HOW TO SET UP AND DEVELOP A GEOMETALLURGICAL PROGRAM

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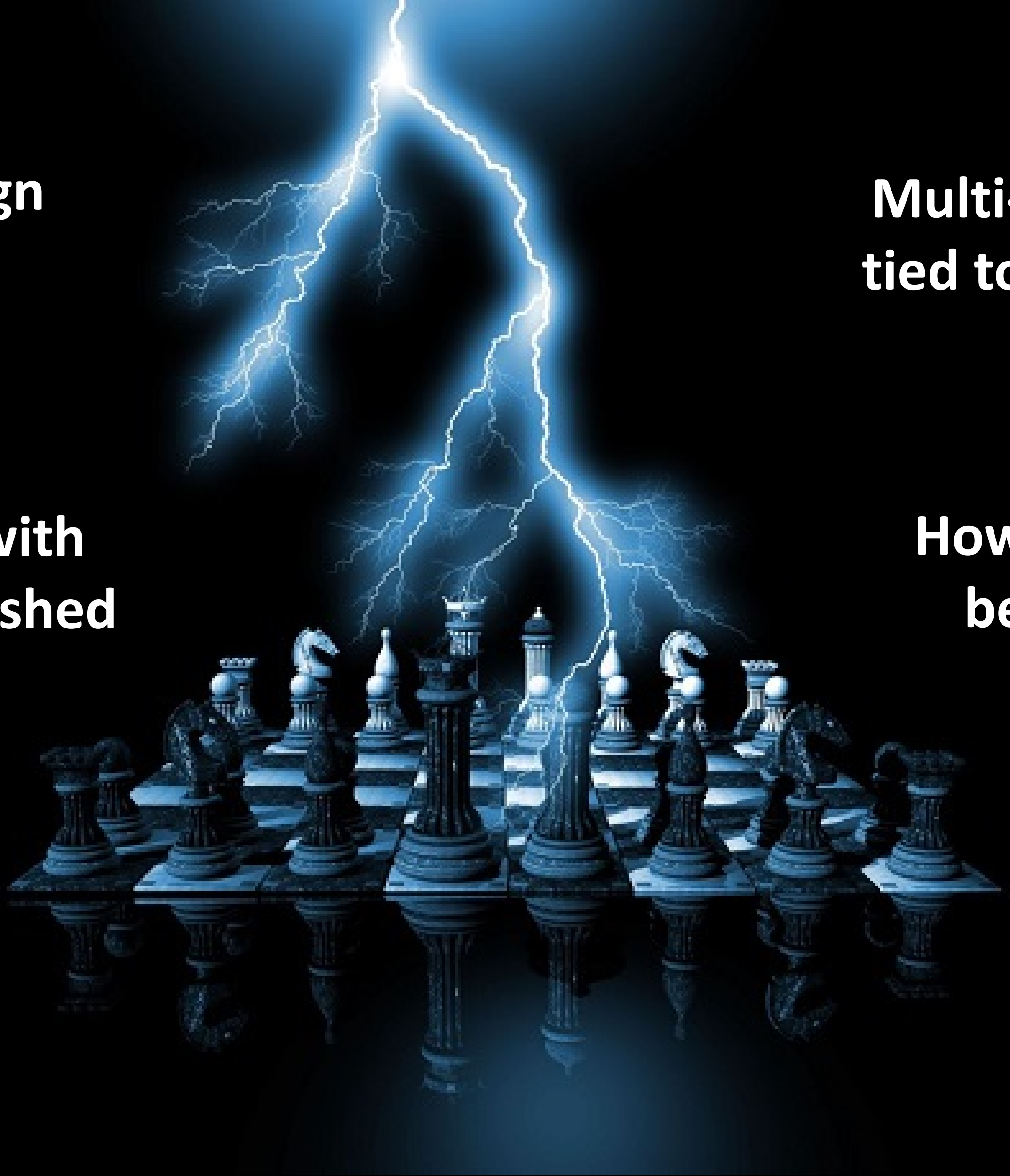
IT’S HARDER THAN IT LOOKS…

”It’s a long way to the top if you want to rock ‘n’ roll”

Bon Scott   ACDC 1975

Sound experimental design done up front

Multi-tiered data analysis tied to strategic objectives



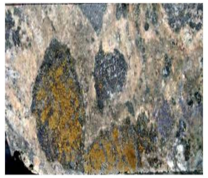
Strategic objectives set with tactical milestones established

How the final product is to be used is planned out

Victory loves preparation

OBJECTIVE 1: DEFINE MINERALOGICAL BASED PROCESS BEHAVIOUR



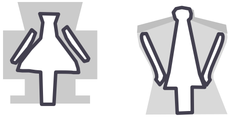



Measurement based efficiency of each individual process in context of a family of ore types

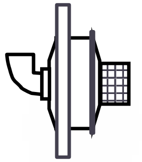
As opposed to a vague one recovery target for the whole process circuit for all ore types

With the capability to map this ore type process behavior into the deposit

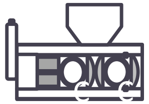
Where previously, only grade and geology domains were mapped



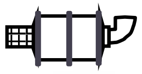
Crushers



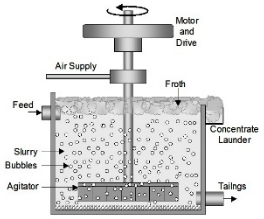
SAG/AG Mill



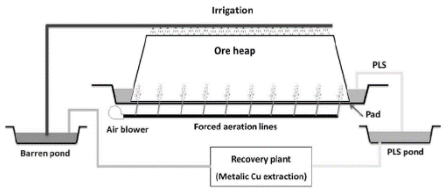
HPGR



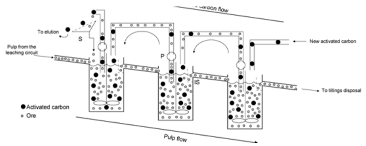
Ball Mill



Flotation

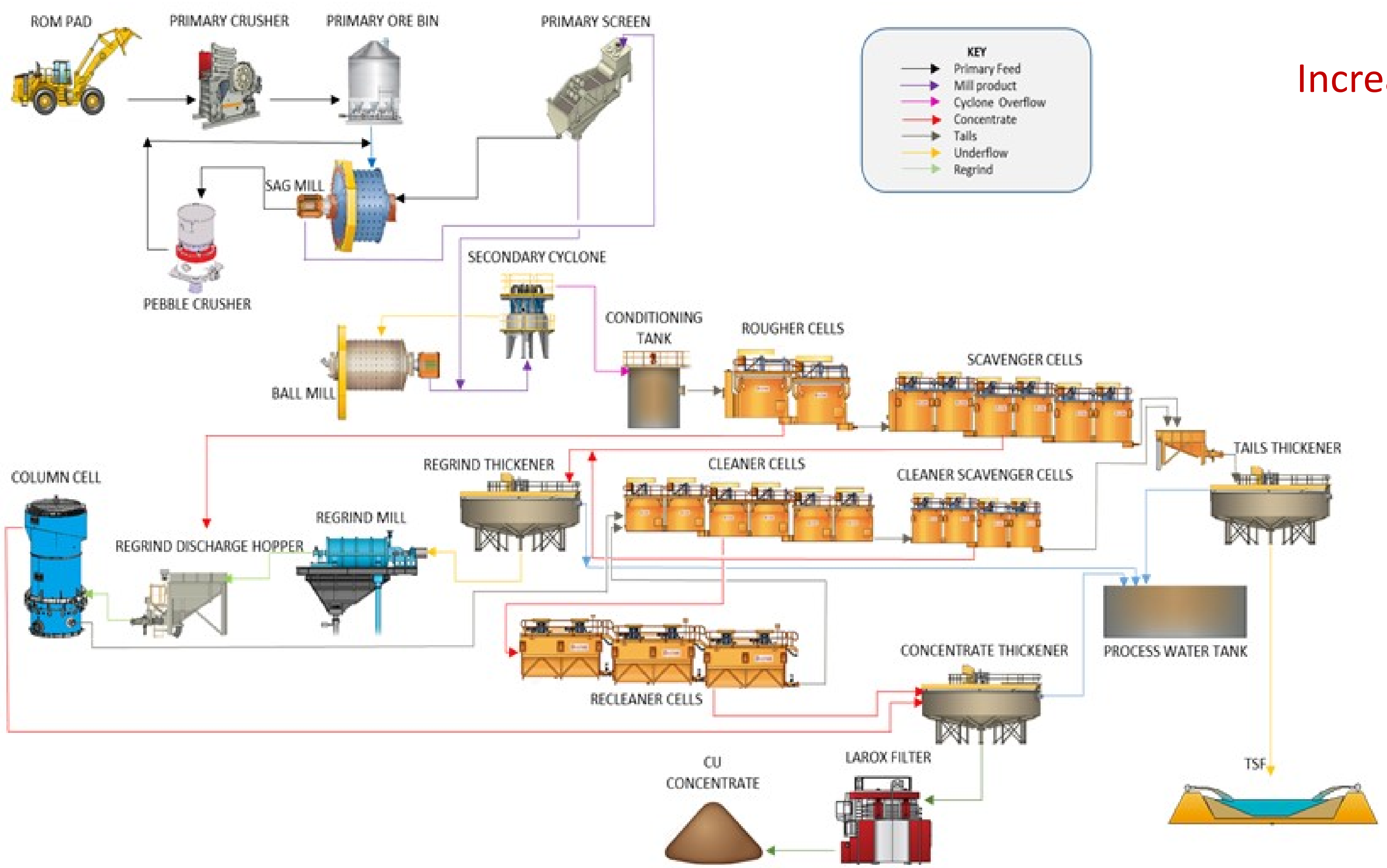


Dump Leach



CIL Leach Tank

OBJECTIVE 2: DEFINE MOST EFFECTIVE PROCESS PLANT DESIGN



Increases precision

Exploration

Geometallurgy

Large scale characterization

Process design

Business model

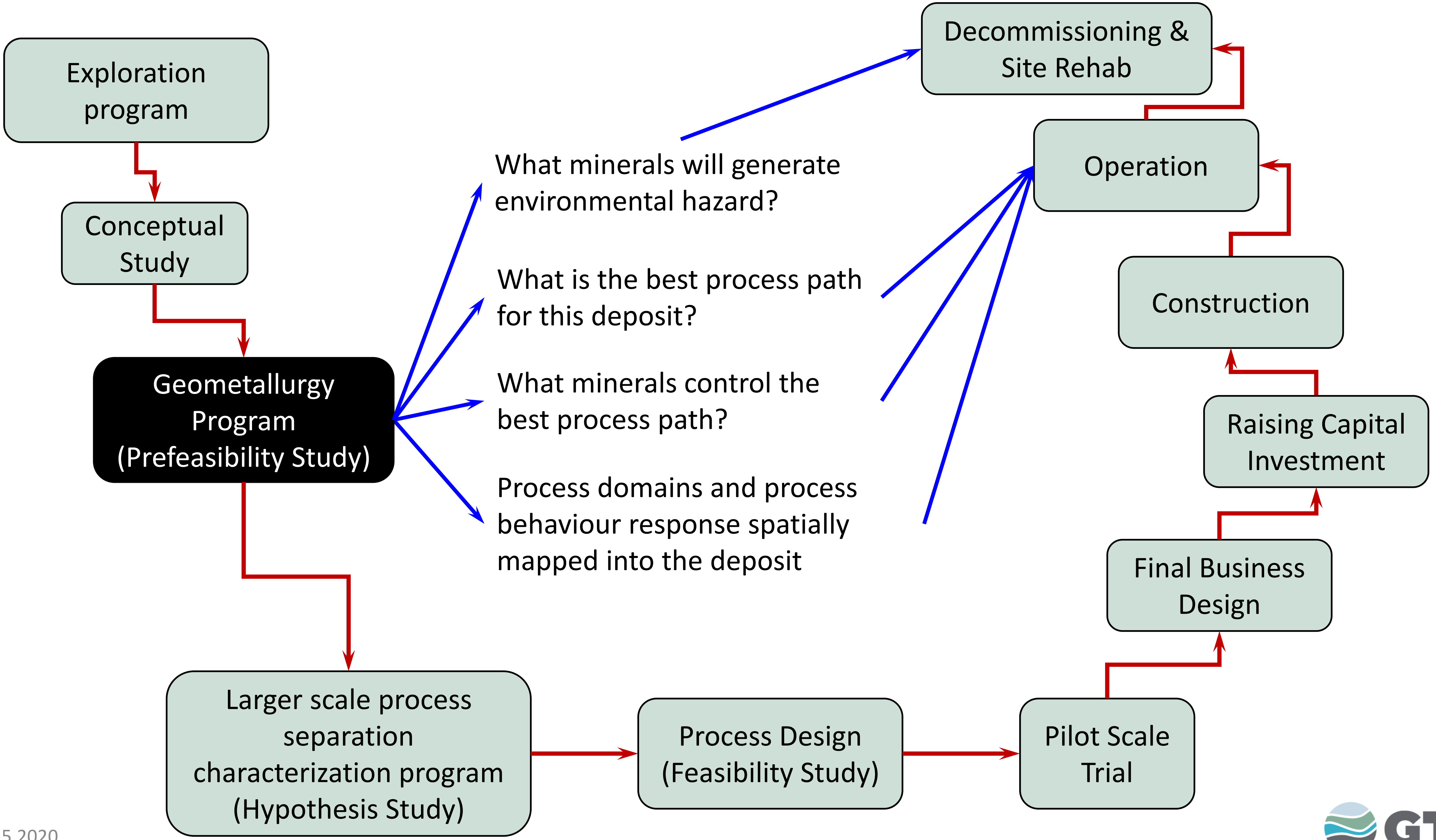
Go/no go decision

Mining sequence to stockpile

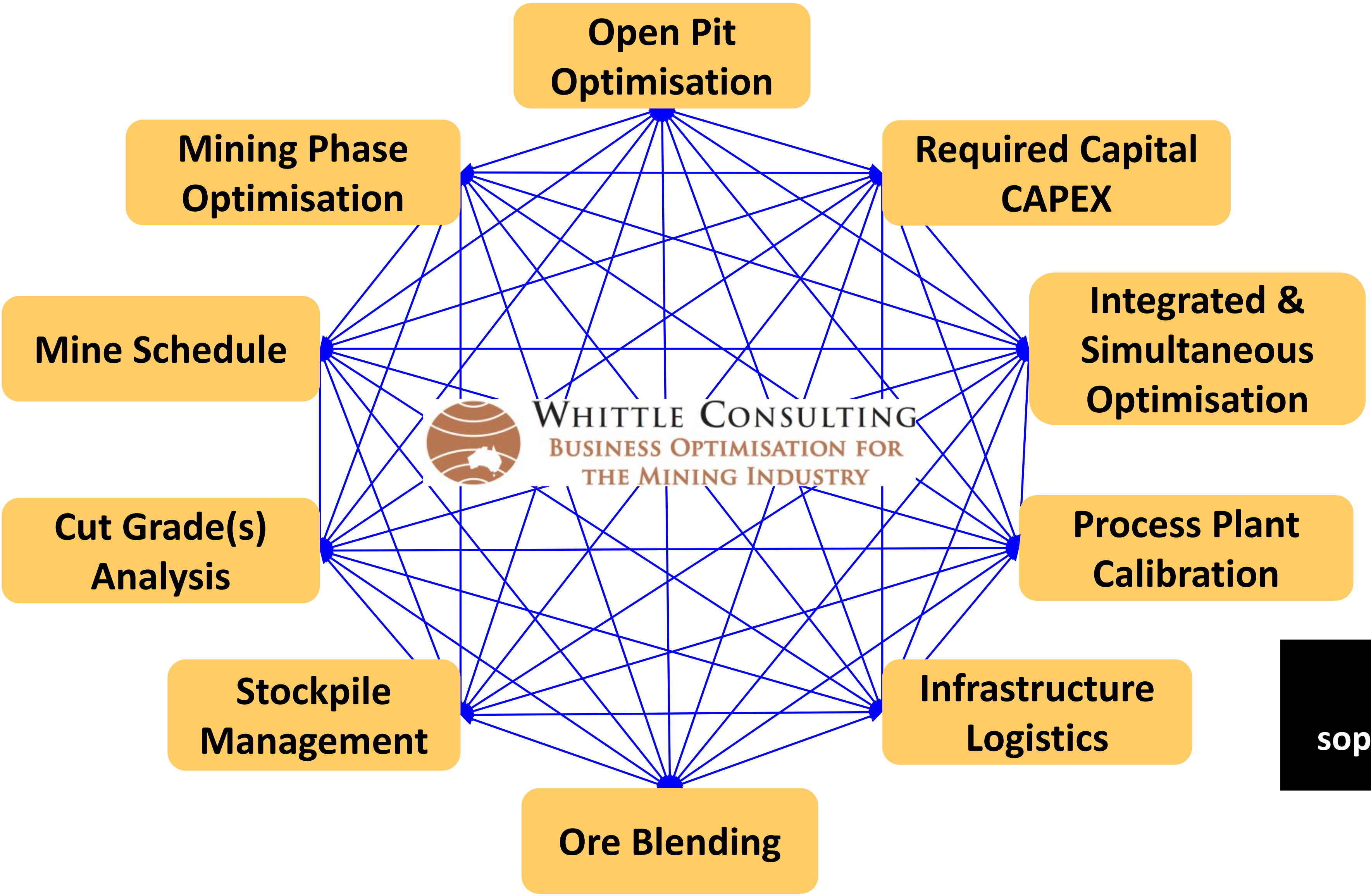
Construction

De-risked

Commissioning


Exploration program
Conceptual Study
Geometallurgy Program (Prefeasibility Study)
What minerals will generate environmental hazard?
What is the best process path for this deposit?
What minerals control the best process path?
Process domains and process behaviour response spatially mapped into the deposit
Larger scale process separation characterization program (Hypothesis Study)
Process Design (Feasibility Study)
Pilot Scale Trial
Final Business Design
Raising Capital Investment
Construction
Operation
Decommissioning & Site Rehab

OBJECTIVE 3 - IDEAL OPTIMISATION CYCLE

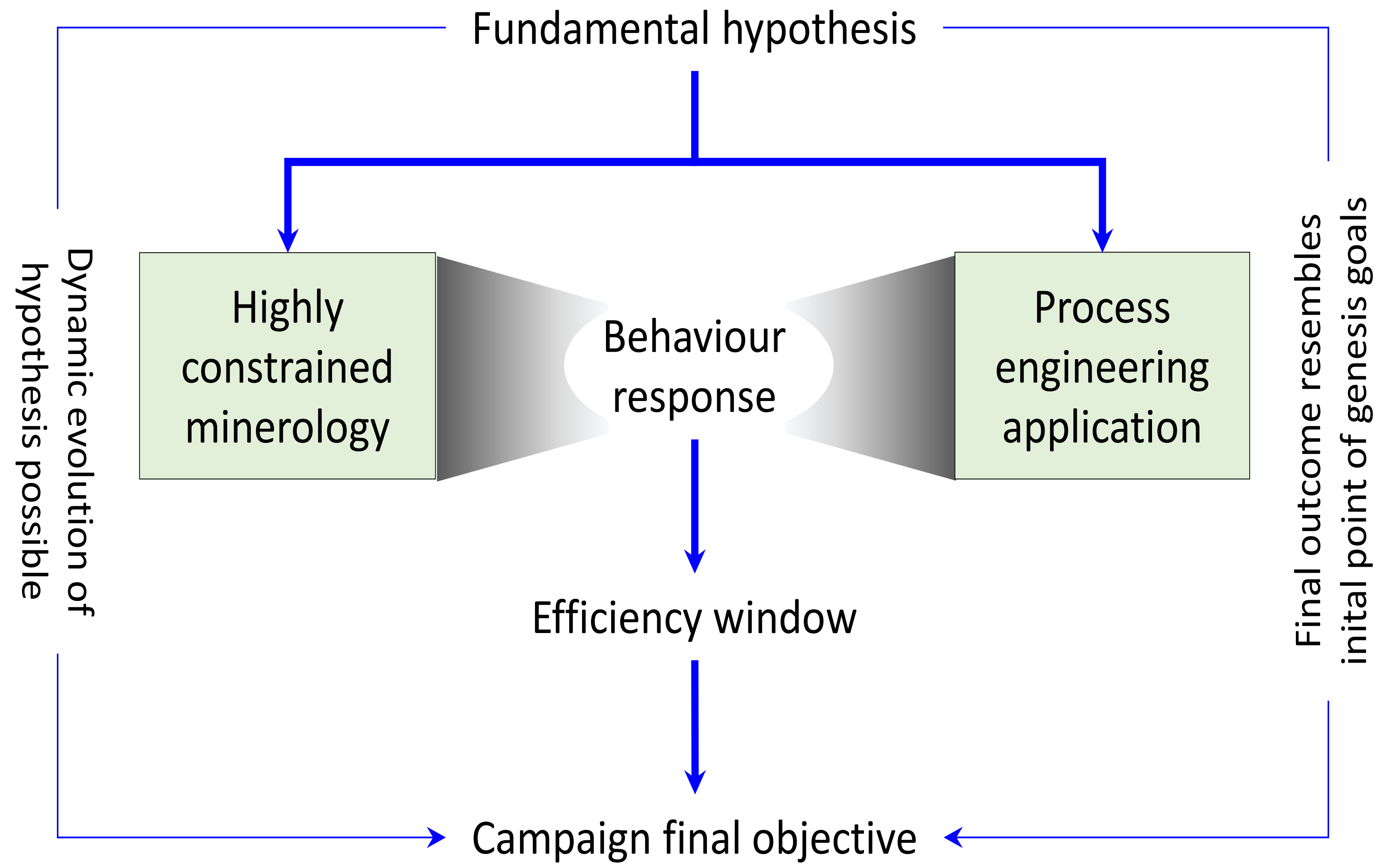


Geometallurgy is sophisticated data support

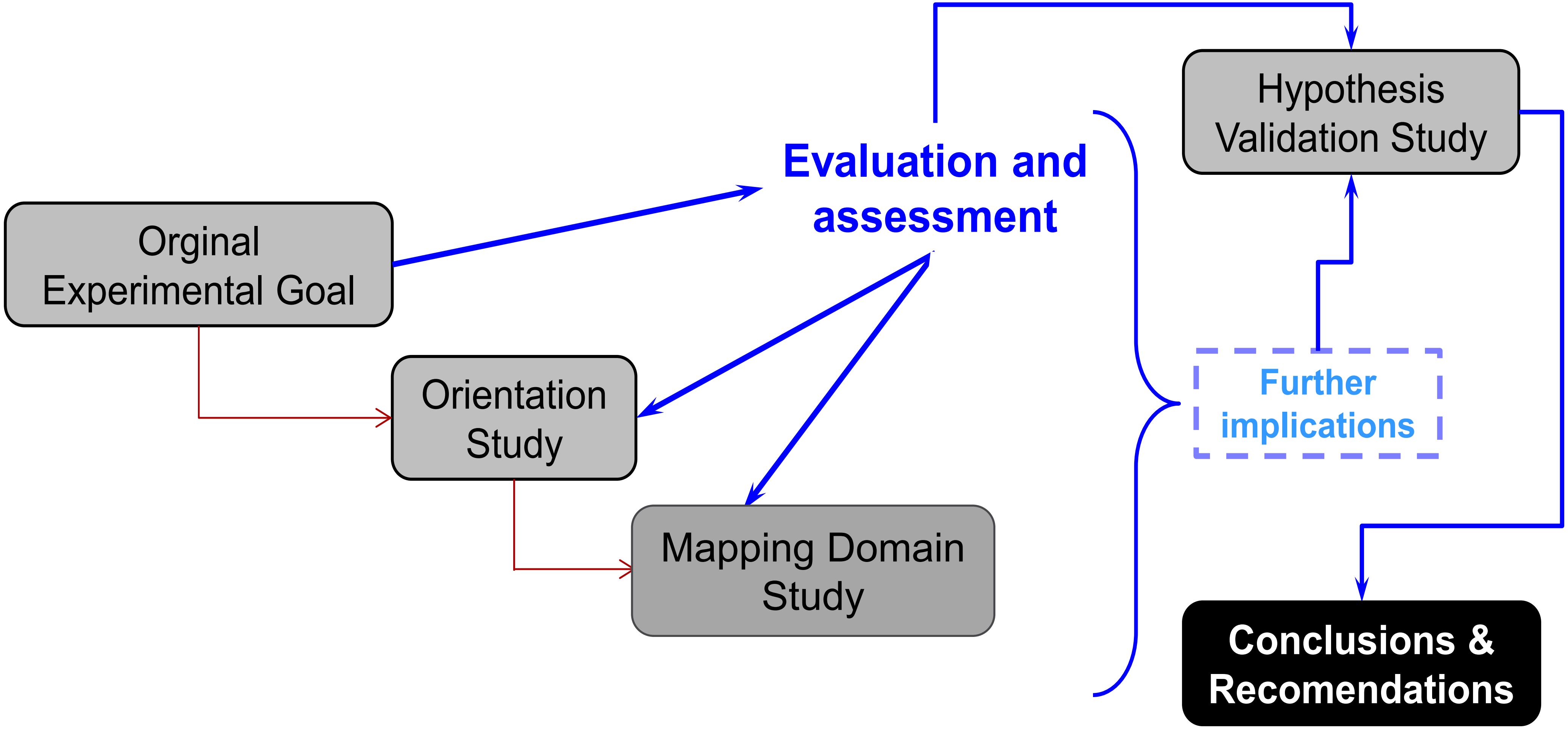
OBJECTIVE 4 – MITIGATE RISK

- At the feasibility stage(s), CAPEX closely resembles the final commissioning reality
- Once operating, the deposit is comprehensively characterised which allows flexible changes in the mine schedule and process response can be accurately predicted
- Where decisions on process plant expansion, open pit cutback expansions and maintenance shutdowns can all be planned in context of risk uncertainty with more precision
- The corporate executive board benefit the most from this outcome

SETTING OBJECTIVES



EVALUATION OF EXPERIMENTAL OBJECTIVE TARGETS AGAINST ORIENTATION AND MAPPING STUDIES



PHASES IN A GEOMETALLURGY CAMPAIGN

1. Campaign planning of objectives
2. Sample selection
3. Experimental test work
4. Analysis of data outcomes
5. Assessment of analytical outcomes
6. Further sampling and test work
7. Economic modelling and optimisation
8. Development of production protocol

AND NOW A WARNING…

Also known as the 'seagull' problem

Be very clear in your mind what you are about and what success looks like

Other departments may try and 'influence' what you spend your budget on

THE FULL PROCEDURE

(0) Geometallurgical Experimental & Analyitcal Goals

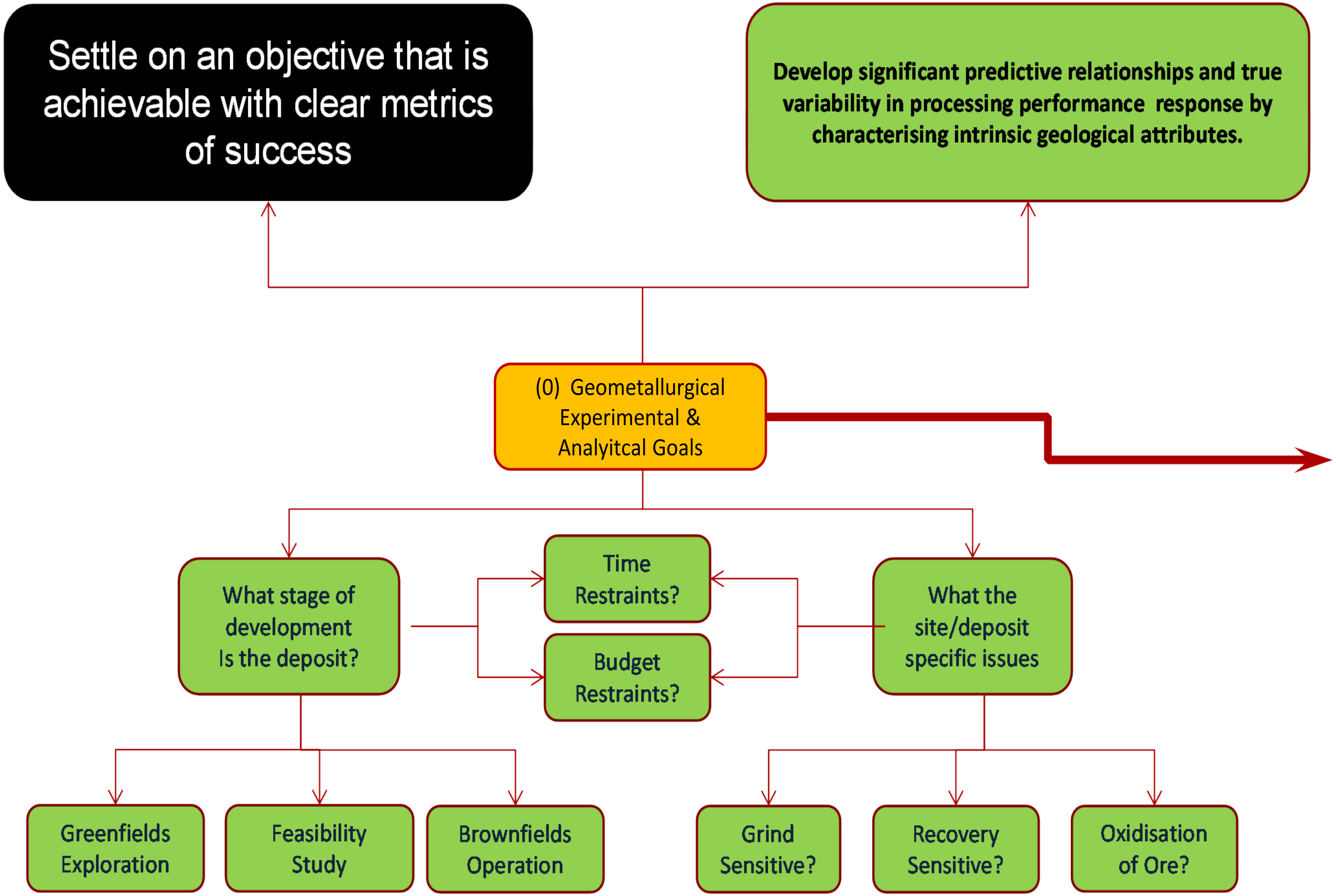
(1) Ore Body Analysis of Existing Knowledge

(2) Creation of foundation geomet matrix based on existing knowledge

(3) Geometallurgical Orientation Study

(4) Orientation Study Test Work Planning

(5) Orientation Study Analysis


Settle on an objective that is achievable with clear metrics of success
Develop significant predictive relationships and true variability in processing performance response by characterising intrinsic geological attributes.
(0) Geometallurgical Experimental & Analyitcal Goals
What stage of development Is the deposit?
Time Restraints?
Budget Restraints?
What the site/deposit specific issues
Greenfields Exploration
Feasibility Study
Brownfields Operation
Grind Sensitive?
Recovery Sensitive?
Oxidisation of Ore?

