Geochemical Mapping:
A Critical Tool in the Search for Mineral Deposits

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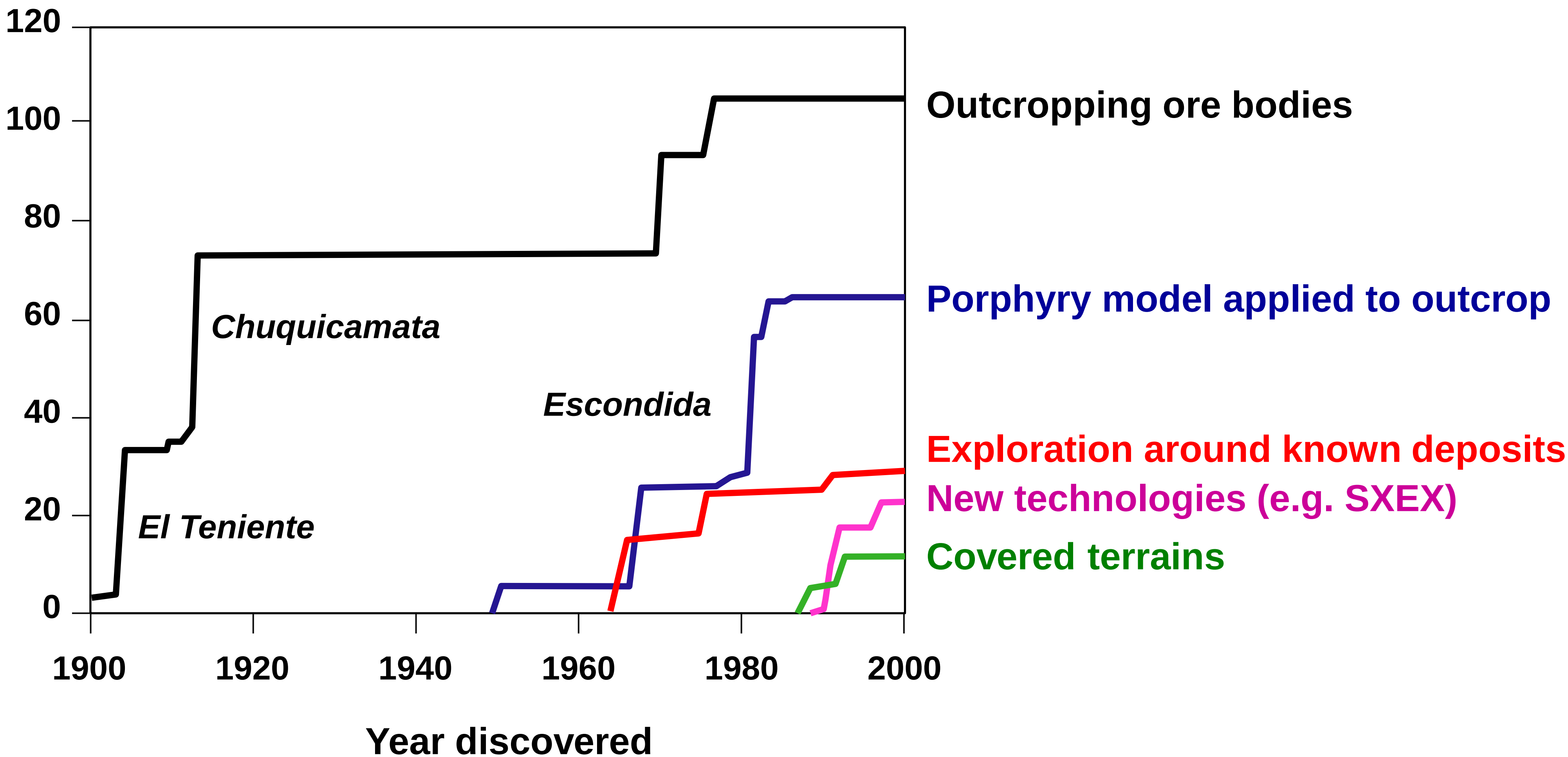
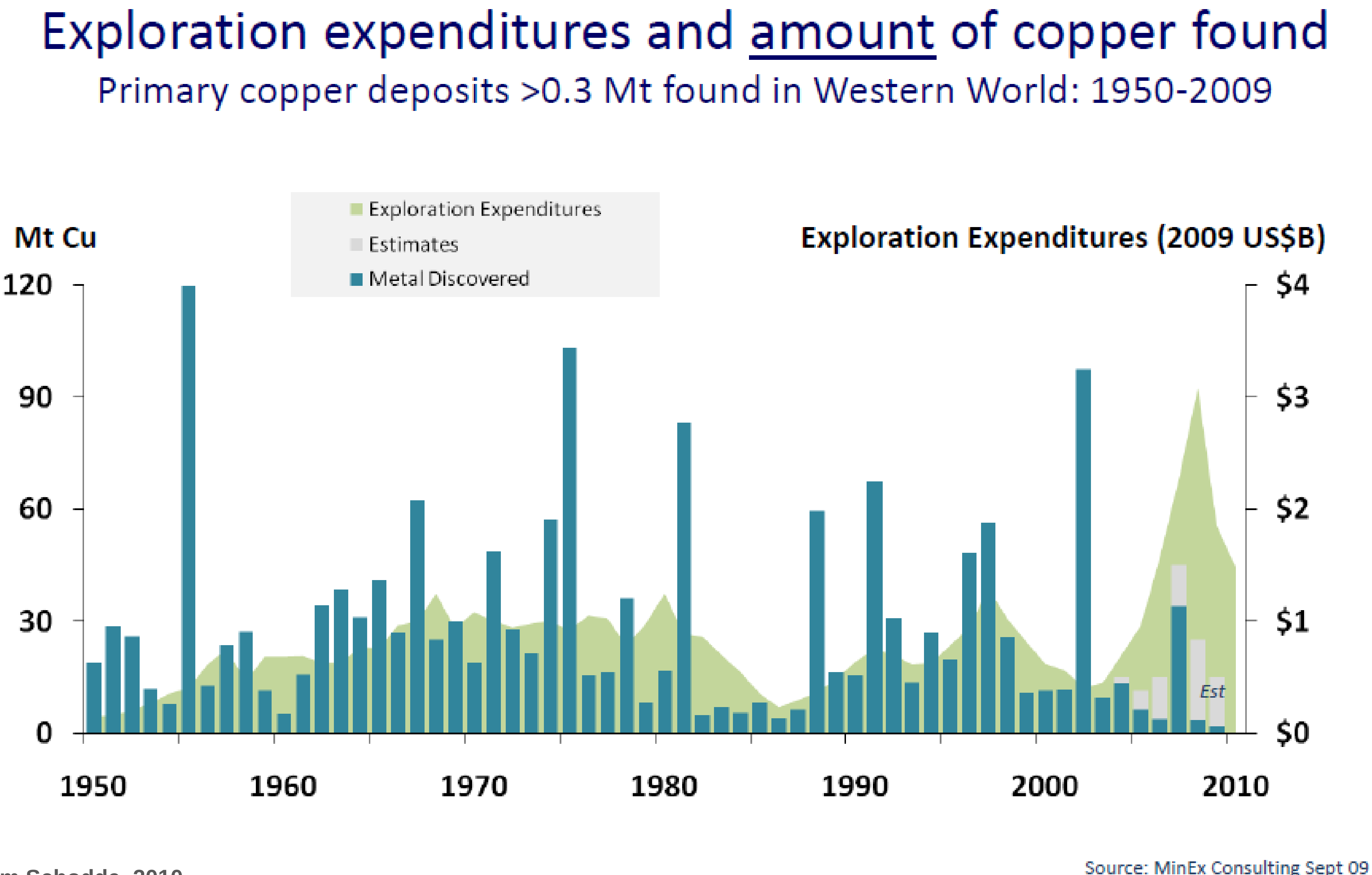
The Technology Push

Cumulative Cu resources discovered in Chile (mt Cu)



Source unknown

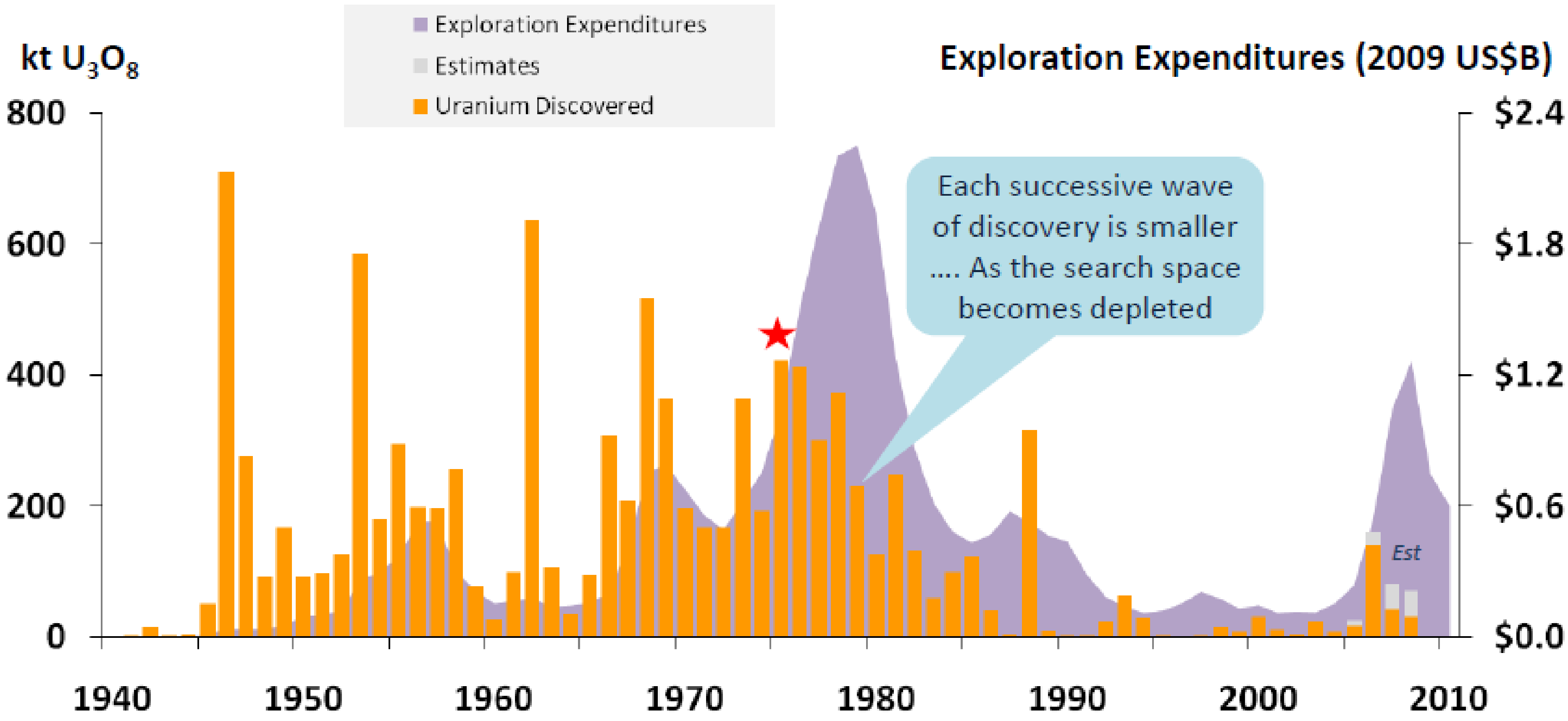
Economics Preliminaries



From Schodde, 2010

Exploration expenditures and amount of uranium found

Primary uranium deposits >0.5 kt U_3O_8 found in the World: 1940-2008



Source: MinEx Consulting May 09
Expenditures from OECD

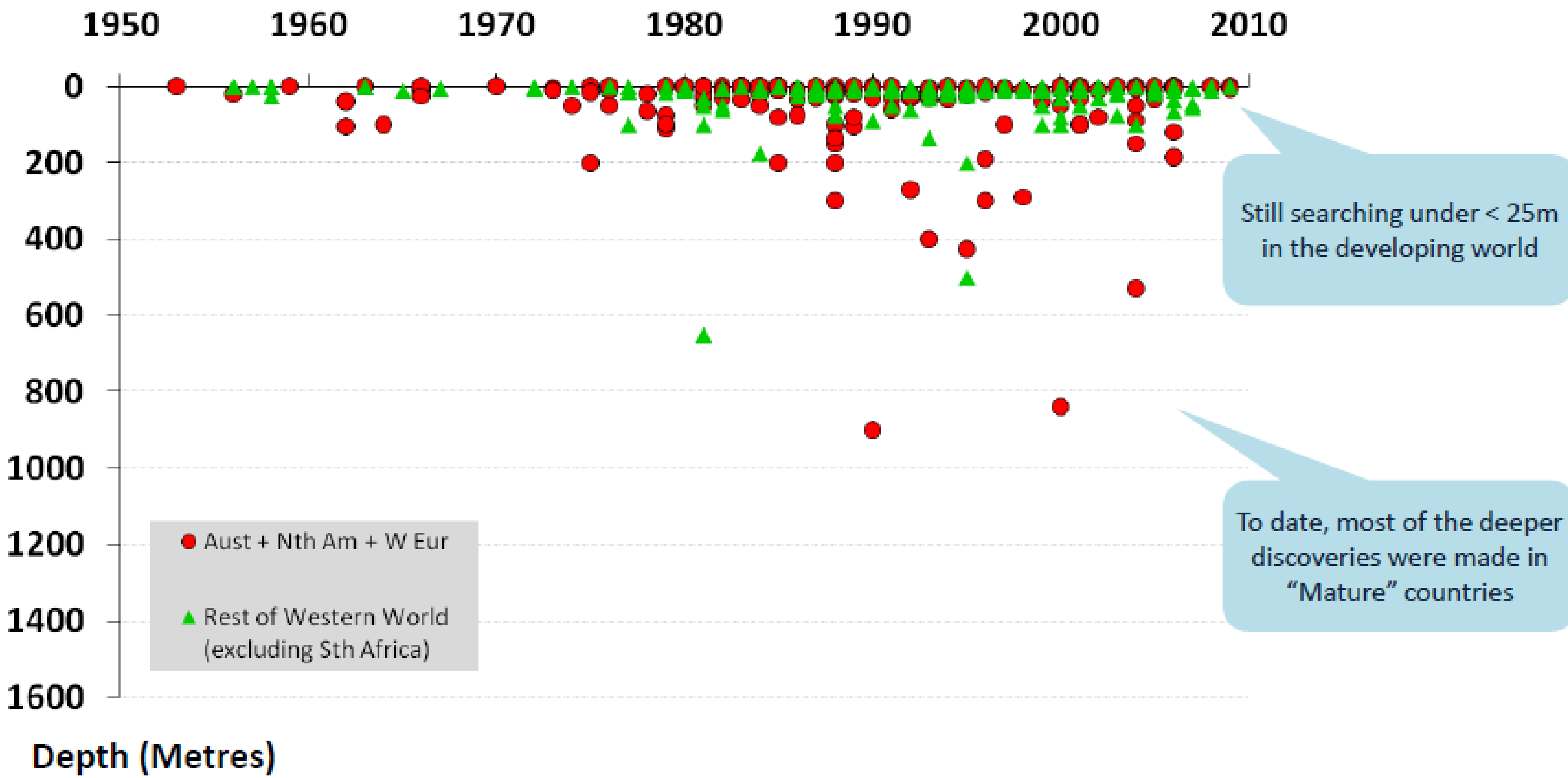
Note: Chart include adjustment for deposits missing from the database

★ Olympic Dam (Cu-U-Au deposit) found in 1975 – contains 2405 kt U_3O_8

From Schodde, 2010

DRIVER 1: District maturity and the need to chase deep targets

Depth to top of ore body for (>0.1 Moz) gold discoveries made in the Western World



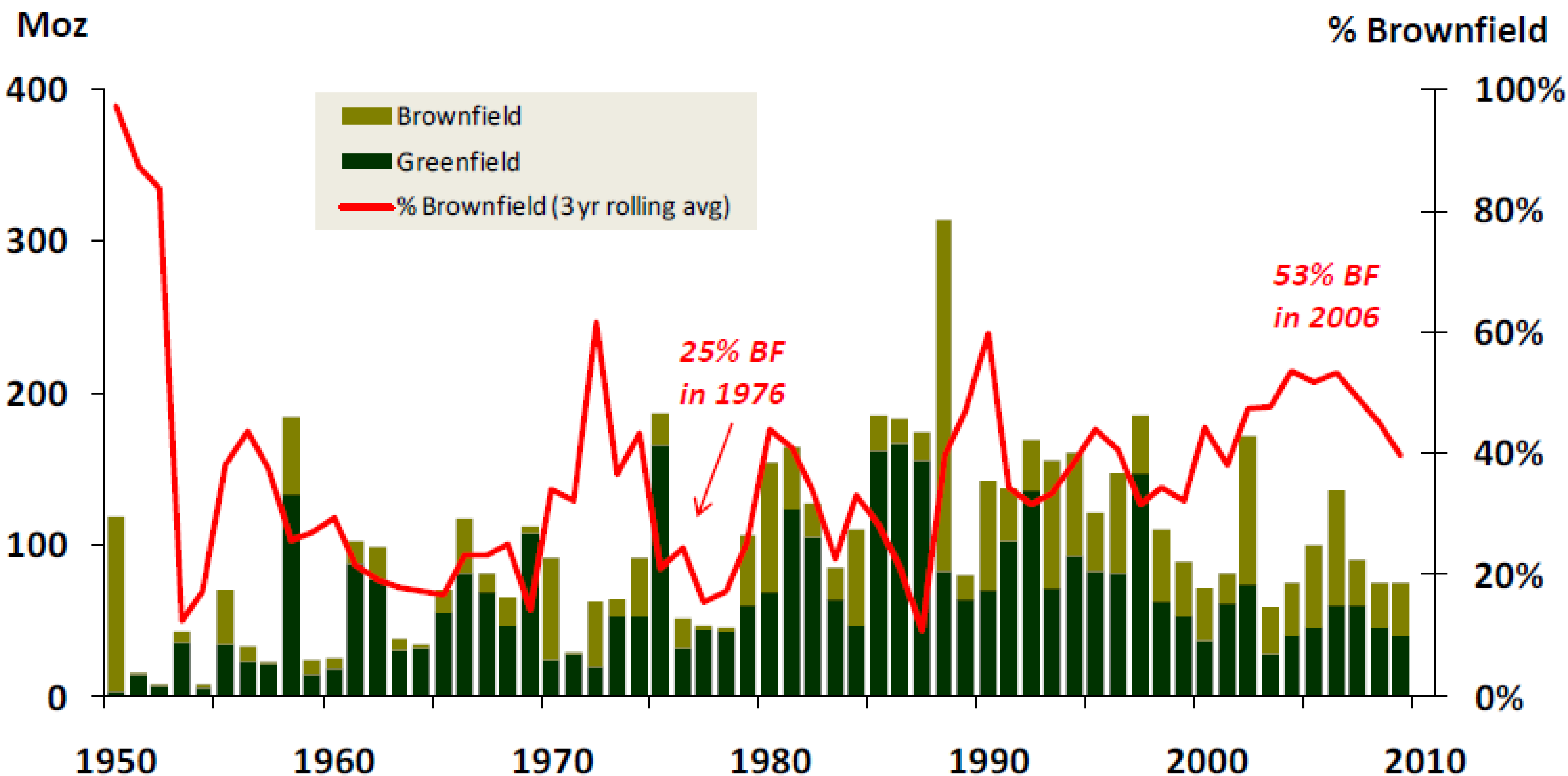
Note: Chart refers to the initial discovery in a camp. – and so excludes subsequent brownfield discoveries which are often deeper

Source: MinEx Consulting Jan 10

From Schodde, 2010

DRIVER 2: Shift towards brownfields exploration

Total World gold discoveries: 1950-2009

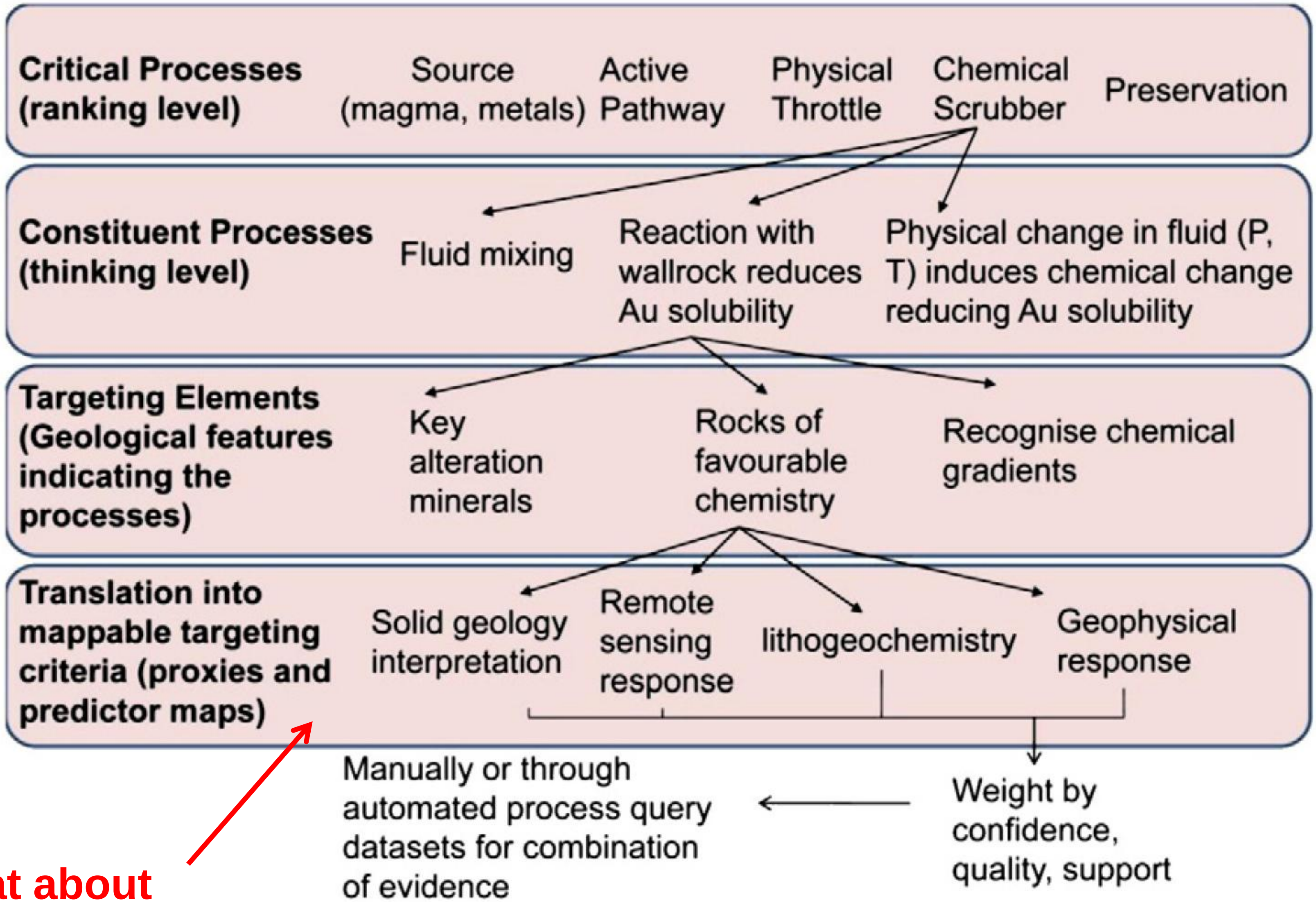


Note: Includes By-Product gold (mainly from base metal deposits)
"Brownfield" is defined as exploration associated with conventional targets within an established mineral district. This includes exploration beneath/immediately along-strike from a known deposit. "Greenfield" is defined as all other exploration.

Source: MinEx Consulting Jan 10

From Schodde, 2010

Where Does Geochemistry Fit In?



What about geochemistry?!

From McCuaig et al 2010

Deposit	Type		Discovery	Discovery methods						
				Primary				Contributory		
				Geol	Geochem	Drilling	Geophys	Geol	Geochem	Geophys
Tampakan, Philippines	Exposed	Greenfields	1992	X						
Mt. Bini, PNG	Exposed	Greenfields	1992	X	**XXX**					
Nth Parkes End' 48, Aust	Concealed	Brownfields	1992			X	X			
Cadia Hill, Aust	Exposed	Brownfields	1992	X	X					
Cadia Ridgeway, Aust	Concealed	Brownfields	1996	X	X	X				X
Cadia East, Aust	Concealed	Brownfields	1994-96	X	X	X				X
Rio Blanco, Peru	Exposed	Greenfields	1994	X	**XXX**					
Sierra Gorda, Chile	Exposed	Greenfields	1992-96	X	X					
Spence, Chile	Concealed	Greenfields	1996		X	X(cov)				
Gaby Sur, Chile	Concealed	Greenfields	1996	X	X		X			
Resolution, USA	Concealed	Brownfields	1996		X	X				
Reko Diq, Pakistan	Exposed	Brownfields	1996	X	X		X			
Galeno, Peru	Exposed	Brownfields	1997	X						
Marsden, Australia	Concealed	Greenfields	1997			X(cov)				X
Antapaccay, Peru	Concealed	Brownfields	1998		X	X	X			
Esperanza, Chile	Exposed	Greenfields	1999	X						X
Oyu Tolgoi field, Mongolia	Exposed	Greenfields	1997-2001	X	X					X
Southern Oyu, Mongolia	Concealed	Brownfields	2002	X	X	X	X			X
Toki cluster, Chile	Concealed	Brownfields	1999-2005	X				X		
Boyongan, Philippines	Concealed	Greenfields	2000	X		X(cov)				
La Fortuna, Chile	Exposed	Greenfields	2000-2001	X	X		X			
Bayugo, Philippines	Concealed	Brownfields	2003			X(cov)		X	X	
Pebble East, USA	Concealed	Brownfields	2005		X	X				
Inca de Oro, Chile	Concealed	Brownfields	2005			X(cov)				
Xietongmen, China	Exposed	Greenfields	2000-05	X	X					

Rohrlach & Loucks 2005; Leaman 1996; Hooper et al. 1996; Wood & Holliday 1995; Tedder et al. 2001; Monterrico Metals 2007; Ristorcelli & Ronning 2005; Sillitoe 2000; Manske & Paul 2002; Tethyan Copper 2007; Northern Peru Copper Corp. 2007; Holliday et al. 1999, 2006; Perello et al. 2004; Kirwin et al. 2003; Rivera 2004, 2007; Rivera & Pardo 2004; Rivera et al. 2003; Sillitoe & Thompson 2006; Camus & Rivera 2006; Waters 2004; Lightner 2001; Rebagliati & Payne 2006; Rebagliati & Laing 2006;

From data compilation in Holliday and Cooke, 2007

Geochemistry

	Exposed	Concealed	Totals
Greenfields	6 / 8	2 / 4	8 / 12
Brownfields	2 / 3	6 / 10	8 / 13
Totals	8 / 11	9 / 14	16 / 25

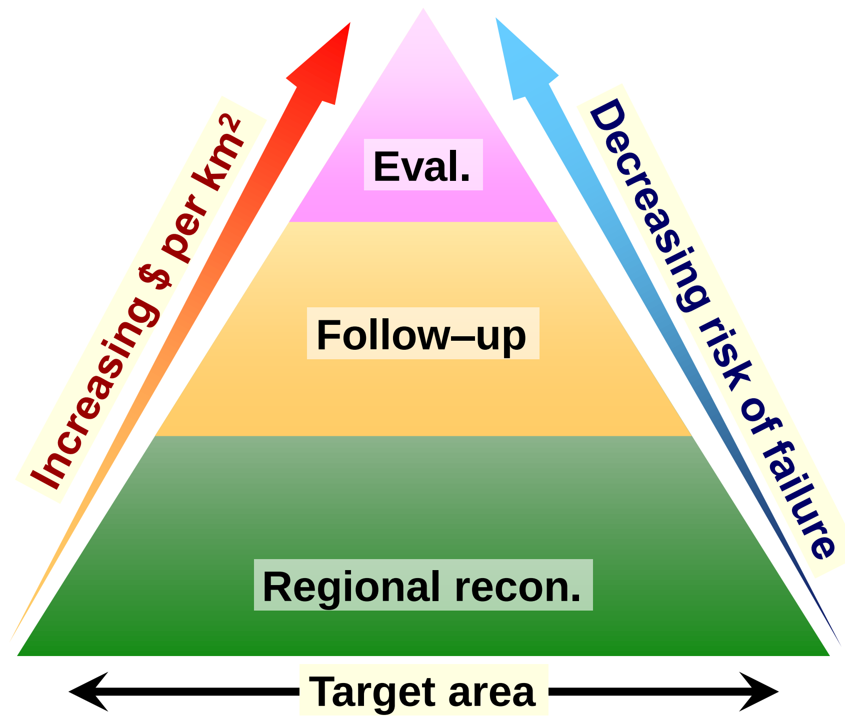
Geophysics

	Exposed	Concealed	Totals
Greenfields	1 / 8	0 / 4	1 / 12
Brownfields	1 / 3	4 / 10	5 / 13
Totals	2 / 11	4 / 14	6 / 25

From data compilation in Holliday and Cooke, 2007

The ultimate utilitarian objective of geochemical exploration is to separate barren from mineralized rock and regolith

Early stages of exploration need to rapidly identify areas of potential for follow–up to reduce overall risk



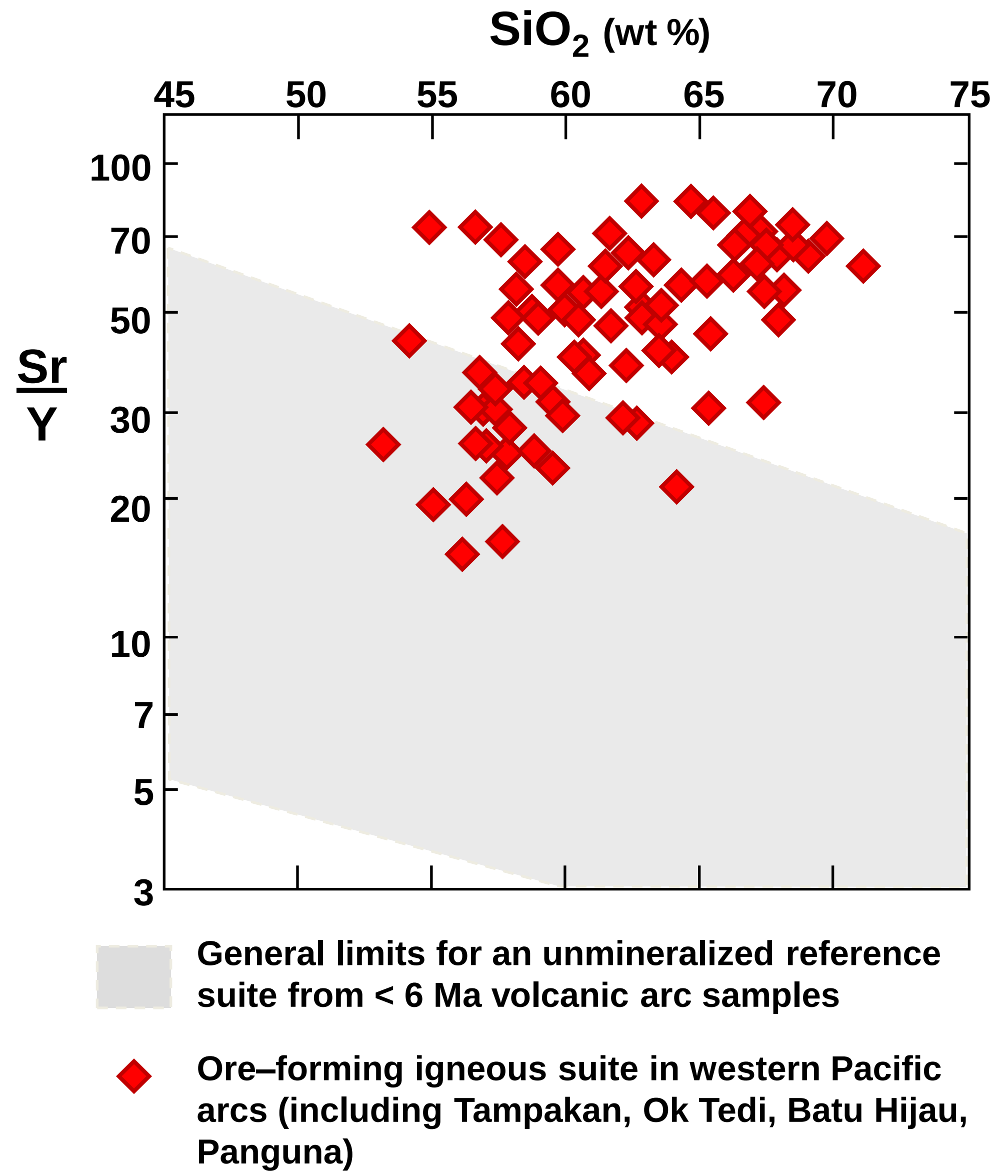
Lithogeochemical Mapping

A long established in geochemical exploration and overlaps broader field of ore deposit geochemistry

