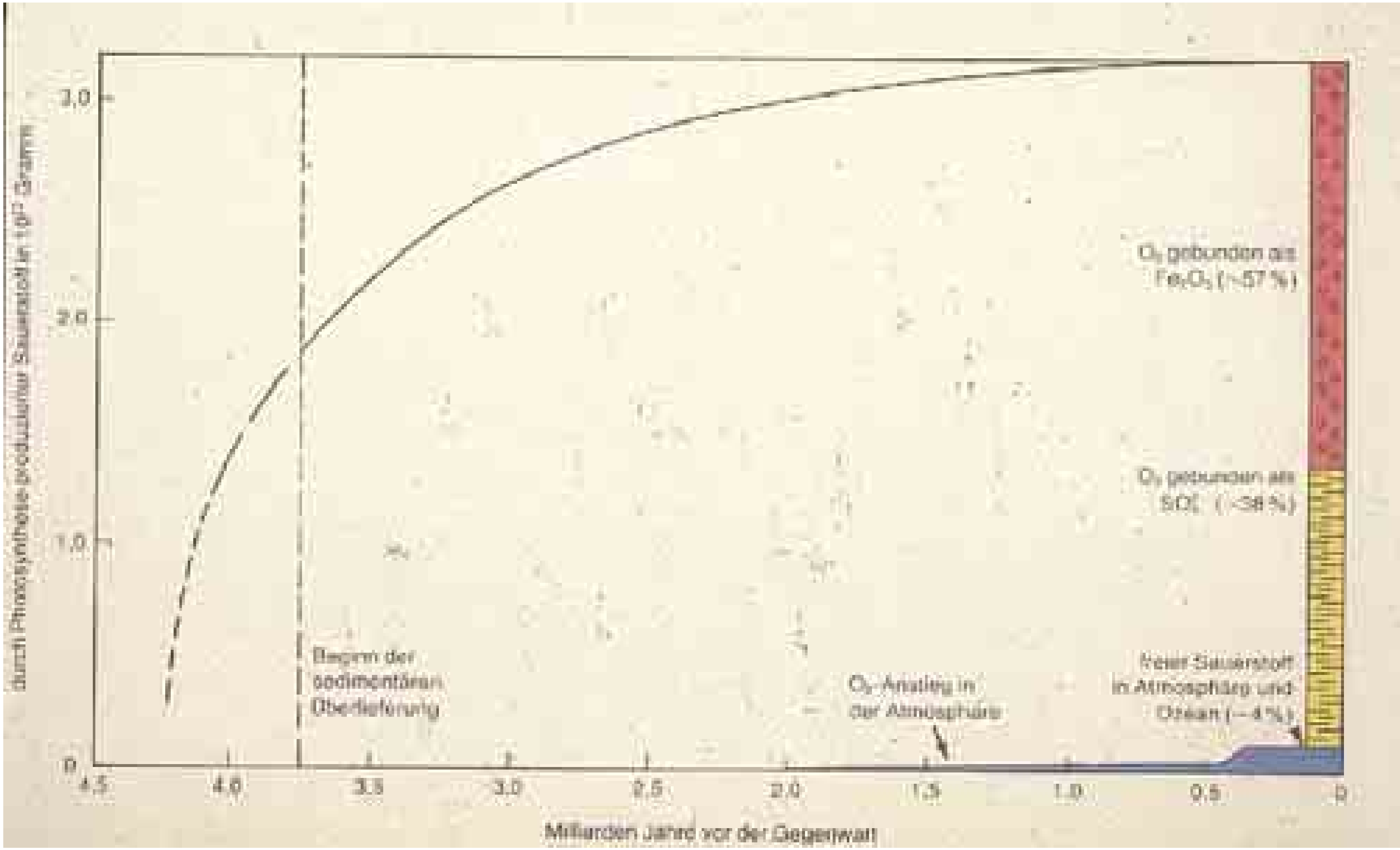
(1) Oxygen from oxygenic photosynthesis is fixed in BIF

$$2Fe^{2+} + 2H_2O + \frac{1}{2}O_2 = Fe_2O_3\,(s) + 4H^+$$

(2) Anoxygenic photosynthesis by reduction of CO_2

$$4Fe^{2+} + CO_2 + 11H_2O = 4Fe(OH)_3\,(s) + 8H^+ + [CH_2O]$$

The two mechanisms for formation of iron ore deposits of the „Banded Iron Formation“ (BIF) family



3,0
2,0
1,0
0
durch Photosynthese produzierter Sauerstoff
Beginn der sedimentären Überlieferung
O_2-Anstieg in der Atmosphäre
O_2 gebunden als Fe_2O_3 (~57 %)
O_2 gebunden als SO_4^{2-} (~38 %)
freier Sauerstoff in Atmosphäre und Ozean (~4 %)
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0
Milliarden Jahre vor der Gegenwart

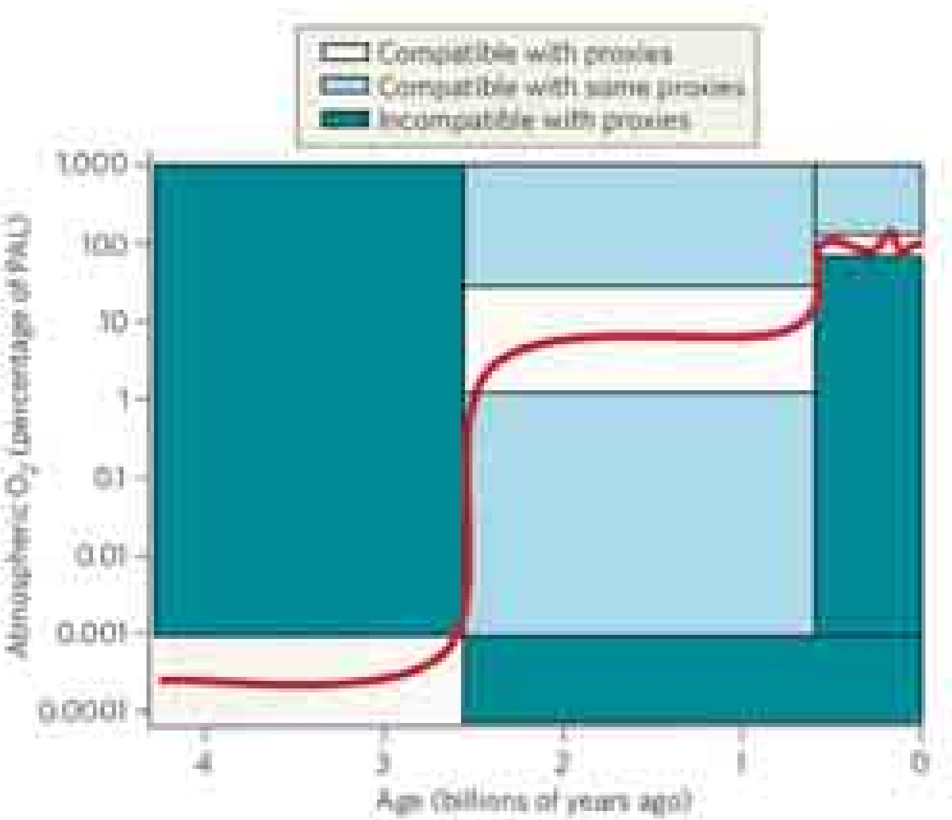
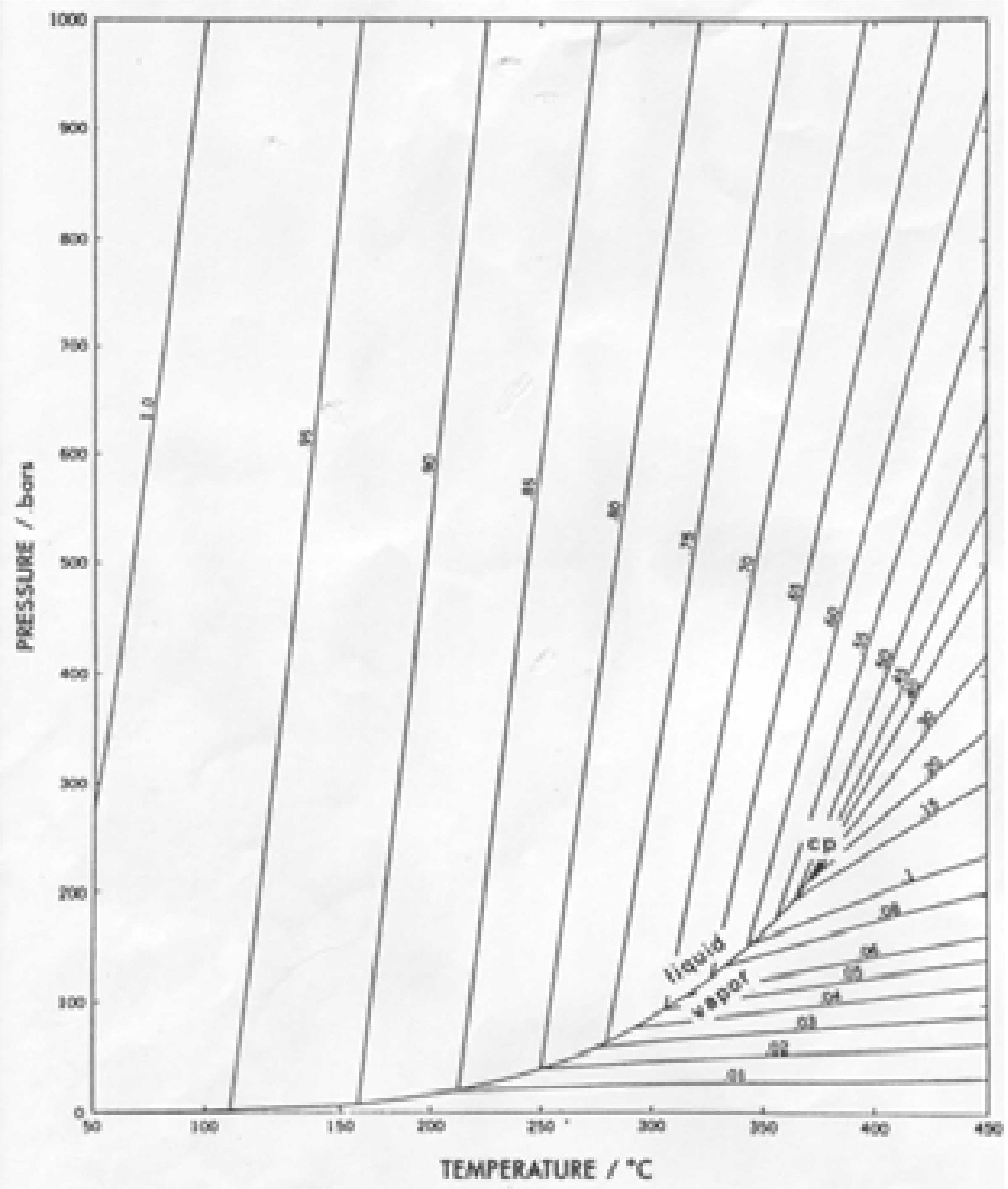
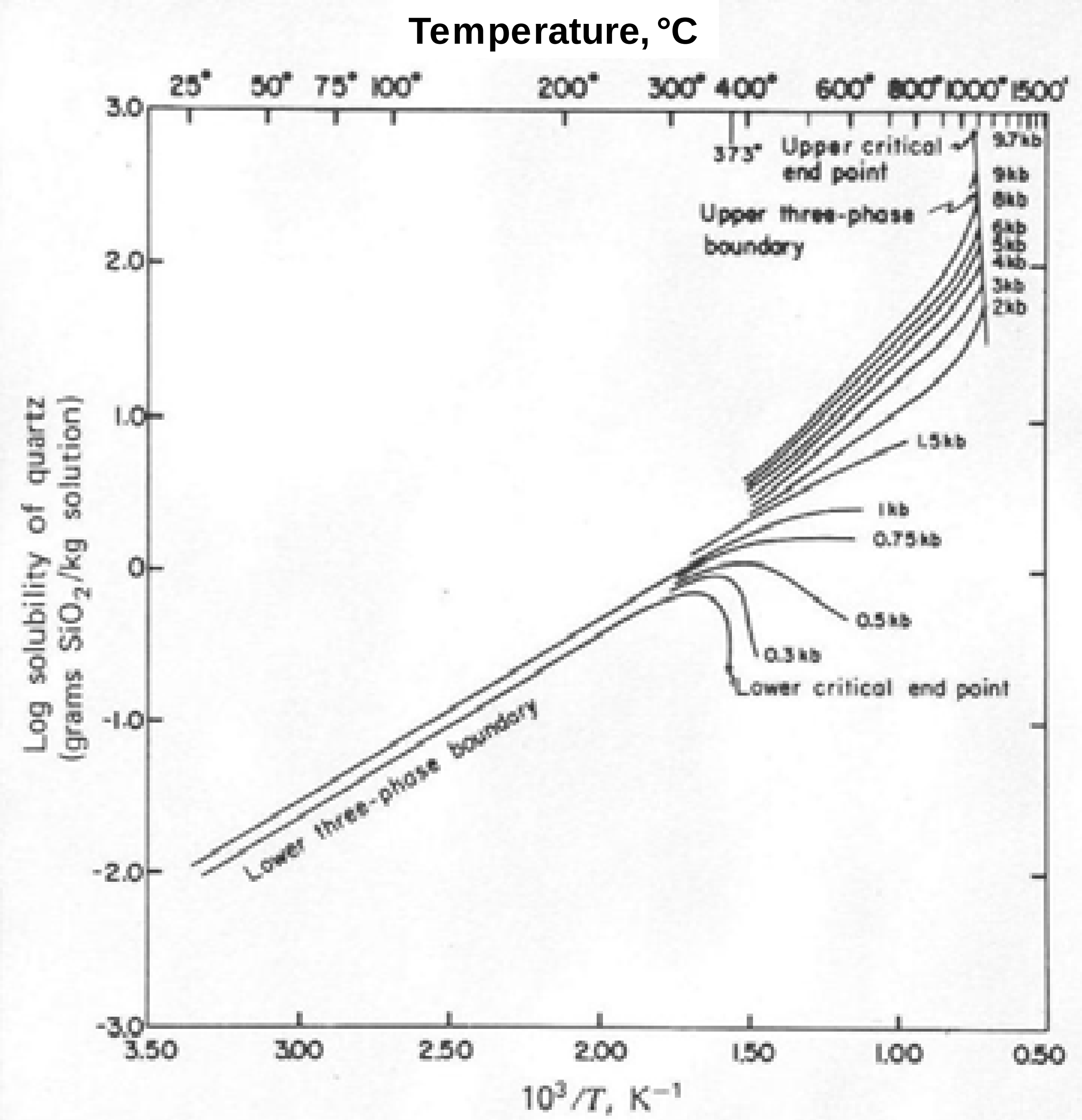


Figure 2 | Prevailing view of atmospheric oxygen evolution over time. The red line shows the inferred level of atmospheric oxygen bounded by the constraints imposed by the proxy record of atmospheric oxygen variation over Earth's history[2,20]. The signature of mass-independent sulphur-isotope behaviour sets an upper limit for oxygen levels before 2.45 billion years ago and a lower limit after that time. The record of oxidative weathering after 2.45 billion years ago sets a lower limit for oxygen levels at 1% of PAL, whereas an upper limit of 40% of PAL is inferred from the evidence for anoxic oceans during the Proterozoic. The tighter bounds on atmospheric oxygen from 420 million years ago to the present is set by the fairly continuous record of charcoal accumulation[19]: flames cannot be sustained below an oxygen level of 60% of PAL, and above about 160% of PAL the persistence of forest ecosystems would be unlikely because of the frequency and vigour of wildfires[21].