CAMPAIGN PLANNING AND SETTING OF OBJECTIVES

- What is the fundamental question?
  - *Establishing the best process path*
  - *Choice between SAG mill or HPGR*
  - *Recovery efficiency, if so, which metal(s)?*
  - *Ore type definition*
  - *Choice between hydromet or pyromet*
  - *Penalty element impact*

- What are the related questions the same samples could be use for at a later date?
- Map out existing site knowledge
  - *Reports, feasibility studies, data sets*
  - *Talk to site personnel of all stripes*

FOR A GIVEN JOB, WHERE ARE YOU IN THE MINING CYCLE?

- Feasibility study
  - *True value of the resource*
  - *Economic viability*
  - *Most effective process design*
- Developing the mine schedule
  - *Block model*
  - *Cut off grade analysis*
- Geomet for long term variability
  - *Life of Mine cycle*
  - *Operation total footprint*
- Commissioning
  - *Bringing plant production up to design expectations*
- Geometallurgy for operations
  - *Show stoppers & penalties in feed stream (clay, Cl, Fl, As, etc)*
  - *Predicted variability in ore hardness*
  - *Metallurgical reconciliation*
  - *Maintenance schedule*
  - *Plant expansion*
- Environmental Impact
  - *Mine site waste plume*
  - *Legacy impact*
  - *Mine closure and site rehabilitation*

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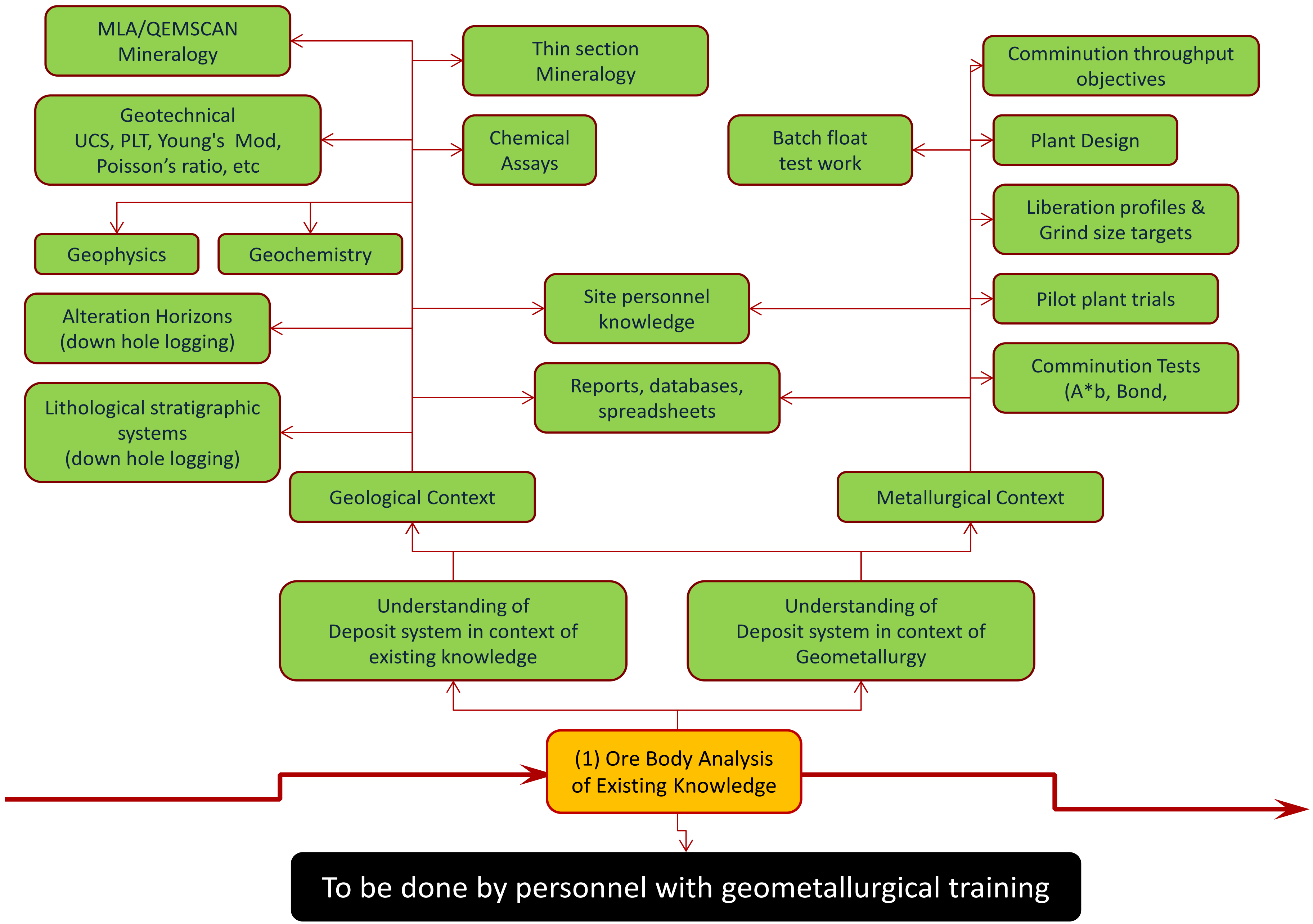
MLA/QEMSCAN Mineralogy
Thin section Mineralogy
Geotechnical UCS, PLT, Young's Mod, Poisson's ratio, etc
Chemical Assays
Batch float test work
Comminution throughput objectives
Plant Design
Liberation profiles & Grind size targets
Geophysics
Geochemistry
Site personnel knowledge
Pilot plant trials
Alteration Horizons (down hole logging)
Reports, databases, spreadsheets
Comminution Tests (A*b, Bond,
Lithological stratigraphic systems (down hole logging)
Geological Context
Metallurgical Context
Understanding of Deposit system in context of existing knowledge
Understanding of Deposit system in context of Geometallurgy
(1) Ore Body Analysis of Existing Knowledge
To be done by personnel with geometallurgical training

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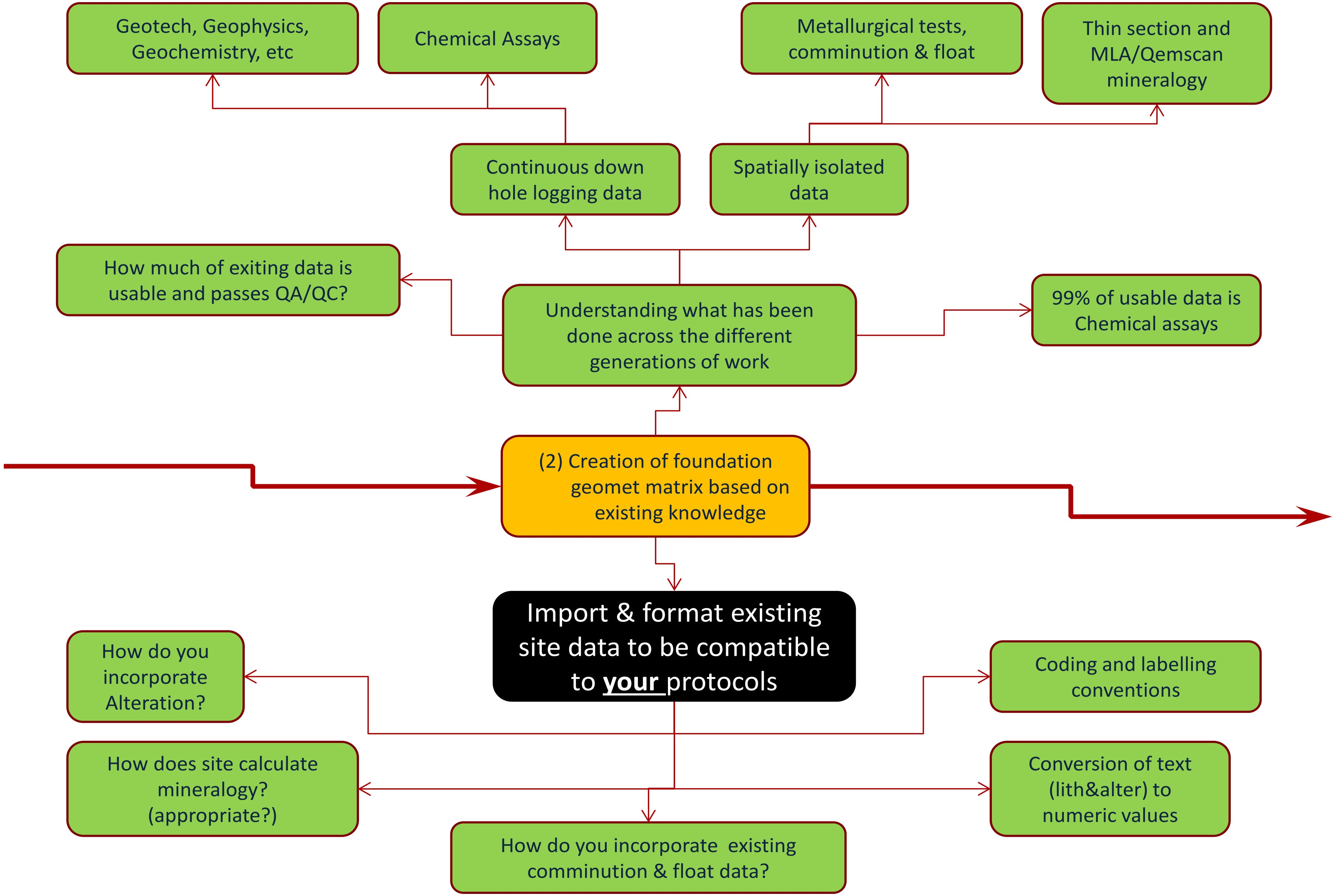
Geotech, Geophysics, Geochemistry, etc
Chemical Assays
Metallurgical tests, comminution & float
Thin section and MLA/Qemscan mineralogy
Continuous down hole logging data
Spatially isolated data
How much of exiting data is usable and passes QA/QC?
Understanding what has been done across the different generations of work
99% of usable data is Chemical assays
(2) Creation of foundation geomet matrix based on existing knowledge
Import & format existing site data to be compatible to your protocols
How do you incorporate Alteration?
Coding and labelling conventions
How does site calculate mineralogy? (appropriate?)
Conversion of text (lith&alter) to numeric values
How do you incorporate existing comminution & float data?

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EXPERIMENTAL TEST PHASES OF A GEOMET CAMPAIGN

Orientation Study

- 10-20 samples of end member samples
- The Race
- Deposit specific hypothesis formation

Mapping Hypothesis samples

- 1500-2000m of drill core
- 4-5 continuous sections across deposit major structures
- Intelligent selection of tests that interrelate with final objectives

Hypothesis Response samples

- 500-1000m of drill core
- To fill in and test missing sections shown up in Mapping Hypothesis Sample set

To be collected only once you know what is missing, not before

If you are able to, collect these samples at the same time

SAMPLE SELECTION FOR THE GEOMETALLURGY STUDY

Site geologist intuition is to be listened to and considered

- What ore types do they think are relevant
- What deposit geology structures are most significant
- What drill holes traverse and map these structures

Site metallurgist intuition is to be listened to and considered

- What is the process range found so far in this deposit?
- Axb & BMWi extremes
- Flotation recovery performance so far
- Leaching recovery so far
- What minerals are causing them grief so far?
- Are there site specific assay models that have been developed?

Settle on the number of extreme textures (end members)

- *Spend time in the core yard and help do the sampling and packing*

Ideal: 1500-2000m of half drill core (biggest size possible)

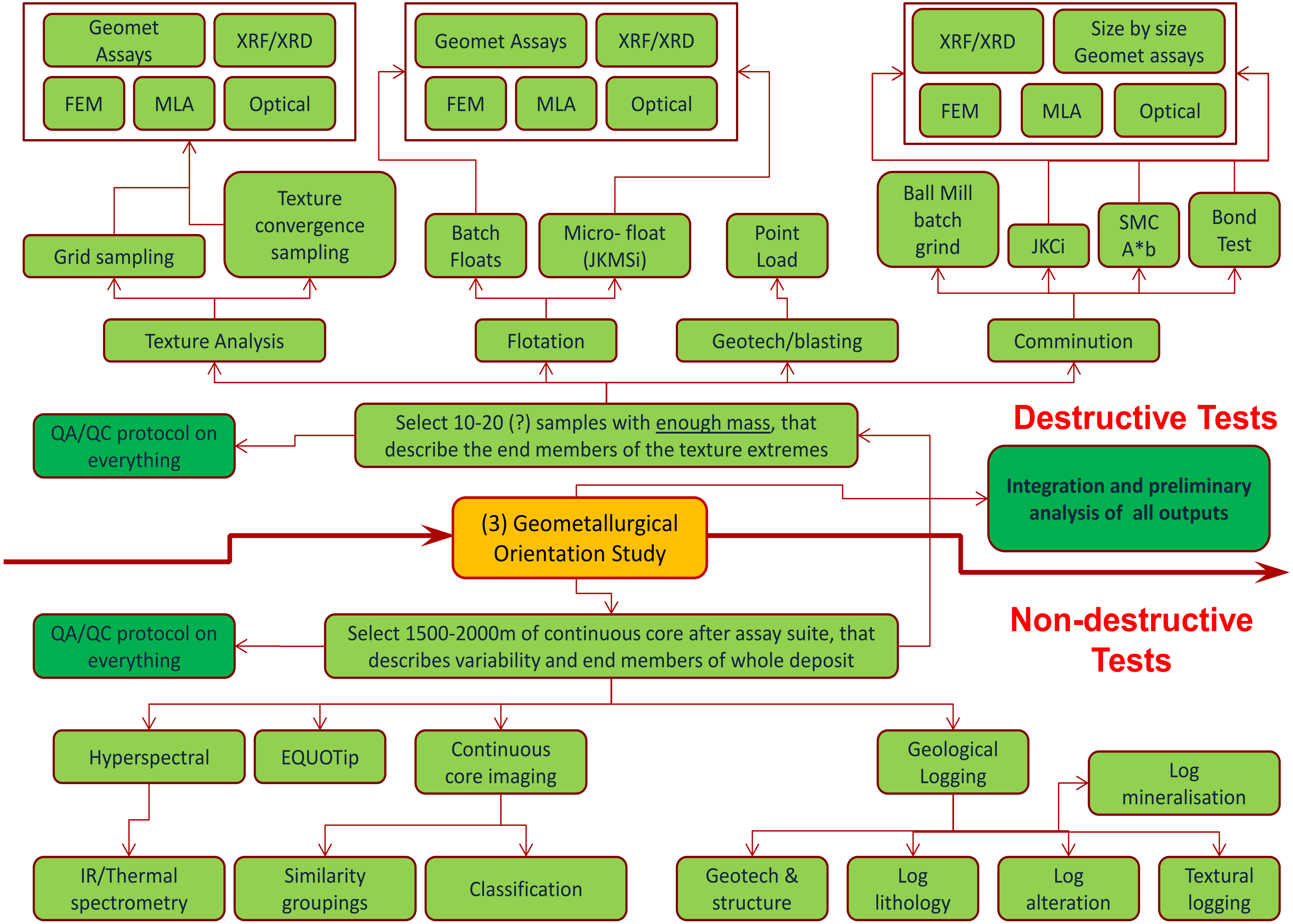
POOR QUALITY CORE IS NOT TO BE REJECTED

- Traditionally metallurgical sampling (comminution in particular) has been done one only the good quality bits of core

- Whereas the core is often broken up due to the friable nature of the rock

- This is often where we find the clays and poor recovery performing ore types
  - *The fines in particular in the bottom of the tray*

- The comminution of these samples might be faster (often softer ore is friable) but the recovery performance could be poor
  - *Needs to be mapped and modelled if this ore type is in large quantities in the drilling library*


Geomet Assays
XRF/XRD
FEM
MLA
Optical
Geomet Assays
XRF/XRD
FEM
MLA
Optical
XRF/XRD
Size by size Geomet assays
FEM
MLA
Optical
Grid sampling
Texture convergence sampling
Batch Floats
Micro- float (JKMSi)
Point Load
Ball Mill batch grind
JKCi
SMC A*b
Bond Test
Texture Analysis
Flotation
Geotech/blasting
Comminution
QA/QC protocol on everything
Select 10-20 (?) samples with enough mass, that describe the end members of the texture extremes
Destructive Tests
Integration and preliminary analysis of all outputs
(3) Geometallurgical Orientation Study
Non-destructive Tests
QA/QC protocol on everything
Select 1500-2000m of continuous core after assay suite, that describes variability and end members of whole deposit
Hyperspectral
EQUOTip
Continuous core imaging
Geological Logging
Log mineralisation
IR/Thermal spectrometry
Similarity groupings
Classification
Geotech & structure
Log lithology
Log alteration
Textural logging

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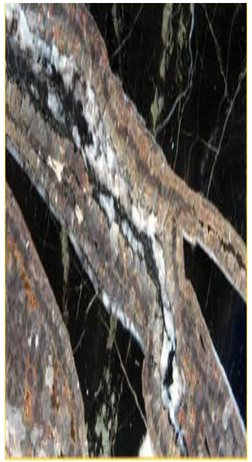
SAMPLE SELECTION FOR THE ORIENTATION STUDY

- Using the 1500-2000m of half core you sampled from site previously
- Isolate the end member textures into assay interval sections
  - *We want to target the extremes of rock textures in the deposit*
  - *Variability mapping will come later*
- Select for each end member a section (2-6m length HQ half core / 20-25kg)
  - *Consistent lithology across whole section (do your best with what you have)*
  - *If veins and intrusions are in the sample, make sure they are all though the sample, not just one or two isolated places*
- So all tests (bankable and proxy) will be done on as close to the same lithology and mineralogy as practically possible
- A good number of end member samples is 10-15
  - *Deposit specific, let the rock speak*

Keep in mind possible future work on these samples

SELECT THE ORIENTATION SAMPLES



Orientation Sample 1

Orientation Sample 2

Orientation Sample 3

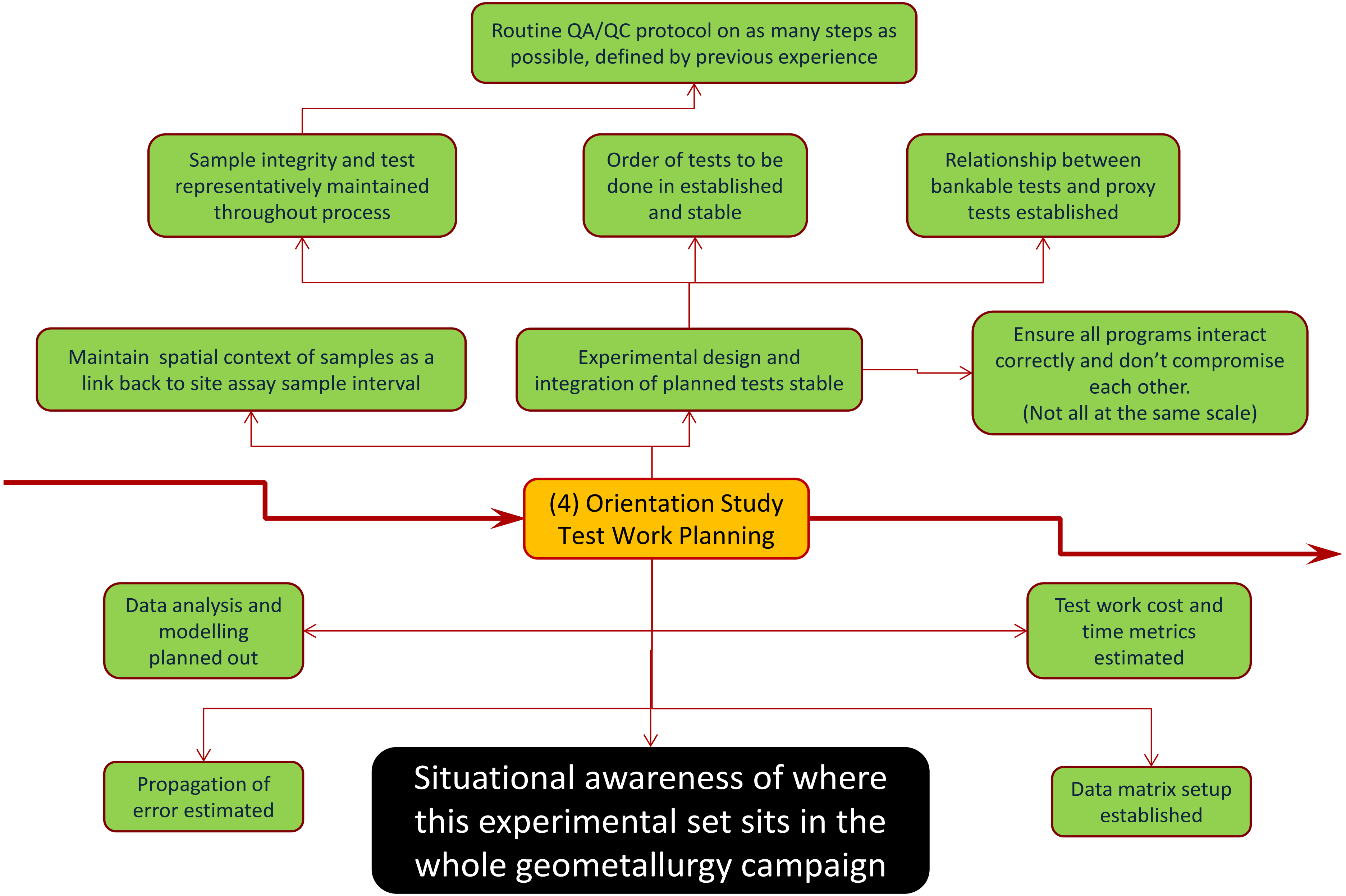
Orientation Sample 4

Orientation Sample 5

Orientation Sample 7

Orientation Sample 8

Selection of all of the rock texture end members, together forming the samples for the Orientation Study. Each sample would be approximately 20-30kg. It is of paramount importance that the mineralogy and lithology rock texture is consistent throughout this sample. It is preferable to have less sample mass and more consistent mineral rock texture, than a larger sample mass.


Routine QA/QC protocol on as many steps as possible, defined by previous experience
Sample integrity and test representatively maintained throughout process
Order of tests to be done in established and stable
Relationship between bankable tests and proxy tests established
Maintain spatial context of samples as a link back to site assay sample interval
Experimental design and integration of planned tests stable
Ensure all programs interact correctly and don't compromise each other.
(Not all at the same scale)
(4) Orientation Study Test Work Planning
Data analysis and modelling planned out
Test work cost and time metrics estimated
Propagation of error estimated
Situational awareness of where this experimental set sits in the whole geometallurgy campaign
Data matrix setup established

Robust data QA/QC in conjunction with competent experimental test work is the best way to manage propagation of error

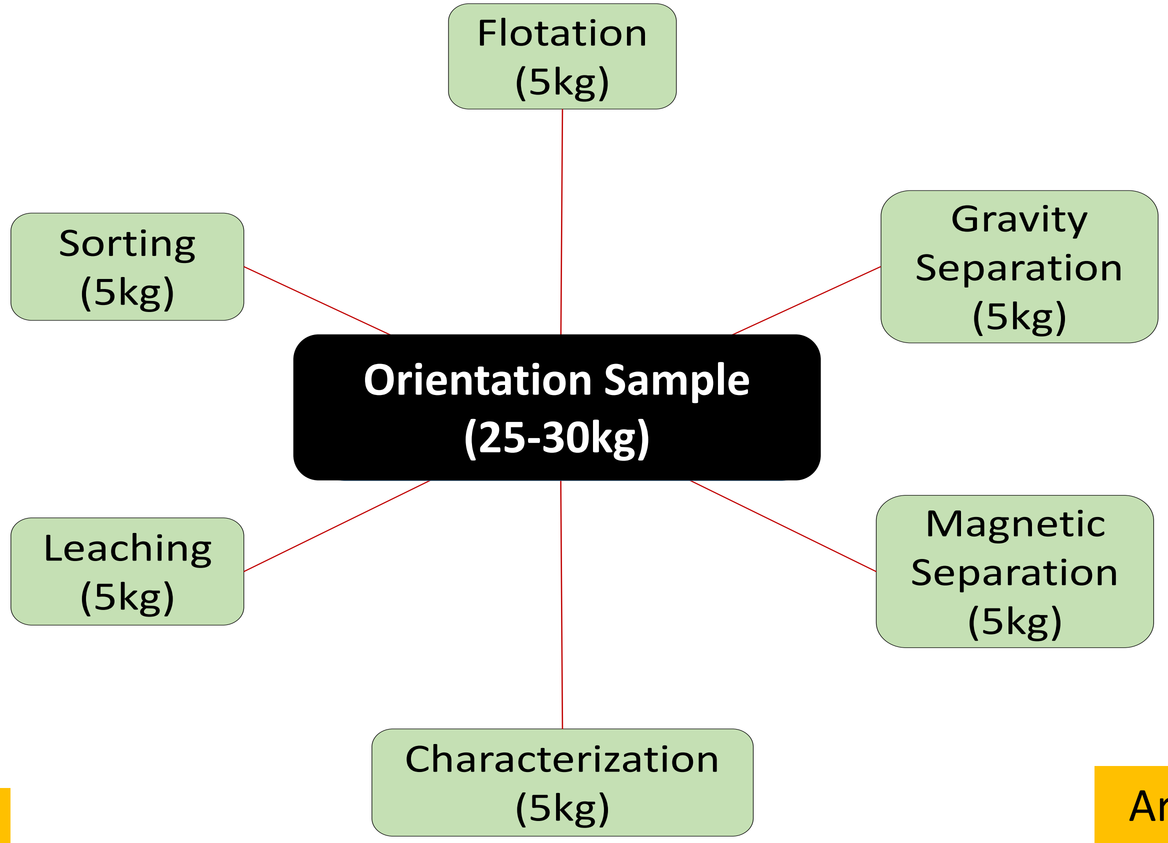
(Plan the flight, then fly the plan)

PROCESS RESPONSE

What minerals control flotation separation?

What minerals control sorting separation?

What minerals control gravity separation?



What minerals control leaching?

What minerals control magnetic separation?

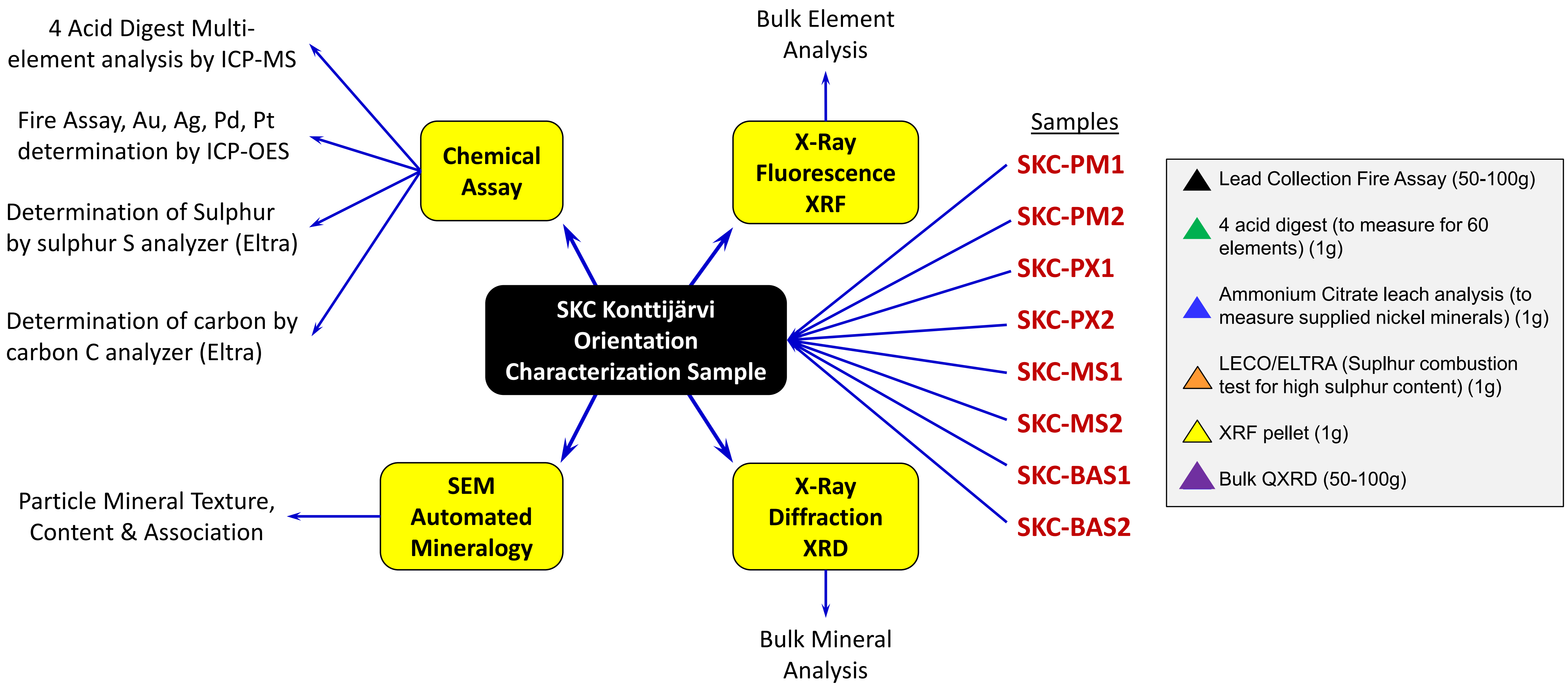
How do those minerals interact with the process separation?