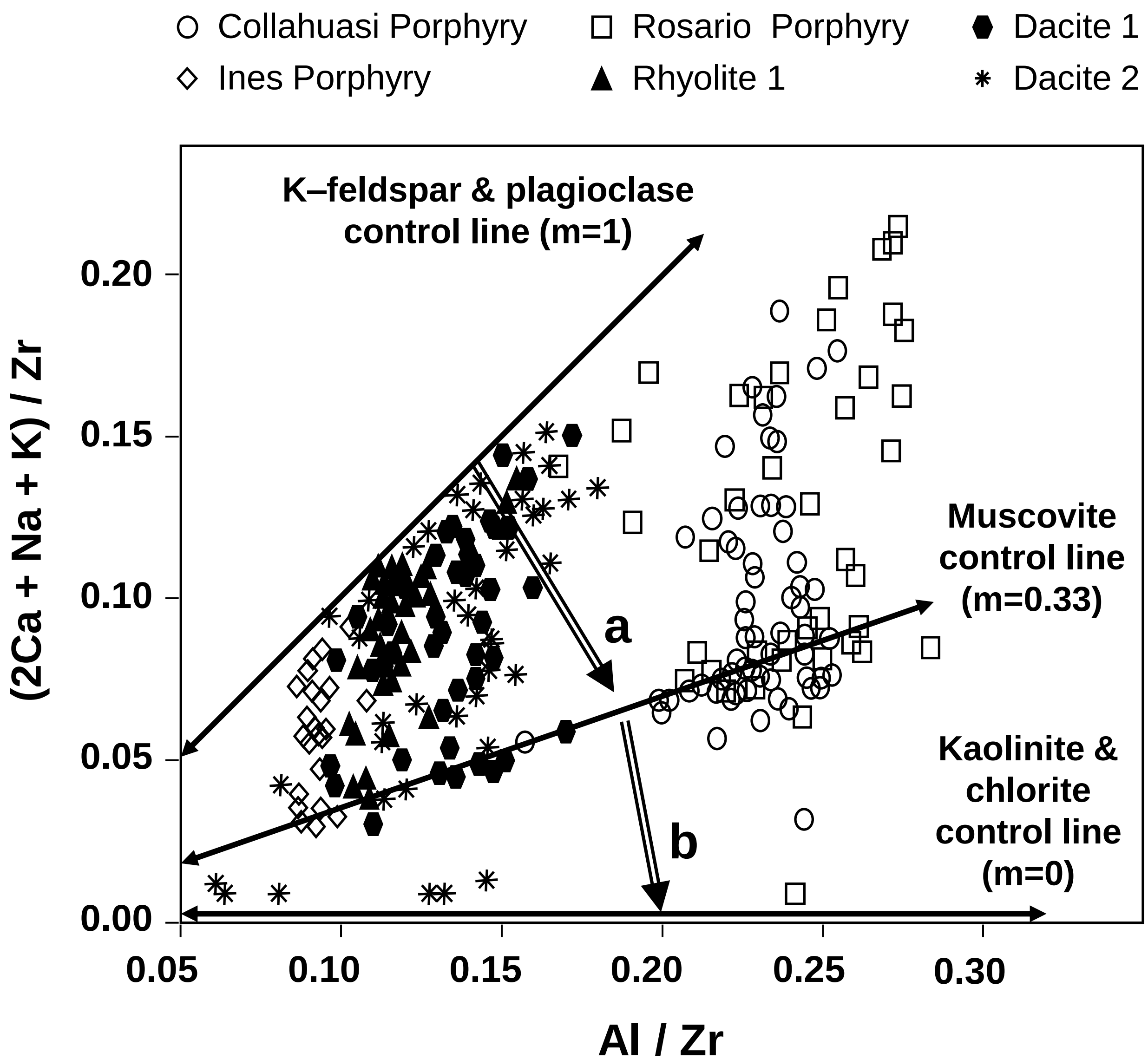
Example:

Porphyry Cu deposit formation is favoured by hydrous melts containing elevated H_2O, SO_3 and Cl_2

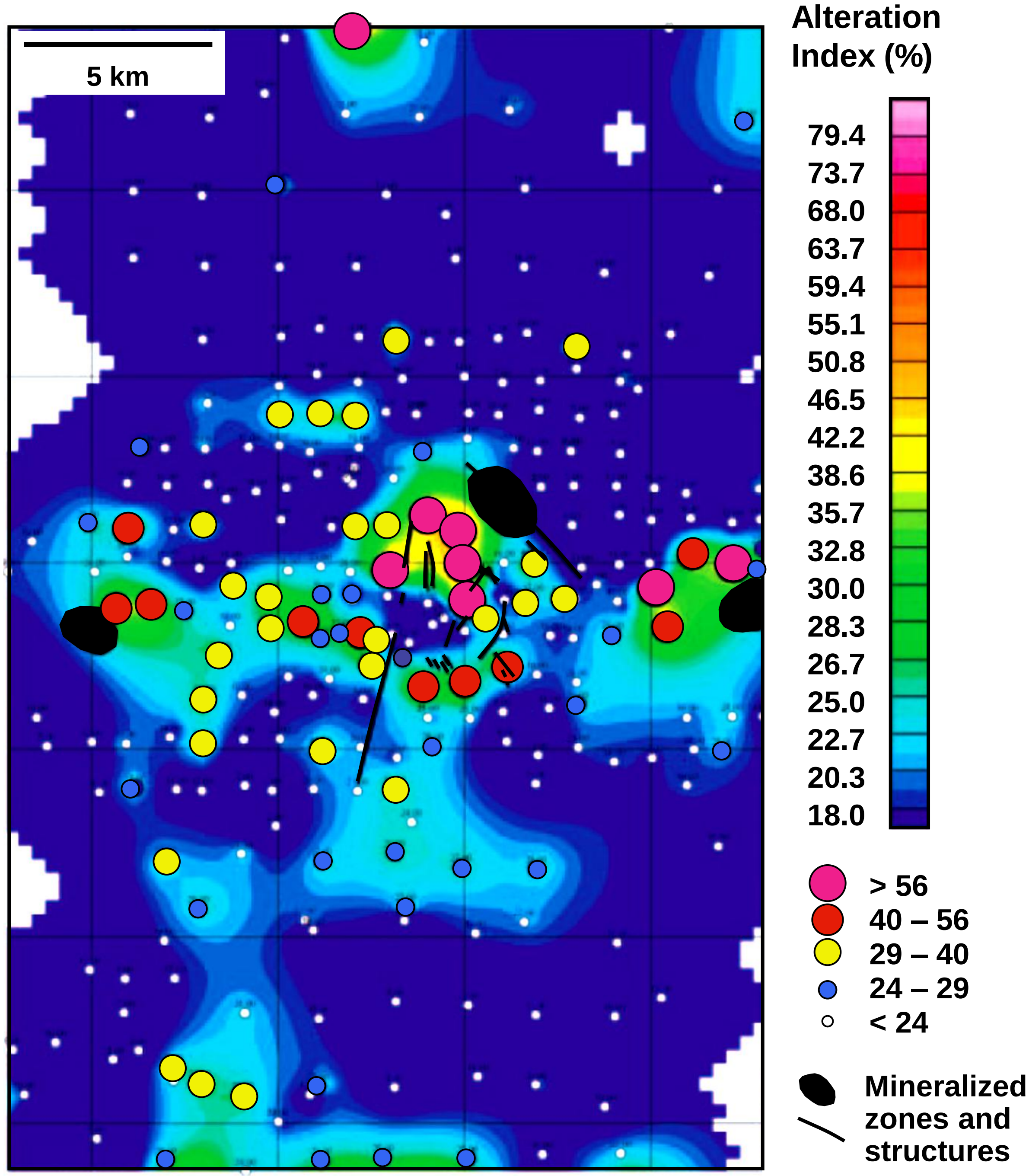
Increase in H_2O suppresses plagioclase (Sr) formation in favour of hornblende (Y) $\Rightarrow$ elevated Sr/Y in fertile magmas



After Rohrlach and Loucks, 2005

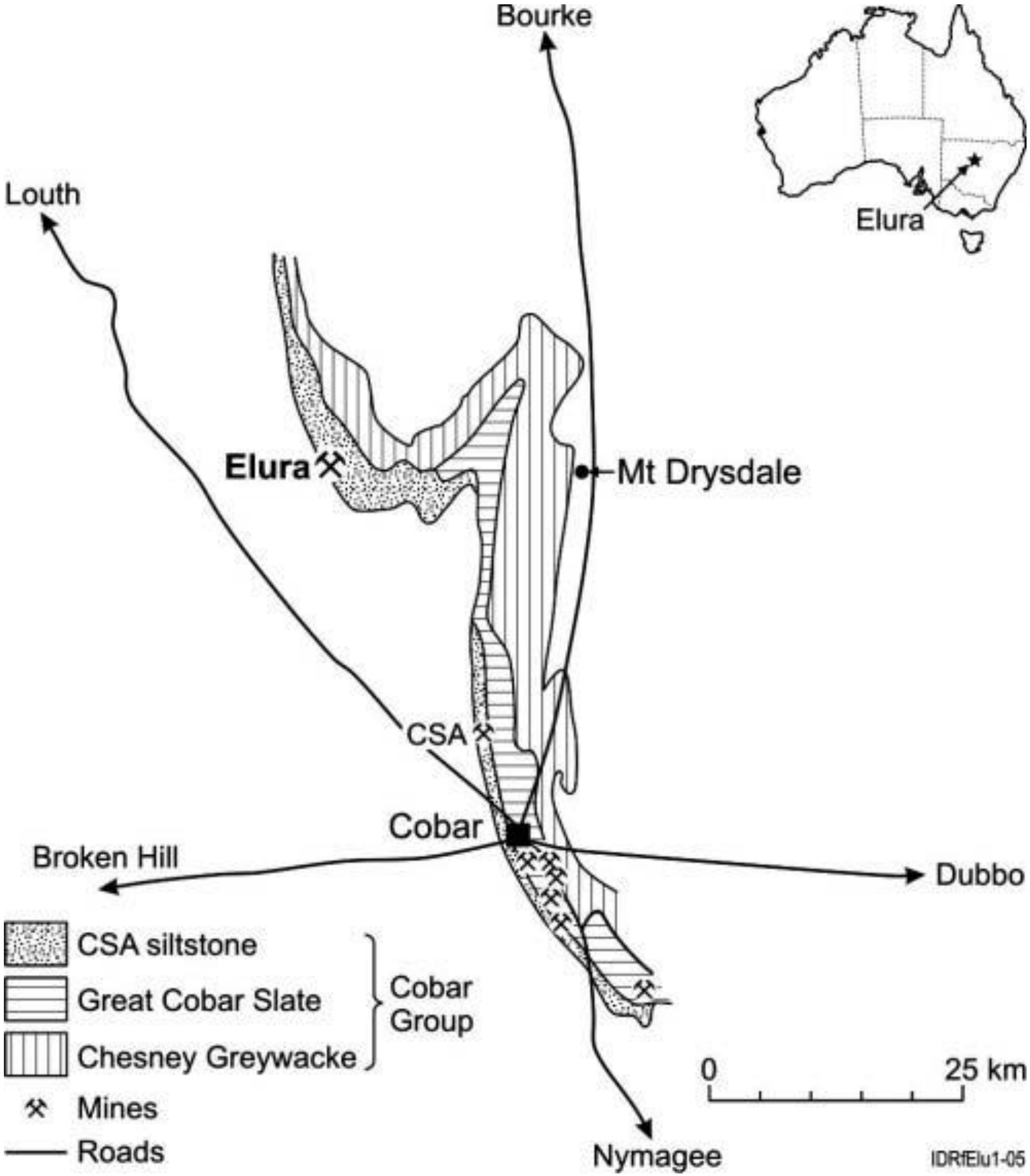


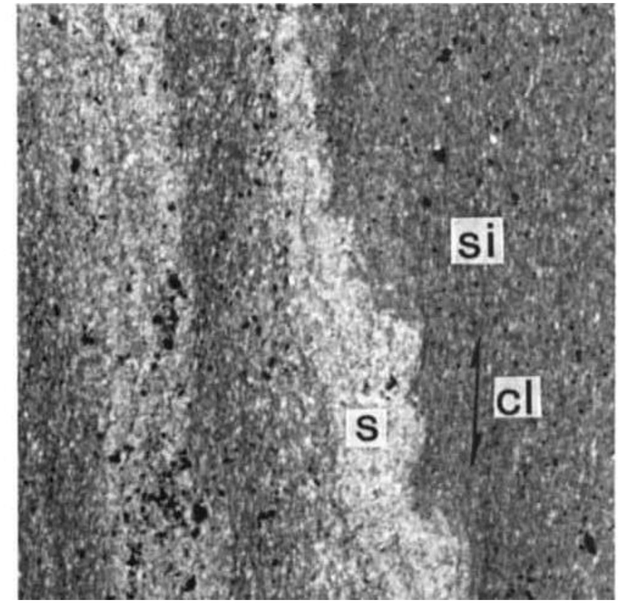
From Urqueta et al, 2009

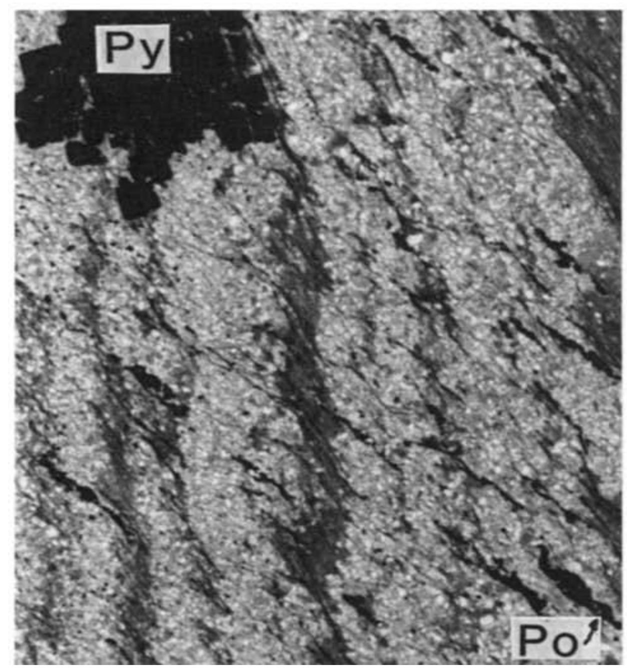


Alteration index of rocks in the Collahuasi area, Chile

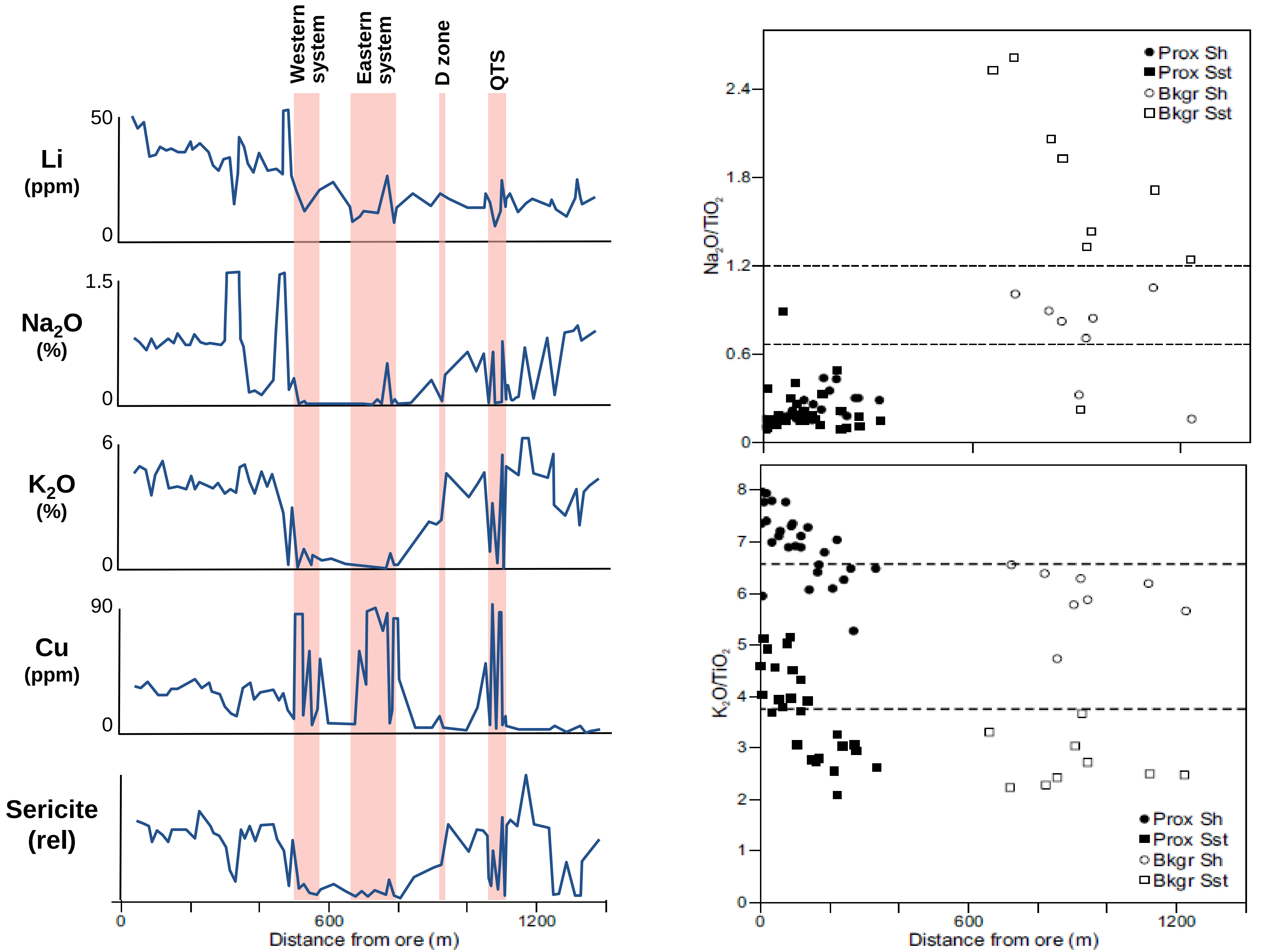
From Urqueta et al, 2009



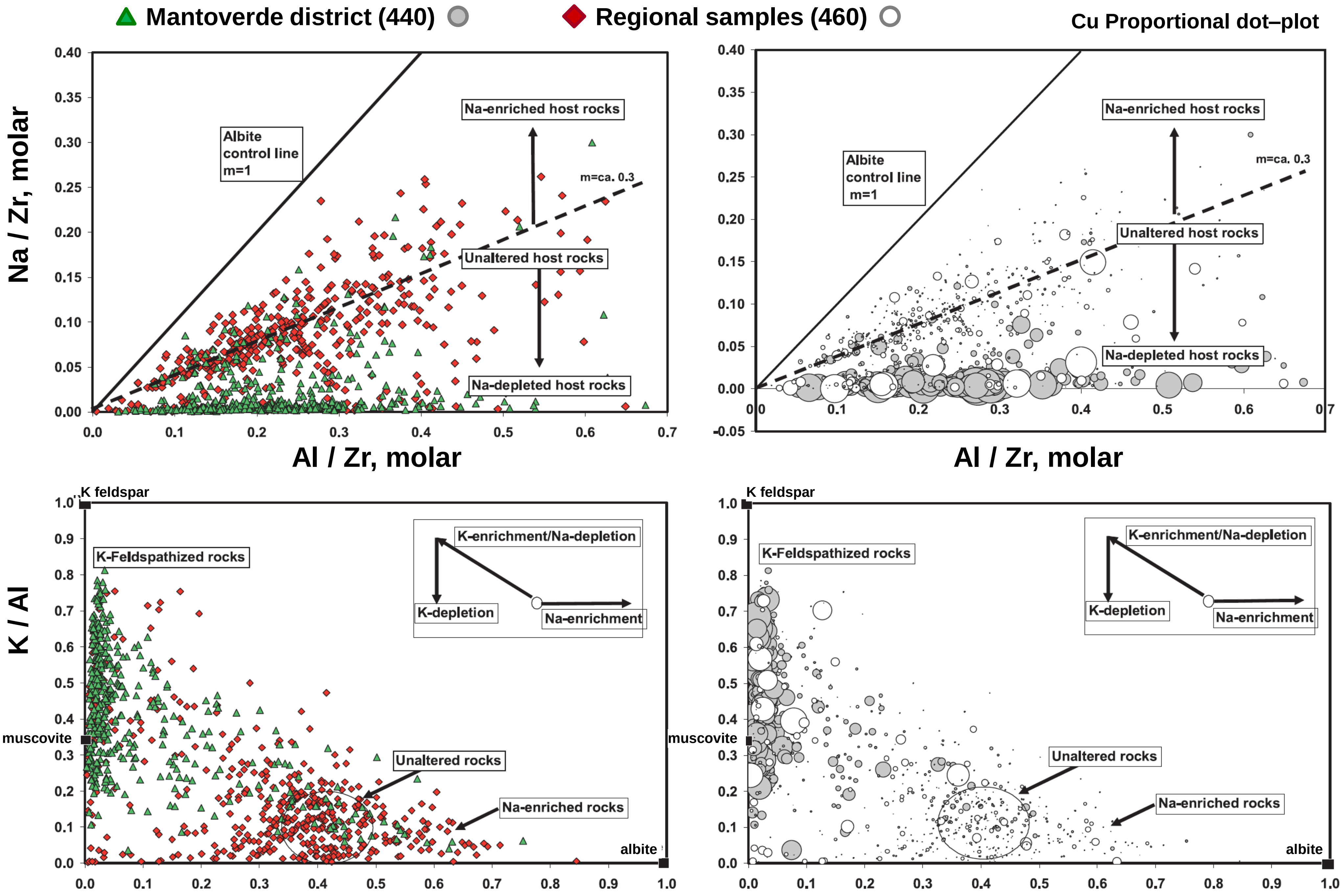




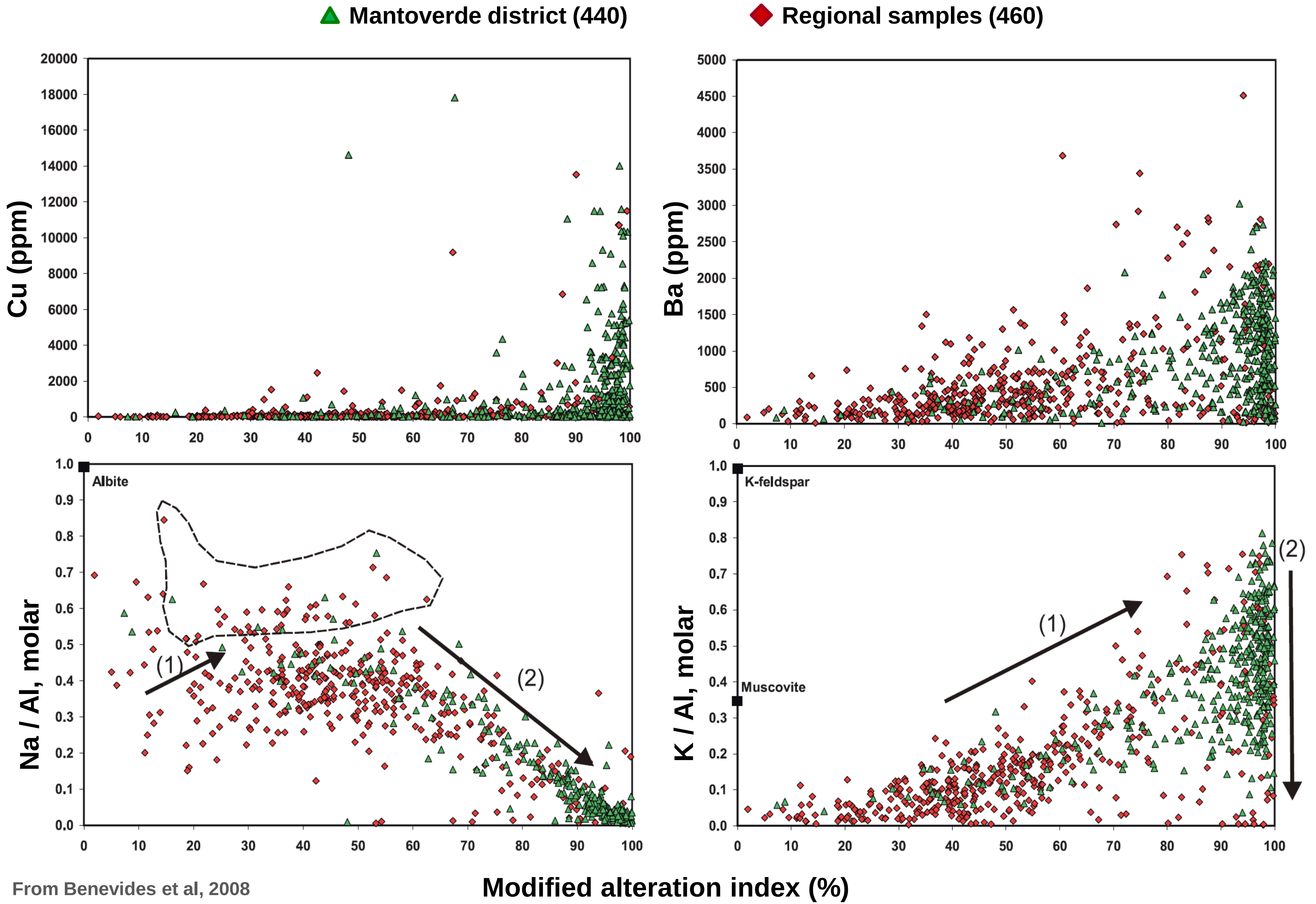
From McQueen and Whitbread, 2011



After Robertson and Taylor 1987, McQueen and Whitbread 2007



From Benevides et al, 2008



From Benevides et al, 2008

Regolith – Arid / Deeply Weathered Terranes

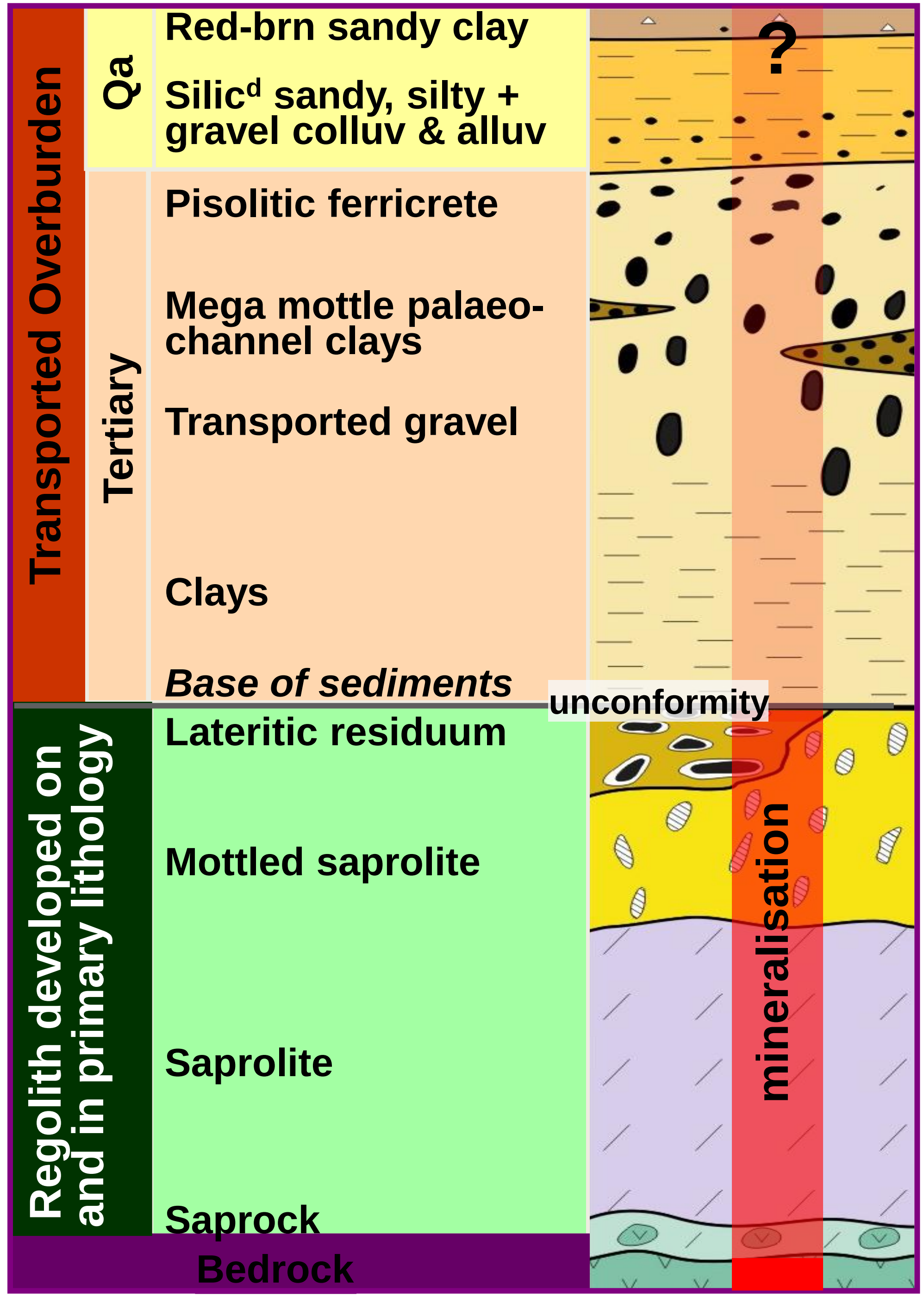
Weathered profiles typically have RESIDUAL and TRANSPORTED components of varying ages

Several distinct phases of creation and destruction of secondary Fe, Ca, Si and Al minerals – each with total or partial resetting of trace element geochemistry

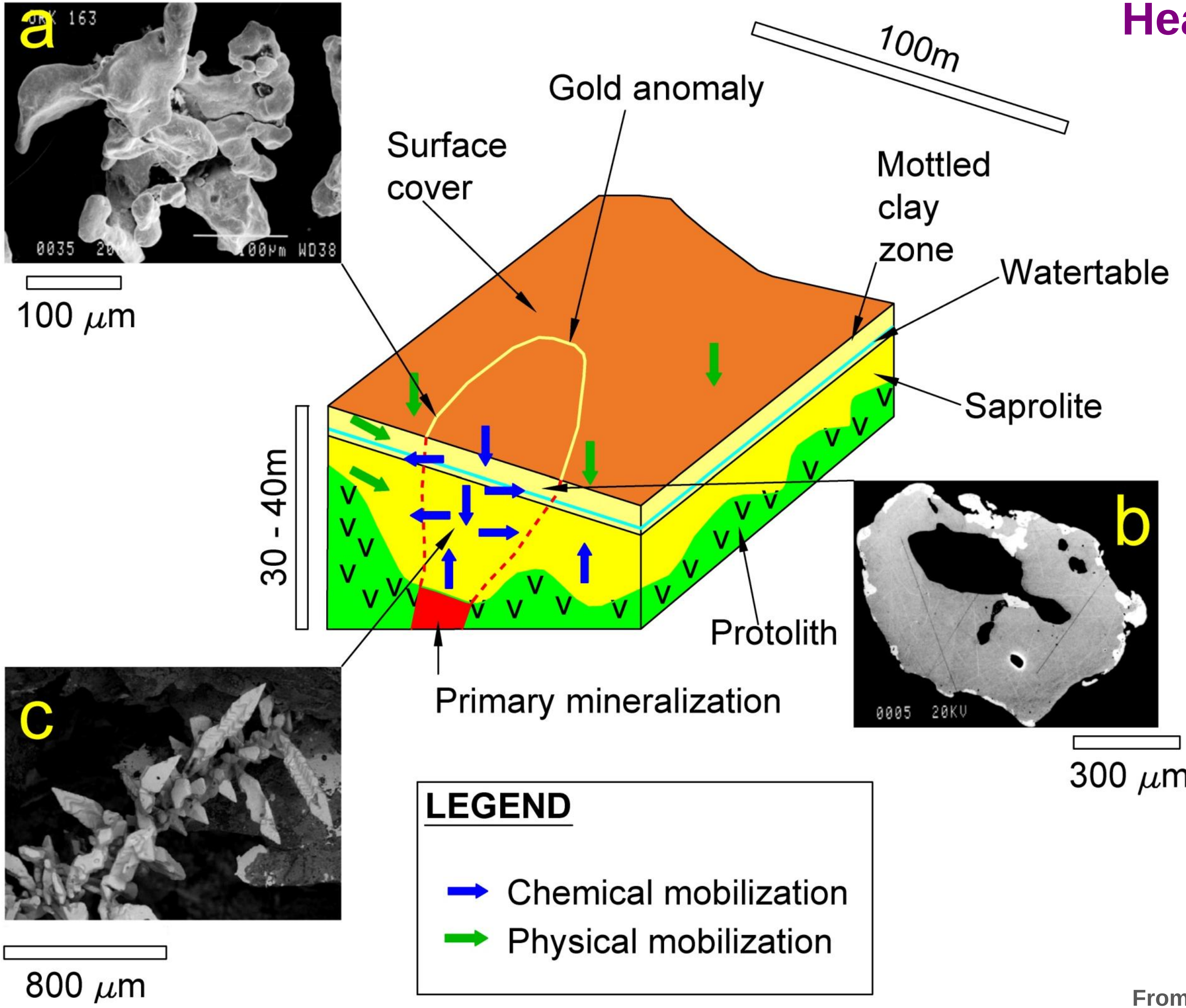
⇒ Systematic approach to identifying regolith materials and landforms

