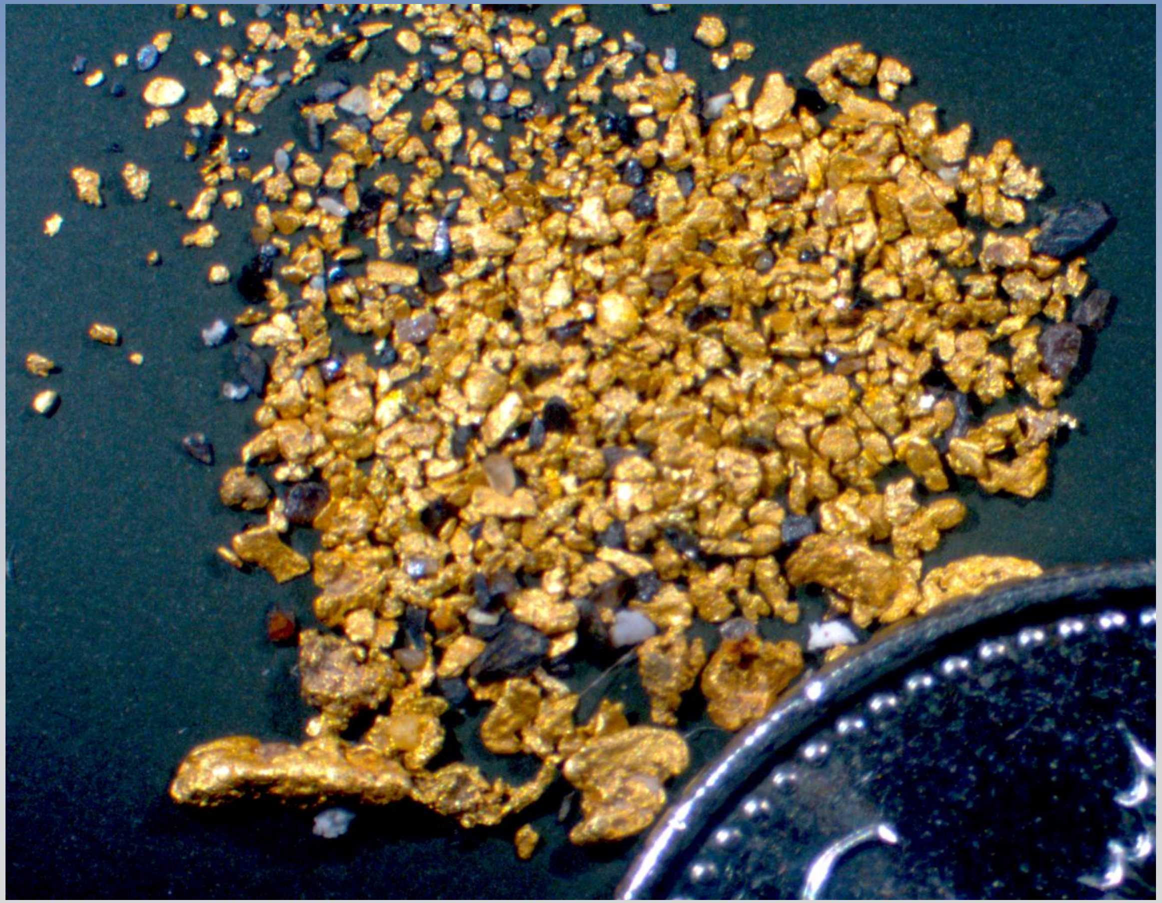
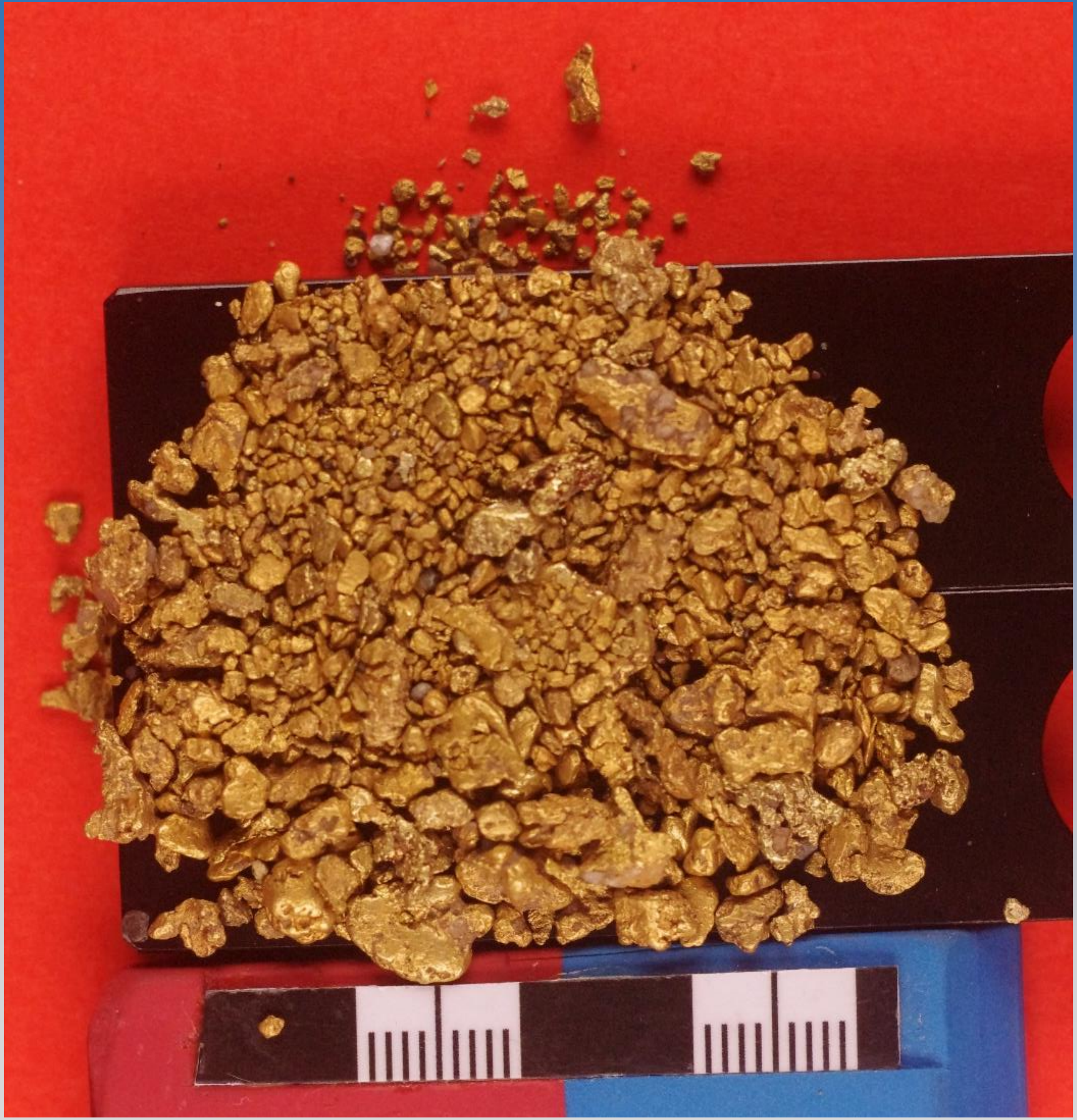
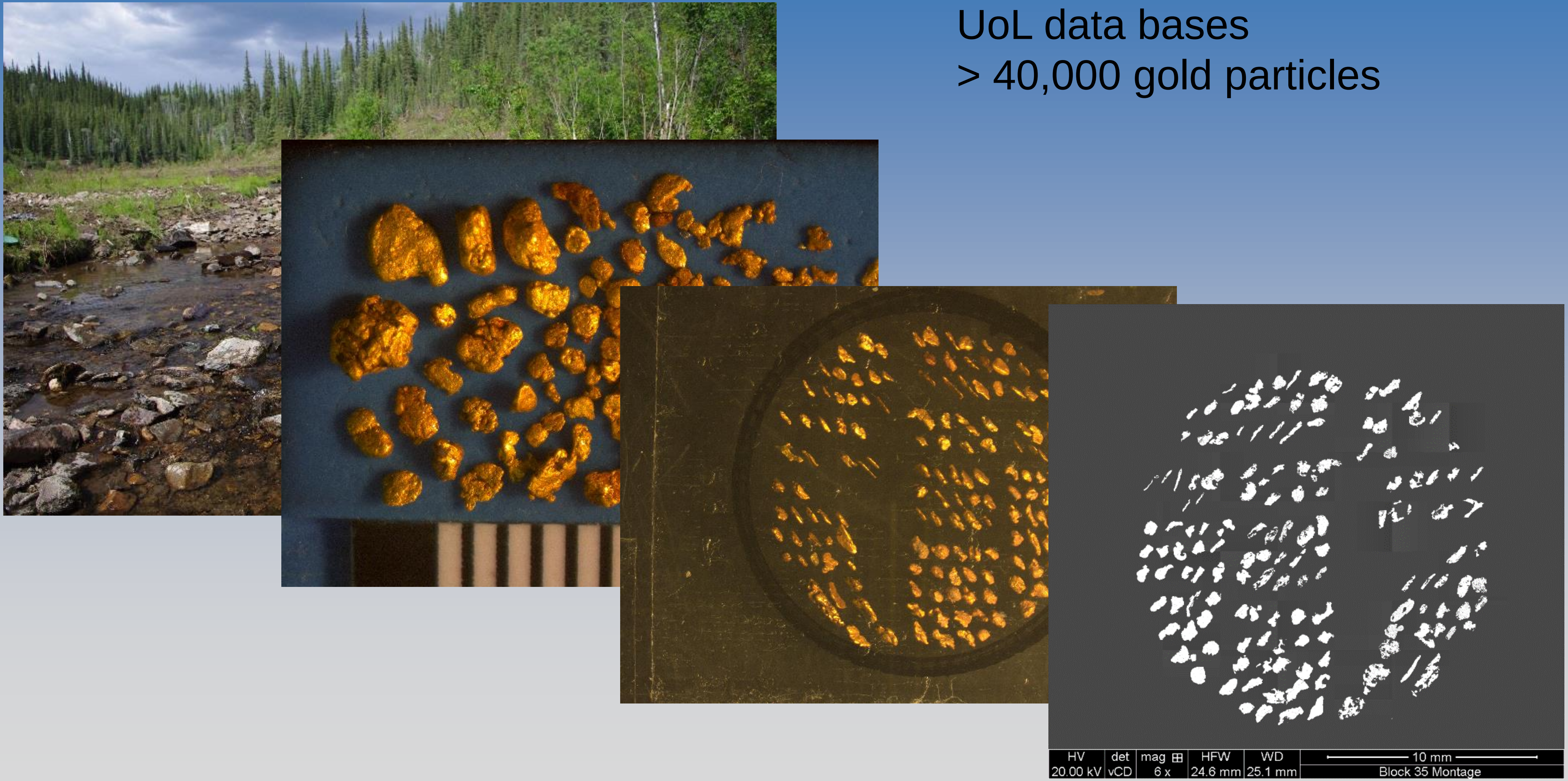
Methodologies to characterise natural gold





