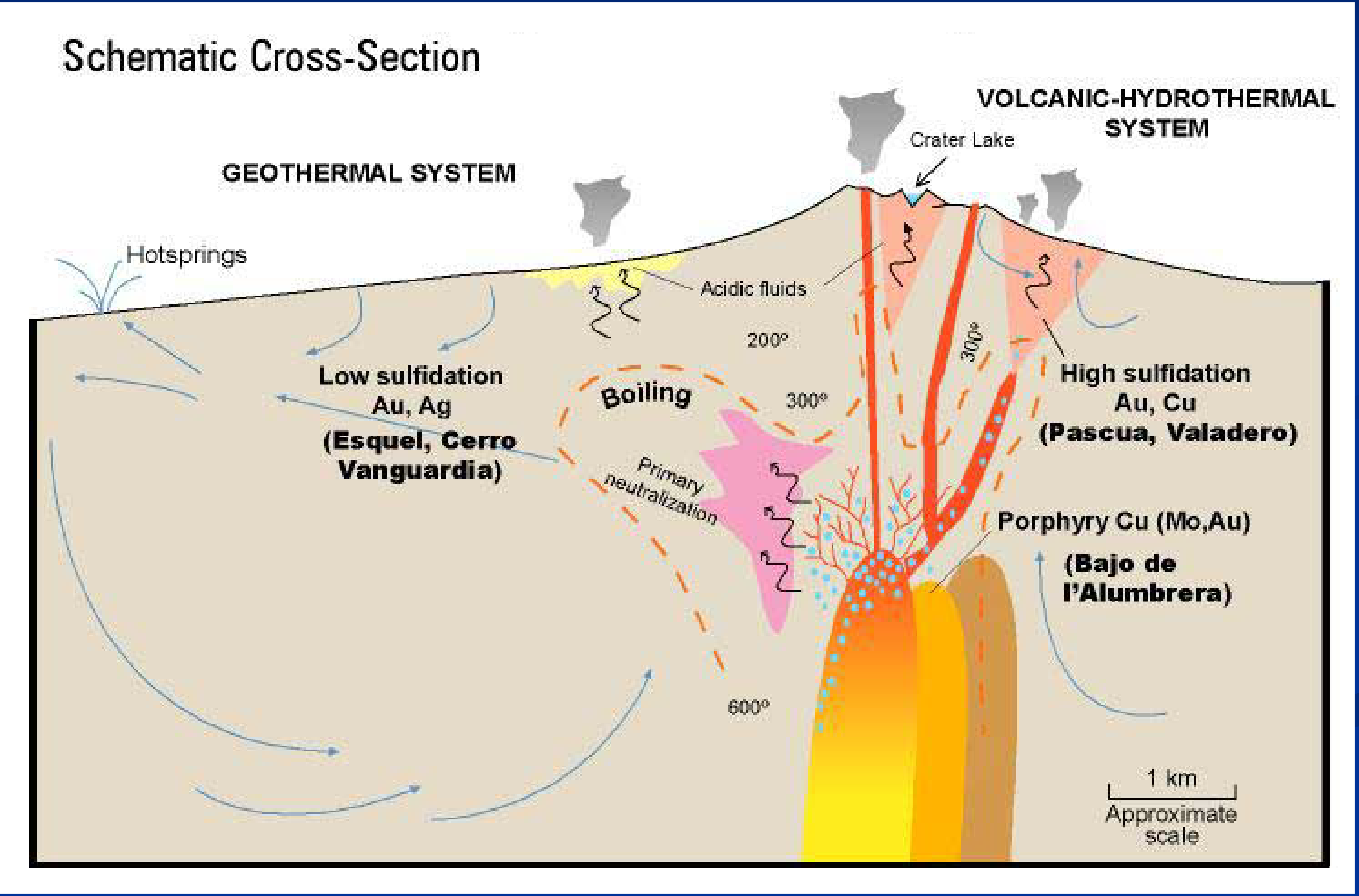
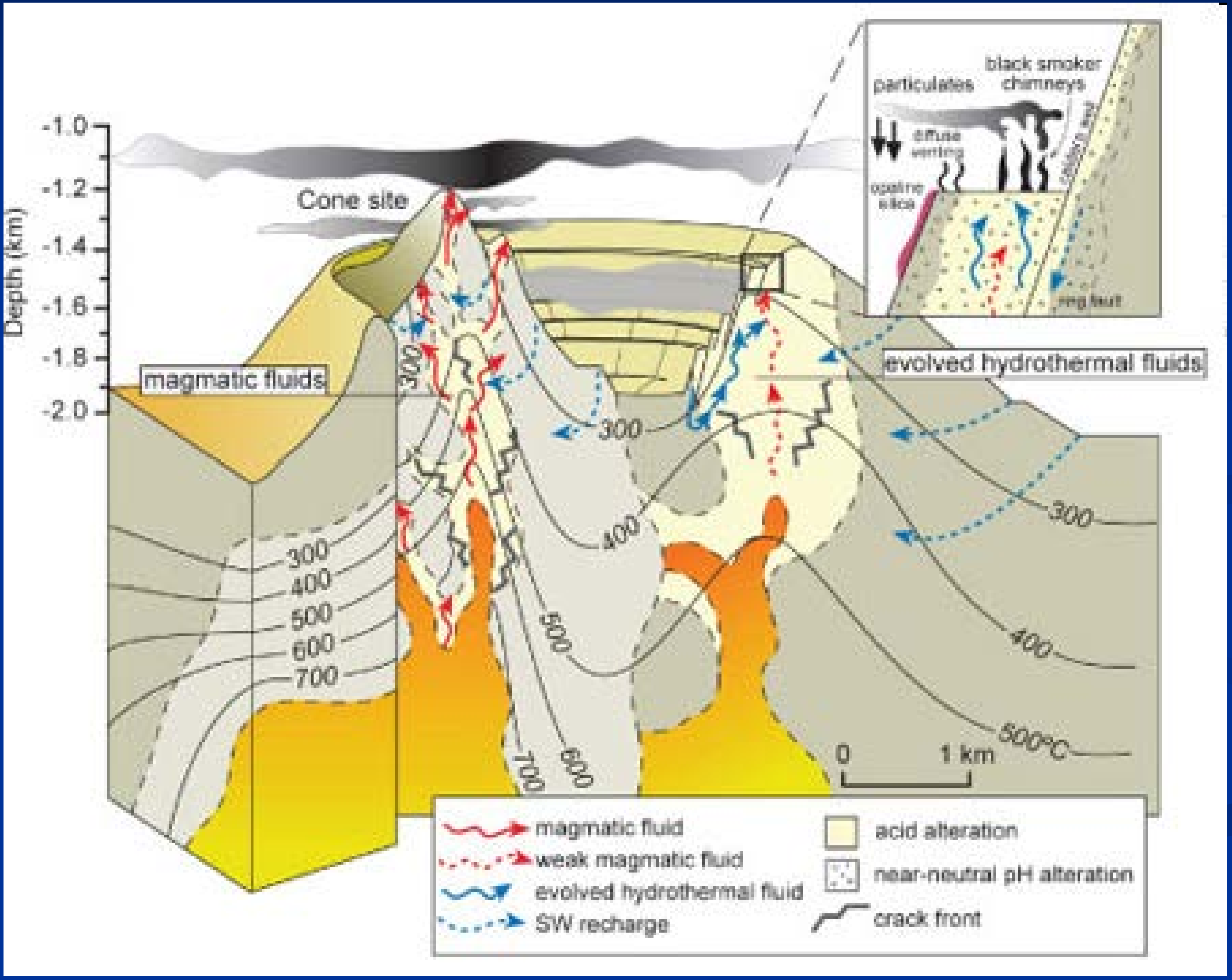
# Epithermal Deposits