⇒ Link evolution of regolith and its components to geochemical processes and sampling strategies

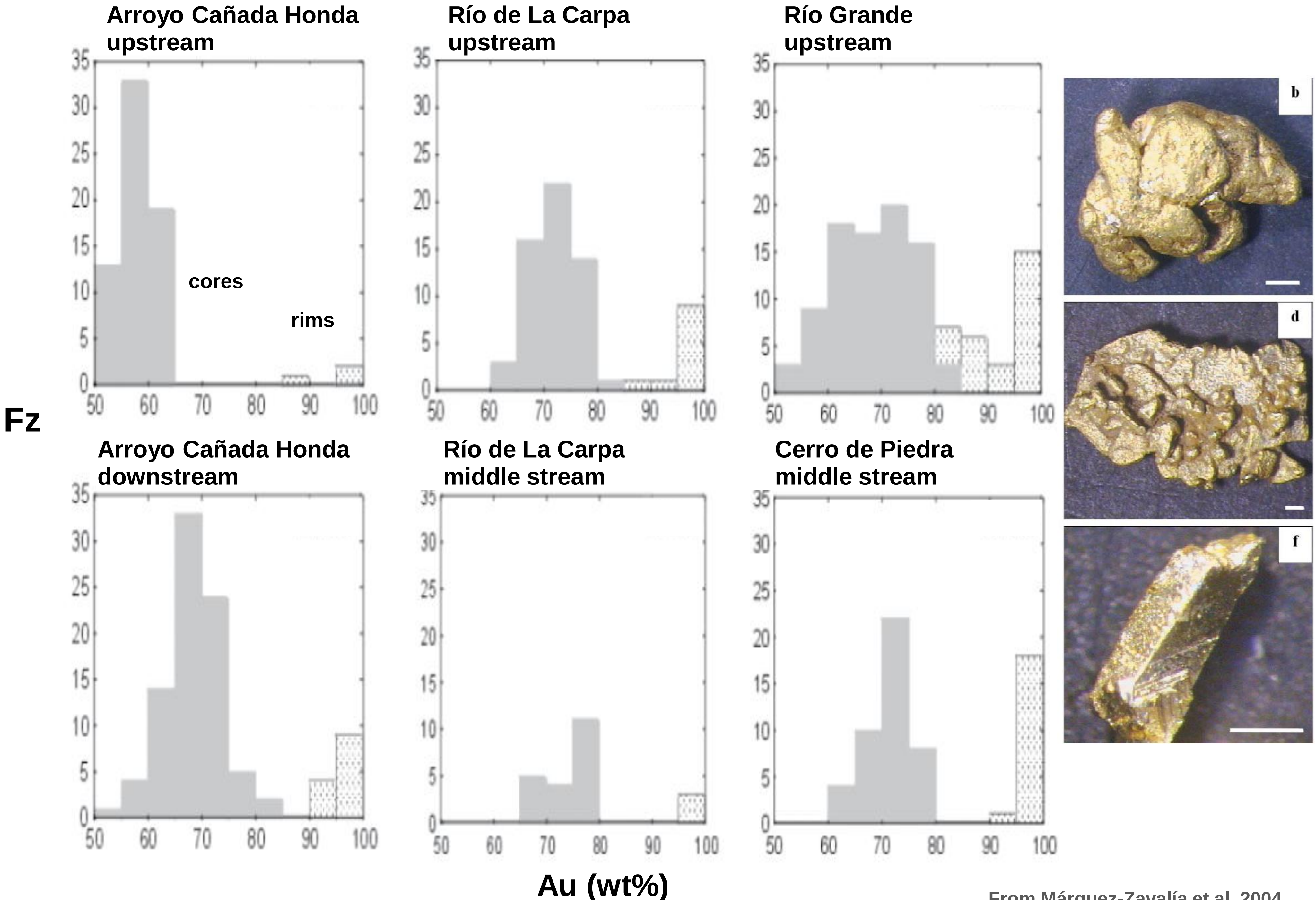
Anand and Smith, 2005



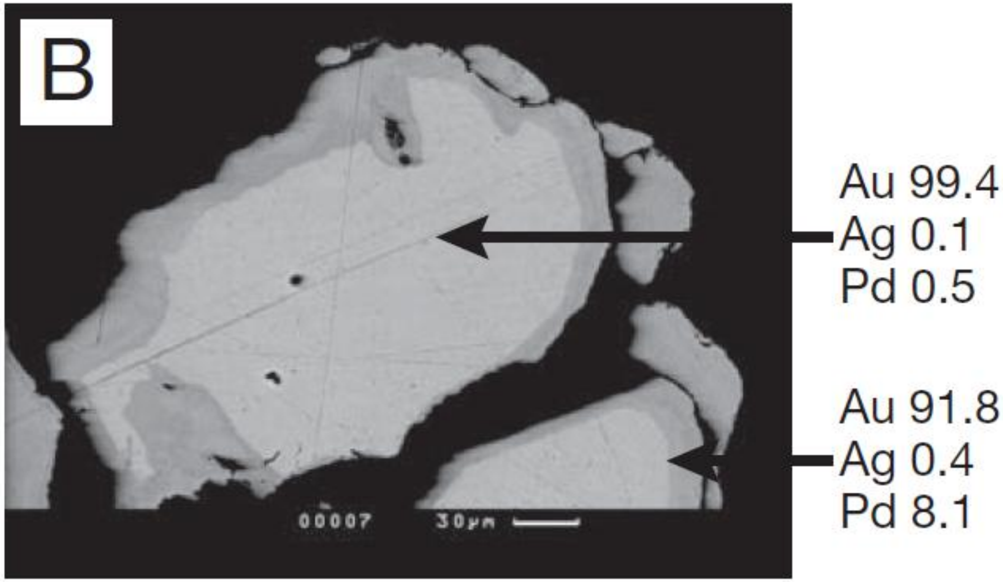
Heavy minerals



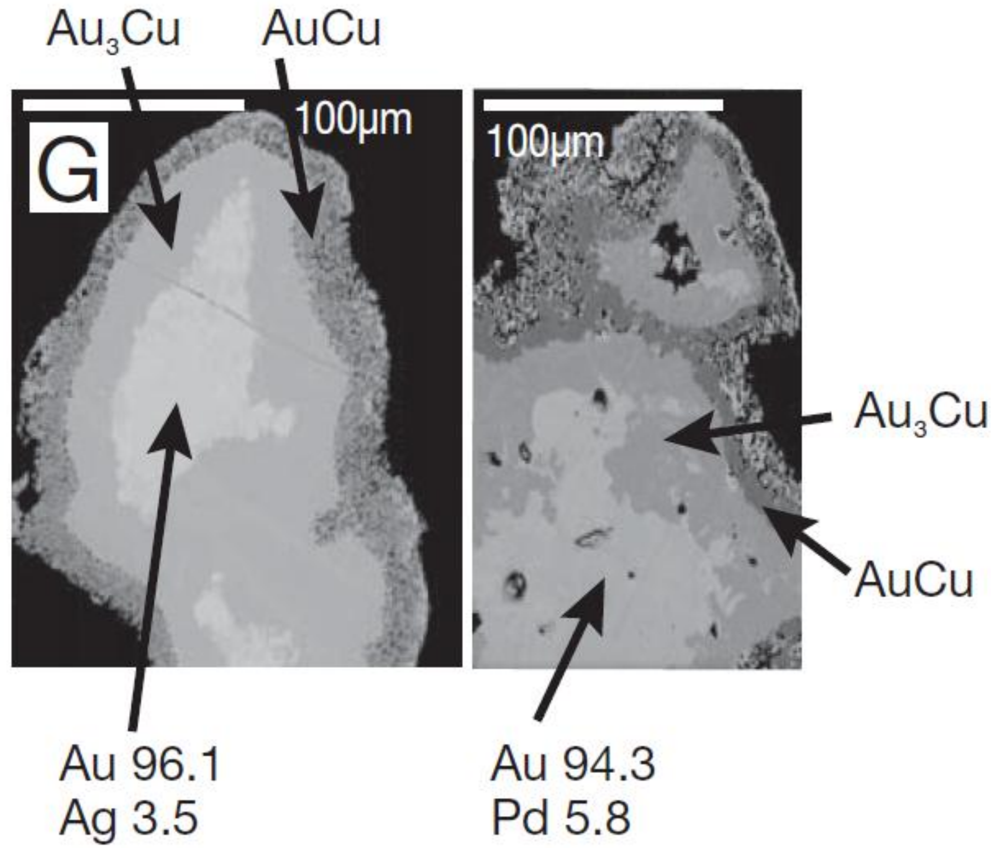
From Cohen and Bowell, 2013



From Márquez-Zavalía et al, 2004



Pd-rich gold forming distinct rim around core, Brownstone (Cornwall).

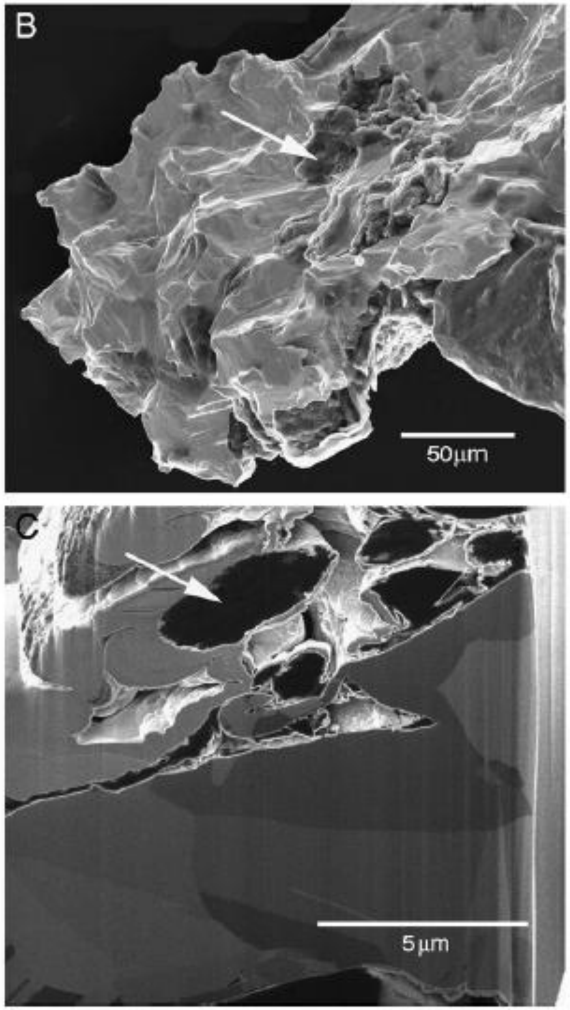


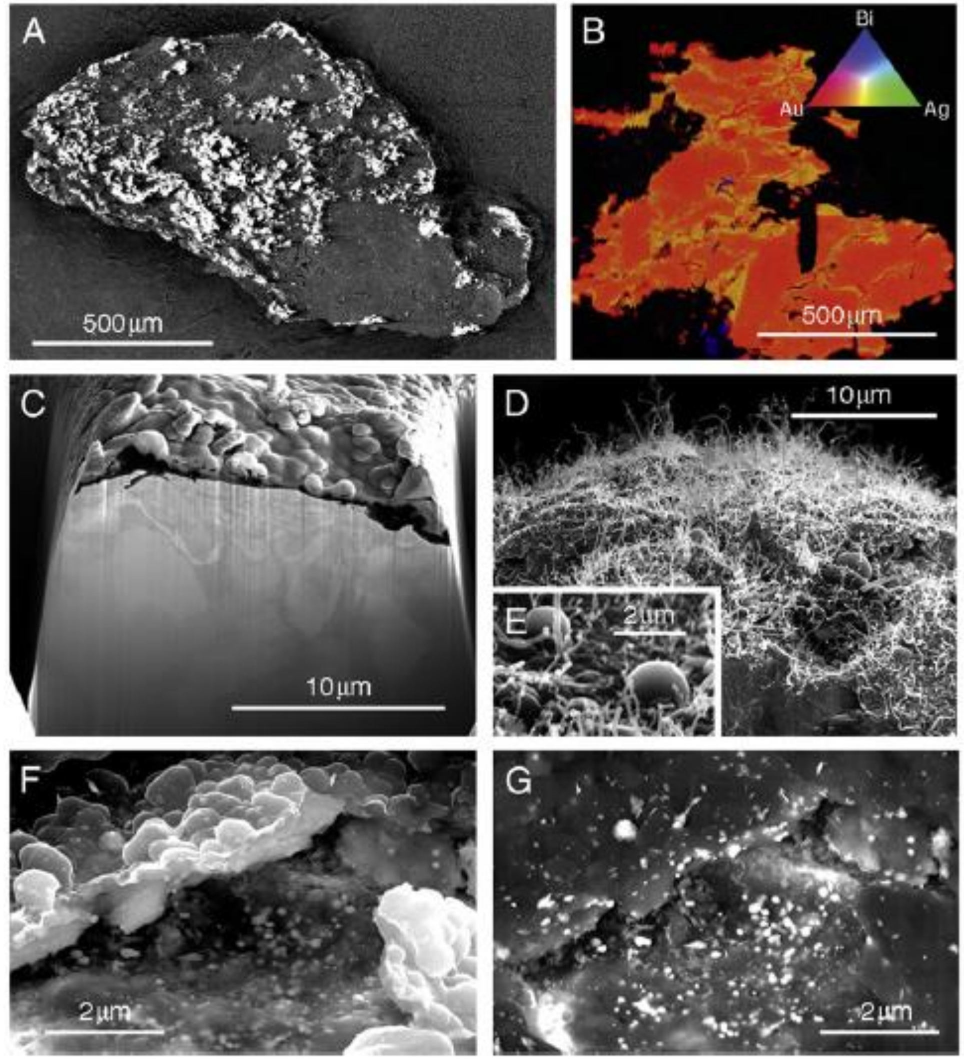
Zonation of Cu-Au compounds surrounding Au-Pd grain core from Kraskov (Czech Rep), and Philip Burn (Lammermuir Hills, Scotland).

Placer Au grains derived from oxidising Cl-rich systems

After Chapman et al, 2009

From Fairbrother et al, 2012



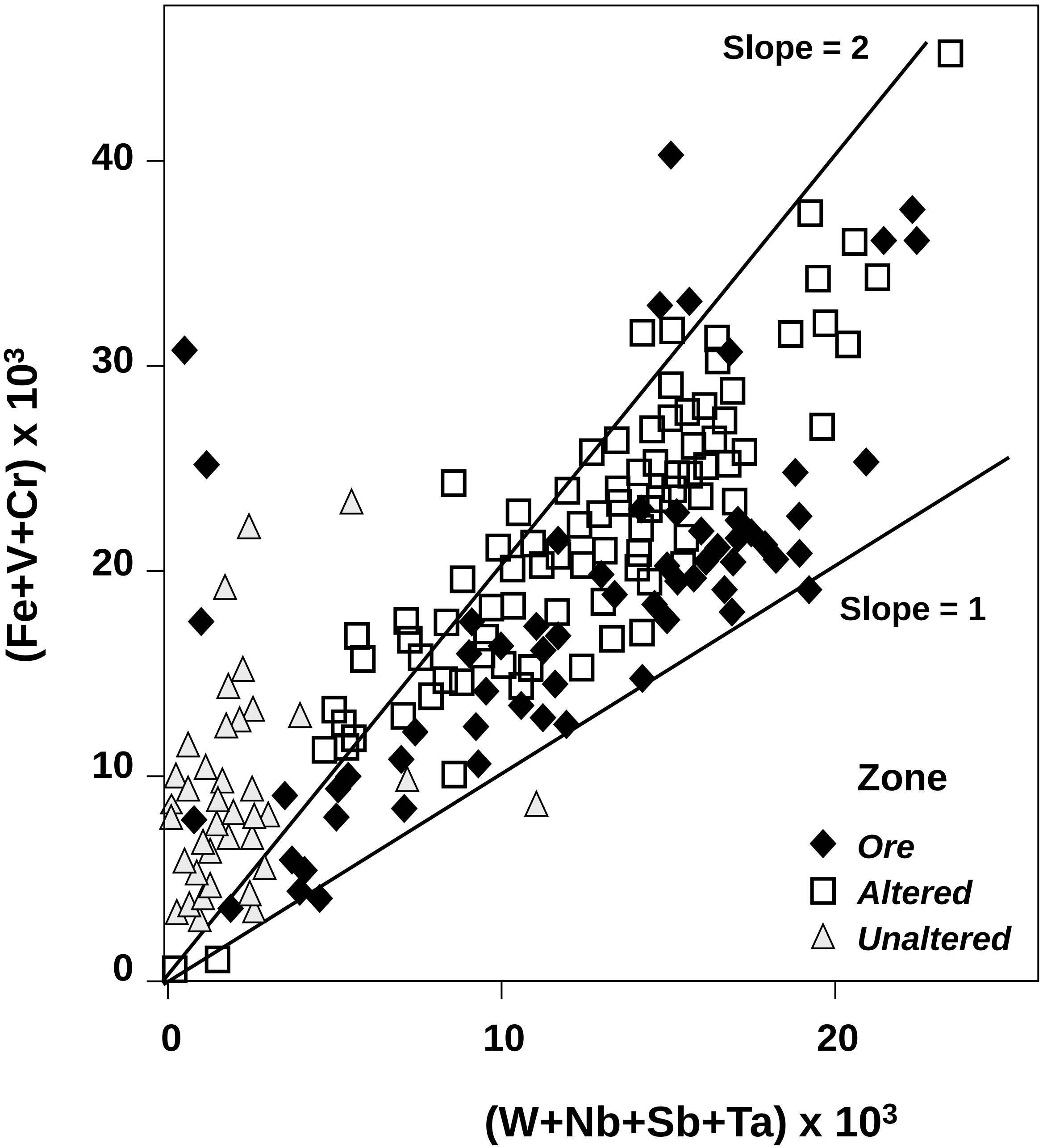


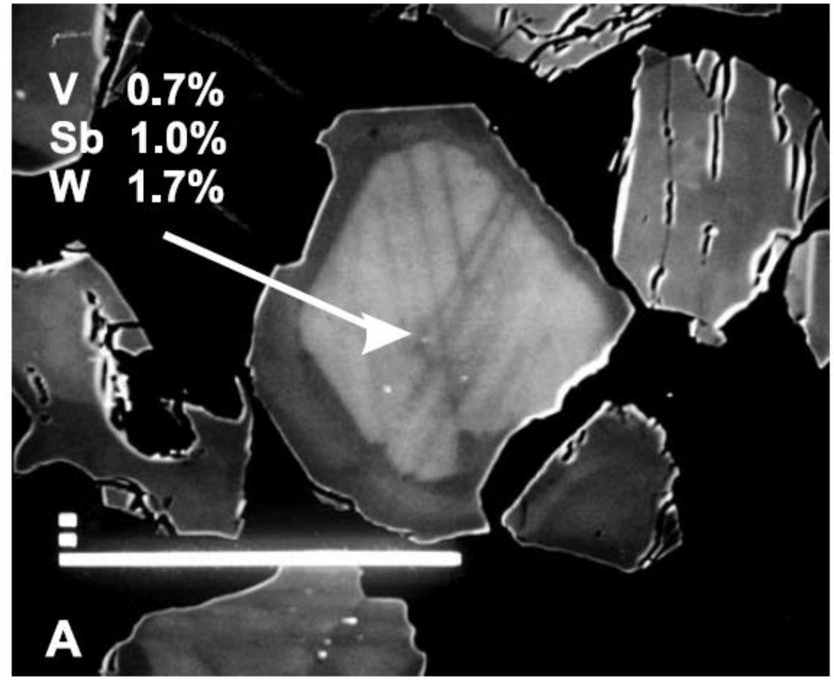
Morphology of Au, Donegal Runoff

B. SEM micrograph showing angular grains and layer composed of Si, Al, O, Na (arrow).
C. FIB-SEM micrograph showing a section through the layer of material shown in B.

Gold grain from Lively's Find, Flinders RA

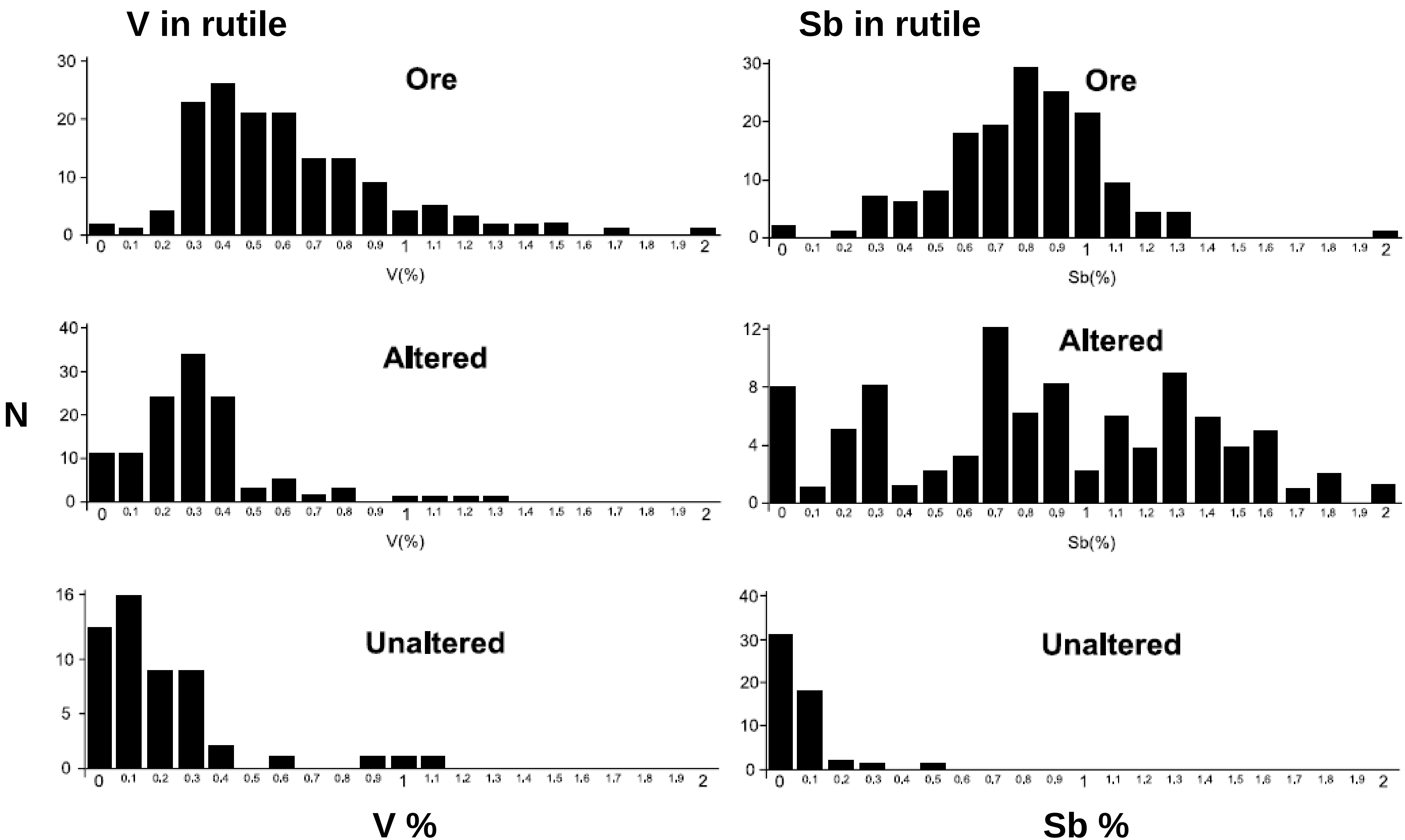
A. SEM micrograph (BSE mode) showing rounded morphology of the Au grains.
B. Alloyed nature of the grain and areas of higher purity Au.
C. Inner crystallinity of the grains via FIB with crystal size smaller on the exterior rim of the grains and larger towards the bulk of the Au grain.
D. SEM micrograph of a viable biofilm on the surface of the grains
E. Surface of grains and Au nanoparticles in interstices between the nano-wires.
F. Au precipitates distributed on the surface of the Lively's Au grains.





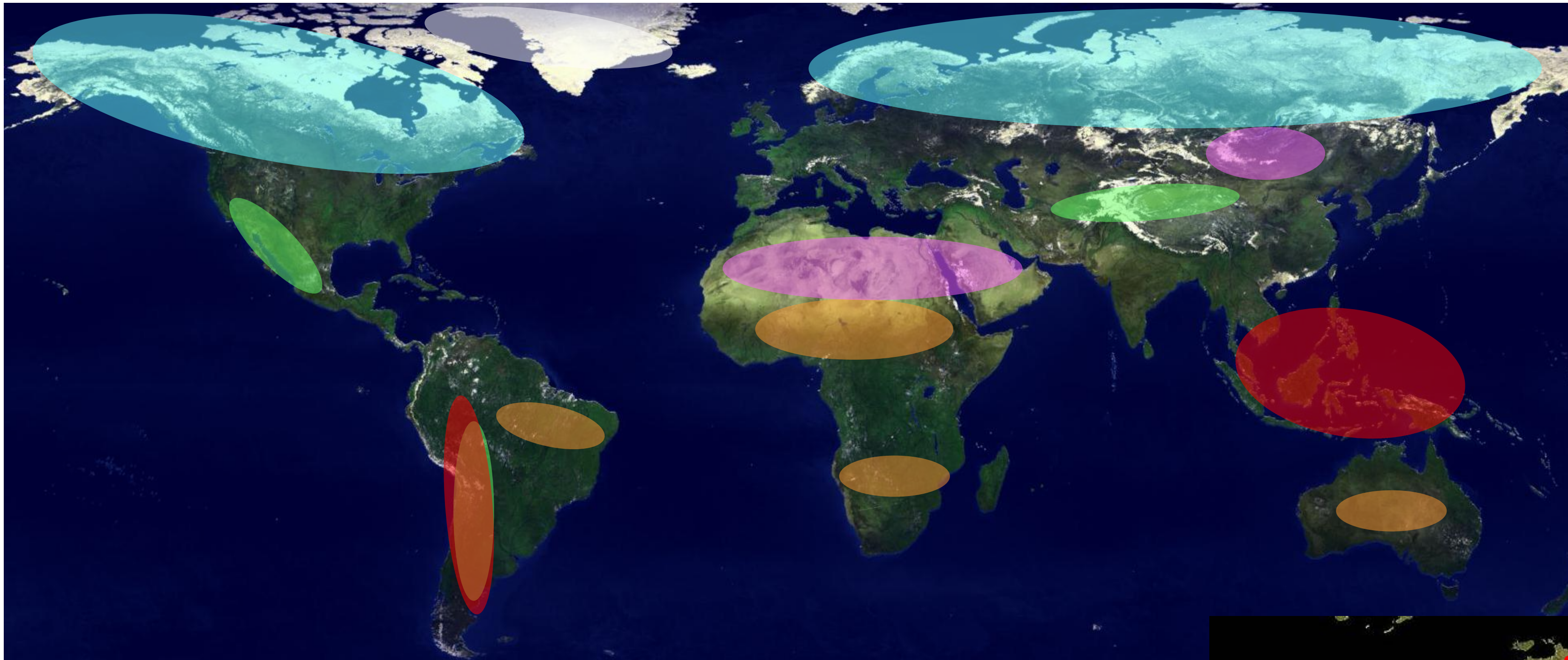
Big Bell Au Deposit

From Scott and Radford, 2007

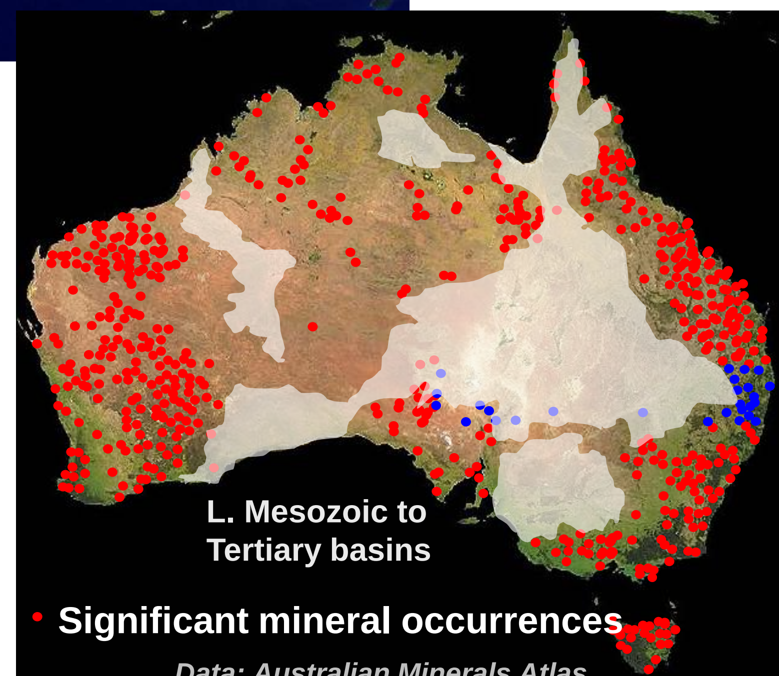


From Scott and Radford, 2007

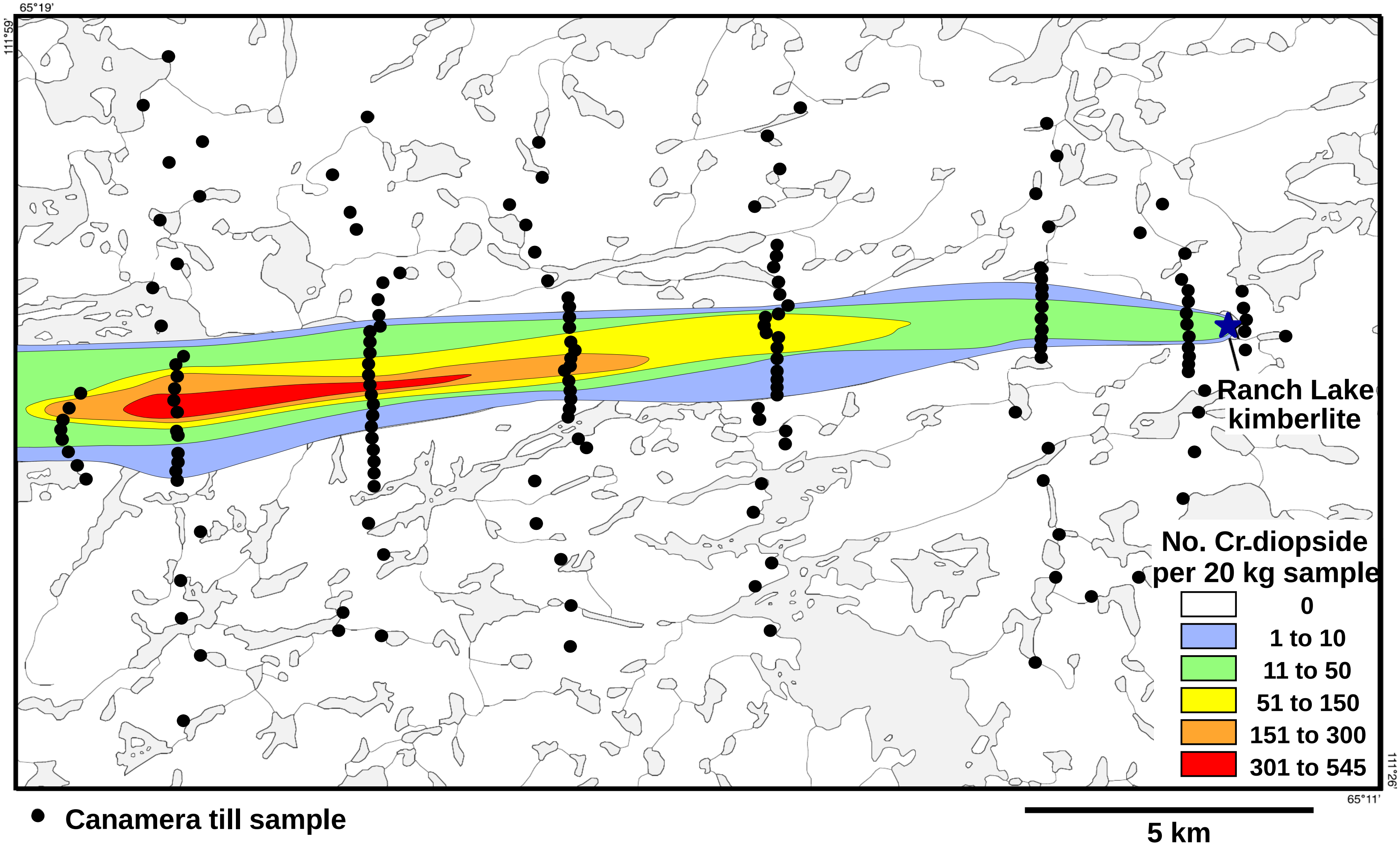
The problematic terrains for geochemical exploration