How do I characterize this ore?

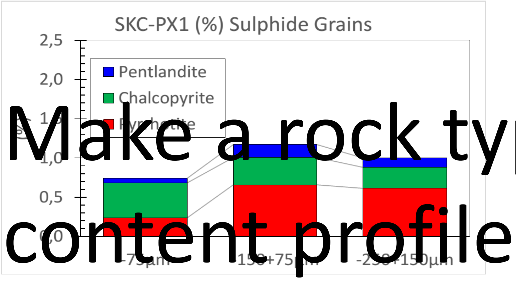
Are the controlling minerals at each expt stream different?

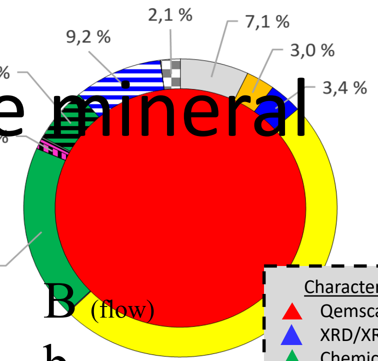
If so, what is really an ore type?

CHARACTERIZATION ANALYSIS OF EACH ORIENTATION SAMPLE



Make a rock type mineral content profile





B (flow)

b_i (components)

PX1 Pyrrhotite, Average Mineral Association (%)

Average Sulphide Mineral Size (µm)

PX1	Pentlandite (µm)	Chalcopyrite (µm)	Pyrrhotite (µm)
-250+150µm	73,32	82,26	95,67
-150+75µm	46,62	59,80	69,09
-75µm	8,53	33,00	12,00

Feed Sample

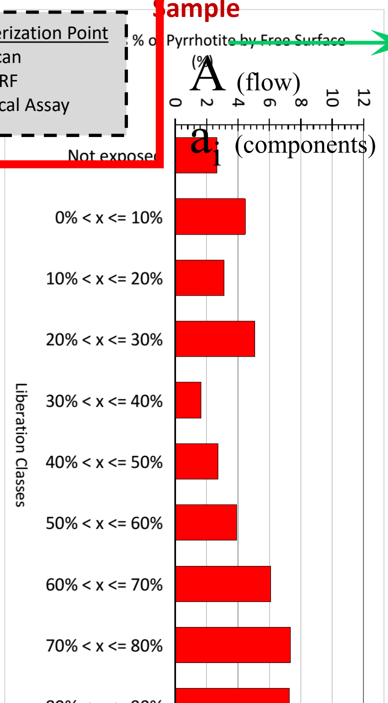
Separation Process

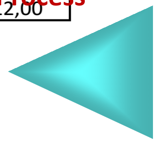
Product Samples

Characterization Point
- Qemscan
- XRD/XRF
- Chemical Assay

A (flow)

a_i (components)





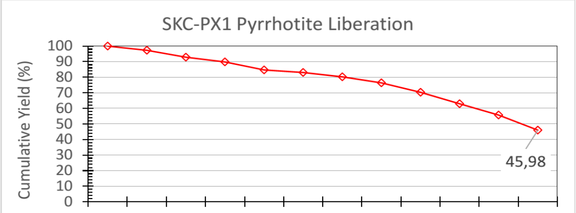
Diopside, Enstatite, Ferrosilite, Tremolite, Chlorite, Calcite, Ankerite, Magnetite, Pyrrhotite, Chalcopyrite, Pentlandite, Unclassified

Characterization Point
- Qemscan
- XRD/XRF
- Chemical Assay

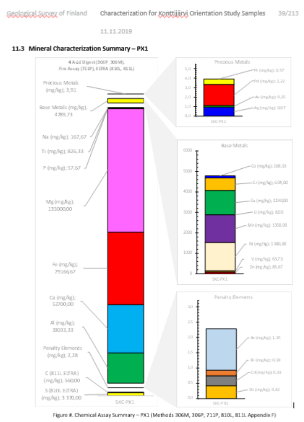
C (flow)

c_i (components)

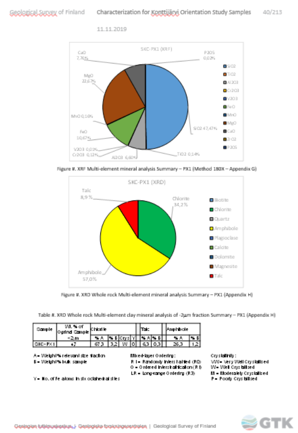
Characterization Point
- Qemscan
- XRD/XRF
- Chemical Assay



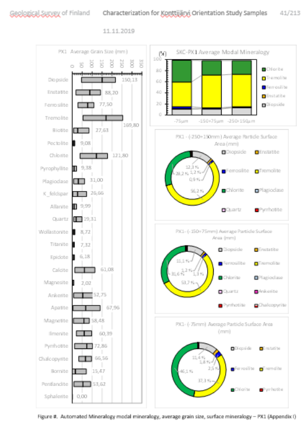
Chem Assay



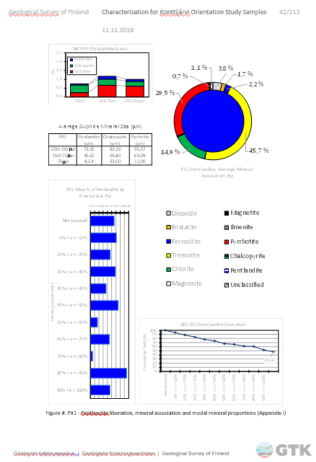
XRD/XRF



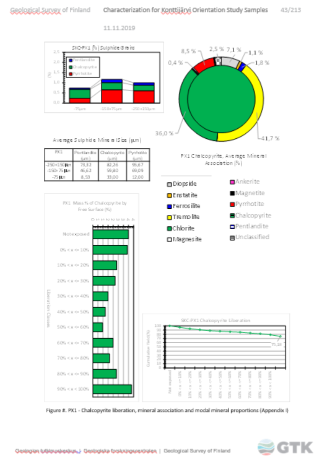
MLA – gangue



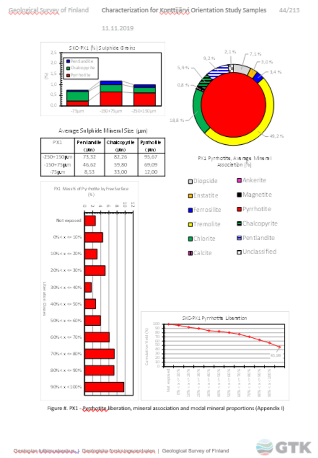
MLA – Value 1



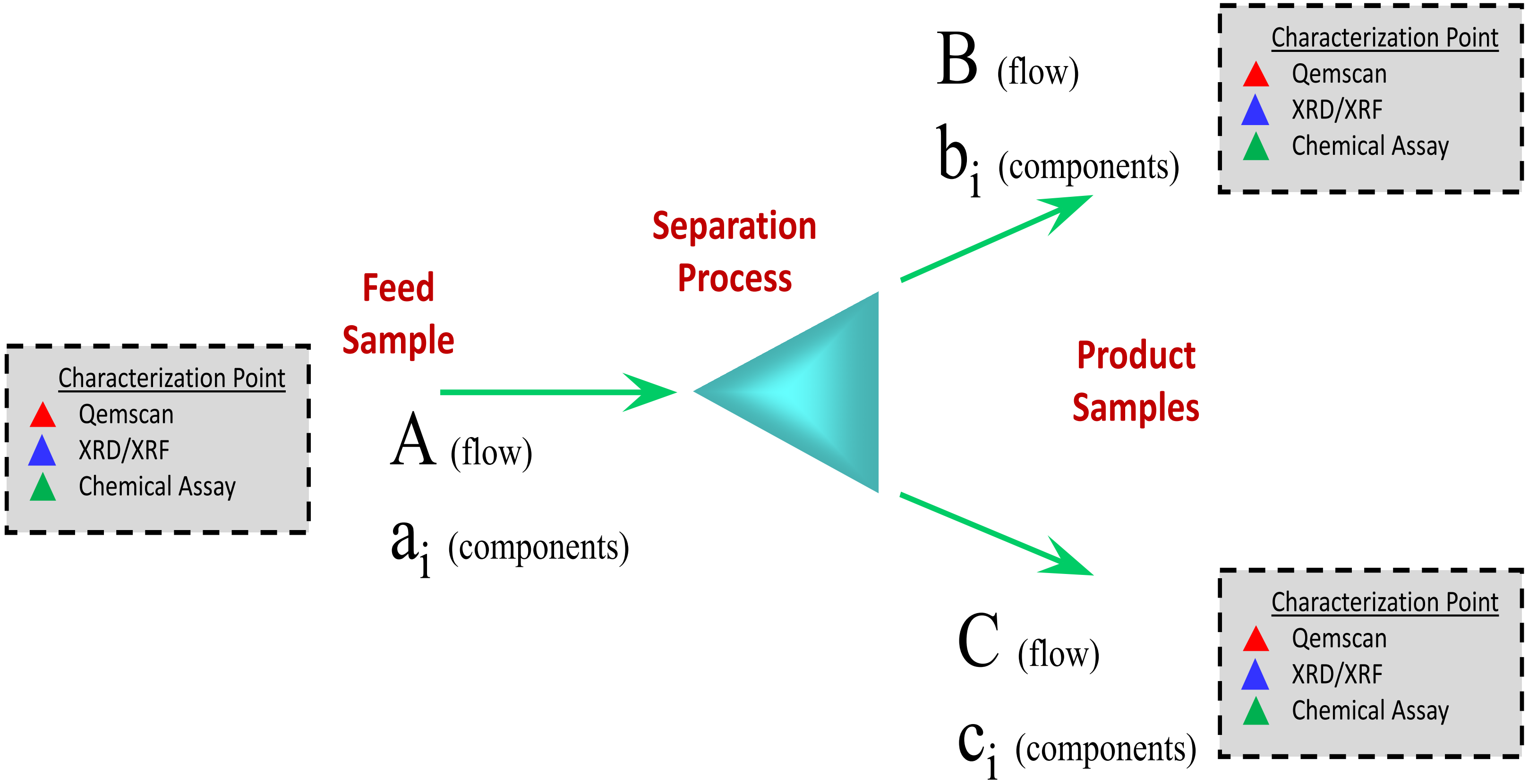
MLA – Value 2



MLA – Smelter Penalty 1



ALL PROCESS SEPARATION METHODS



Mineralogical mass balance

ORIENTATION STUDY - THE RACE…

- This is a race.
  - *Racers are selected by past demonstrated usefulness and intuition based selection of new technology*
  - *Stragglers will be shot*
  - *Not everyone will make it across the finish line*

- Nothing is sacred. Sacred cows get eaten first unless they continue to prove their usefulness
  - *Steak is good but maybe we are now vegetarians?*
  - *And can meatarians and vegetarians eat at the same table, or should they be separated?*

- Measurement is the key to demonstrating usefulness
  - *Don't tell me, come and show me*
  - *Reason, consequence and accountability*

This is why sound experimental design is required at the very beginning, coupled with competent data analysis & statistical comparison

Process Engineering Field	Process Behaviour Characterised	Test	Reference
Geotechnical	Compressive Strength	UCS	Brady & Brown 2006
	Tensile Strength	Brazilian Disc	Brady & Brown 2006
	Fracture Toughness	KiC	Brady & Brown 2006
Comminution	Impact Breakage	Drop Weight Test (DWT)	Napier-Munn *et al* 1996
	Bed Breakage	Lab Scale High Pressure Grinding Roll (HPGR)	Wills & Napier-Munn 2005
	Grinding	Bond Ball Mill Work Index (BMWi)	Napier-Munn *et al* 1996
		Bond Rod Mill Work Index	Napier-Munn *et al* 1996
	Fine Grinding	Laboratory Scale Isa Mill	Wills & Napier-Munn 2005
	Abrasion	Bond Abrasion Index (Allis Chalmers Abrasion Test)	Wills & Napier-Munn 2005
Flotation	Flotation Recovery	Batch Flotation Test	Runge 2010
Hydrometallurgy Leaching	Leaching Recovery	Column Leach Test	
Acid Mine Drainage	Acid Mine Drainage (AMD)	Static & Kinetic Tests	Parbhakar-Fox 2013, 2015, 2016

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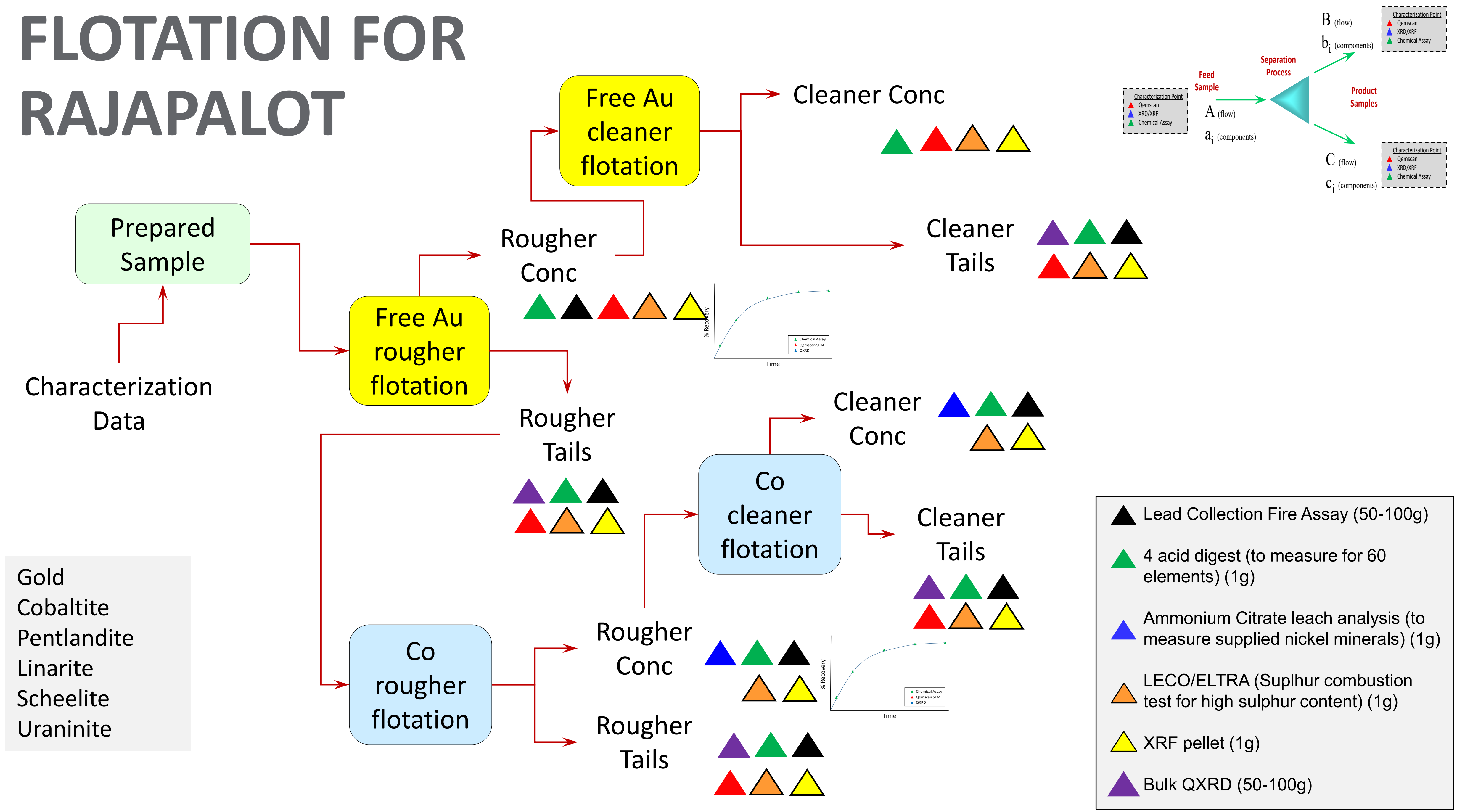
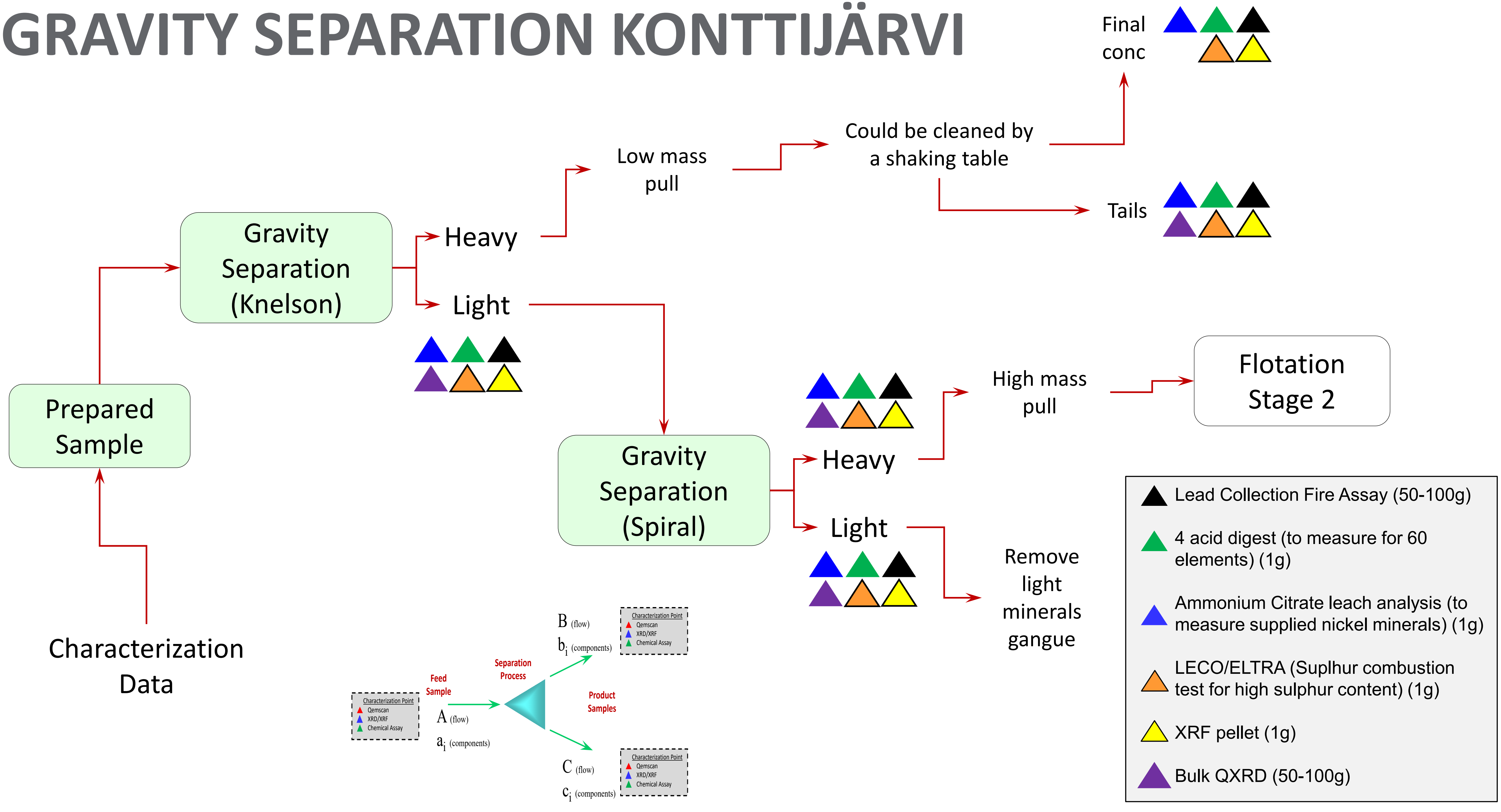
Process Engineering Field	Test	Reference
Geotechnical	Point Load Index (PLT)	Brady & Brown 2006
Comminution	RBT SMC JKCi SPi	Wills & Napier-Munn 2005 Wills & Napier-Munn 2005 JKTech Wills & Napier-Munn 2005 Kojovic *et al* 2011 Wills & Napier-Munn 2005 SGS 2018
Flotation	Separability Indicator (JKMSI)	Vos & Bradshaw 2014 Chauhan 2013 Morgan *et al* 2012
Hydrometallurgy Leaching	CSIRO Diagnostic Leach Test	Kuhar *et al* 2011 Li *et al* 2016
Acid Mine Drainage	Geo -environmental modelling Rinse Rinse /paste pH Carbonate staining	Parbhakar-Fox 2015 Parbhakar-Fox 2016 Parbhakar-Fox 2013
Meso scale mineralogy	Hyperspectral image analysis	Schodlok *et al* 2016
Rock Hardness	EQUOtip hardness	Keeney & Nguyen 2014

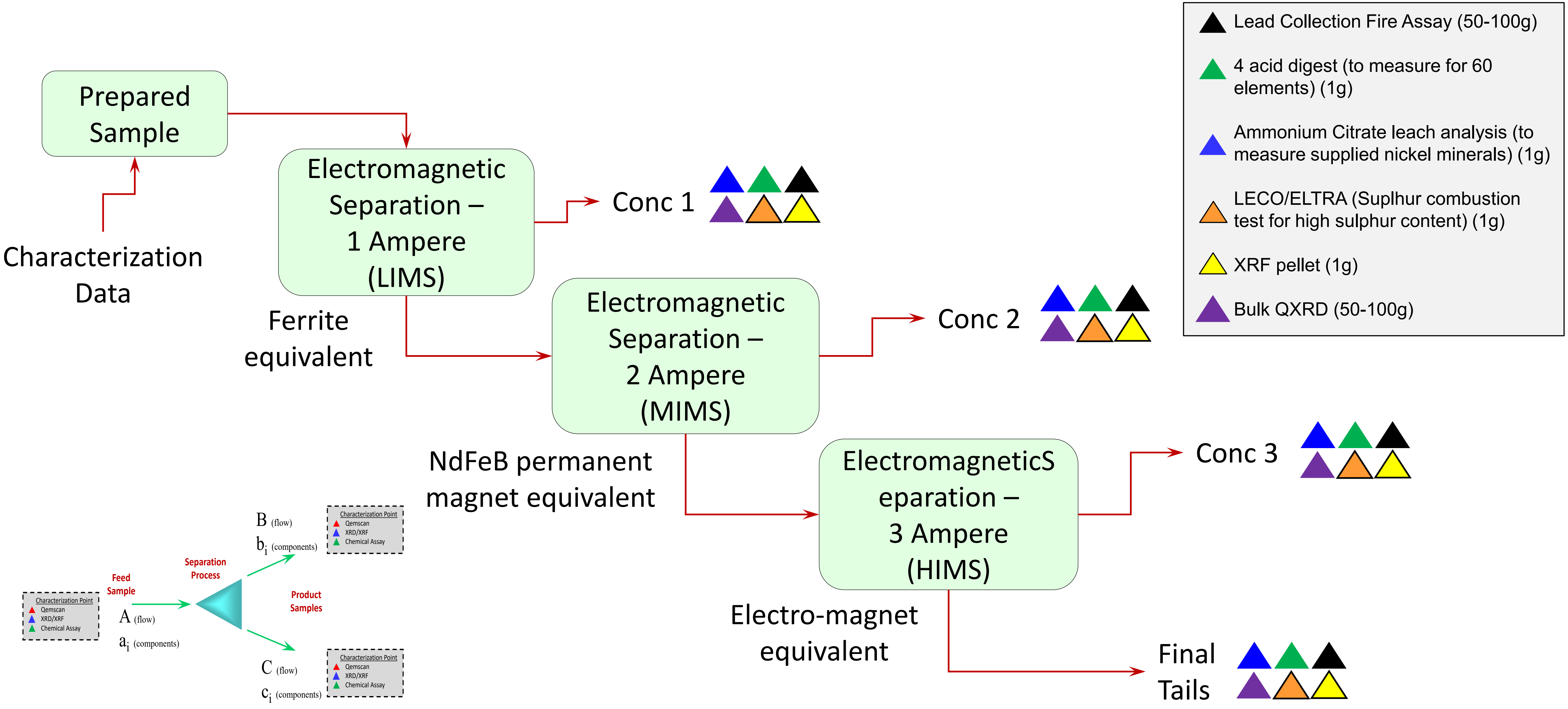
FLOTATION FOR RAJAPALOT

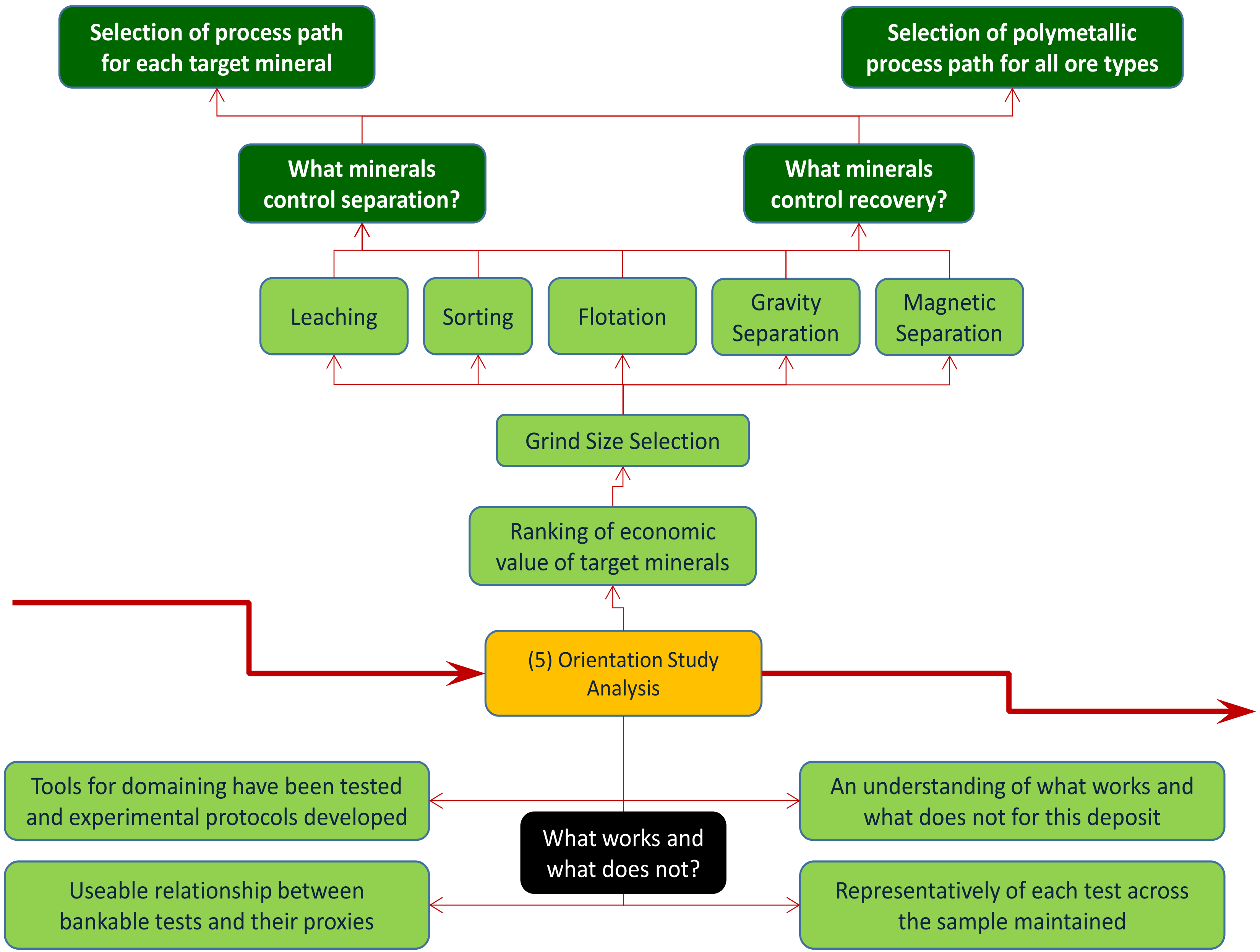


GRAVITY SEPARATION KONTTIJÄRVI



MAGNETIC SEPARATION KONTTIJÄRVI




Selection of process path for each target mineral
Selection of polymetallic process path for all ore types
What minerals control separation?
What minerals control recovery?
Leaching
Sorting
Flotation
Gravity Separation
Magnetic Separation
Grind Size Selection
Ranking of economic value of target minerals
(5) Orientation Study Analysis
Tools for domaining have been tested and experimental protocols developed
Useable relationship between bankable tests and their proxies
What works and what does not?
An understanding of what works and what does not for this deposit
Representatively of each test across the sample maintained

DATA ANALYSIS OF ORIENTATION STUDY SAMPLES

- What tests showed the greatest spread in variability?
  - *What tests are useful here?*
  - *Are some end member ore types very similar in process response space?*
  - *Should they be merged into one ore type in this process?*

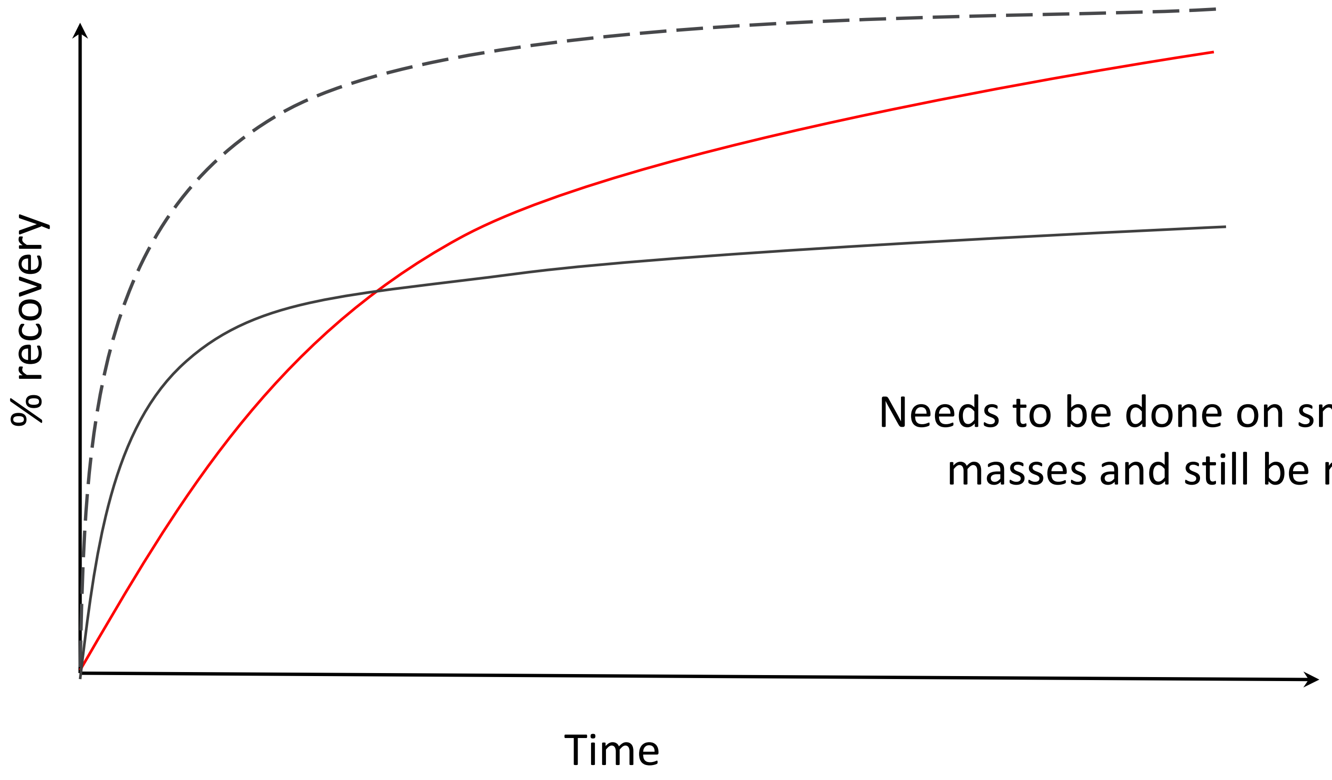
- Do the tests interrelate?