# Epithermal Systems

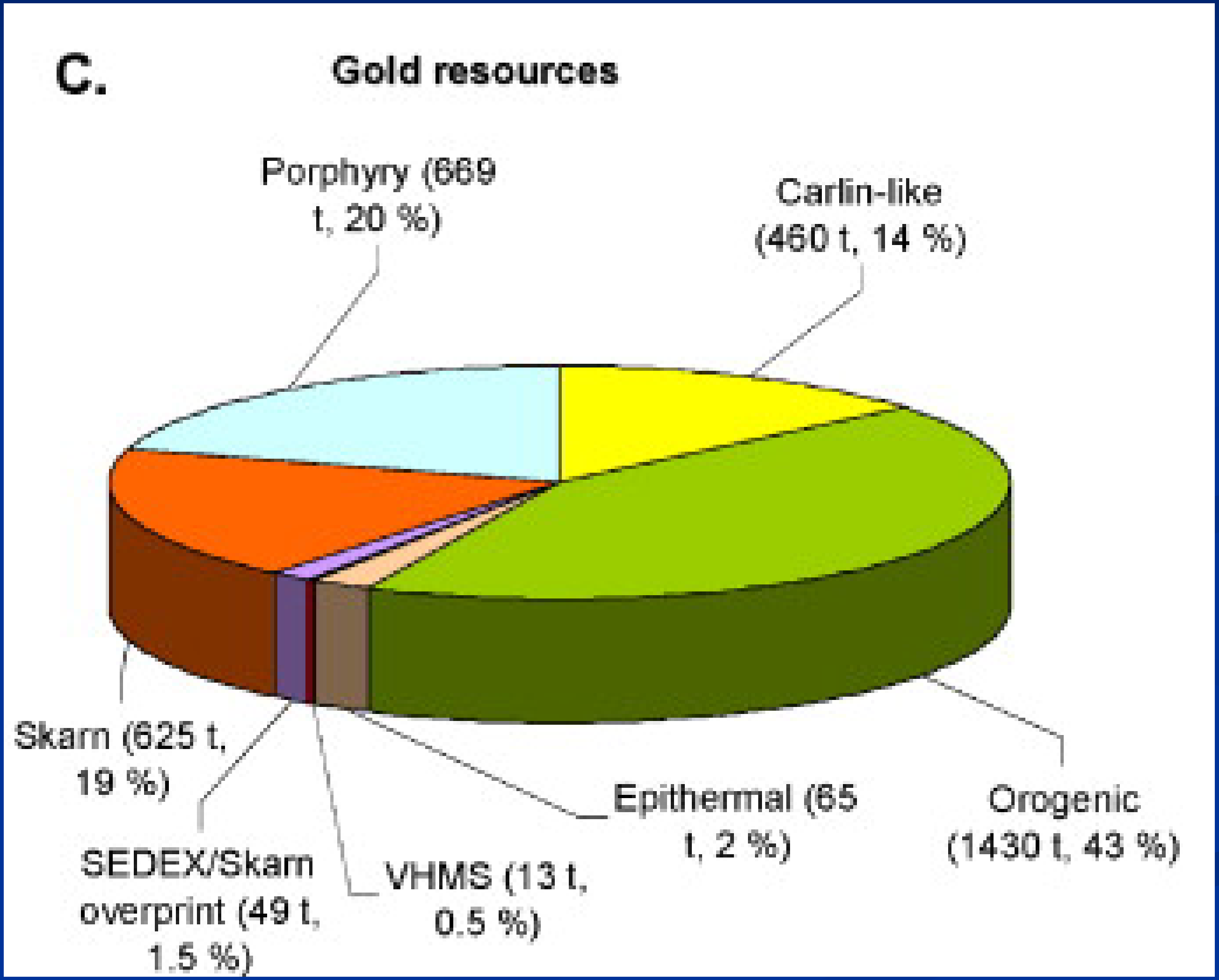
## Low and high sulphidation deposits



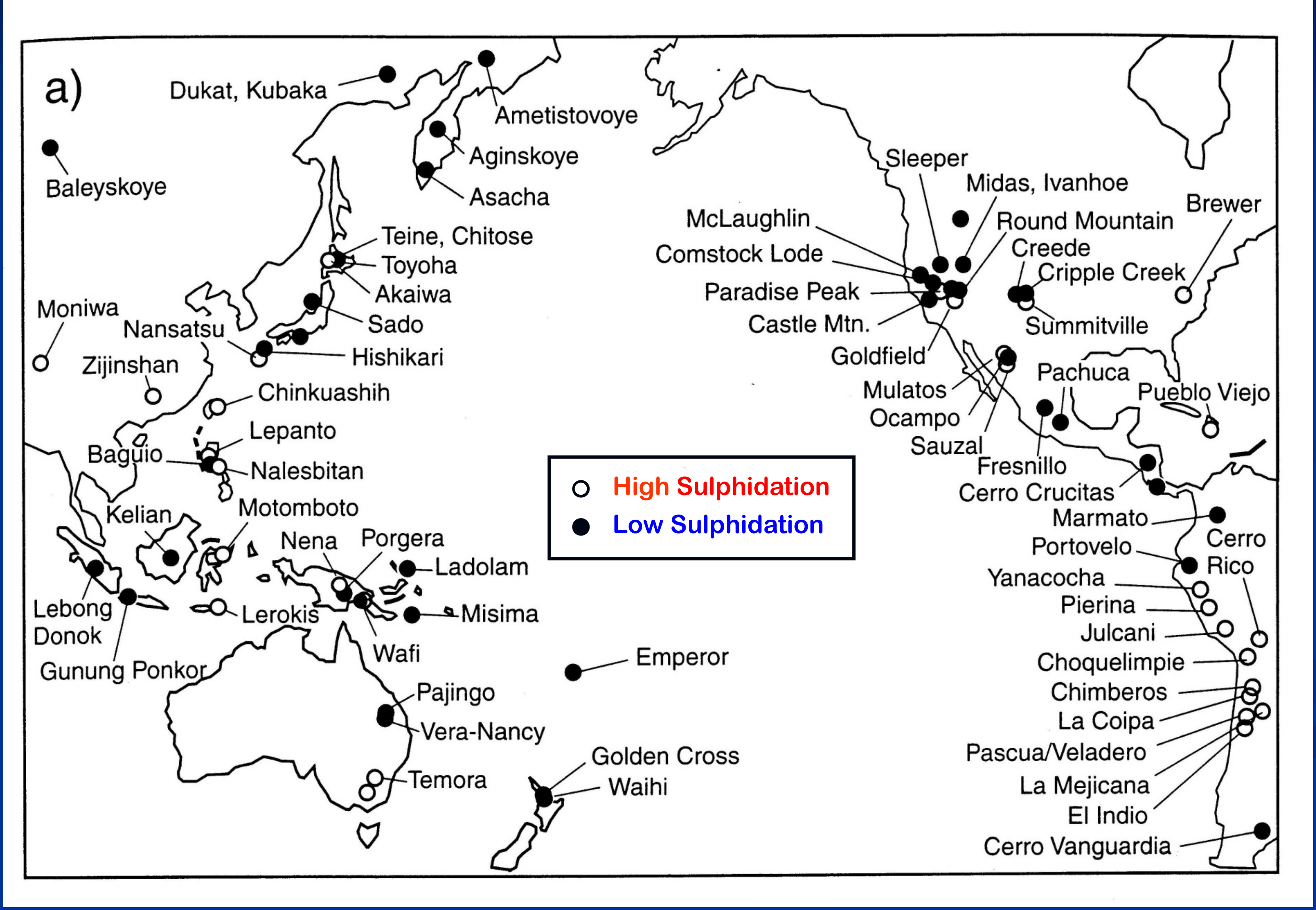
# Submarine Epithermal Systems



# The significance of Epithermal Deposits as a Gold Resource

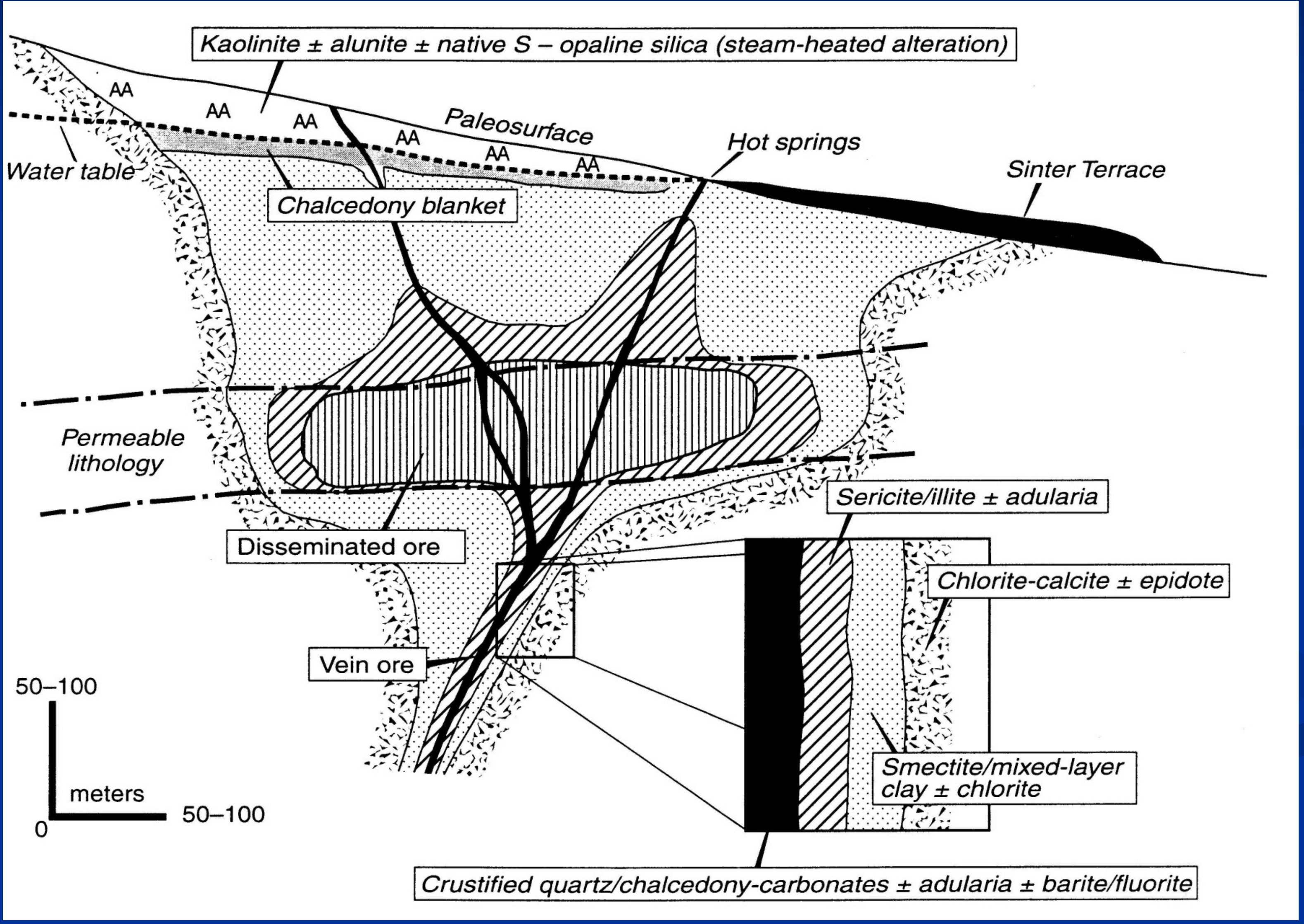


# Distribution of Epithermal Deposits

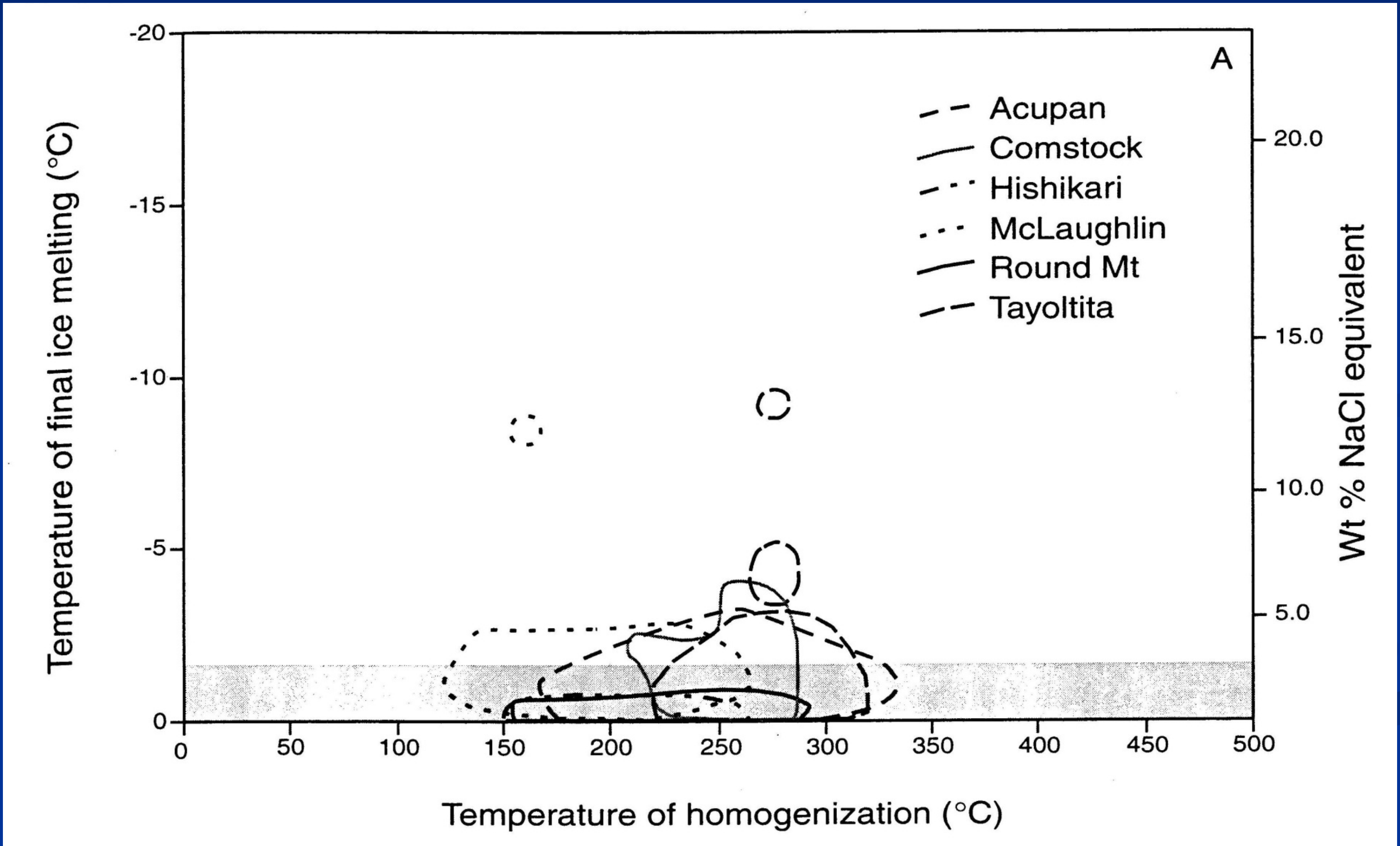


# Surface expression of a low sulphidation epithermal deposit

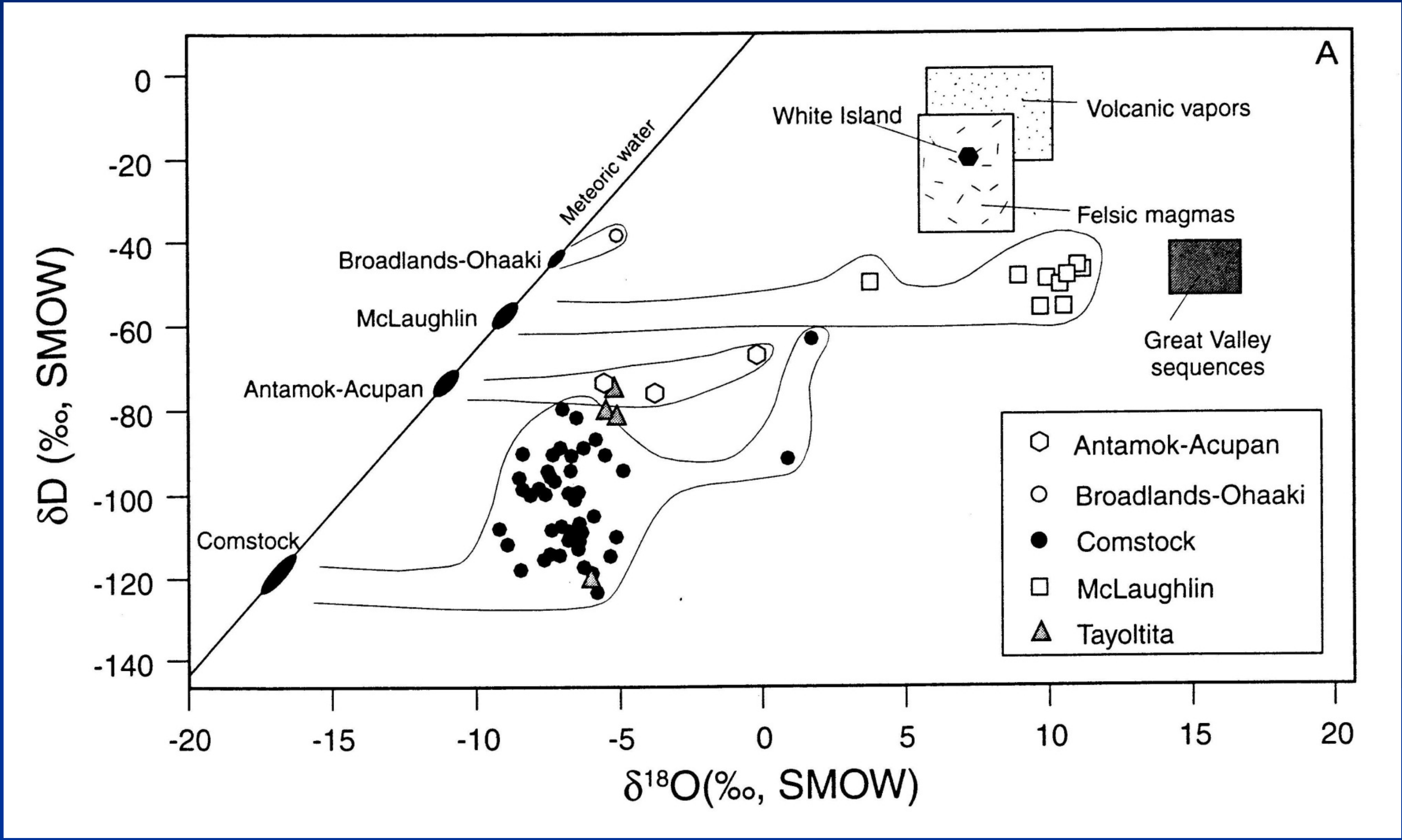
# Low Sulphidation Deposits
# Ore Styles and Alteration Assemblages



# Low Sulphidation Deposits
# Fluid Inclusion Temperatures and Salinities

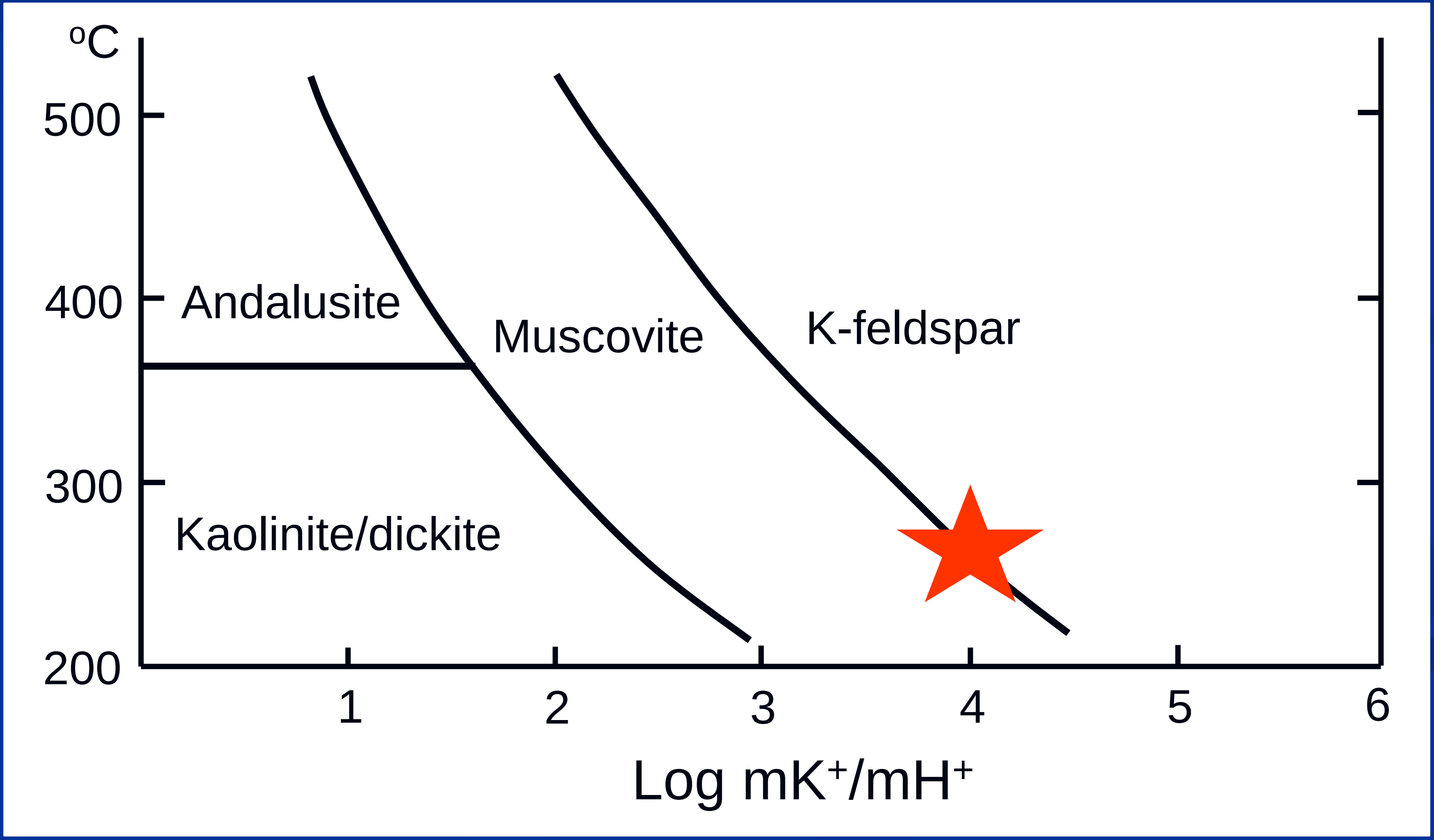


# Low Sulphidation Deposits
# Oxygen and Hydrogen Isotopic Data



# Low Sulphidation Deposits
# Temperature-pH Conditions

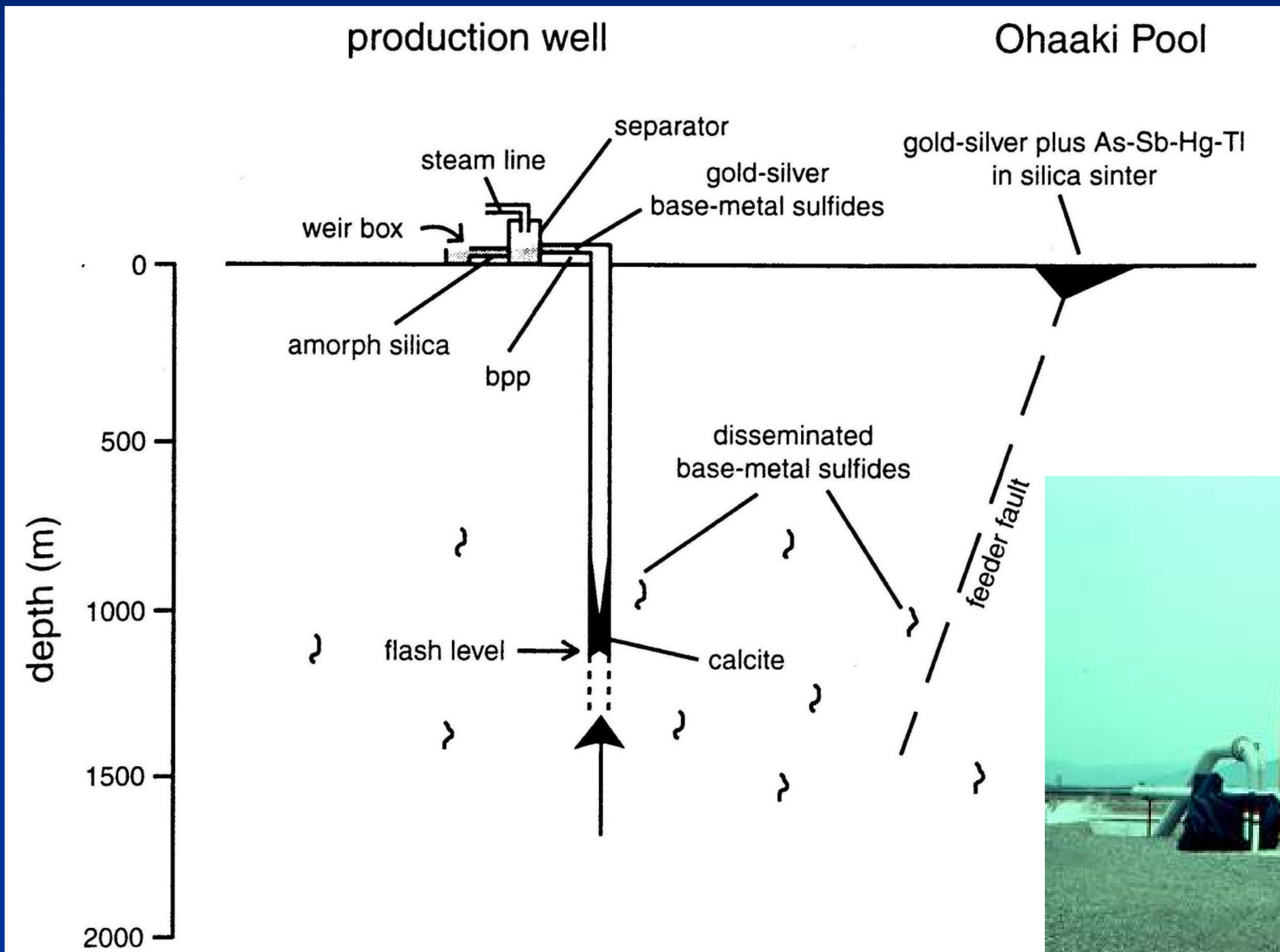
$$3\ KAlSi_3O_8 + 2\ H^+ = KAl_3Si_3O_{10}(OH)_2 + 6\ SiO_2 + 2\ K^+$$