Analytical approaches

UoL data bases
> 40,000 gold particles



Standard analytical approach : location records

Site	Belt	Region	Sample Type	Sample No.	Population_ID	Deposit Type 1	UTM	E	N	map sheet/Lat long	Reference
Lytton	ntermontane	Kamloops	Detrital	AU-001	Lytton	Orogenic	10	596648	5572573	10U 596648.28 5572573.46	JK notes
Gold Pan	ntermontane	Kamloops	Detrital	AU-002	Gold Pan	Unknown	10	614002	5579526	10U 614001.66 5579526.13	JK notes
Kanaka Bar	ntermontane	Kamloops	Detrital	AU-006	Kanaka Bar	Unknown	10	602627	5552726	10U 602626.88 5552726.38	JK notes
Stirrup Ck	ntermontane	Clinton	Detrital	AU-008	Stirrup Ck	LS Epithermal	10	557997	5659116	10U 557997.23 5659116.36	https://pdfs.semanticscholar.org/a753/b28
Unknown	Omineca	Liard	Hypogene	AU-009	Choa	Orogenic	9	491768	6456575	9U 491768.31 6456575.15	https://aris.empr.gov.bc.ca/ArisReports/12
Lillooet	Coast	Lillooet	Detrital	AU-011	Lillooet	Orogenic	10	576883	5618322	10U 576882.61 5618321.9	JK notes
Bridge River	Coast	Lillooet	Detrital	AU-012	Bridge R_1	Orogenic	10	569676	5627361	10U 569675.93 5627360.55	JK notes
Bridge-Yalakom	Coast	Lillooet	Detrital	AU-013	Bridge-Yalakom	Orogenic	10	558221	5634927	10U 558220.93 5634926.86	JK notes
Yalakom	Coast	Lillooet	Detrital	AU-014	Yalakom	Orogenic	10	535584	5657087	10U 535583.88 5657086.87	JK notes
Relay	Coast	Lillooet	Detrital	AU-015	Relay	Porphyry	10	509681	5664325	10U 509681.37 5664325.45	Schiarizza, P. & Gaba, R. & Coleman, M.
Bassford Ck	Omineca	Cariboo	Detrital	AU-018	Bassford Ck	Orogenic	10	582546	5874825	10U 582545.89 5874825.25	JK notes
Lightening Ck	Omineca	Cariboo	Detrital	AU-019	Lightening	Orogenic	10	561728	5874567	10U 561728.31 5874566.74	JK notes
Tillicum	Omineca	Slocan	Hypogene	AU-020	Tillicum	Skarn	11	449002	5537267	11U 449002 5537267	082FNW220
Bralorne Mine	Coast	Lillooet	Hypogene	AU-021	Bralorne_Coronation	Orogenic	10	515477	5623283	10U 515477 5623283	092JNE007
Bralorne Mine	Coast	Lillooet	Hypogene	AU-022	Bralorne	Orogenic	10	515477	5623283	10U 515477 5623283	092JNE001
Pioneer	Coast	Lillooet	Hypogene	AU-023	Pioneer	Orogenic	10	515477	5623283	10U 515477 5623283	092JNE004
Bralorne Mine	Coast	Lillooet	Hypogene	AU-024	Bralorne	Orogenic	10	512632	5624910	10U 512632 5624910	092JNE001
Pioneer	Coast	Lillooet	Hypogene	AU-025	Pioneer	Orogenic	10	515477	5623283	10U 515477 5623283	092JNE004
Bralorne Mine	Coast	Lillooet	Hypogene	AU-026	Bralorne	Orogenic	10	512632	5624910	10U 512632 5624910	092JNE001

Each ‘site’ describes a number of gold particles from the same location .

This is what we mean by ‘sample population’

Standard analytical approach

Data for individual site

	Population_ID	Block	Population	Grain	Phase	Phase_ID	Au	Ag	Cu	Hg	Pd	Total	Inclusion_	Inclusion_
							Alloy composition EMP						**Inclusion suite SEM**	
2	Friday Ck_1	RJC 50	13	1	1	Friday Ck_1_RJC 50_13_1_1	87.1893	10.2943	0.09135	1.72156	0	99.244		
3	Friday Ck_1	RJC 50	13	2	1	Friday Ck_1_RJC 50_13_2_1	88.3394	10.0616	0.06822	0.57216	0	98.9265		
4	Friday Ck_1	RJC 50	13	3	1	Friday Ck_1_RJC 50_13_3_1	88.4841	10.0864	0.06729	0.29604	0	98.8986		
5	Friday Ck_1	RJC 50	13	4	1	Friday Ck_1_RJC 50_13_4_1	90.0696	8.15869	0.06972	0.30662	0	98.5386	PbBiTe	
6	Friday Ck_1	RJC 50	13	5	1	Friday Ck_1_RJC 50_13_5_1	74.8358	23.6313	0.03598	0.28696	0	98.7712		
7	Friday Ck_1	RJC 50	13	6	1	Friday Ck_1_RJC 50_13_6_1	73.1381	25.4763	0.04337	0.45105	0	99.0698		
8	Friday Ck_1	RJC 50	13	7	1	Friday Ck_1_RJC 50_13_7_1	84.1415	14.7487	0.09751	0.4481	0	99.3911		
9	Friday Ck_1	RJC 50	13	8	1	Friday Ck_1_RJC 50_13_8_1	77.5377	21.2891	0.04416	0.59234	0	99.4072		
10	Friday Ck_1	RJC 50	13	9	1	Friday Ck_1_RJC 50_13_9_1	81.9131	16.805	0.03291	0.14291	0	98.8284		
11	Friday Ck_1	RJC 50	13	10	1	Friday Ck_1_RJC 50_13_10_1	84.4428	13.3583	0.07031	1.47969	0.01235	99.3635		
12	Friday Ck_1	RJC 50	13	11	1	Friday Ck_1_RJC 50_13_11_1	80.2548	18.649	0.06933	0.3438	0.01412	99.3311		
13	Friday Ck_1	RJC 50	13	12	1	Friday Ck_1_RJC 50_13_12_1	89.0539	9.49555	0.08318	0.86857	0	99.4116		
14	Friday Ck_1	RJC 50	13	13	1	Friday Ck_1_RJC 50_13_13_1	89.7584	7.27425	0.1083	1.19317	0	98.2322		
15	Friday Ck_1	RJC 50	13	14	1	Friday Ck_1_RJC 50_13_14_1	66.3474	31.7184	0.03113	0.31127	0	98.379		
16	Friday Ck_1	RJC 50	13	15	1	Friday Ck_1_RJC 50_13_15_1	87.1047	11.9422	0.038	0.36656	0	99.3501		
17	Friday Ck_1	RJC 50	13	16	1	Friday Ck_1_RJC 50_13_16_1	74.6538	23.9337	0.03872	0.36998	0	98.979		
18	Friday Ck_1	RJC 50	13	17	1	Friday Ck_1_RJC 50_13_17_1	88.7457	7.81619	0.36946	2.67295	0.10851	99.7128		
19	Friday Ck_1	RJC 50	13	18	1	Friday Ck_1_RJC 50_13_18_1	97.2693	1.59931	0.22311	0.35342	0	99.3926		
20	Friday Ck_1	RJC 50	13	19	1	Friday Ck_1_RJC 50_13_19_1	91.2828	7.42735	0.07839	0.56861	0	99.2685		
21	Friday Ck_1	RJC 50	13	20	1	Friday Ck_1_RJC 50_13_20_1	83.3657	15.1055	0.04049	0.77292	0	99.2053		
22	Friday Ck_1	RJC 50	13	25	1	Friday Ck_1_RJC 50_13_25_1	80.7097	18.0856	0.04253	0.28302	0	99.1048		
23	Friday Ck_1	RJC 50	13	24	1	Friday Ck_1_RJC 50_13_24_1	86.1369	12.8282	0.03179	0.23202	0	99.1936		
24	Friday Ck_1	RJC 50	13	23	1	Friday Ck_1_RJC 50_13_23_1	82.1732	16.6481	0.01963	0.21279	0	98.9544		
25	Friday Ck_1	RJC 50	13	22	1	Friday Ck_1_RJC 50_13_22_1	85.6636	12.3412	0.04353	1.42408	0	99.4103		
26	Friday Ck_1	RJC 50	13	21	1	Friday Ck_1_RJC 50_13_21_1	86.8665	11.7479	0.13014	0.74704	0	99.3796		
27	Friday Ck_1	RJC 52	10	1	1	Friday Ck_1_RJC 52 _10_1_1	94.3245	6.34176	0.41327	0.21136	0.00047	101.291	ap	
28	Friday Ck_1	RJC 52	10	2	1	Friday Ck_1_RJC 52 _10_2_1	90.3312	8.72385	0.04442	1.3077	0	100.373		
29	Friday Ck_1	RJC 52	10	3	1	Friday Ck_1_RJC 52_10_3_1	83.2958	16.7244	0.04174	0.3111	0	100.32		
30	Friday Ck_1	RJC 52	10	4	1	Friday Ck_1_RJC 52_10_4_1	93.6367	6.03361	0.04623	0.63797	0	100.306		
31	Friday Ck_1	RJC 52	10	5	1	Friday Ck_1_RJC 52_10_5_1	92.3362	8.57083	0.07884	0.31532	0	101.29		
32	Friday Ck_1	RJC 52	10	10	1	Friday Ck_1_RJC 52_10_10_1	80.3067	20.1829	0.02285	0.21488	0	100.656		
33	Friday Ck_1	RJC 52	10	9	1	Friday Ck_1_RJC 52_10_9_1	93.0709	2.96167	1.07484	2.27944	2.59765	101.985	stpd	cc
34	Friday Ck_1	RJC 52	10	8	1	Friday Ck_1_RJC 52_10_8_1	88.3015	12.4948	0.12704	0.37191	0	101.195	bn	