Kump (2008)
Nature 451: 278



PT diagram of water and isochores (lines of equal density)
cp = critical point



Solubility of quartz in water

Yellowstone River, Wyoming, USA

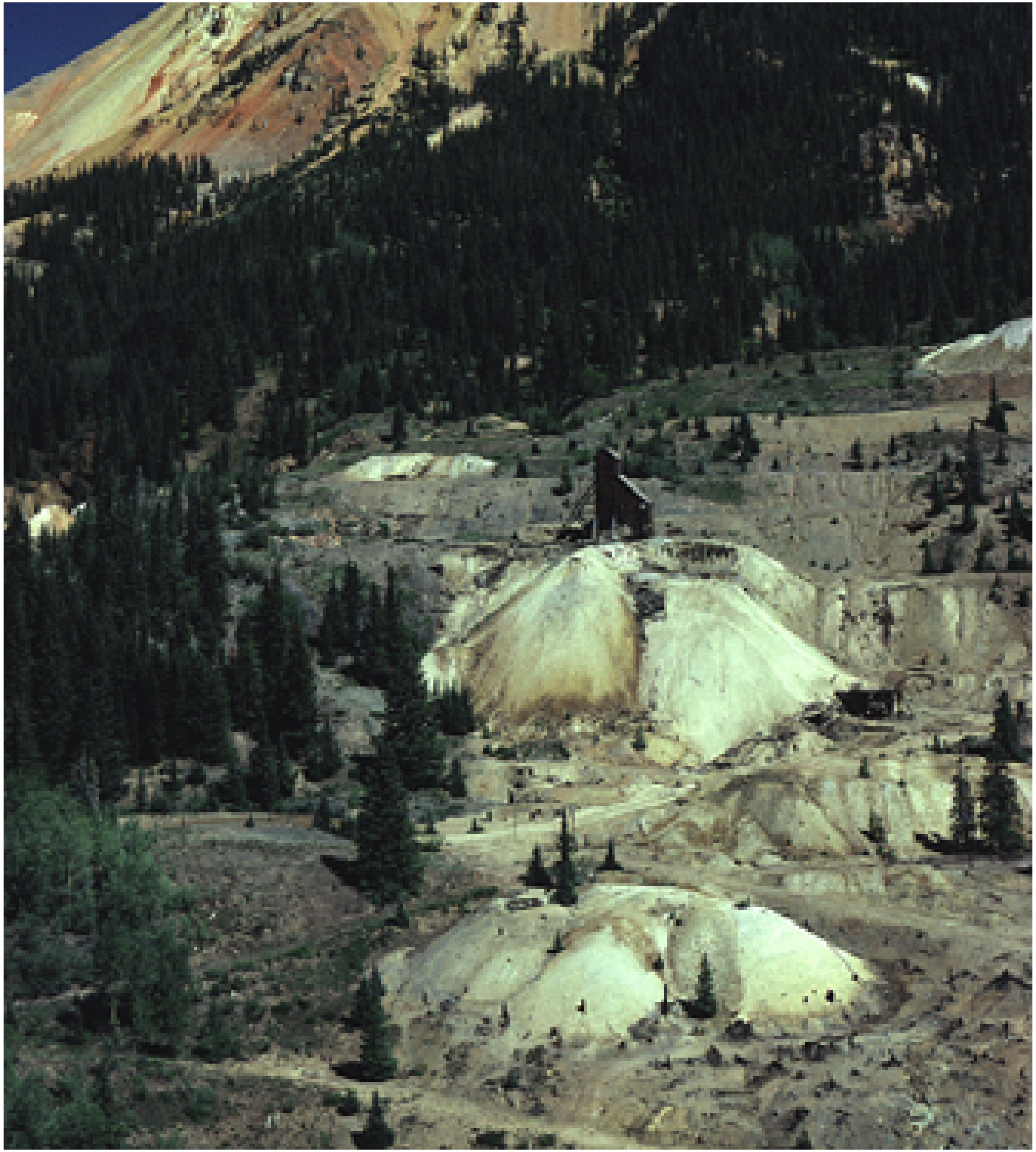
Mammoth hot springs, Yellowstone Park, Wyoming

Mammoth hot springs, Yellowstone Park, Wyoming

Old Faithful
(1 eruption/h)

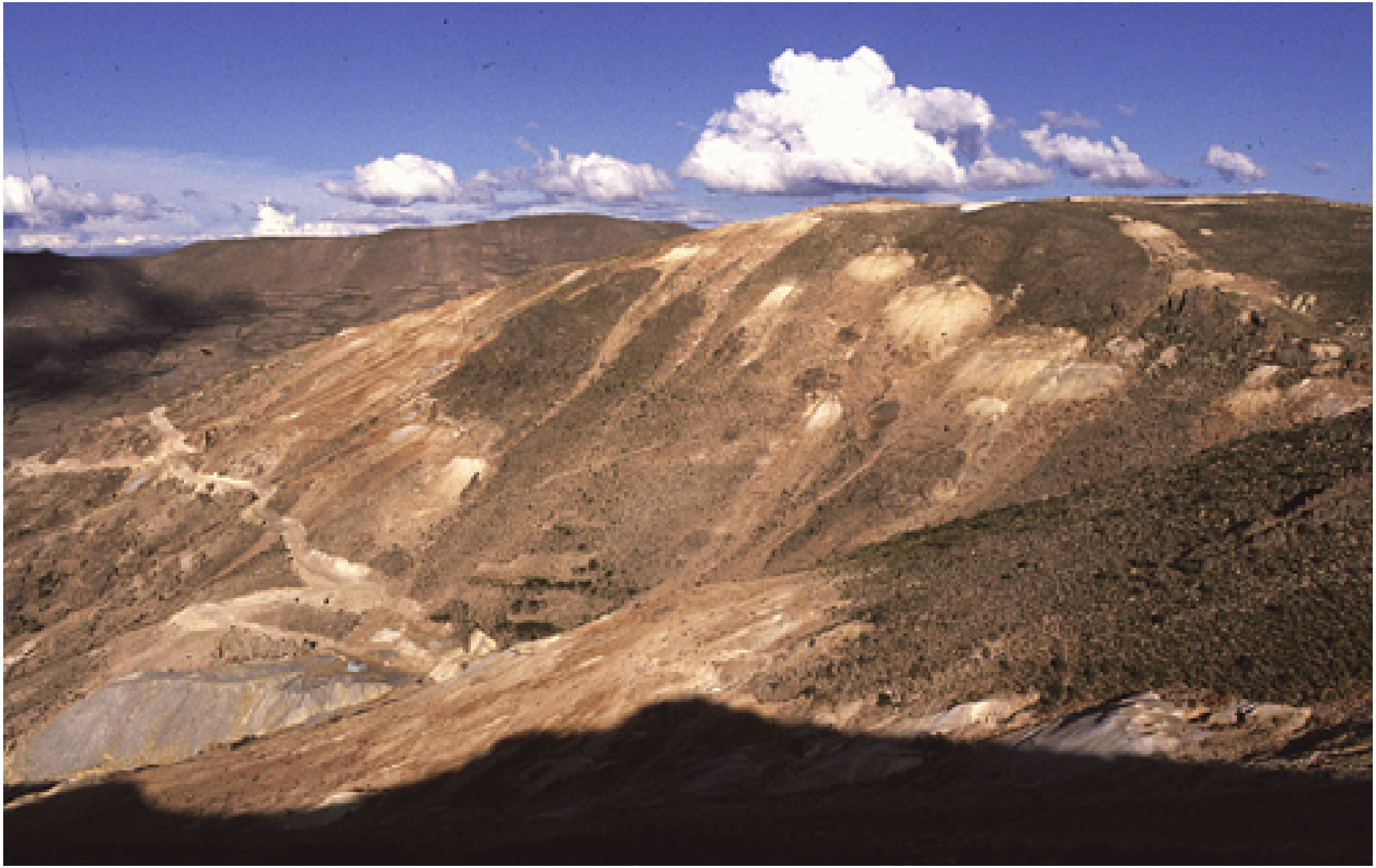
Mud pot/mud volcano (water-deficient hot spring, CO_2 + SO_2)

Red Mountain, Colorado



Julcani, Peru


Andean arc, Peru:
75 Moz, HS deposits
SIPAN
YANACOCHA
ALTO CHICAMA
PIERINA
BRASIL
OCEANO
PACIFICO
ARUNTANI
Aruntani



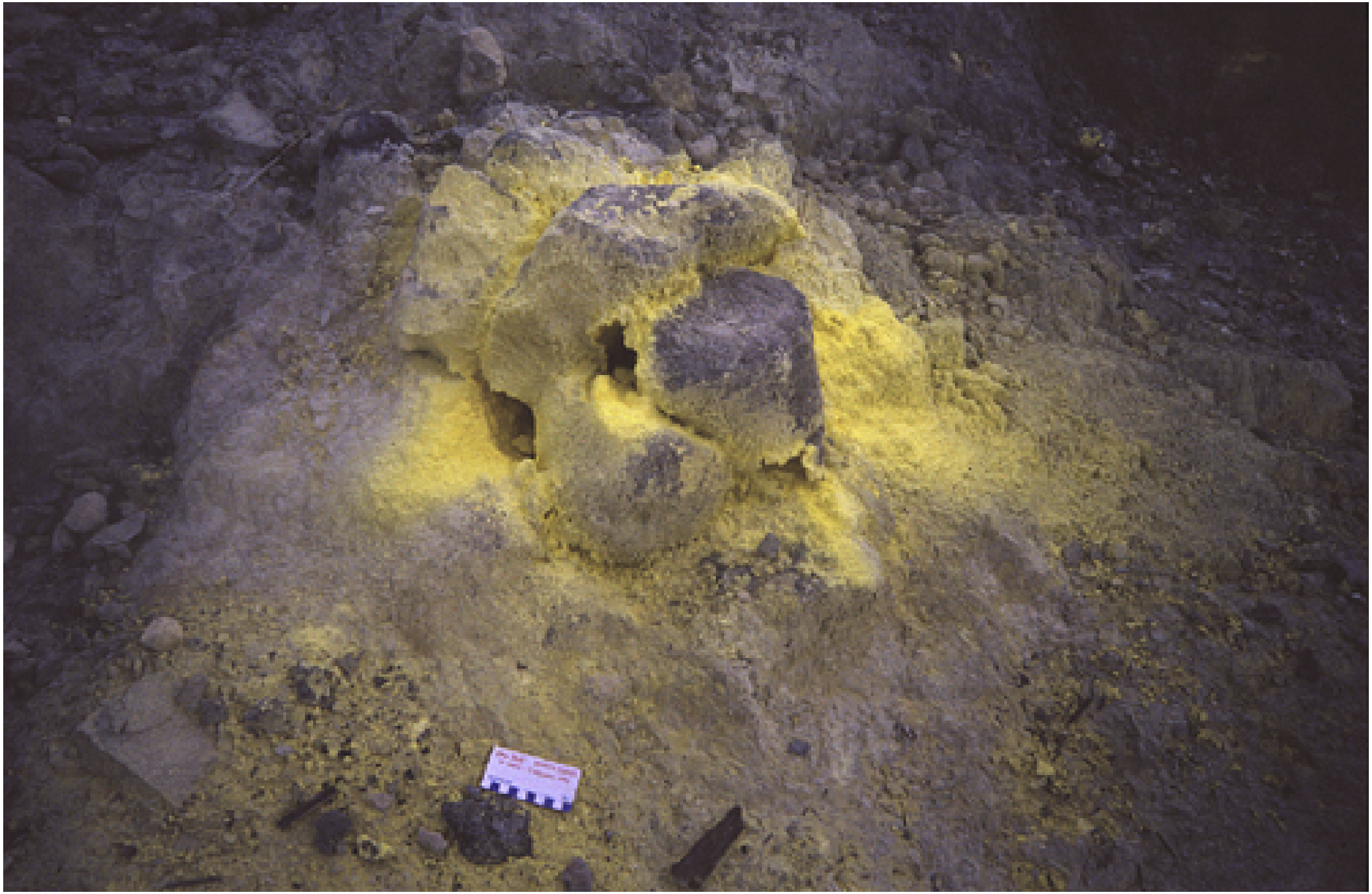
Laurani, Bolivia: high-sulfidation gold (quartz-alunite alteration)