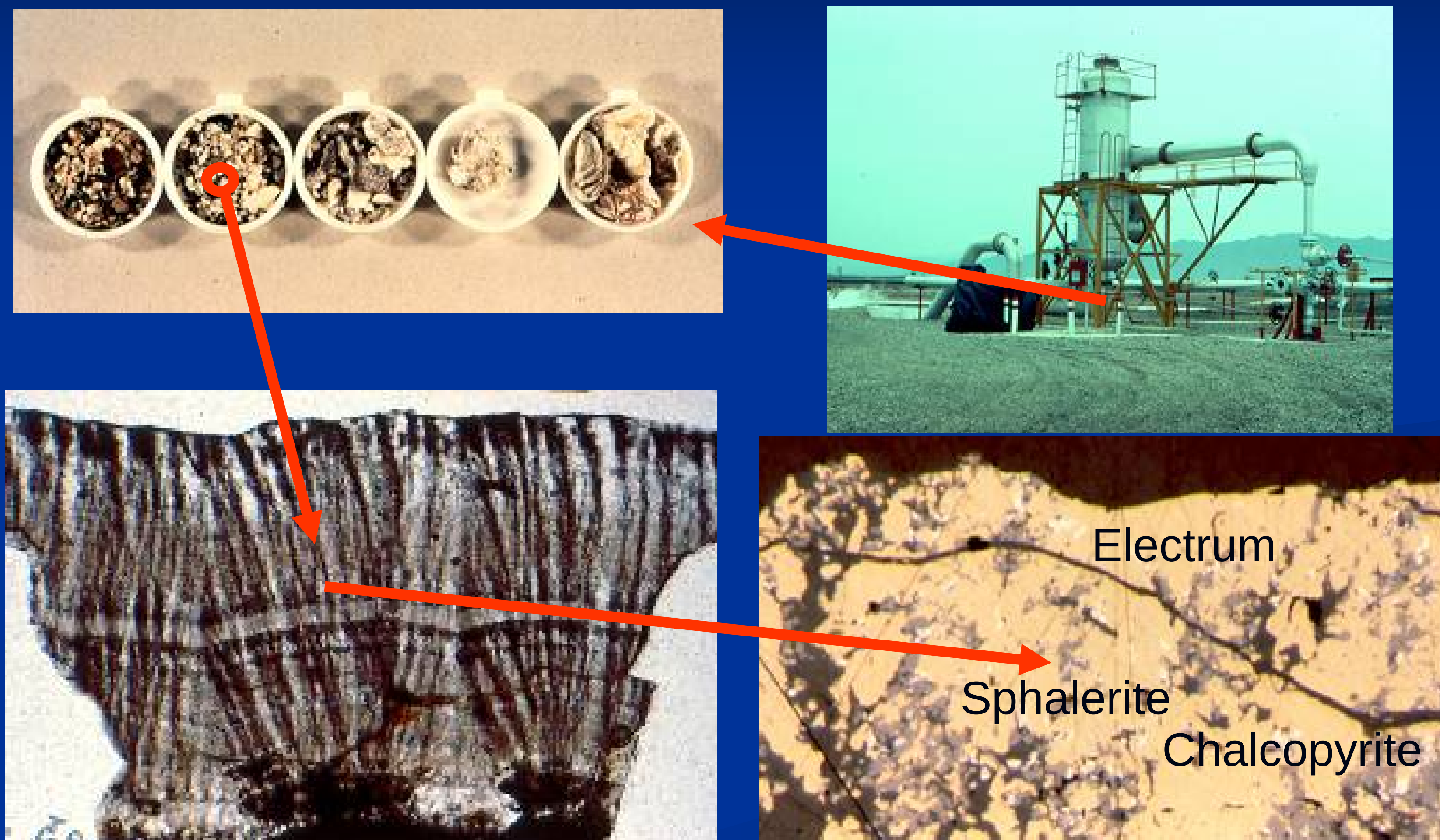
# The Low Sulphidation Epithermal – Geothermal Link



# The Low Sulphidation Epithermal – Geothermal Link




# Geothermal Well Scalings from Cerro Prieto, Mexico



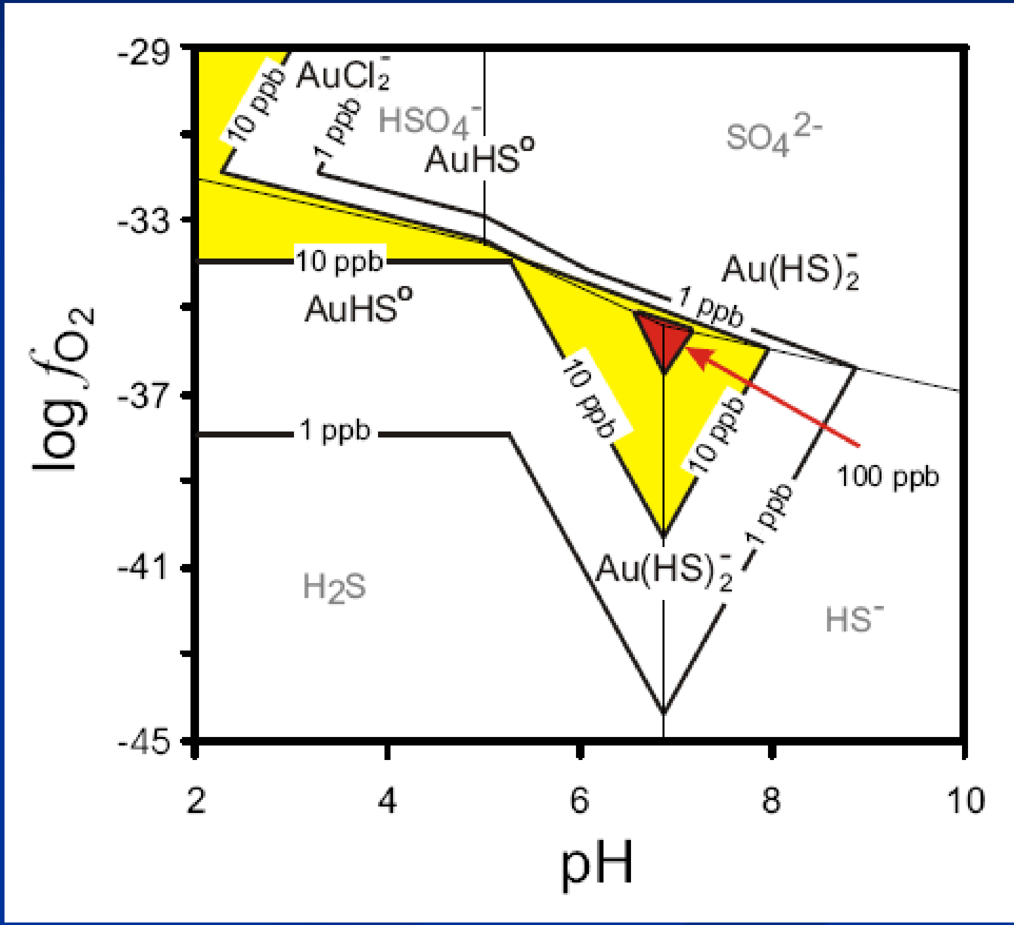

Clark, J.R. & Williams-Jones, A.E., (1990) Analogues of epithermal gold-silver deposition in geothermal well scales: Nature, v. 346, no. 6285, pp 644-645.

# Controls on the Solubility of Gold

$Au(HS)_2^- + H^+ + 0.5\ H_2O$
$= Au + 2H_2S + 0.25O_2$

$Au(HS)^o + 0.5\ H_2O$
$= Au + H_2S + 0.25O_2$

$AuCl_2^- + 0.5H_2O$
$= Au + 2Cl^- + H^+ + 0.25O_2$




Williams-Jones et al. 2009

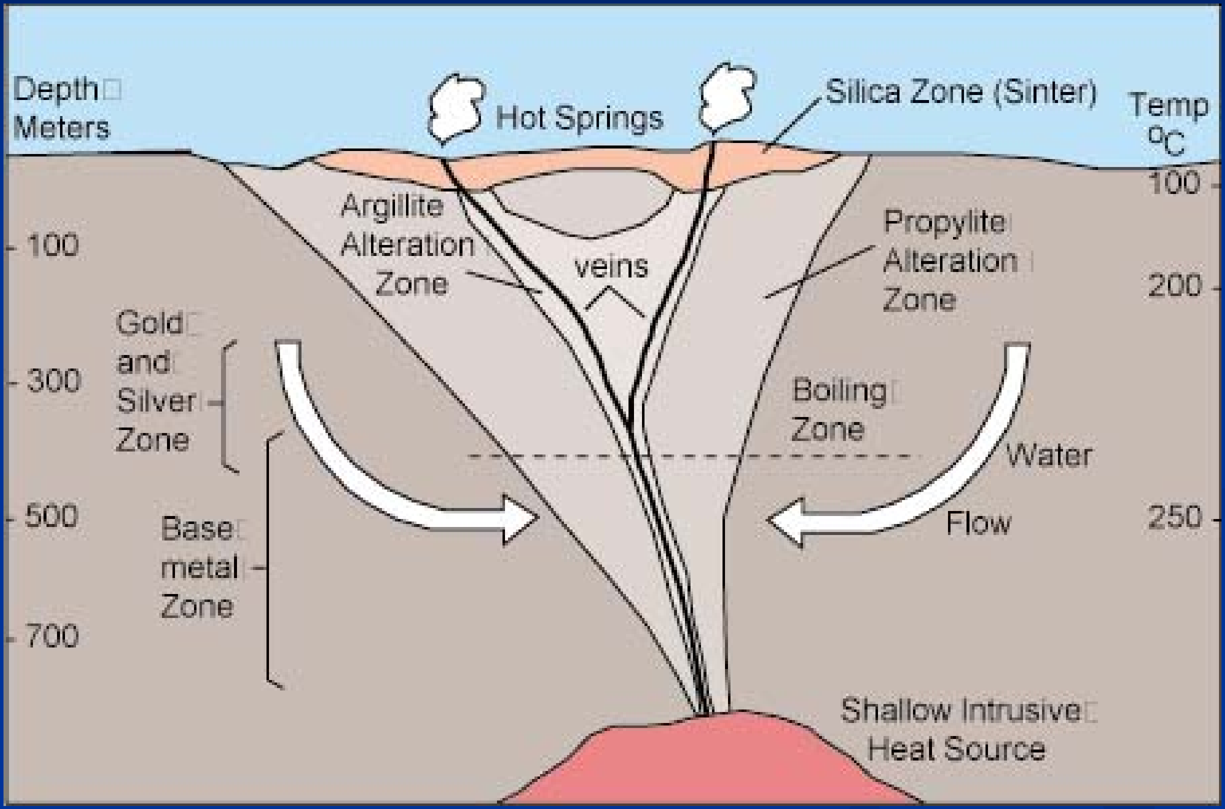
# A model for the formation of low sulphidation epithermal deposits

$Au(HS)_2^- + H^+ + 0.5\ H_2O$

$=$

$Au + 0.25O_2 + 2H_2S$

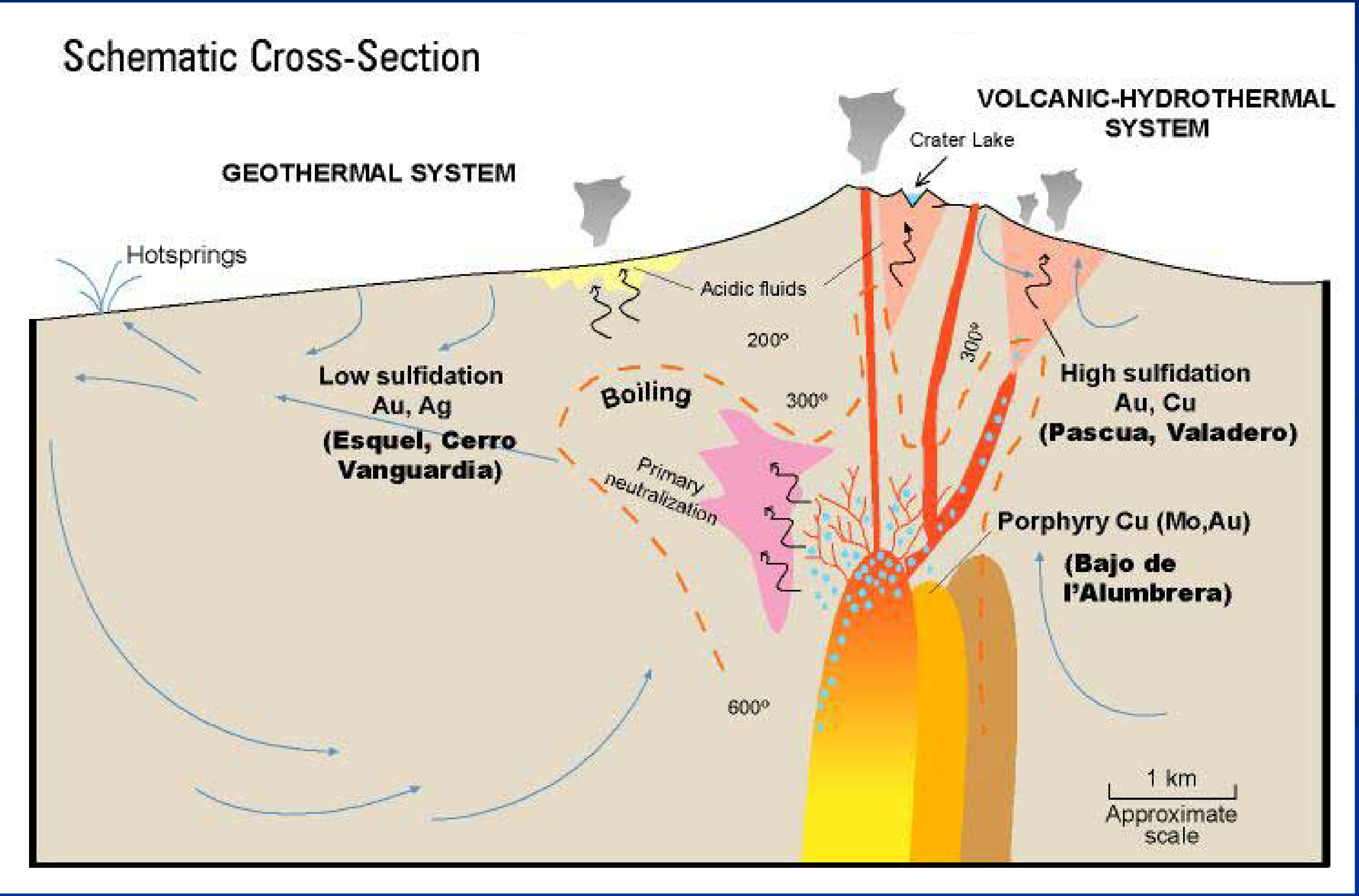
Removed by boiling



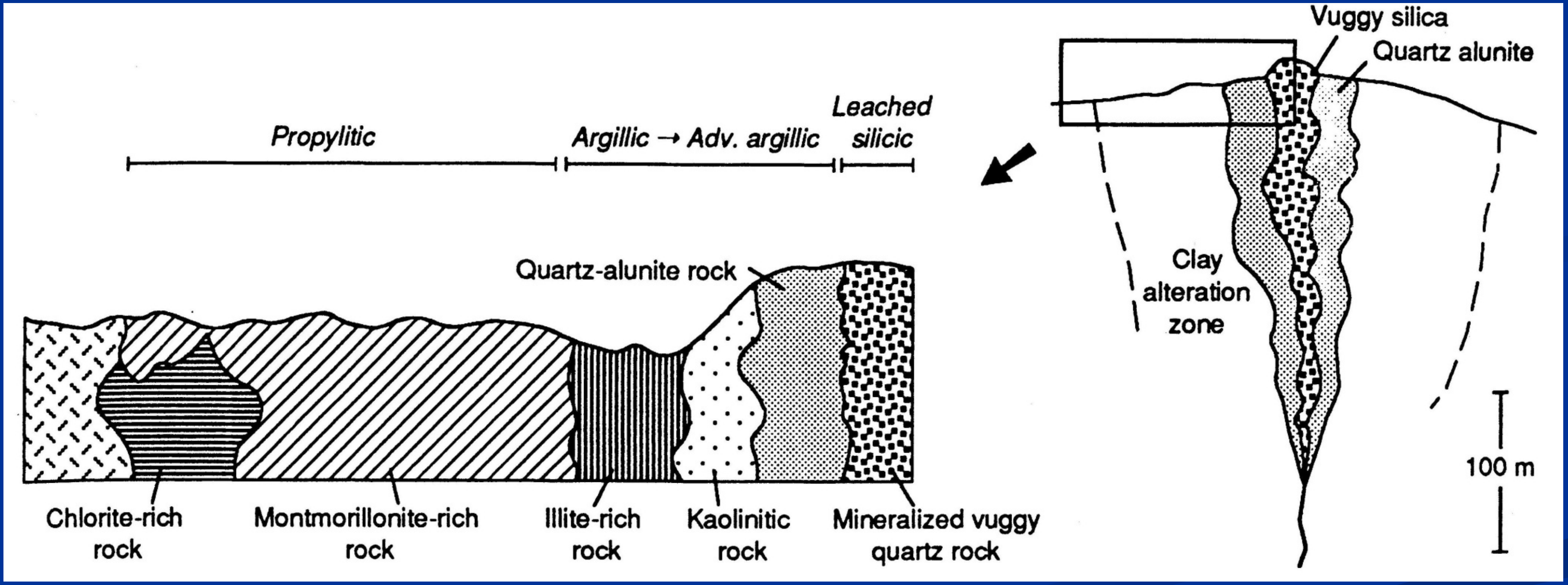

1) Magmatic vapour condenses in meteoric water
2) Gold transported as $Au\ (HS)_2^-$
3) Water rises and boils, releasing $H_2S$ and destabilizing $Au(HS)_2$-
4) Gold deposits as the native metal