- Is a good relationship between bankable tests and proxy tests viable for this deposit?

- What are mineralogical influences that can be seen as patterns across the samples?

- What is the process engineering simulation outcomes using orientation samples as input

TO DIFFERENTIATE AND RANK THESE THREE SAMPLES IN CONTEXT OF LEACHING RECOVERY

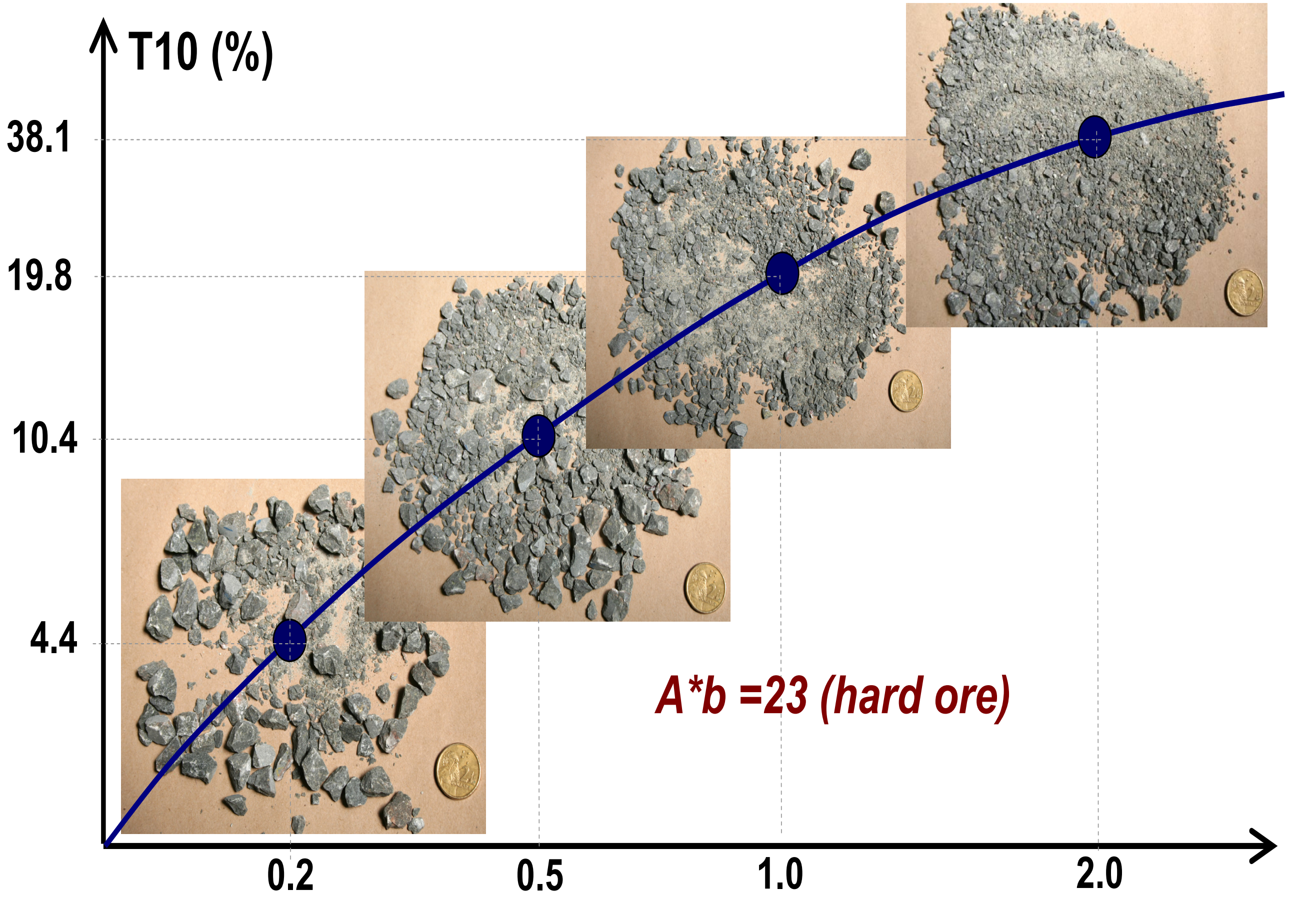


Needs to be done on small sample masses and still be relevant

Which of these results would I prefer to have in my plant?

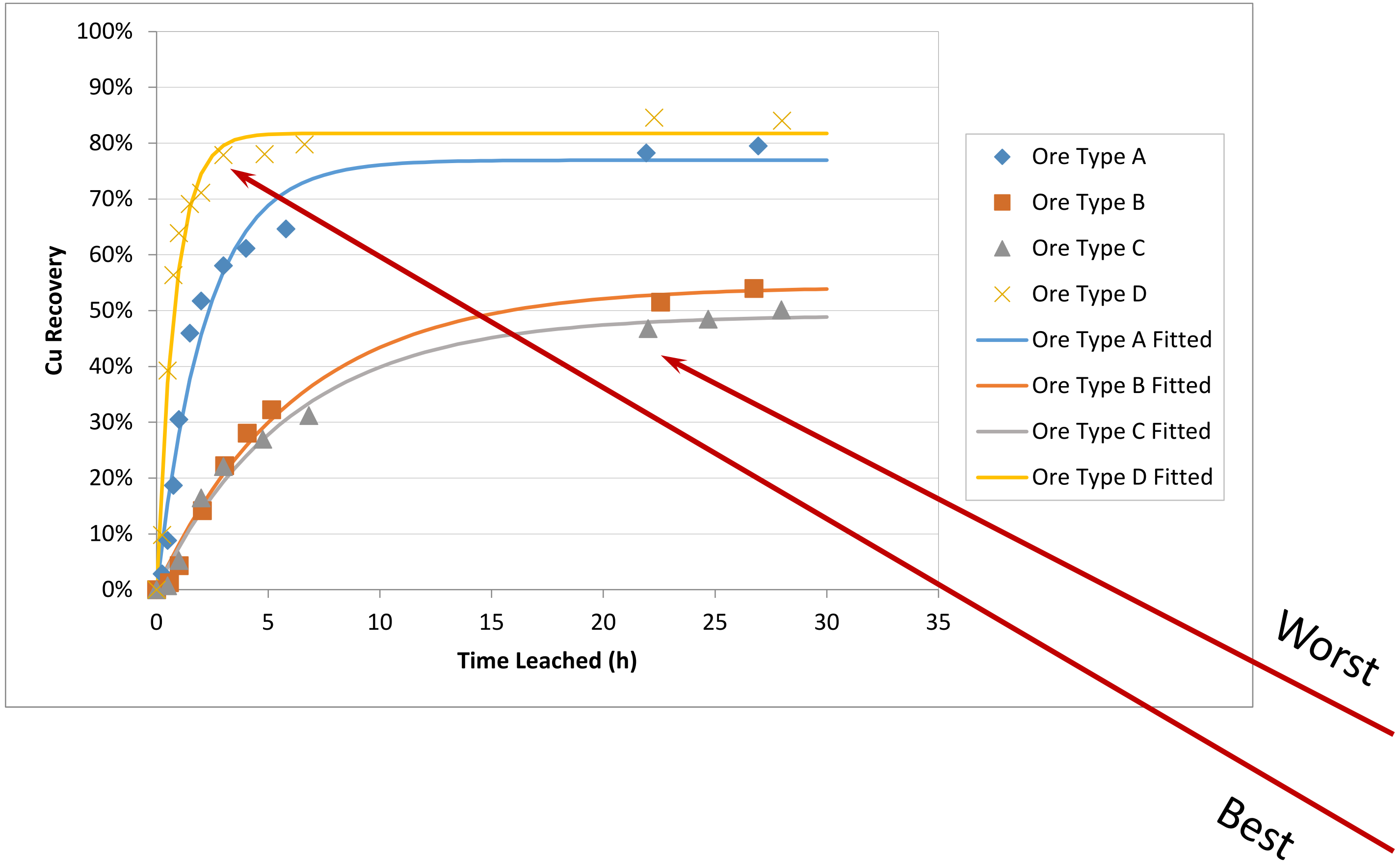
Rank them and compare against mineral content

THE AXB BREAKAGE CURVE



$$t_{10} = A[1-e^{(-b.Ecs)}]$$

THE RANKING OF RECOVERIES



$$Q = R[1 - e^{(-s.t)}]$$

Where:

Q = Cu Output %

t = Time leached

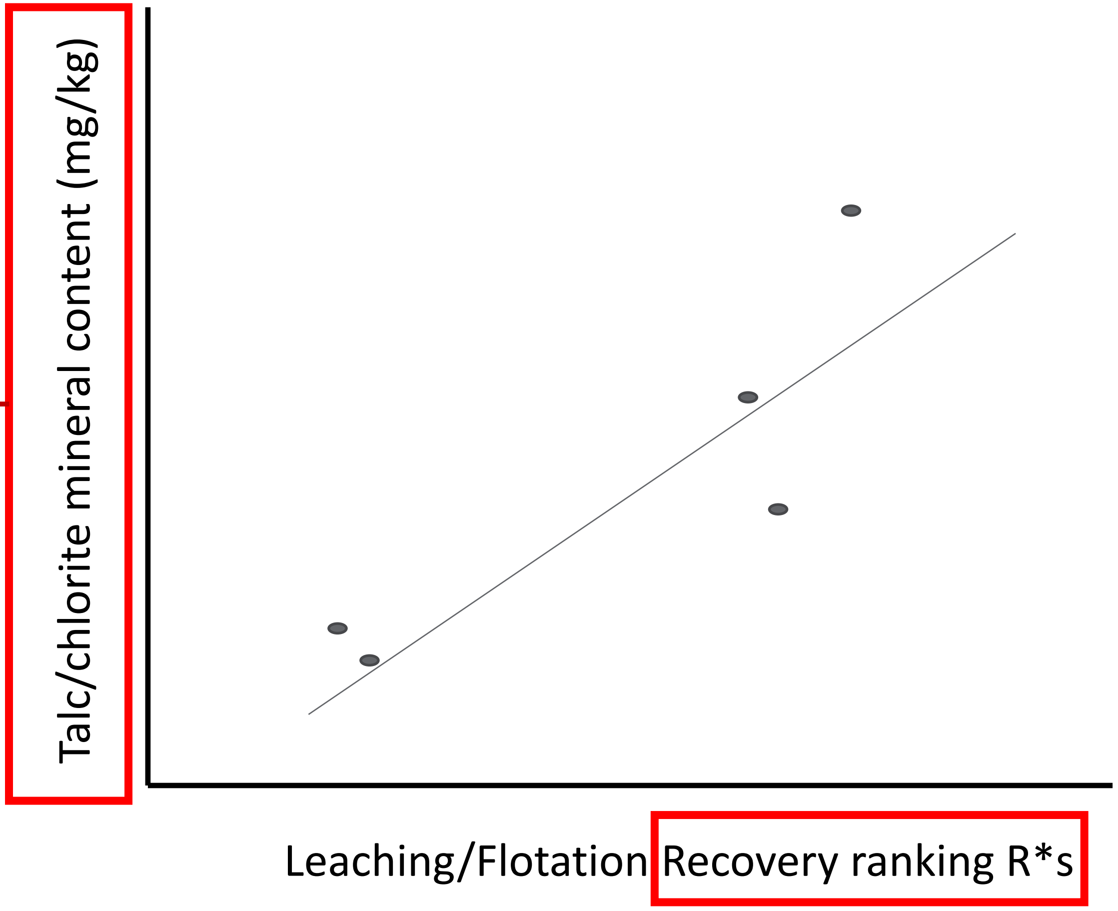
Sample	R	s	R*s
Ore Type A	76.9%	0.45	34.6
Ore Type B	54.3%	0.16	8.7
Ore Type C	49.2%	0.17	8.2
Ore Type D	81.8%	1.21	98.9

This is what is studied in the Mapping Study to look at process domains & variability

Develop a relationship between XRD/XRF and chemical assays for each rock type

Using data you have already collected

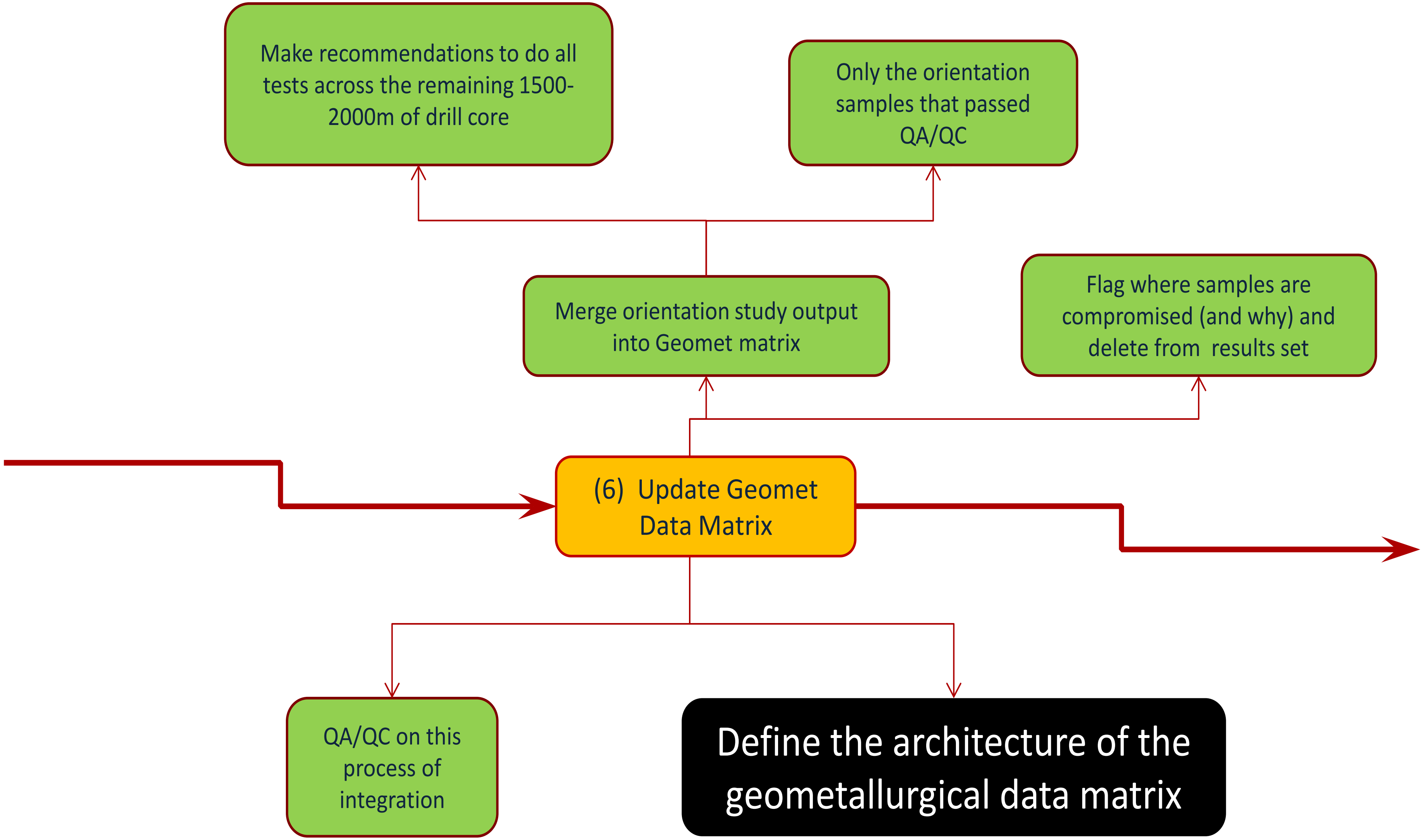
This is modelled in a geometallurgical block model



(Theoretical example – not data)

CONCLUSIONS OF ORIENTATION STUDY

- An understanding of what works and what does not for this deposit
- Useable relationship between bankable tests and their proxies
- Experimental design for what tests are to be done on the Mapping Study Sample set (the remaining samples of the 1500-2000m drill core)
    - *Representatively of each test across the sample maintained*
    - *The order of tests to be done, where some of them will destroy the core*
    - *QA/QC established*
    - *Data analysis & modelling planned out to milestone conclusion*
- Sample size and drill core depth interval for each Hypothesis sample
- Tools for domaining have been tested and experimental protocols developed


Make recommendations to do all tests across the remaining 1500-2000m of drill core
Only the orientation samples that passed QA/QC
Merge orientation study output into Geomet matrix
Flag where samples are compromised (and why) and delete from results set
(6) Update Geomet Data Matrix
QA/QC on this process of integration
Define the architecture of the geometallurgical data matrix

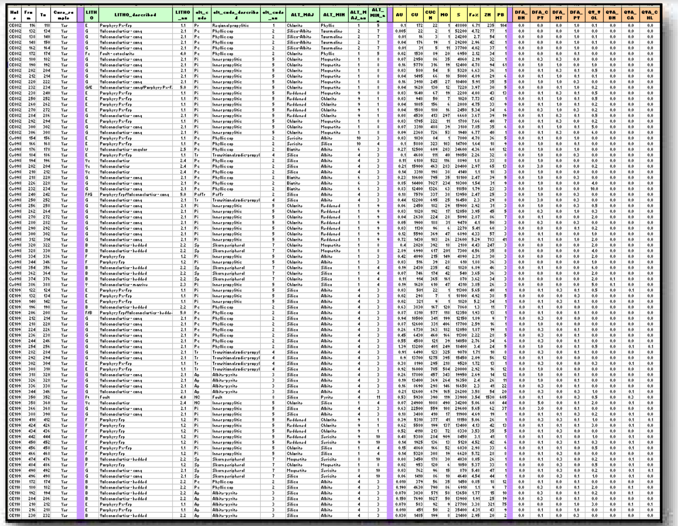
THE GEOMETALLURGICAL DATA MATRIX IS READY!!!

Small scale comminution testing

PLT	Crushing Index	A*b from RBT	Batch Grind

Grind and Flotation Testing

- *Texture-based recoveries*
- *Texture-based liberation*



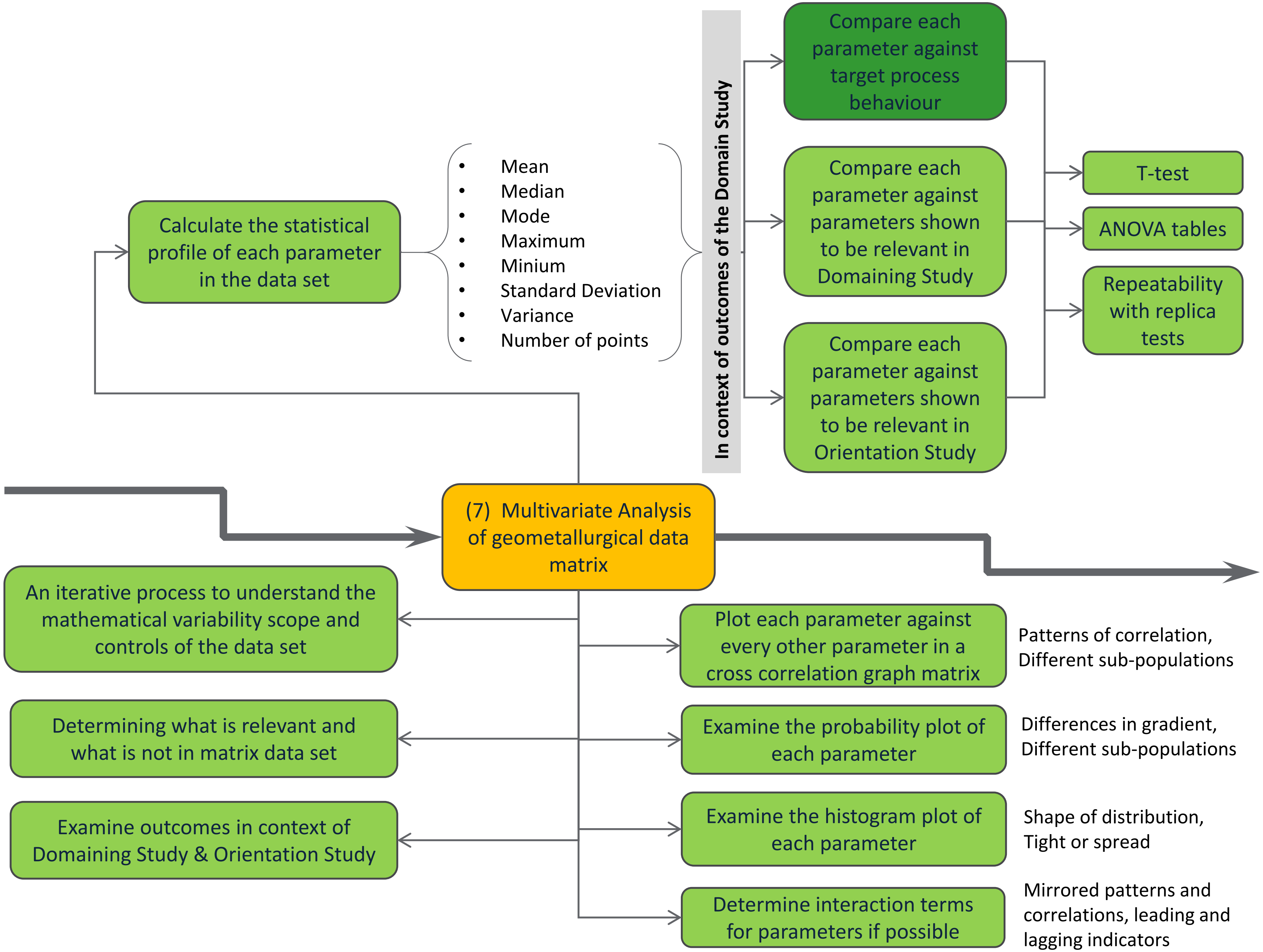
Hyperspectral Characterization & Core Imaging

- *Classified images*
- *Texture groupings*

Intact texture libraries	Classified textures	Mineralogical definition	Texture-based FEM models

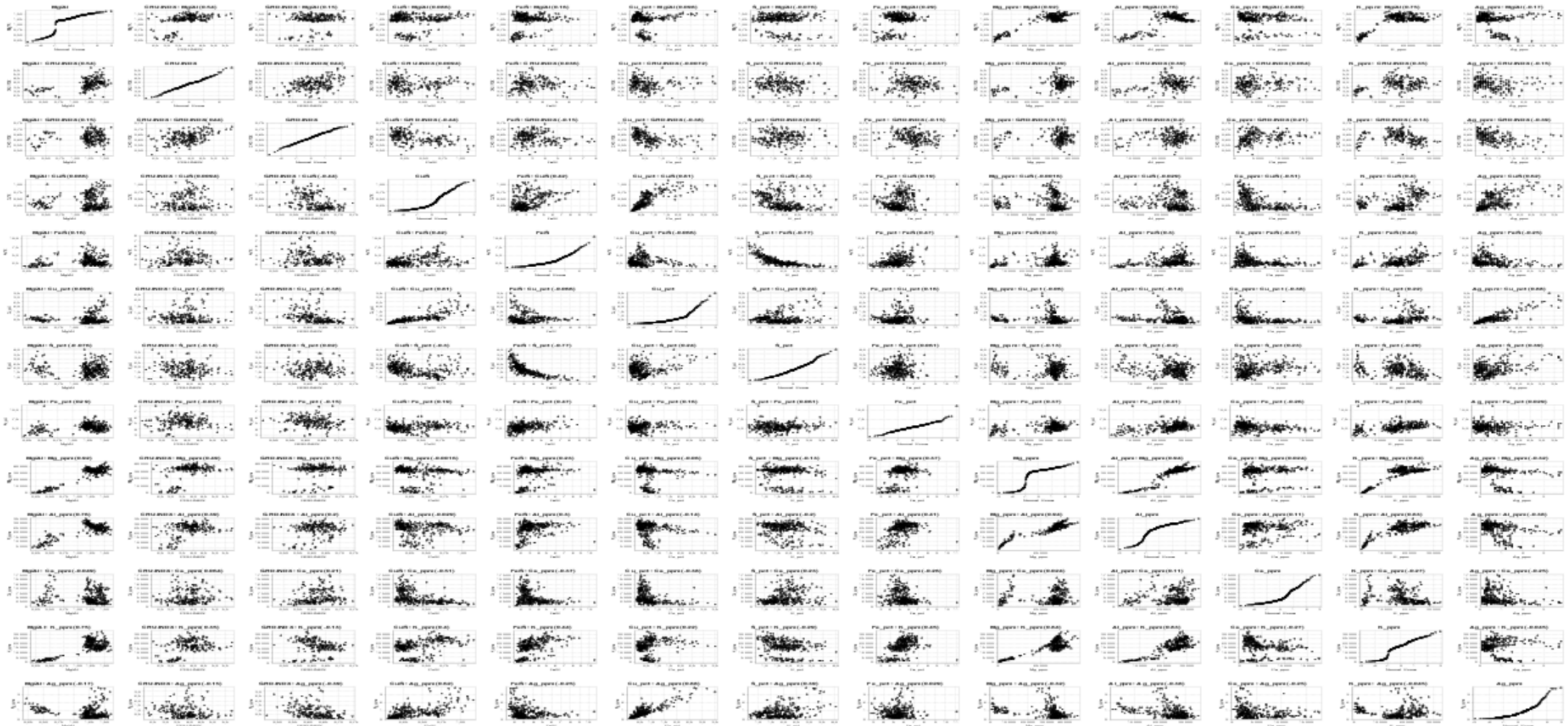
MLA and optical microscopy

GTK

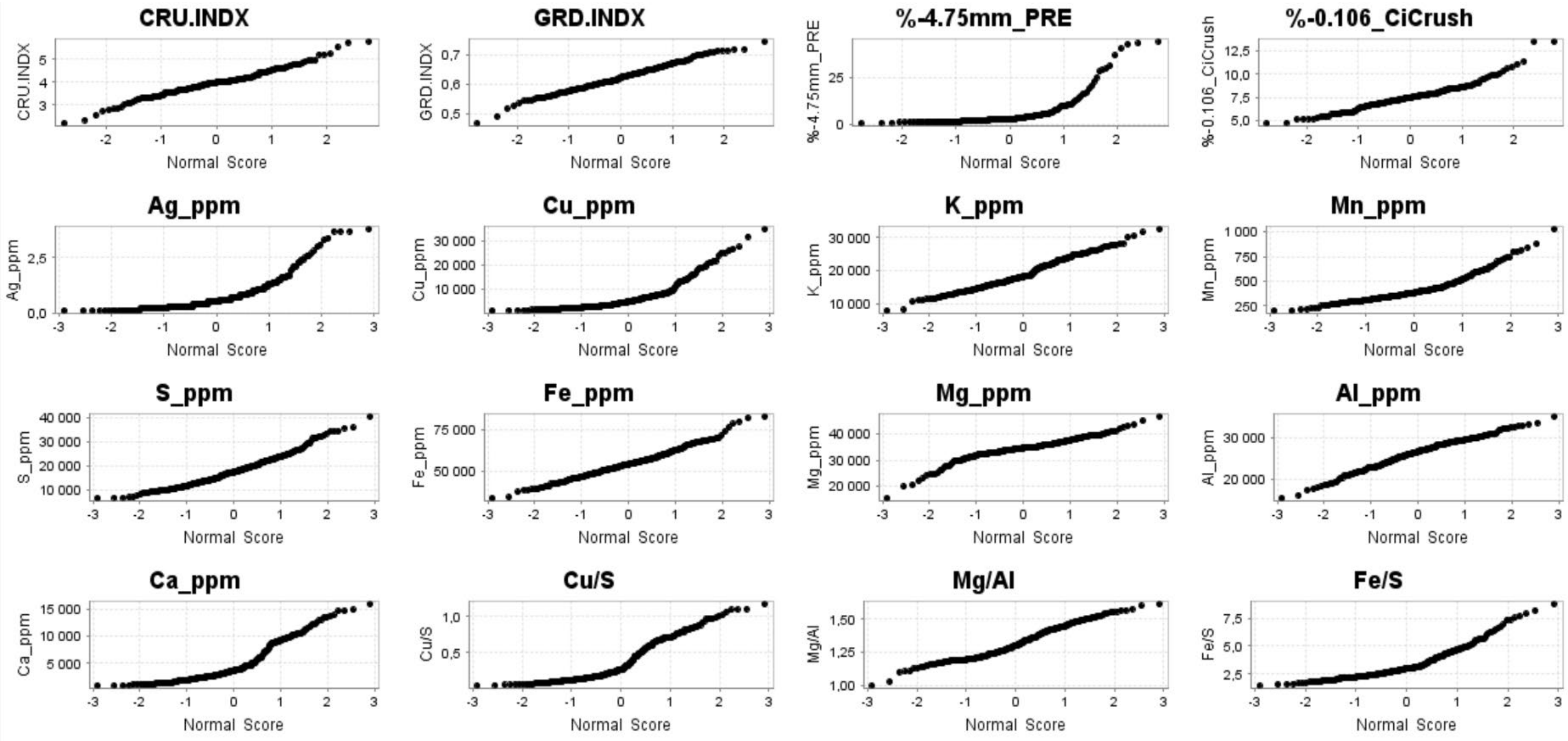


Compare each parameter against target process behaviour
Compare each parameter against parameters shown to be relevant in Domaining Study
Compare each parameter against parameters shown to be relevant in Orientation Study
In context of outcomes of the Domain Study
T-test
ANOVA tables
Repeatability with replica tests
Calculate the statistical profile of each parameter in the data set
Mean
Median
Mode
Maximum
Minium
Standard Deviation
Variance
Number of points
(7) Multivariate Analysis of geometallurgical data matrix
An iterative process to understand the mathematical variability scope and controls of the data set
Determining what is relevant and what is not in matrix data set
Examine outcomes in context of Domaining Study & Orientation Study
Plot each parameter against every other parameter in a cross correlation graph matrix
Patterns of correlation, Different sub-populations
Examine the probability plot of each parameter
Differences in gradient, Different sub-populations
Examine the histogram plot of each parameter
Shape of distribution, Tight or spread
Determine interaction terms for parameters if possible
Mirrored patterns and correlations, leading and lagging indicators