Cerro Rico de Potosi. Bolivia

Osorezan, Japan

Osorezan, Japan

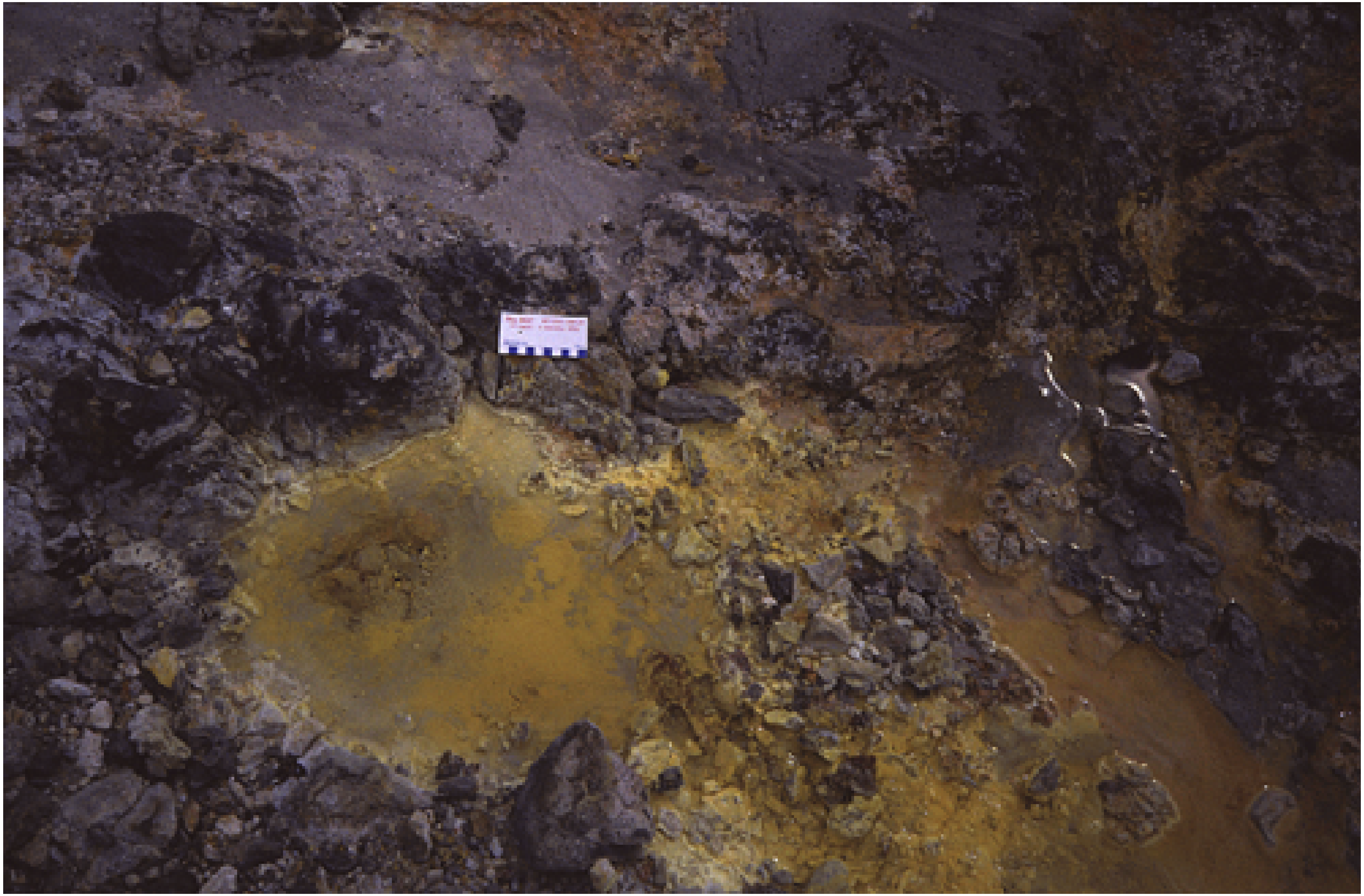
Osorezan, Japan



Osorezan, Japan

Osorezan, Japan

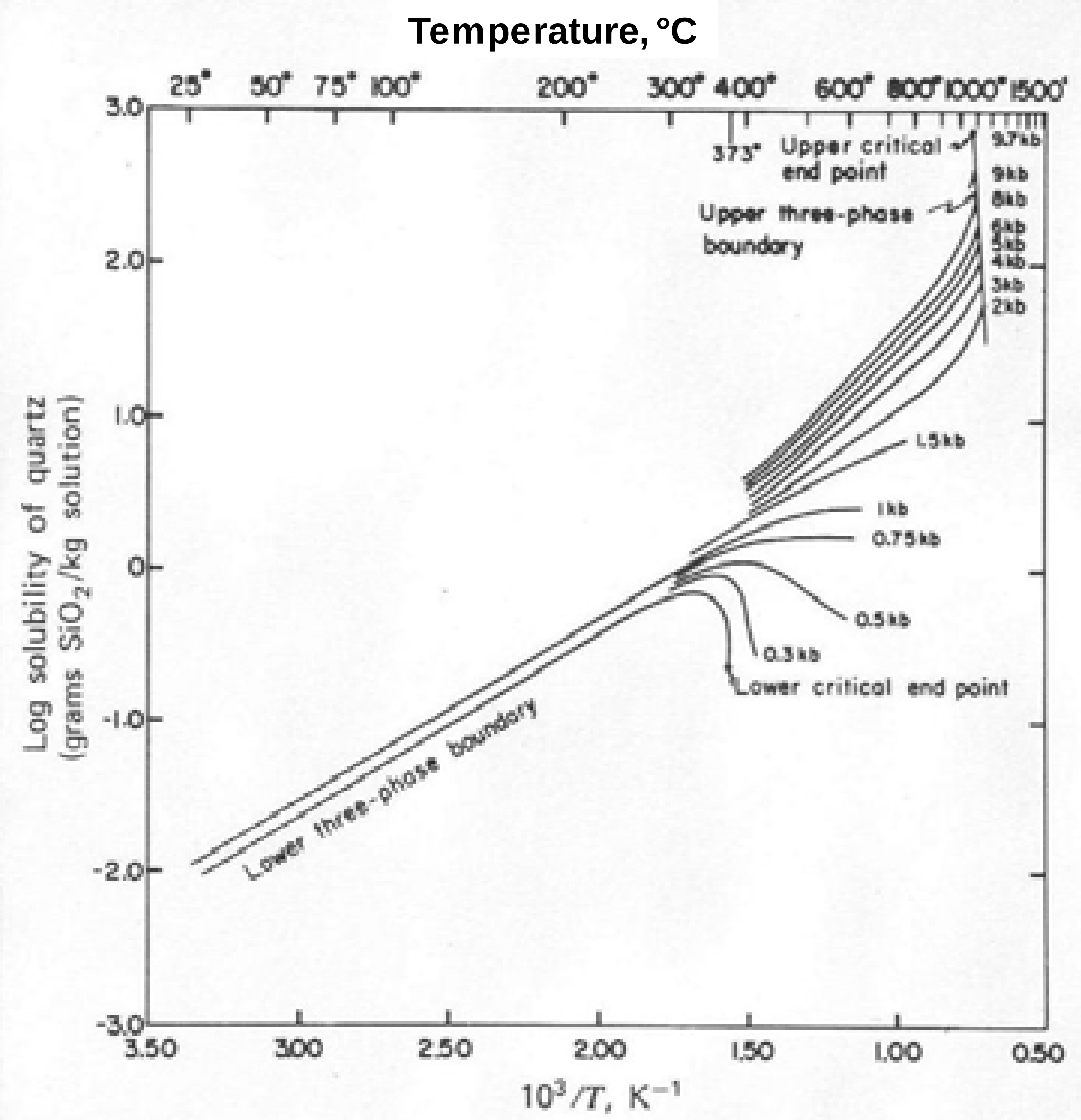
Osorezan, Japan



Osorezan, Japan

Osorezan, Japan

Hishikari,
Japan



Solubility of quartz in water

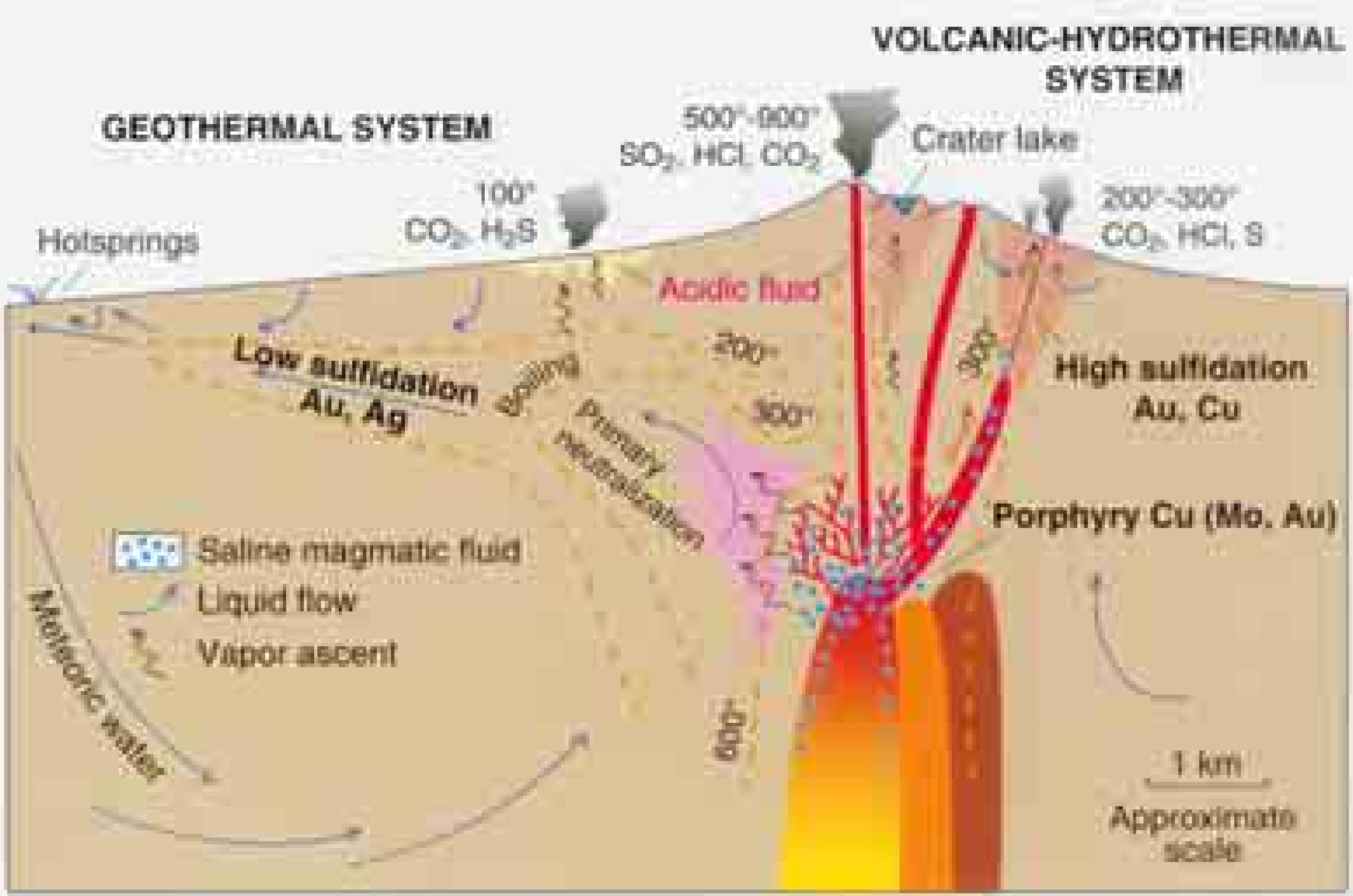
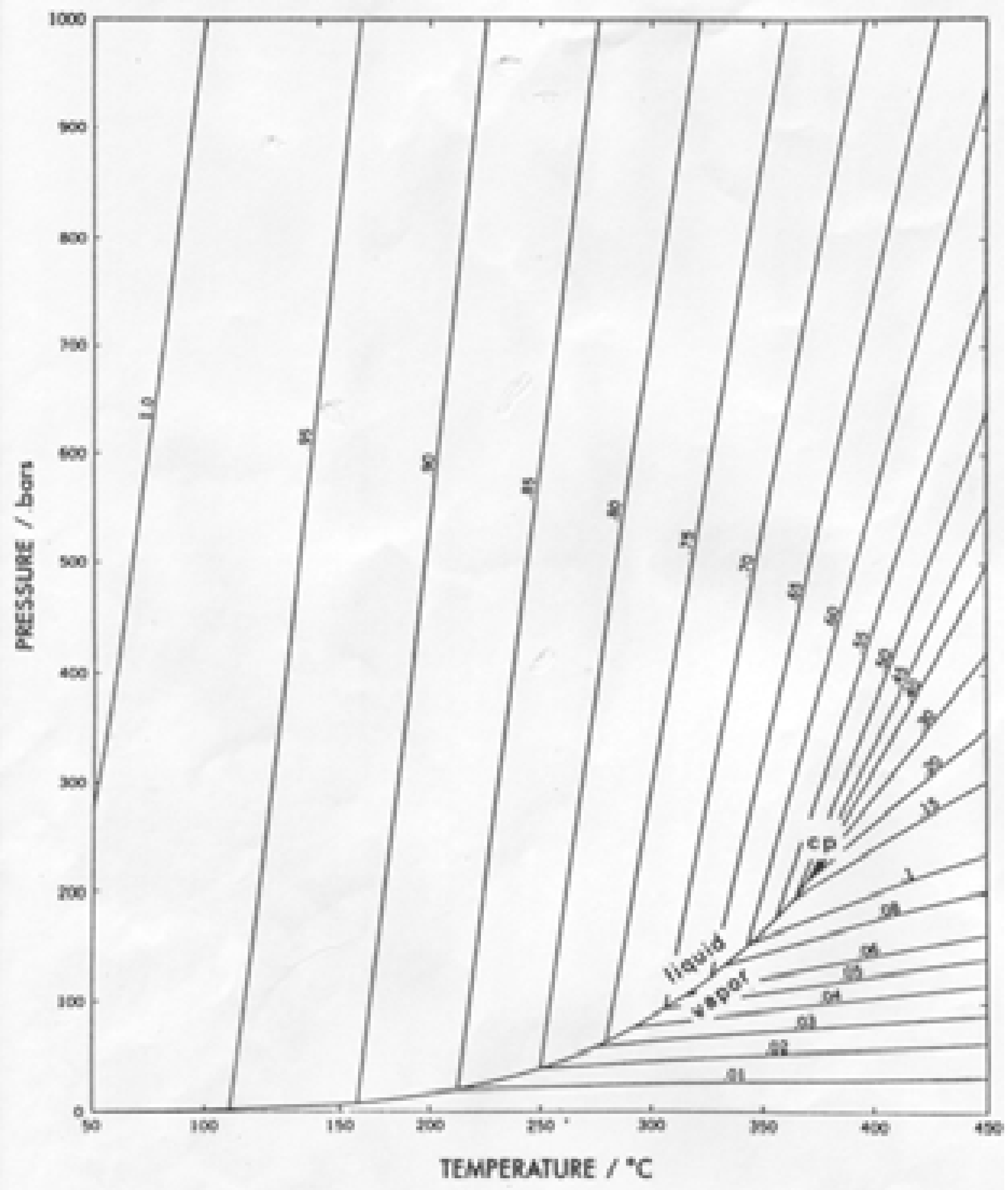


Fig. 1.1 Schematic cross-section showing shallow sub-volcanic intrusions and associated stratovolcano, and environments deduced for formation of porphyry Cu, and high- and low-sulfidation epithermal ore deposits [20,25]. Active volcanic-hydrothermal systems extend from degassing magma to fumaroles and acidic springs, and incorporate porphyry and/or high-sulfidation ore environments, whereas low-sulfidation ore deposits form from geothermal systems characterized by neutral-pH waters that may discharge as hot springs.

Hedenquist et al. (1996) Soc Res Geol Japan



PT diagram of water and isochores (lines of equal density)
cp = critical point

Kori Kollo, Altiplano, Bolivia

Kori Kollo, Altiplano, Bolivia

Kori Kollo, Altiplano, Bolivia

Kori Kollo, Bolivia: 59 Mt @ 2.3 g/t Au + 14 g/t Ag
Annual production: 10 t Au/a, worked out in 2002

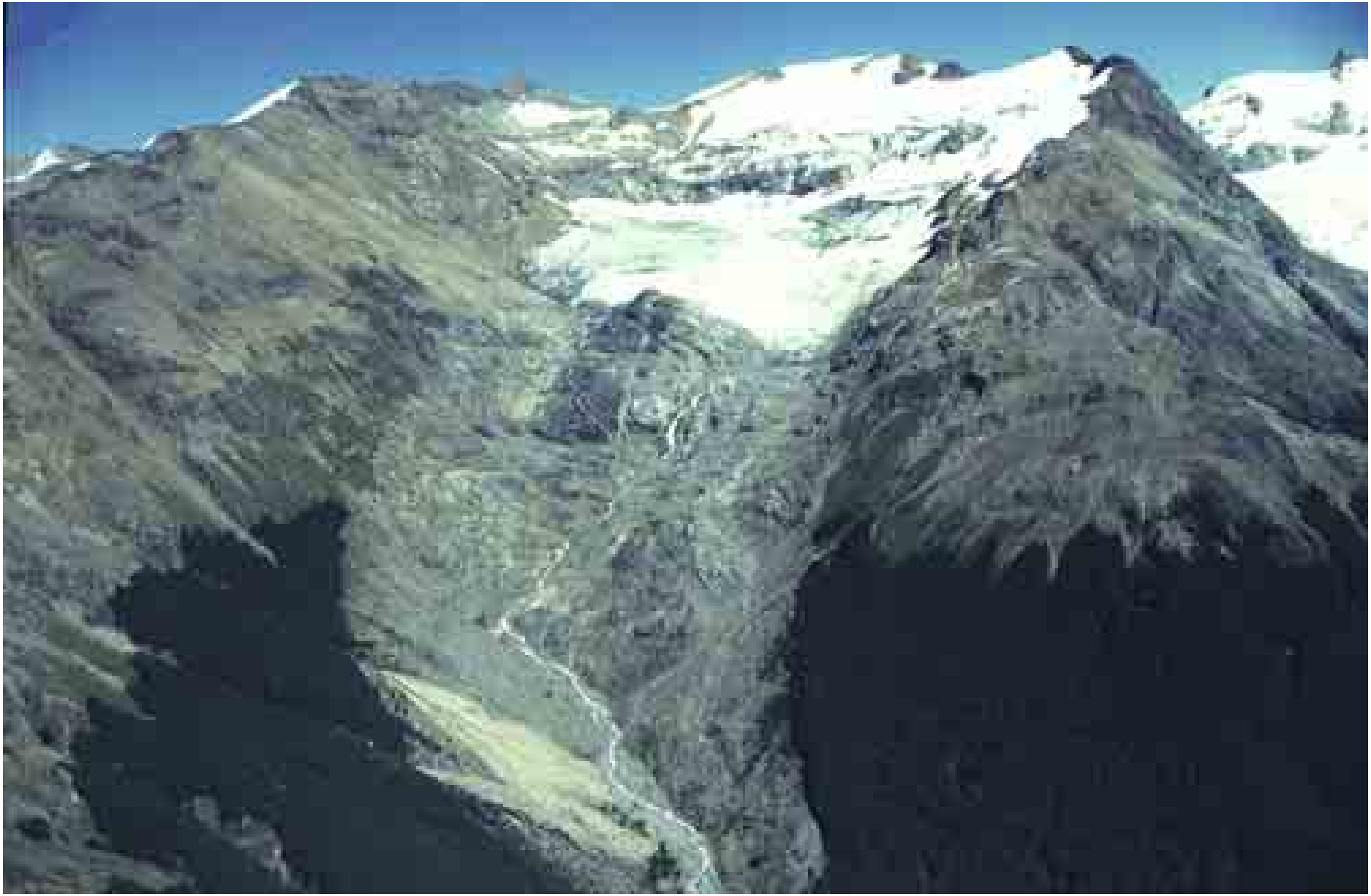
Kori Kollo, Bolivia: Leach pads

Kori Kollo, Bolivia: Leach pads

Kori Kollo, Bolivia: Leach pads

Kori Kollo, Bolivia: Pregnant ponds

Kori Kollo, Bolivia: Pregnant ponds



Basin and range province, Nevada

Round Mountain gold mine, Nevada

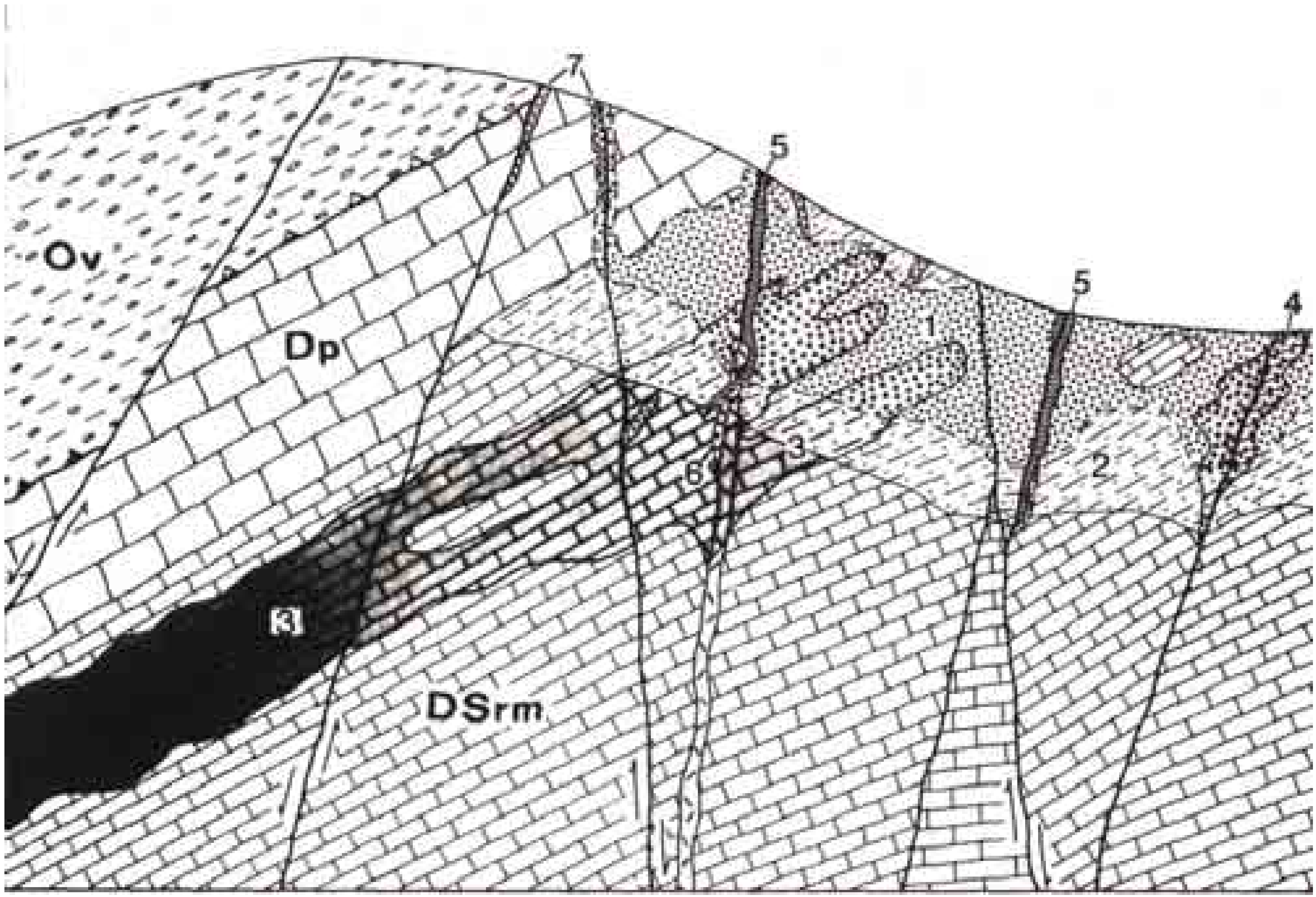
Round Mountain, 300 Mt @ 0.8 g/t Au (0.18 g/t Au cut-off in final pads), 200-250 USD/oz

Round Mountain mine in 1990: 320 t Au until 2006 .