LOD (wt %) : 0.02 0.3 0.02

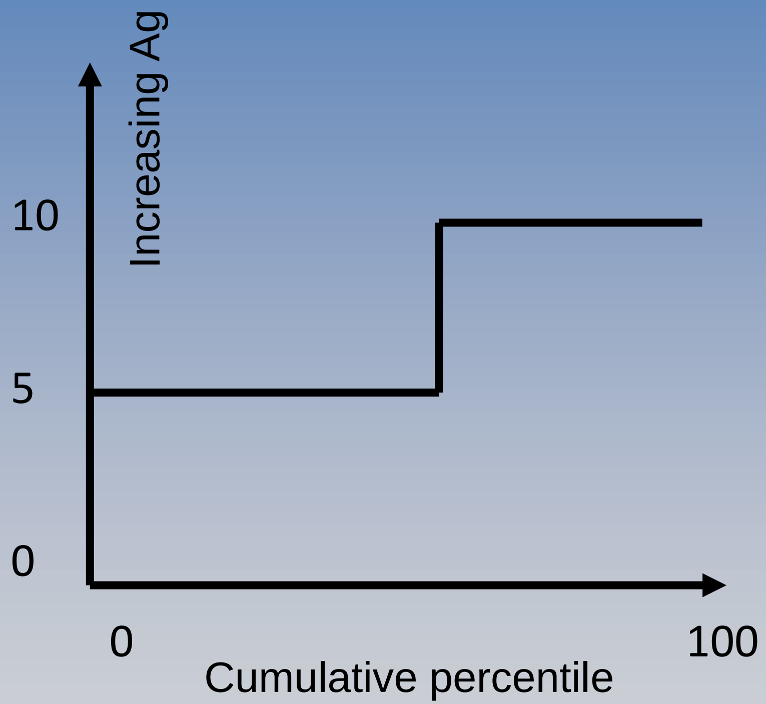
Useful quantitative data is 3σ

Cu: 0.06%
Hg: 0.3%
Pd: 0.02%

Different software gives different results at low concentrations

Comparing the minor alloy metal content of different populations

Particle number	%Ag	Cumulative percentile	Increasing Ag
1	5	10	5
2	10	20	5
3	10	30	5
4	5	40	5
5	5	50	5
6	5	60	10
7	10	70	10
8	10	80	10
9	5	90	10
10	10	100	10

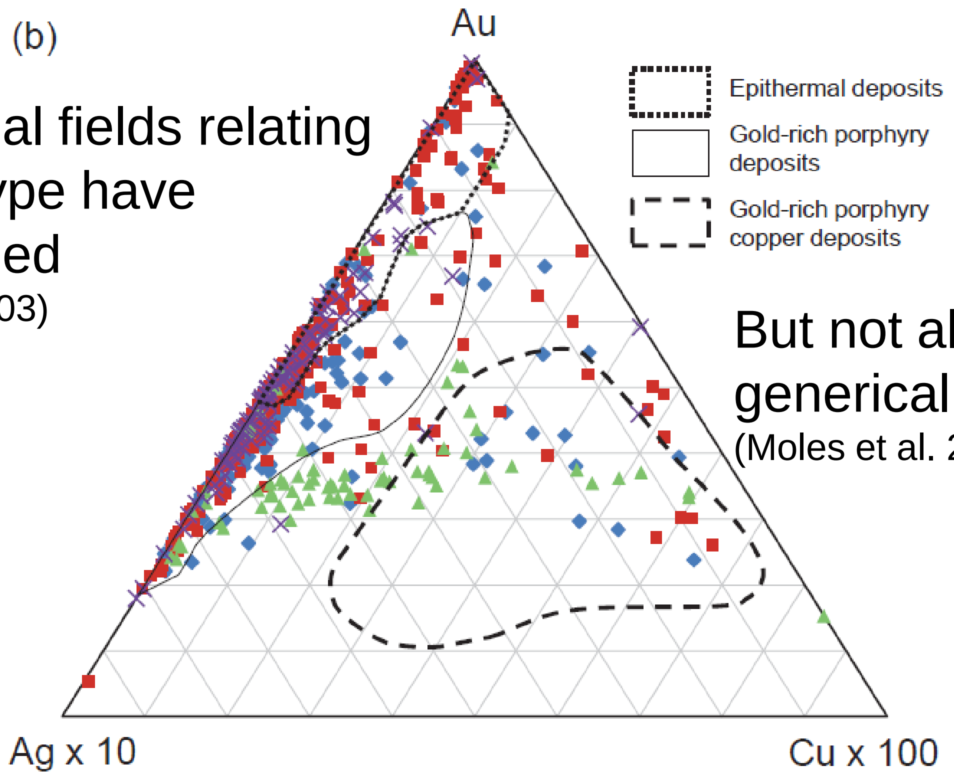


Can use same approach for Cu, Hg, Pd where values permit

Other methods of representation: 1

Triangular plots

Compositional fields relating to deposit type have been proposed
(Townley et al. 2003)



But not always generically applicable
(Moles et al. 2013)

Fig. 9. Ternary Au-Cu-Ag plots of the compositions of Au grains from the Mournes (symbols) with compositional fields (dashed outlines) of gold grains from: (a) Balwoges placer occurrence (Chapman *et al.* 2000*a*), Celopech epithermal deposit (Bonev *et al.* 2002) and Indian River placer 'type 5' (Chapman *et al.* 2011); (b) three bedrock source types in the central coastal Cordillera, Chile (Townley *et al.* 2003). Data from the environs of alkali Cu-Au porphyries described in Table 1 have not been included because not all the placer grains may represent gold grains from that specific source.

There are problems with this approach….

1. We lose absolute data
2. Errors between LOD and 3σ are amplified
3. Au ≈ (100-Ag)

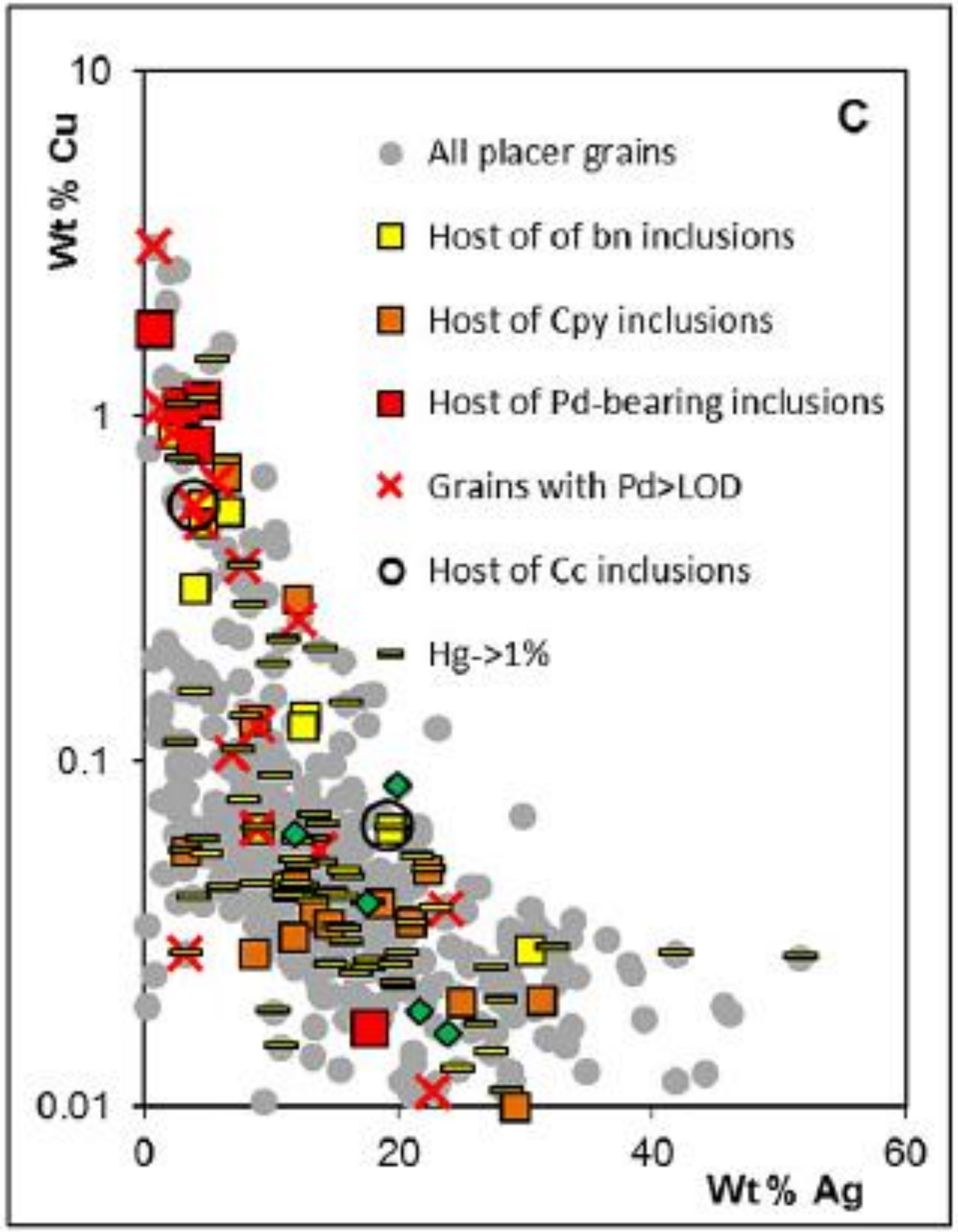
Other methods of representation: 1

Covariance plots

Retain quantitative data

Build compositional fields with other data sets:

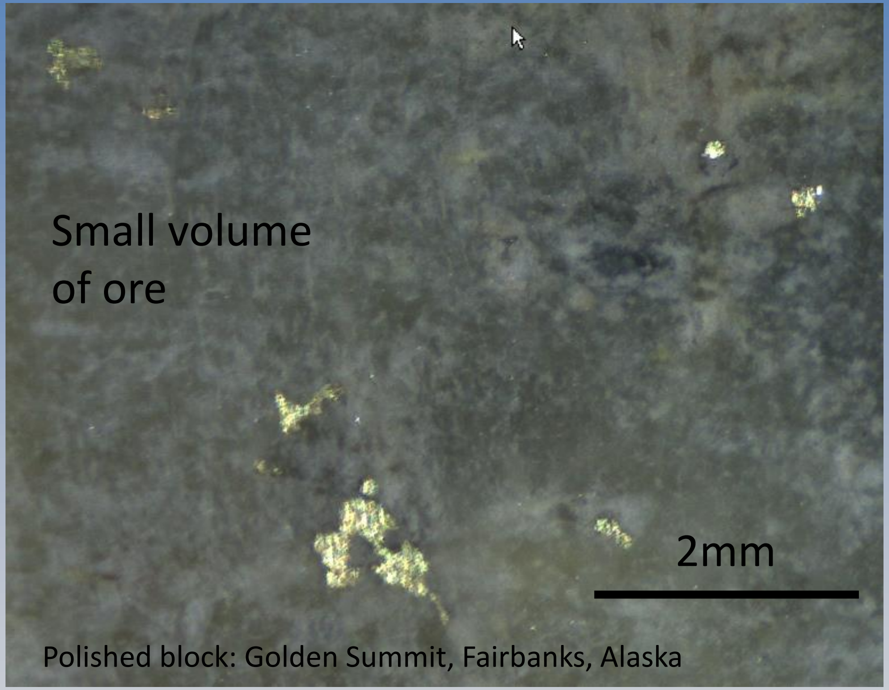
- Other alloy components
- Inclusion species