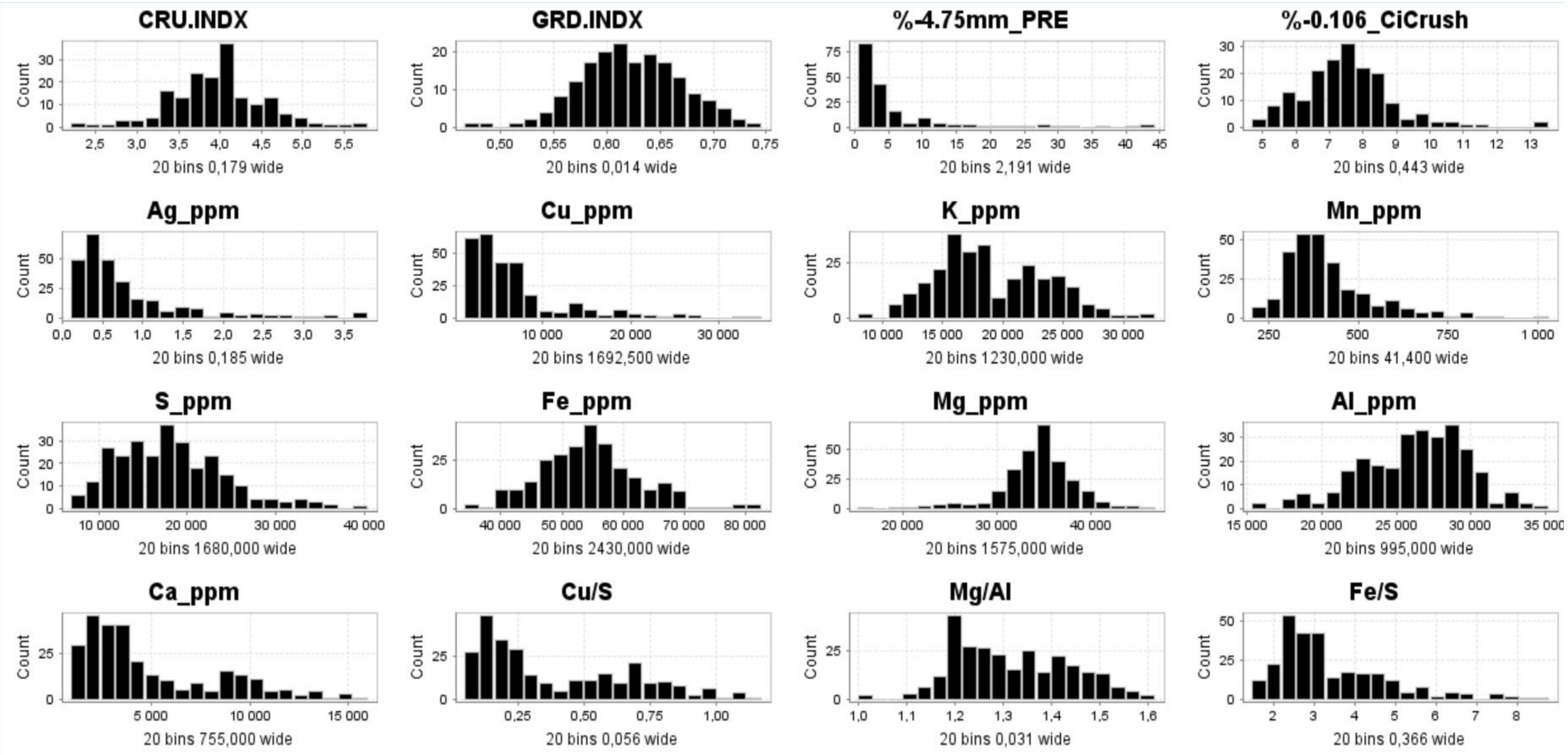
EXAMINE THE CORRELATION BETWEEN ALL PARAMETERS AGAINST ALL OTHER PARAMATERS



EXAMINE ALL PARAMETERS IN PROABLITY PLOTS TO DIAGNOSE SUB-POPULATIONS



EXAMINE ALL PARAMETERS IN HISTOGRAMS TO DIAGNOSE SKEWNESS SHAPE OF POPULATIONS



PRINCIPLE COMPONENT ANALYSIS (PCA)

EigenValues

	Values	Variance Proportion
e1	1.975	32.9
e2	1.586	26.4
e3	0.894	14.9
e4	0.691	11.5
e5	0.583	9.7
e6	0.271	4.5

EigenVectors

	V1	V2	V3	V4	V5	V6
%py	-0.315	0.463	-0.253	0.647	0.446	-0.065
%cp	-0.629	0.088	-0.114	-0.140	-0.296	0.690
%bn	0.161	-0.601	0.186	0.666	-0.072	0.359
%cc	0.278	-0.219	-0.924	-0.070	0.019	0.123
U3O8 (ppm)	-0.532	-0.357	-0.176	0.143	-0.402	-0.613
Au (ppm)	-0.344	-0.491	0.053	-0.303	0.739	0.014

Describes the proportion of variance for each eigenvector in this case the first two components account for around 60% of total variance.

List the variables used in the principal component analysis in this case only six components represent a relatively simple system to analyze

Shows the relative scores for each component, high values have the strongest effect and positive versus negative values indicate opposing discriminant trends

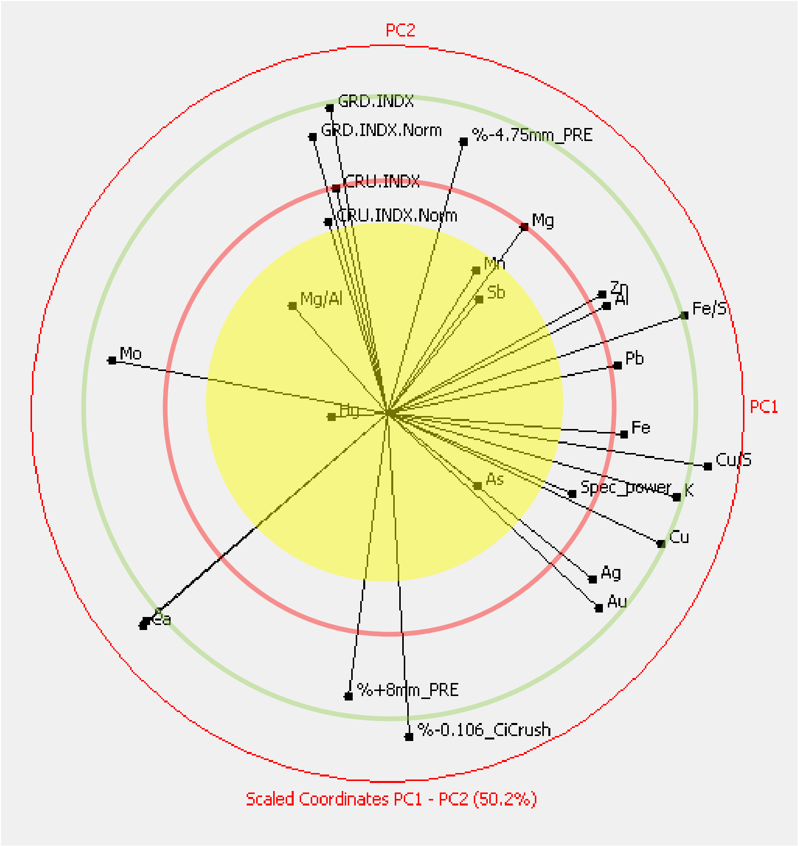
Actual weighting values used to calculate the principal components. These values are based on training sets but can be transferred into Excel and used to calculate principal components for new 'unknown' samples

V1 -0.13685955*'%py'-0.25199805*'%cp'+0.087340186*'%bn'+0.58723749*'%cc'-0.0014709545*'U3O8 (ppm)'-0.63977939*'Au (ppm)'+1.2815472

V2 0.22465695*'%py'+0.039256248*'%cp'-0.36381083*'%bn'-0.51623515*'%cc'-0.0011000002*'U3O8 (ppm)'-1.0202435*'Au (ppm)'+0.74344882

GTK

PRINCIPLE COMPONENT ANALYSIS (PCA) – CASE STUDY P



Primary Influence

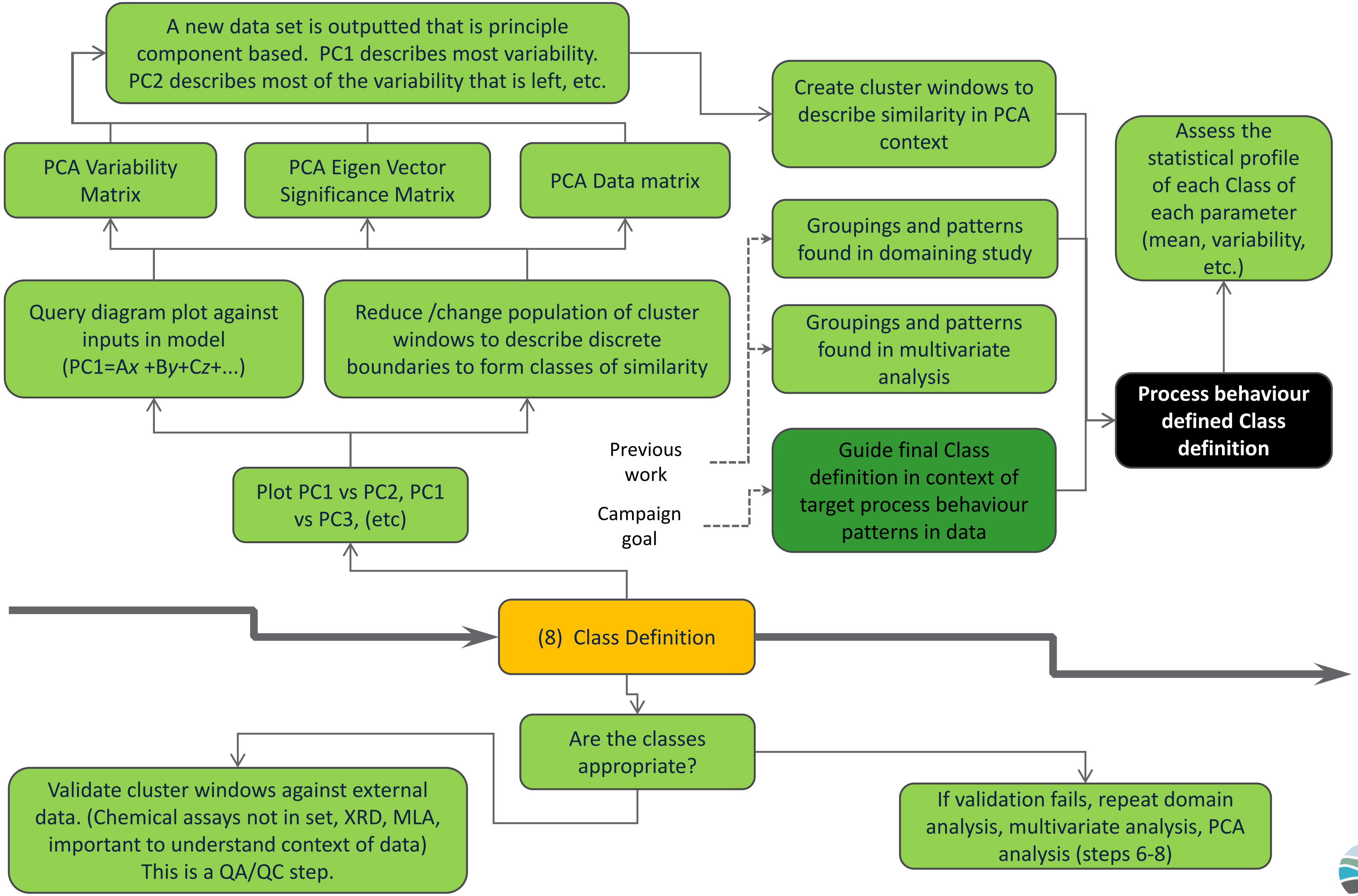
- Ca, S, %-106, Cu/S
- Ci-GRD, Cu, K, Fe/S
- Au, Ci-GRD_Norm
- %-4.75, %+8mm

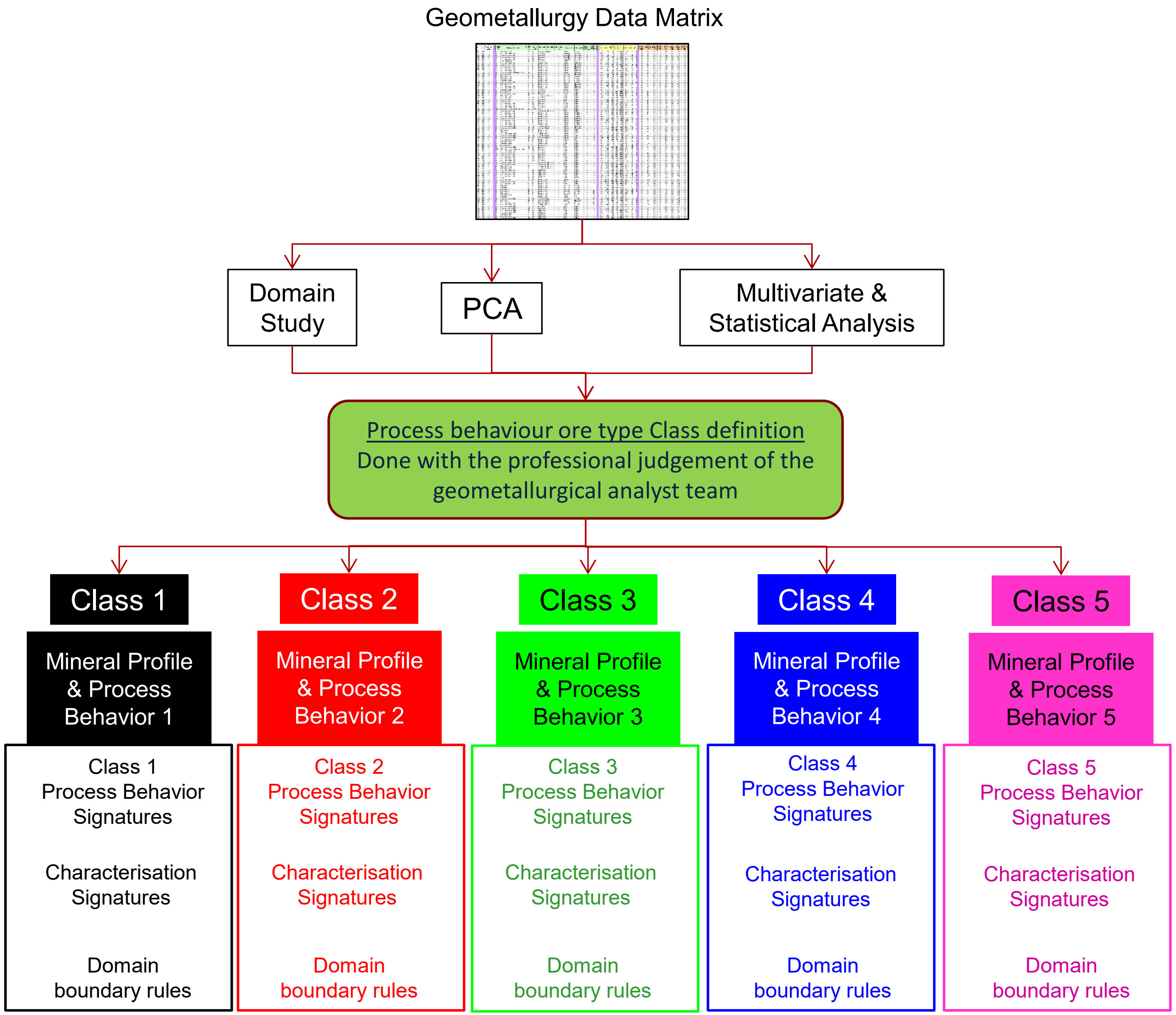
Secondary Influence

- Ag, Zn, Al, Fe, Pb
- Ci-CRU, Ci-CRU_Norm
- Spec_Power

Reduced Influence

- Mn, Sb, Mg/Al
- As, Hg

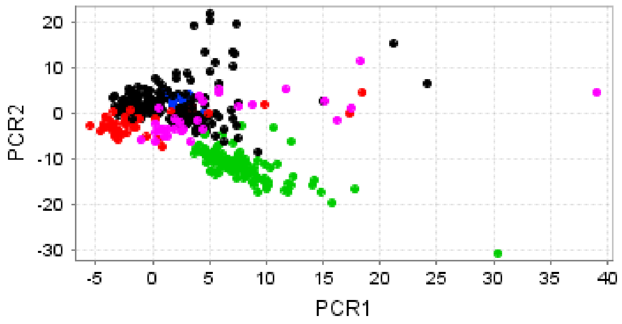

A new data set is outputted that is principle component based. PC1 describes most variability. PC2 describes most of the variability that is left, etc.
PCA Variability Matrix
PCA Eigen Vector Significance Matrix
PCA Data matrix
Query diagram plot against inputs in model (PC1=Ax +By+Cz+...)
Reduce /change population of cluster windows to describe discrete boundaries to form classes of similarity
Plot PC1 vs PC2, PC1 vs PC3, (etc)
Create cluster windows to describe similarity in PCA context
Groupings and patterns found in domaining study
Groupings and patterns found in multivariate analysis
Guide final Class definition in context of target process behaviour patterns in data
Previous work
Campaign goal
Assess the statistical profile of each Class of each parameter (mean, variability, etc.)
Process behaviour defined Class definition
(8) Class Definition
Are the classes appropriate?
Validate cluster windows against external data. (Chemical assays not in set, XRD, MLA, important to understand context of data) This is a QA/QC step.
If validation fails, repeat domain analysis, multivariate analysis, PCA analysis (steps 6-8)



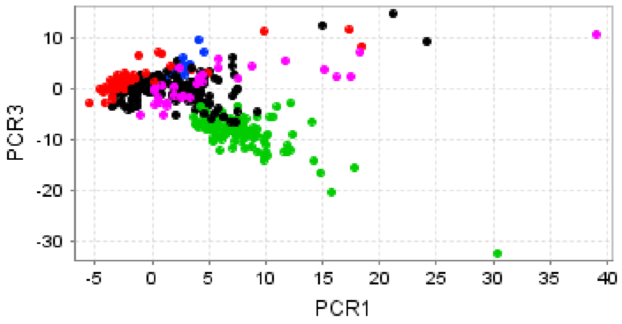
Geometallurgy Data Matrix
Domain Study
PCA
Multivariate & Statistical Analysis
Process behaviour ore type Class definition
Done with the professional judgement of the geometallurgical analyst team
Class 1
Mineral Profile & Process Behavior 1
Class 1 Process Behavior Signatures
Characterisation Signatures
Domain boundary rules
Class 2
Mineral Profile & Process Behavior 2
Class 2 Process Behavior Signatures
Characterisation Signatures
Domain boundary rules
Class 3
Mineral Profile & Process Behavior 3
Class 3 Process Behavior Signatures
Characterisation Signatures
Domain boundary rules
Class 4
Mineral Profile & Process Behavior 4
Class 4 Process Behavior Signatures
Characterisation Signatures
Domain boundary rules
Class 5
Mineral Profile & Process Behavior 5
Class 5 Process Behavior Signatures
Characterisation Signatures
Domain boundary rules