Round Mountain, 24 t Au in 2002, 100,000 t/d ore + 100,000 t/d waste

Round Mountain open pit in July 2004

Experimental biooxidation-bioleaching reactor at the Gold Quarry Mine



Carlin type: „invisible“ gold in carbonaceous, decarbonated limestone

Alchem Pit, Jerritt Canyon, Nevada

Alchem Pit, Jerritt Canyon, Nevada

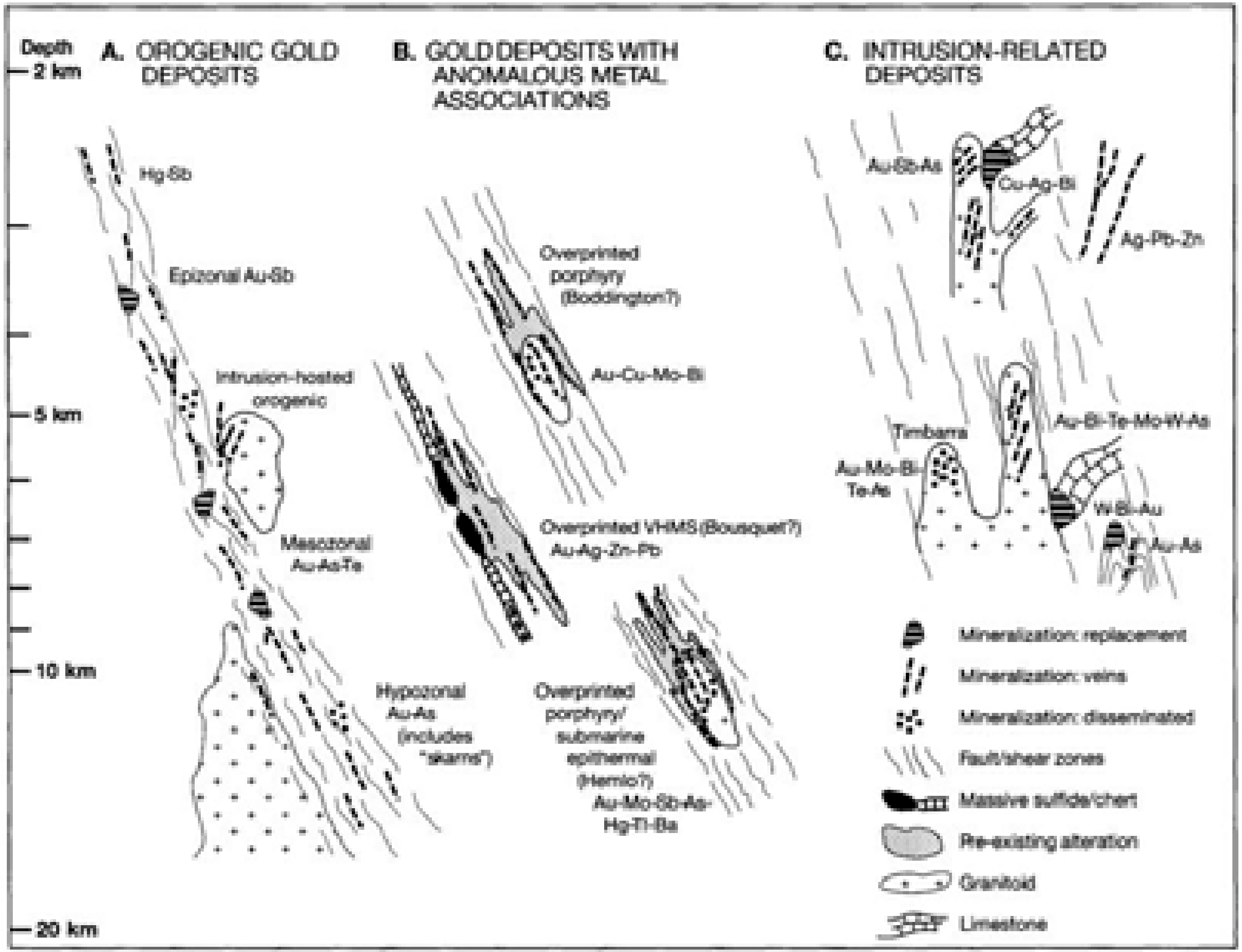


FIG. 2. Schematic representation of crustal environments of orogenic gold deposits, gold deposits with anomalous metal associations, and intrusion-related gold deposits, in terms of depth of formation and structural setting. The figure is, by necessity, stylized. Adapted partly from Groves et al. (1998) and Lang et al. (2000). Abbreviations: VHMS = volcanic-hosted massive sulfide.

Groves et al., Econ Geol 98: 5 (2003)

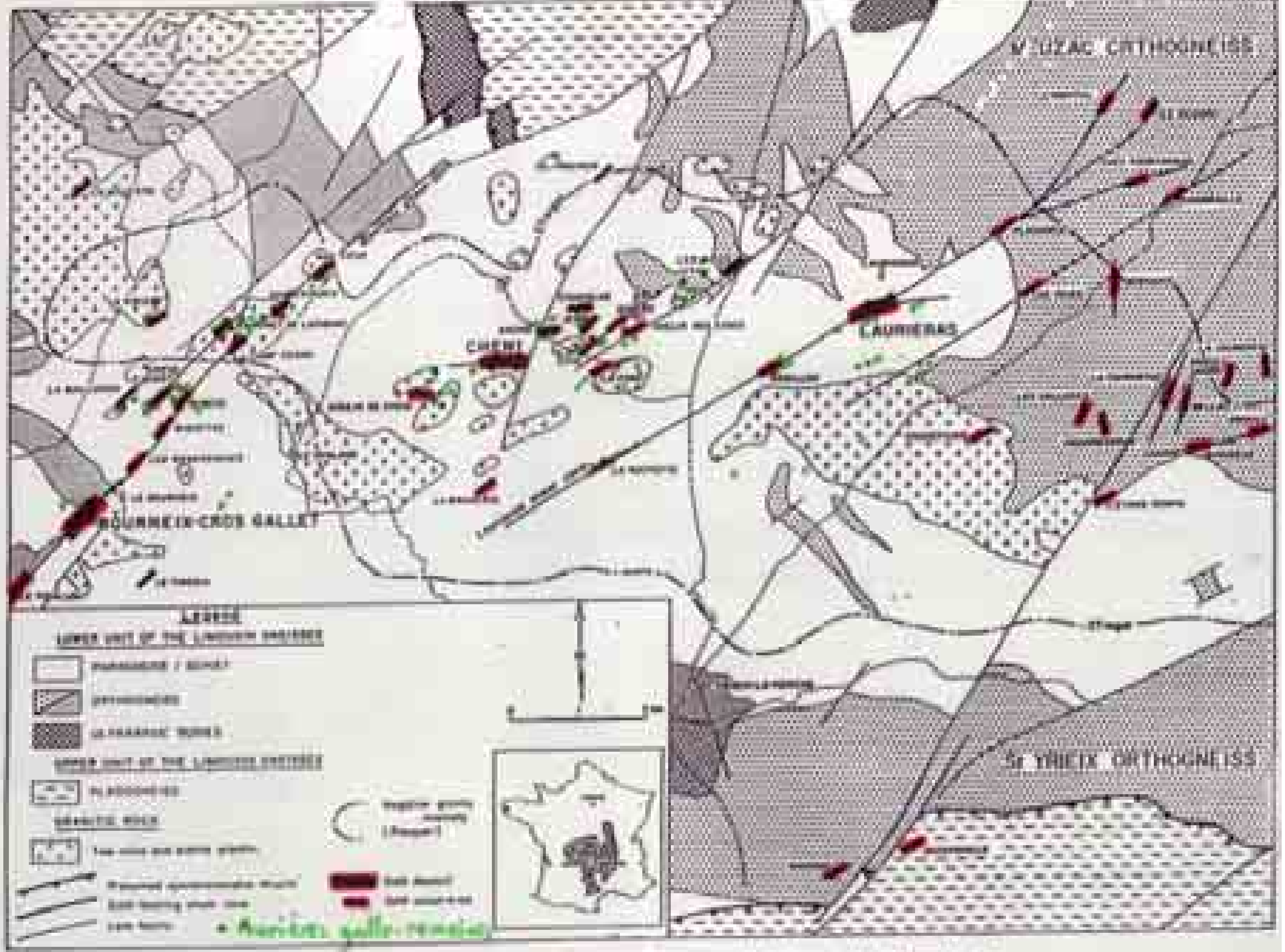
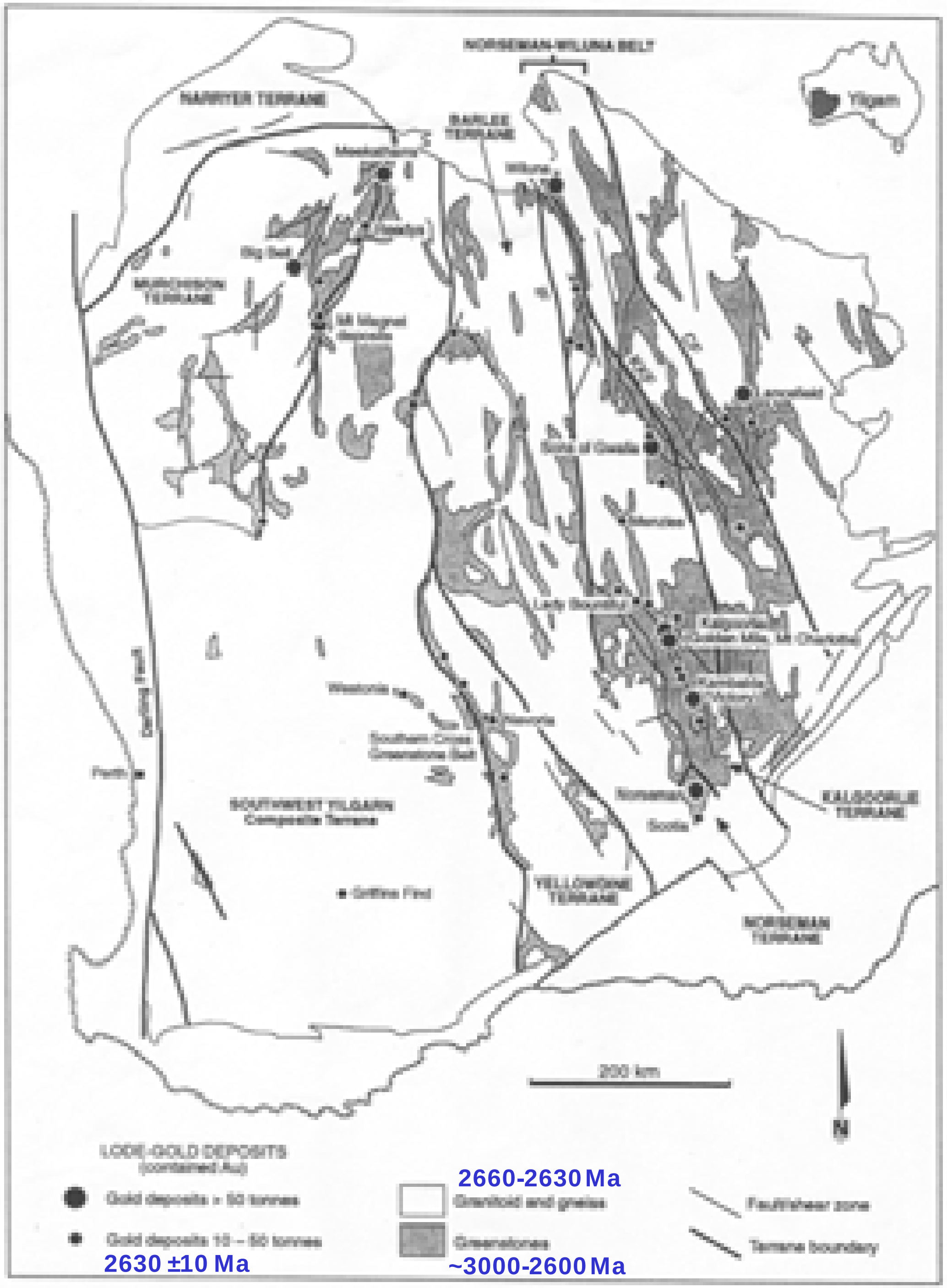


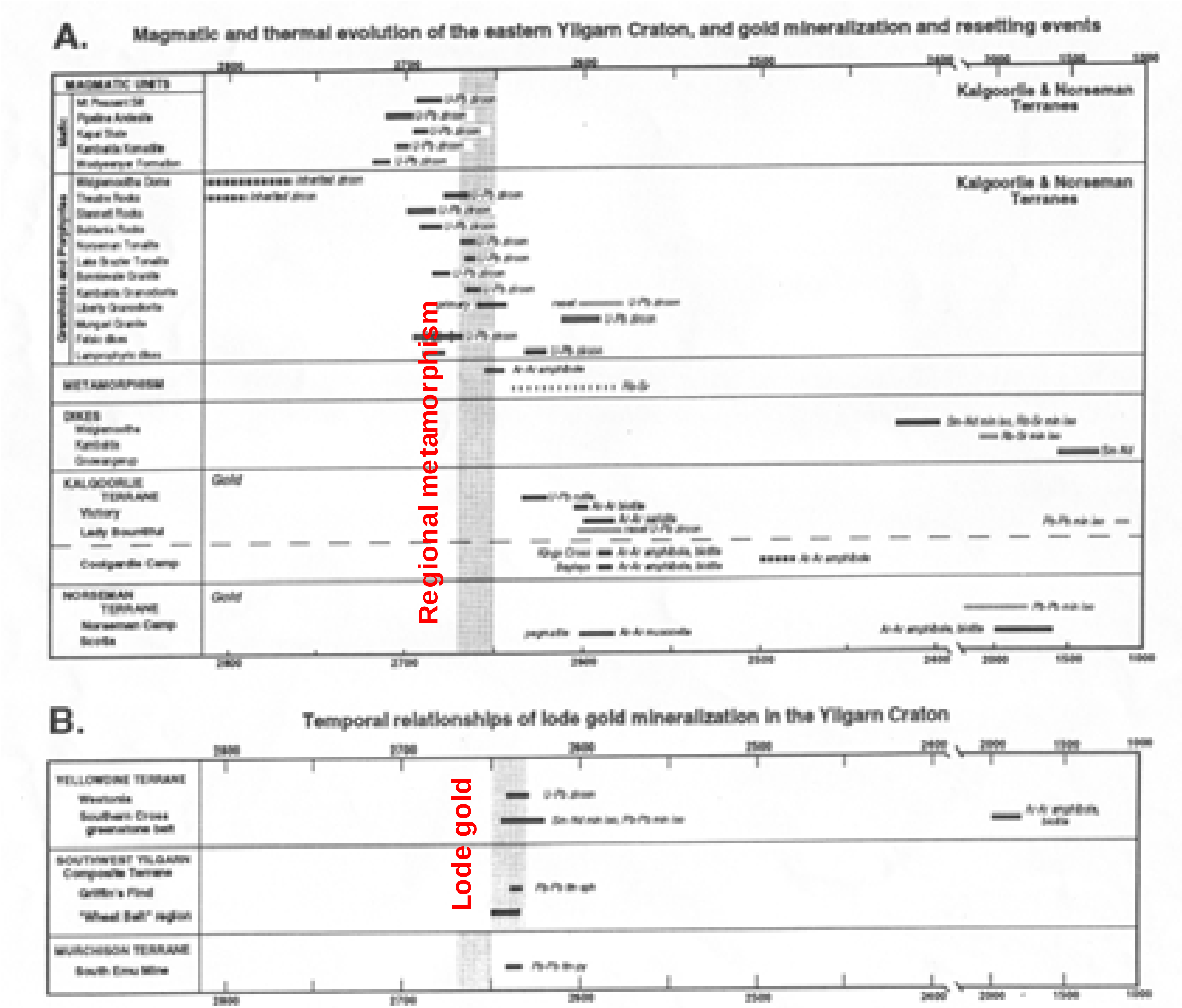
Fig. 3-1 - Carte géologique et gîtologique synthétique de l'ouest du district de St-Yrieix. Localisation du gisement de Cros Gallet.