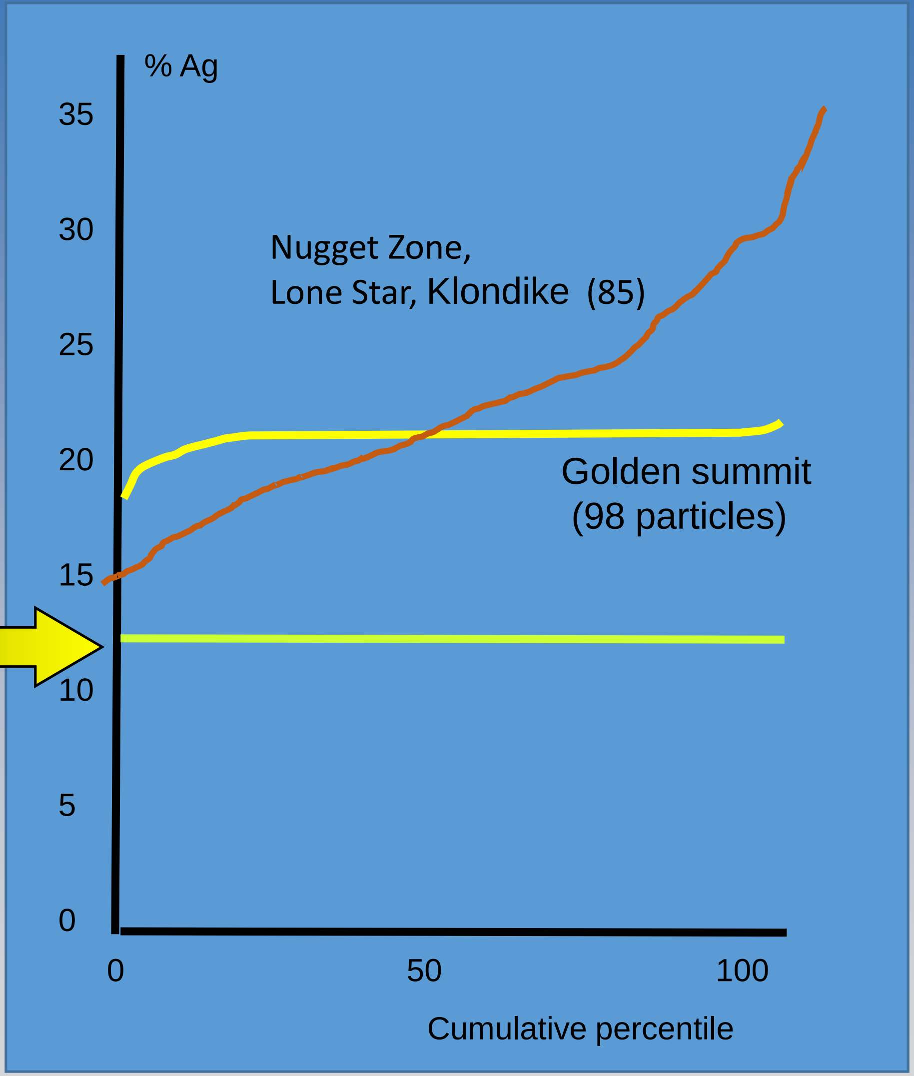
From Chapman et al. 2017

Cumulative percentile plots: interpreting plot shape: 1

1. Gold from in situ samples



Same conditions of precipitation = same Au/Ag ratio



Key message: signatures from a single vein may themselves be complex:

i. Evolving system
ii. Multiples pulses of fluid

Cumulative percentile plots: interpreting plot shape: 2

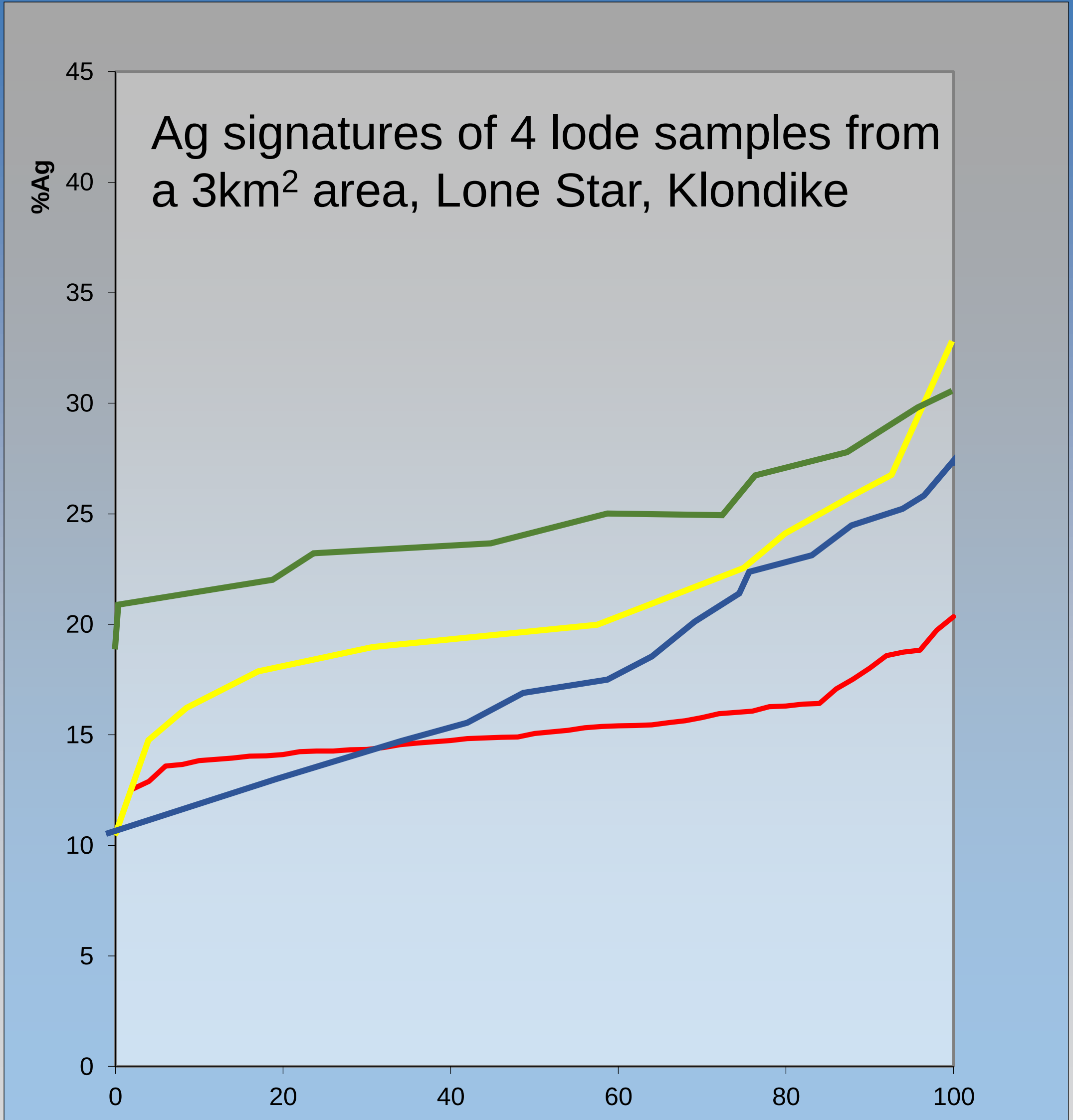
1. Gold from in situ samples (10T bulk samples processed in pilot plant)

Relatively stable mineralizing environment

Relatively stable mineralizing environment

Stable, then evolving (or vice versa?)

Evolving environment



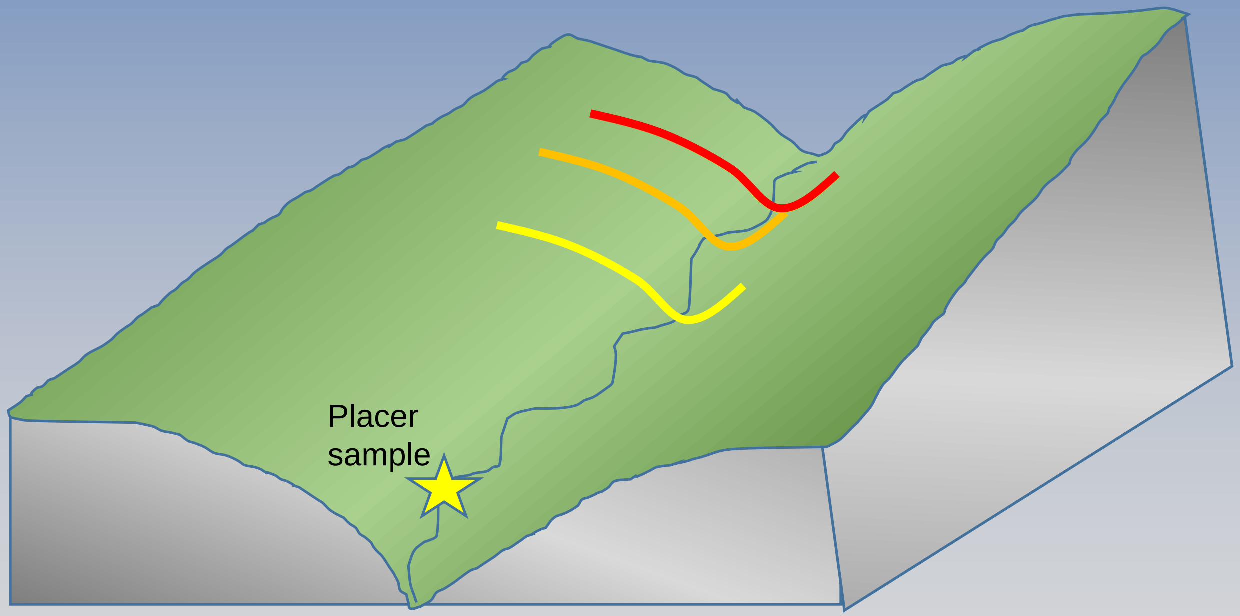
Chapman et al. 2010

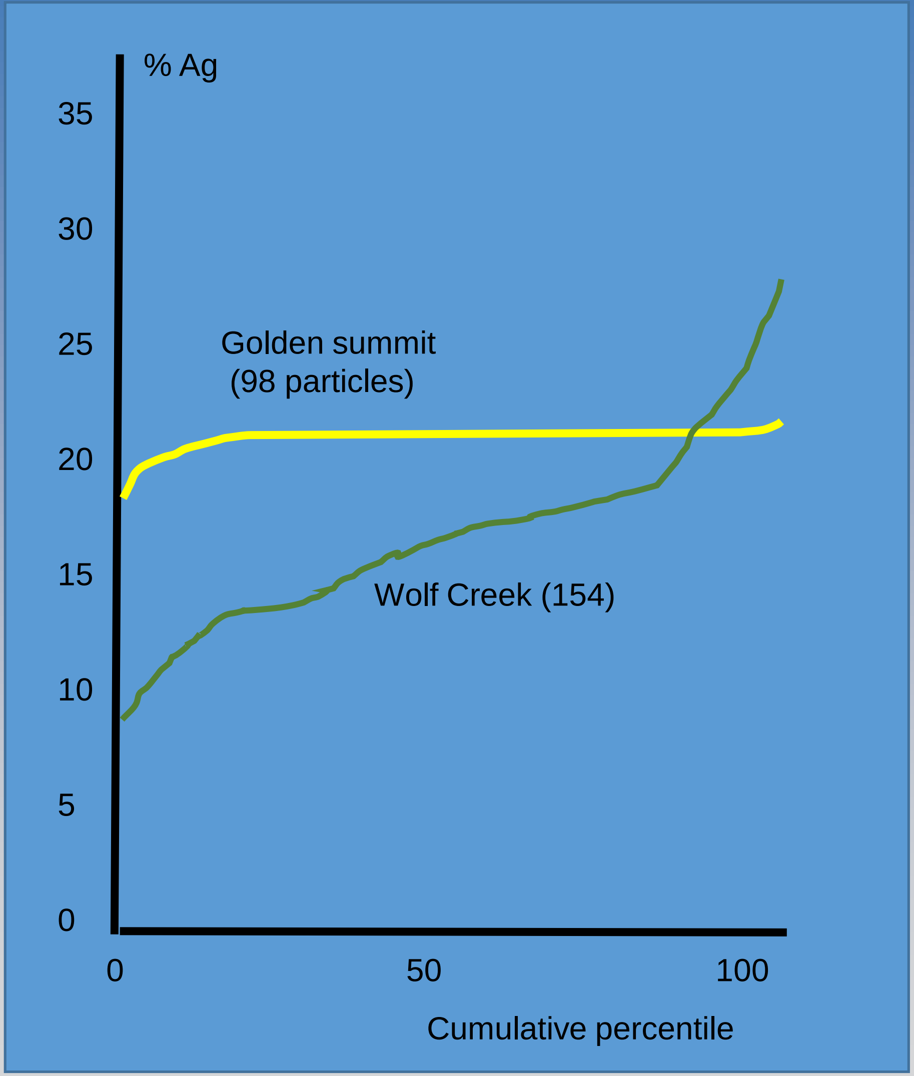
Cumulative percentile plots: interpreting plot shape: 3