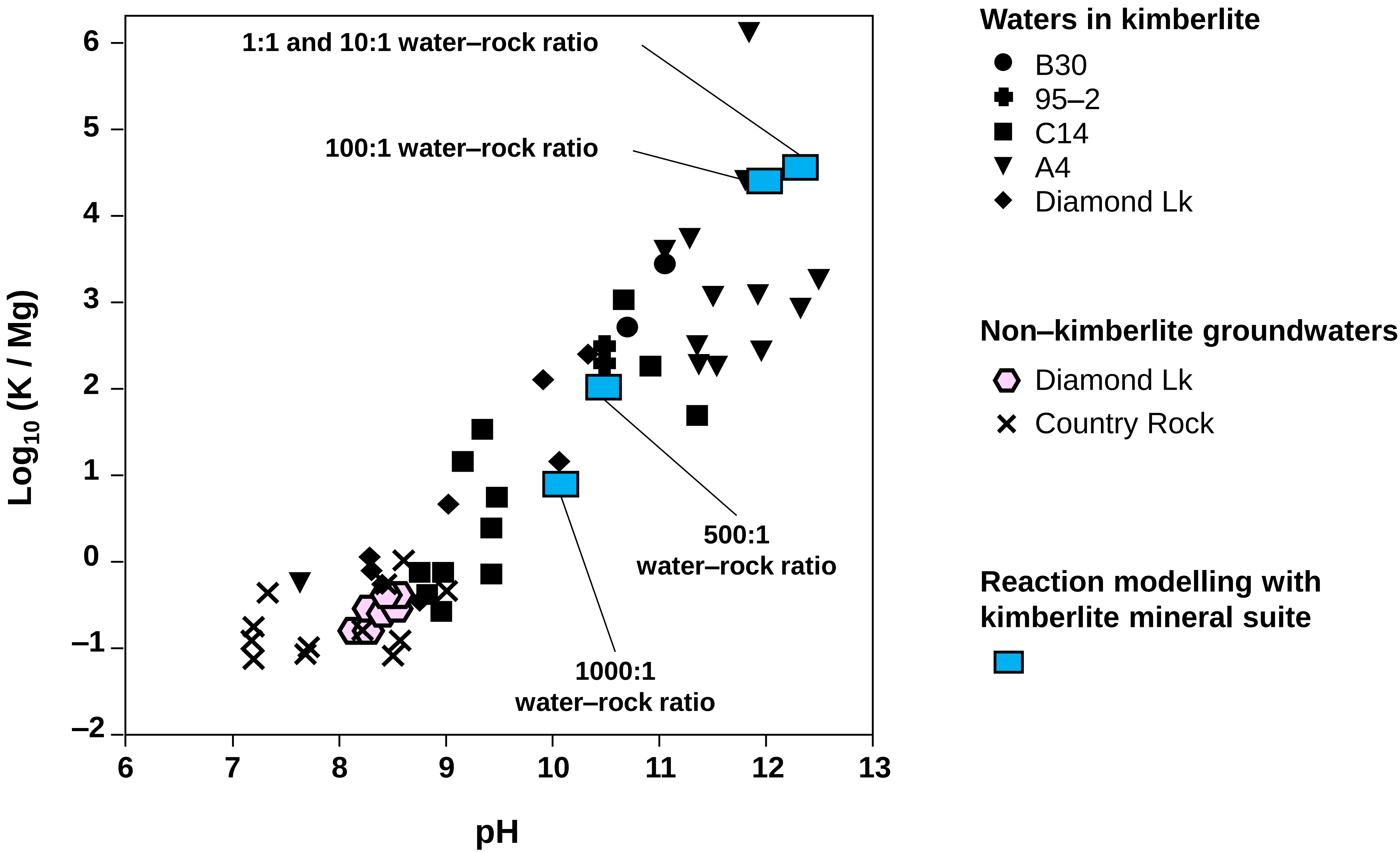


- Glacial deposits
- Thick gravel and scree deposits
- Thick alluvium or colluvium + deep weathering
- Aeolian deposits
- Volcanic ash
- ?Ice



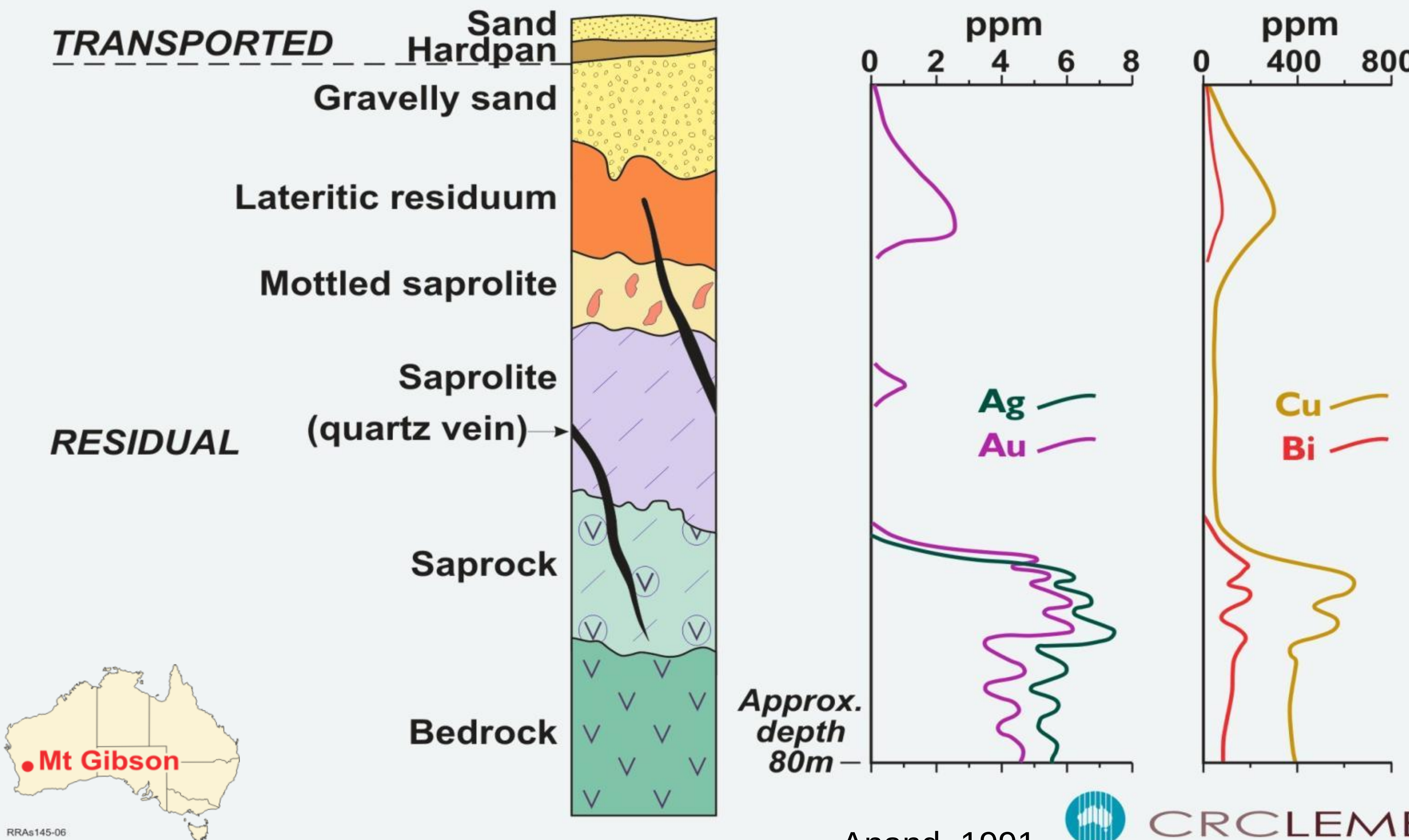
Glaciated terranes



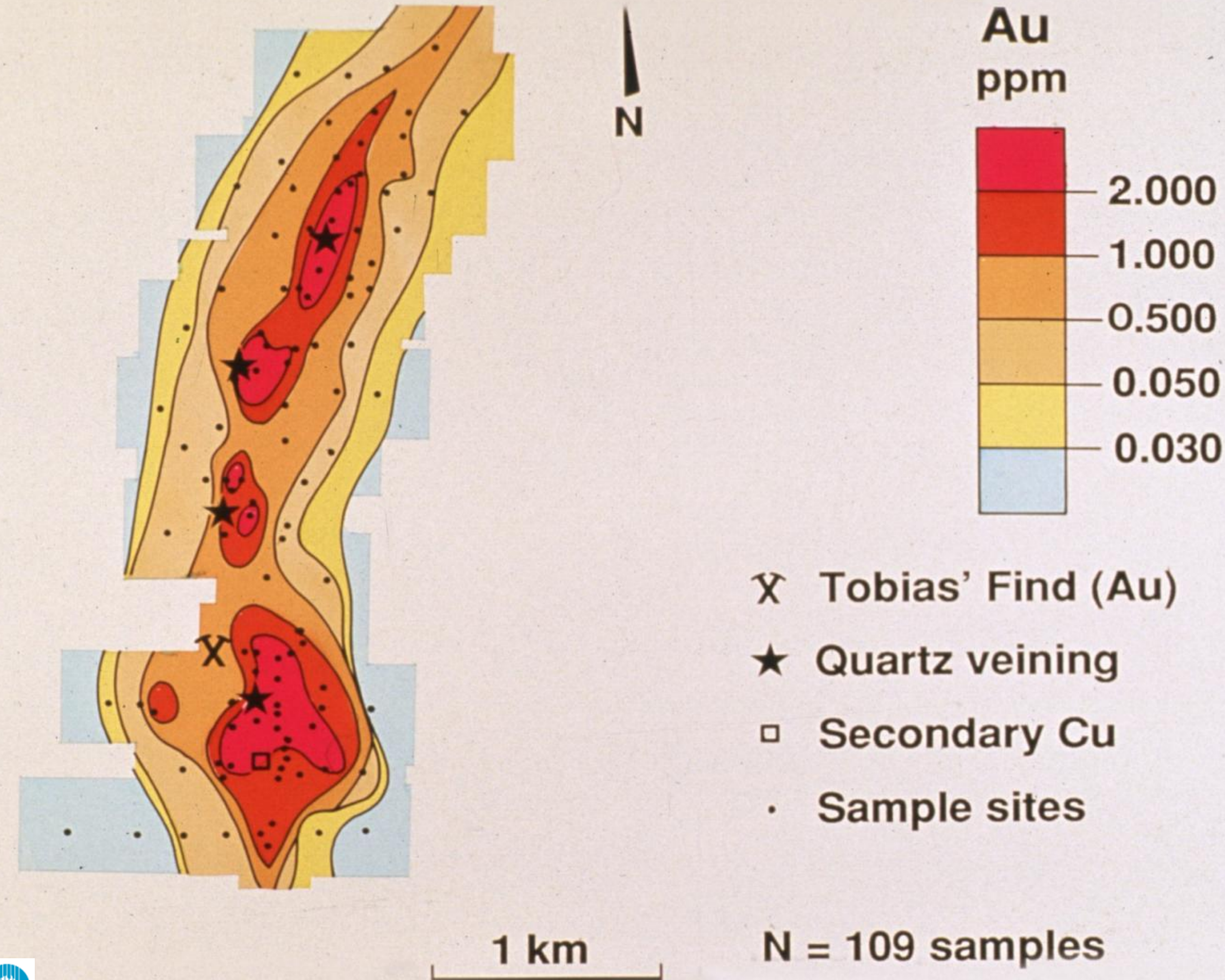


From Sader *et al.*, 2007

Generalised geochemical profile, Mt Gibson Au deposit

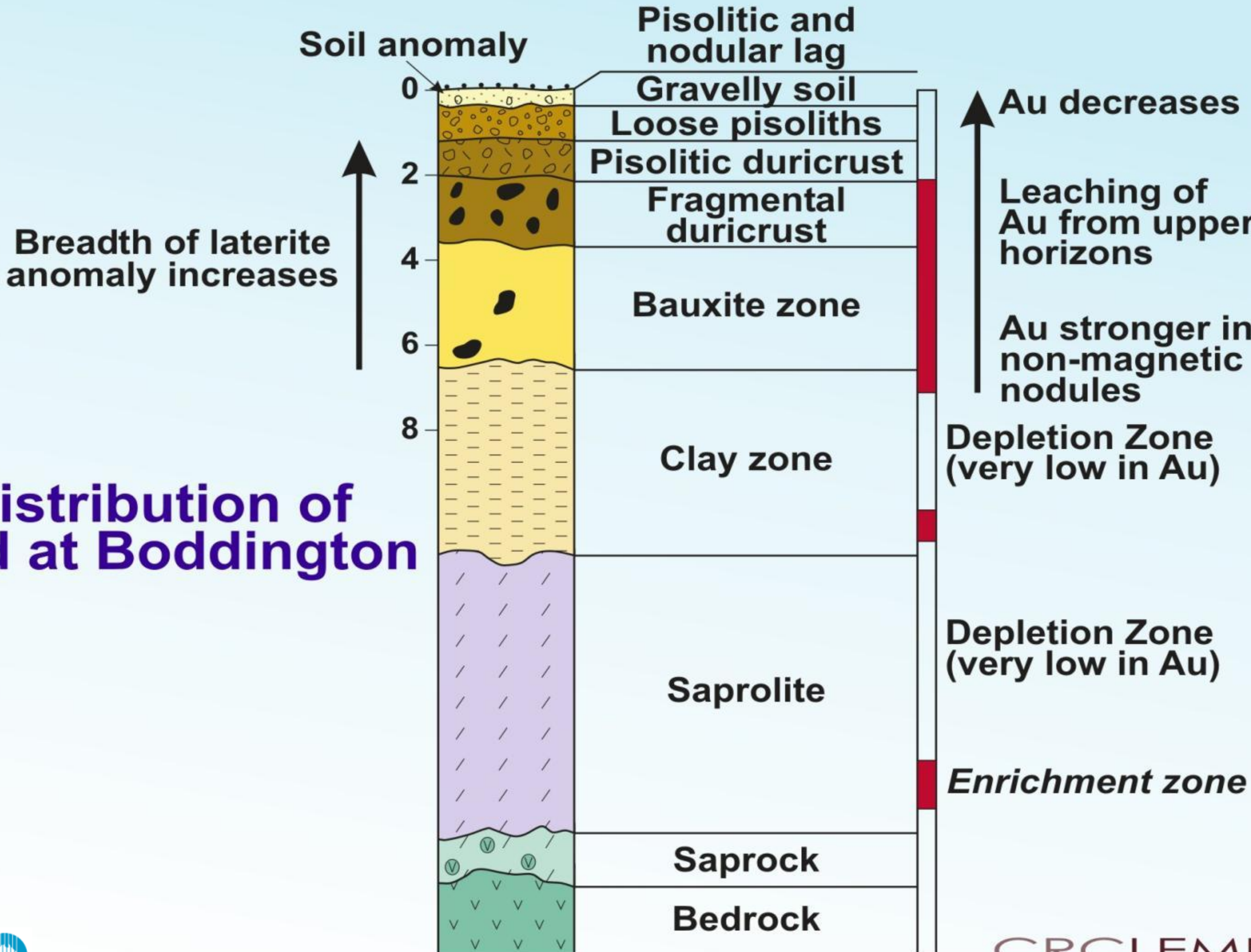


Anand, 1991



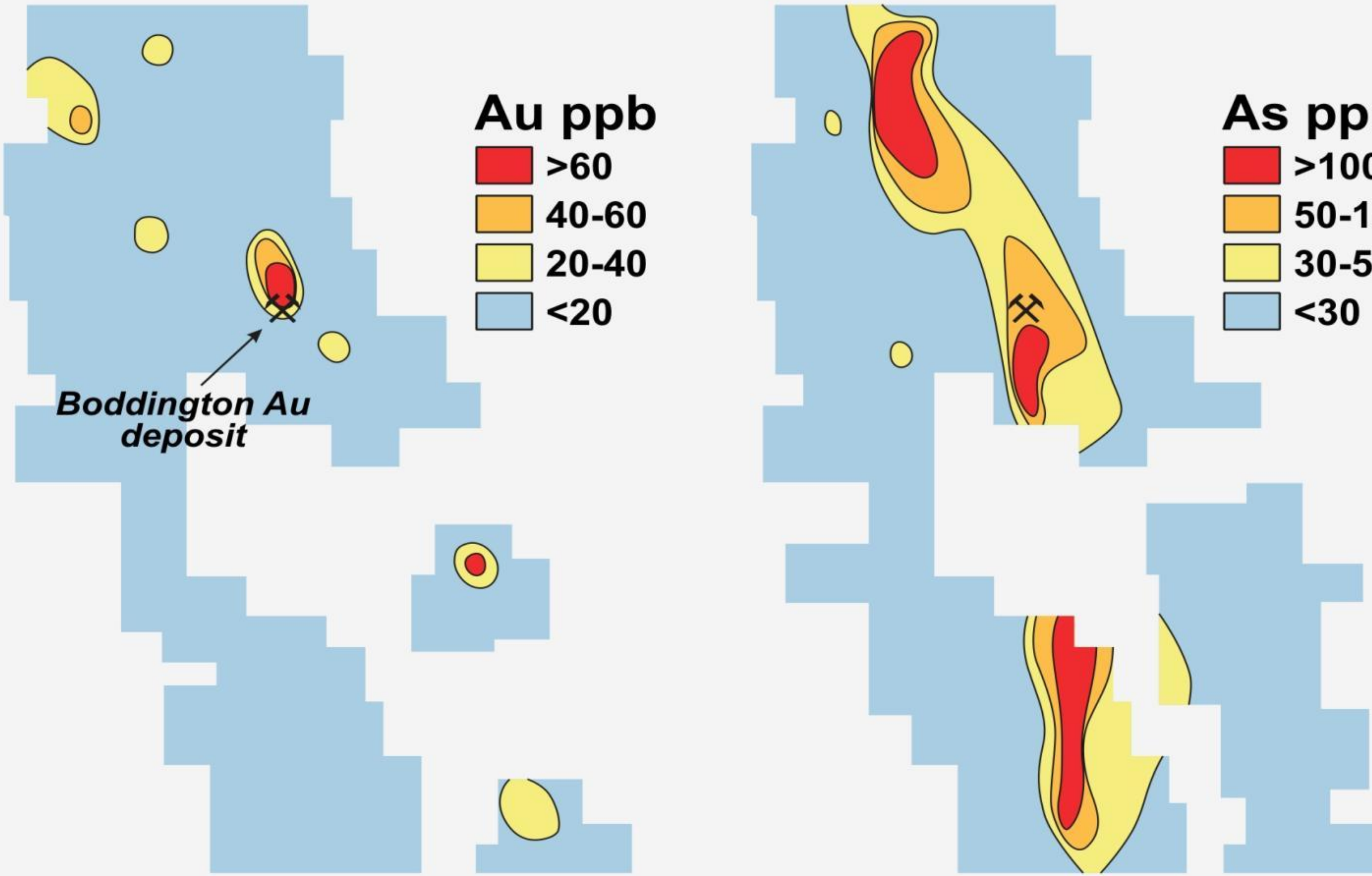
Anand et al., 1989

Distribution of gold at Boddington



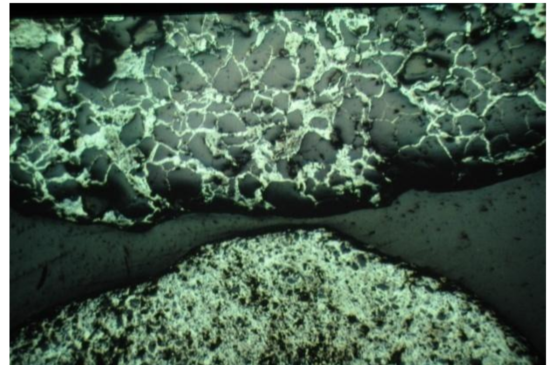
Anand, 1994

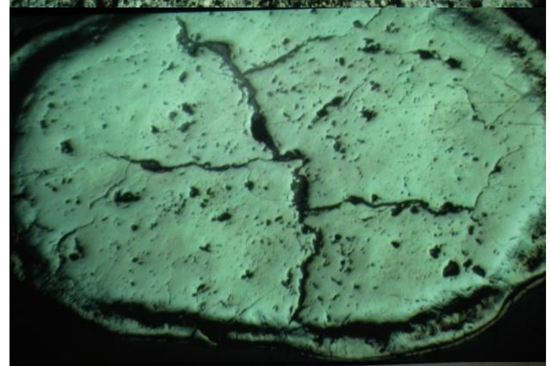
Boddington

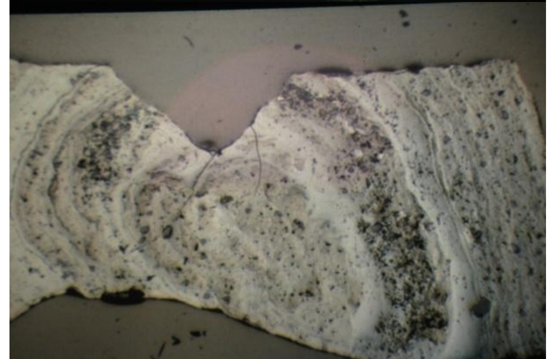


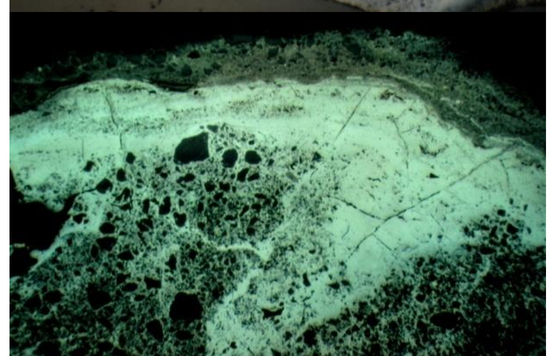
Au ppb
>60
40-60
20-40
<20
Boddington Au deposit
As ppm
>100
50-100
30-50
<30

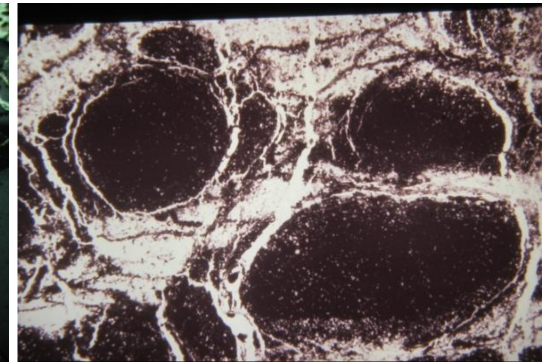
Lag

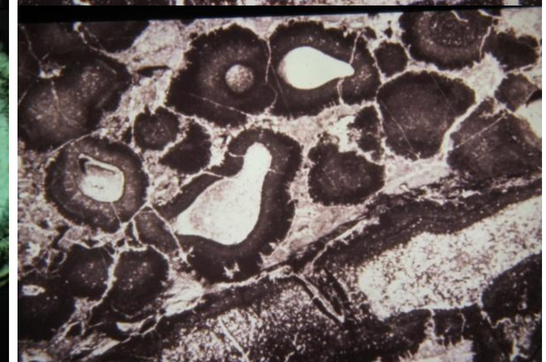


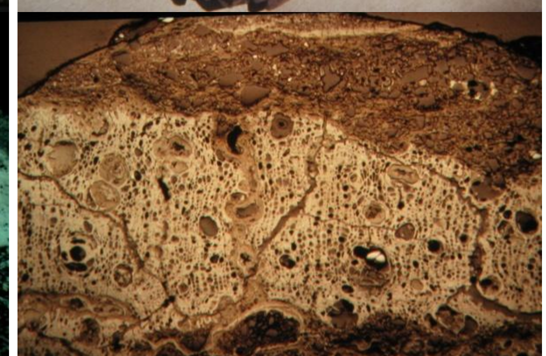




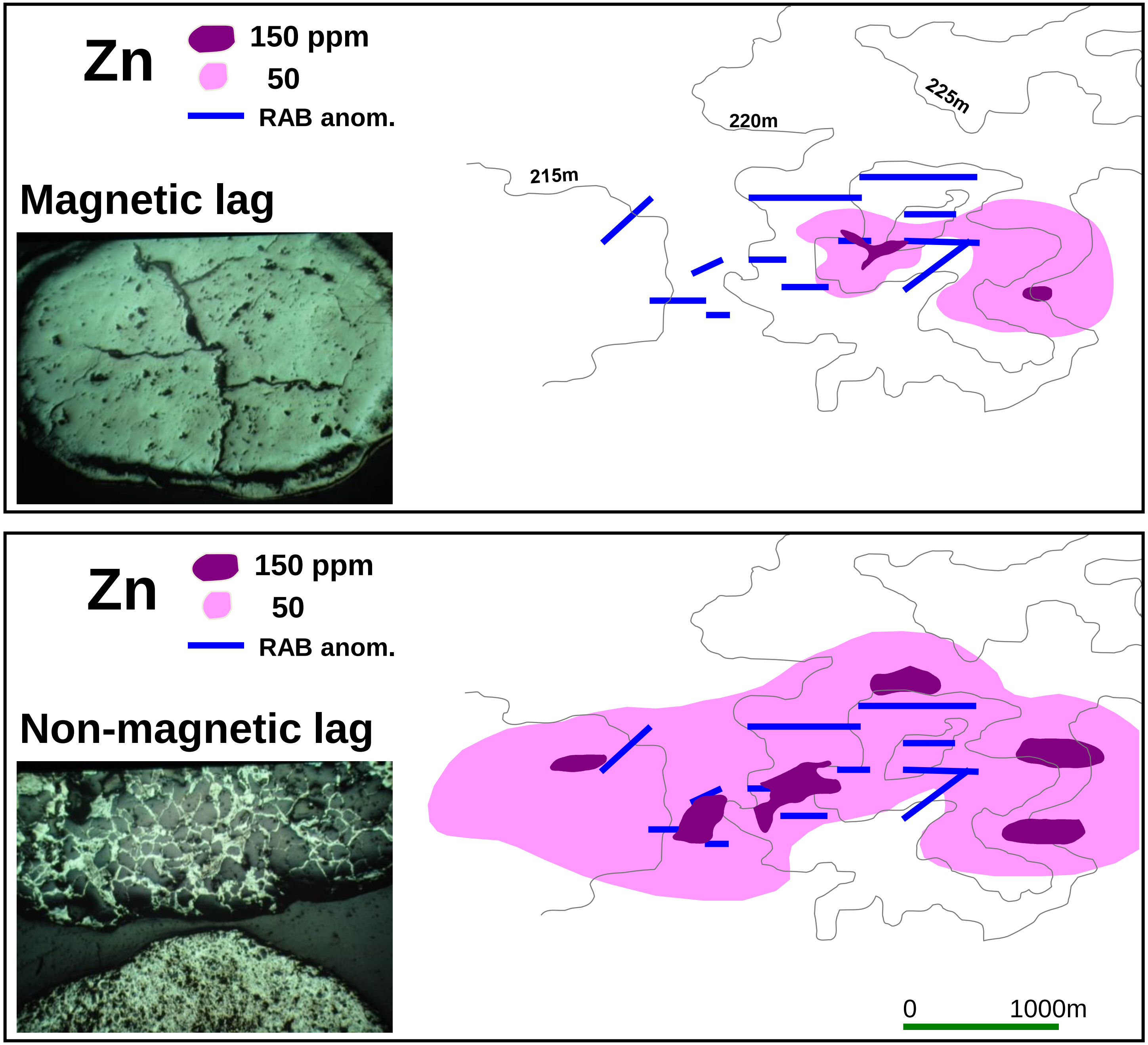




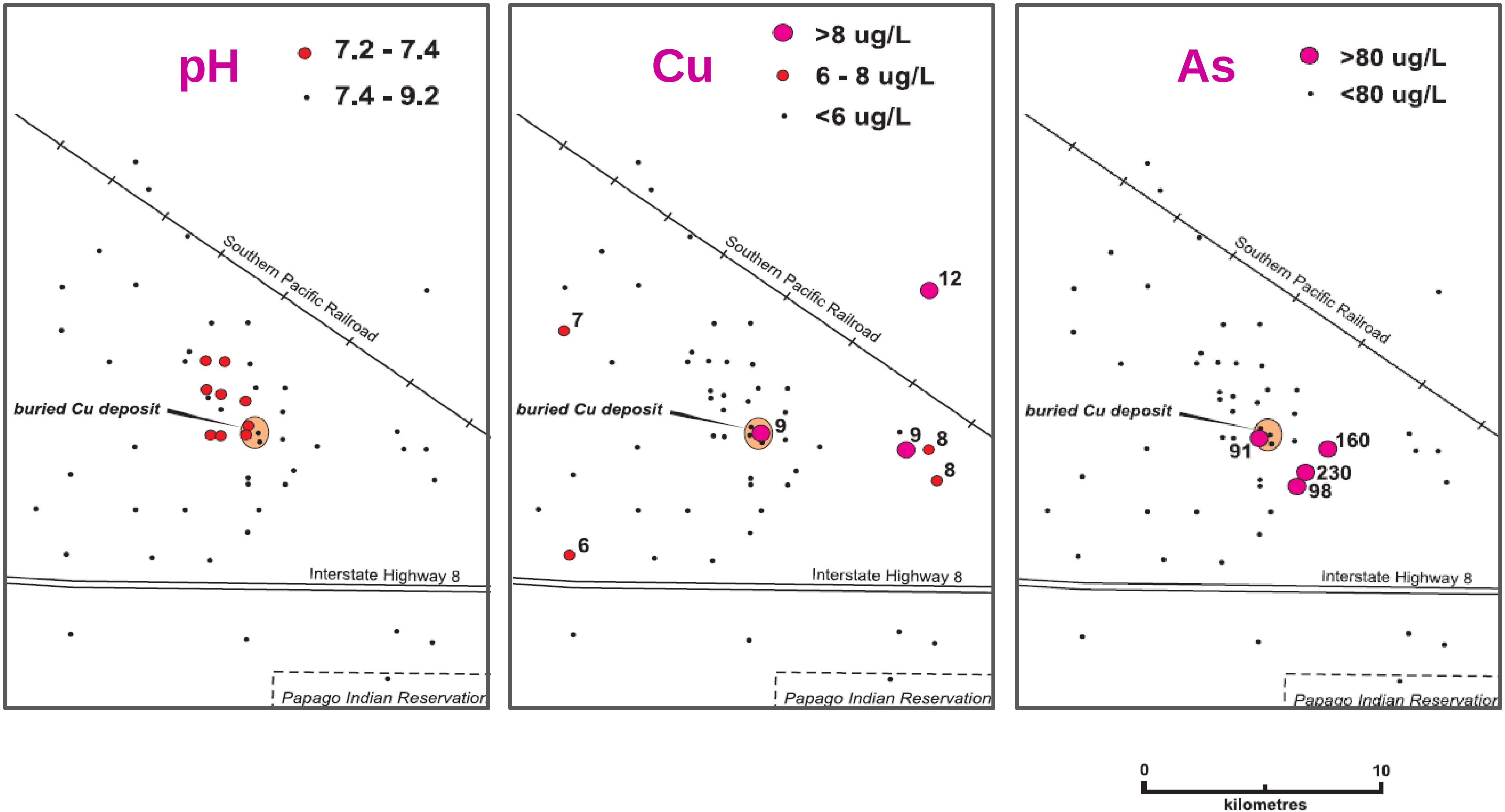




Mrangelli, Cobar

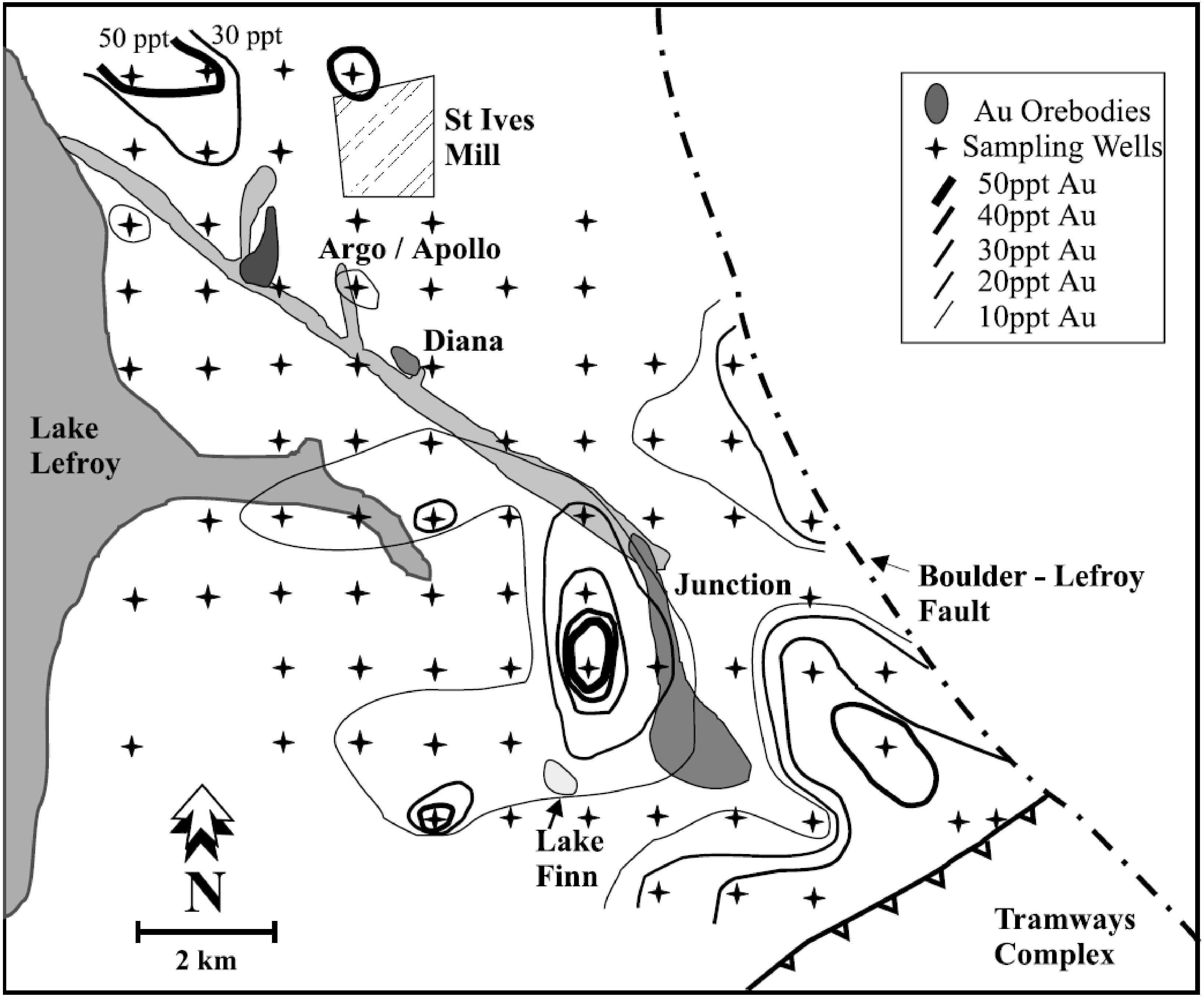


Water



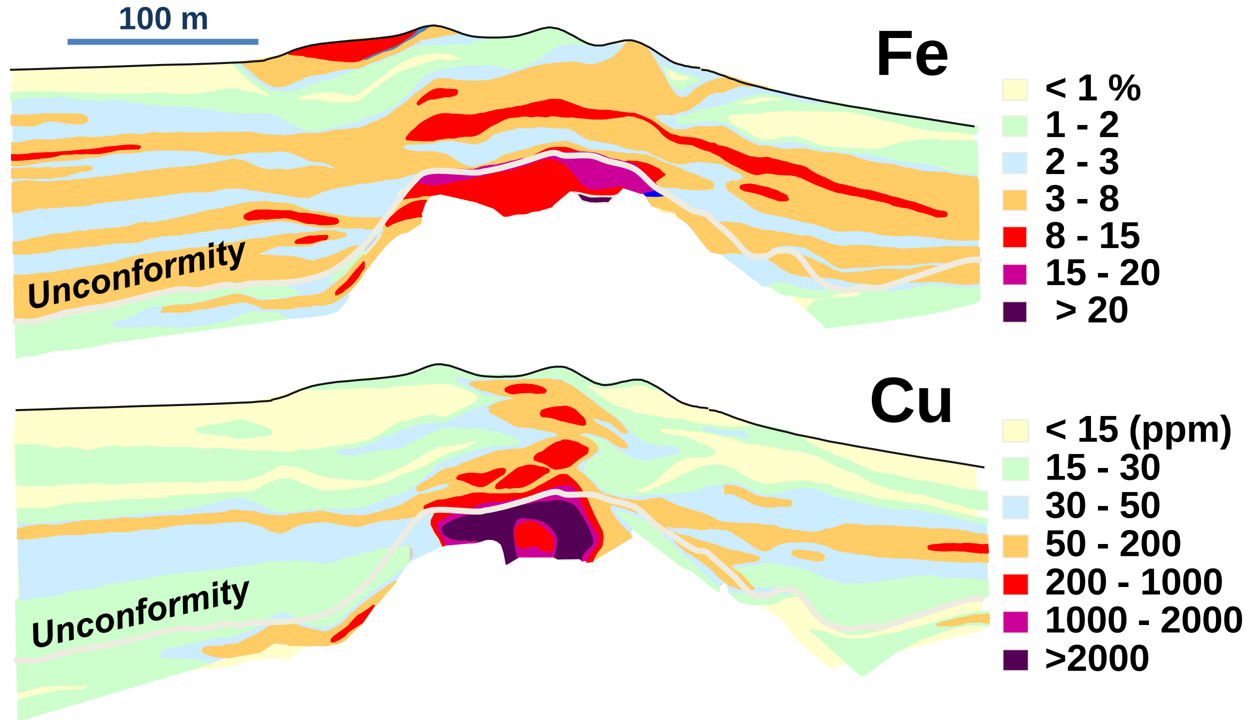
Geochemical data from irrigation well waters in the Casa Grande area, Arizona