PCA – CASE STUDY P

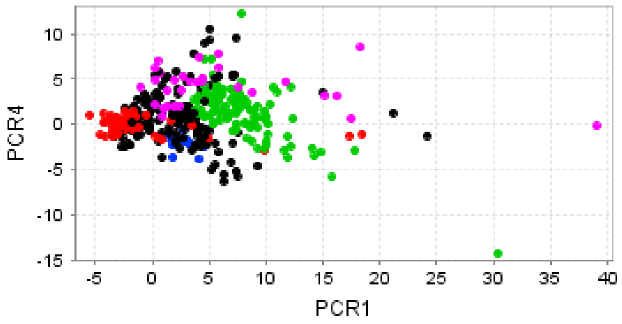
PCR1 : PCR2



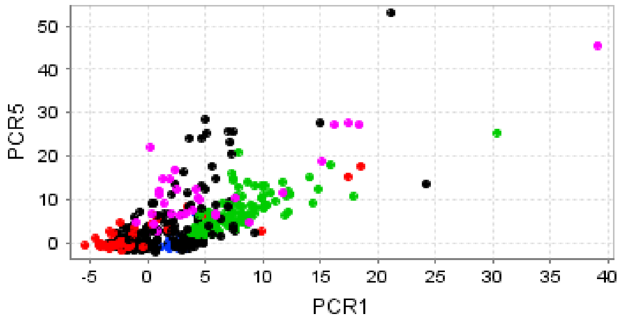
PCR1 : PCR3



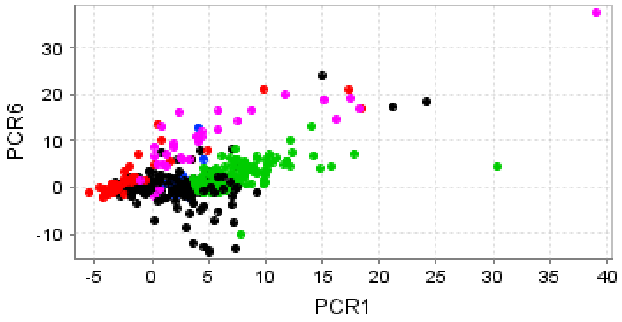
PCR1 : PCR4



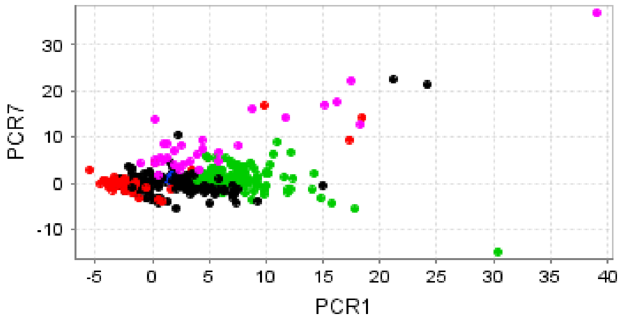
PCR1 : PCR5



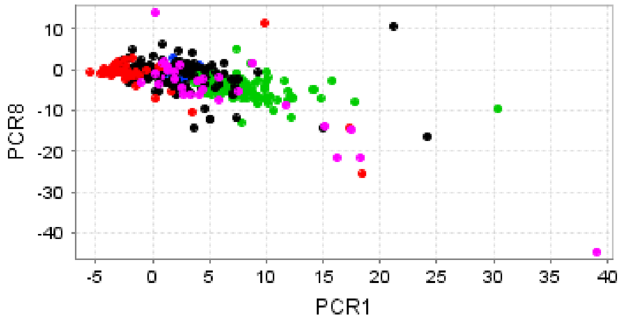
PCR1 : PCR6



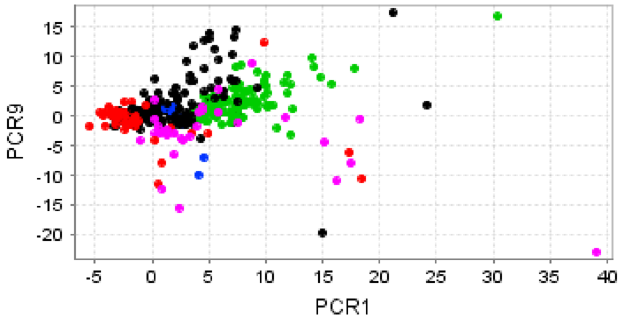
PCR1 : PCR7



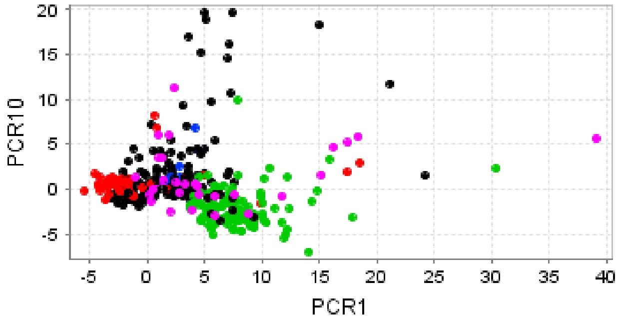
PCR1 : PCR8



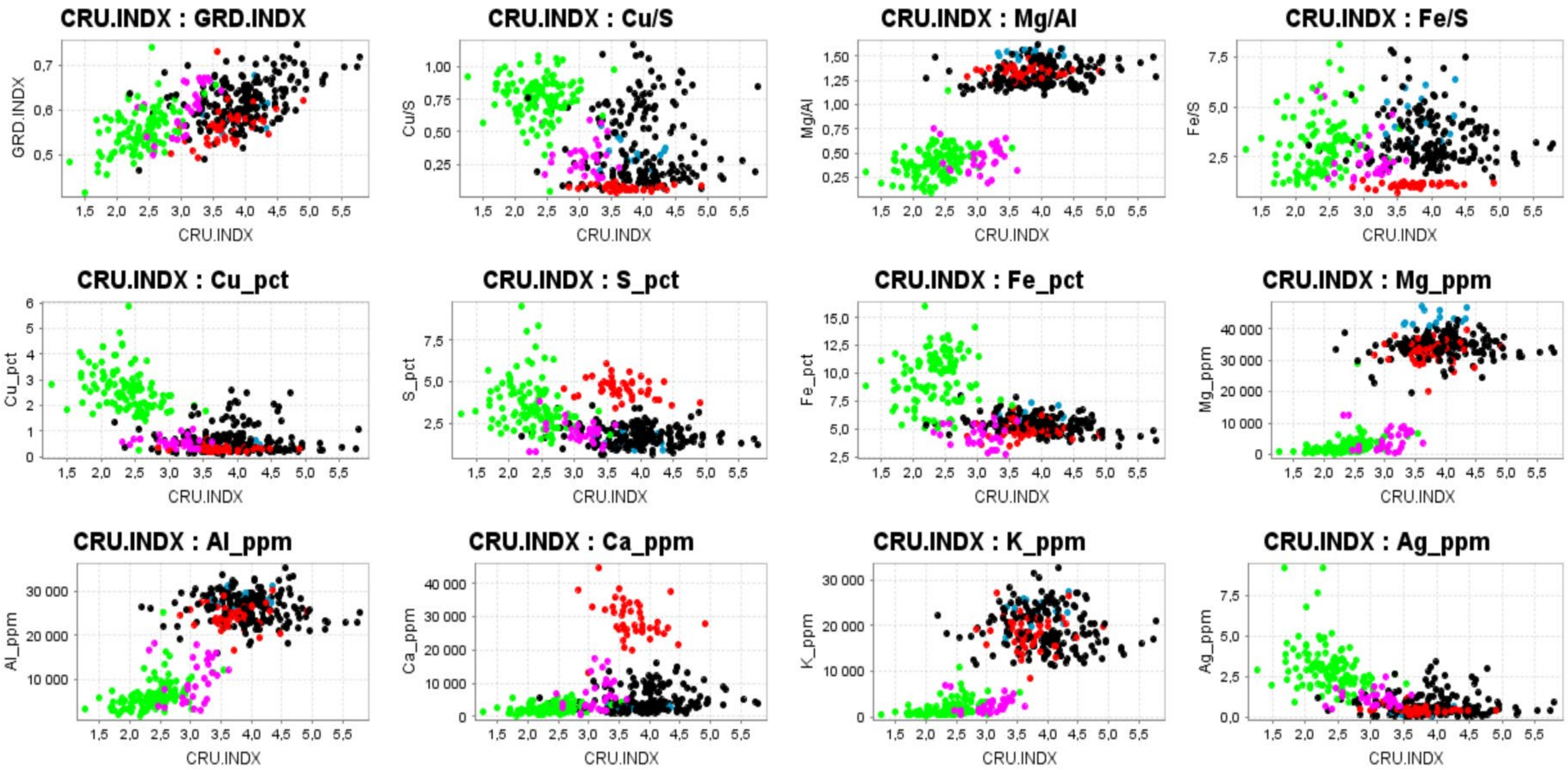
PCR1 : PCR9



PCR1 : PCR10

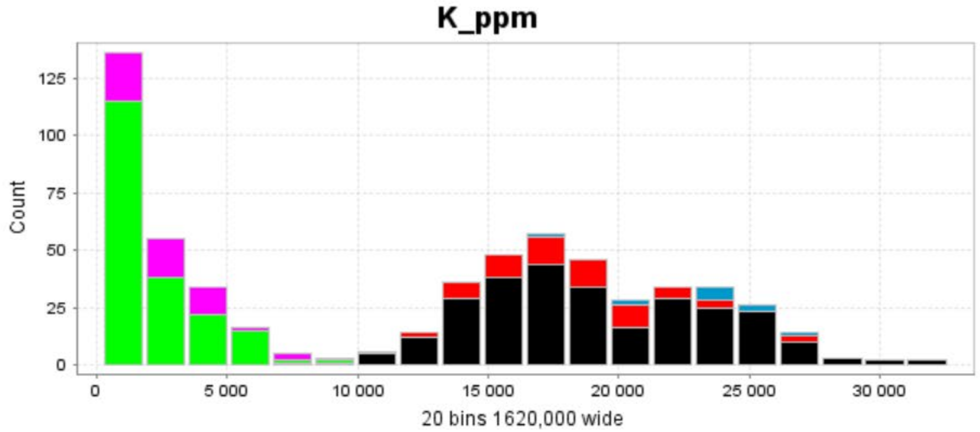


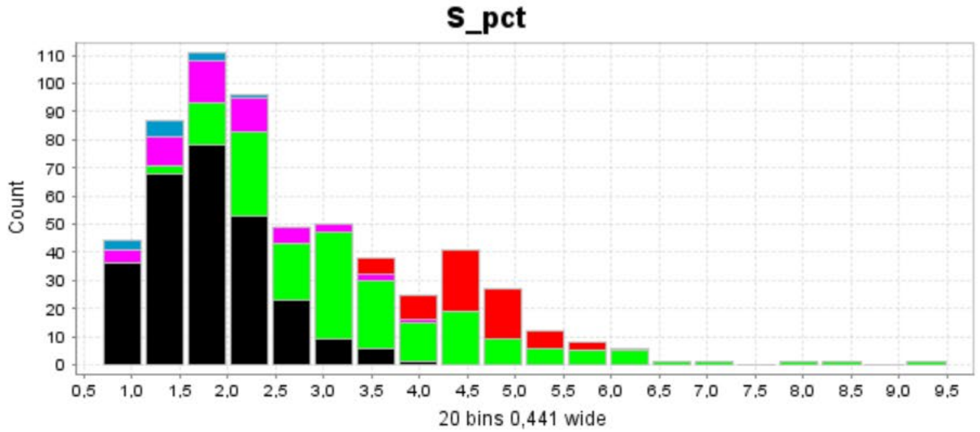
CASE STUDY P

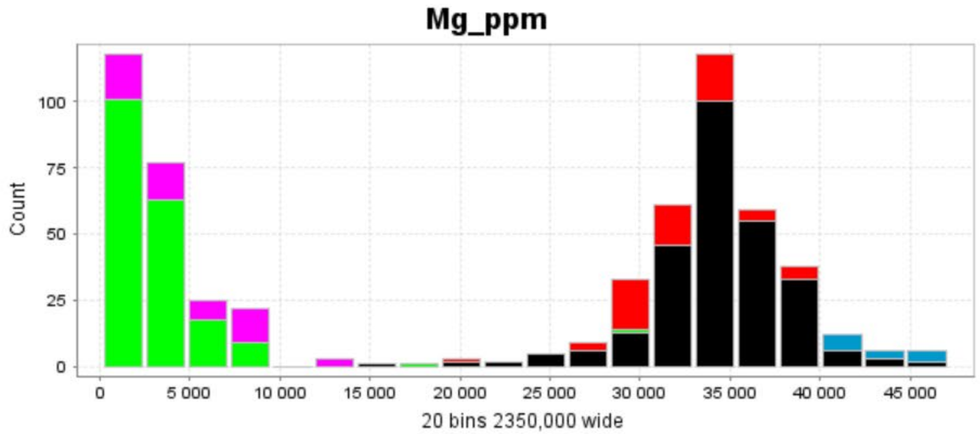


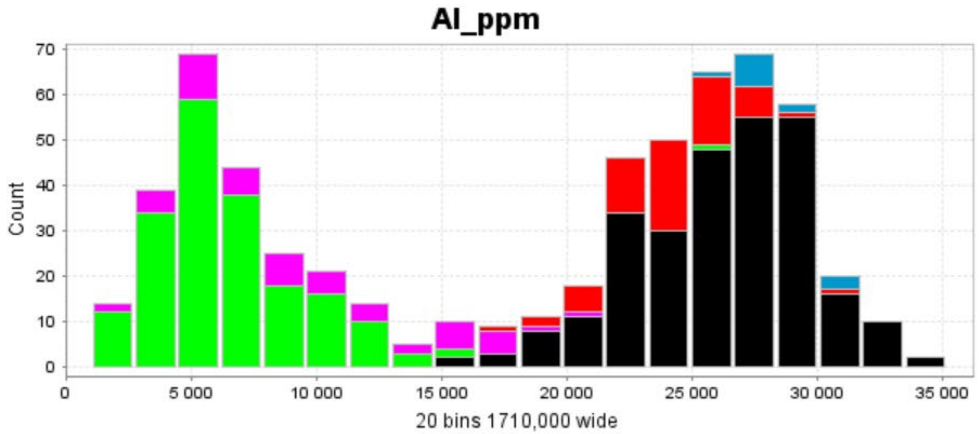
Comminution

CASE STUDY P

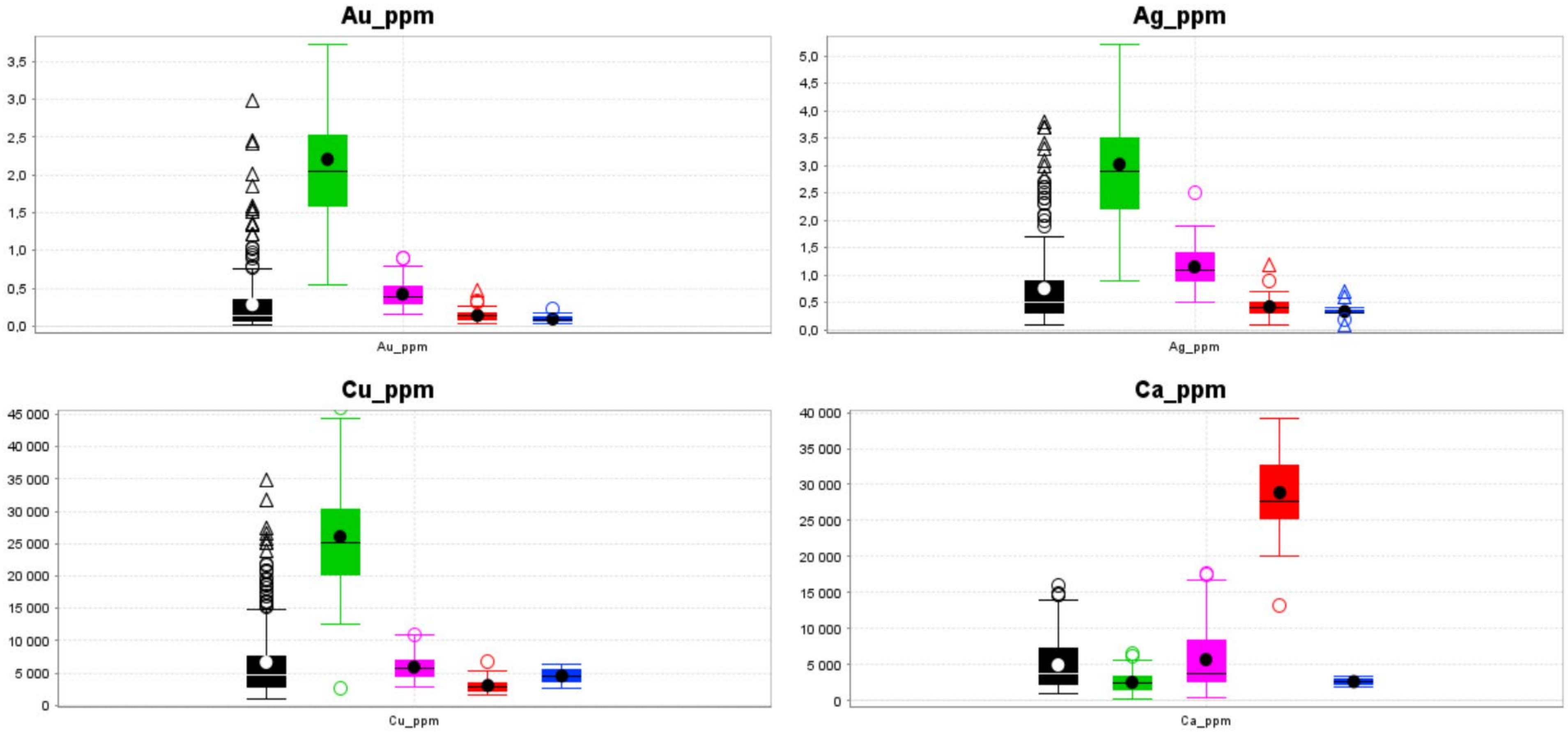

K_ppm
Count
0
25
50
75
100
125
0
5 000
10 000
15 000
20 000
25 000
30 000
20 bins 1620,000 wide


S_pct
Count
0
10
20
30
40
50
60
70
80
90
100
110
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
5,0
5,5
6,0
6,5
7,0
7,5
8,0
8,5
9,0
9,5
20 bins 0,441 wide


Mg_ppm
Count
0
25
50
75
100
0
5 000
10 000
15 000
20 000
25 000
30 000
35 000
40 000
45 000
20 bins 2350,000 wide

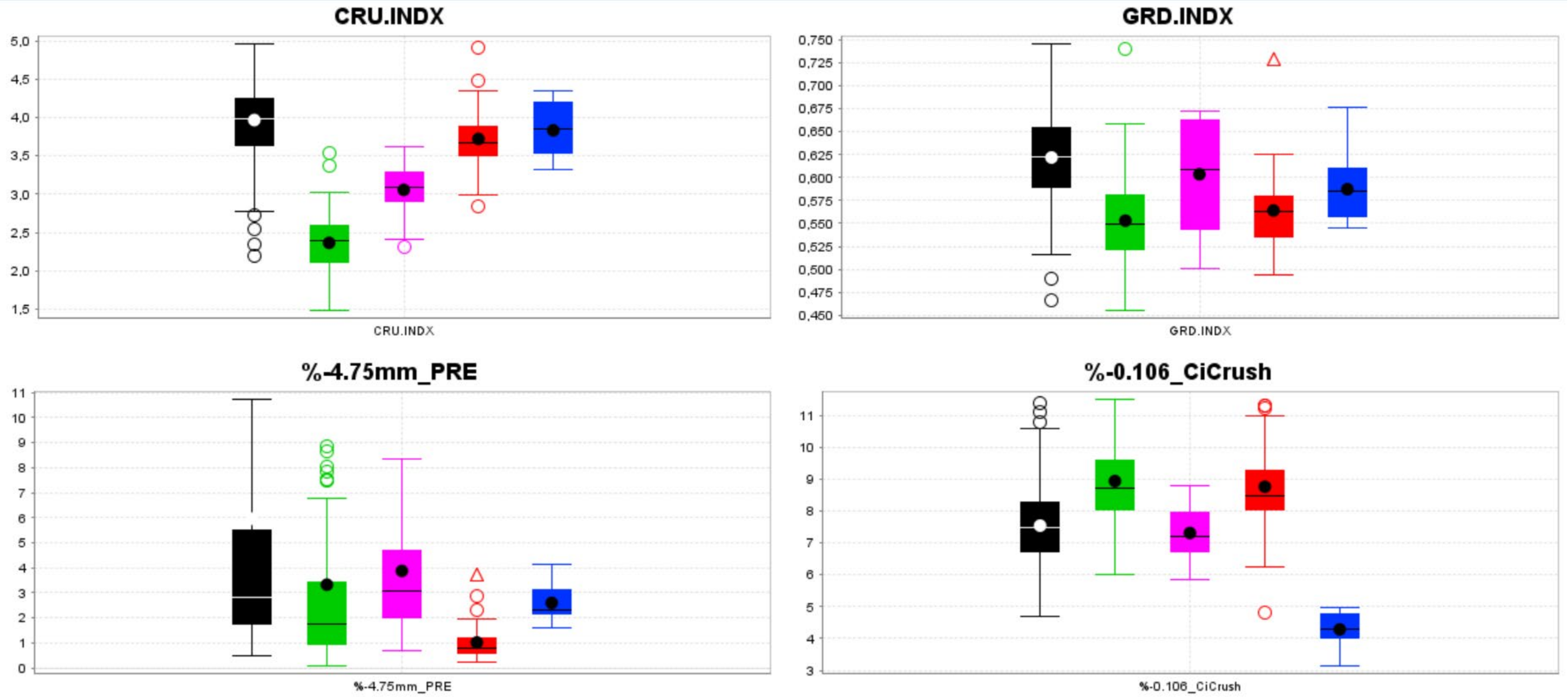

Al_ppm
Count
0
10
20
30
40
50
60
70
0
5 000
10 000
15 000
20 000
25 000
30 000
35 000
20 bins 1710,000 wide

CASE STUDY P



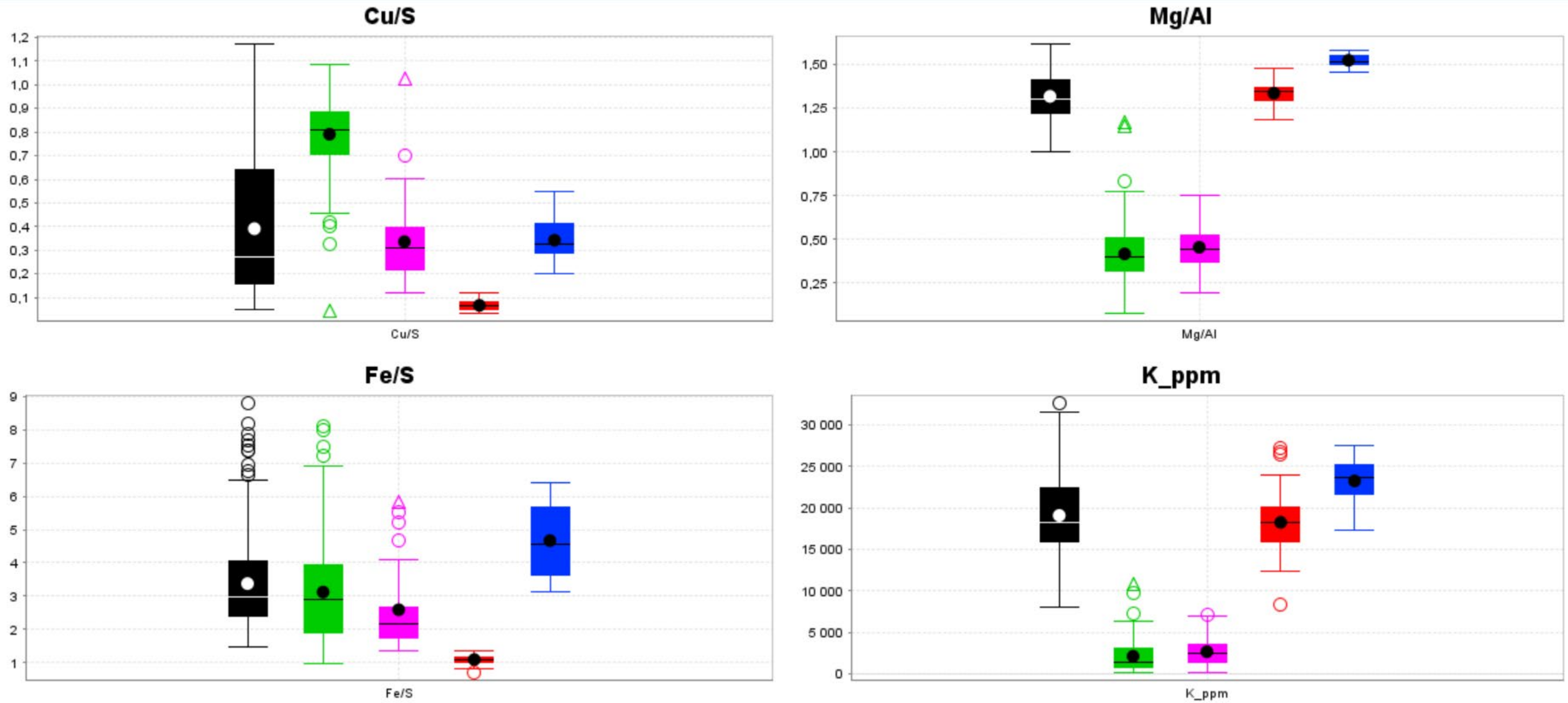
Valuable target metals

CASE STUDY P



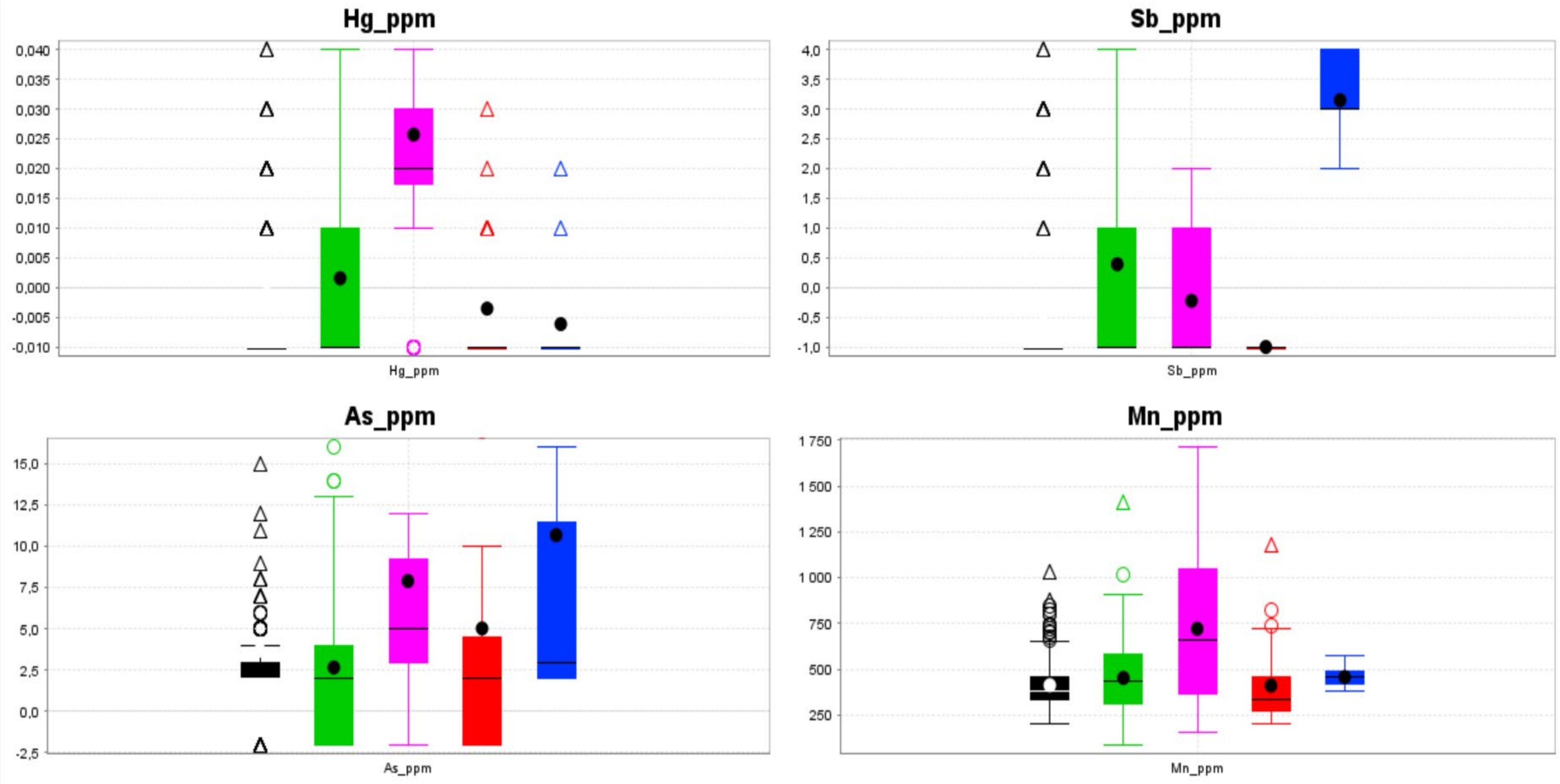
Comminution

CASE STUDY P



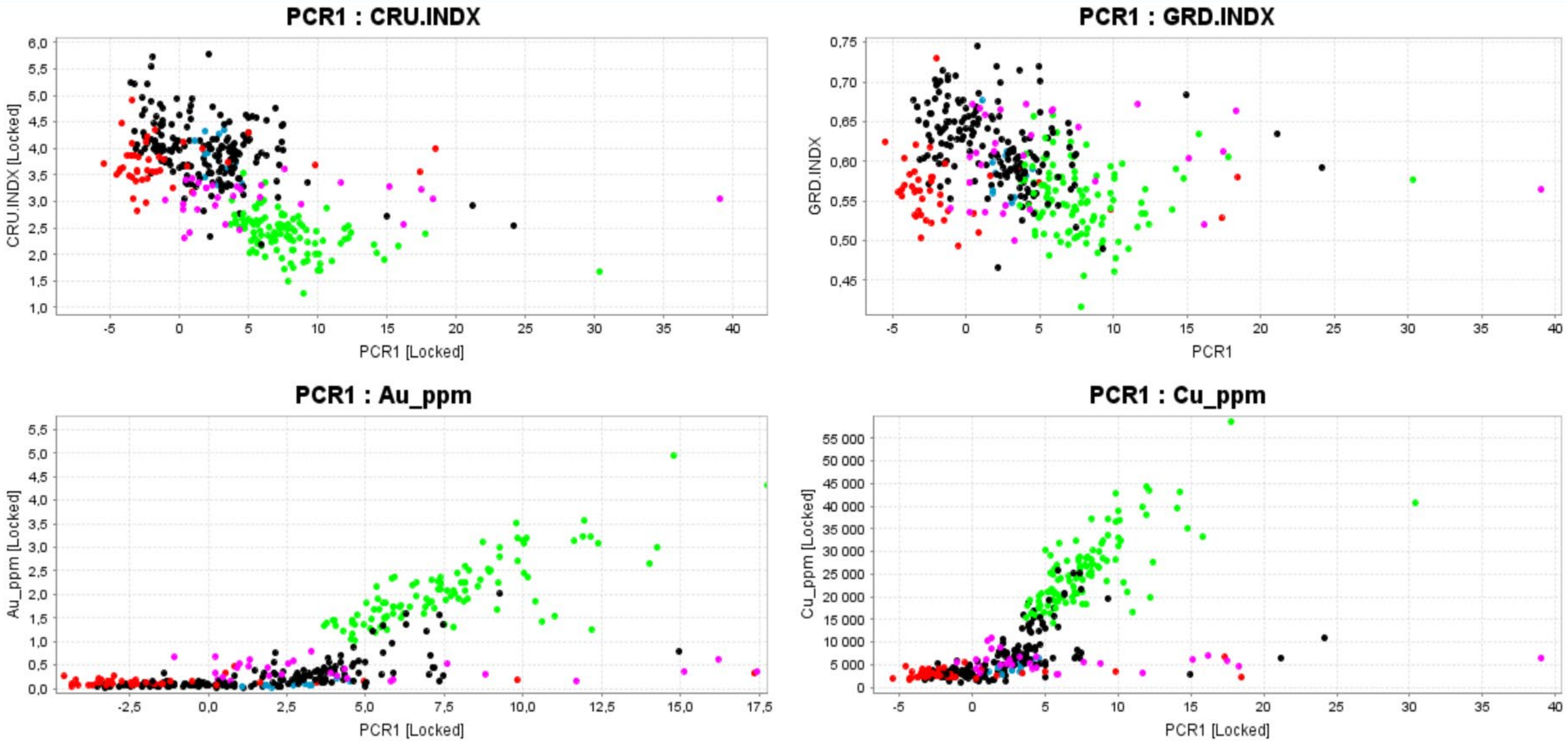
Gangue minerals

CASE STUDY P

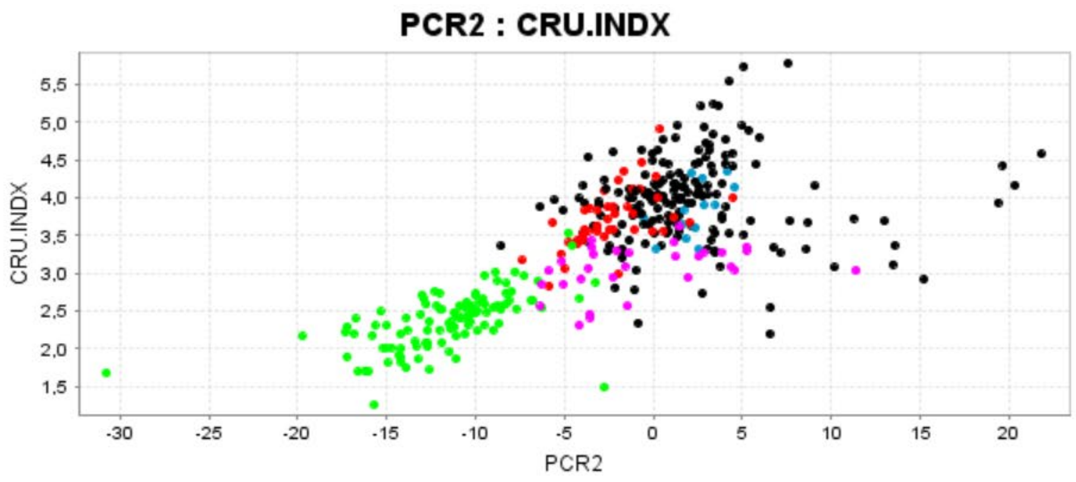


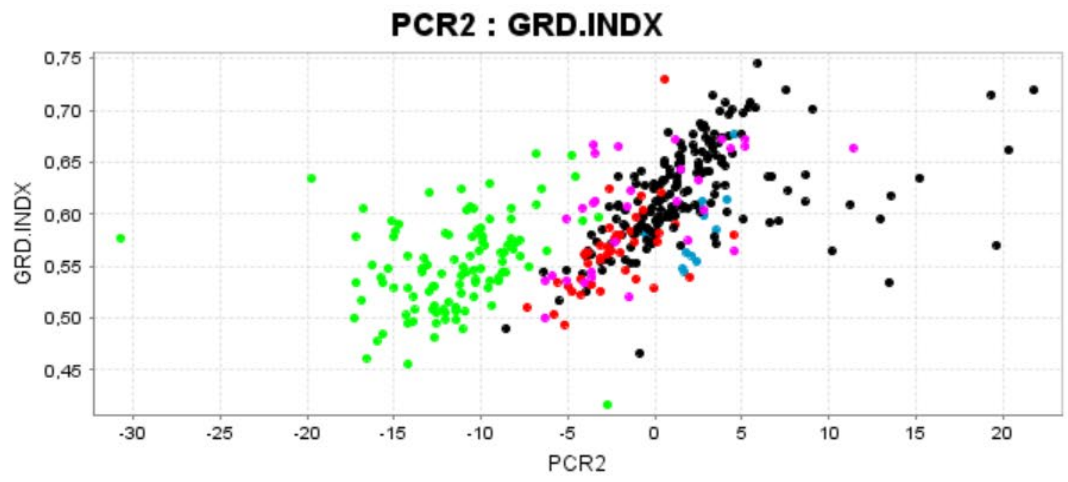
Penalty elements

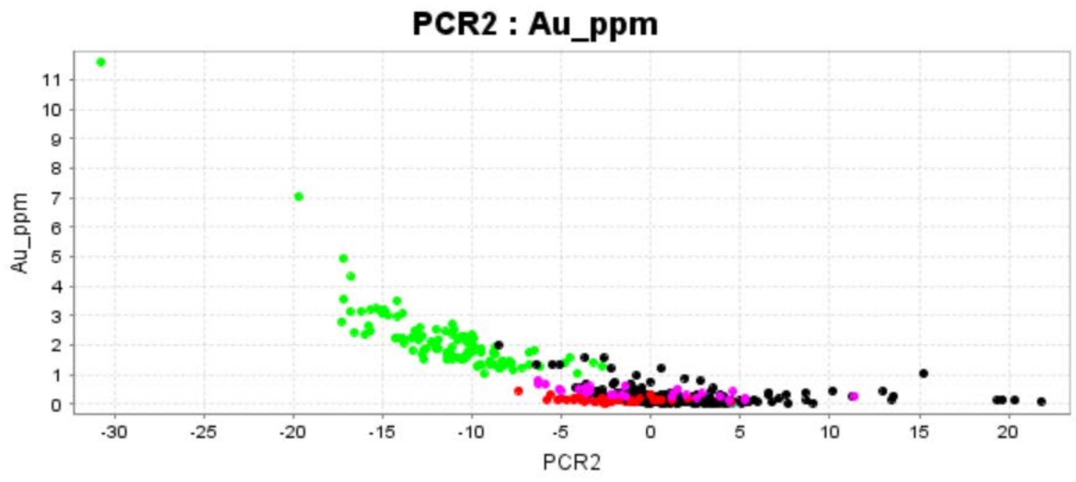
CASE STUDY P

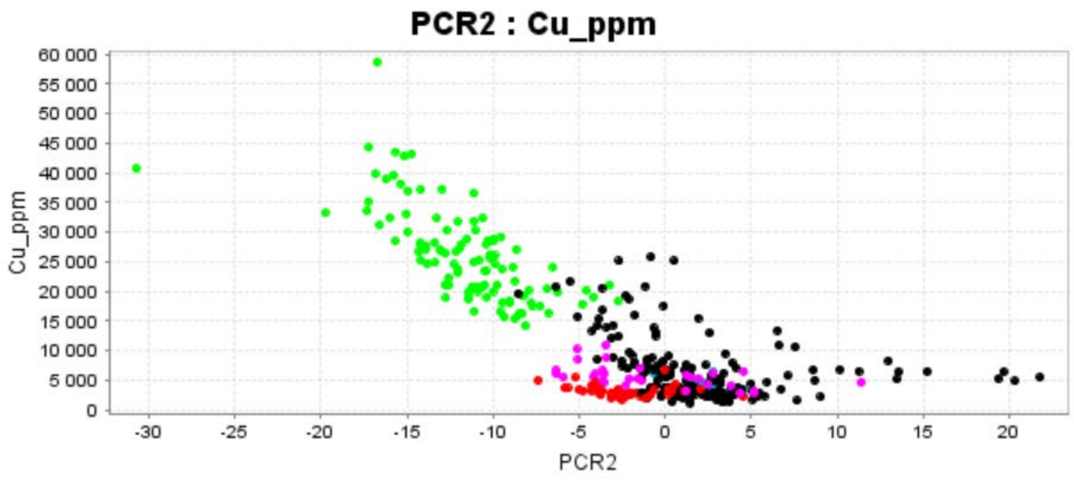

PCR1 : CRU.INDX
CRU.INDX [Locked]
PCR1 [Locked]
PCR1 : GRD.INDX
GRD.INDX
PCR1
PCR1 : Au_ppm
Au_ppm [Locked]
PCR1 [Locked]
PCR1 : Cu_ppm
Cu_ppm [Locked]
PCR1 [Locked]