Relationship of placer signature

to lode signature

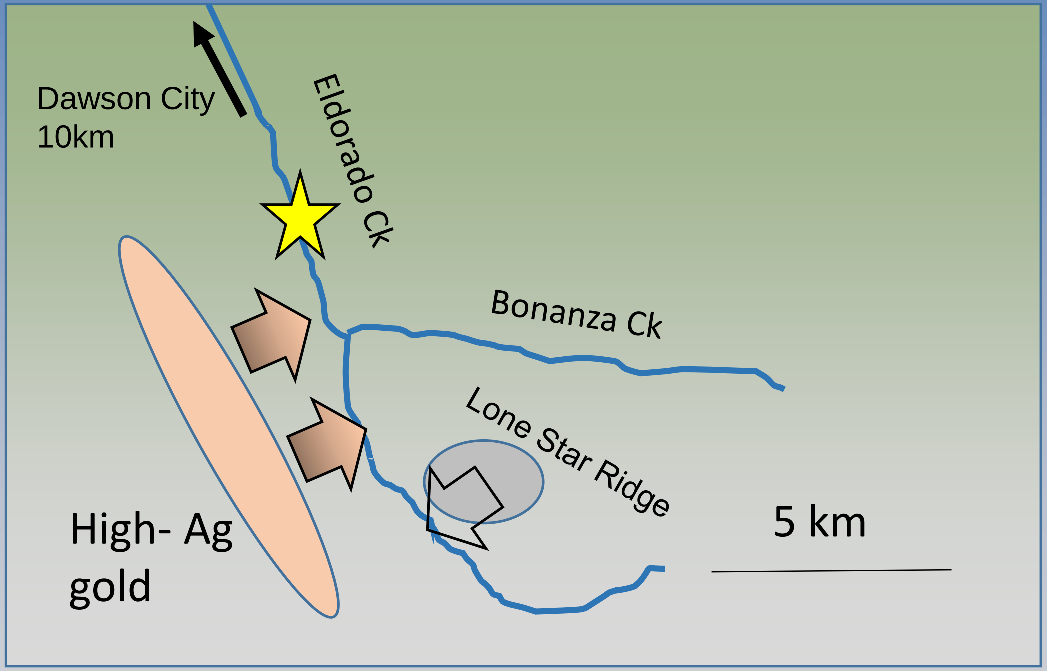
Gold signature varies within a single system

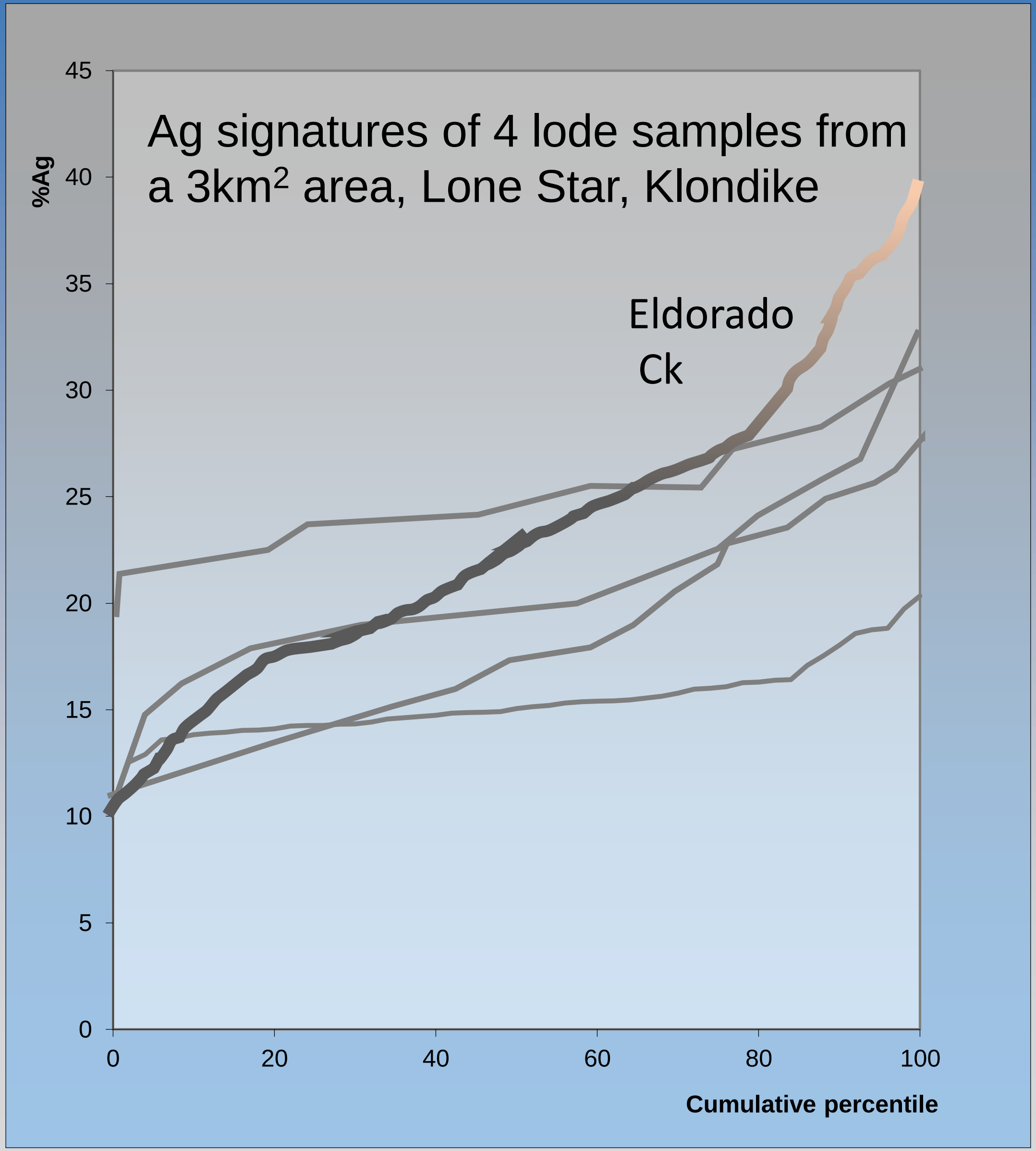




Cumulative percentile plots: interpreting plot shape: 4

Placer samples





If we know what the sources are- the placer signature makes sense. If we Don't know this- its challenging…

Cumulative percentile plots: interpreting plot shape: 5

Reproducability

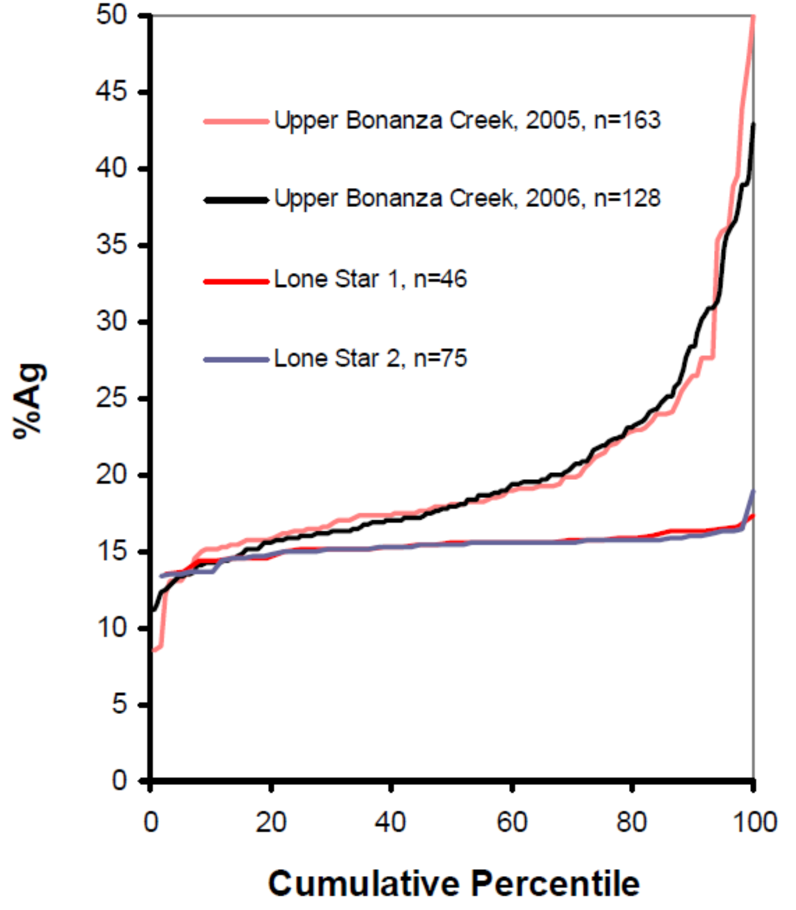


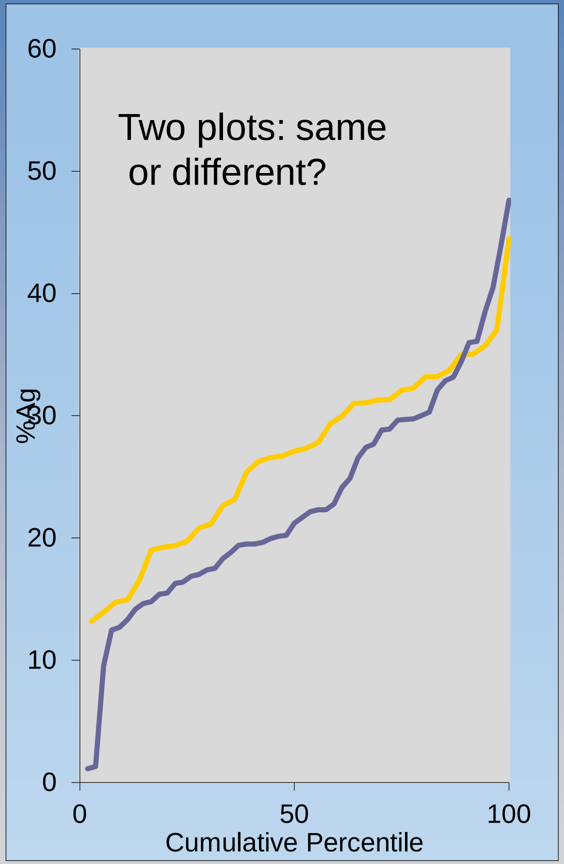
FIG. 4. Reproducibility of Ag data: Placer gold populations collected from Bonanza Creek in 2005 and 2006 and analyzed at UBC; and two sets of gold grains separated from the same lode sample, analyzed at UBC by Knight et al. (1999) and at UBC in this study.