From Taufen, 1997

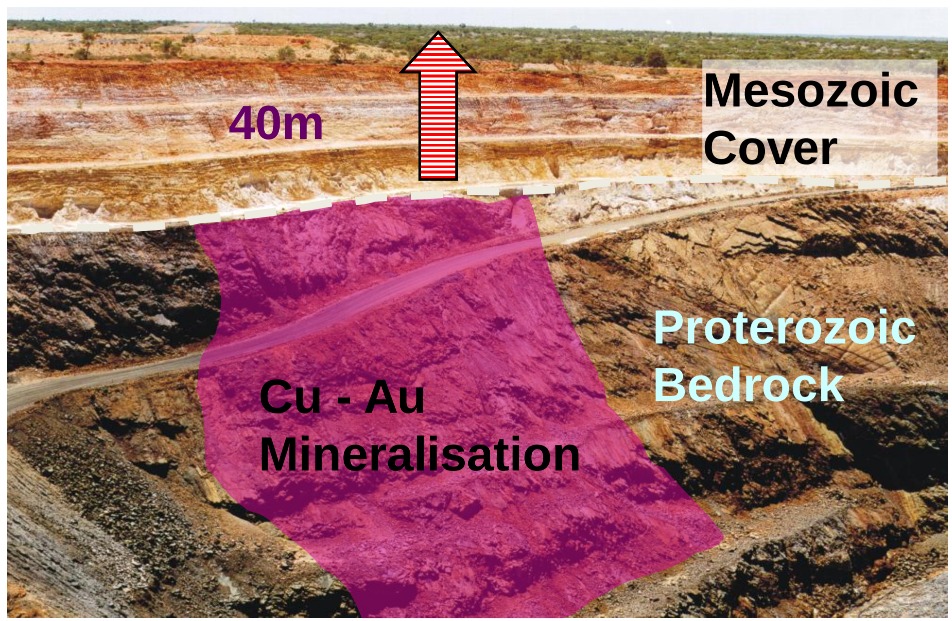


From Carey et al 2003.

Does dispersion occur through deep, transported cover?



Osborne Cu-Au deposit, Qld

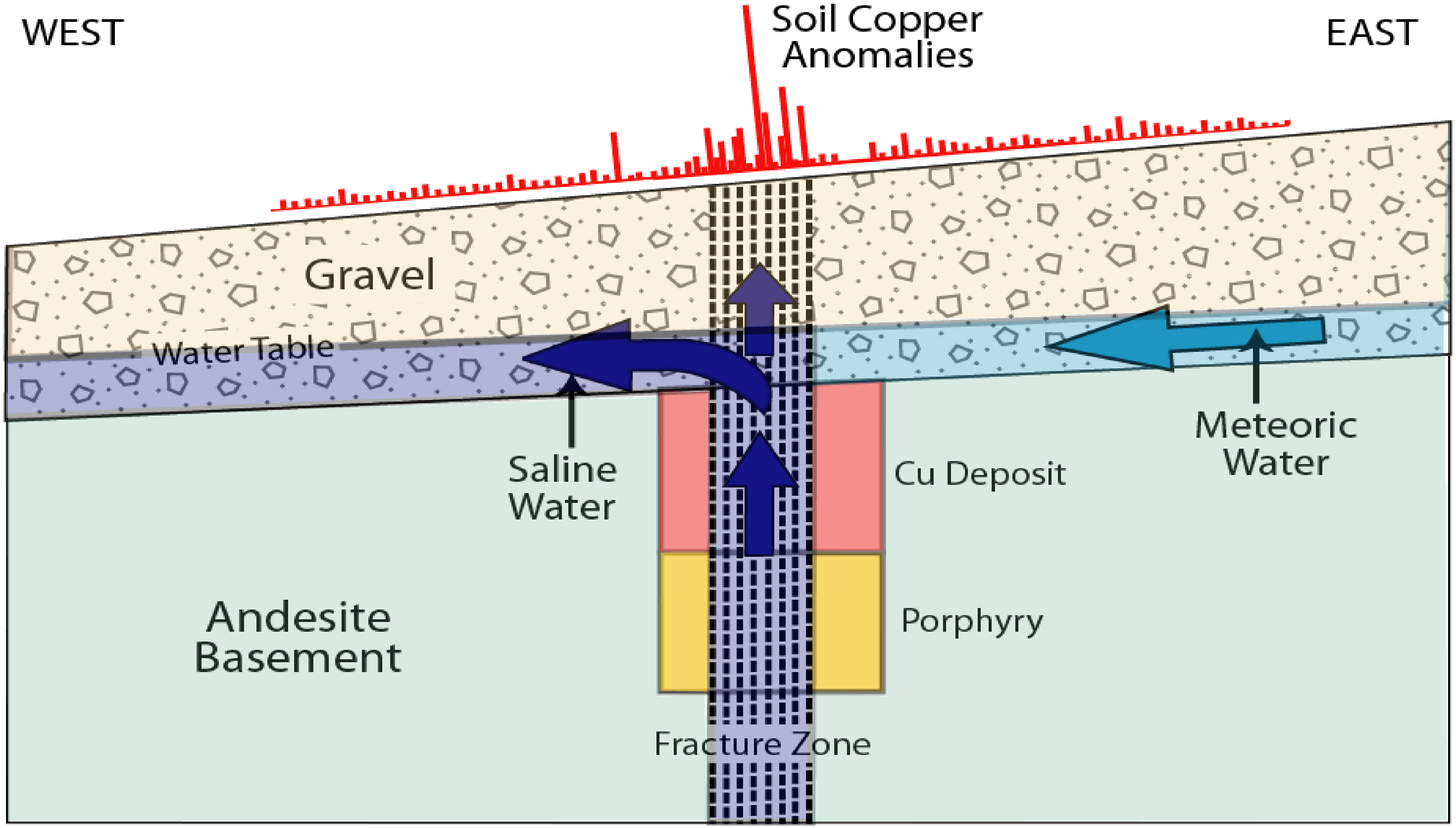


Dispersion mechanisms?

Dispersion timing?

Data from Lawrance, 1999

Dispersion models – dilatancy pumping

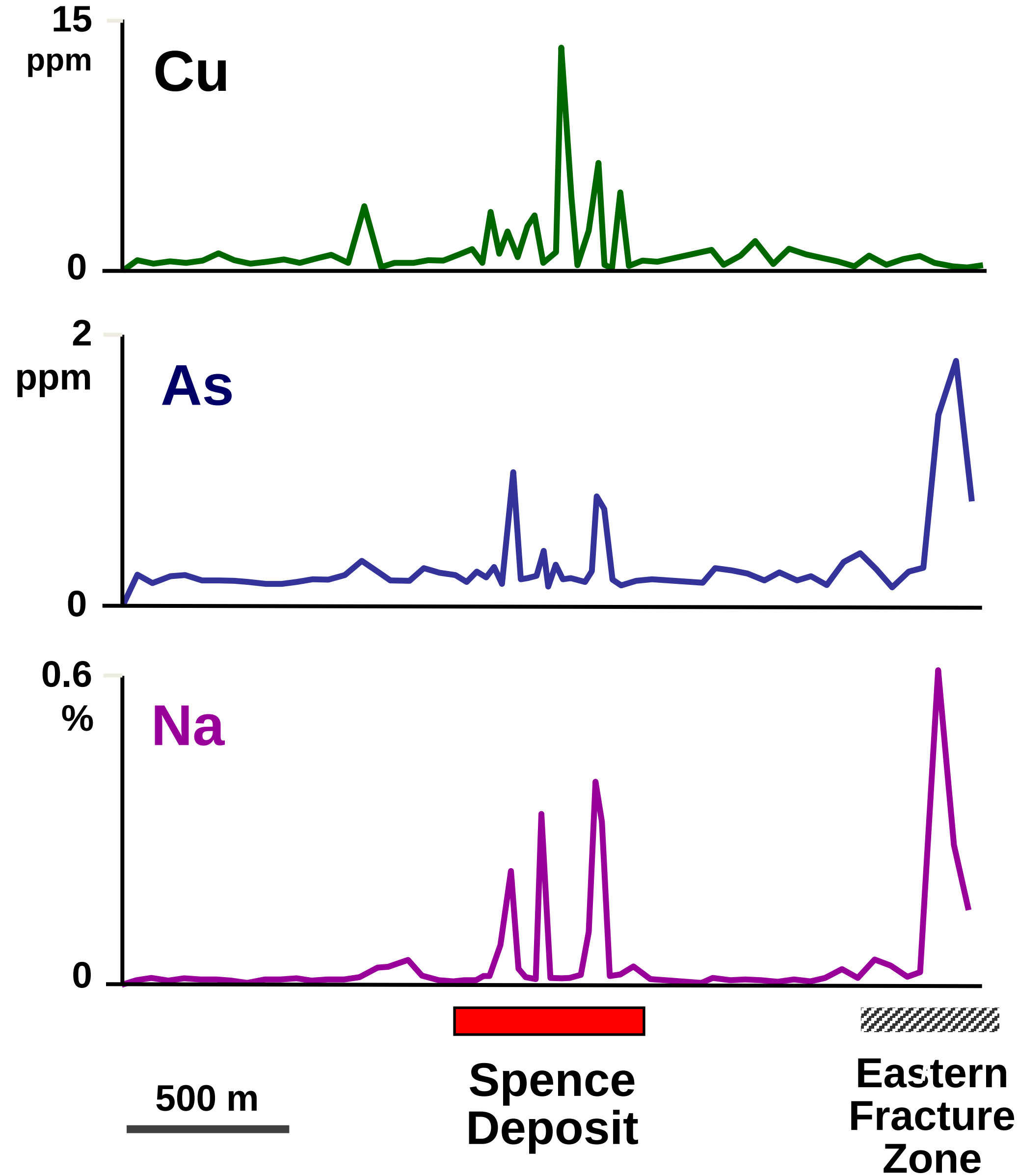


Cameron et al., 2004

Spence porphyry Cu deposit, Northern Chile

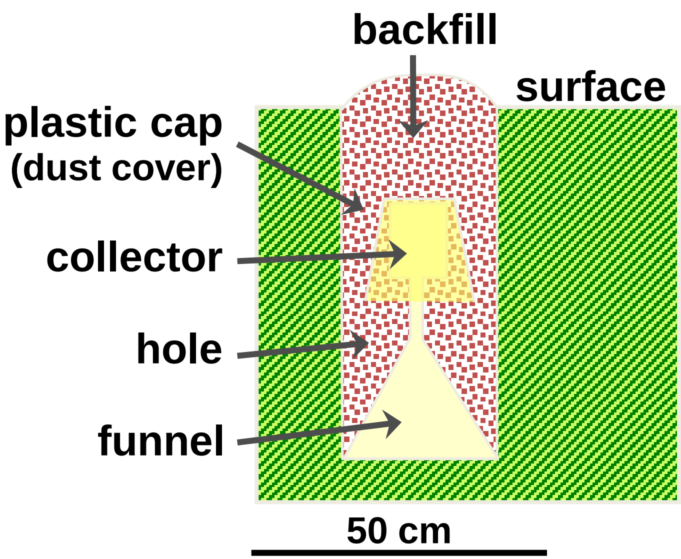
Burial under 250m of Tertiary gravels

Surface regolith samples; weak selective extraction

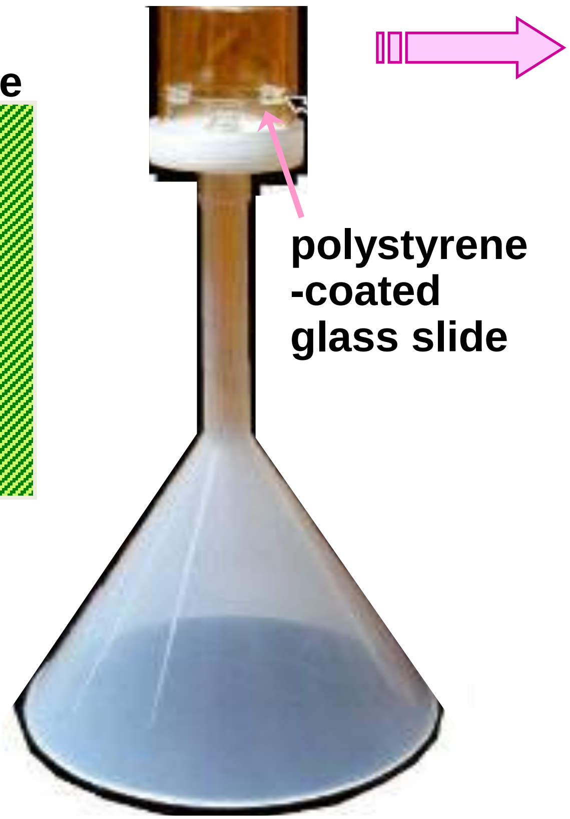


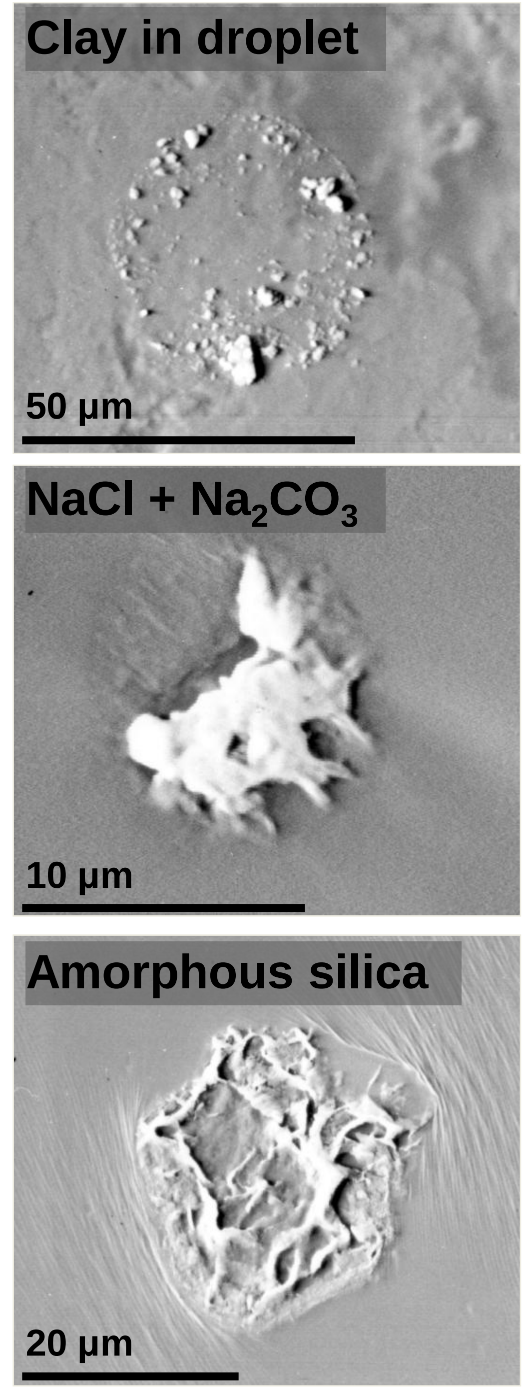
Dispersion models – gases and aerosols

Deployment arrangement



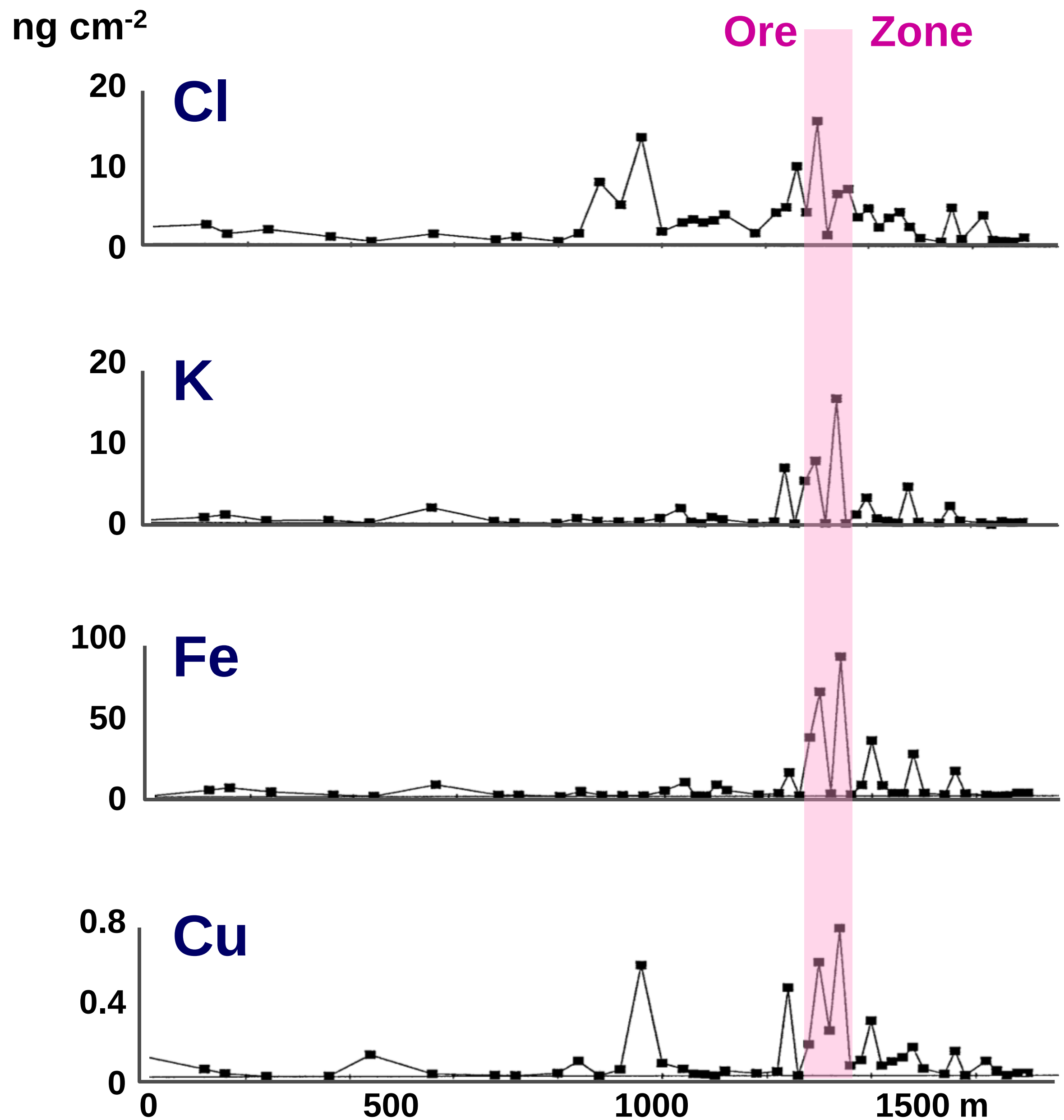
Collector assembly





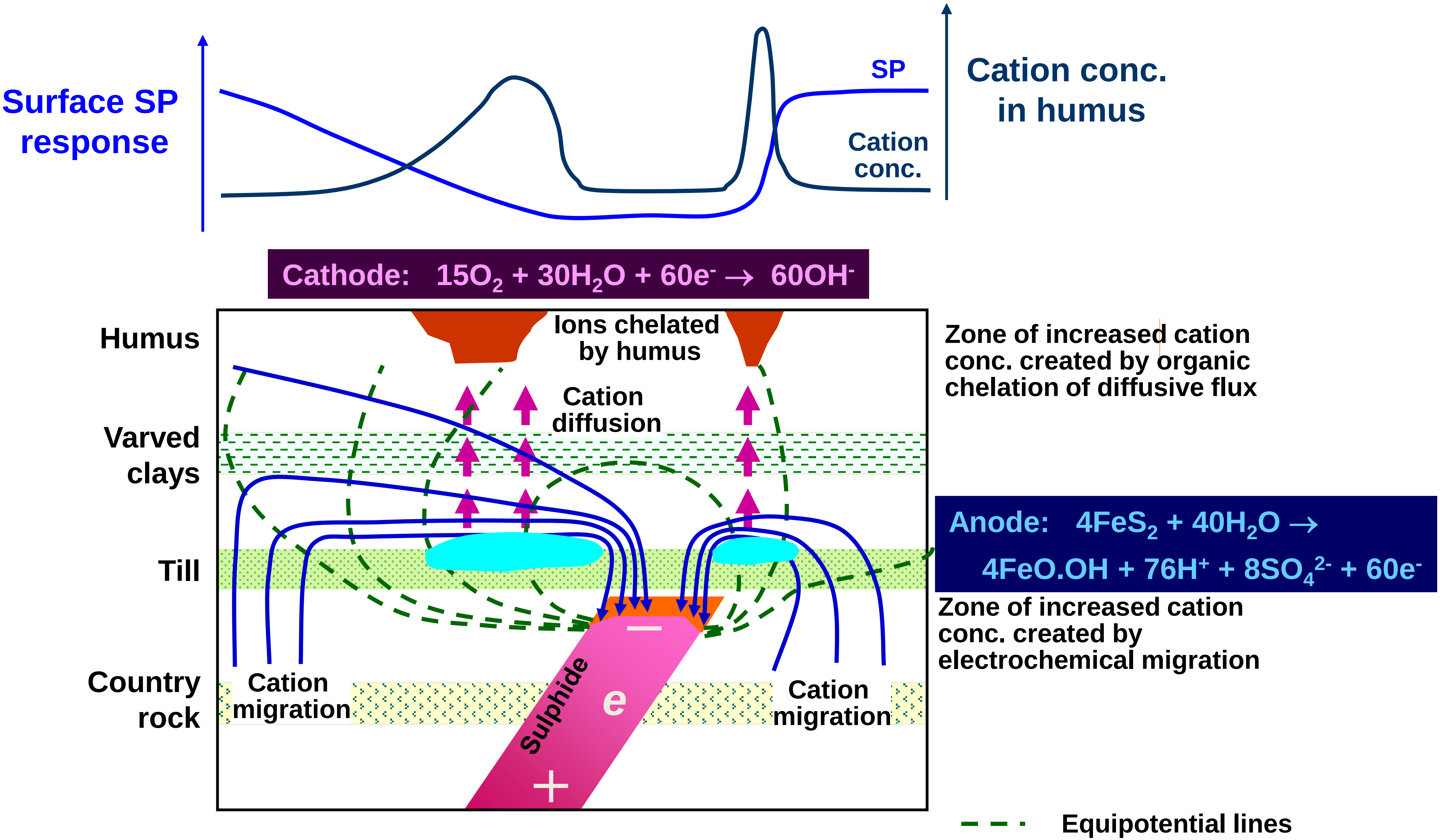
Rutherford et al., (2005)