CASE STUDY P

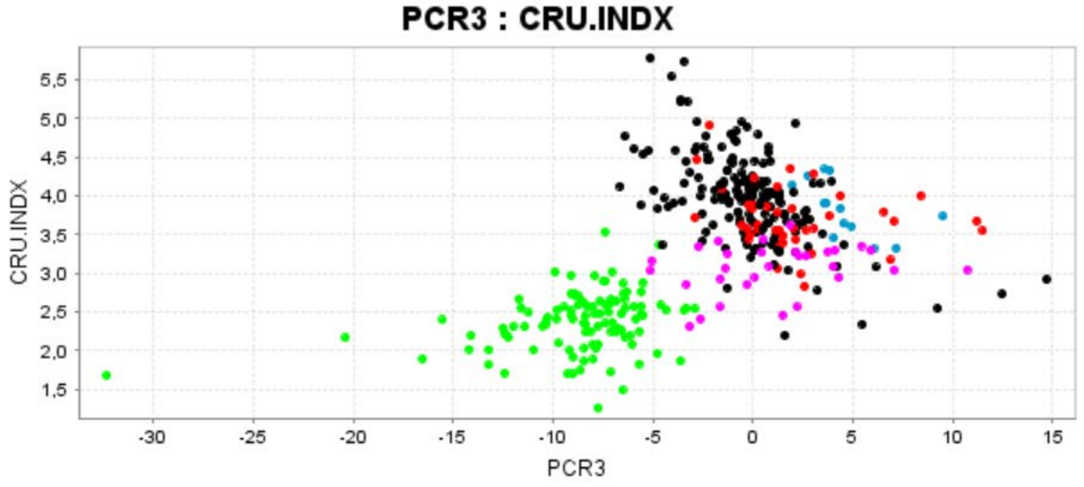

PCR2 : CRU.INDX
CRU.INDX
PCR2

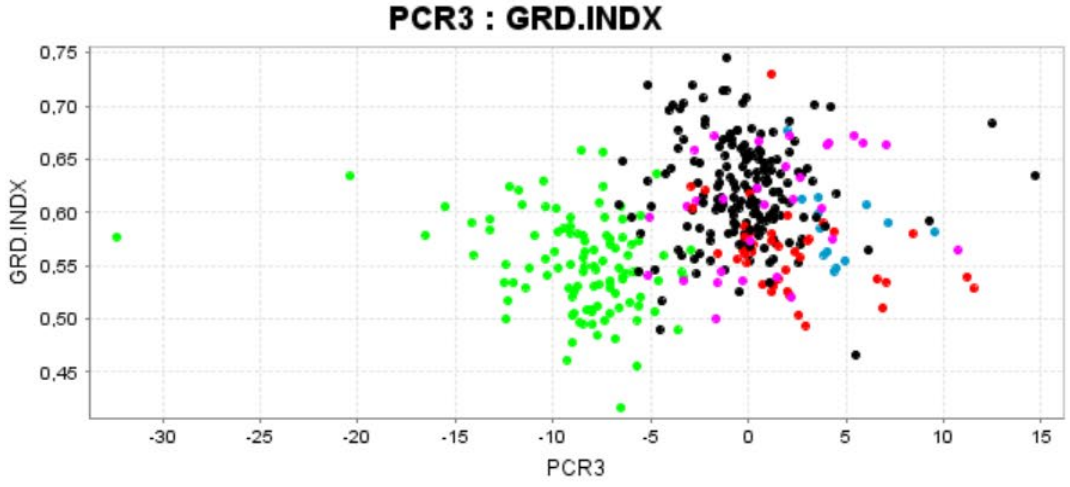

PCR2 : GRD.INDX
GRD.INDX
PCR2

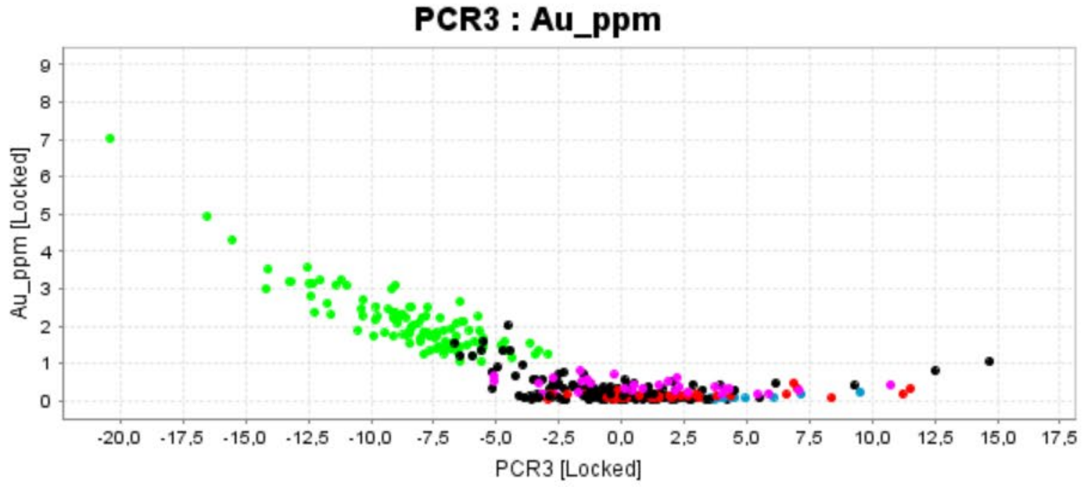

PCR2 : Au_ppm
Au_ppm
PCR2

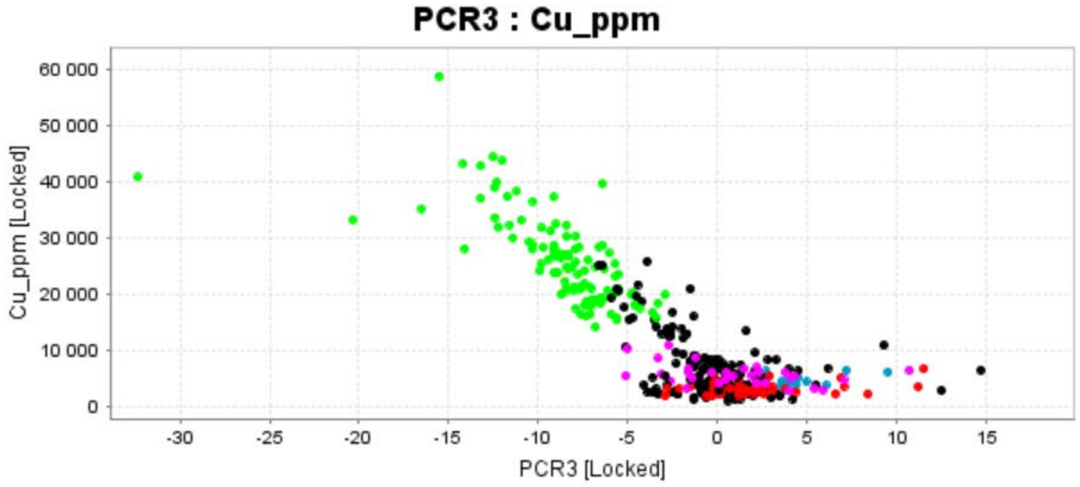

PCR2 : Cu_ppm
Cu_ppm
PCR2

CASE STUDY P



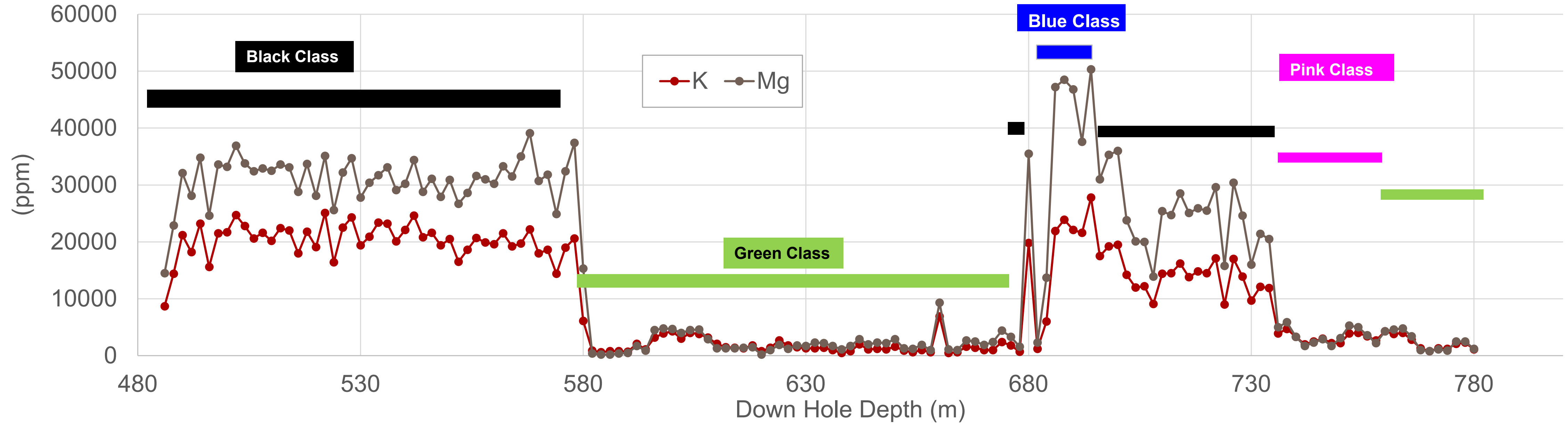




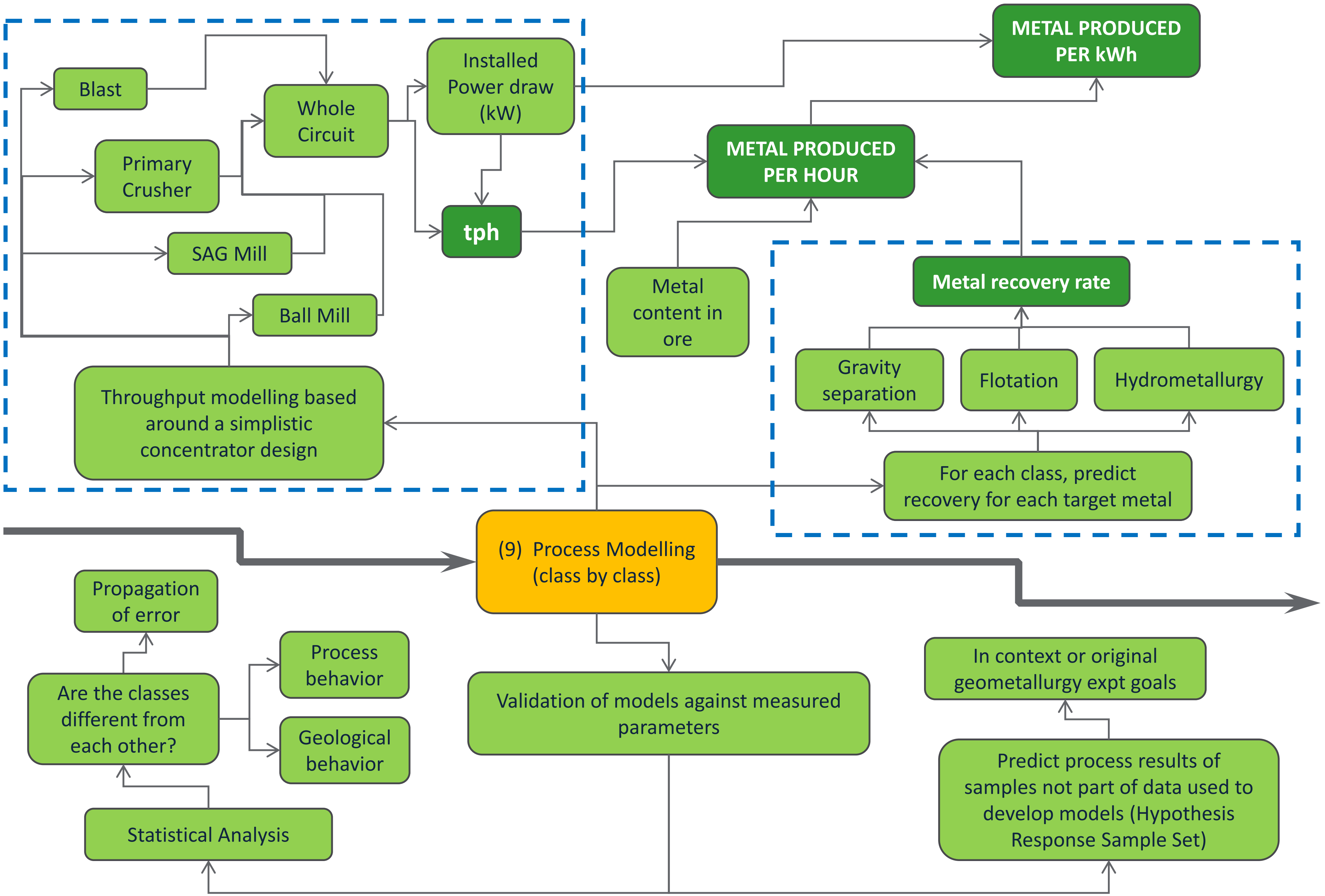


GTK

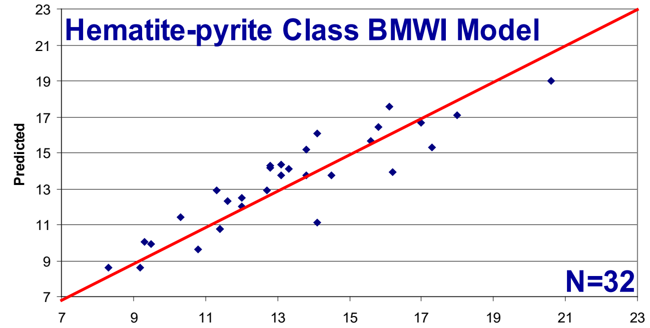
CASE STUDY P – CLASSES PROJECTED BACK INTO DRILL CORE



GTK


METAL PRODUCED PER kWh
Blast
Installed Power draw (kW)
Whole Circuit
Primary Crusher
METAL PRODUCED PER HOUR
tph
SAG Mill
Metal content in ore
Metal recovery rate
Ball Mill
Gravity separation
Flotation
Hydrometallurgy
Throughput modelling based around a simplistic concentrator design
For each class, predict recovery for each target metal
(9) Process Modelling (class by class)
Propagation of error
Process behavior
In context or original geometallurgy expt goals
Are the classes different from each other?
Validation of models against measured parameters
Geological behavior
Predict process results of samples not part of data used to develop models (Hypothesis Response Sample Set)
Statistical Analysis

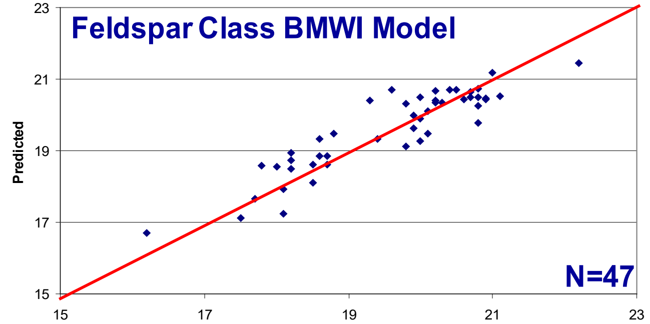
MODELING EXAMPLE R



Model:

BMWI= $-66.65 + 1.24Flu^{0.61} - 0.27Hem - 1.49Py + 19.23SG + 8.39(Py/Sul)^{0.84} + 0.72QHard^{1.22} + 0.72(Chl/Sul)^{1.31}$

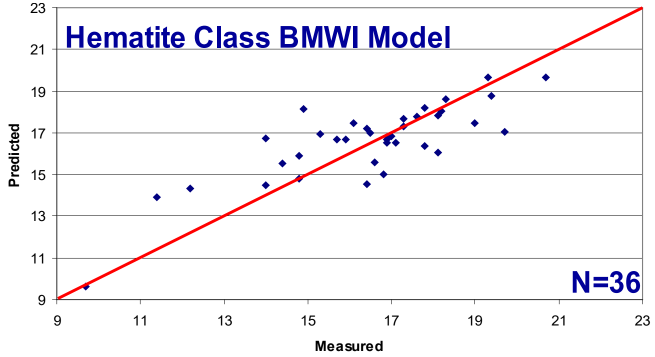
S.E.=0.90 R^2=0.84 Model prediction relative error =7.4%



Model:

BMWI= $-104.4 - 0.17Ksp - 0.88Qtz - 0.12Sid - 0.47Flu - 0.43Sul - 0.54(Ser/Ksp) + 0.88(Sul/Hem) + 8.56QHard$

S.E.=0.41 R^2=0.83 Model prediction relative error =2.1%

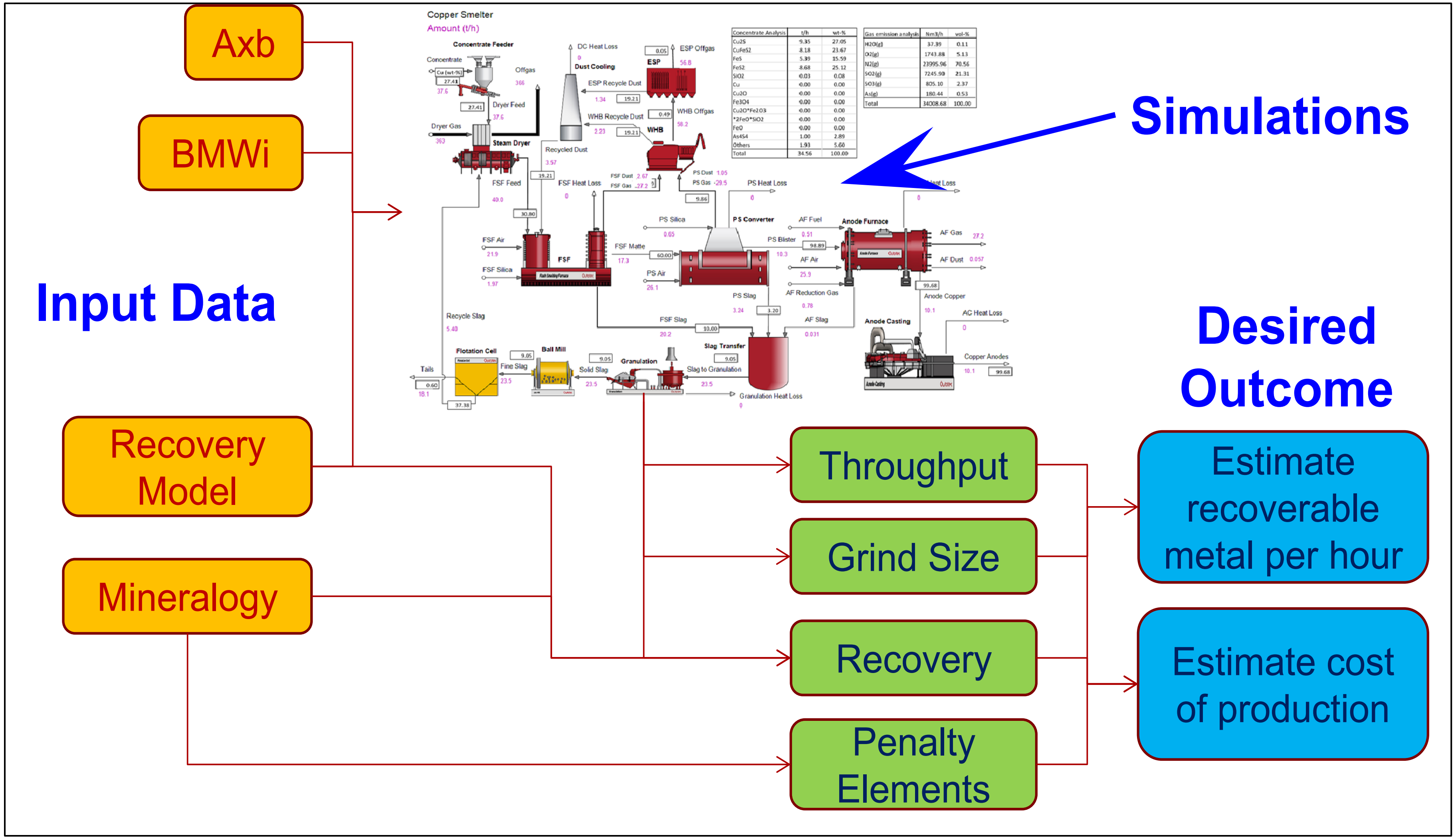


Model:

BMWI= $-44.99 + 0.67Ser^{0.56} + 0.19Sid + 0.13Flu^{1.64} + 0.63Bar^{0.81} + 6.80SG + 1.90QHard$

S.E.=0.99 R^2=0.66 Model prediction relative error =6.2%

PROCESS SIMULATION FOR EACH END MEMBER SAMPLE



GTK

BATCircle

ECONOMIC SIGNATURE MODELLING

Primary metal
Secondary metal?
Trace elements?

Penalty elements that retard smelting & refining performance

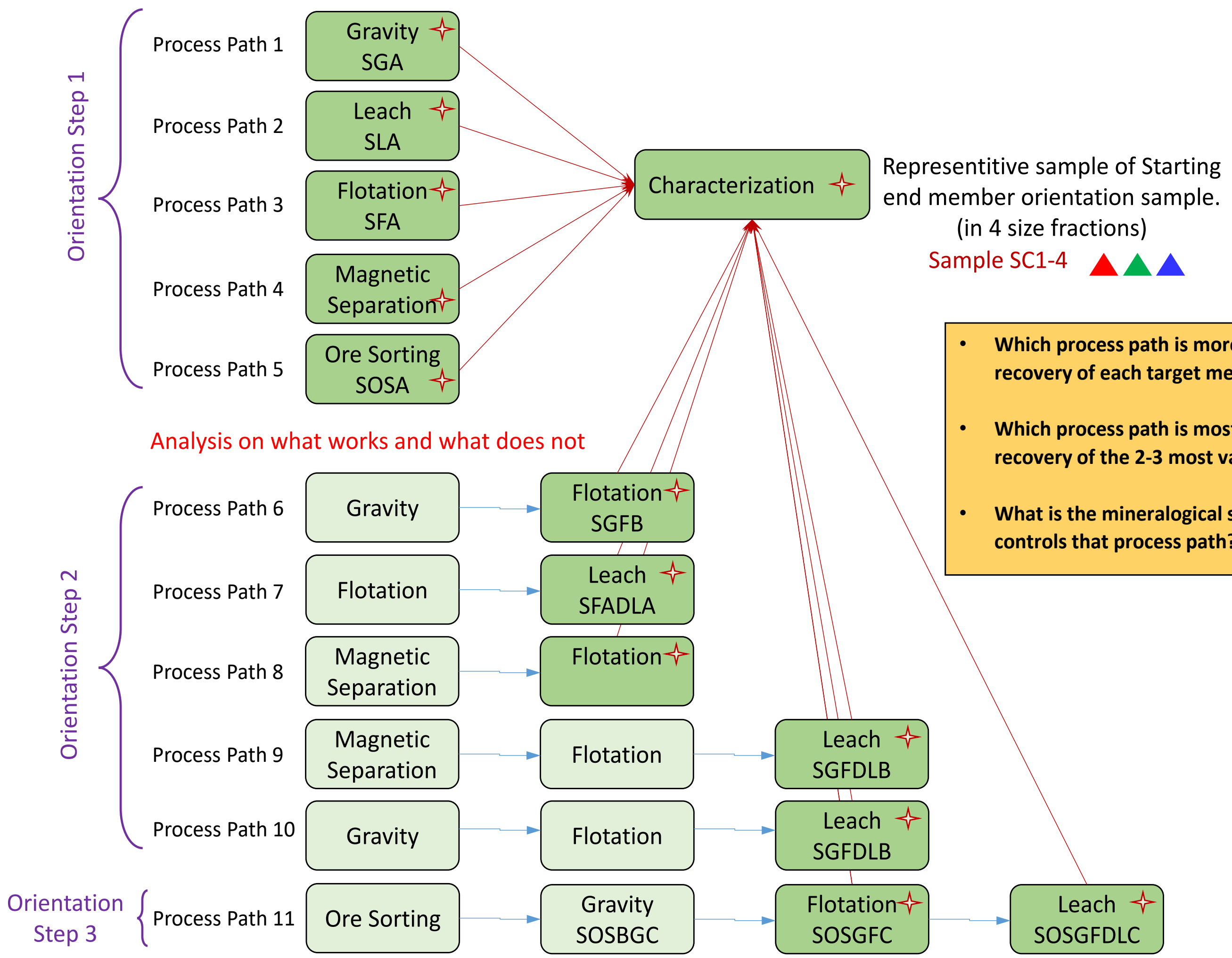
Net Revenue of End Member Ore = (Metal content of end member ore X Recovery model for end member ore X Projected market metal sell price) - Cost of extraction & process of end member ore - Penalty elements at point of sale

Penalty elements that retard flotation recovery?

Power draw comminution
Power draw flotation
Consumables estimate per tonne

GTK

COMPARISON OF DIFFERENT PROCESS PATHS FOR EACH ORIENTATION STUDY SAMPLE



- **Which process path is more effective in the recovery of each target metal?**
- **Which process path is most effective in recovery of the 2-3 most valuable metals?**
- **What is the mineralogical signature that controls that process path?**

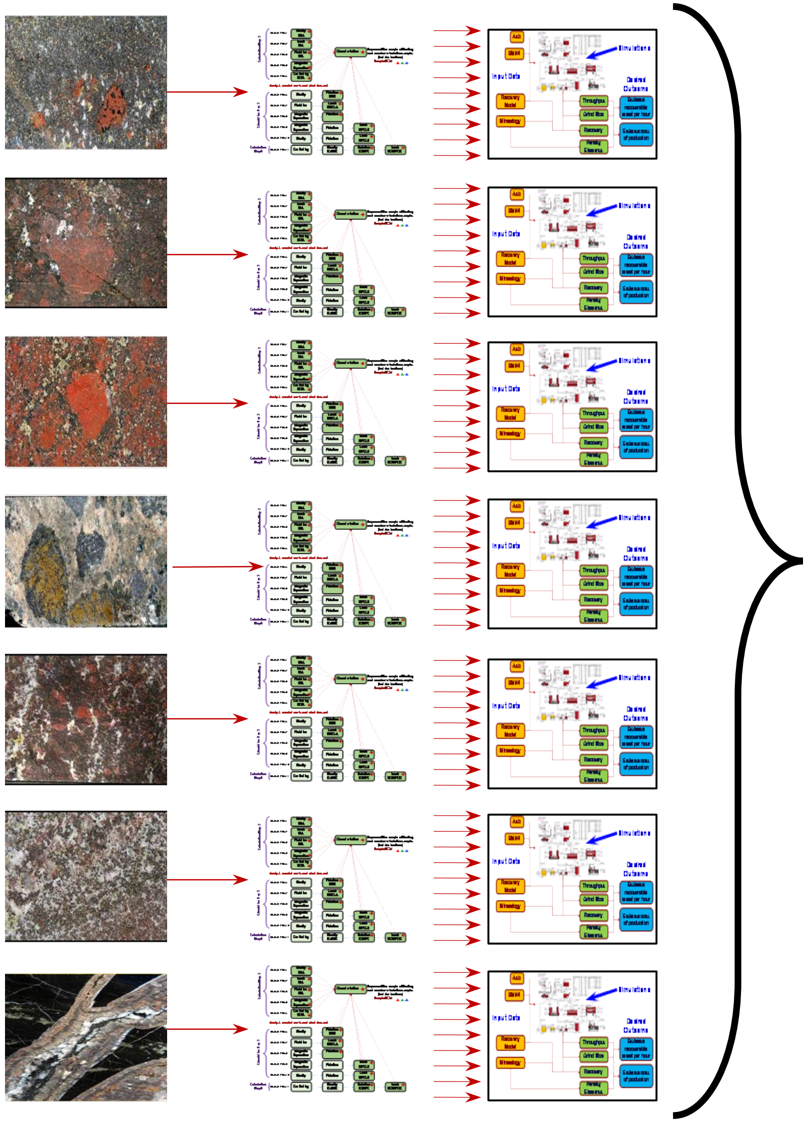
EXPERIMENTAL DESIGN TO STATISTICAL ANALYSIS

- How can we know if which process separation method is more effective?
  - *Flotation/Hydrometallurgy/Gravity/Magnetic*
- How can we know that the process response is really statistically different between rock types?
- T-test
- ANOVA if you can do it

How do we draw conclusions that are defendable?