Yilgarn Craton, western Australia

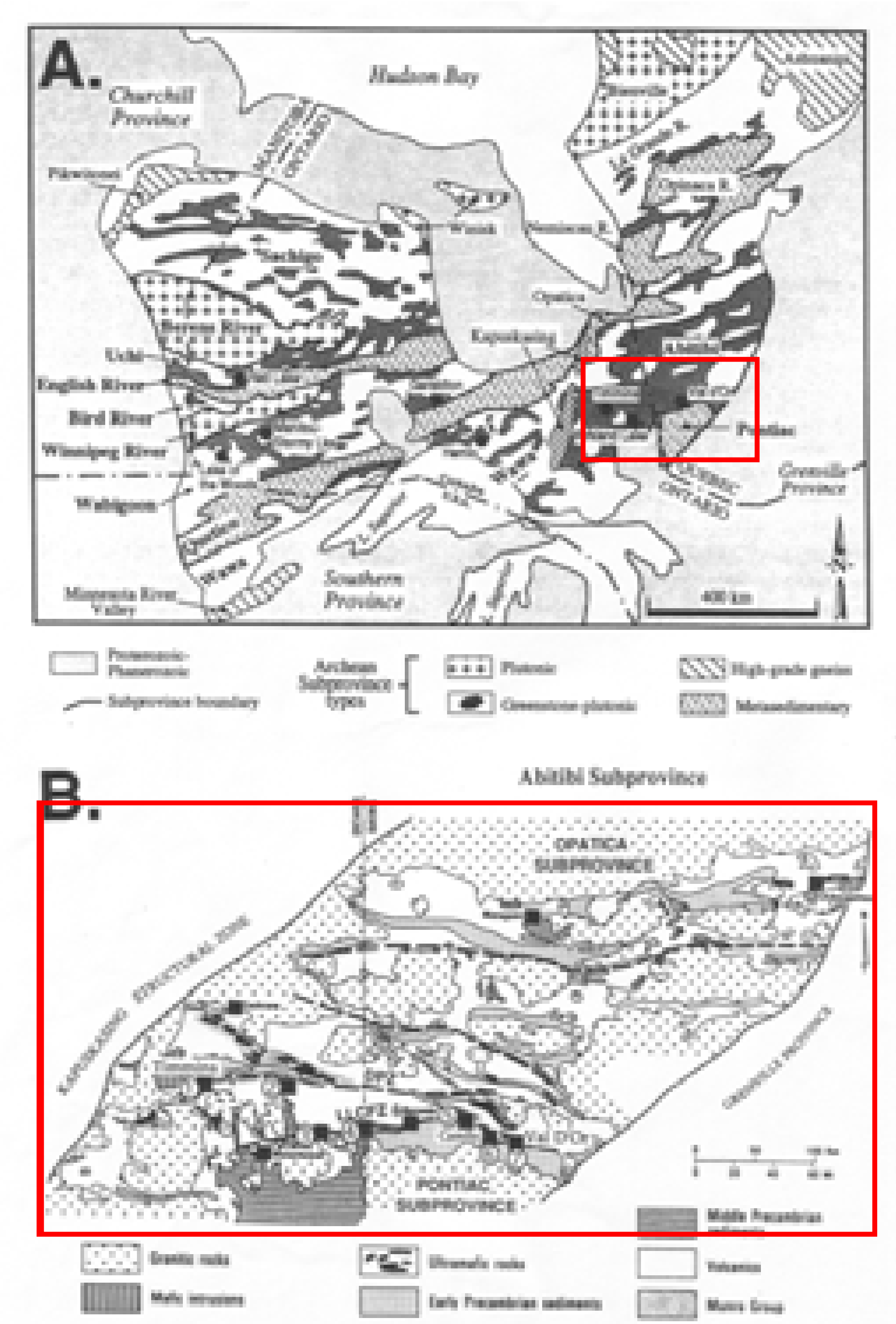
Golden Mile: ~1200 t Au

Kerrich and Cassidy (1994) OGR 9: 277



Yilgarn Craton, western Australia

Kerrich and Cassidy (1994) OGR 9: 278



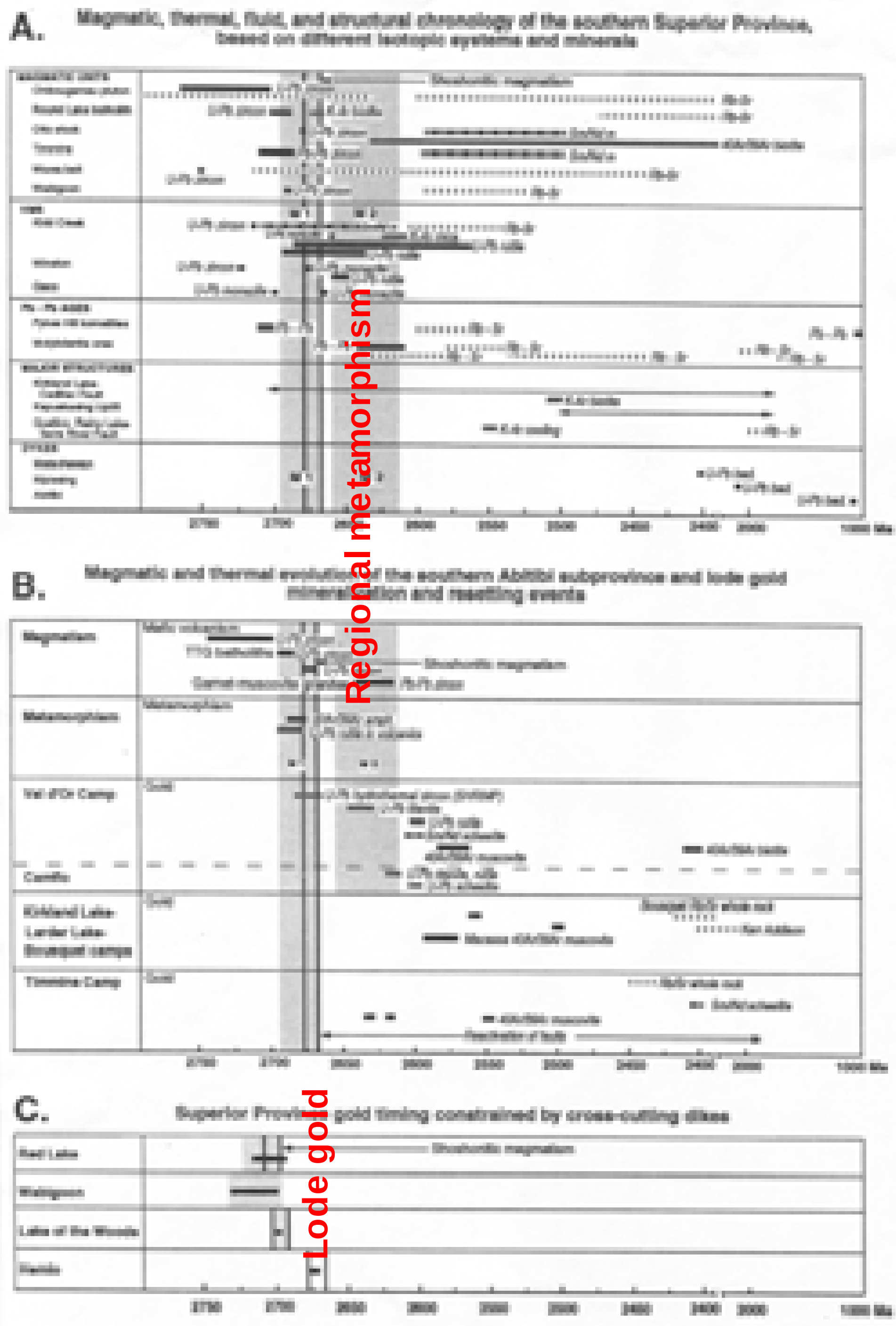
Superior Province, Canada

Hemlo: >300 t Au

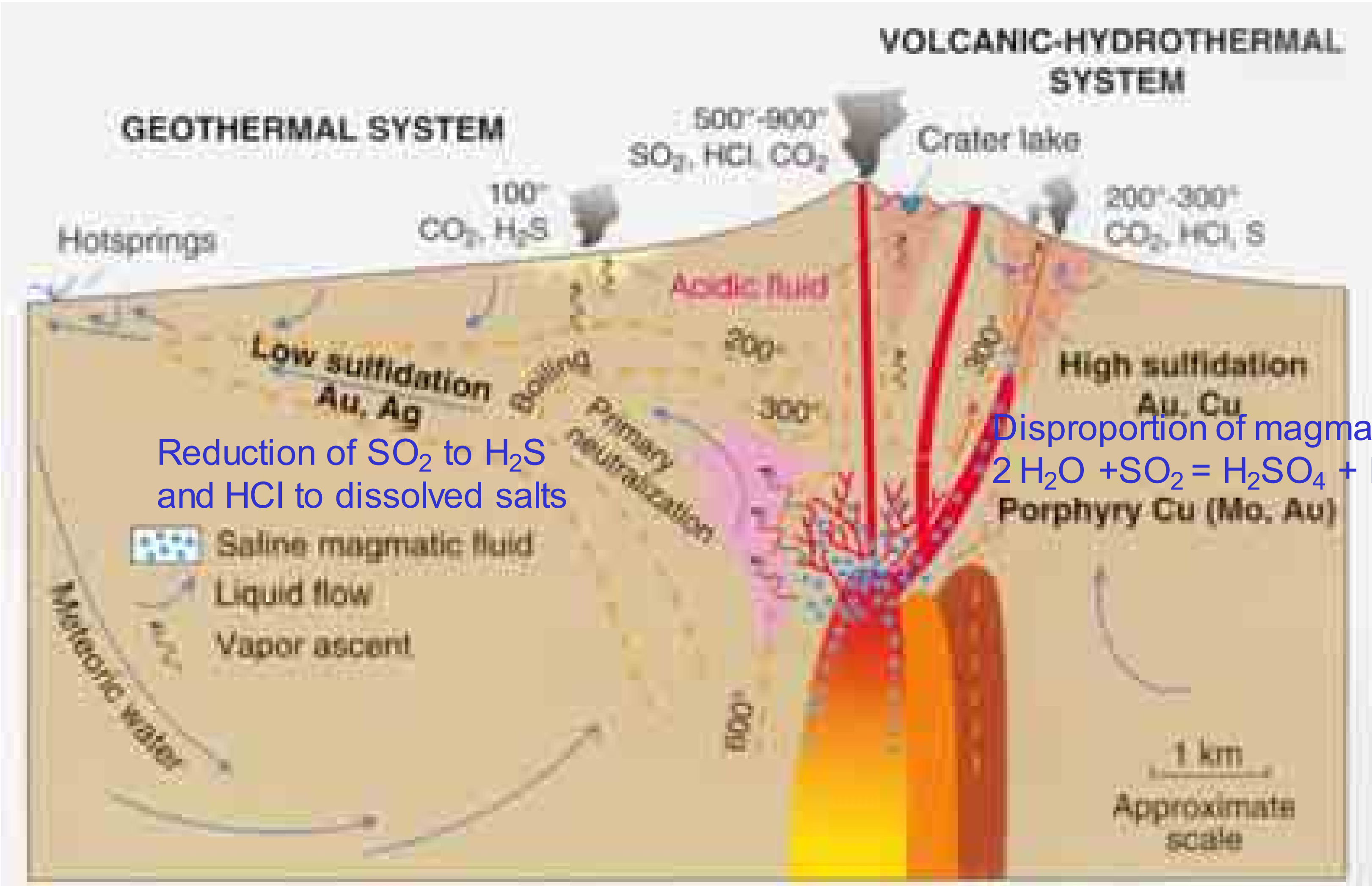
Timmins-Hollinger: >600 t Au

Larder Lake Shear Zone:
Larder Lake: >300 t Au,
Val d‘Or >100 t Au

Kerrich and Cassidy (1994) OGR 9: 268



Kerrich and Cassidy (1994) OGR 9: 270

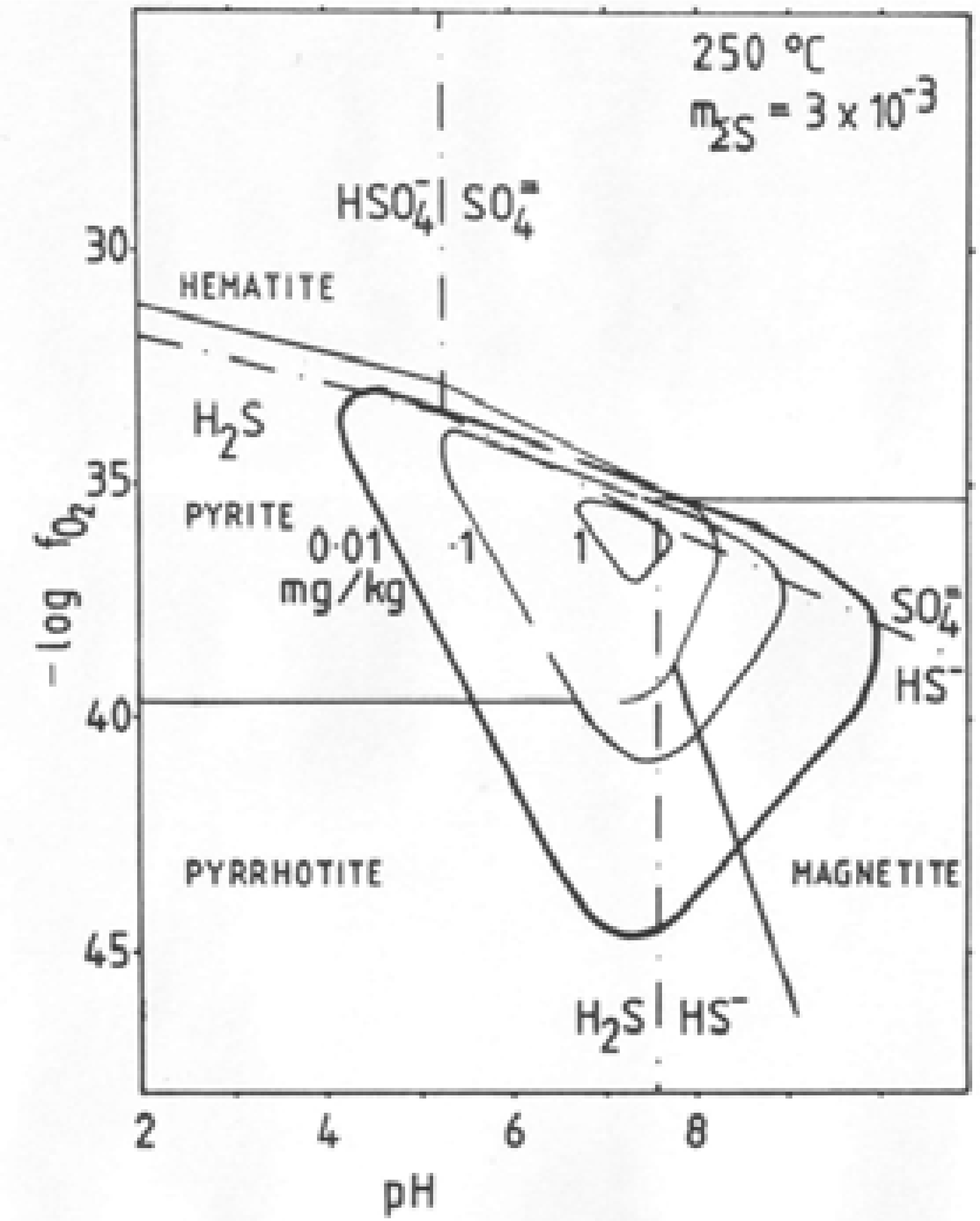


Reduction of SO_2 to H_2S and HCl to dissolved salts

Disproportion of magmatic SO_2:
$2\ H_2O + SO_2 = H_2SO_4 + H_2S$

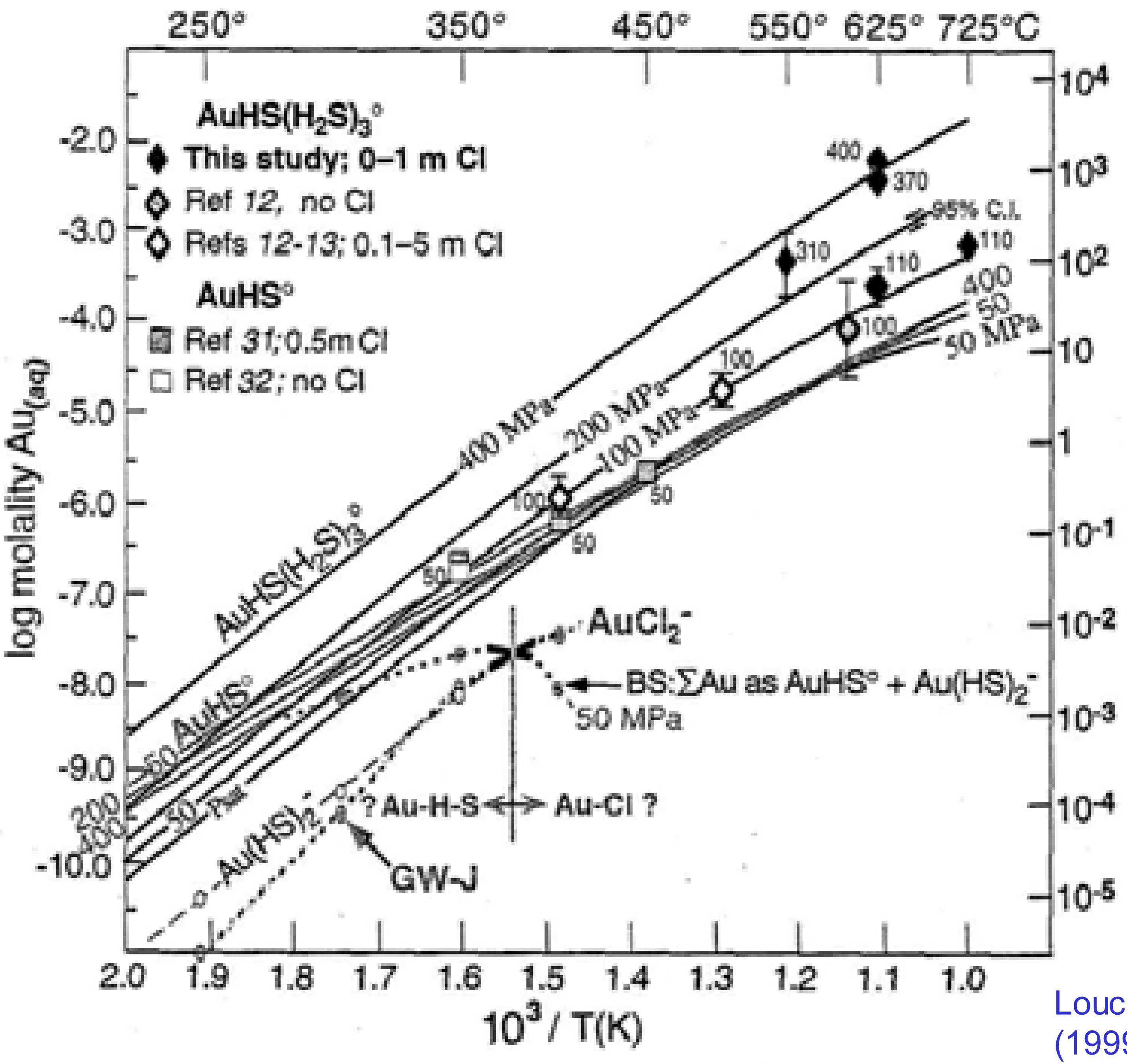
Fig. 1.1 Schematic cross-section showing shallow sub-volcanic intrusions and associated stratovolcano, and environments deduced for formation of porphyry Cu, and high- and low-sulfidation epithermal ore deposits [20,25]. Active volcanic-hydrothermal systems extend from degassing magma to fumaroles and acidic springs, and incorporate porphyry and/or high-sulfidation ore environments, whereas low-sulfidation ore deposits form from geothermal systems characterized by neutral-pH waters that may discharge as hot springs.