# Epithermal Systems

## High sulphidation deposits



# High Sulphidation Deposits
# Ore Style and Alteration Assemblages

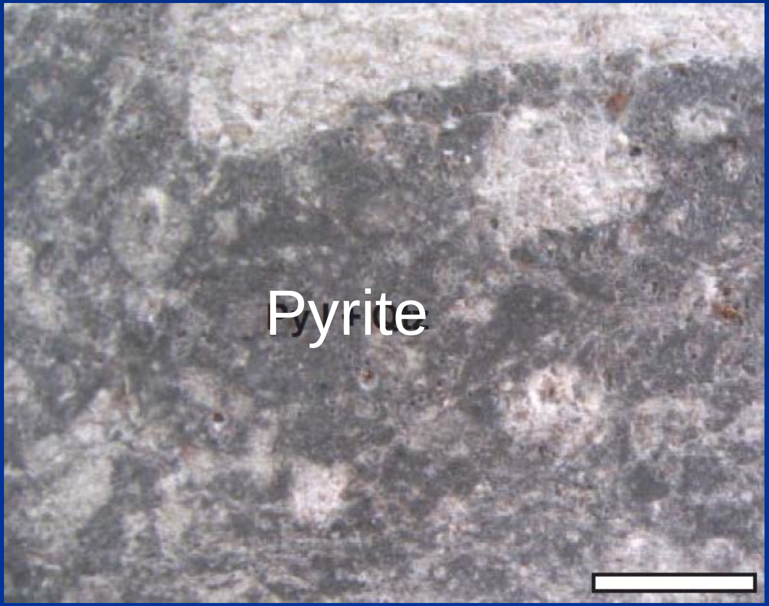


# Acid-Sulphate Alteration

## Vuggy silica

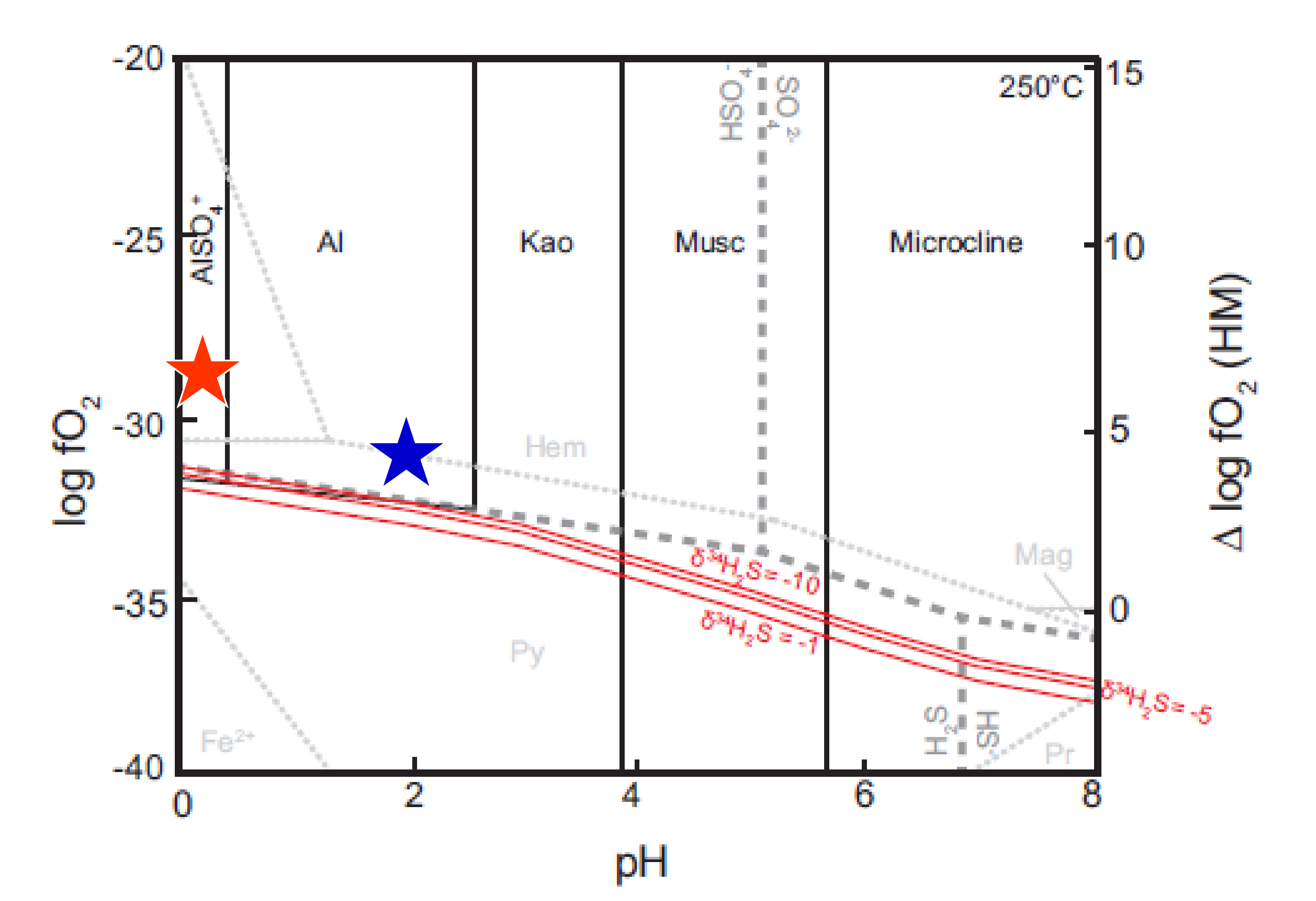
All components of the rock leached leaving behind vuggy silica (pH < 1)