Osborne Cu-Au deposit, Qld

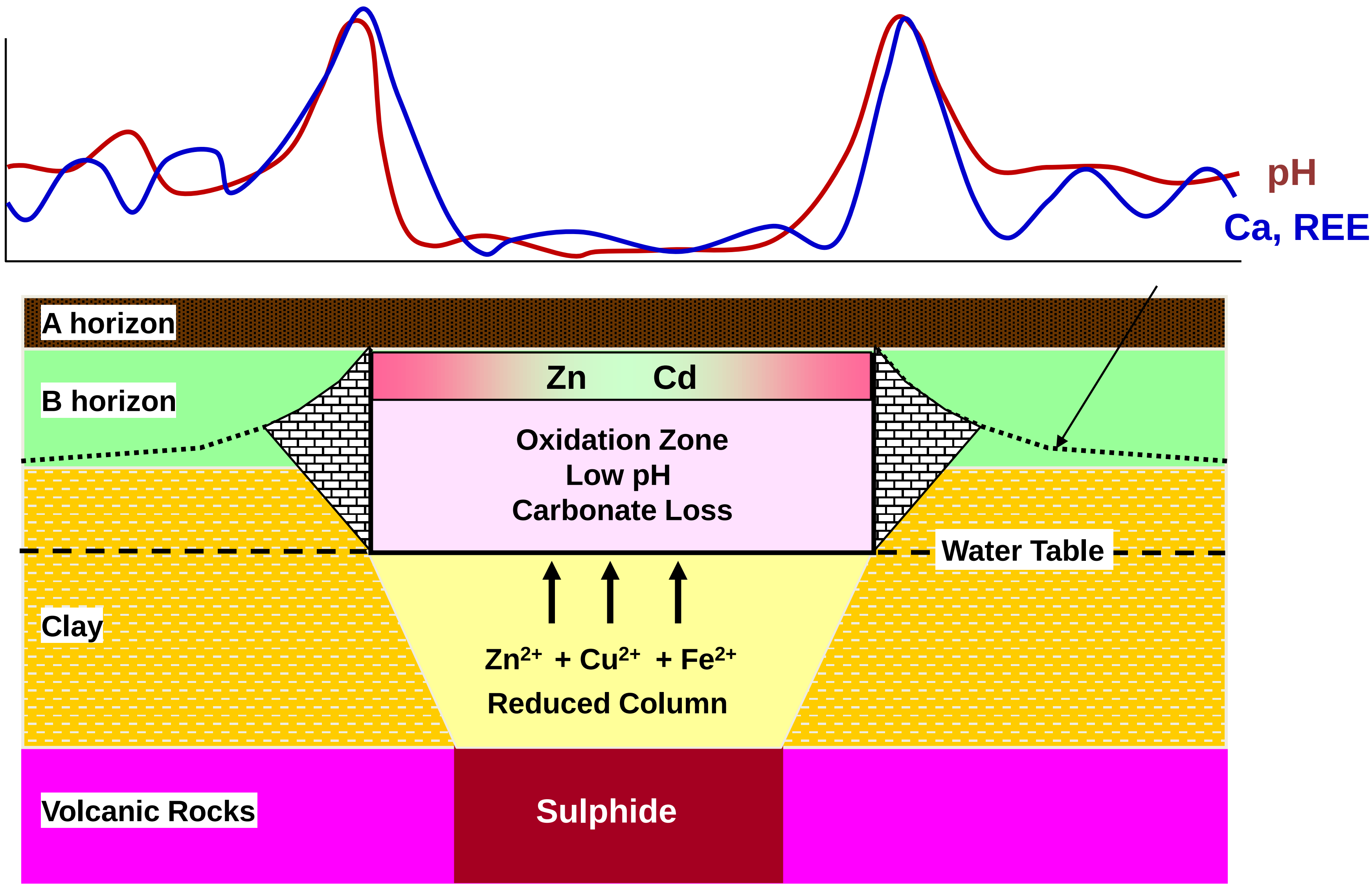


Plus a range of other transition and group I and group II elements

Dispersion models – electrochemical

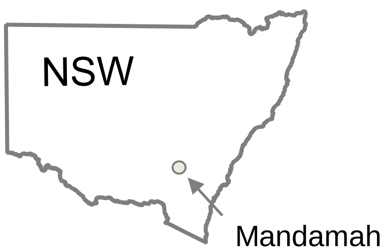


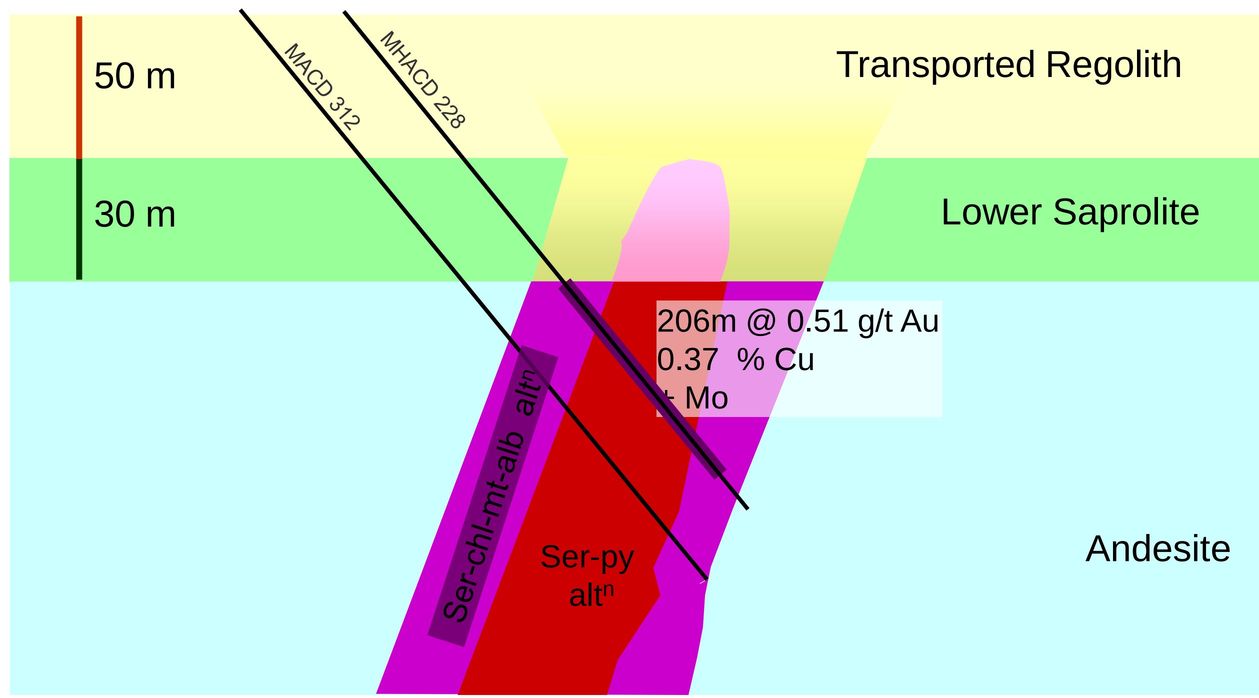
Govett, 1977
Smee, 1983

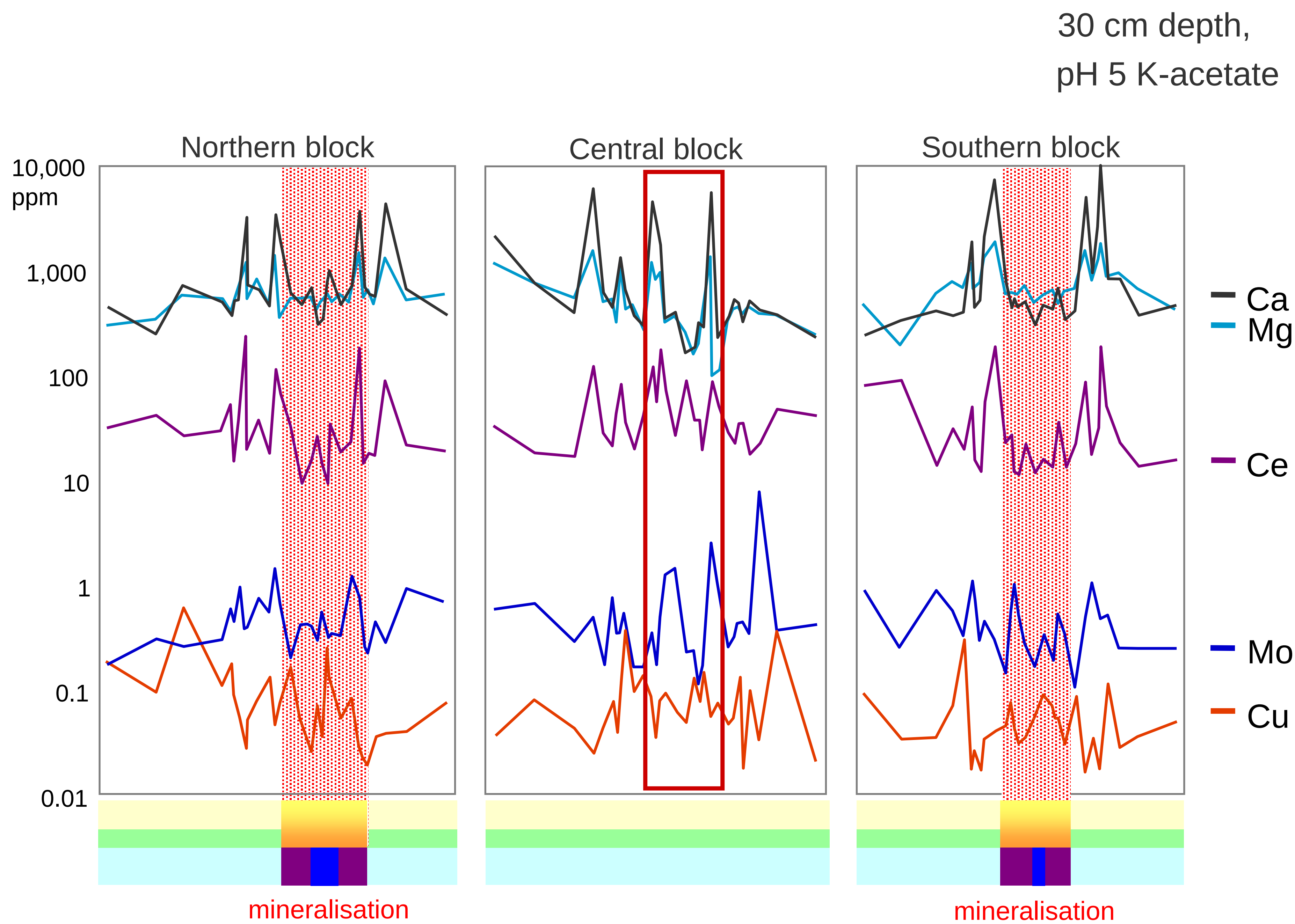


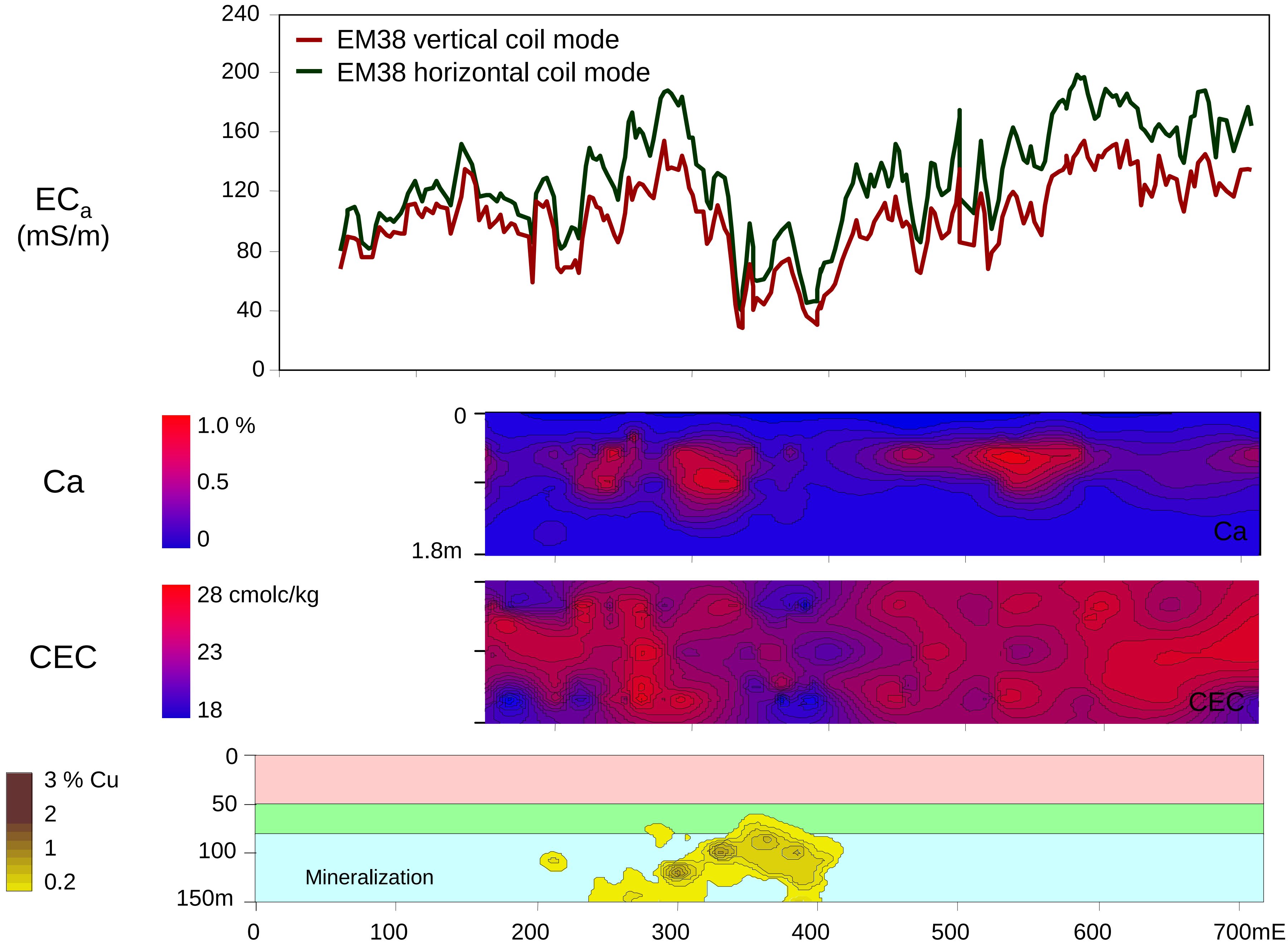
Hamilton, 1998

Mandamah, NSW



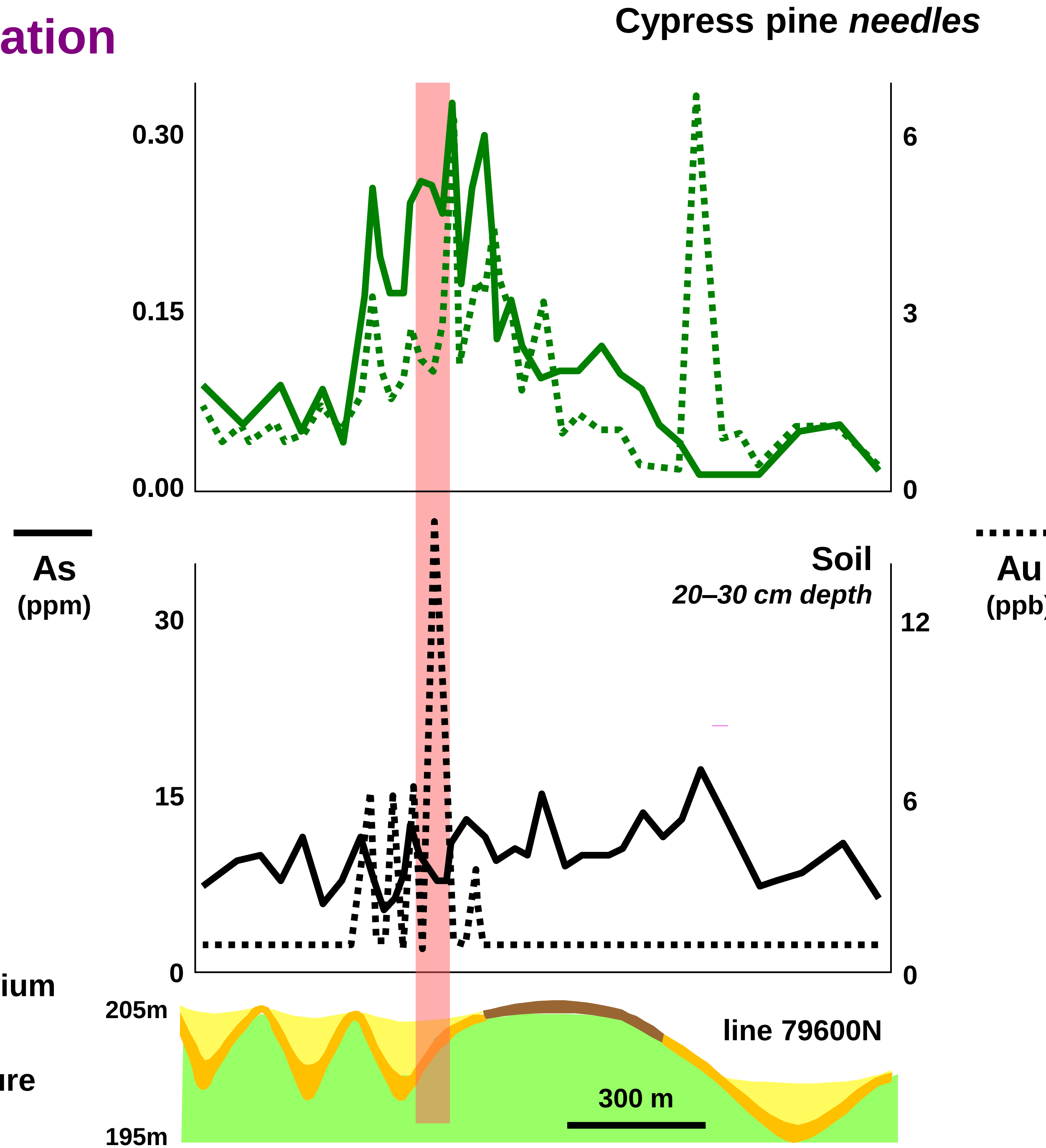



30 cm depth,
pH 5 K-acetate
Northern block
Central block
Southern block
10,000 ppm
1,000
100
10
1
0.1
0.01
Ca
Mg
Ce
Mo
Cu
mineralisation
mineralisation


EM38 vertical coil mode
EM38 horizontal coil mode
EC_a (mS/m)
240
200
160
120
80
40
0
Ca
1.0 %
0.5
0
0
1.8m
Ca
CEC
28 cmolc/kg
23
18
CEC
3 % Cu
2
1
0.2
0
50
100
150m
Mineralization
0
100
200
300
400
500
600
700mE

Dispersion models - vegetation

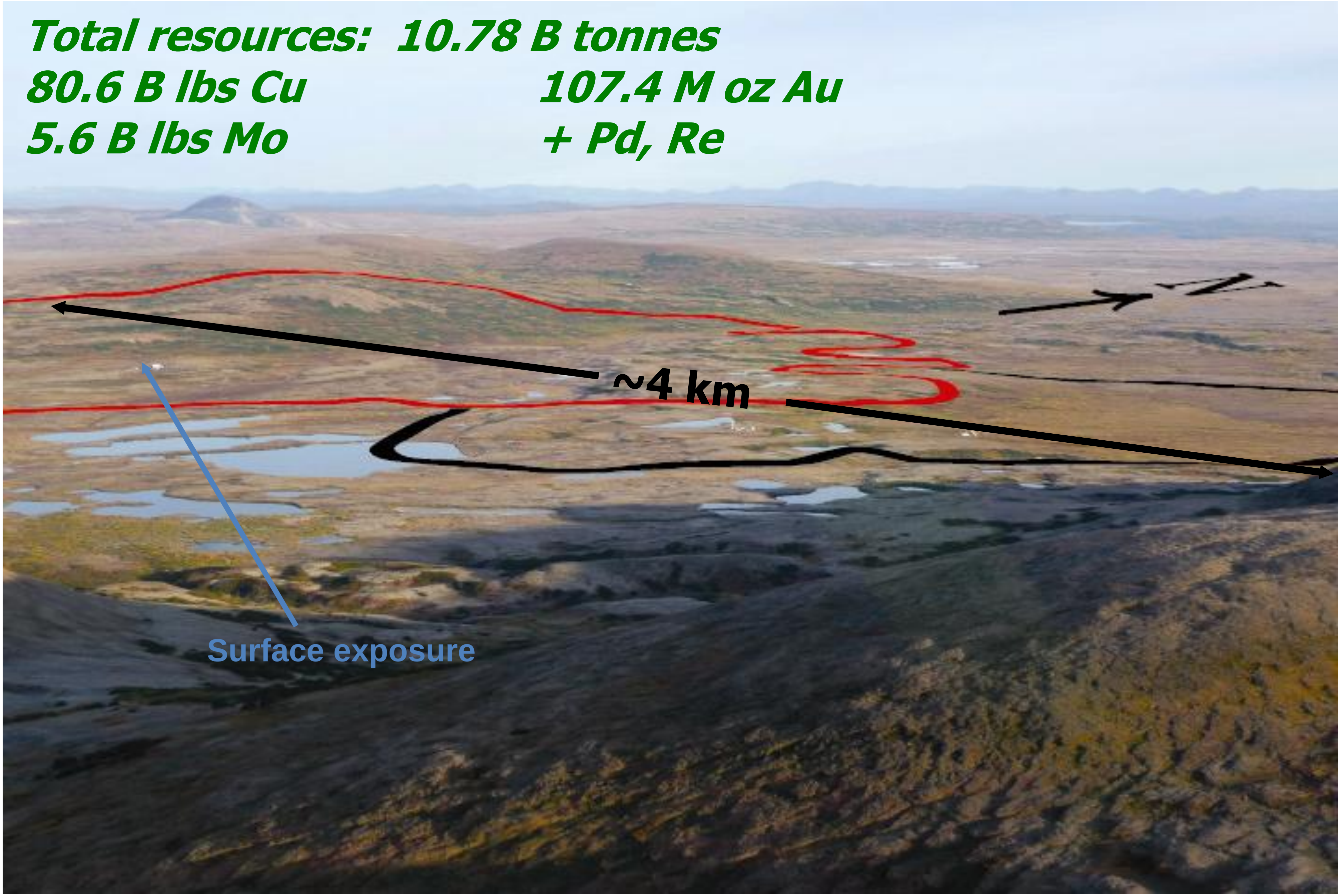
McKinnons deposit, Cobar
- Alluvial fill
- Pediment
- Mixed pediment / alluvium
- Saprolite
- Au mineralised structure



Cohen et al, 1996

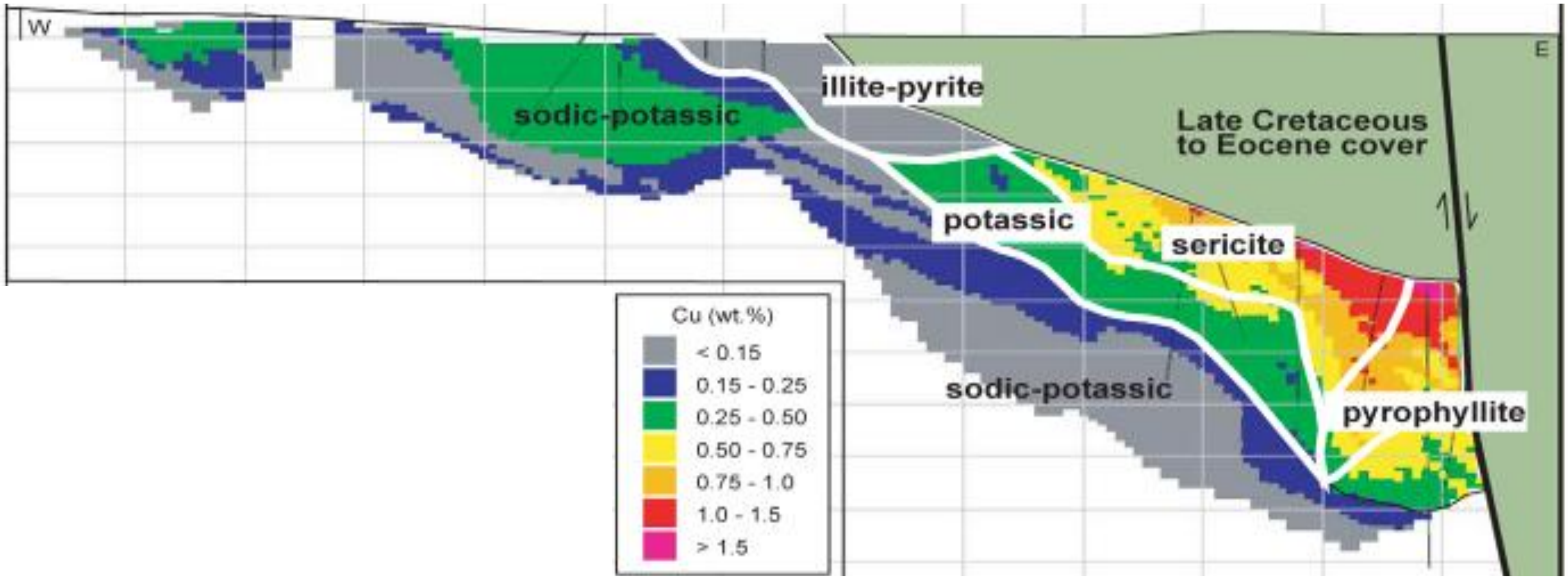
Case study at Pebble, Alaska

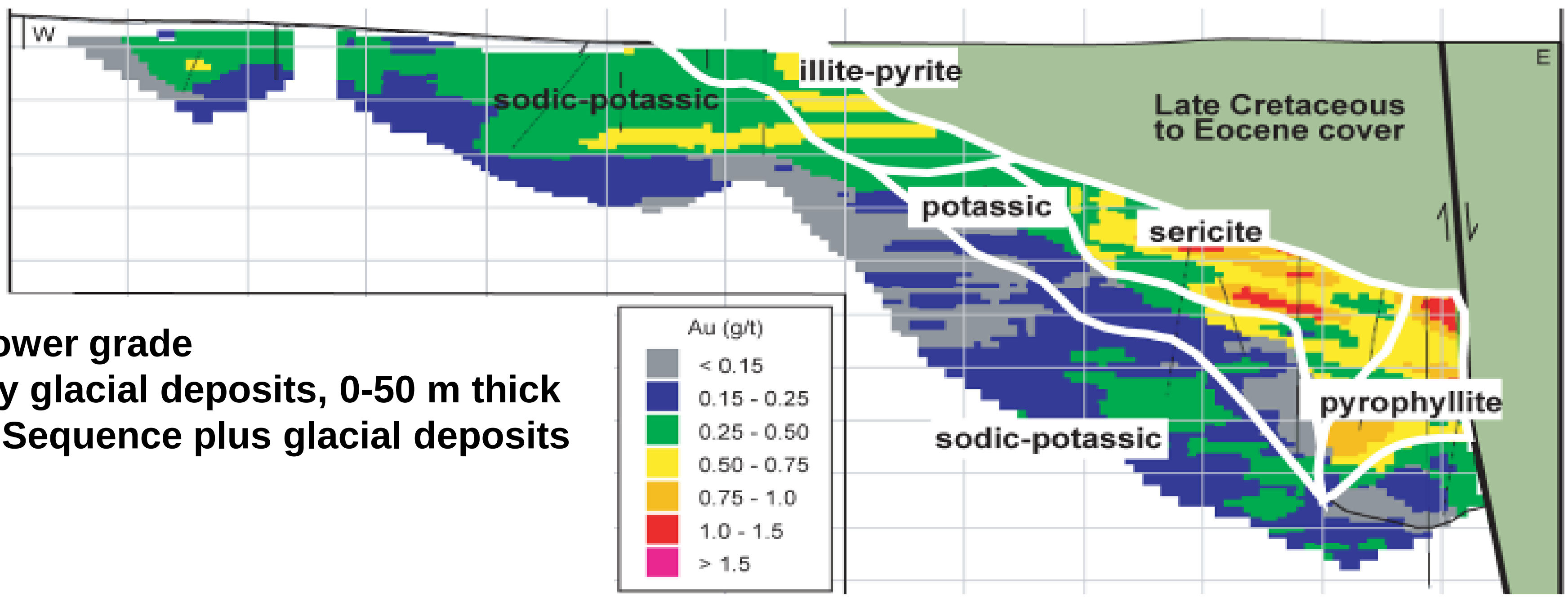
From Eppinger and Kelley, 2012



From Eppinger and Kelley, 2012

Grade Distribution

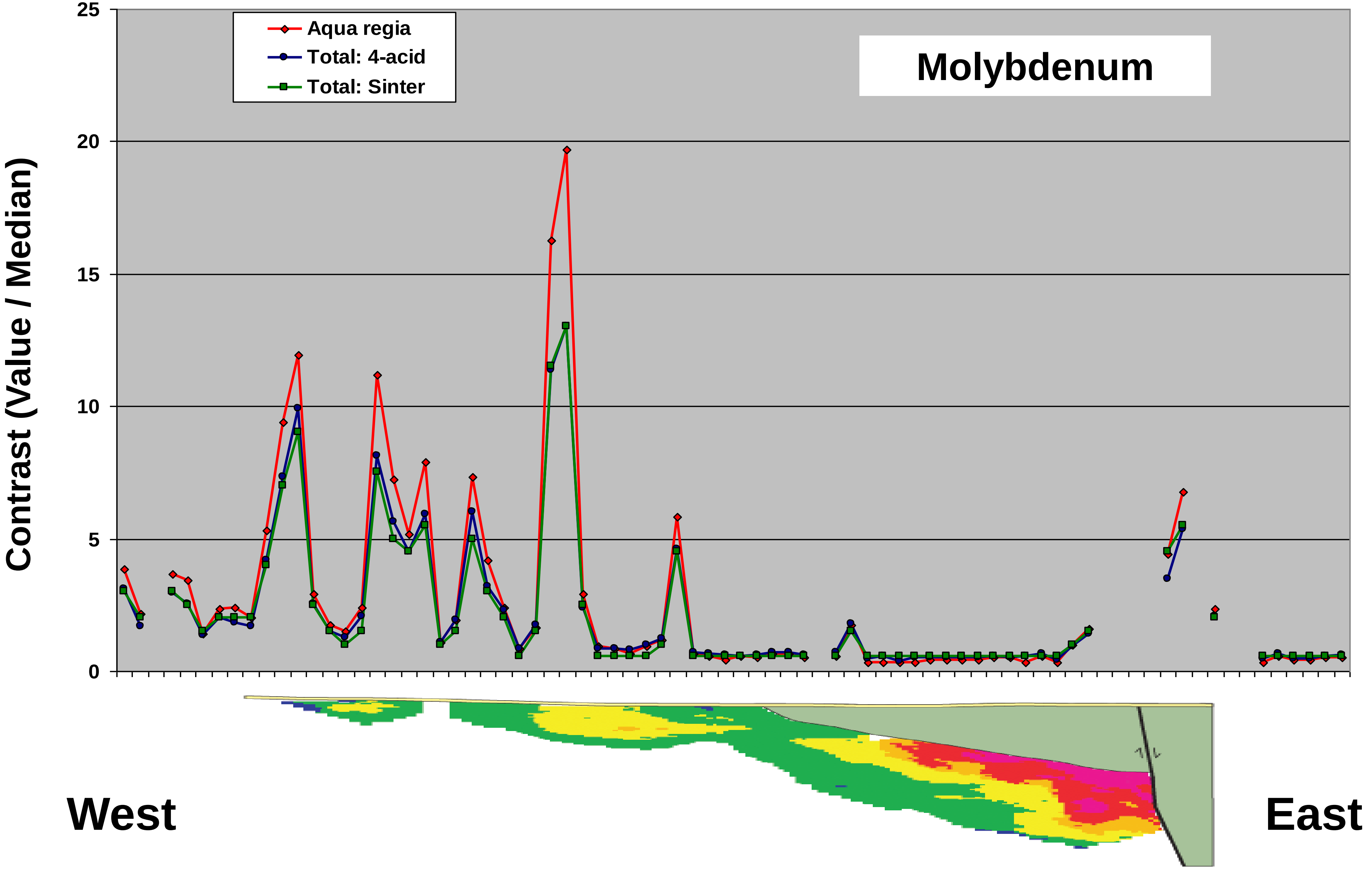




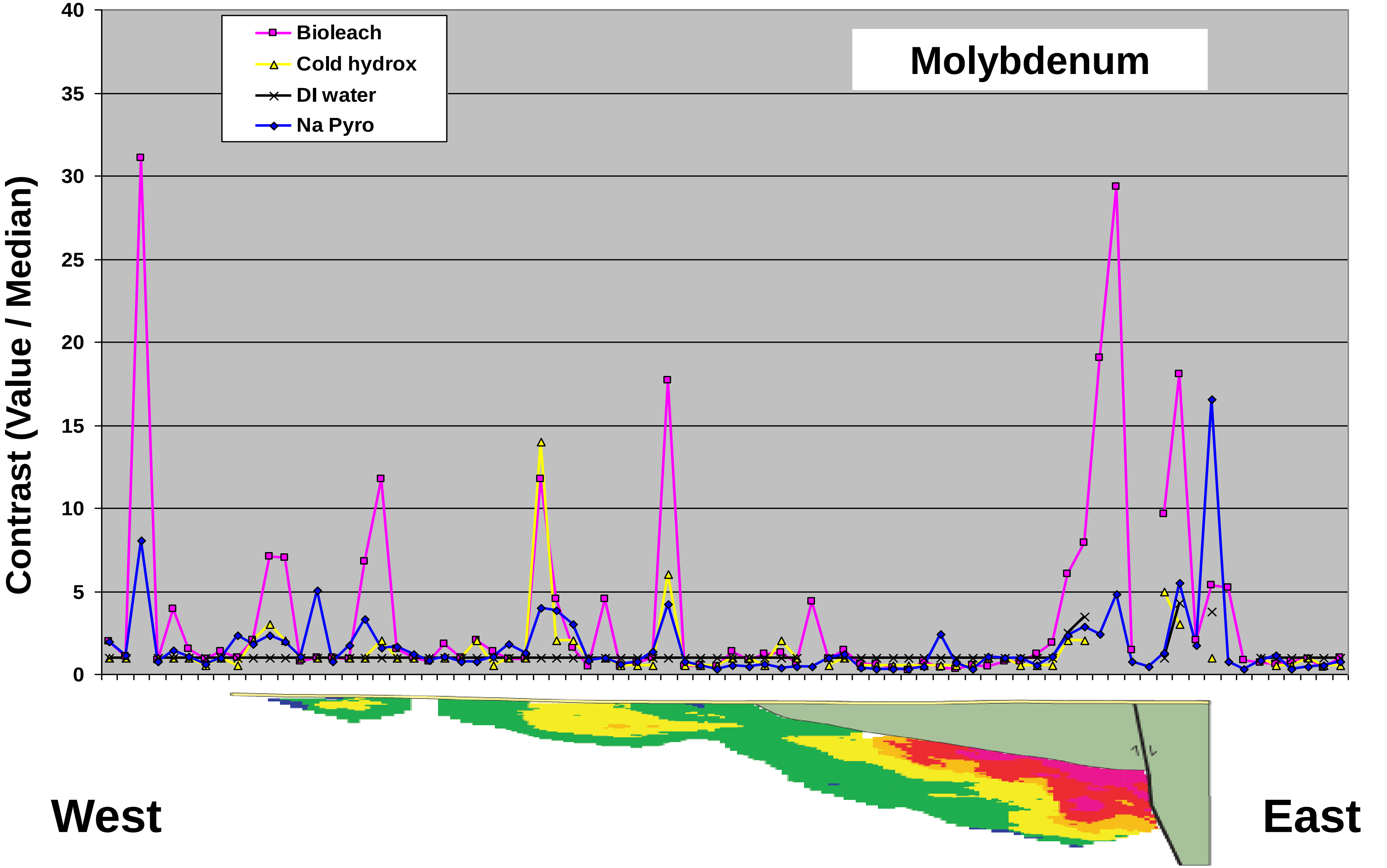
PW shallow, lower grade
PW covered by glacial deposits, 0-50 m thick
PE has Cover Sequence plus glacial deposits