Hedenquist et al. (1996) Soc Res Geol Japan



$$Au^0 + 2H_2S + \tfrac{1}{4}O_2 = [Au(HS)_2]^- + H^+ + \tfrac{1}{2}H_2O$$

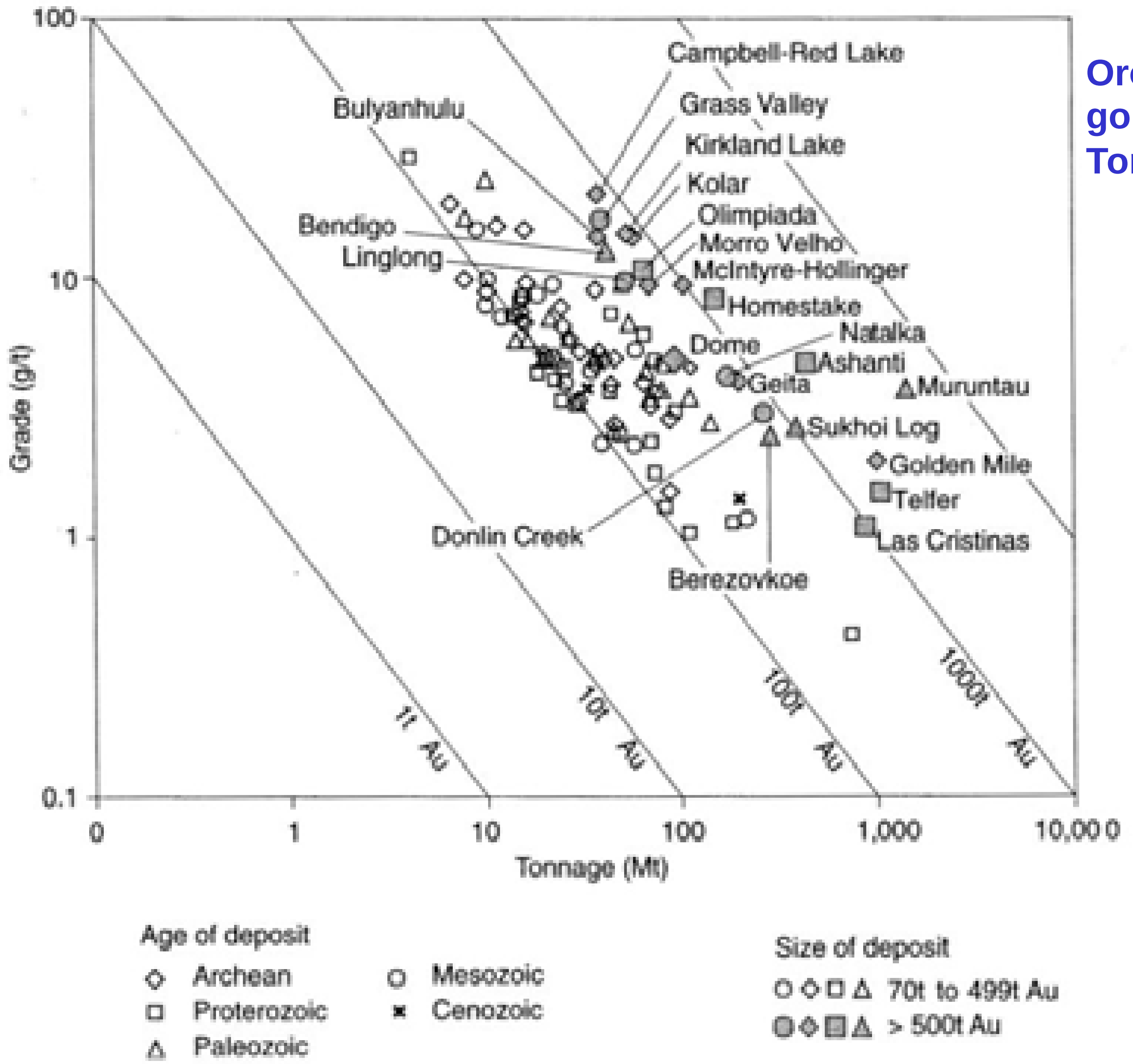
$Au + 4H_2S + ½O_2 = AuHS(H_2S)_3 + ½H_2O$



Gold solubilty oxygen-buffered (pyrrhotite-pyrite-magnetite) and pH-buffered (orthoclase-muscovite-quartz) as typical of orogenic gold deposits

Loucks and Mavrogenes (1999) Nature 284: 2162

Orogenic gold deposits: Tonnage-grade plot



Road to Grasberg (Freeport McMoRan) in Irian Jaya

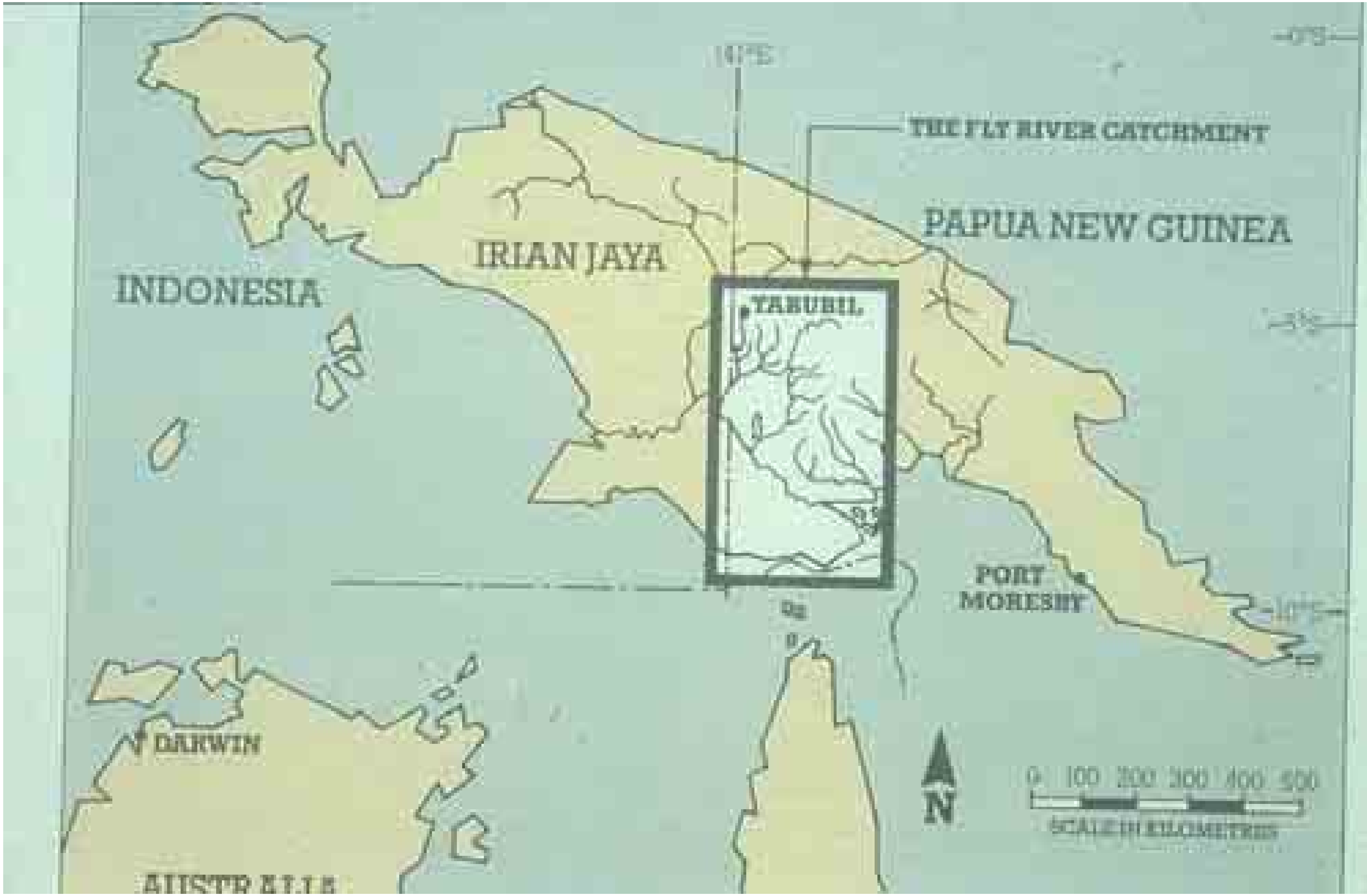
Irian Jaya: Grasberg road

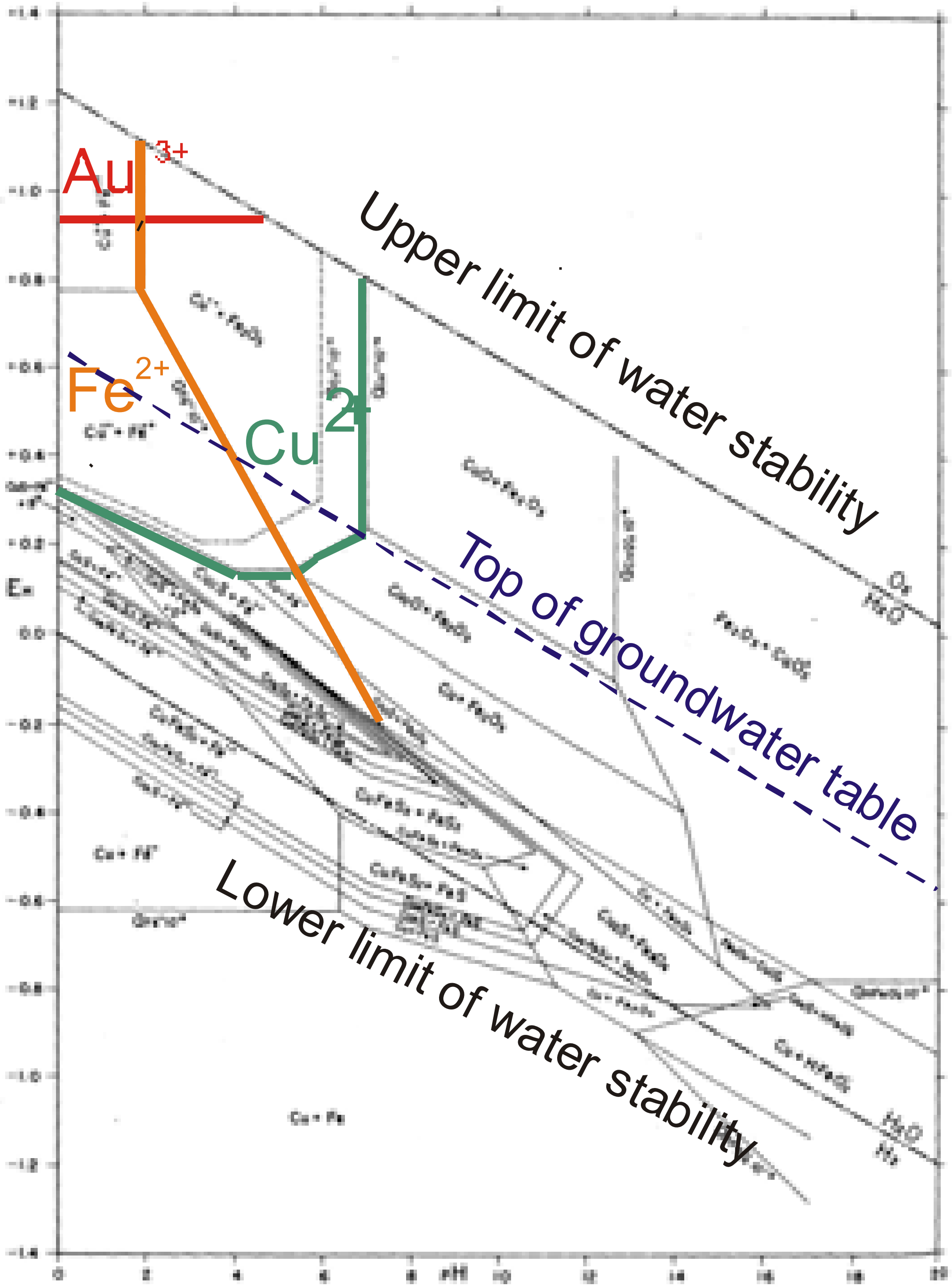
Grasberg

Grasberg open pit (Aug 1999), 1.2 Gt @ 1.41 % Cu + 1.5 g/t Au, 1 Gt overburden
Production in 2003: 600,000 t Cu + 80 t Au, 26 ct/pound Cu, 113 USD/oz Au

Grasberg open pit (Aug 99)

Grasberg Open Pit
View Looking South
October 9, 2003
View Direction
N
6S
Ramp Access
5S


THE FLY RIVER CATCHMENT
PAPUA NEW GUINEA
IRIAN JAYA
INDONESIA
TABUBIL
PORT
MORESBY
DARWIN
AUSTRALIA
N
0 100 200 300 400 500
SCALE IN KILOMETRES



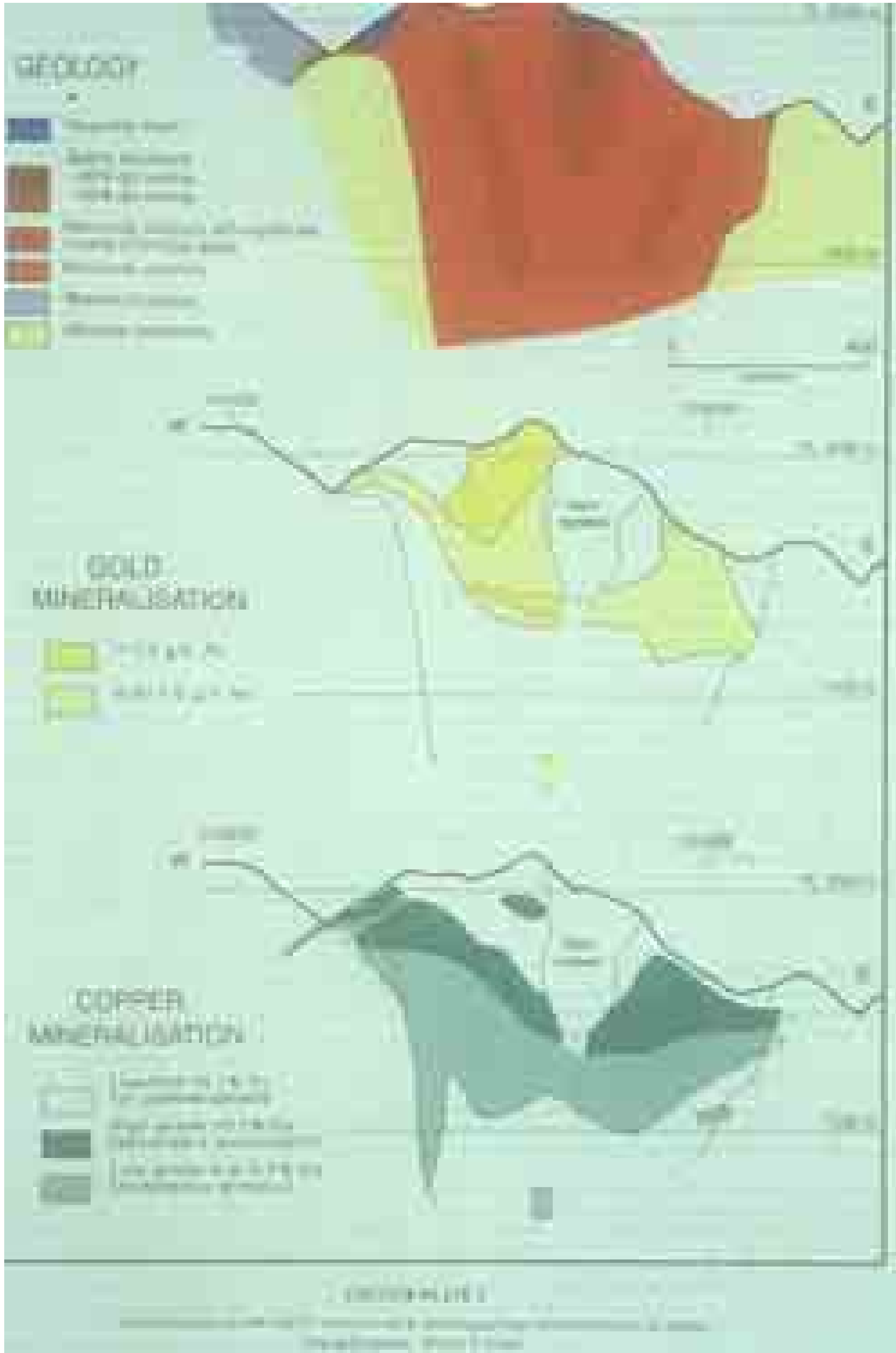
The system Cu-Fe-S-O-H at 25°C and 1 bar.
Total dissolved sulfur = 10^{-4} m
From Garrels and Christ (1965: 231)

The colored solubility limits of Au^{3+}, Fe^{2+} and Cu^{2+} are drawn at 10^{-6} m Fe (56 ppb Fe), 10^{-6} m Cu (64 ppb Cu) and 10^{-8} m Au (2 ppb Au).