## Advanced argillic alteration



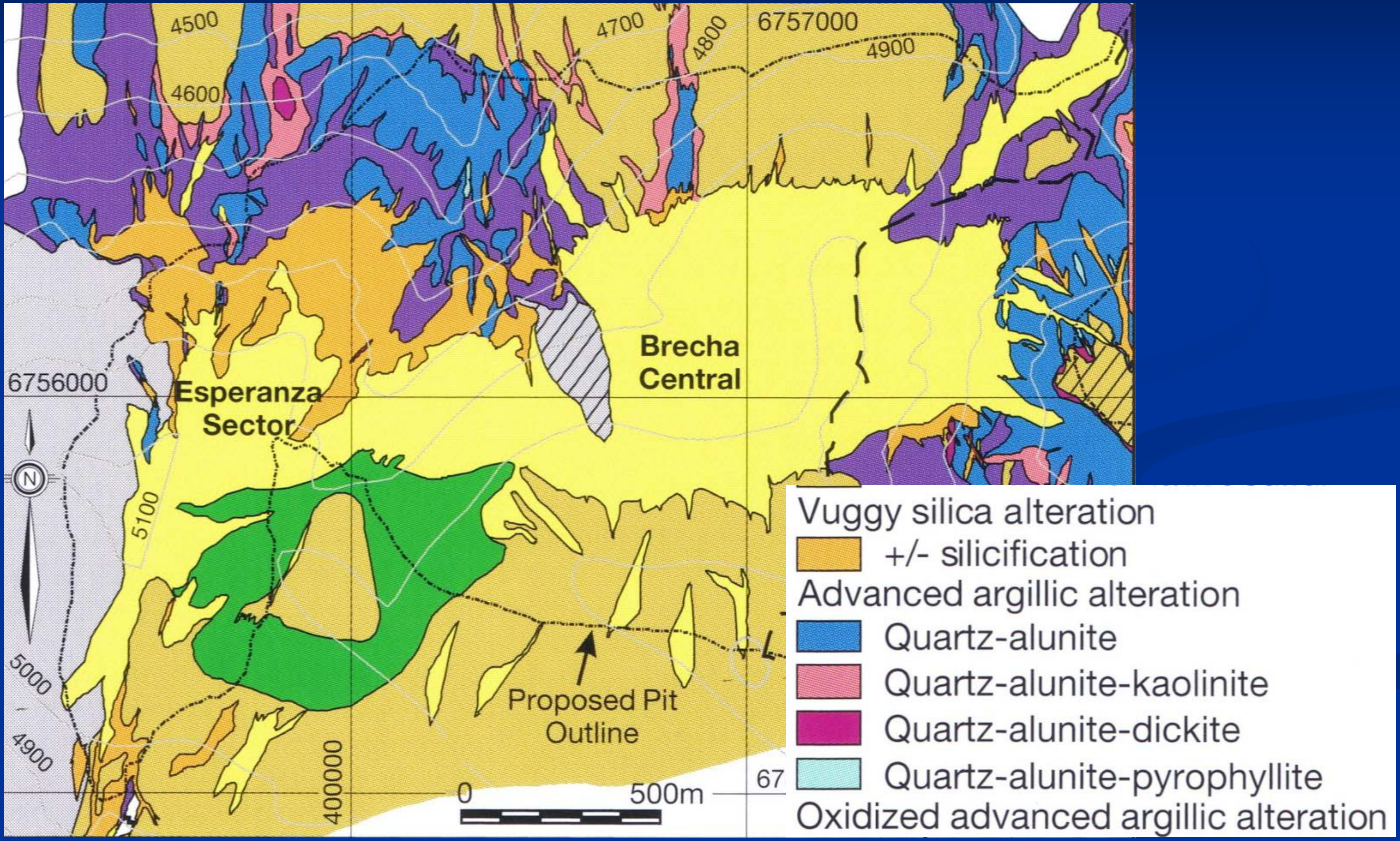

Alunite $(KAl_3(SO_4)_2(OH)_6$
Kaolinite $(Al_2Si_2O_5(OH)_4$
Quartz and Pyrite

# Conditions of Acid-Sulphate Alteration



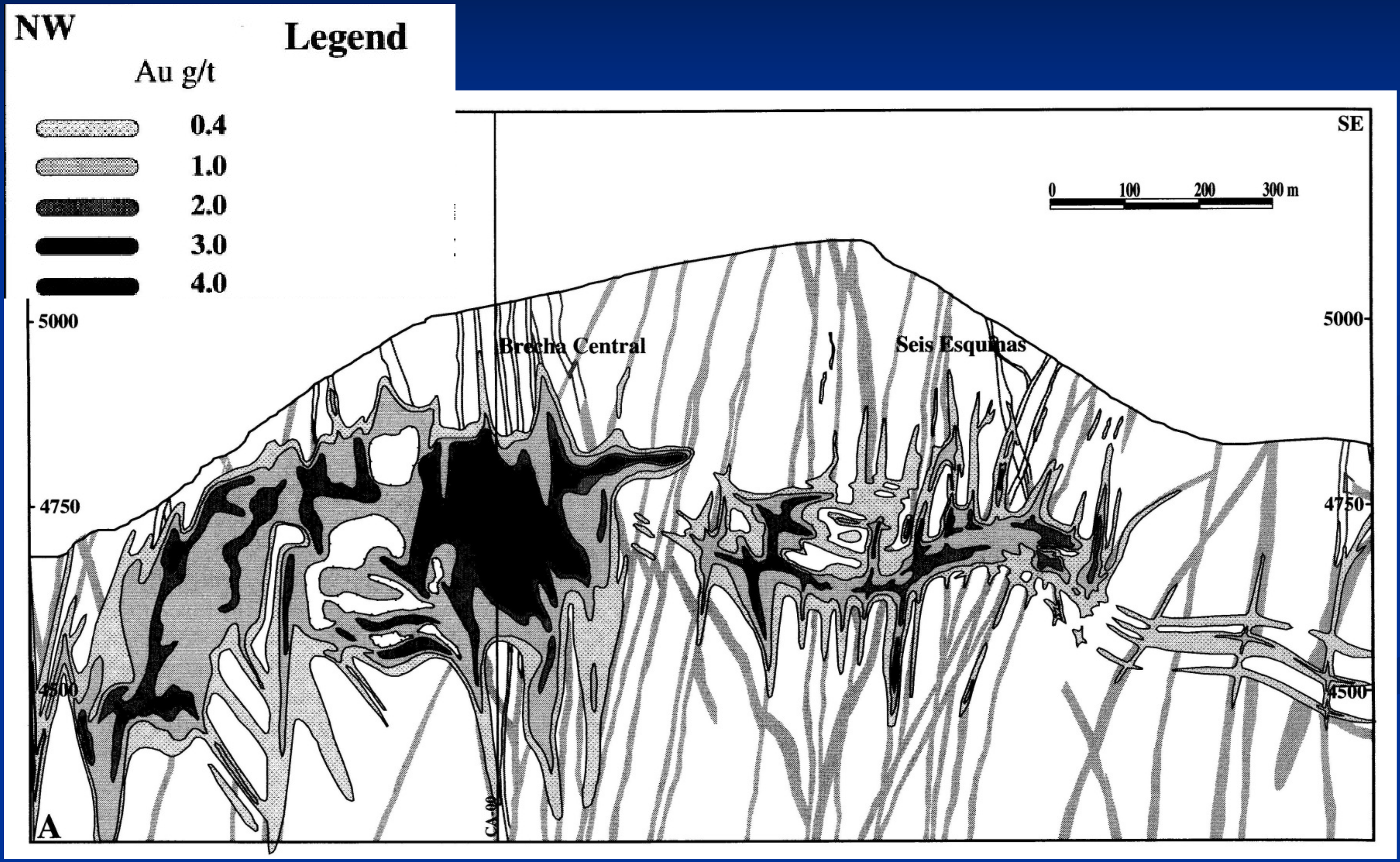

King et al., 2014

# The high sulphidation Pascua epithermal deposit, Chile

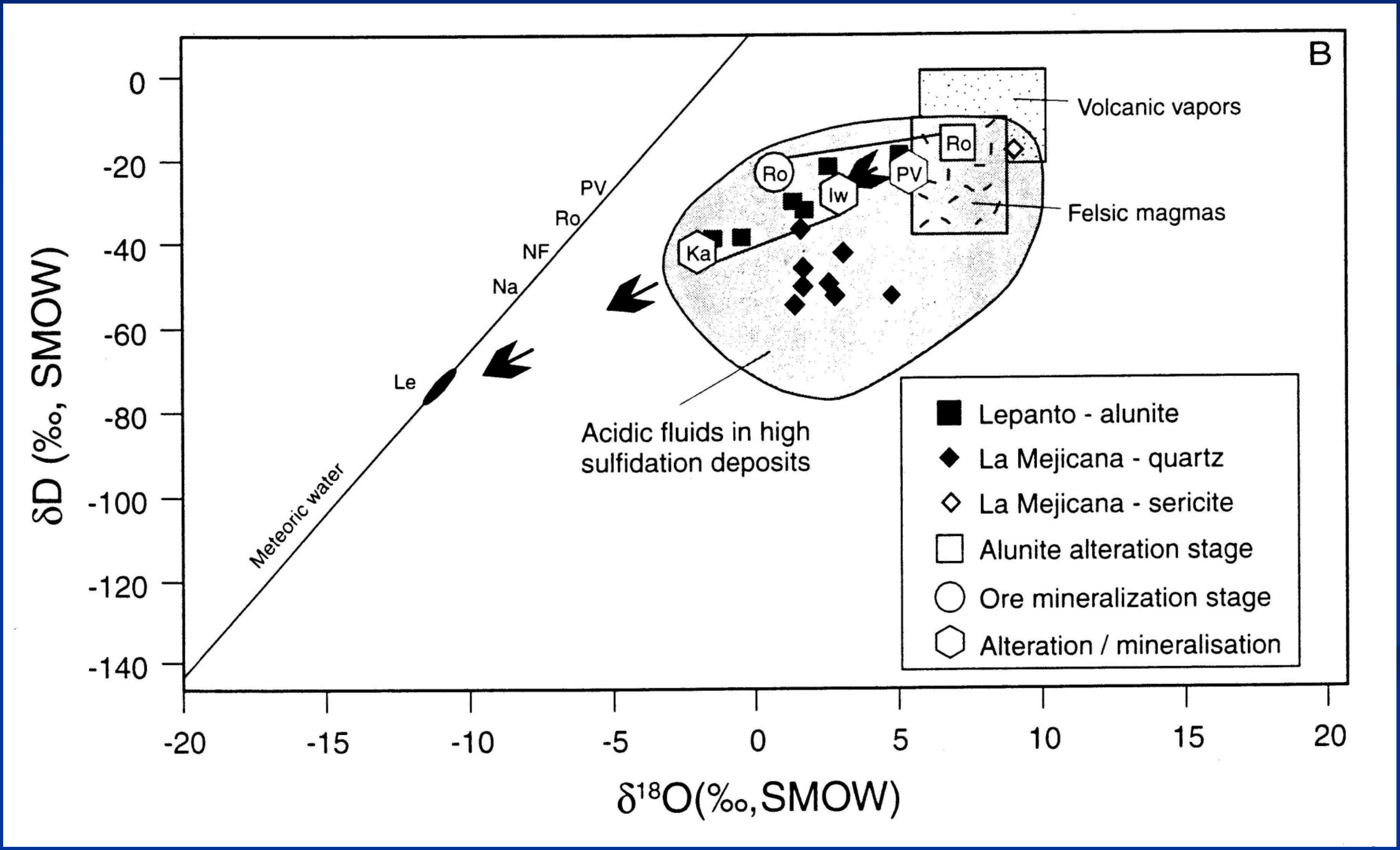



Chouinard et al., 2005

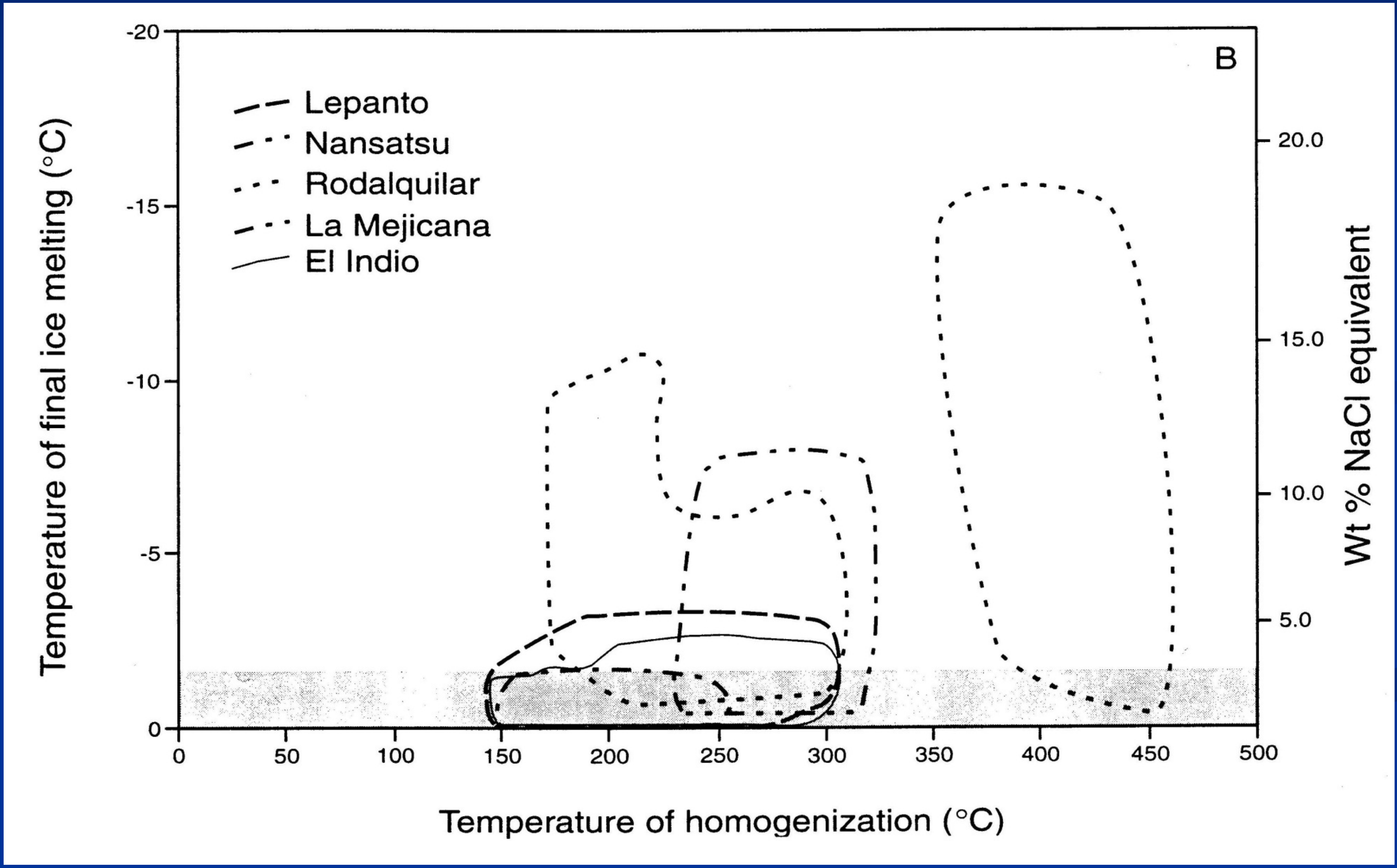
# Mineralization at Pascua



# High Sulphidation Deposits
# Oxygen and Hydrogen Isotopic Data



# High Sulphidation Deposits
# Fluid Inclusion Temperatures and Salinities



# A Model for the Formation of High Sulphidation Deposits

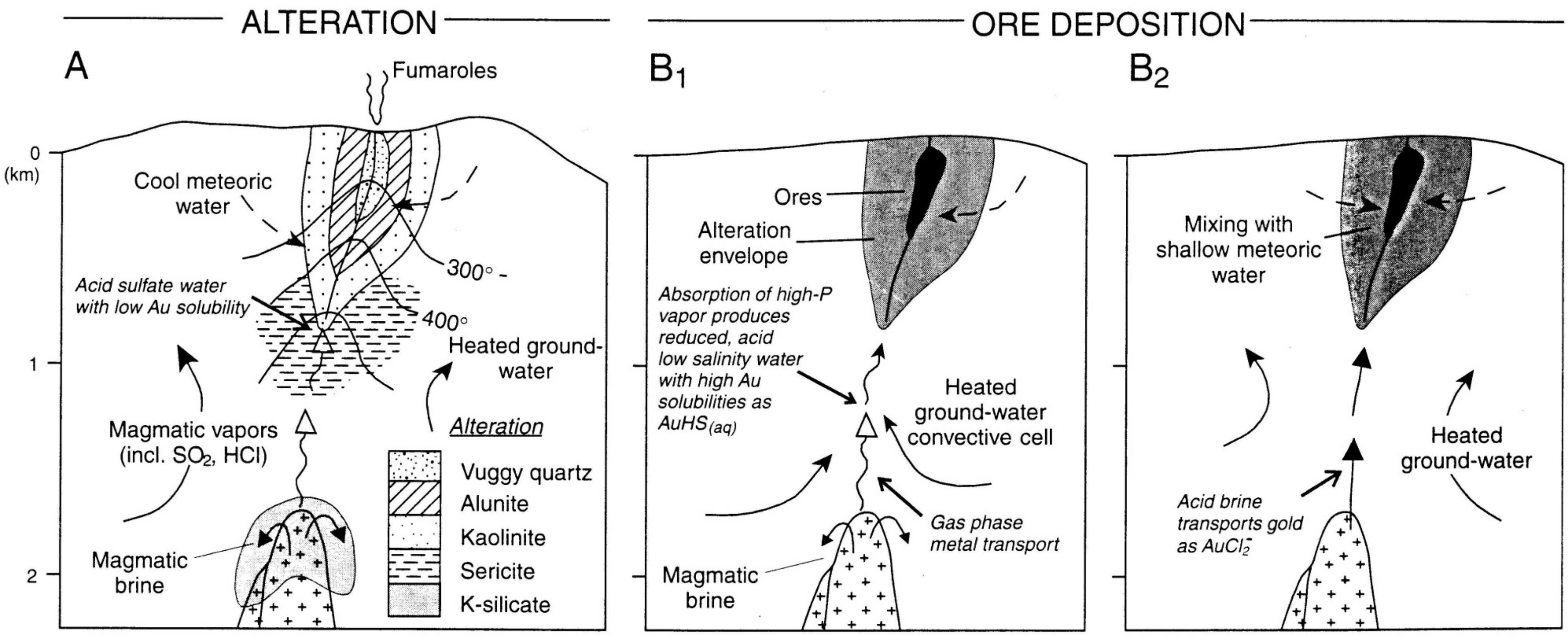



FIG. 12. Two-stage model for high-sulfidation ore formation proposed by Arribas (1995), modified to highlight likely water compositions involved in each stage of ore genesis. Stage 1 (A) is the ground preparation stage, whereby magmatic gases generate an acid sulfate high-sulfidation water that is responsible for the initial barren stage of residual silica and advanced argillic alteration. The second stage involves gold deposition from acid chloride low-sulfidation waters ($B_1$) or acid chloride brines ($B_2$).

Cooke and Simmons, 2000

# Controls on the Solubility of Gold

$Au(HS)_2^- + H^+ + 0.5\ H_2O$
$= Au + 2H_2S + 0.25O_2$

$Au(HS)^o + 0.5\ H_2O$
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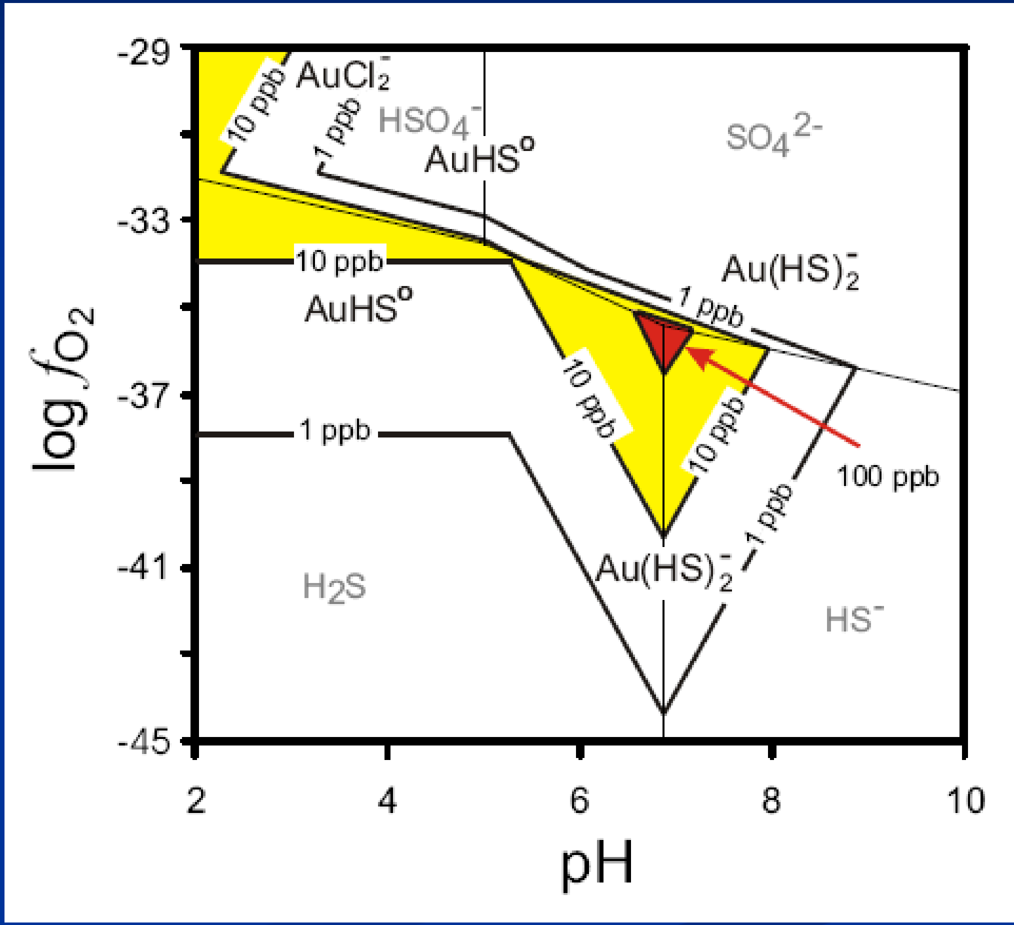
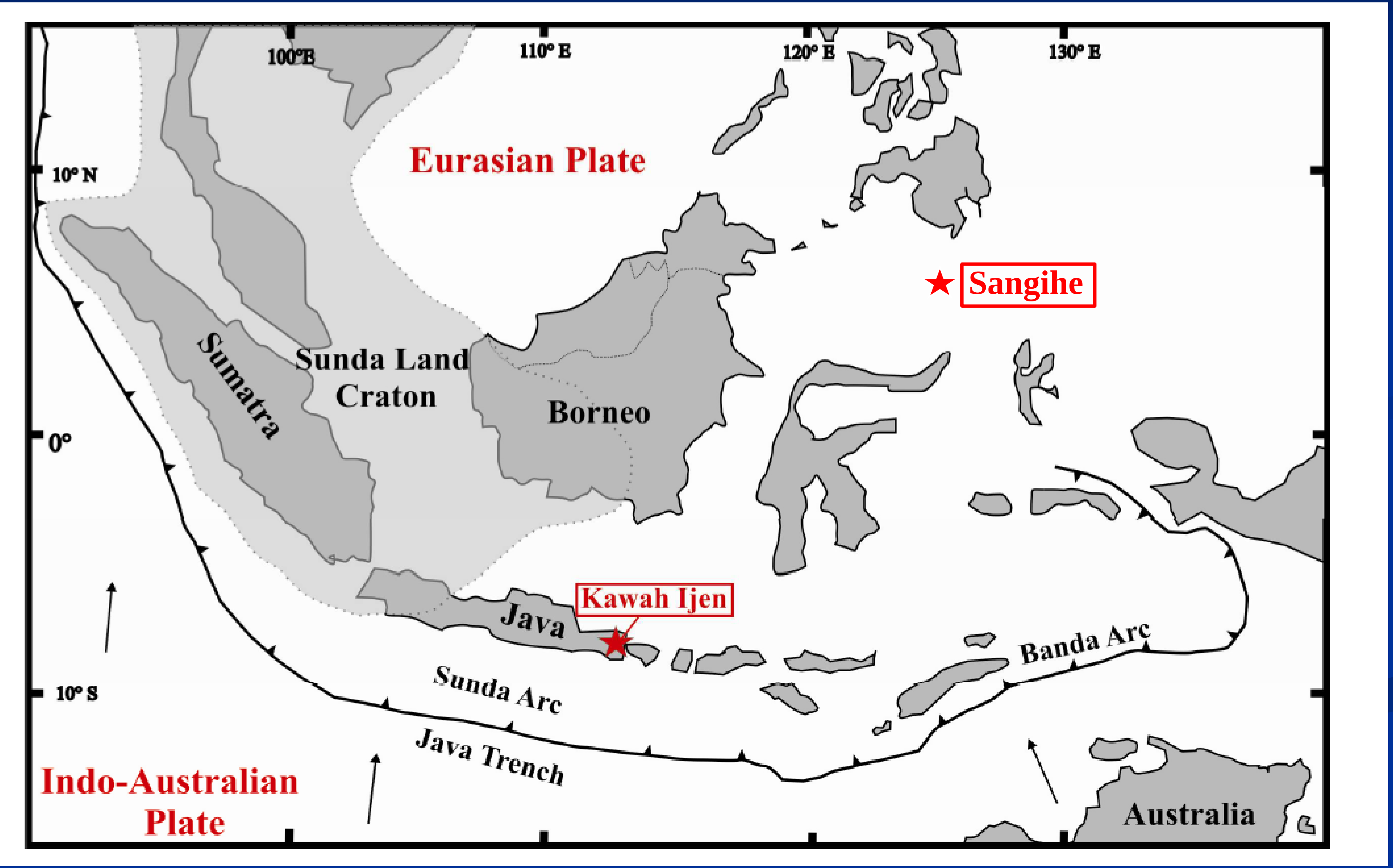
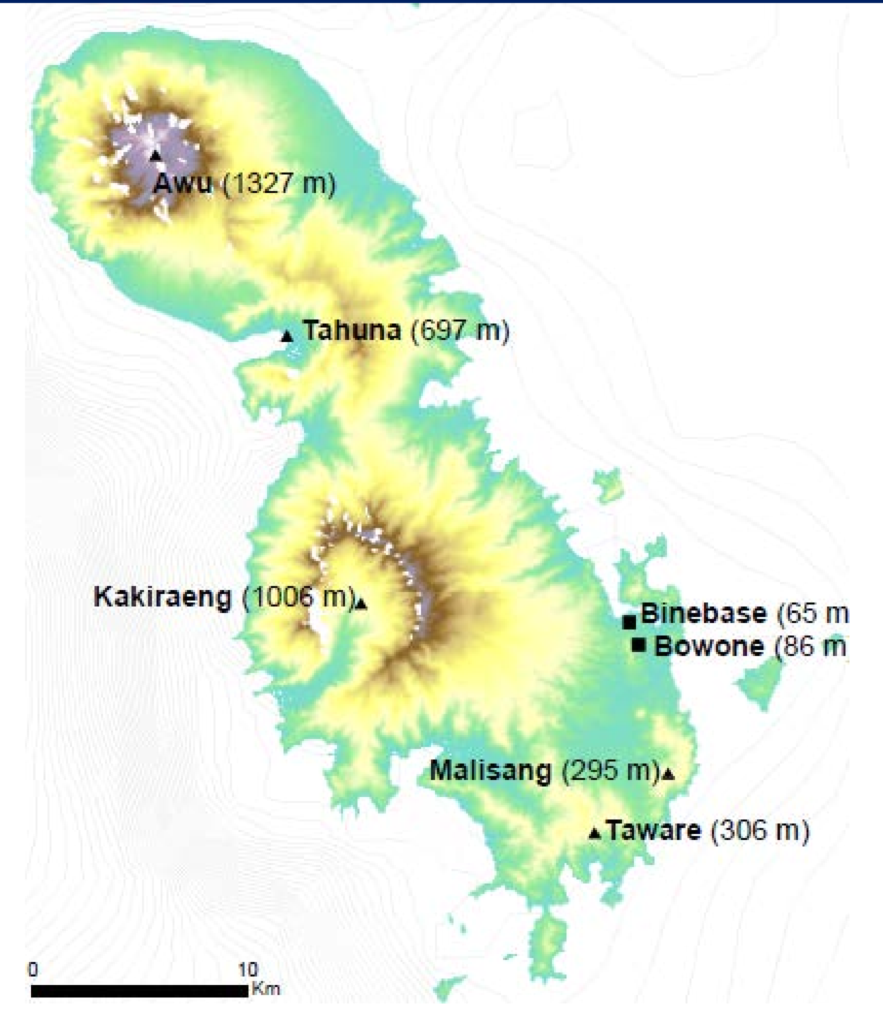