From Eppinger an

After Gregory et al, 2012

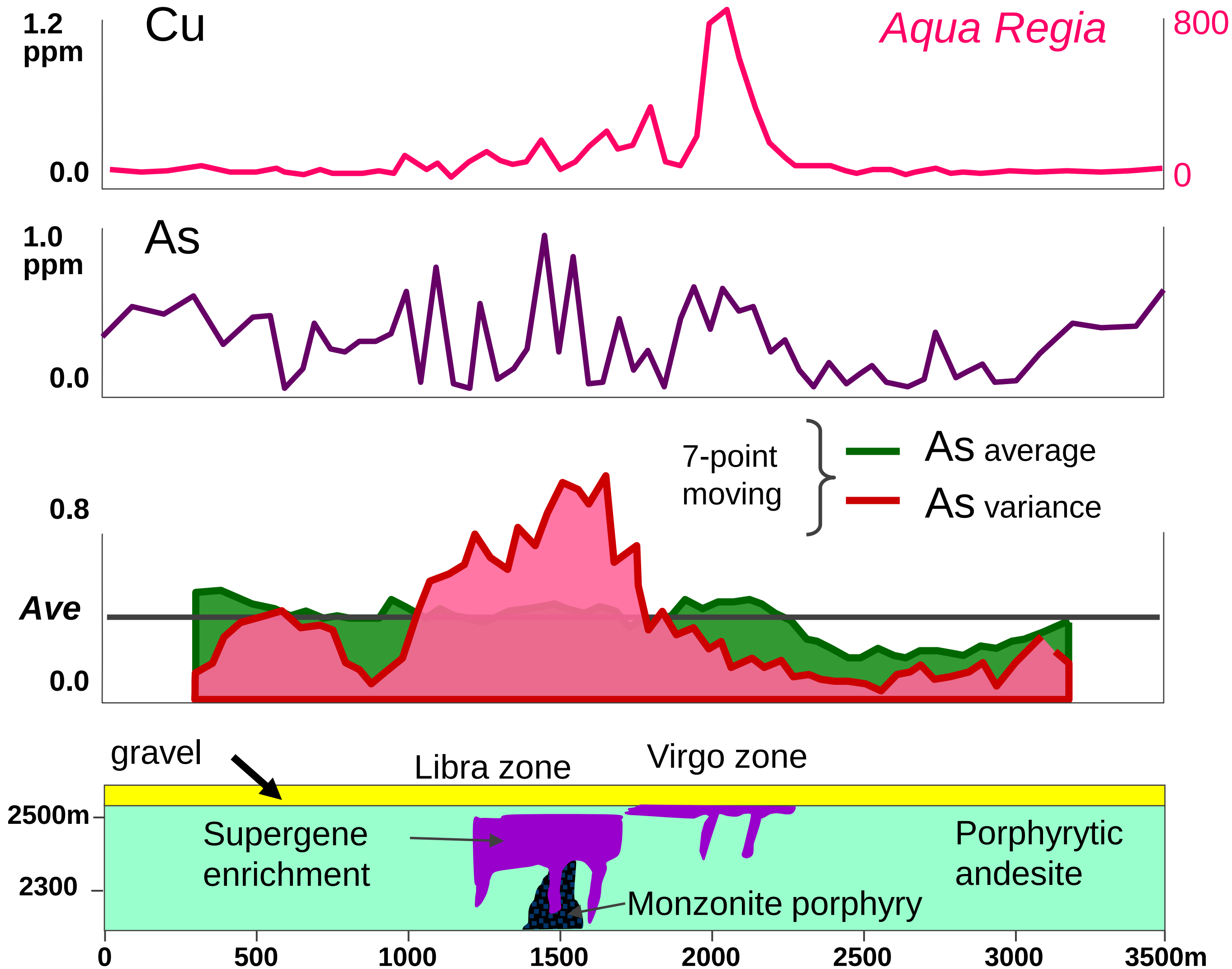


From Eppinger and Kelley, 2012



From Eppinger and Kelley, 2012

Chimborazo porphyry Cu, Chile

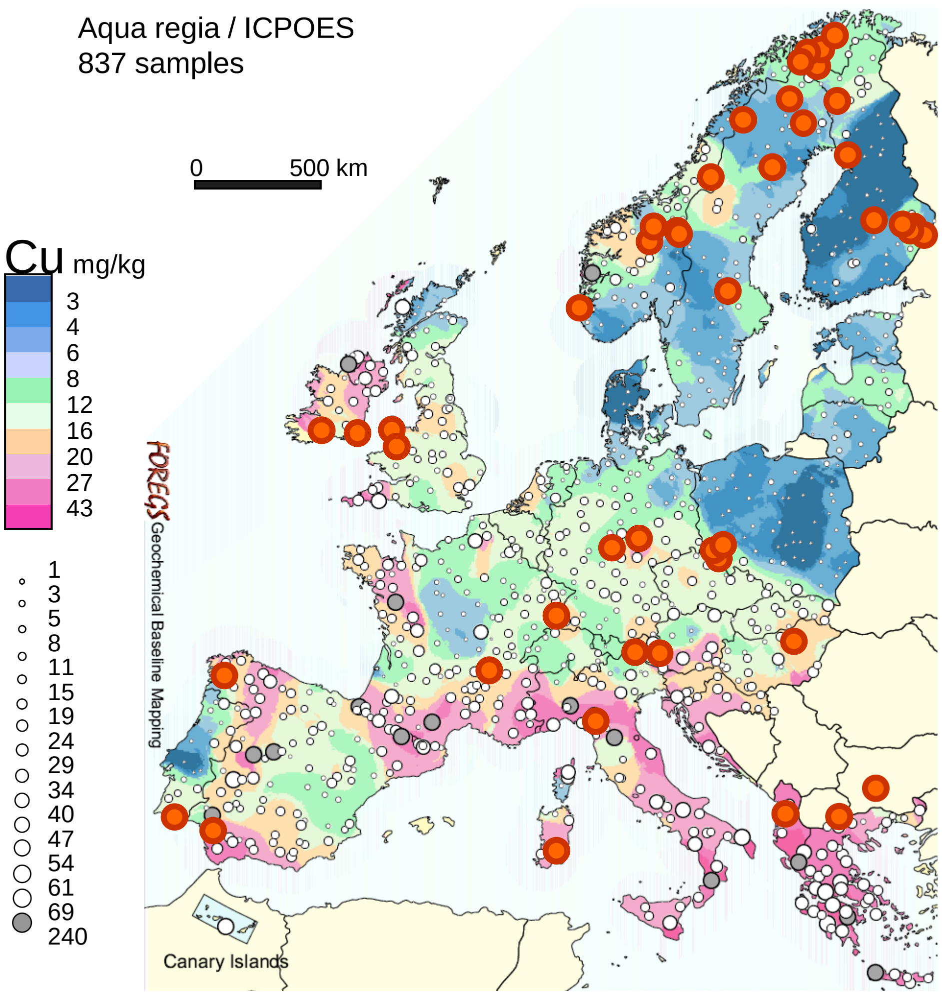


Regional Geochemical Mapping

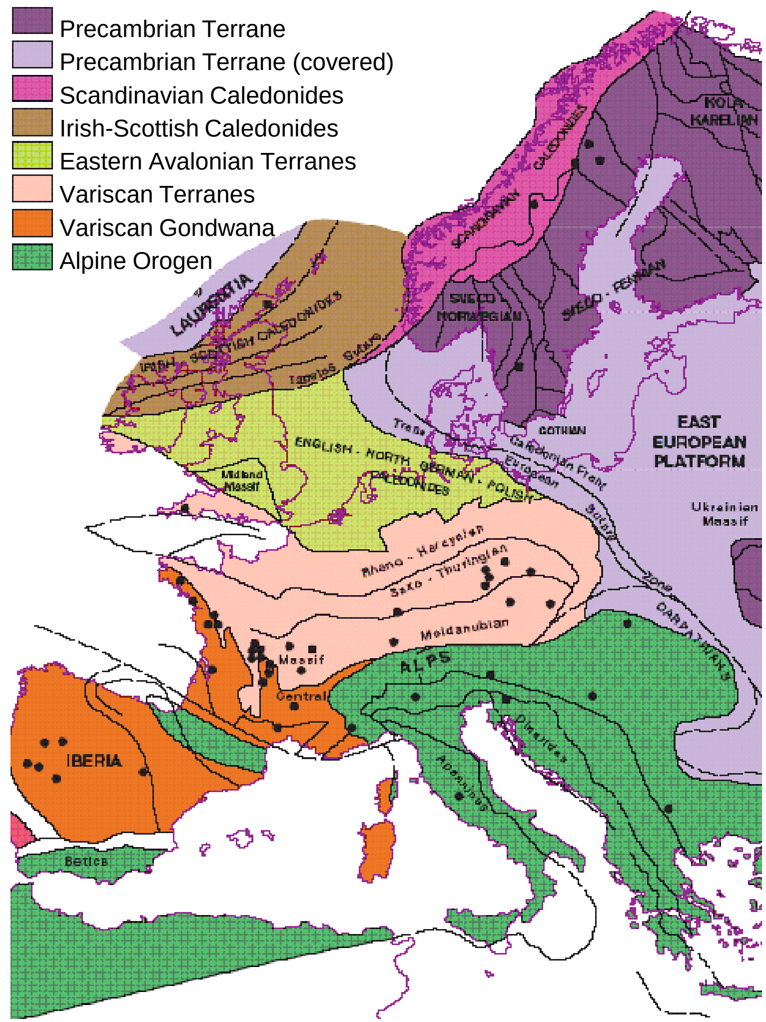
FOREGS
Geochemical Atlas of Europe
1 sample per 3,000 km^2

Copper in Topsoil

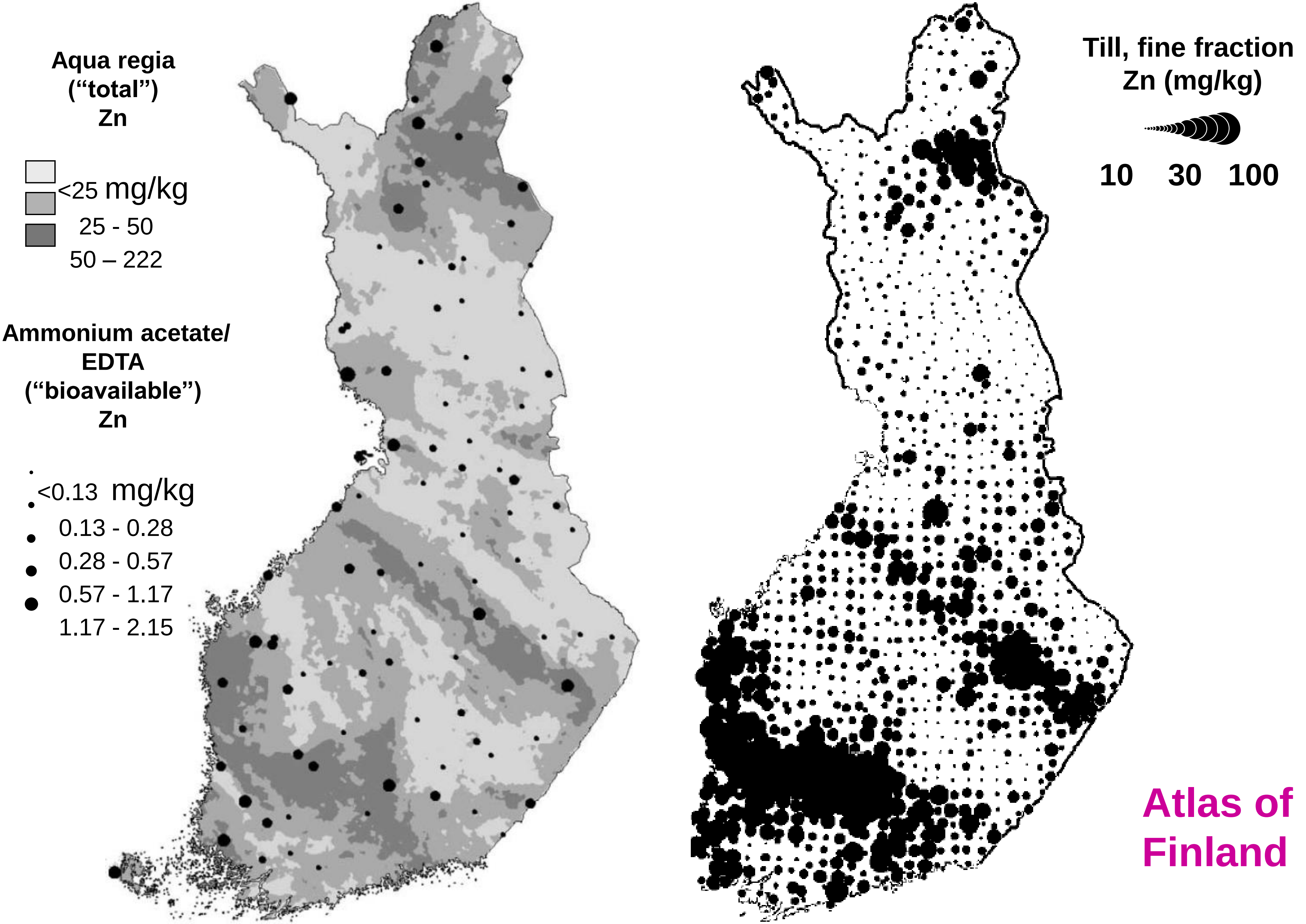
Aqua regia / ICPOES
837 samples

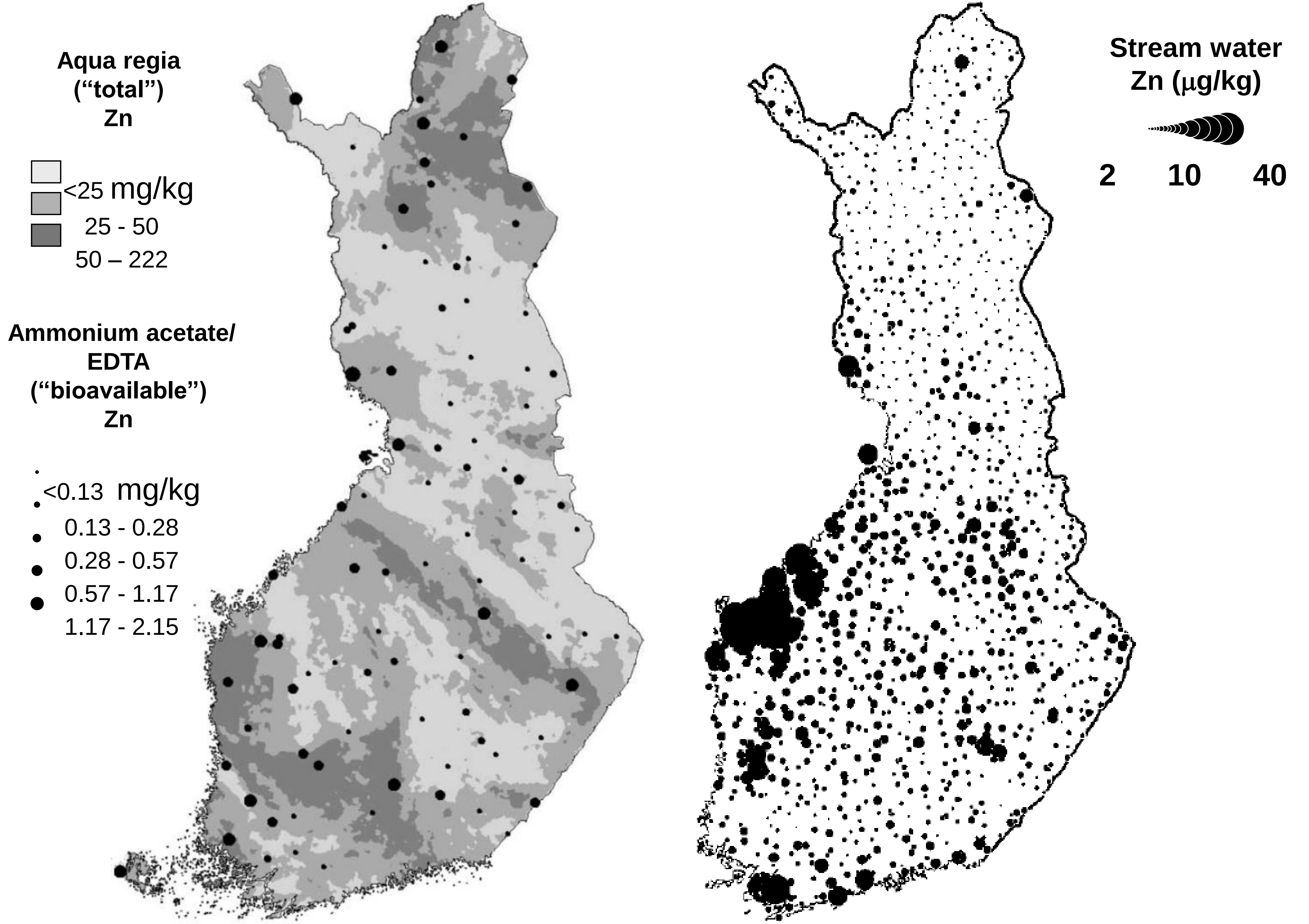


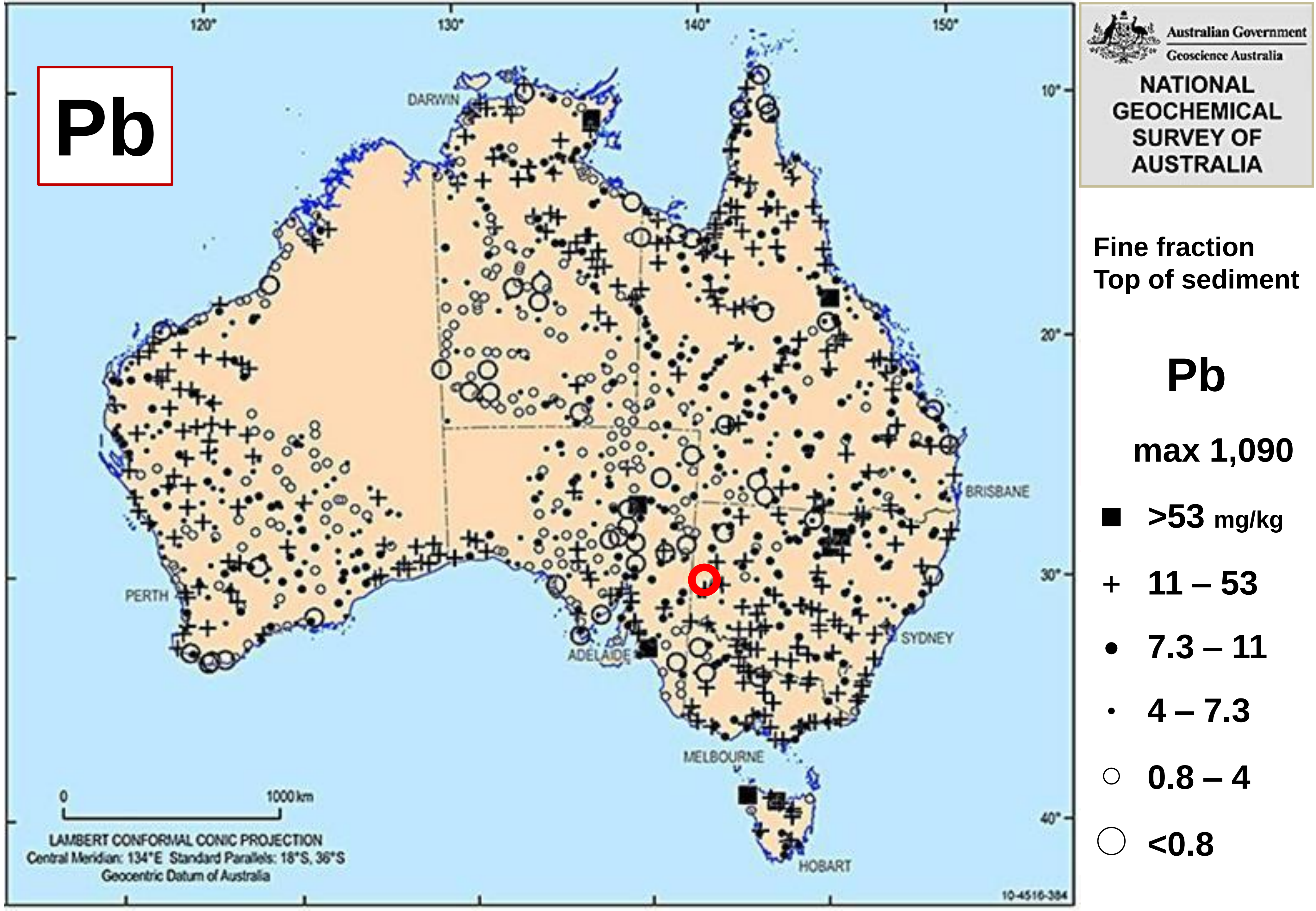
Major Cu deposits

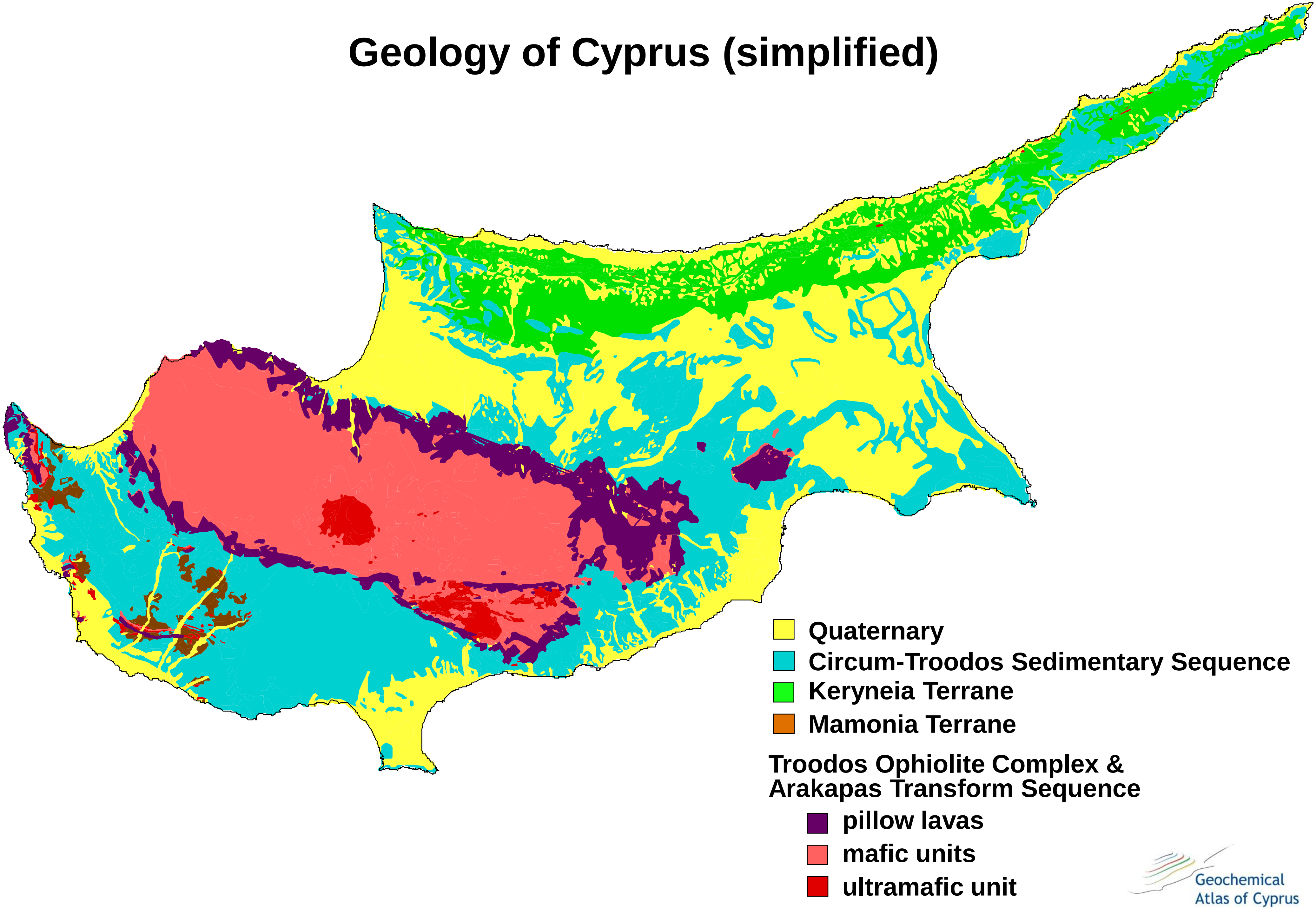


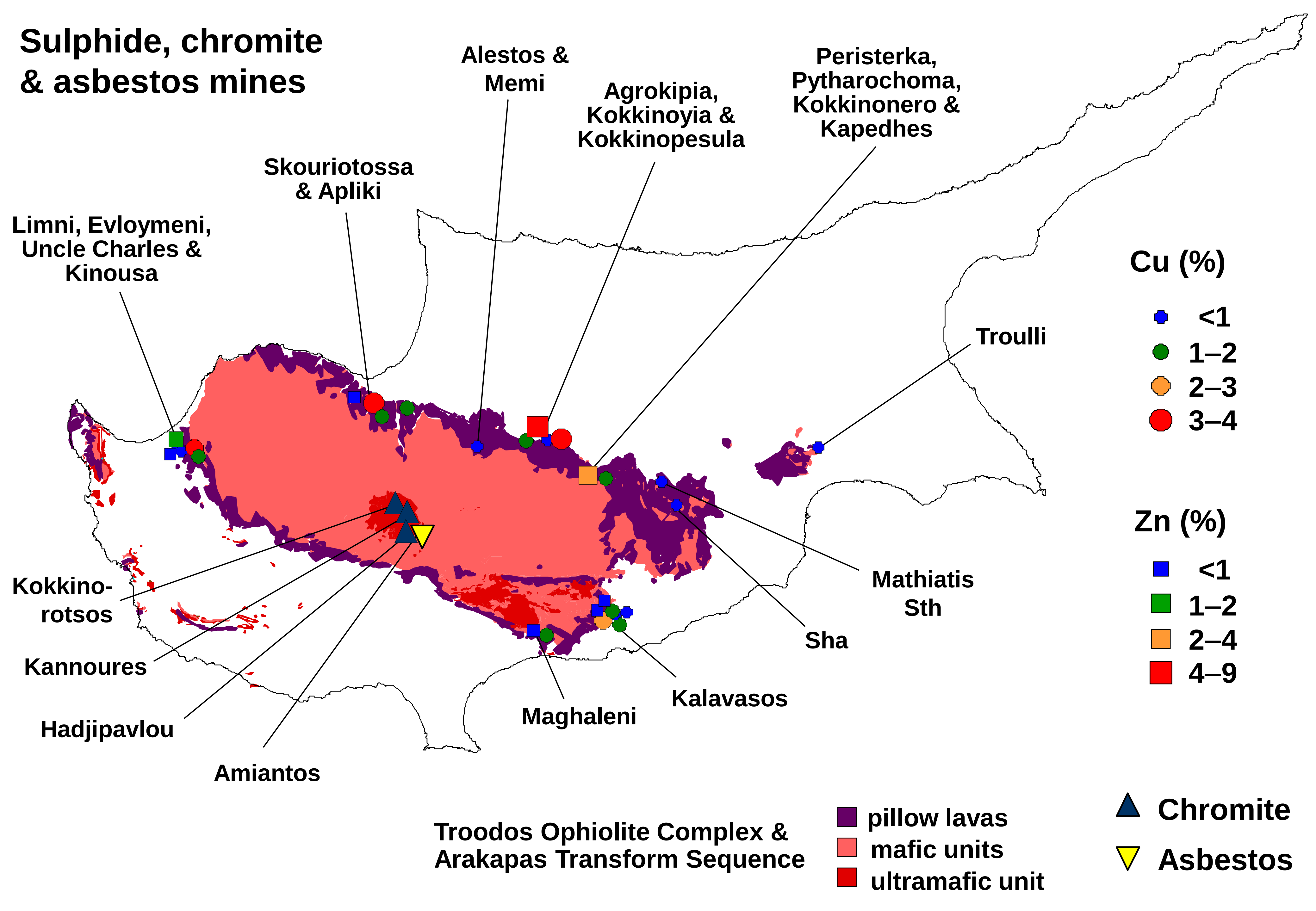
Modified from www.gtk.fi/publ/foregsatlas/ and Plant et al. (2007)

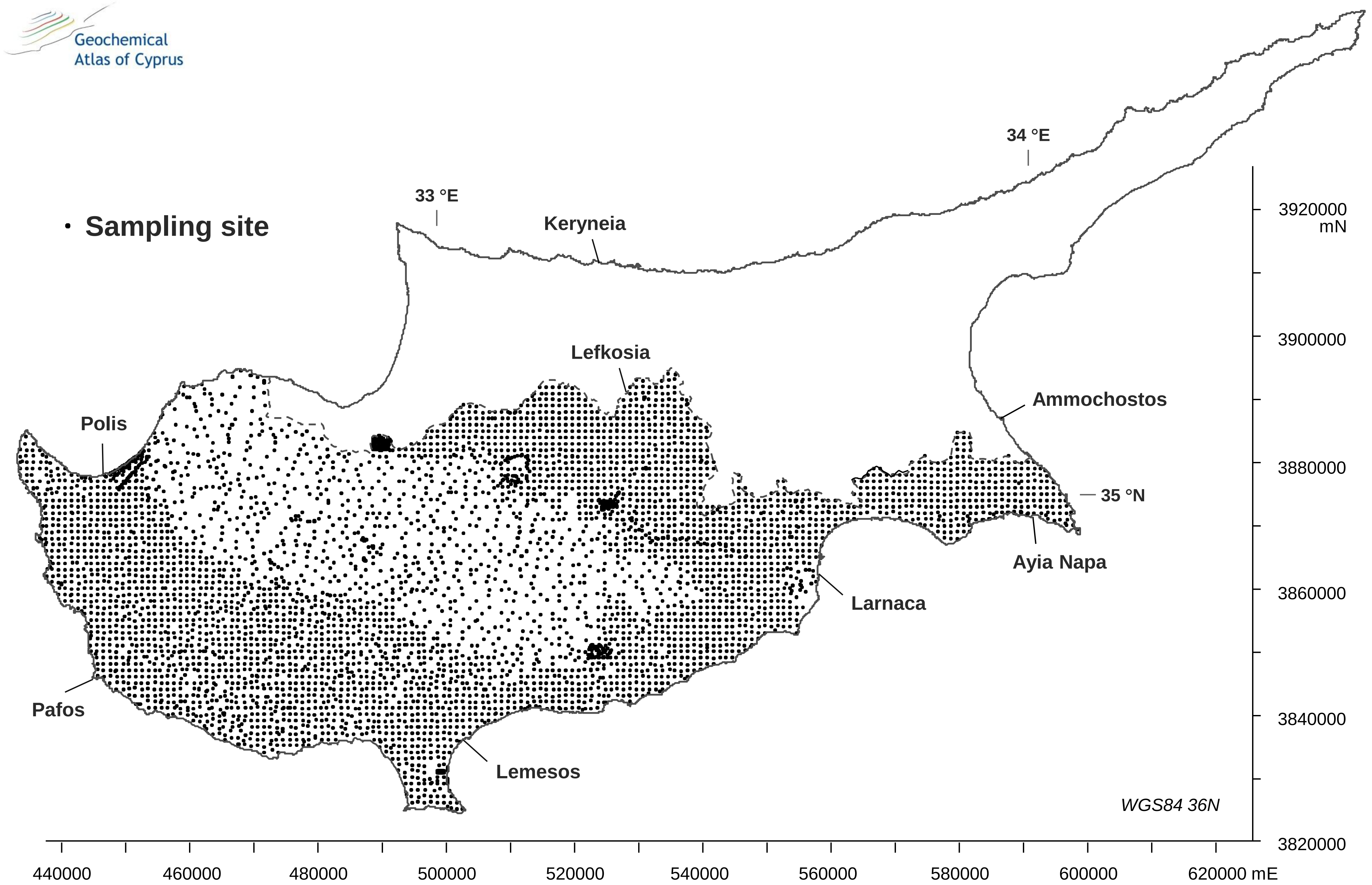

Aqua regia
("total")
Zn
<25 mg/kg
25 - 50
50 – 222
Ammonium acetate/
EDTA
("bioavailable")
Zn
<0.13 mg/kg
0.13 - 0.28
0.28 - 0.57
0.57 - 1.17
1.17 - 2.15
Till, fine fraction
Zn (mg/kg)
10 30 100
Atlas of
Finland

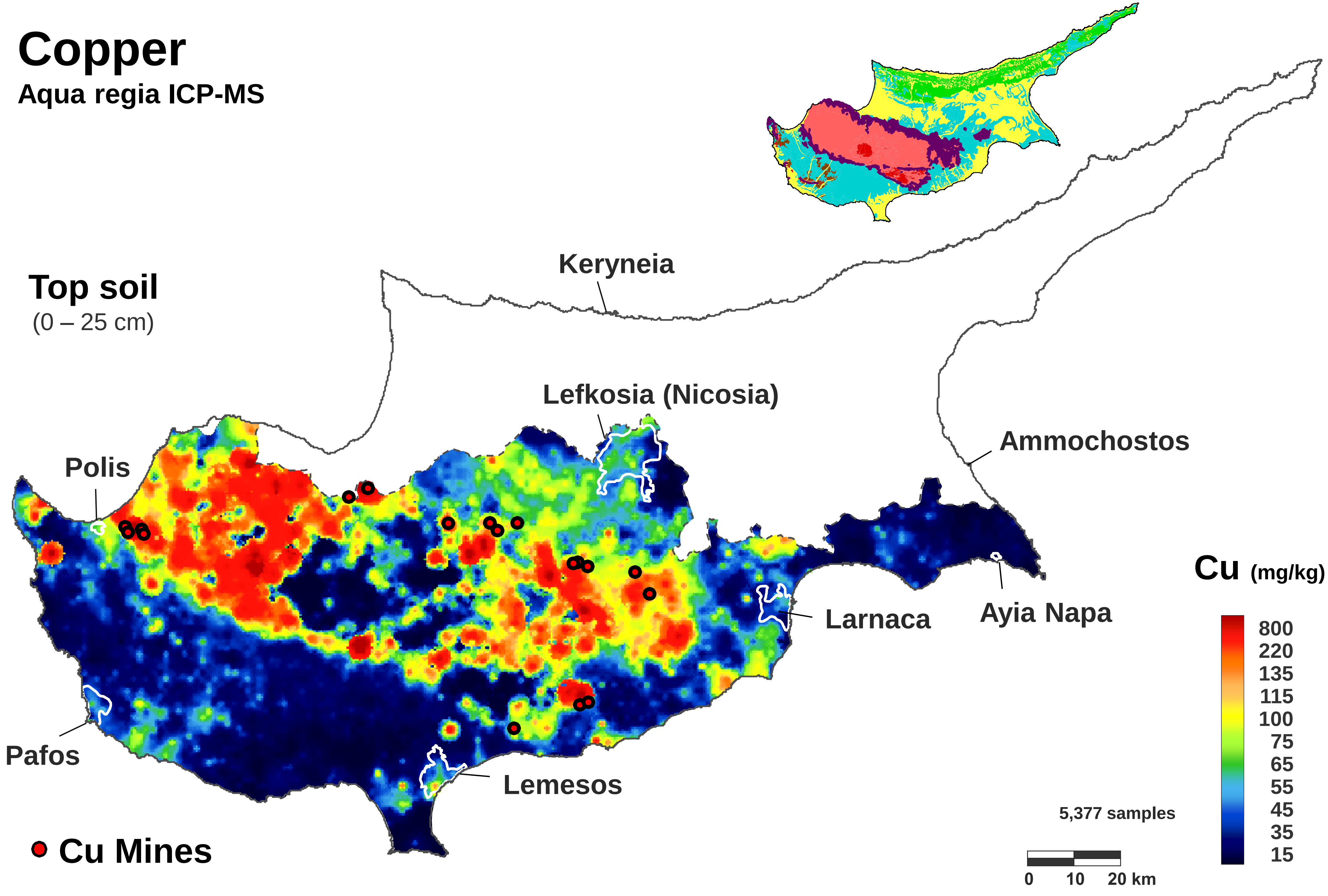

Aqua regia
("total")
Zn
<25 mg/kg
25 - 50
50 – 222
Ammonium acetate/
EDTA
("bioavailable")
Zn
<0.13 mg/kg
0.13 - 0.28
0.28 - 0.57
0.57 - 1.17
1.17 - 2.15
Stream water
Zn (μg/kg)
2
10
40