OK Tedi, Papua New Guinea (1976) Drill sites, helicopter landing pads
EG 73: 597 (1978)

OK Tedi (1992)

OK Tedi, Papua New Guineas (1994), 265 Mt @0.82 % Cu + 0.65 g/t Au
Production in 2003: 210,000 t Cu + 16 t Au



Ok Tedi/
Papua New Guinea

460 Mt @ 0.72 % Cu,
0.7 g/t Au

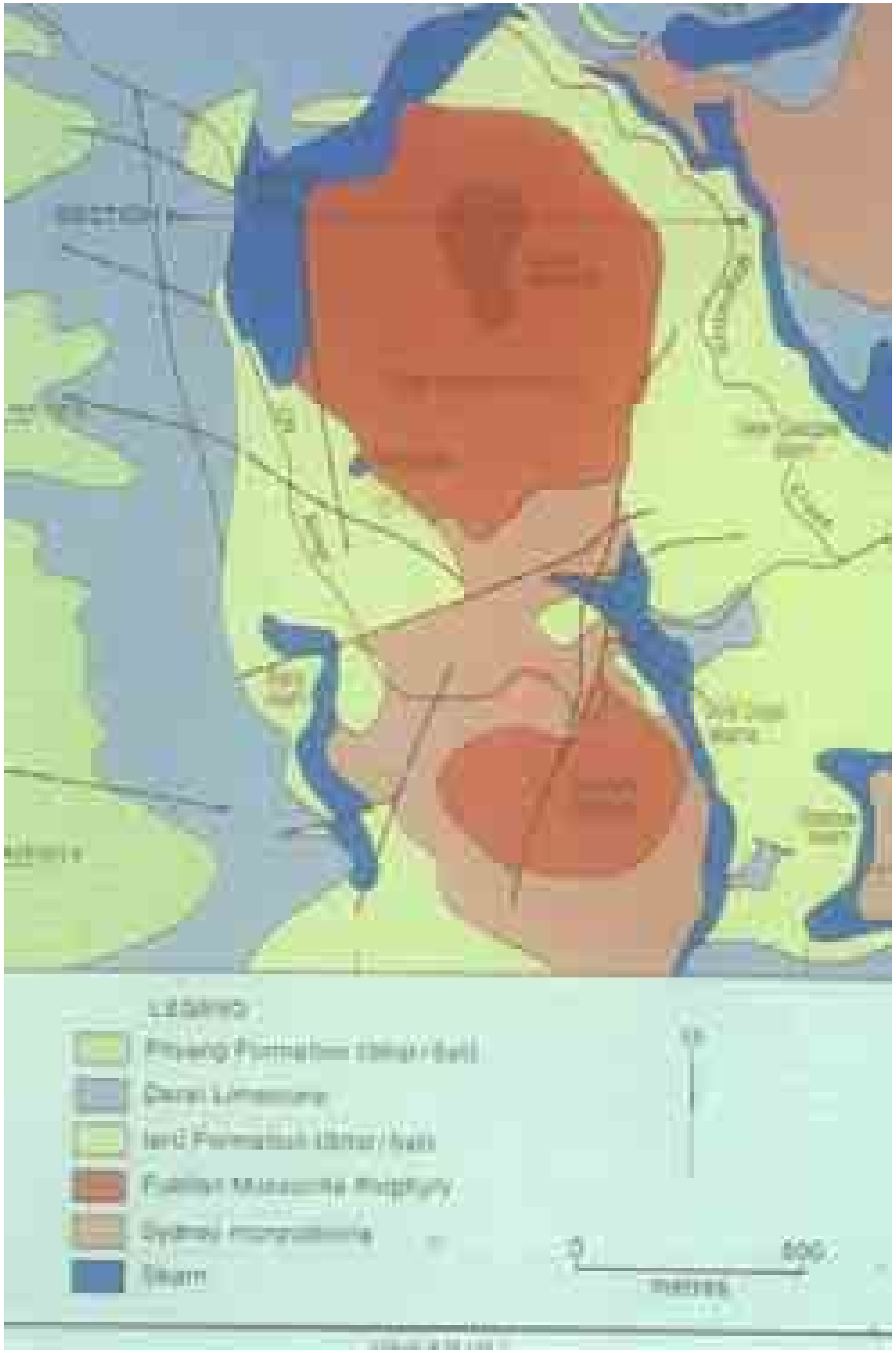
Gossan ore:
30 Mt x 3 g/t Au =
90 t Au
~ 2.5 billion USD

Secondary enrich-
ment zone:
265 Mt x 0.82 % Cu =
2 Mt Cu
~ 14 billion USD

265 Mt x 0.65 g/t Au =
170 t Au

Protore:
0.2-0.4 % Cu
0.3-0.5 g/t Au

Davies et al. (1978)
Econ Geol 73: 796-809



LEGEND
Darai Limestone
Skarn
0
500
metres

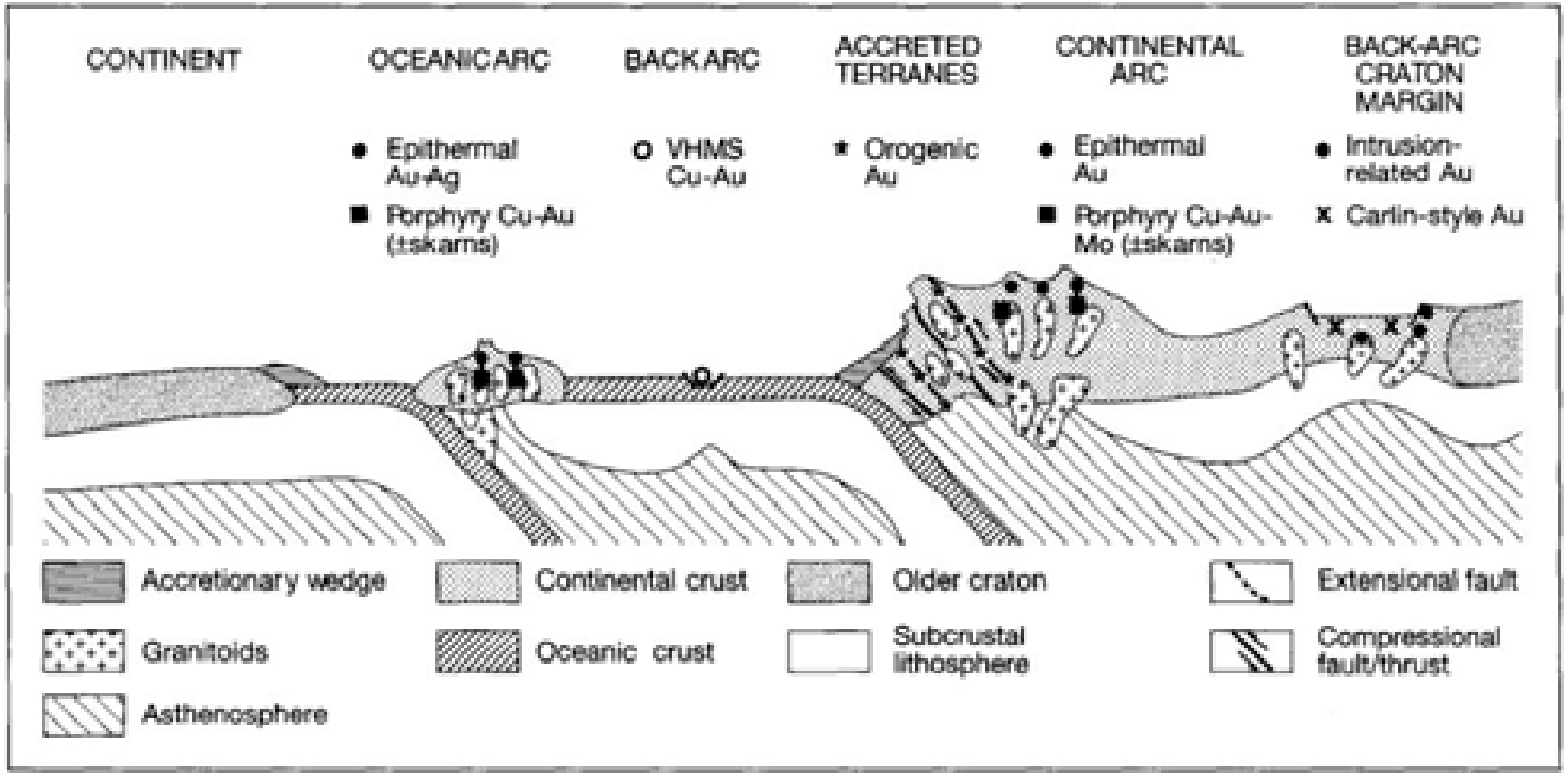
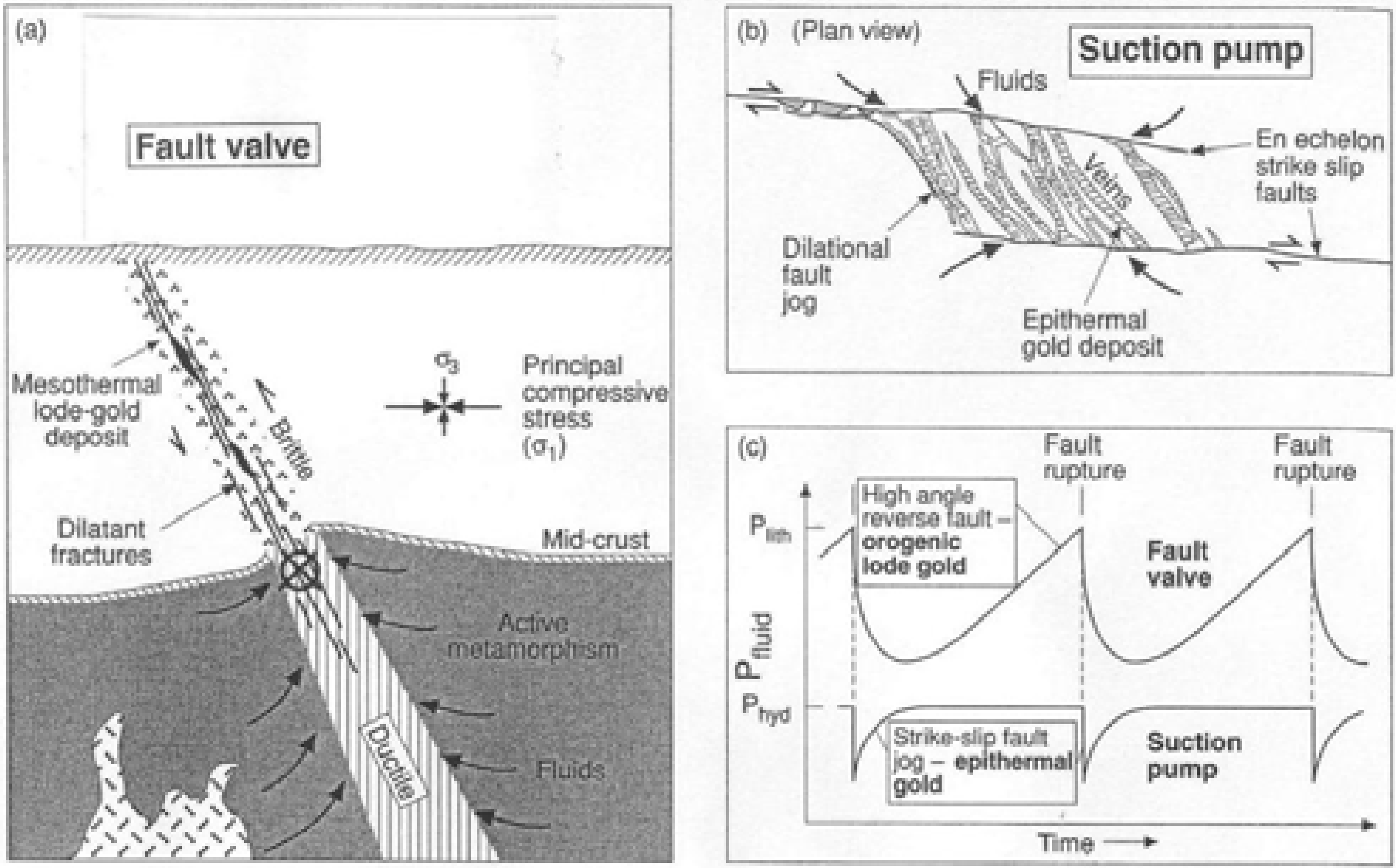


FIG. 1. Tectonic settings of gold-rich epigenetic mineral deposits. Vertical scale is exaggerated to allow schematic depths of formation of various deposit styles to be shown. Adapted from Groves et al. (1998). Abbreviations: VHMS = volcanic-hosted massive sulfide.

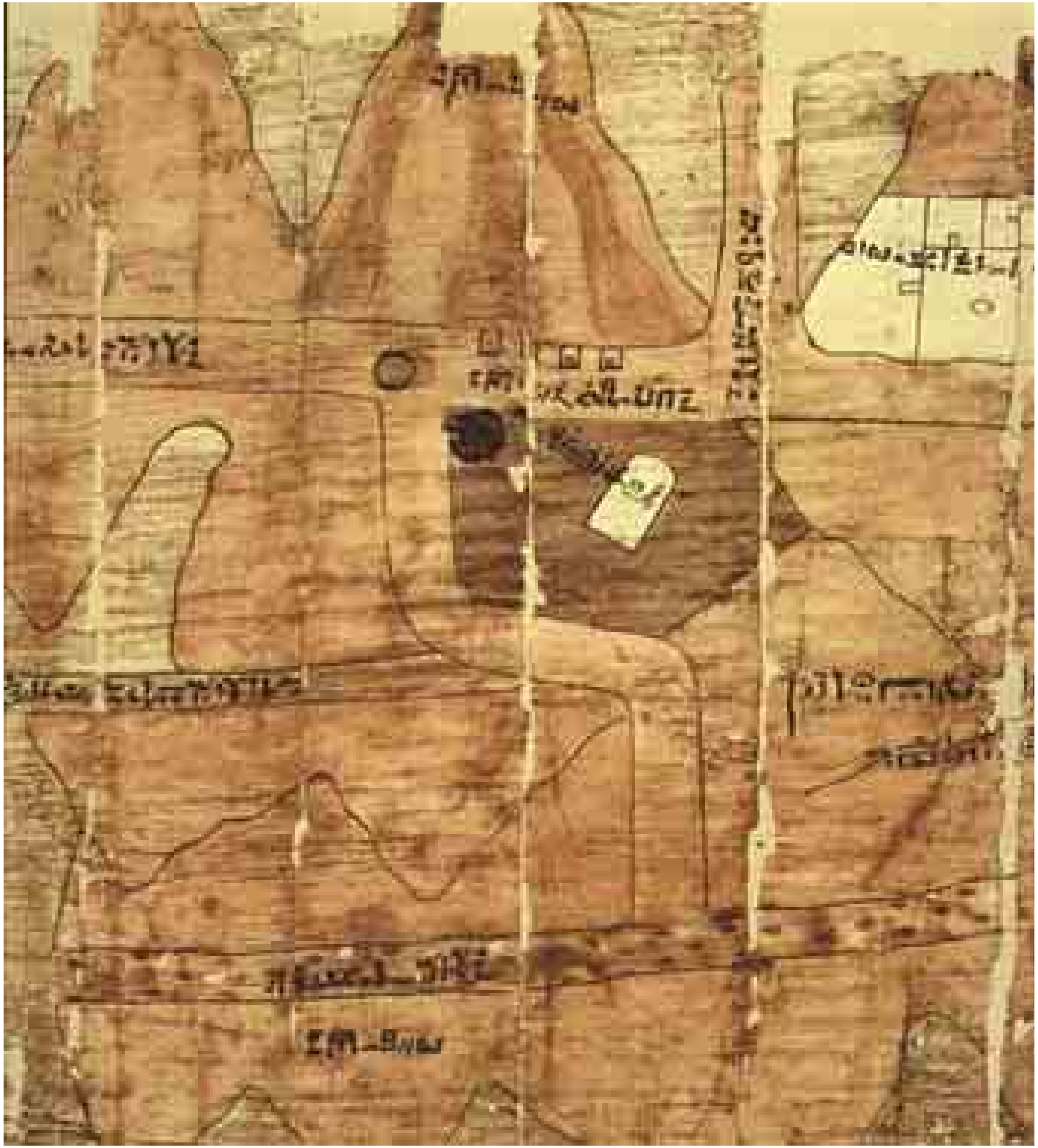
Groves et al., Econ Geol 98: 4 (2003)