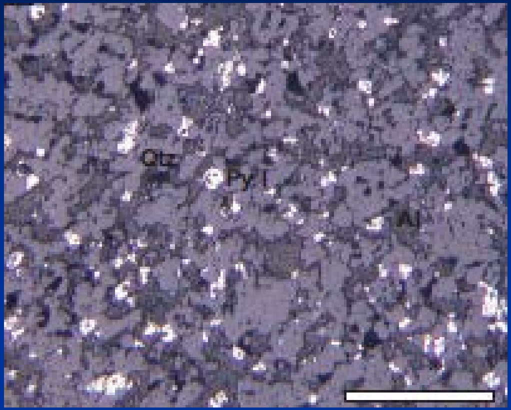

Williams-Jones et al. 2009

# Lessons from Indonesia

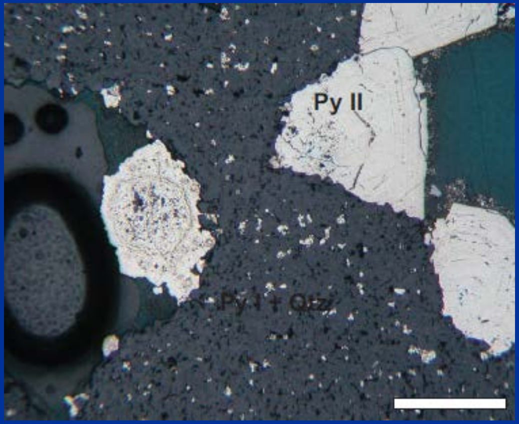


# The Sangihe Au-Ag Deposits




Py I Au 1.1 ppm
Ag 33 ppm

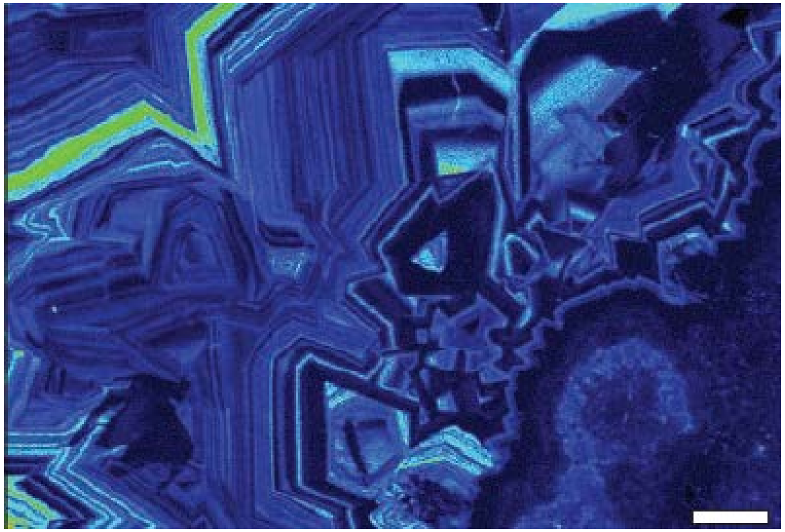



Py II Au 1 ppm
Ag 81 ppm

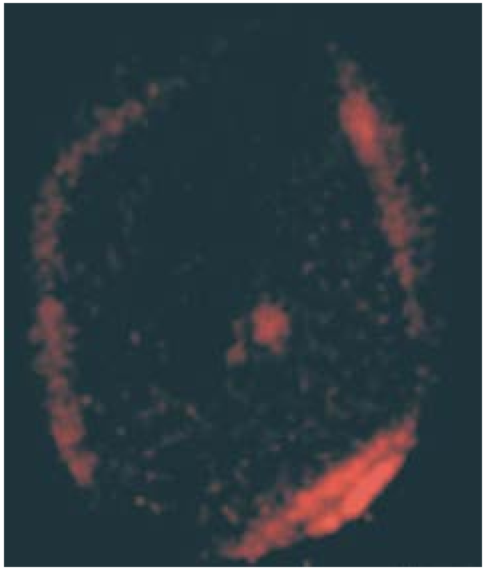
| Deposit | | tonnes (t) | Au (g/t) | Ag (g/t) |
|---|---|---|---|---|
| Bawone | Sulphide | 5,999,000 | 1.12 | 0.97 |
| Binebase | Oxide | 7,851,000 | 1.10 | 25.13 |
| | Sulphide | 10,002,000 | 0.49 | 13.60 |

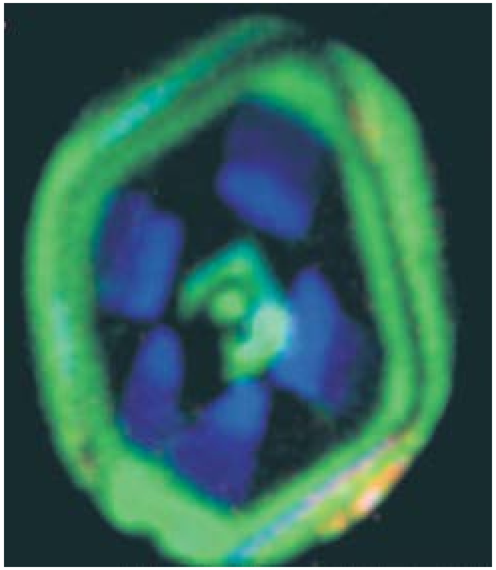
# Metal zoning in pyrite

Copper map for Py II at Sangihe



Gold map for pyrite at Pascua





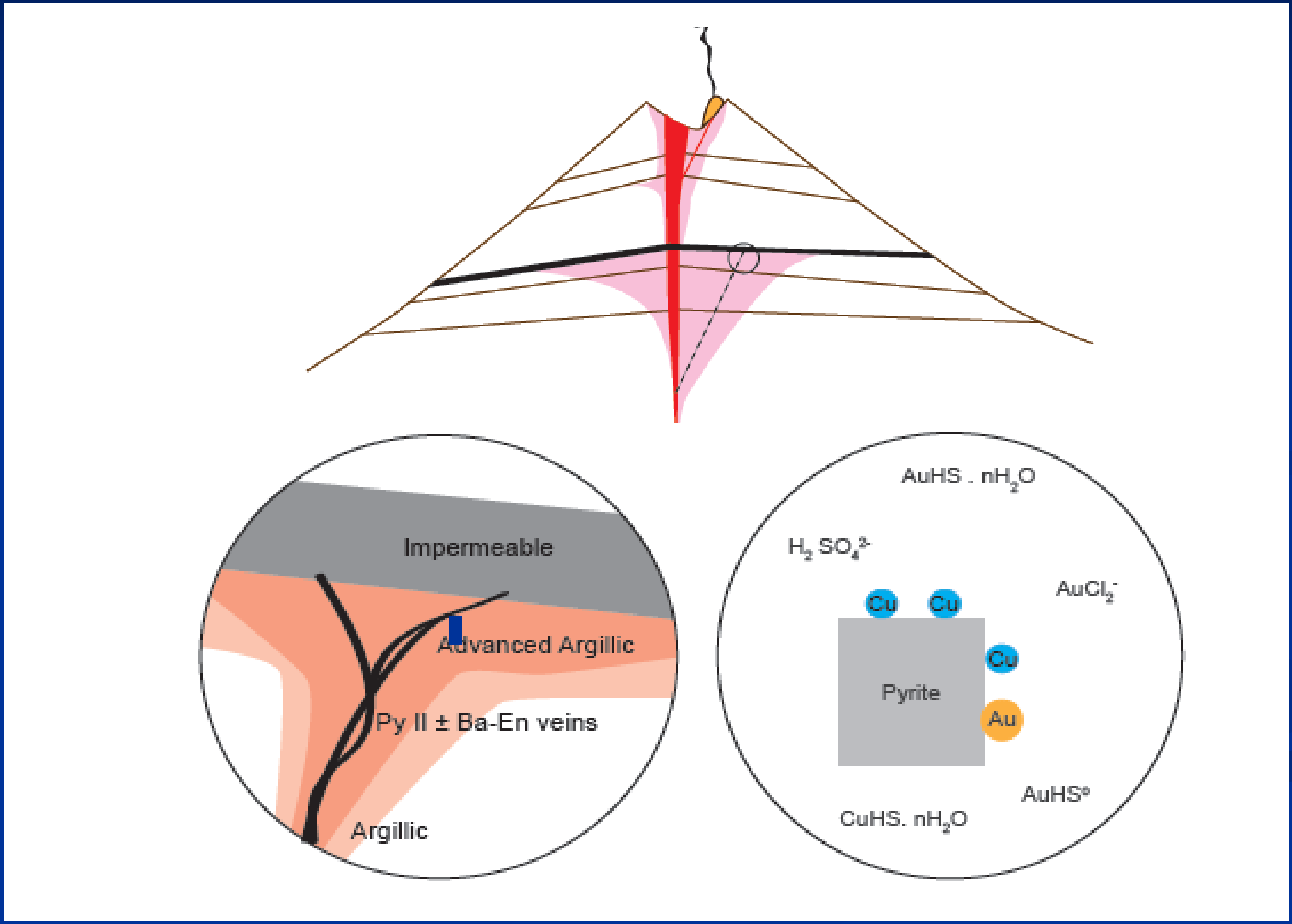
Cu (green) As (blue) maps for pyrite at Pascua

# The Lycurgus Cup – dichroic glass and nanogold


A possible explanation for “invisible gold” in pyrite – electrostatic attraction of negatively charged nanogold particles to the surfaces of positively charged pyrite