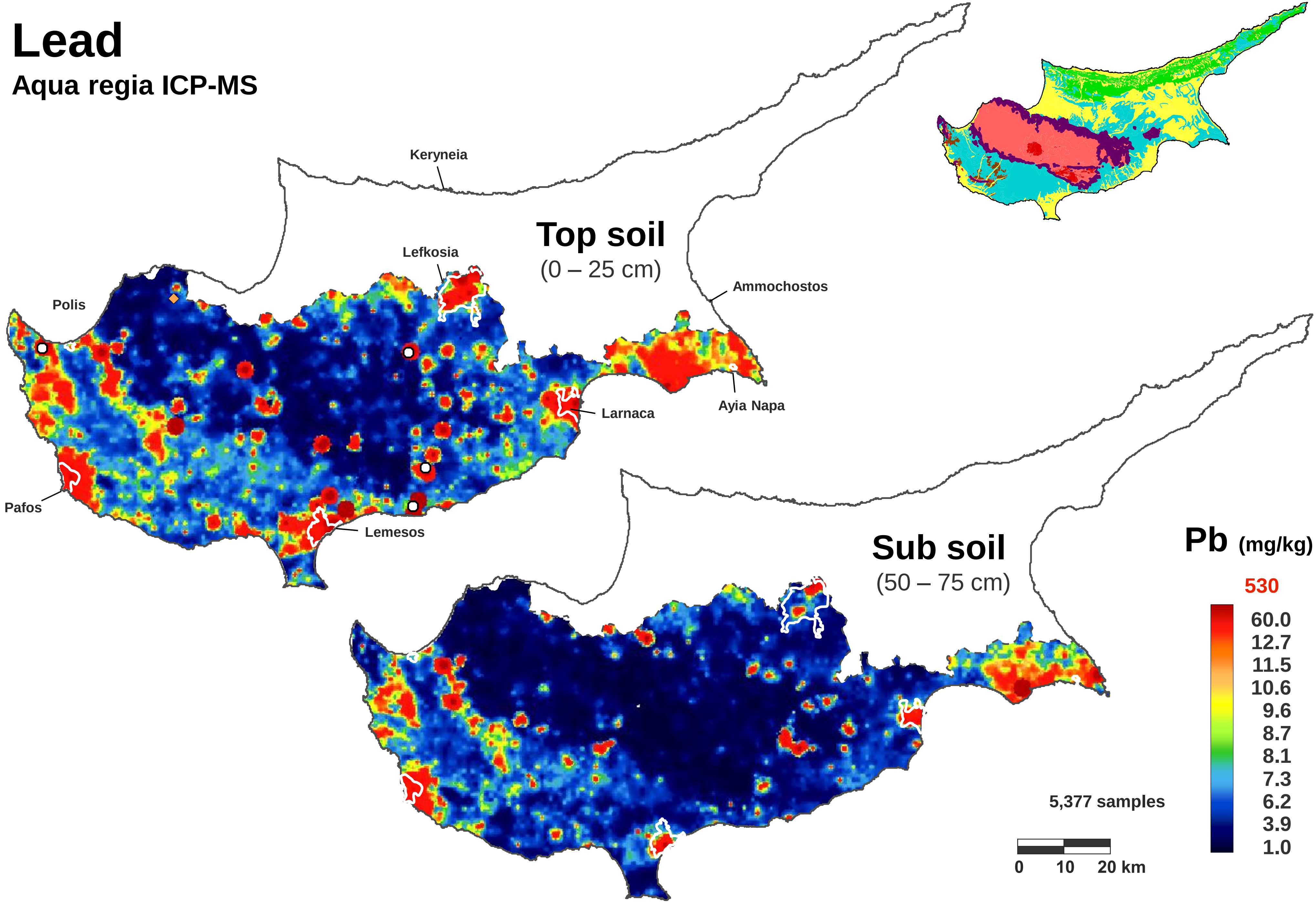

Pb
120°
130°
140°
150°
10°
20°
30°
40°
DARWIN
PERTH
ADELAIDE
MELBOURNE
SYDNEY
BRISBANE
HOBART
0
1000 km
LAMBERT CONFORMAL CONIC PROJECTION
Central Meridian: 134°E Standard Parallels: 18°S, 36°S
Geocentric Datum of Australia
10-4516-384
Australian Government
Geoscience Australia
NATIONAL GEOCHEMICAL SURVEY OF AUSTRALIA
Fine fraction
Top of sediment
Pb
max 1,090
>53 mg/kg
11 – 53
7.3 – 11
4 – 7.3
0.8 – 4
<0.8


Geology of Cyprus (simplified)
Quaternary
Circum-Troodos Sedimentary Sequence
Keryneia Terrane
Mamonia Terrane
Troodos Ophiolite Complex &
Arakapas Transform Sequence
pillow lavas
mafic units
ultramafic unit
Geochemical
Atlas of Cyprus

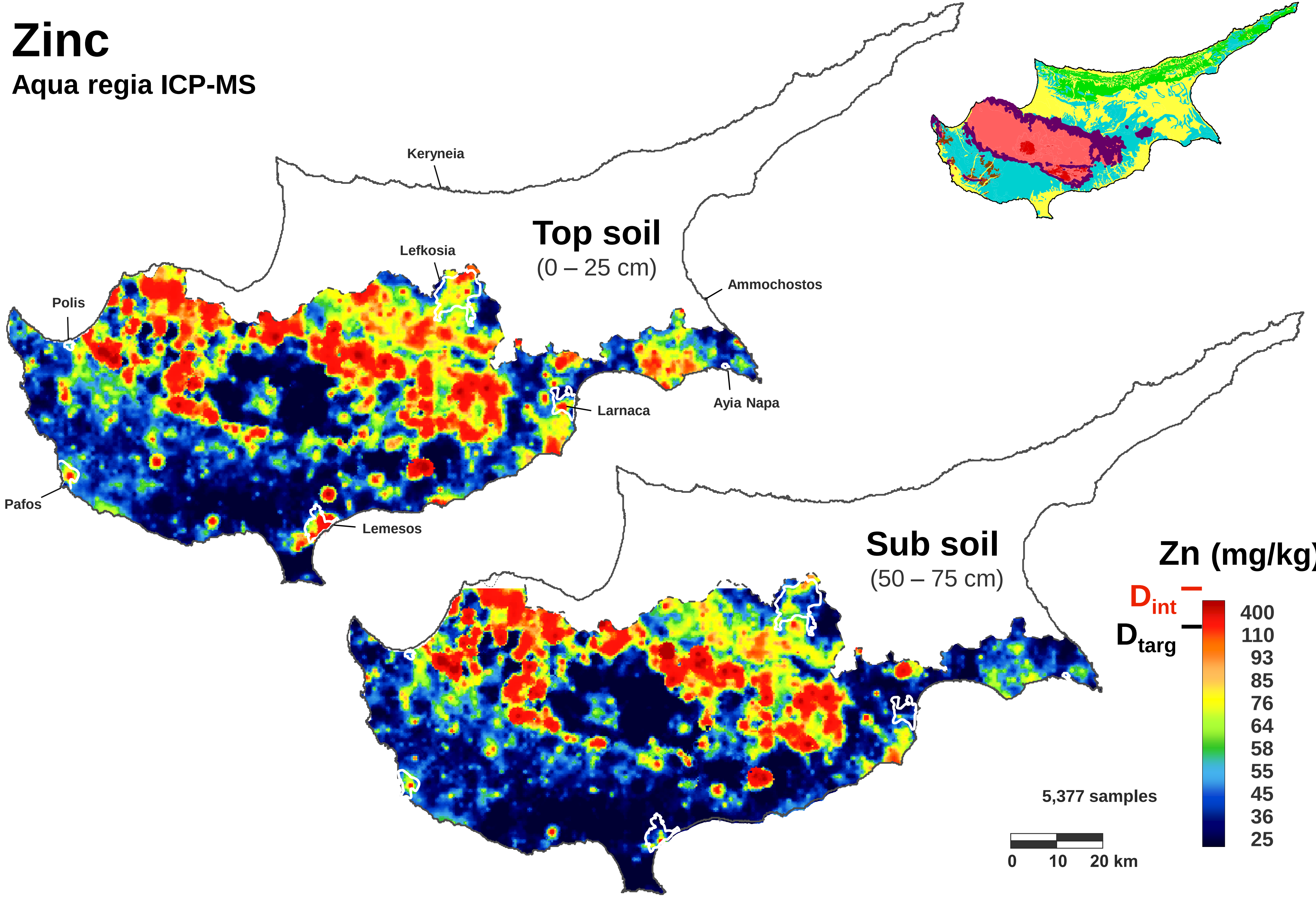

Sulphide, chromite & asbestos mines
Alestos & Memi
Agrokipia, Kokkinoyia & Kokkinopesula
Peristerka, Pytharochoma, Kokkinonero & Kapedhes
Skouriotossa & Apliki
Limni, Evloymeni, Uncle Charles & Kinousa
Troulli
Cu (%)
<1
1–2
2–3
3–4
Zn (%)
<1
1–2
2–4
4–9
Mathiatis Sth
Sha
Kokkino-rotsos
Kannoures
Hadjipavlou
Amiantos
Maghaleni
Kalavasos
Troodos Ophiolite Complex & Arakapas Transform Sequence
pillow lavas
mafic units
ultramafic unit
Chromite
Asbestos


Geochemical
Atlas of Cyprus
• Sampling site
33 °E
34 °E
35 °N
Keryneia
Lefkosia
Ammochostos
Polis
Pafos
Lemesos
Larnaca
Ayia Napa
3920000
mN
3900000
3880000
3860000
3840000
3820000
440000
460000
480000
500000
520000
540000
560000
580000
600000
620000 mE
WGS84 36N

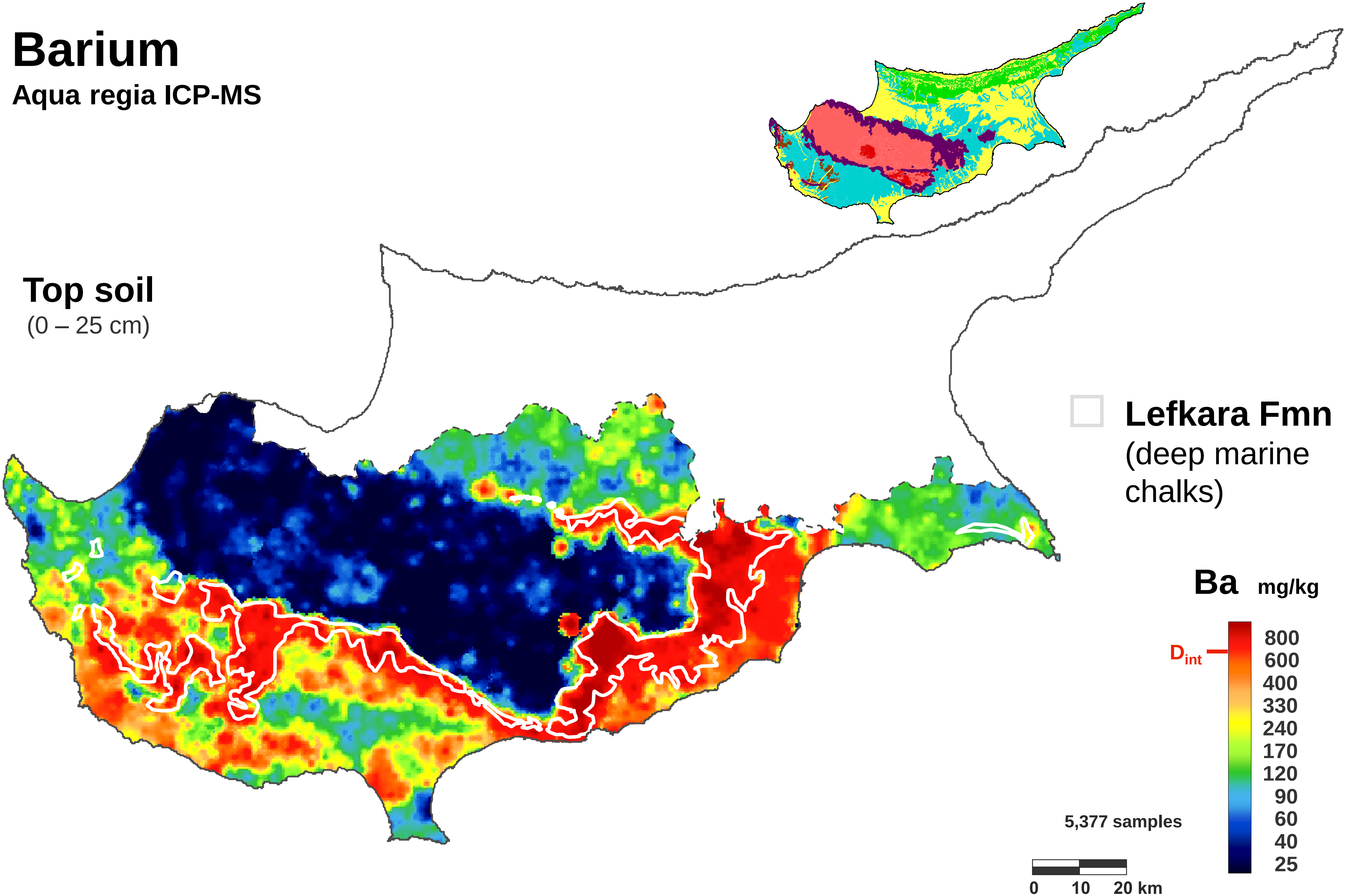

Copper
Aqua regia ICP-MS
Top soil
(0 – 25 cm)
Keryneia
Lefkosia (Nicosia)
Ammochostos
Polis
Larnaca
Ayia Napa
Pafos
Lemesos
Cu Mines
Cu (mg/kg)
800
220
135
115
100
75
65
55
45
35
15
5,377 samples
0
10
20 km



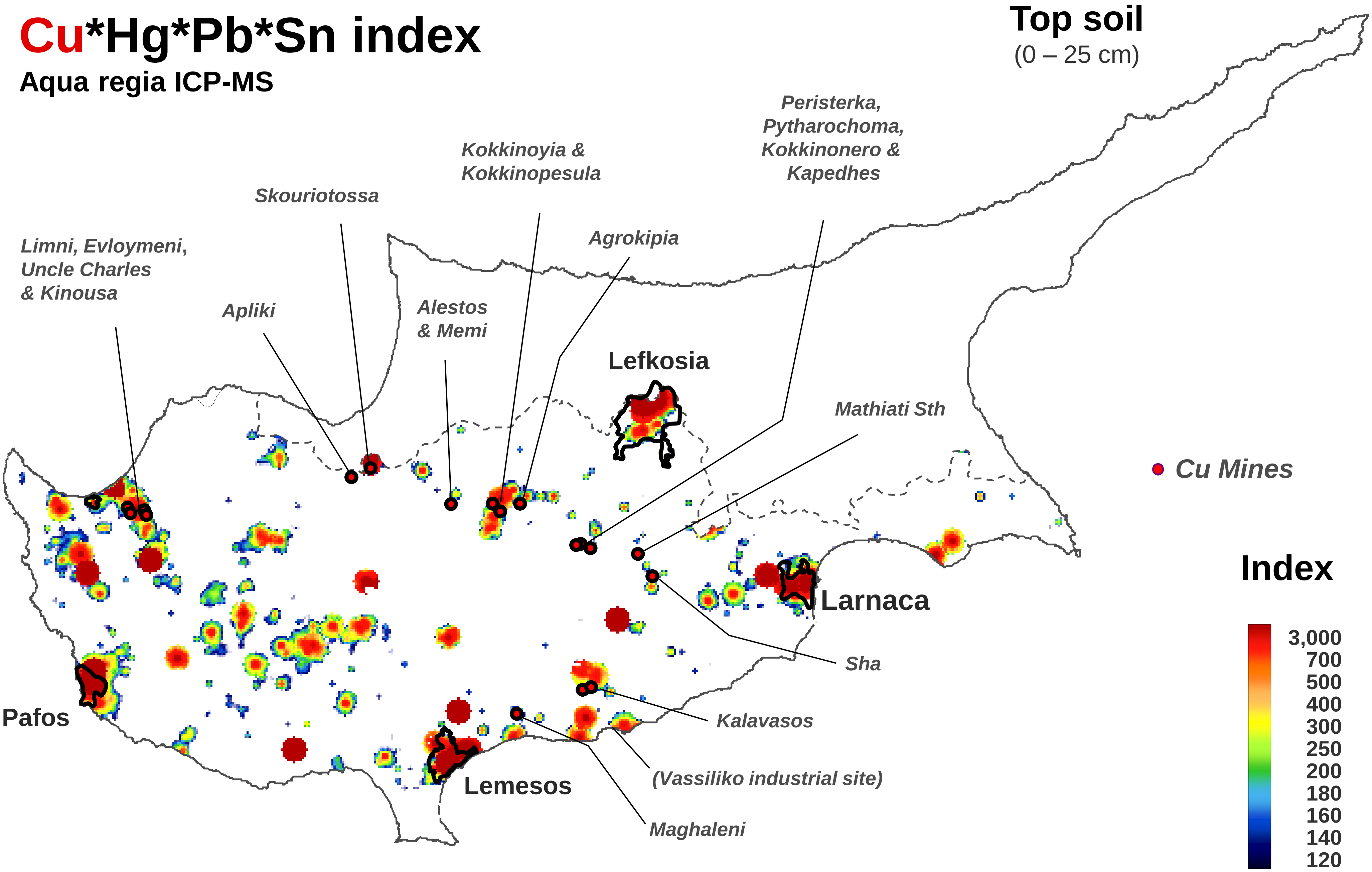
Lead
Aqua regia ICP-MS
Keryneia
Top soil
(0 – 25 cm)
Lefkosia
Ammochostos
Polis
Larnaca
Ayia Napa
Pafos
Lemesos
Sub soil
(50 – 75 cm)
Pb (mg/kg)
530
60.0
12.7
11.5
10.6
9.6
8.7
8.1
7.3
6.2
3.9
1.0
5,377 samples
0 10 20 km



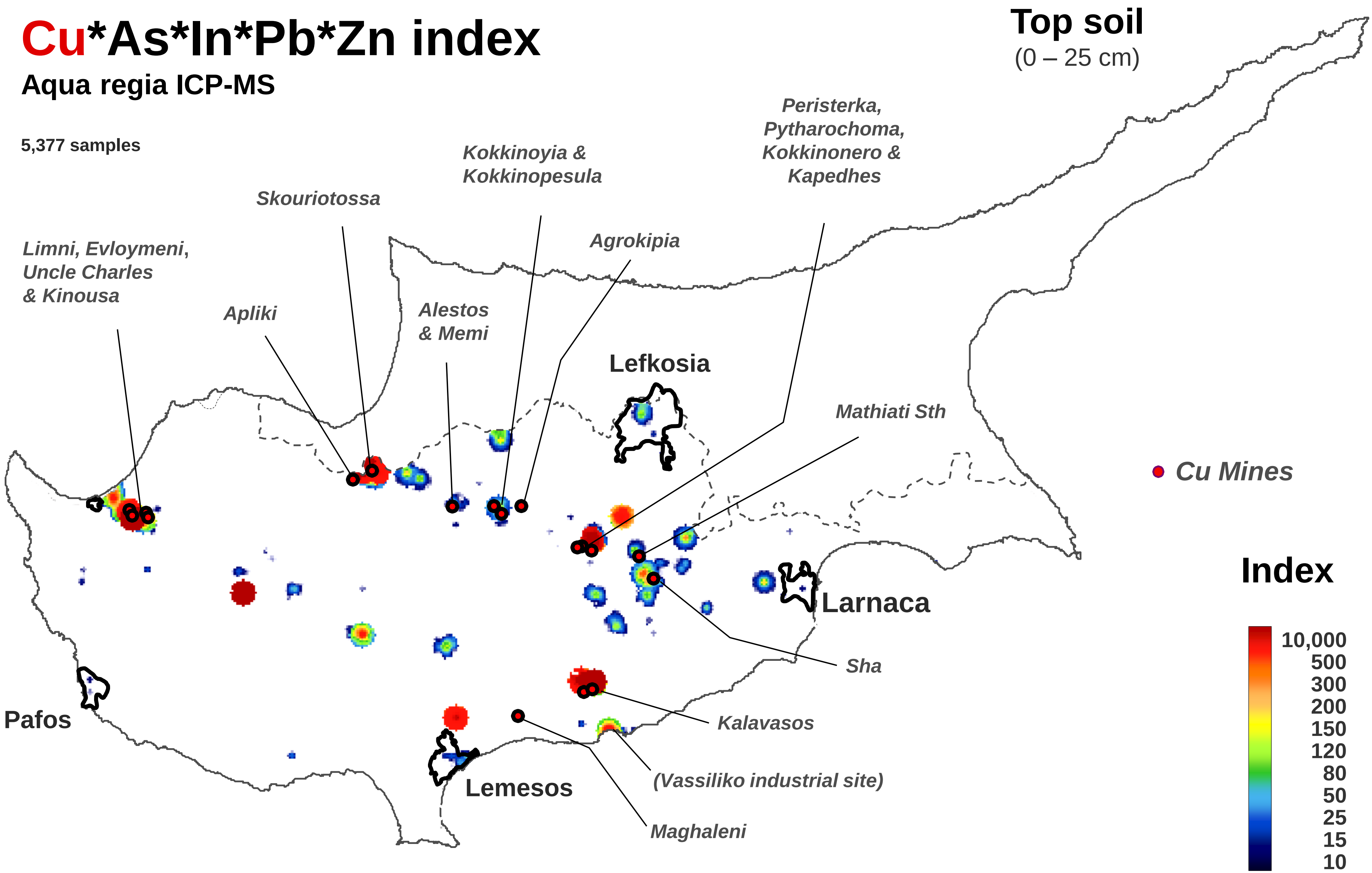
Zinc
Aqua regia ICP-MS
Keryneia
Top soil
(0 – 25 cm)
Lefkosia
Ammochostos
Polis
Larnaca
Ayia Napa
Pafos
Lemesos
Sub soil
(50 – 75 cm)
Zn (mg/kg)
D int
D targ
400
110
93
85
76
64
58
55
45
36
25
5,377 samples
0
10
20 km



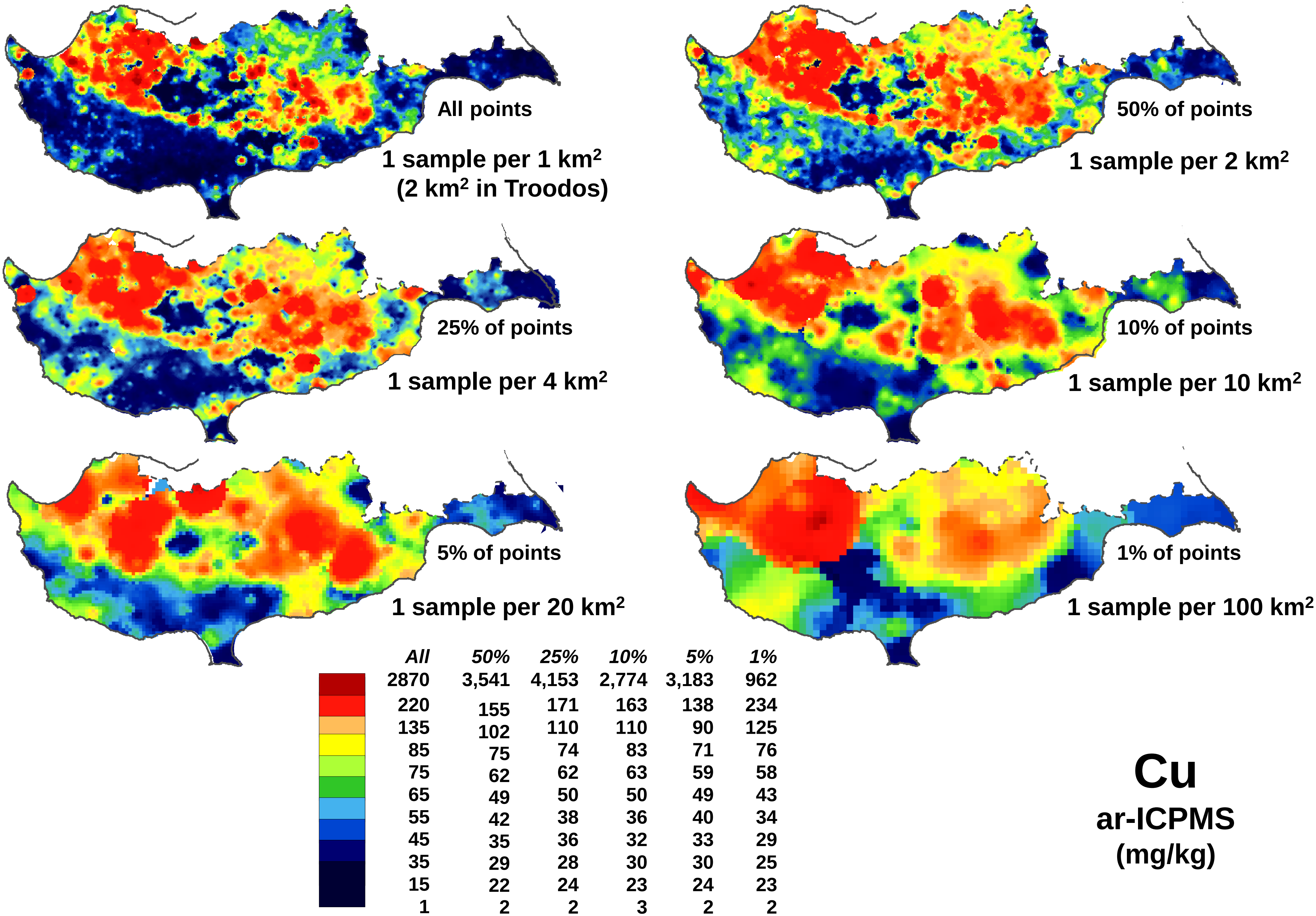
Barium
Aqua regia ICP-MS
Top soil
(0 – 25 cm)
Lefkara Fmn
(deep marine
chalks)
Ba mg/kg
D int
800
600
400
330
240
170
120
90
60
40
25
5,377 samples
0
10
20 km



Cu*Hg*Pb*Sn index
Aqua regia ICP-MS
Top soil
(0 – 25 cm)
Limni, Evloymeni, Uncle Charles & Kinousa
Apliki
Skouriotossa
Alestos & Memi
Kokkinoyia & Kokkinopesula
Agrokipia
Peristerka, Pytharochoma, Kokkinonero & Kapedhes
Mathiati Sth
Lefkosia
Larnaca
Sha
Kalavasos
(Vassiliko industrial site)
Maghaleni
Lemesos
Pafos
Cu Mines
Index
3,000
700
500
400
300
250
200
180
160
140
120



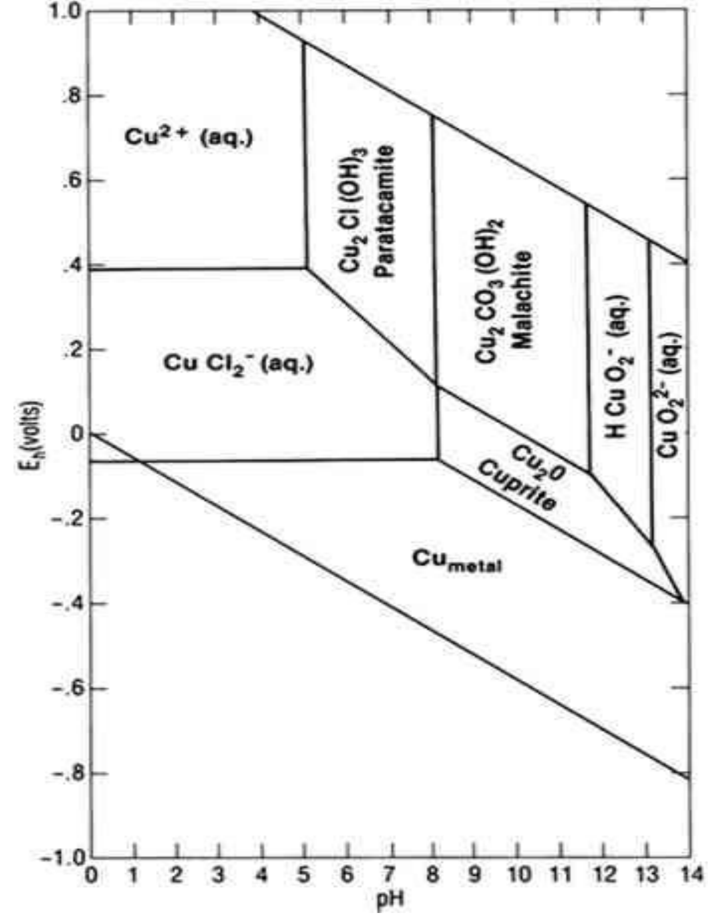
Cu*As*In*Pb*Zn index
Aqua regia ICP-MS
5,377 samples
Top soil
(0 – 25 cm)
Limni, Evloymeni,
Uncle Charles
& Kinousa
Apliki
Skouriotossa
Alestos
& Memi
Kokkinoyia &
Kokkinopesula
Agrokipia
Peristerka,
Pytharochoma,
Kokkinonero &
Kapedhes
Mathiati Sth
Lefkosia
Larnaca
Pafos
Lemesos
Sha
Kalavasos
(Vassiliko industrial site)
Maghaleni
Cu Mines
Index
10,000
500
300
200
150
120
80
50
25
15
10

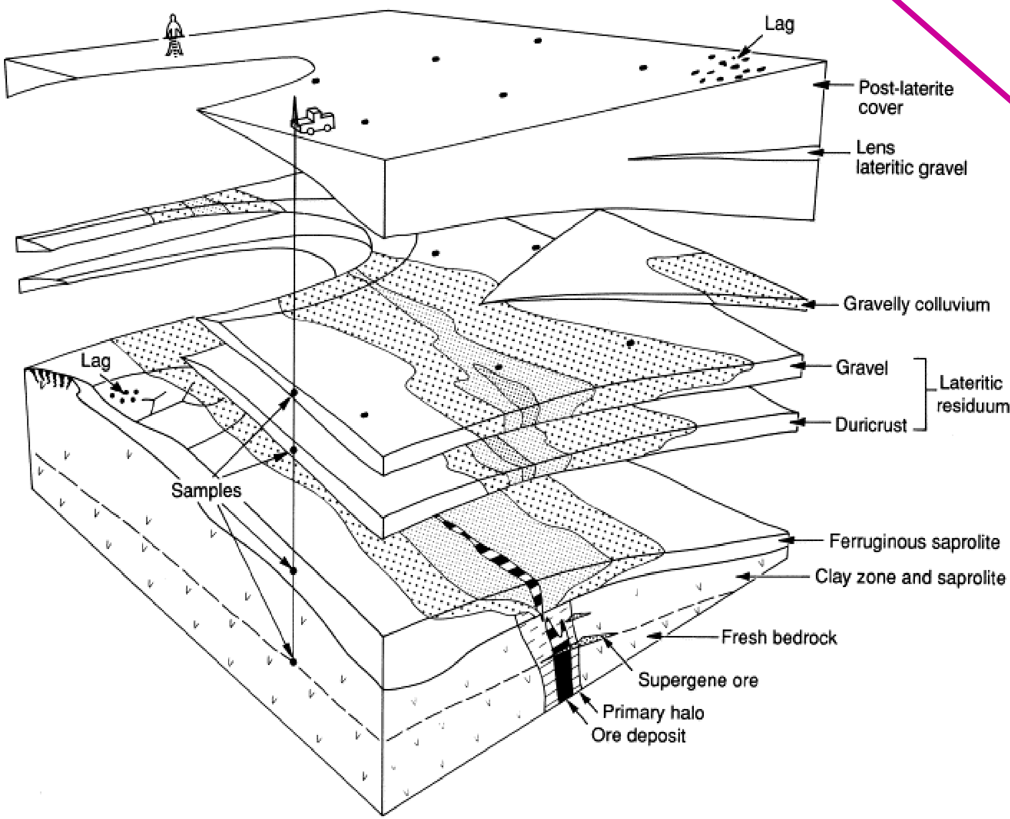


All points
1 sample per 1 km²
(2 km² in Troodos)
50% of points
1 sample per 2 km²
25% of points
1 sample per 4 km²
10% of points
1 sample per 10 km²
5% of points
1 sample per 20 km²
1% of points
1 sample per 100 km²
All 50% 25% 10% 5% 1%
2870 3,541 4,153 2,774 3,183 962
220 155 171 163 138 234
135 102 110 110 90 125
85 75 74 83 71 76
75 62 62 63 59 58
65 49 50 50 49 43
55 42 38 36 40 34
45 35 36 32 33 29
35 29 28 30 30 25
15 22 24 23 24 23
1 2 2 3 2 2
Cu
ar-ICPMS
(mg/kg)

Rock and regolith formation and modification processes

Geochemical behaviour of elements





Conceptual geochemical models

Geochemical mapping

27th International Applied Geochemistry Symposium

20 - 24 April 2014

Tucson, Arizona, USA

www.27iags.com