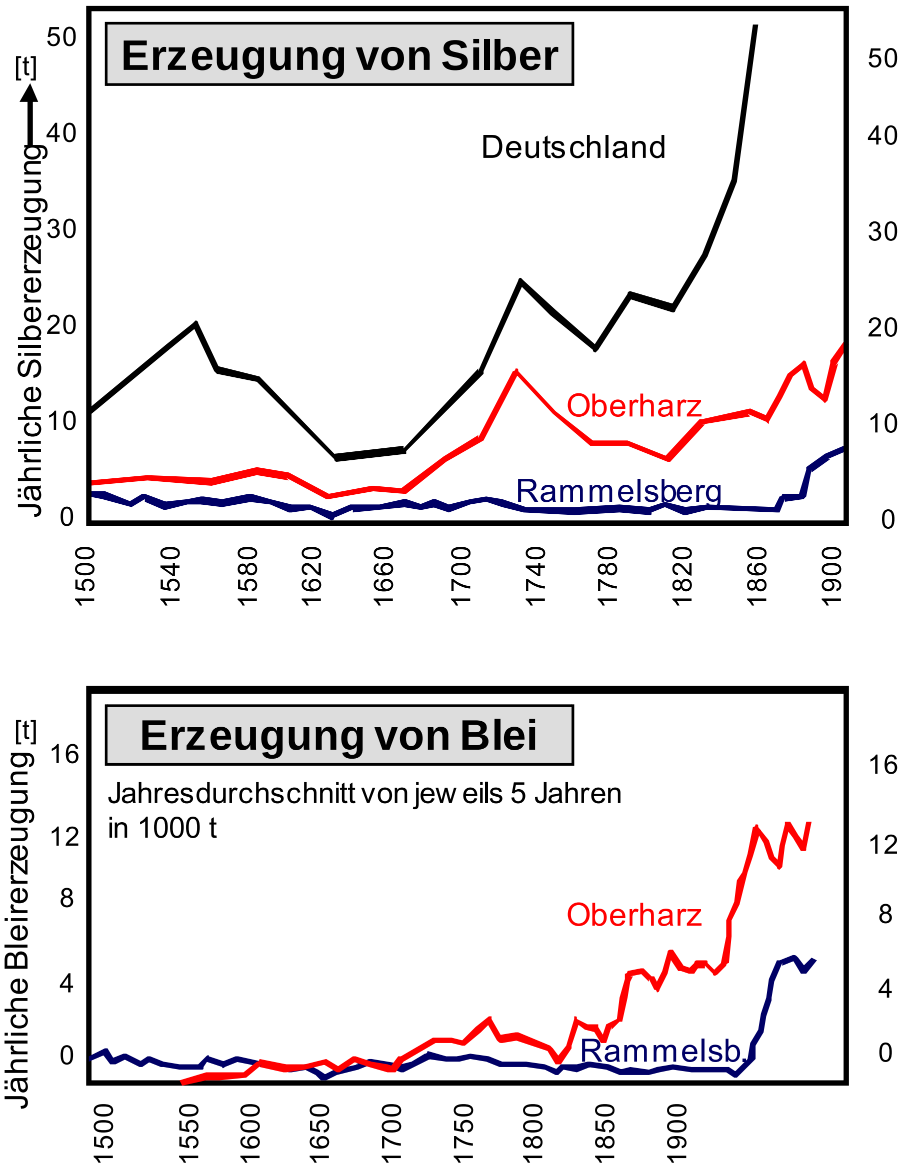
Hydrothermal fluid flow at deep levels (compressive stress regime at several km depth) » Fault valve model: orogenic gold/mesothermal gold; and at shallow levels (extensional regime) » Suction pump model: epithermal gold

Wadi Hammamat,
Eastern Desert, Egypt

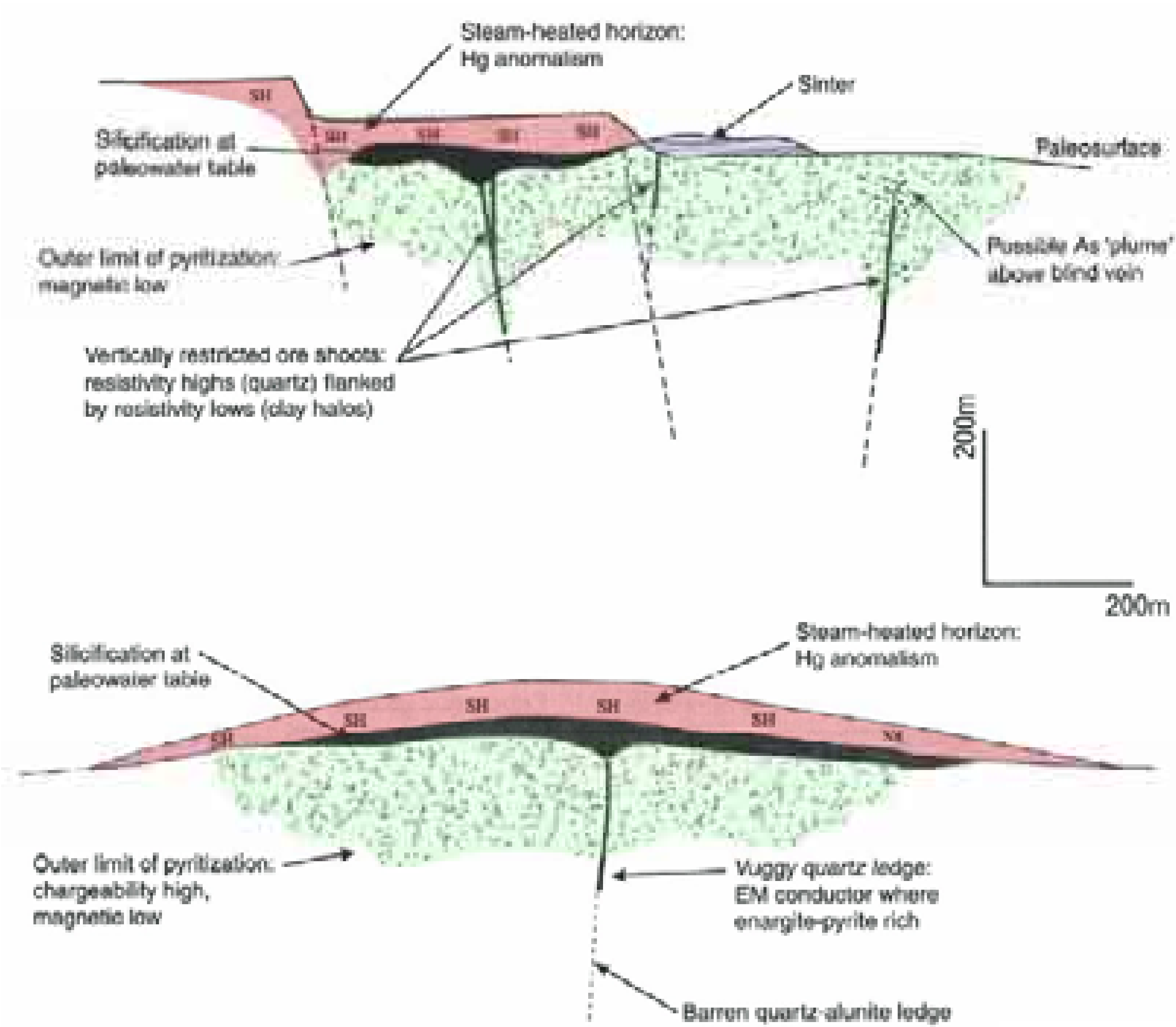
Turin Mine Papyrus,
Museo Egizio
ca. 1200-1000 A.D.
(XXth Dynasty)



Die Oberharzer Blei- und Silbererzeugung von 1500 bis 1900

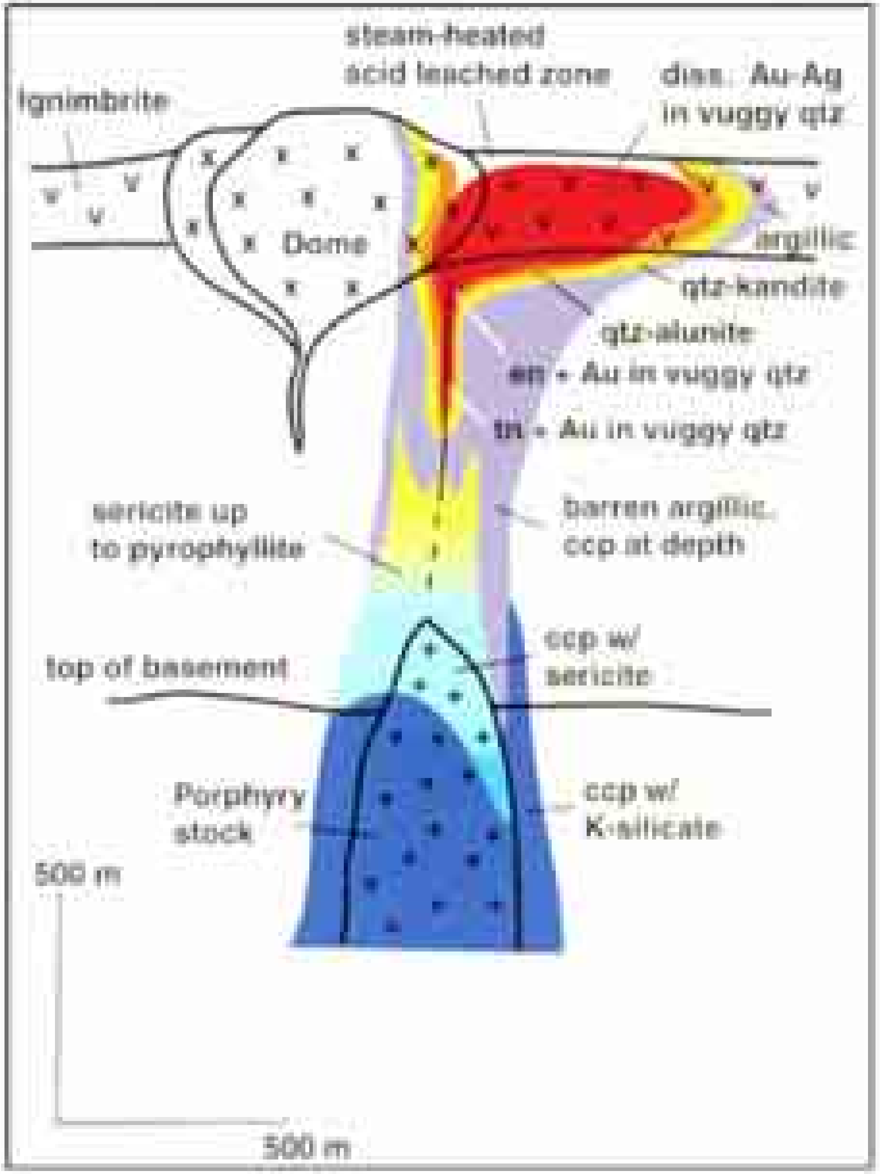


Quelle: Bornhardt, OBA Clausthal-Zellerfeld, Fleisch, 1982, Clausthal-Zellerfeld



Sillitoe, ProExplo Lima 2009

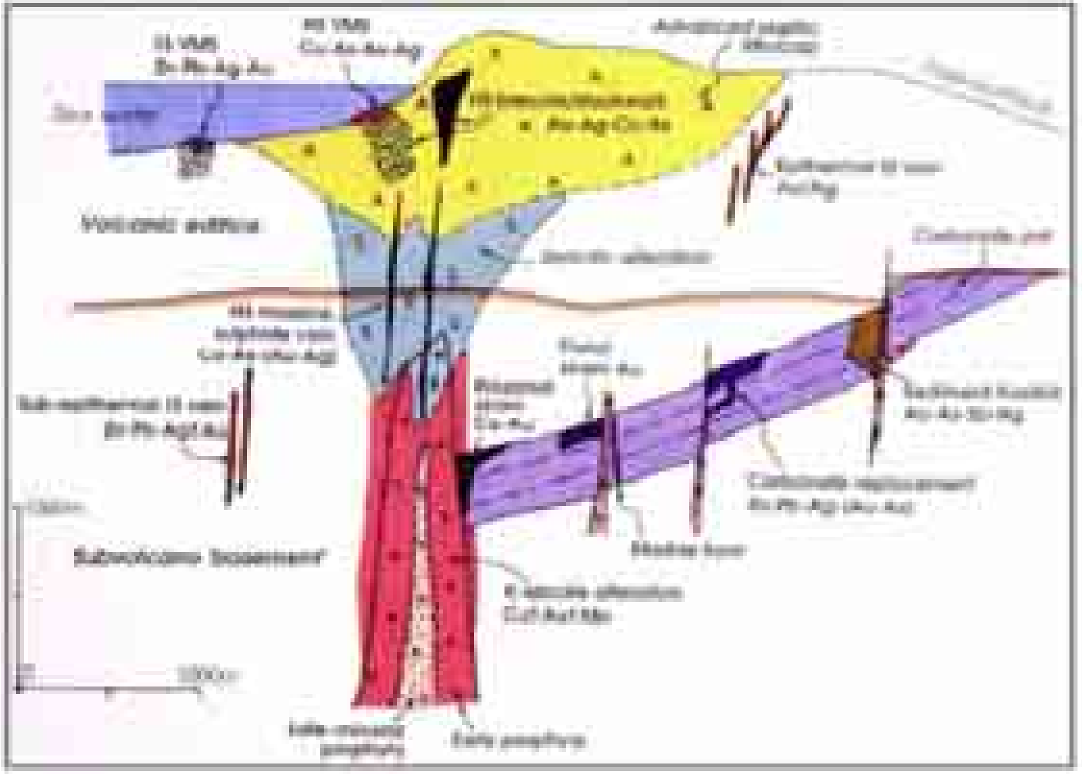
High-sulphidation - porphyry transition



- 1.5 – 2 km vertical interval represented from paleo-surface to porphyry deposit
- Vuggy quartz → quartz-alunite → quartz-pyrophyllite → quartz-sericite from top downwards
- Au-dominated → Cu-dominated from top downwards

Sillitoe, ProExplo Lima 2009

Porphyry-epithermal relationships

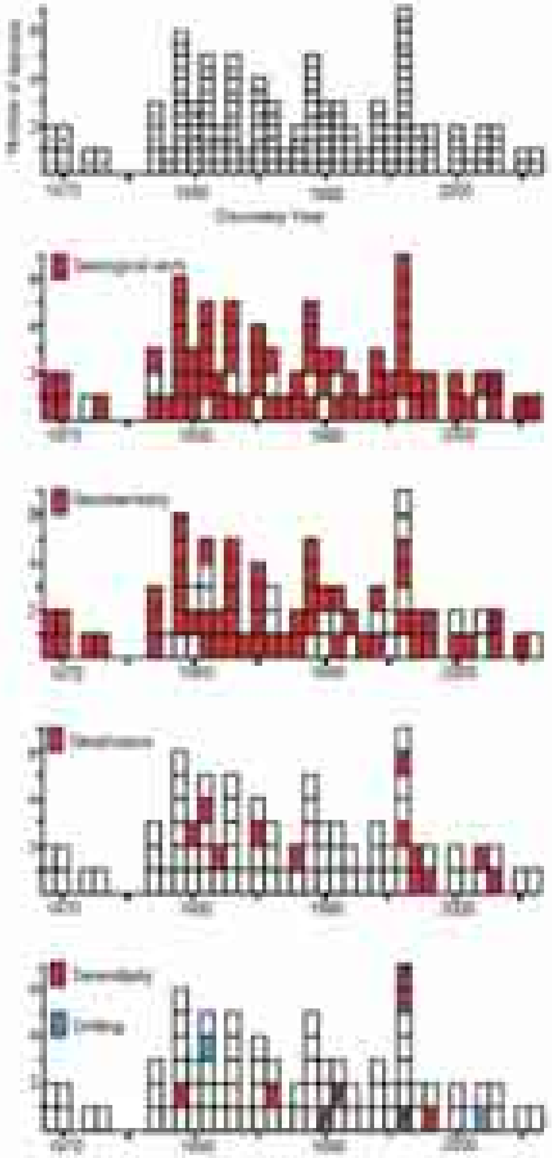


Linkages between porphyry, high- and intermediate-sulphidation epithermal, skarn, carbonate-replacement, and Carlin-like environments now widely appreciated

The necessary information was supplied by worldwide exploration activities

Sillitoe, ProExplo Lima 2009

Key role of geology in porphyry and epithermal exploration



Circum-Pacific Region

Parameters

- 37–year history
- 81 deposits
- Mainly porphyry, epithermal, & sediment-hosted gold (minor VMS & orogenic gold)

Main conclusions

- Notwithstanding exploration changes, little overall evolution in discovery methodology (but see next slide)
- Geologic fieldwork: 90% of discoveries
  - routine observation, mapping, & interpretation
  - familiarity with deposit models (since 1980s)
- Geochemistry: 70% of discoveries
  - stream sediment, soil, & rock chip
- Geophysics: 15% of discoveries (only 50% of programs)
  - Ground IP & EM
- Drilling & serendipity: 12% of discoveries
- Remote sensing (satellite imagery, airborne scanners: 0%)

Sillitoe, ProExplo Lima 2009