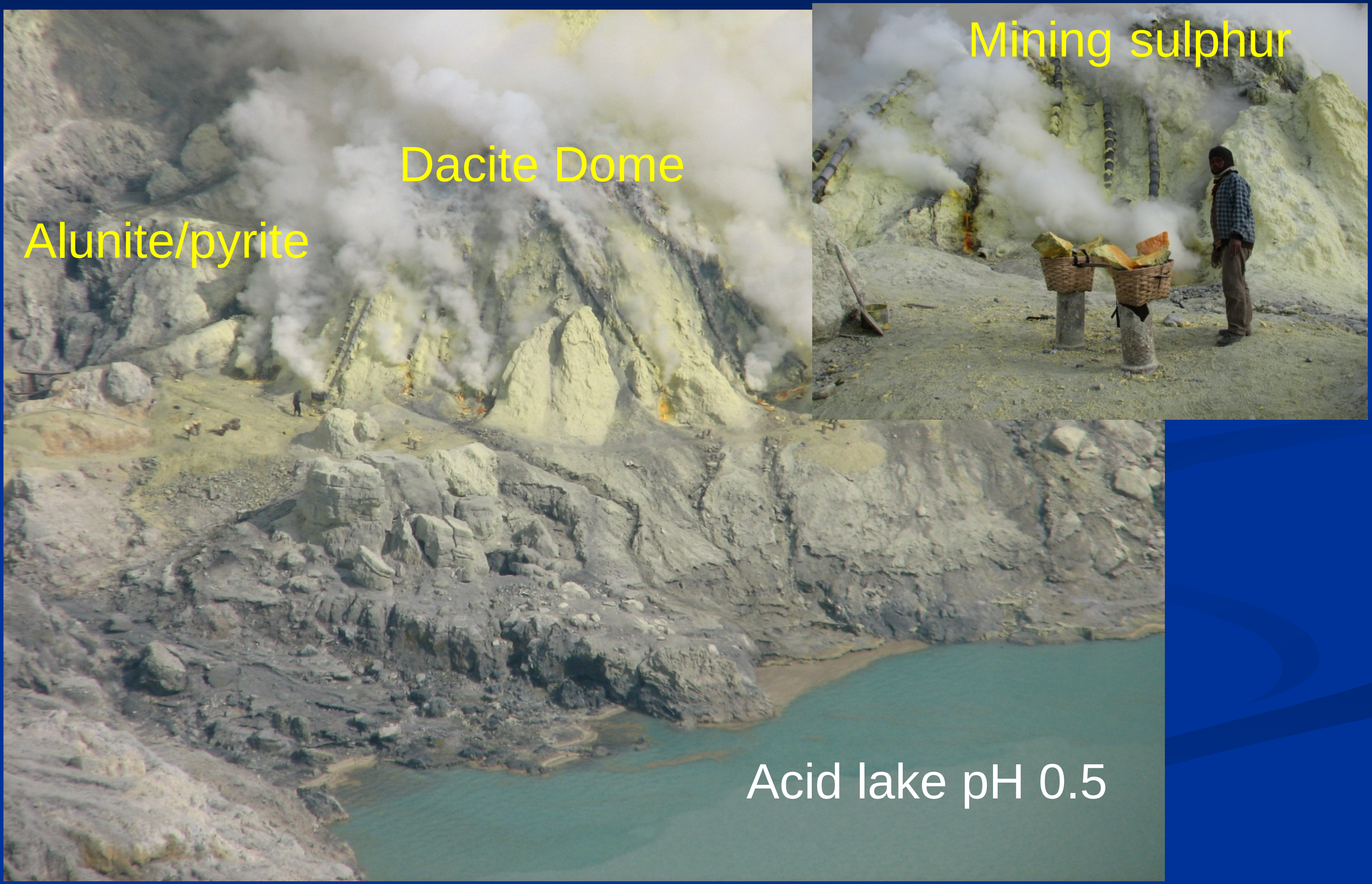
Williams-Jones et al. 2009

# The Sangihe Model




*King et al.(2014)*

# Kawah Ijen - High Sulphidation Epithermal Deposit in the Making?



# Sulphur condensation and acidity creation


$$4H_2O\ (gas) + 4SO_2(gas) = 2S\ (solid) + 2H_2SO_4\ (gas)$$

$$H_2SO_4(aq) = 2H^+ + SO_4^{2-}$$

# Sampling the gases



# Vapour-induced acid-sulphate Alteration

# Acid-Sulphate Alteration

Pyroclastic rocks altered to alunite ($KAl_3(SO4)_2(OH)_6$) and pyrite

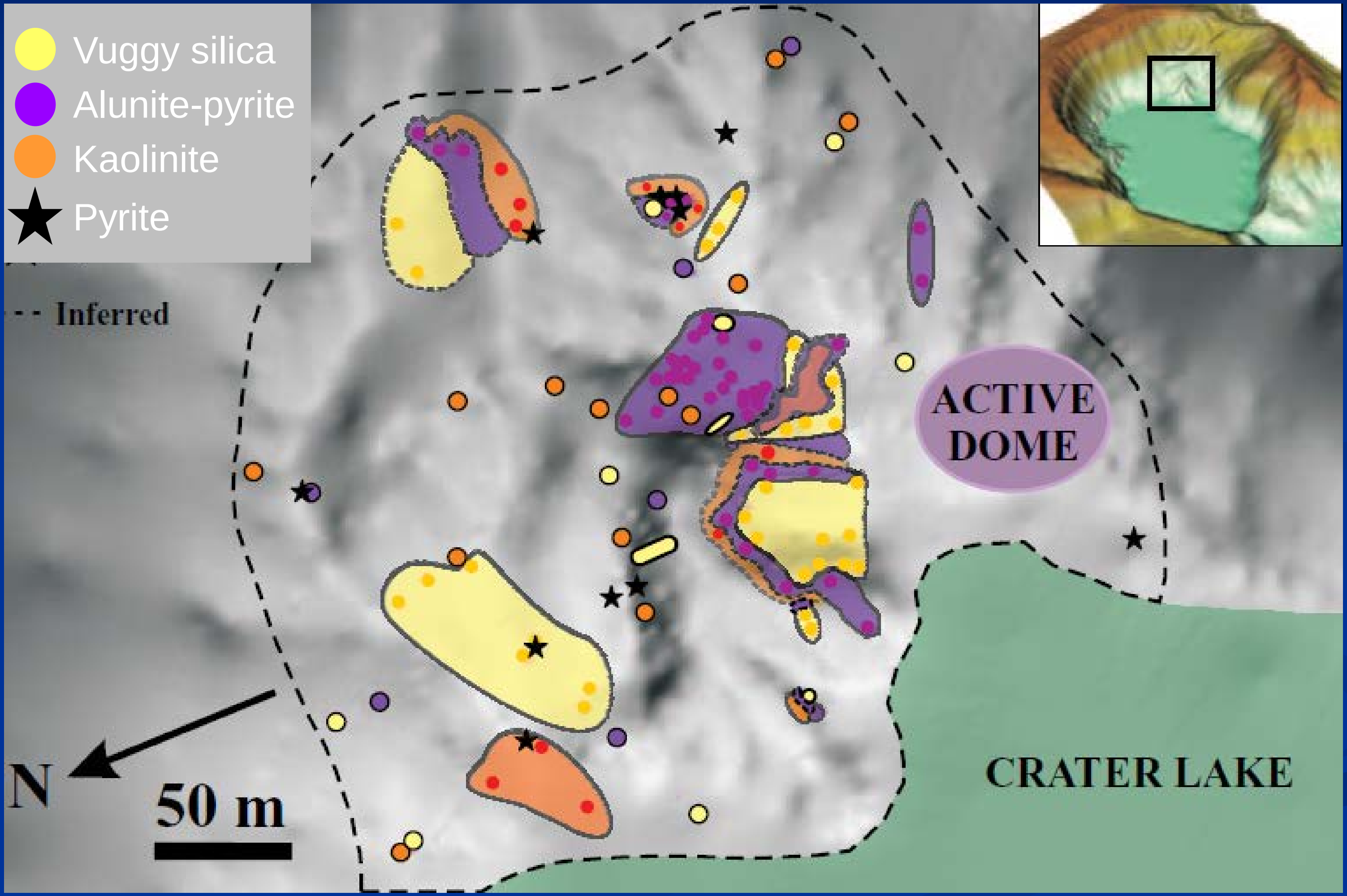
Leached andesite pillow containing > 85 wt.% $SiO_2$ – residual silica

# Acid Sulphate Alteration at Kawah Ijen

Alunite-pyrite alteration

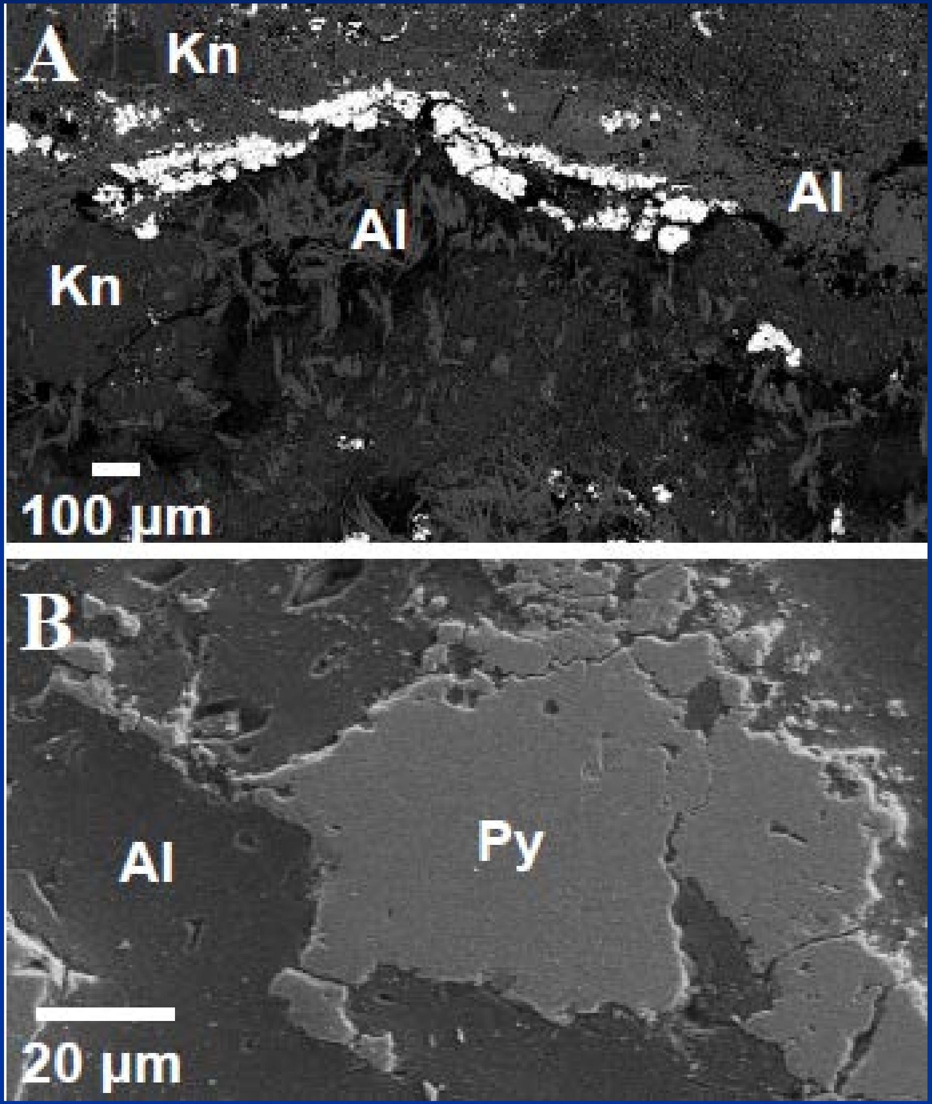
Alunite-pyrite vein

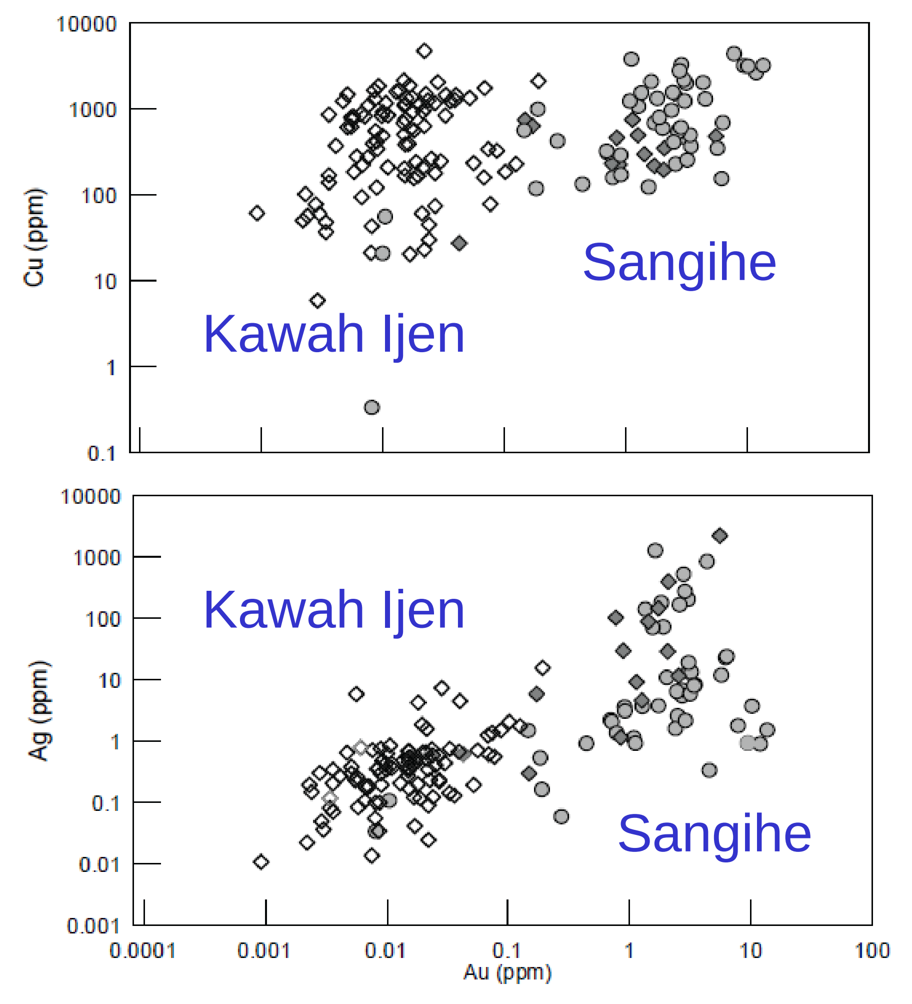

# Distribution of Alteration at Kawah Ijen




Scher et al. (2013)

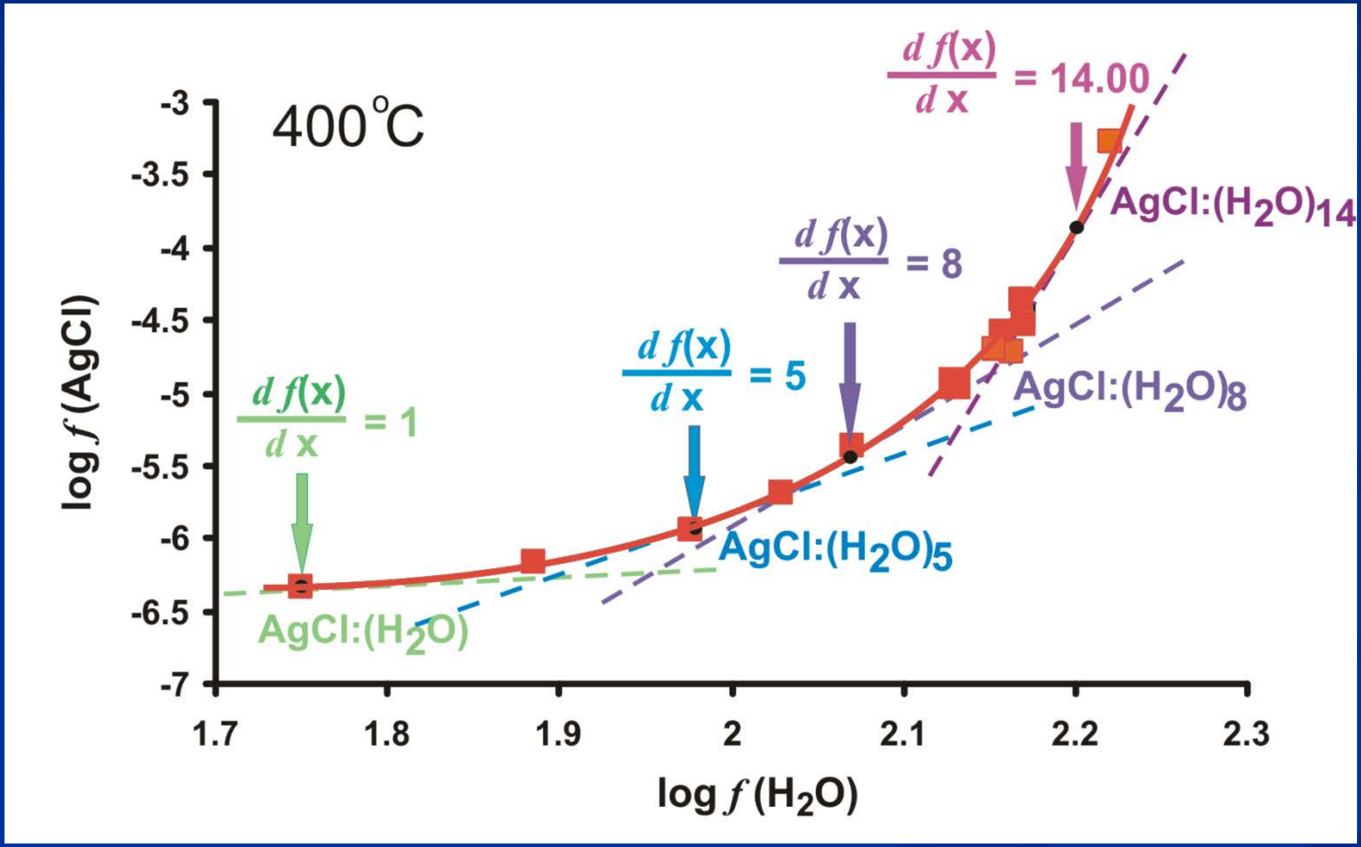
# Gold Silver mineralisation at Kawah Ijen



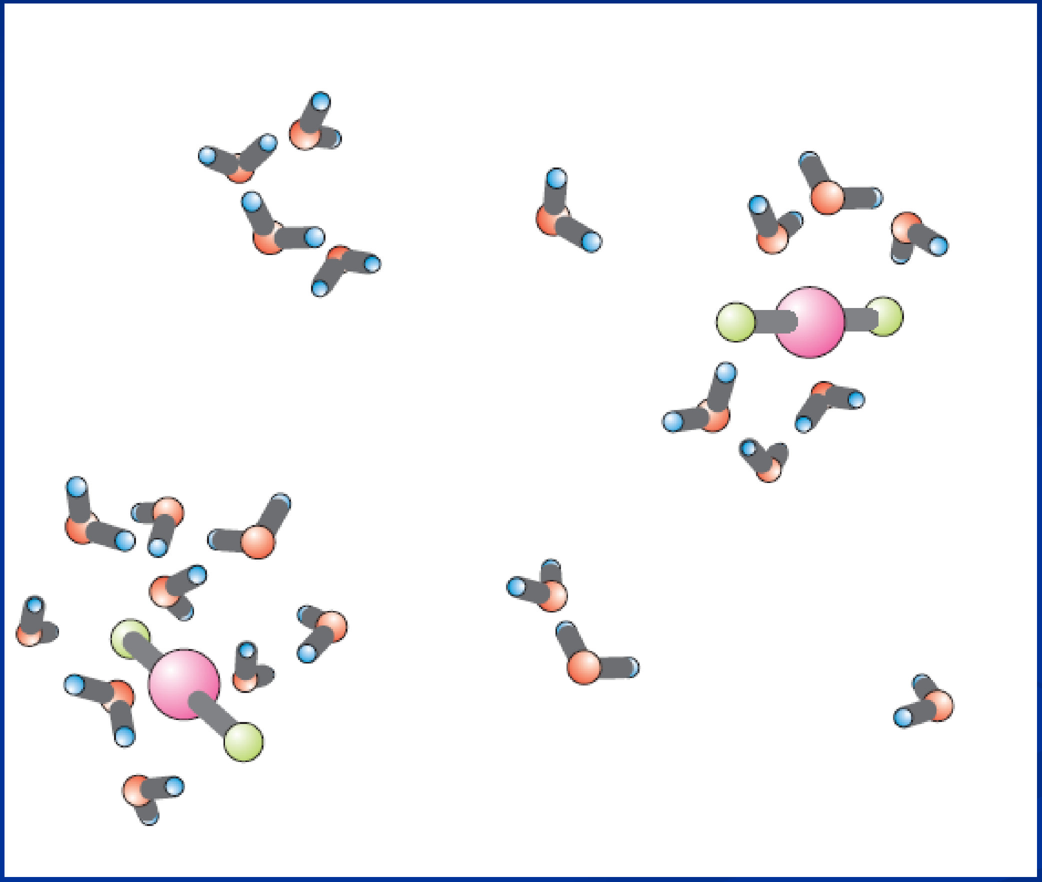
# Solubility of Silver in HCl-$H_2O$ Vapour