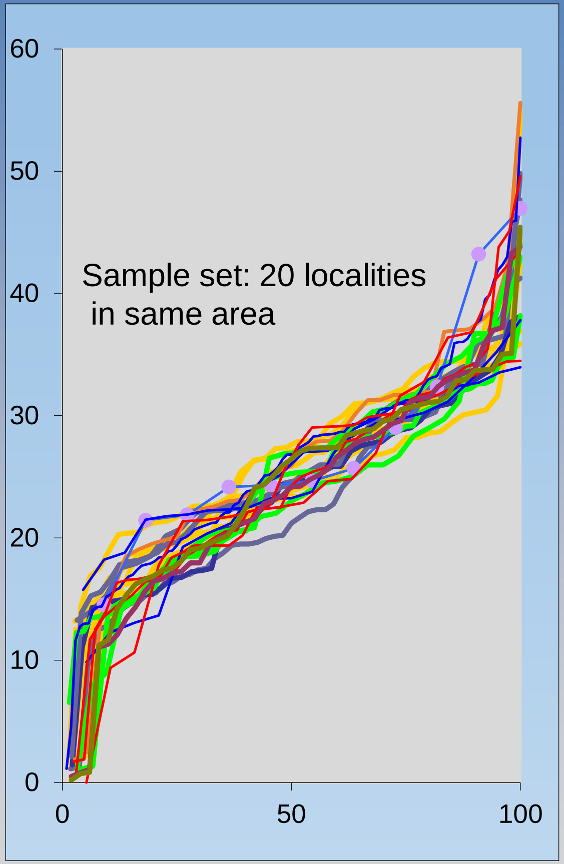
Other examples too
Chapman et al. 2000
Chapman and Mortensen 2016
Moles and Chapman 2019

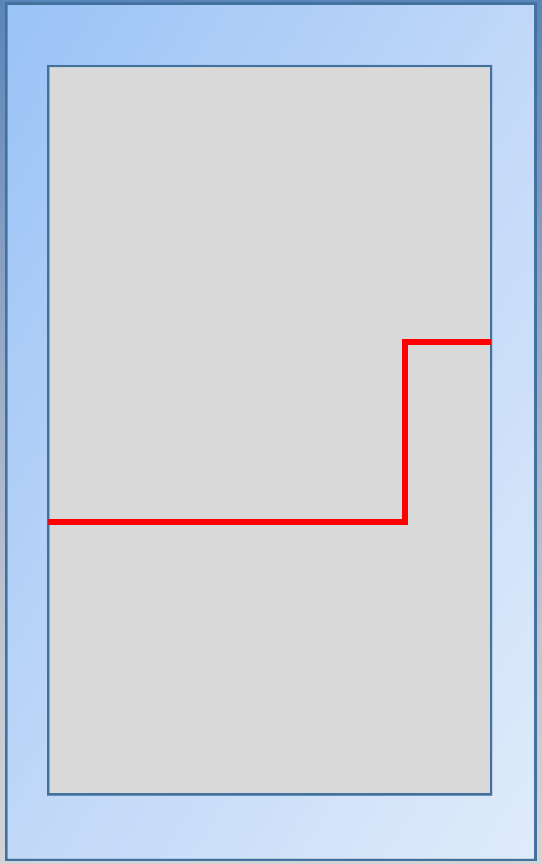
Robust because we decide where to analyse in a heterogeneous particle- analyse first alloy phase

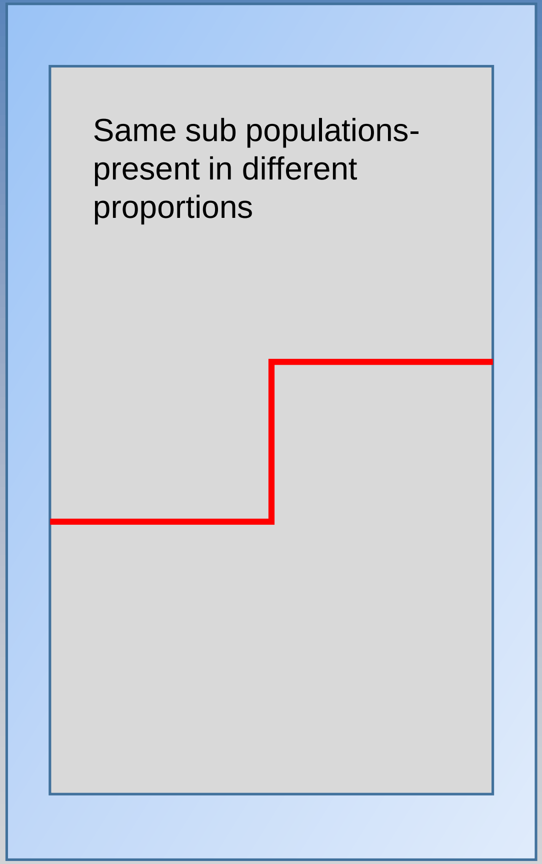
Cumulative percentile plots: interpreting plot shape: 5

In the context of 'same or different': What is a result?



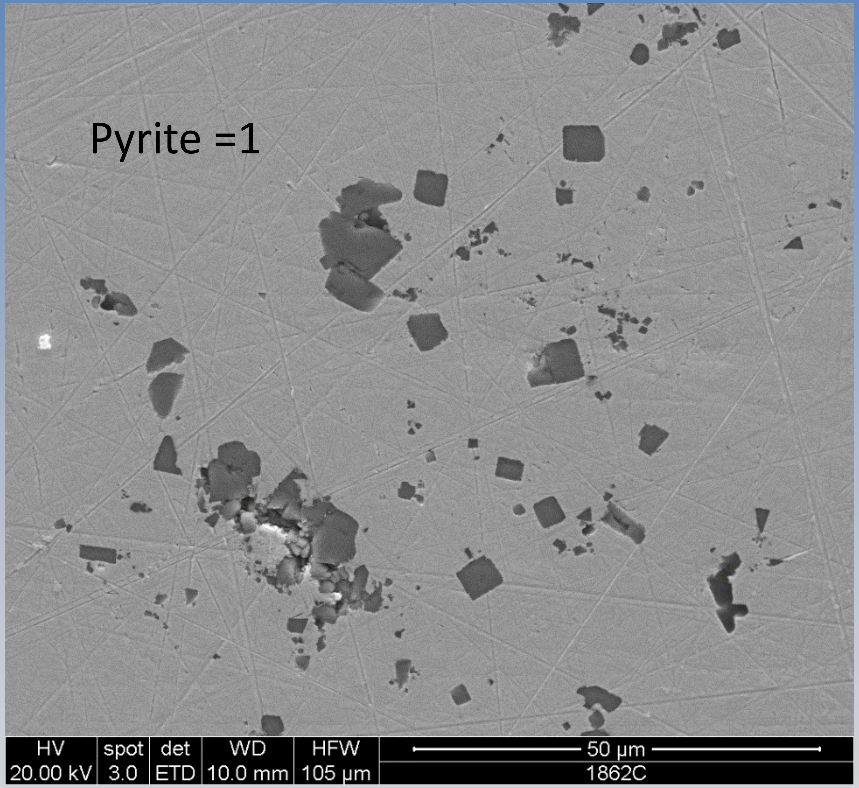


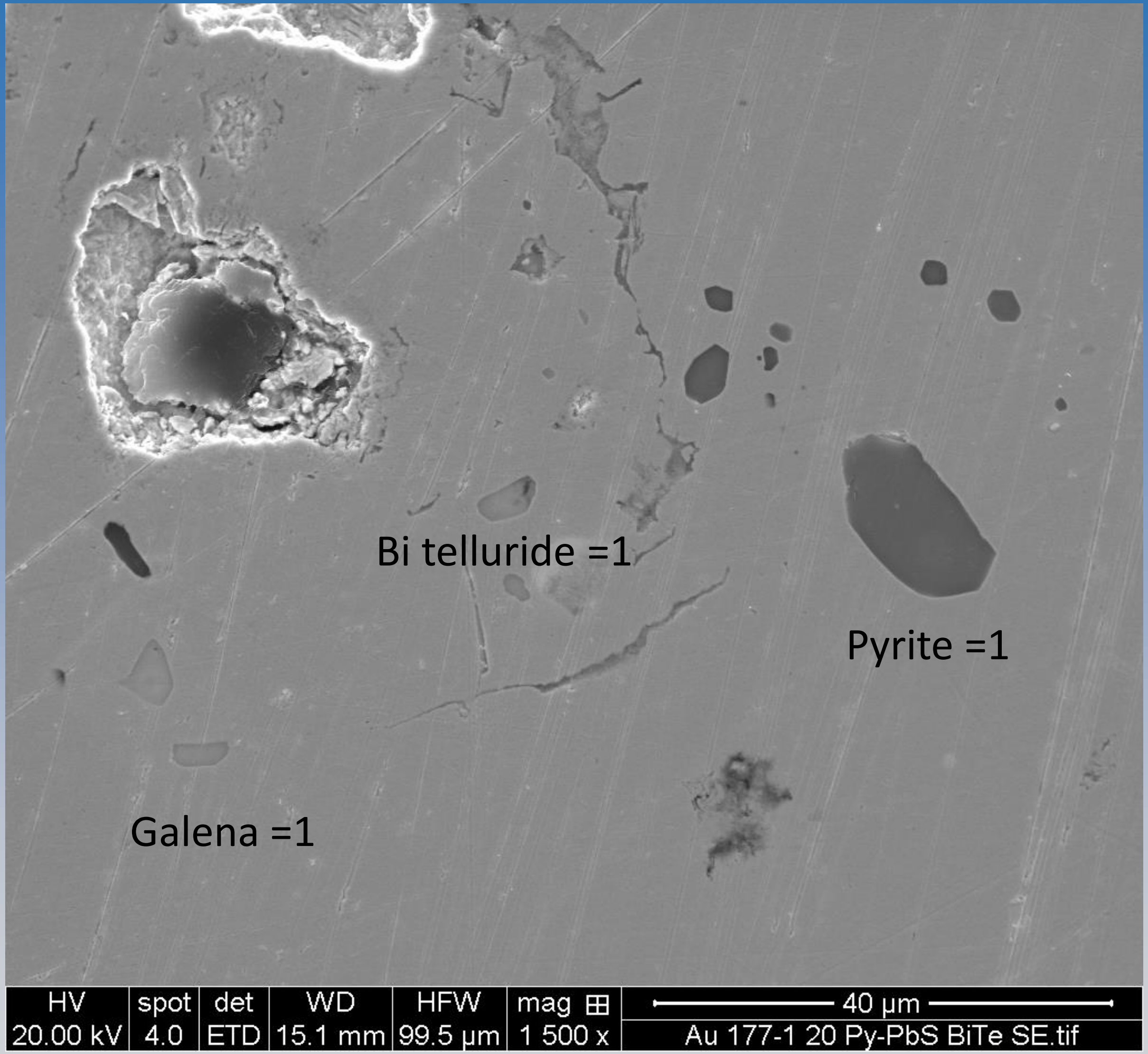




Mineral inclusions

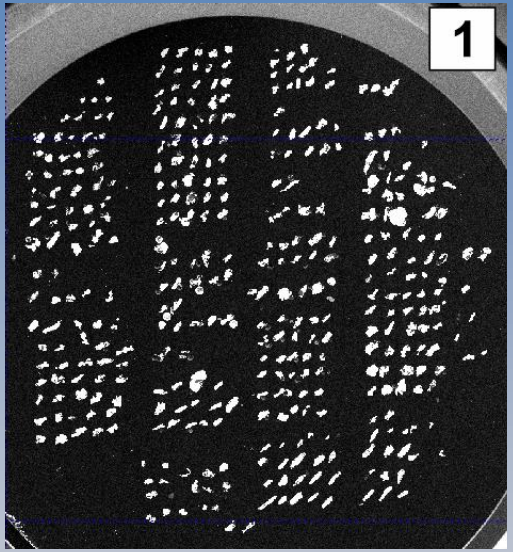
‘Rules’ for characterizing inclusion suites

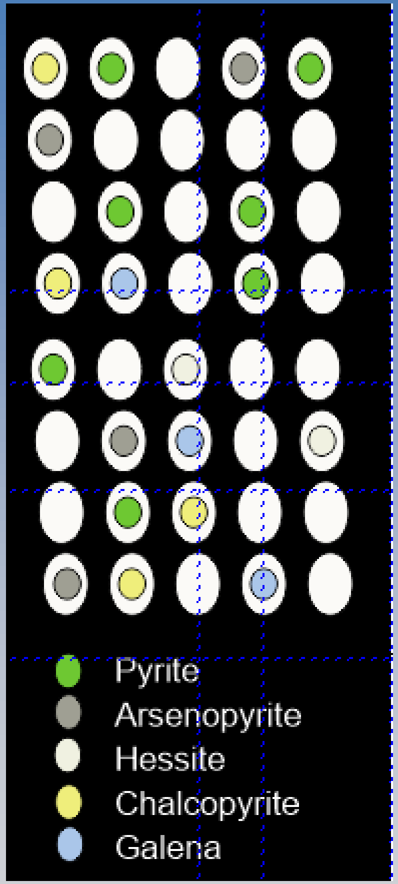




Measure the number of particles that contain an inclusion : NOT the number of inclusions
We focus on ore minerals as these are generally more diagnostic than quartz, carbonate etc

Mineral inclusions: characterizing a sample population





Tally

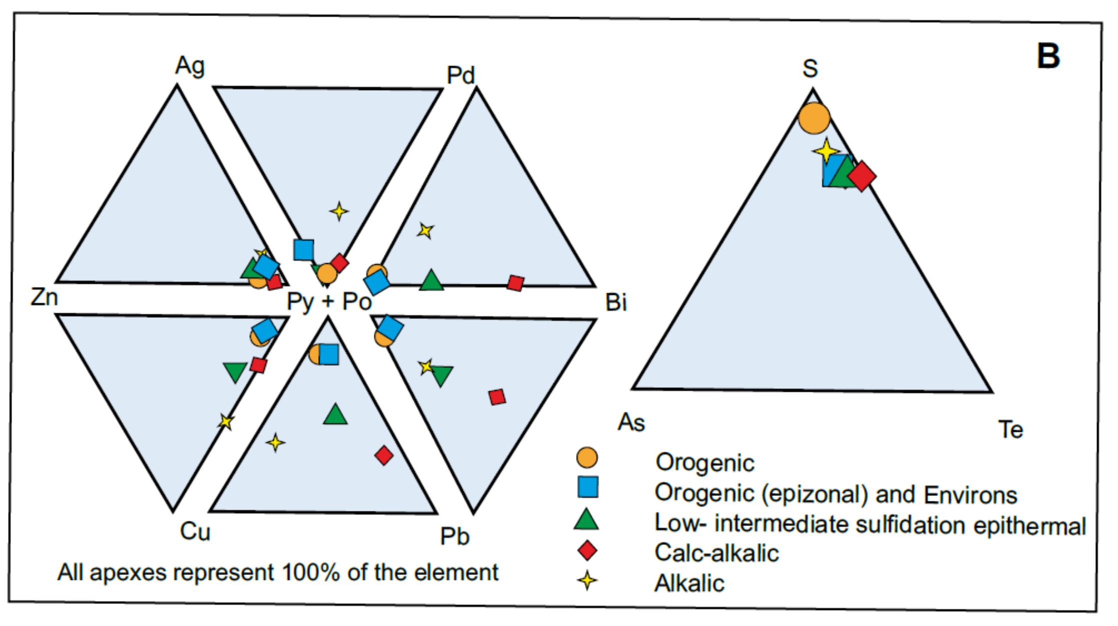
Inclusion	No. particles
Pyrite:	7
Arsenopyrite:	4
Hessite:	2
Chalcopyrite :	4
Galena :	3

Mineral basis?

Chemical basis?

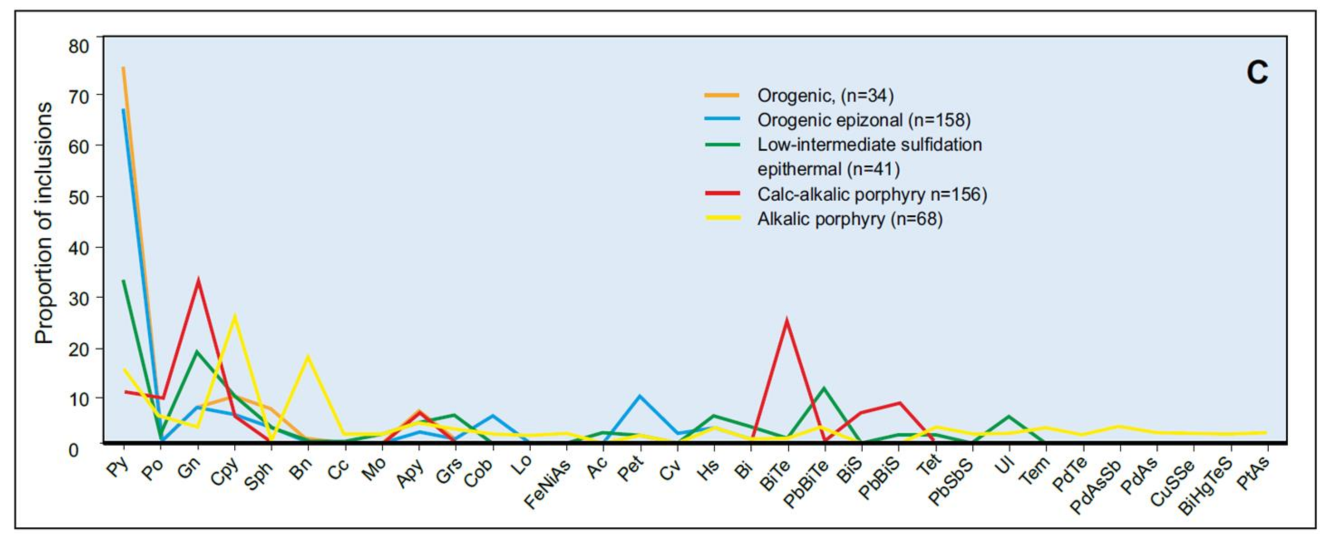
Problems:
How to depict a diverse range of minerals
Small sample sizes

Mineral inclusions:characterizing a sample population



Triangular diagrams: Lots of problems

- For complex signature need lots of triangles
- Some triangles based on very small sample sets
- OR omit some data
- Designing a generic template impossible



Spider diagrams- improvement

- Identify specific diagnostic minerals/associations
- Can accommodate large number of mineral species
- Get difficult to read with >3 plots

Chapman et al. (in press)

Mineral inclusions: characterizing a sample population

Mineral inclusion	Number of particles containing mineral
Pyrite	7
Arsenopyrite	4
Hessite	2
Chalcopyrite	2
Galena	3

'Score' inclusions according to:
1. Metal component
2. non metal component

Examples:

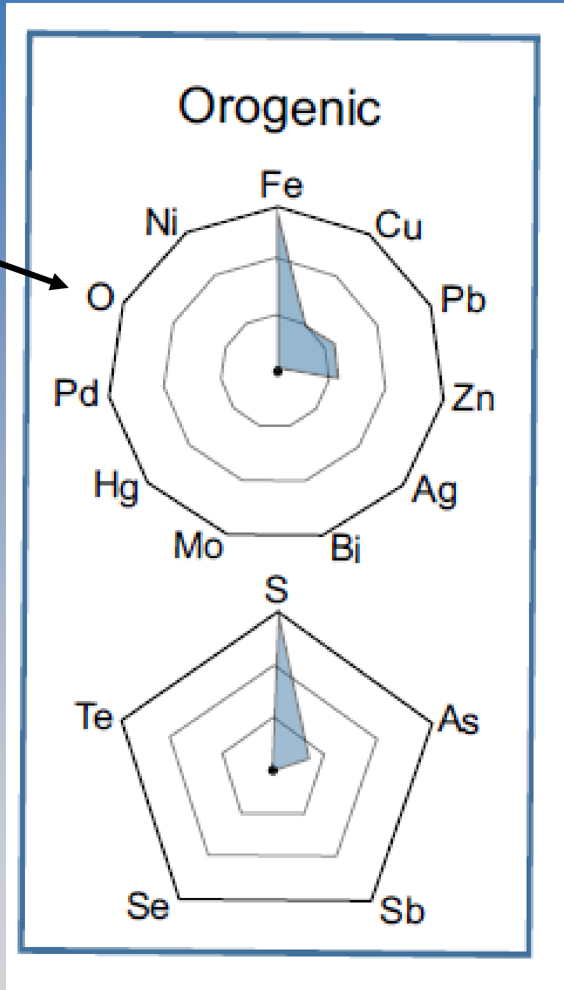
Pyrite : Fe=1, S=1
Chalcopyrite Cu=0.5, Fe= 0.5, S=1
Hessite: Ag=1, Te=1
Arsenopyrite Fe=1, S=0.5, As=0.5
Galena: Pb=1, S=1