## Silver solubility increases with hydration




*Migdisov and Williams-Jones (2013)*

# Water Clusters Hydrating a Metal Species in the Gas Phase

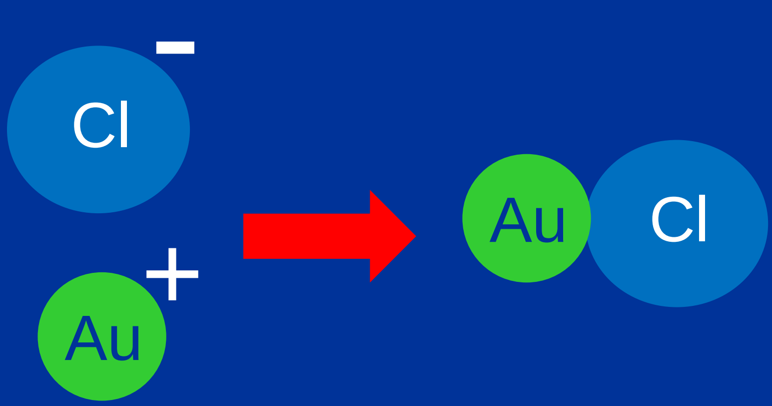


*Williams-Jones and Migdisov (2014)*

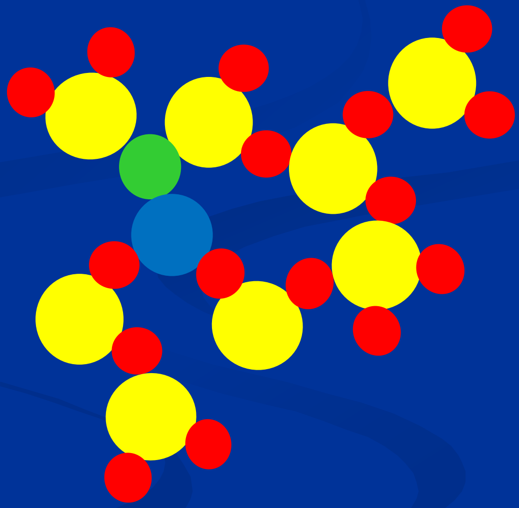
# Think about clowns and balloons

The effects of complexation and particularly solvation by $H_2O$ clusters make heavy metals volatile

Reaction

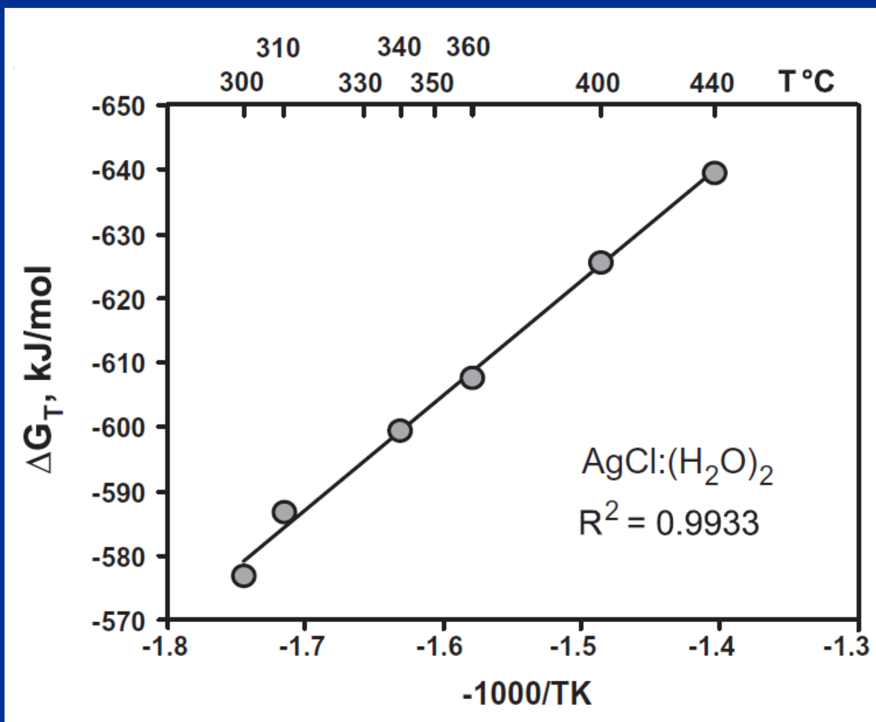


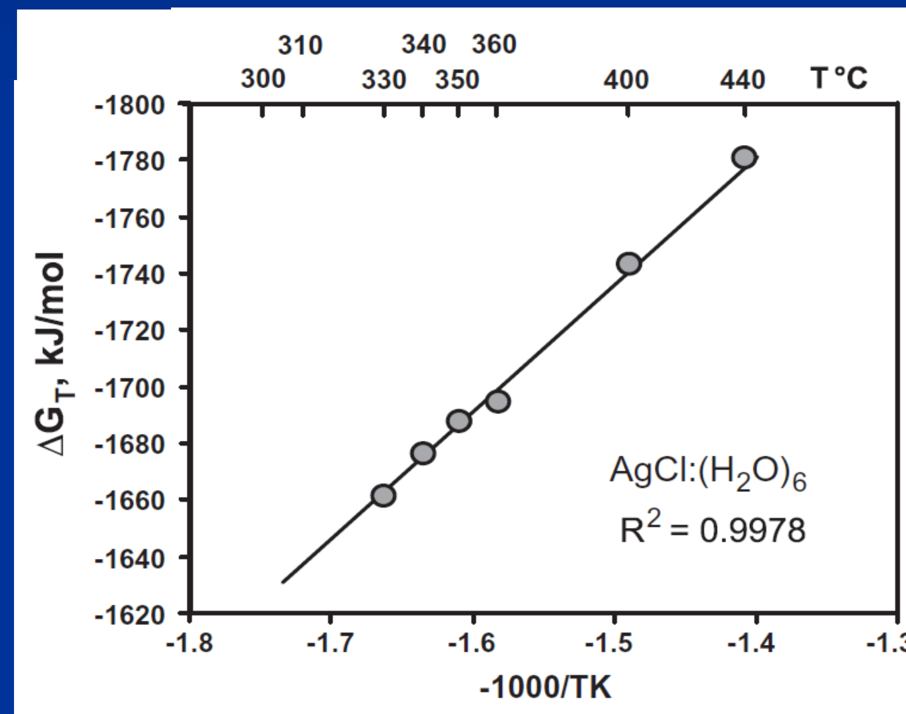

Hydration



# Extracting Thermodynamic Data

The linear relationship between ΔG and reciprocal temperature enables extrapolation to high temperature



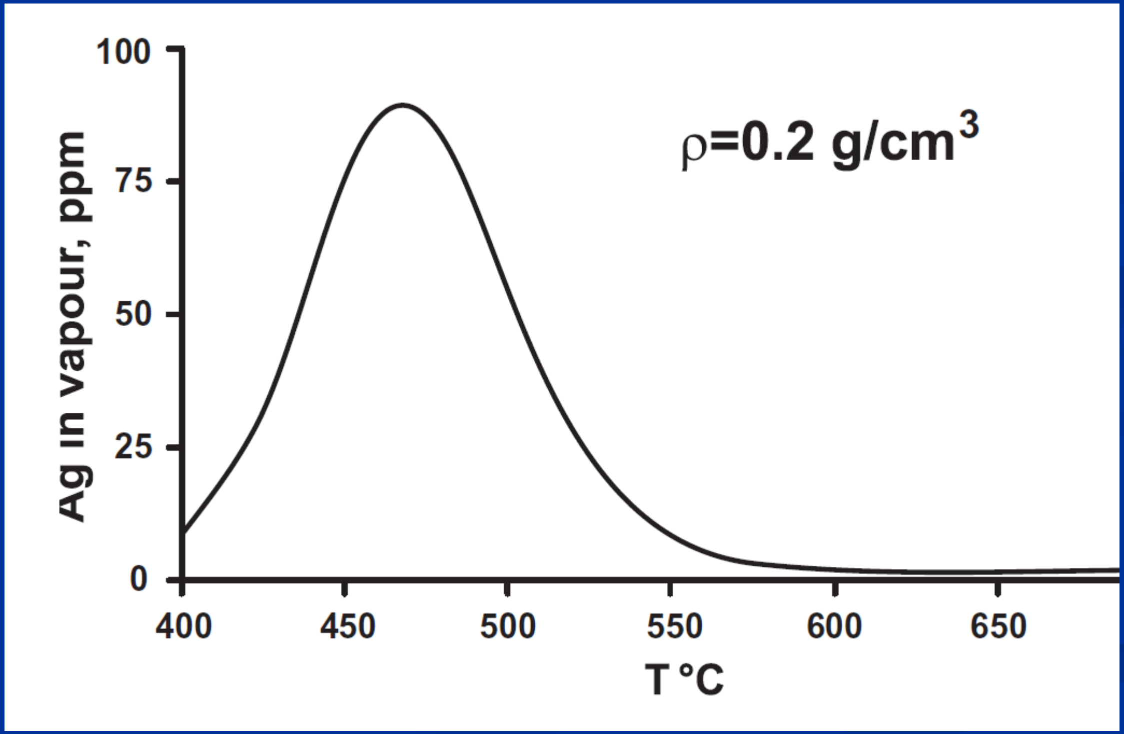

Log K = -ΔG/RT

*Migdisov and Williams-Jones (2013)*

# Solubility of Silver in HCl-$H_2O$ Vapour

Hydration increases with increasing $H_2O$ pressure or density but decreases with increasing temperature

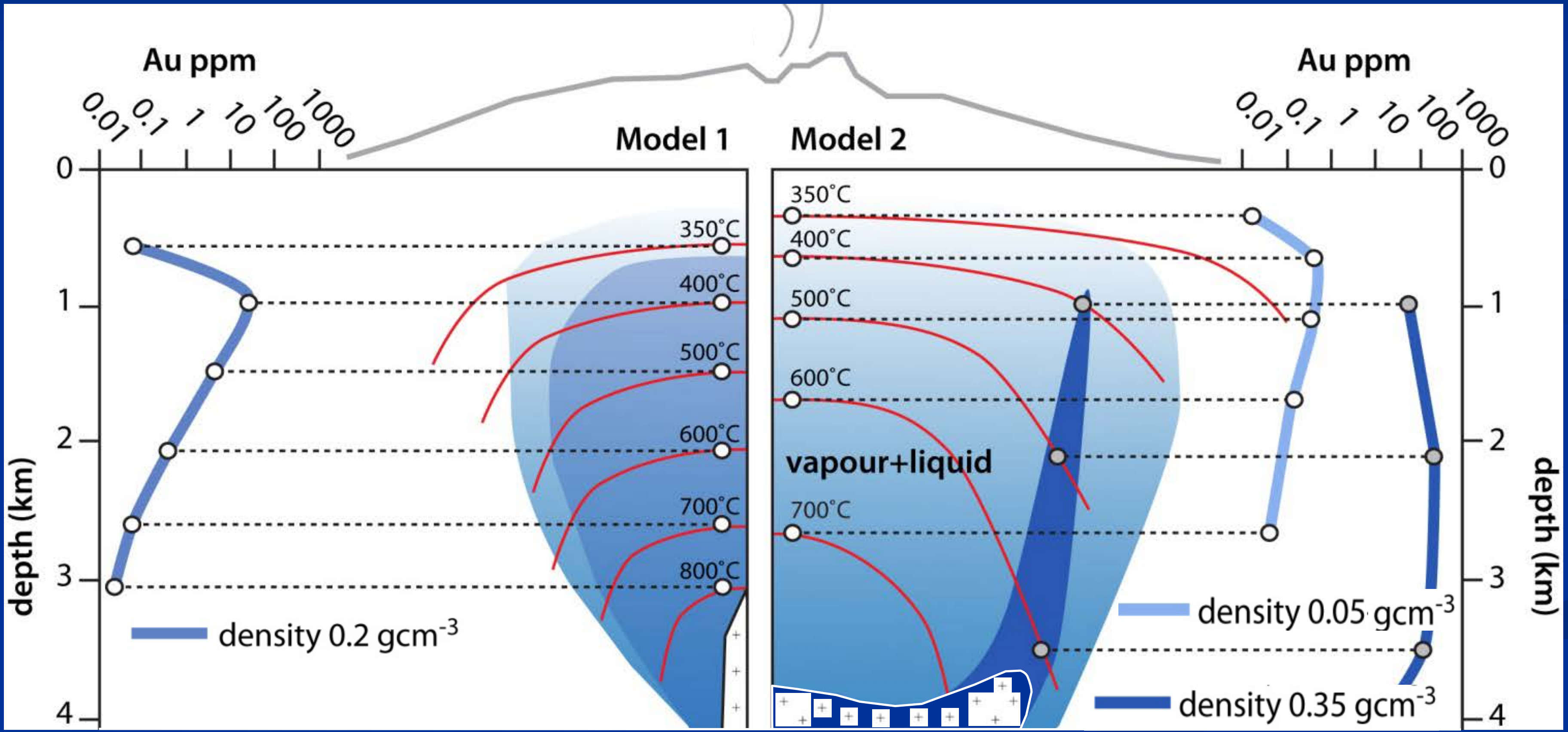
Solubility increases with increasing temperature but reaches a maximum because of the effect of decreasing hydration




*Migdisov and Williams-Jones (2013)*

# Epithermal Au Ore Formation

Vapour-dominated hydrothermal plume rises from magma transporting Au and depositing it as temperature drops below 400°C




*Hurtig and Williams-Jones (2014)*

# References

Chouinard, A., Williams-Jones, A.E., Leonardson, R.W., Hodgson, C.J., Silva,P., Téllez, C, Vega, J., and Rojas, F., 2005a, Geology and genesis of the multistage high-sulfidation epithermal Pascua Au-Ag-Cu deposit, Chile and Argentina: Econ. Geol., v. 100, p. 463–490.

Clark, J.R. and Williams-Jones, A.E., (1990) Analogues of epithermal gold-silver deposition in geothermal well scales: Nature, v. 346, no. 6285, pp 644-645.

Cooke, D.R, Simmons, S.F., 2000. Characteristics and genesis of epithermal gold deposits. In: Hagemann, S.G., Brown, P.E. (Eds.), Gold in 2000, Reviews in Econ. Geol. vol. 13. Society of Economic Geology, Boulder, CO, pp. 221–244.

Williams-Jones, A.E. and Heinrich, C.H., 2005, Vapor transport of metals and the formation of magmatic-hydrothermal ore deposits: Econ. Geol., 100, p.1287-1312.

King, J., Williams-Jones, A.E., van Hinsberg, V., and Williams-Jones, G. High sulfidation epithermal pyriote-hosted Au (Ag-Cu) ore formation by condensed magmatic vapors on Sangihe Island, Indonesia: Economic Geology, v. 109, p. 1705-1733.

Scher, S., Williams-Jones, A.E., and Williams-Jones, G., 2013. Fumarolic activity, acid sulfate alteration and high sulfidation epithermal precious metal mineralization in the crter of Kawah Ijen volcano (Java, Indonesia). Economic Geology, 108, 1099-1118.

Migdisov, A.A. and Williams-Jones, A.E., 2013. A predictive model for the transport of silver chlioride by aqueous vapor in ore-forming magmatic-hydrothermal systems. Geochmica et Cosmochimica Acta, 104, 123-135.

Hurting, N., and Williams-Jones, A.E., 2014. An experimental study of the transport of gold through hydration of AuCl in aqueous vapor and vapor-like fluids. Geochimica et Cosmochimica Acta, 127, 305-325.

Williams-Jones, A.E., and Migdisov, A.A., 2014. Experimental constraints on the transport and deposition of metals in ore-forming hydrothermal systems. Society of Economic Geologists, Specia;l Publication 18, 77-95.