Radar Diagrams

- Generically applicable template
- Design of axes generates distinctive shapes for element associations commonly associated with different deposit types
- Log scale elevates roles of minor metals
- Lose mineralogical information

Individual scores from Inclusions					Total	%
Fe	7	4	2		13	65
Cu	2				2	10
Pb	3				3	15
Ag	2				2	10
S	7	2	4	3	16	80
As	2				2	10
Te	2				2	10

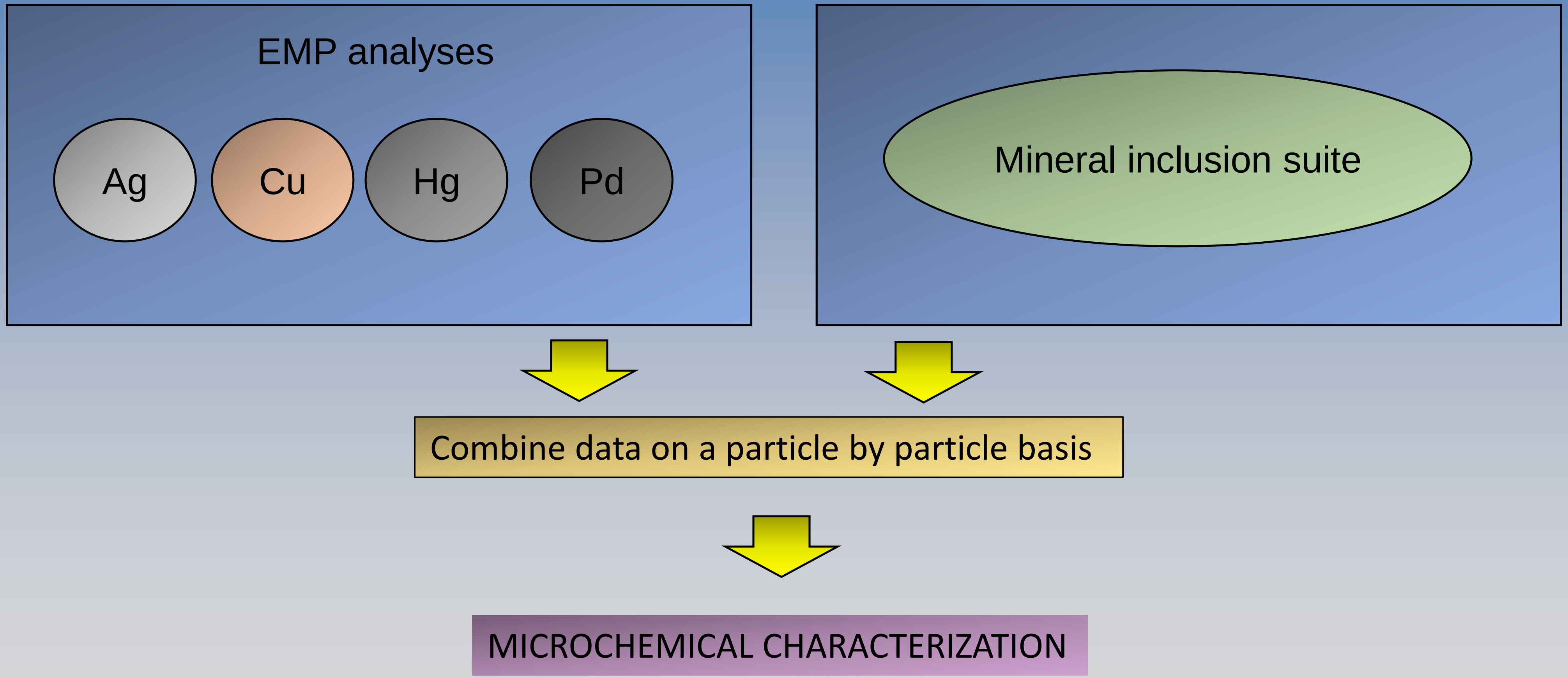
'Other'



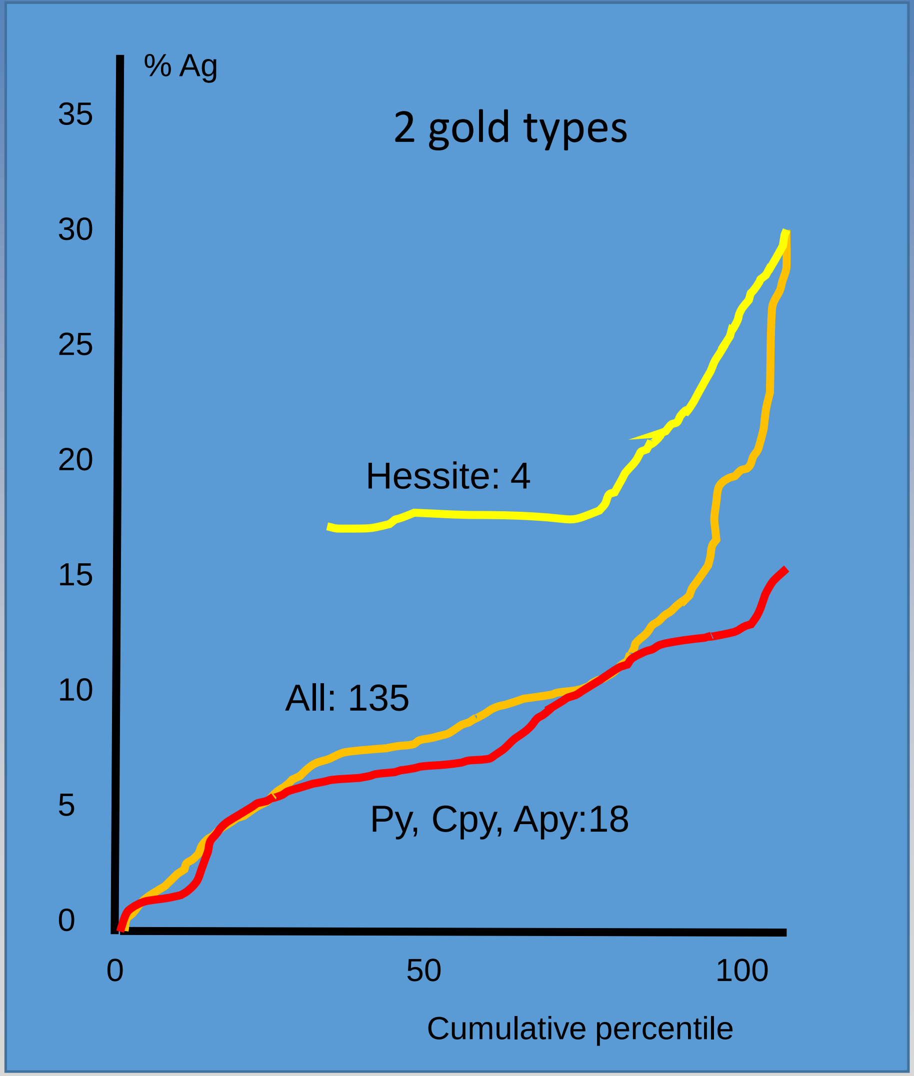
Elements considered as 'metals' and 'non metals/ metalloids'

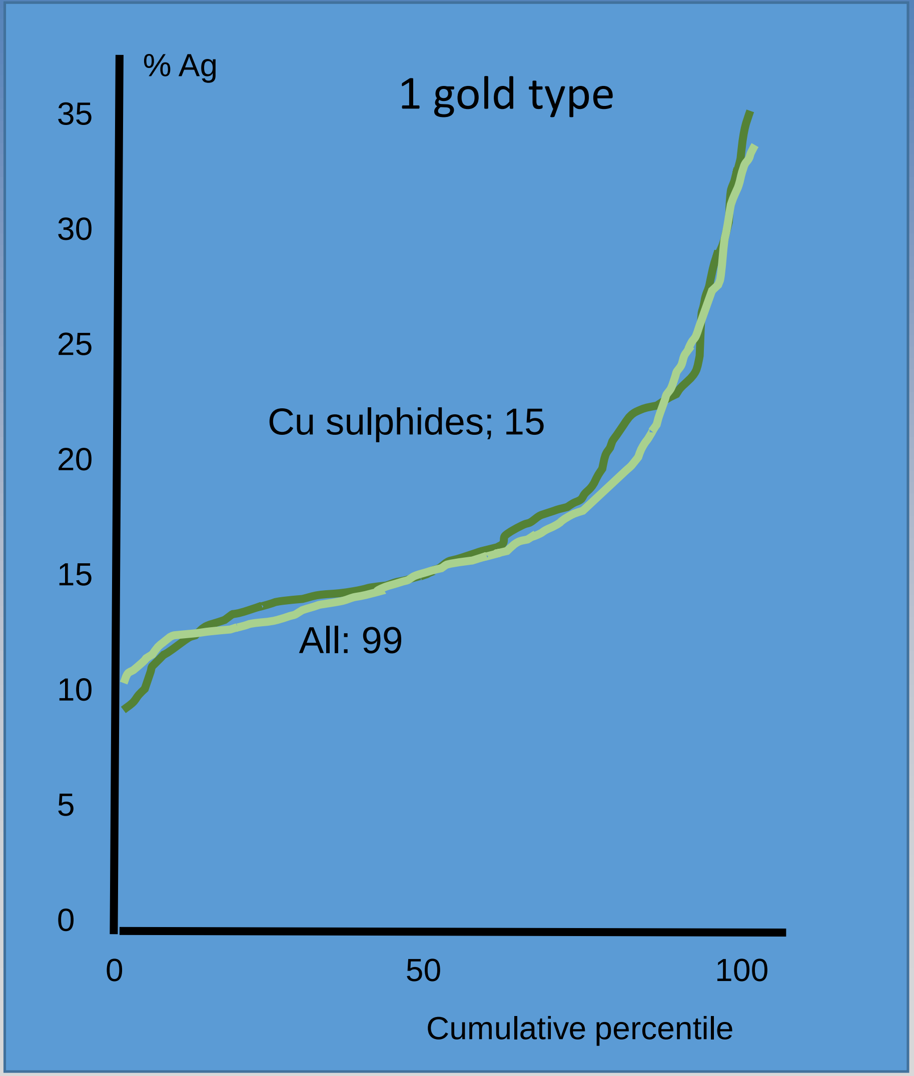
Combinations of alloy and inclusion data sets

Approach labelled ‘microchemical characterization’ by BGS in early 1990’s



Combinations of alloy and inclusion data sets





Recap

- There are various methods to depict gold compositional characteristics
- The most useful ones are generically applicable
- Specific studies may take advantage of approaches that permit multi-variate analysis
- Minor metal profiles may be interpreted in terms of
  - i. The stability of the primary mineralizing environment
  - ii the number of contributing sub- populations to a sample population
- Mineral inclusion profiles can yield more detailed information on the deposit type