COMPARISON OF DIFFERENT PROCESS PATHS FOR ALL ORIENTATION STUDY SAMPLES

Orientation Study

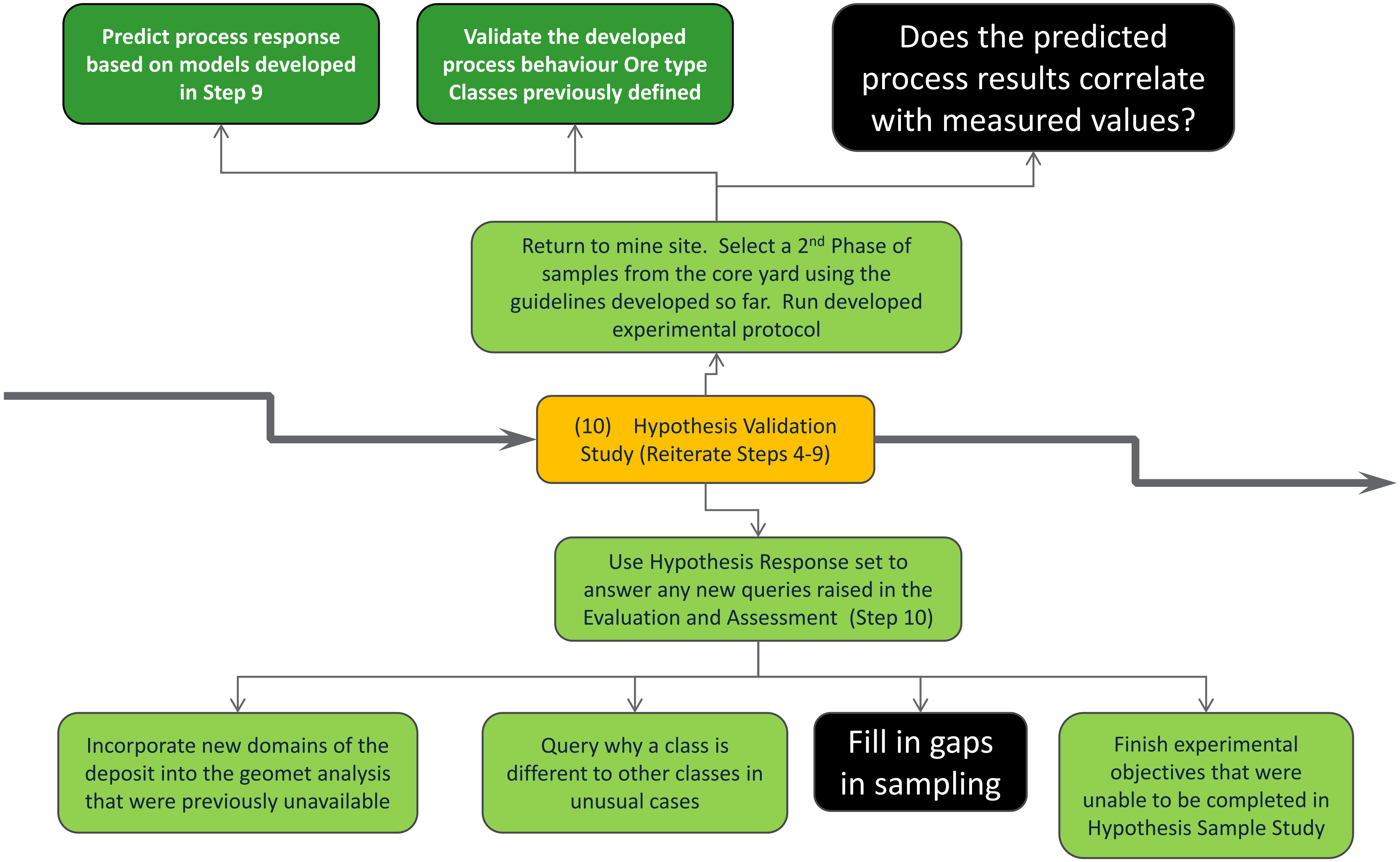


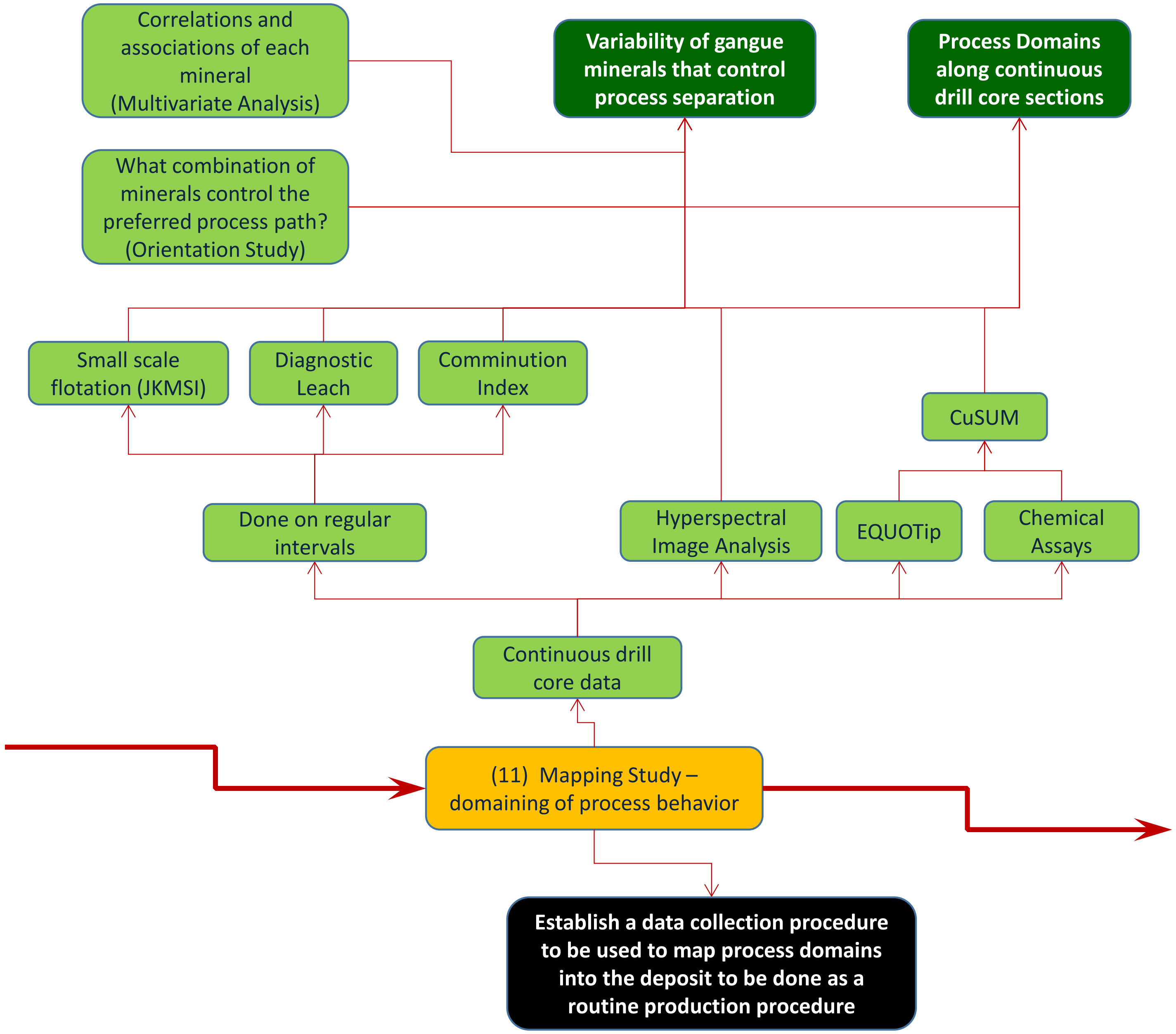
- **Which process path is more effective in the recovery of each target metal?**
- **Which process path is most effective in recovery of the 2-3 most valuable metals?**
- **What is the mineralogical signature that controls that process path?**

Mapping Study

- Process domains
- Variability

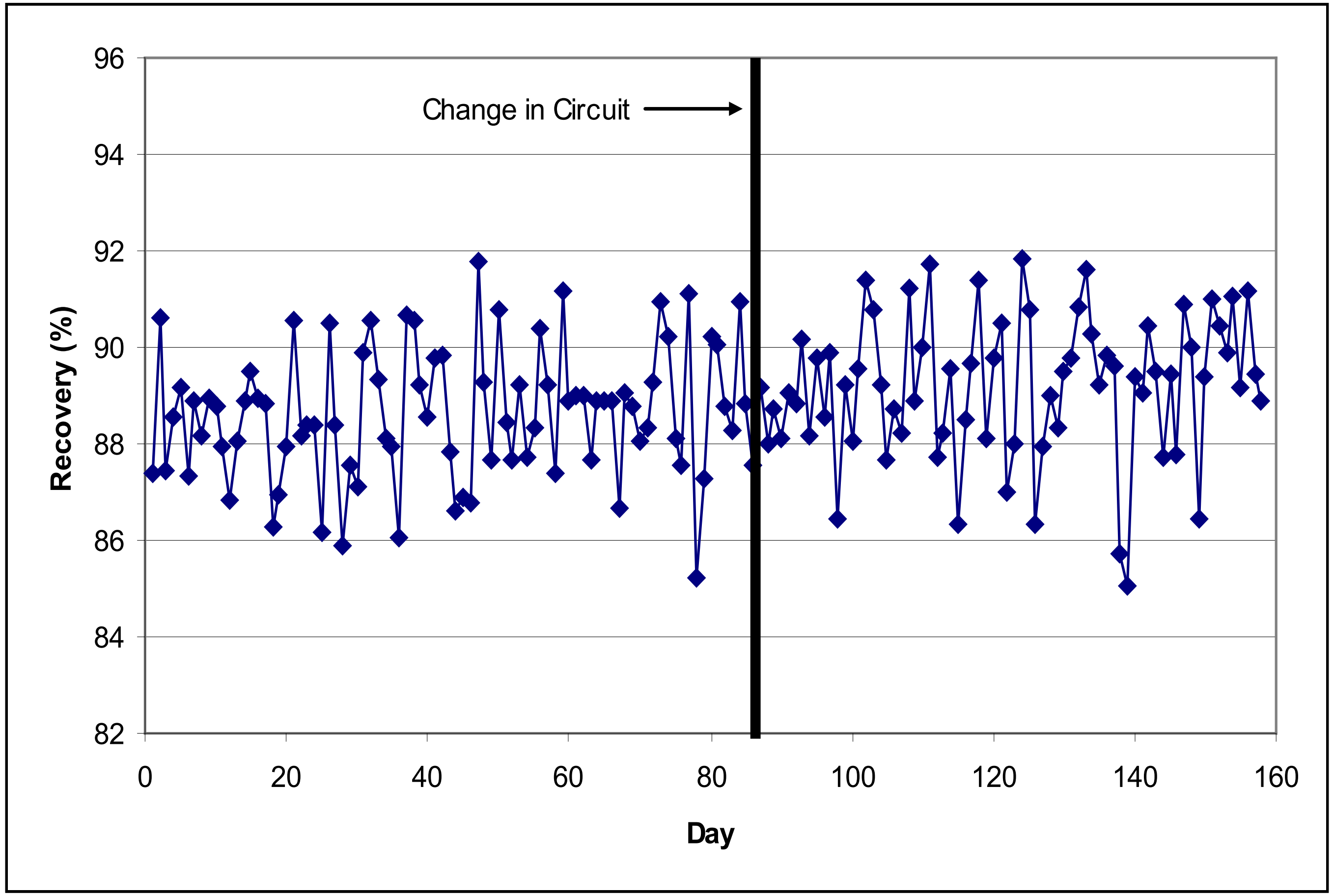
GTK


Predict process response based on models developed in Step 9
Validate the developed process behaviour Ore type Classes previously defined
Does the predicted process results correlate with measured values?
Return to mine site. Select a 2nd Phase of samples from the core yard using the guidelines developed so far. Run developed experimental protocol
(10) Hypothesis Validation Study (Reiterate Steps 4-9)
Use Hypothesis Response set to answer any new queries raised in the Evaluation and Assessment (Step 10)
Incorporate new domains of the deposit into the geomet analysis that were previously unavailable
Query why a class is different to other classes in unusual cases
Fill in gaps in sampling
Finish experimental objectives that were unable to be completed in Hypothesis Sample Study


Correlations and associations of each mineral (Multivariate Analysis)
Variability of gangue minerals that control process separation
Process Domains along continuous drill core sections
What combination of minerals control the preferred process path? (Orientation Study)
Small scale flotation (JKMSI)
Diagnostic Leach
Comminution Index
CuSUM
Done on regular intervals
Hyperspectral Image Analysis
EQUOTip
Chemical Assays
Continuous drill core data
(11) Mapping Study – domaining of process behavior
Establish a data collection procedure to be used to map process domains into the deposit to be done as a routine production procedure

CUMULATIVE SUMMATION (CUSUM) ANALYSIS

Time Series Recovery Chart

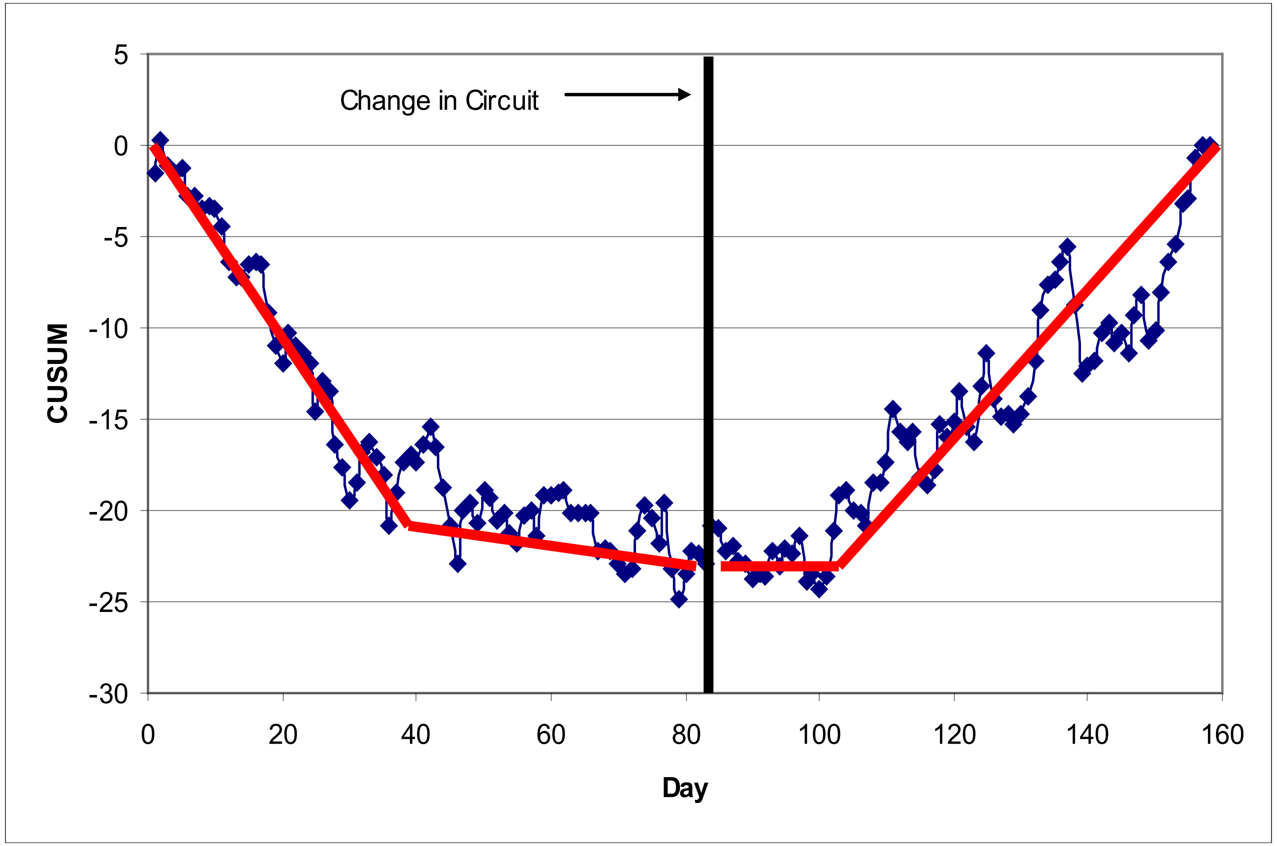


Example Source: T. Napier-Munn

A change was made to a flotation plant circuit at day 85 and the data was analyzed to determine if there was a change in recovery performance of the circuit.

The time series plot does not provide any visible indication of any change in the day to day recovery data.

CUMULATIVE SUMMATION (CUSUM) ANALYSIS



μ=88.87% (overall mean of dataset)

The cusum plot identifies four periods:

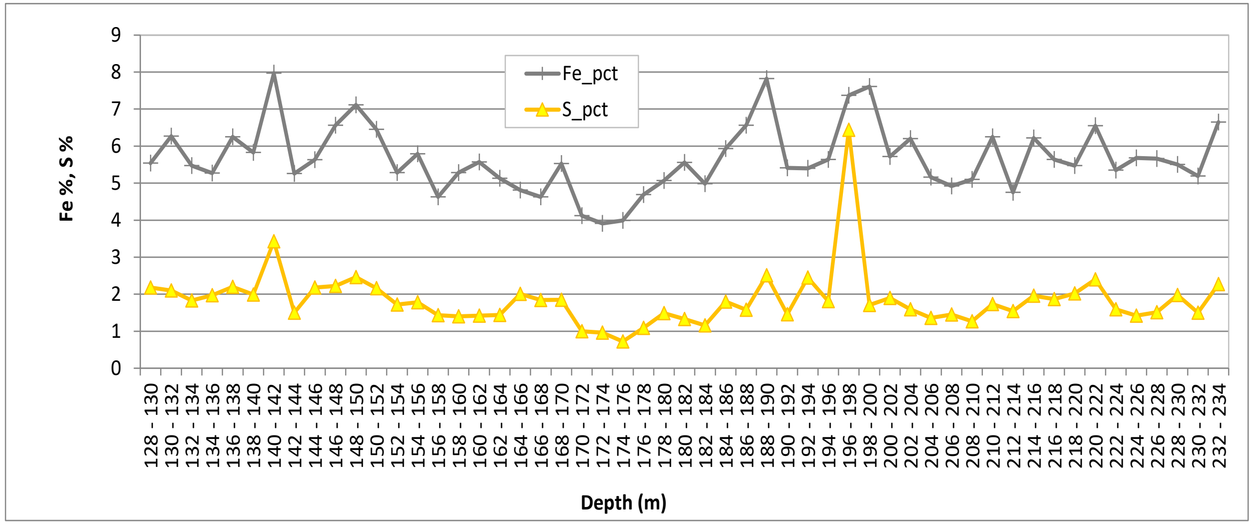
- two –ve gradients
- one horizontal gradient
- one positive gradient

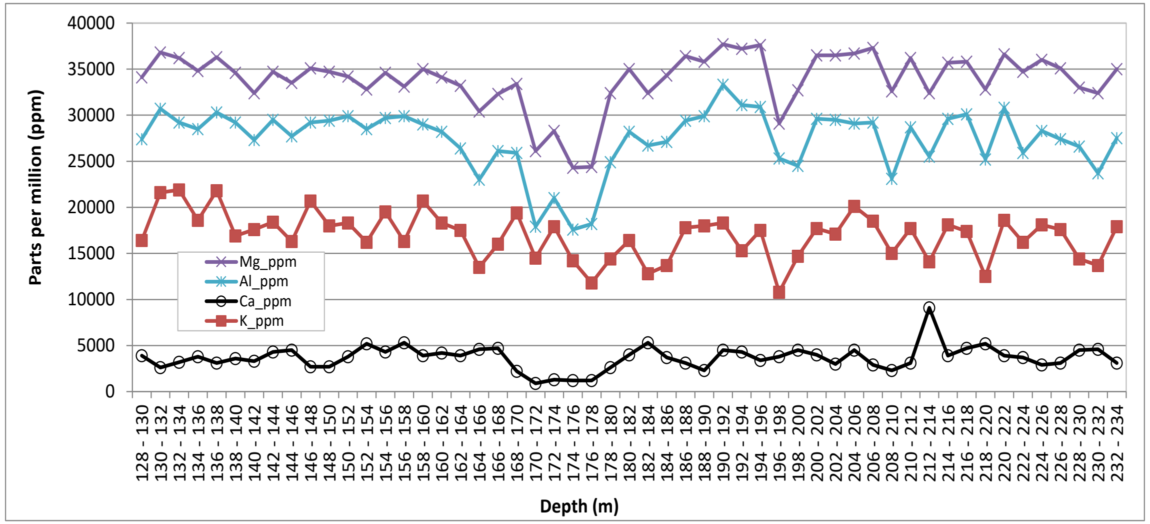
Difference between lowest and highest recoveries are only 1%

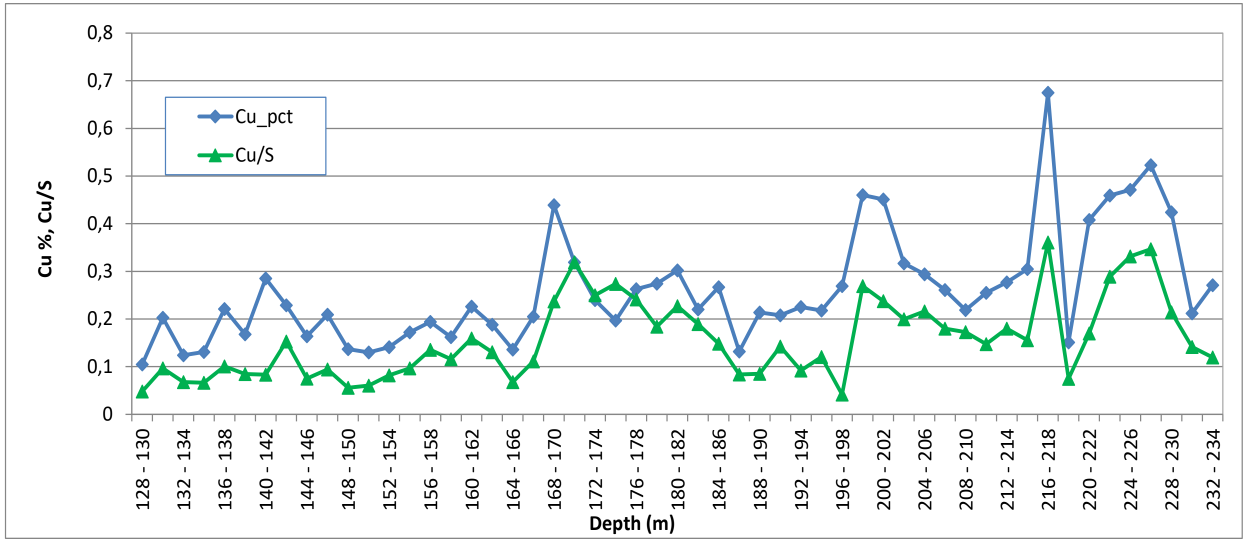
Example Source: T. Napier-Munn

GTK

HOW DO WE LOOK AT DOWN HOLE DATA?





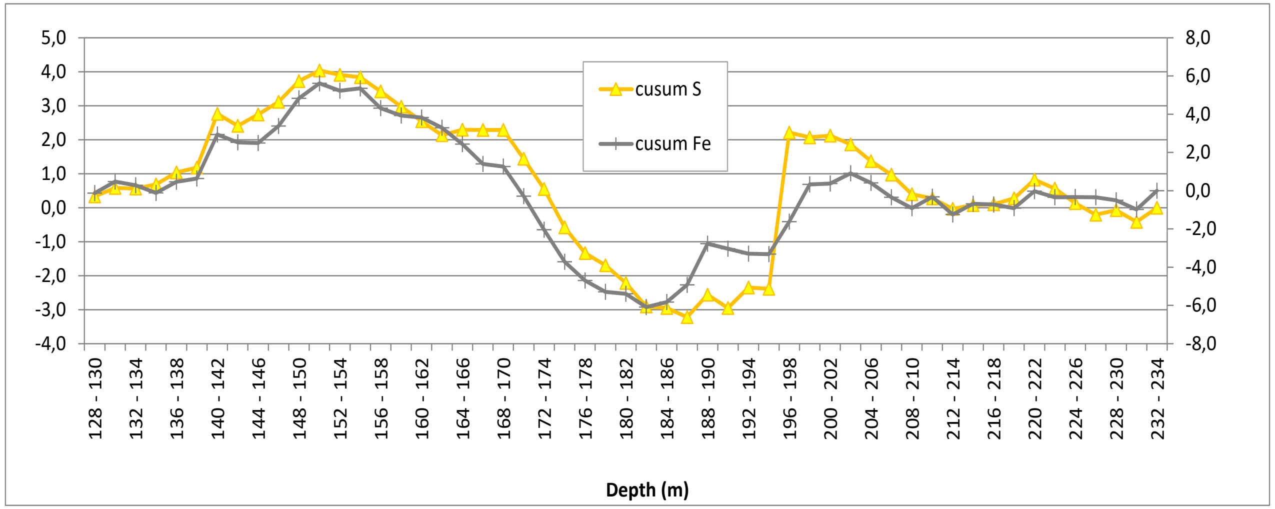


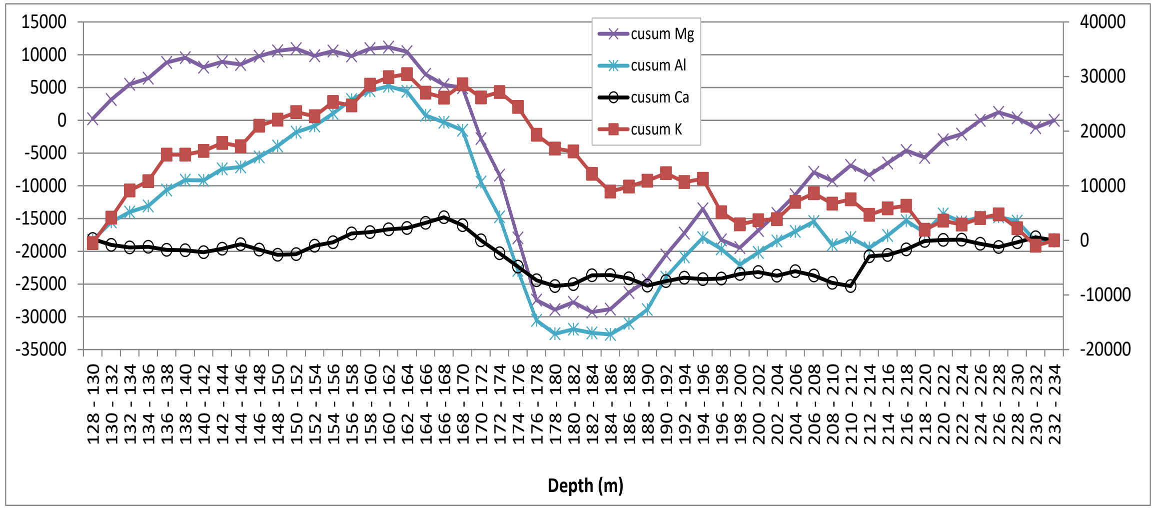
Need a statistically valid method that can filter data

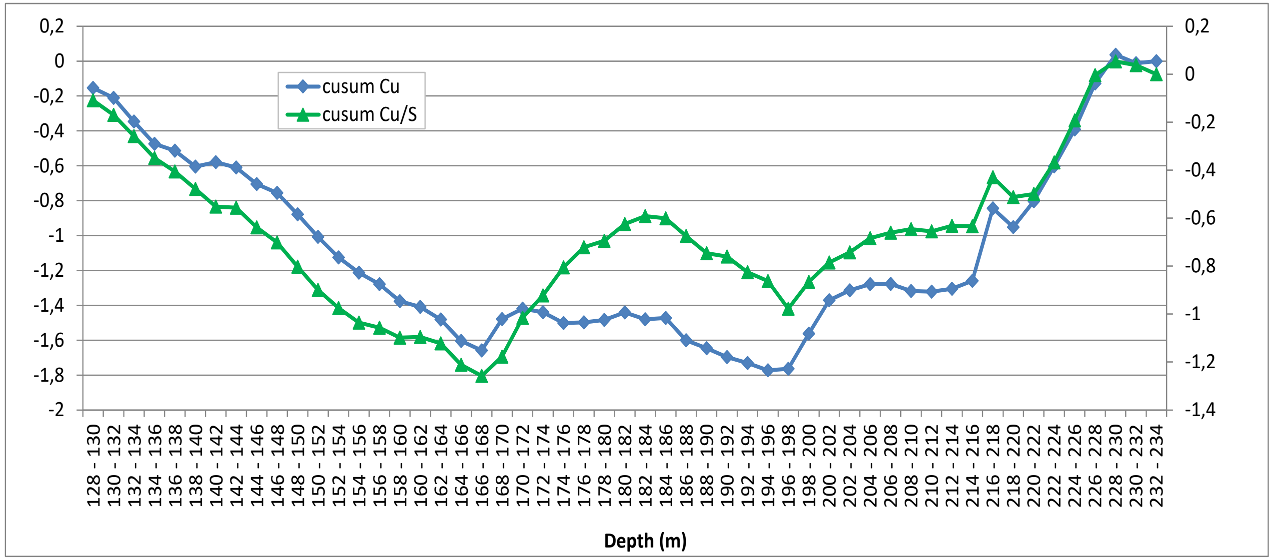
Case Study P

GTK

THE CUSUM TOOL



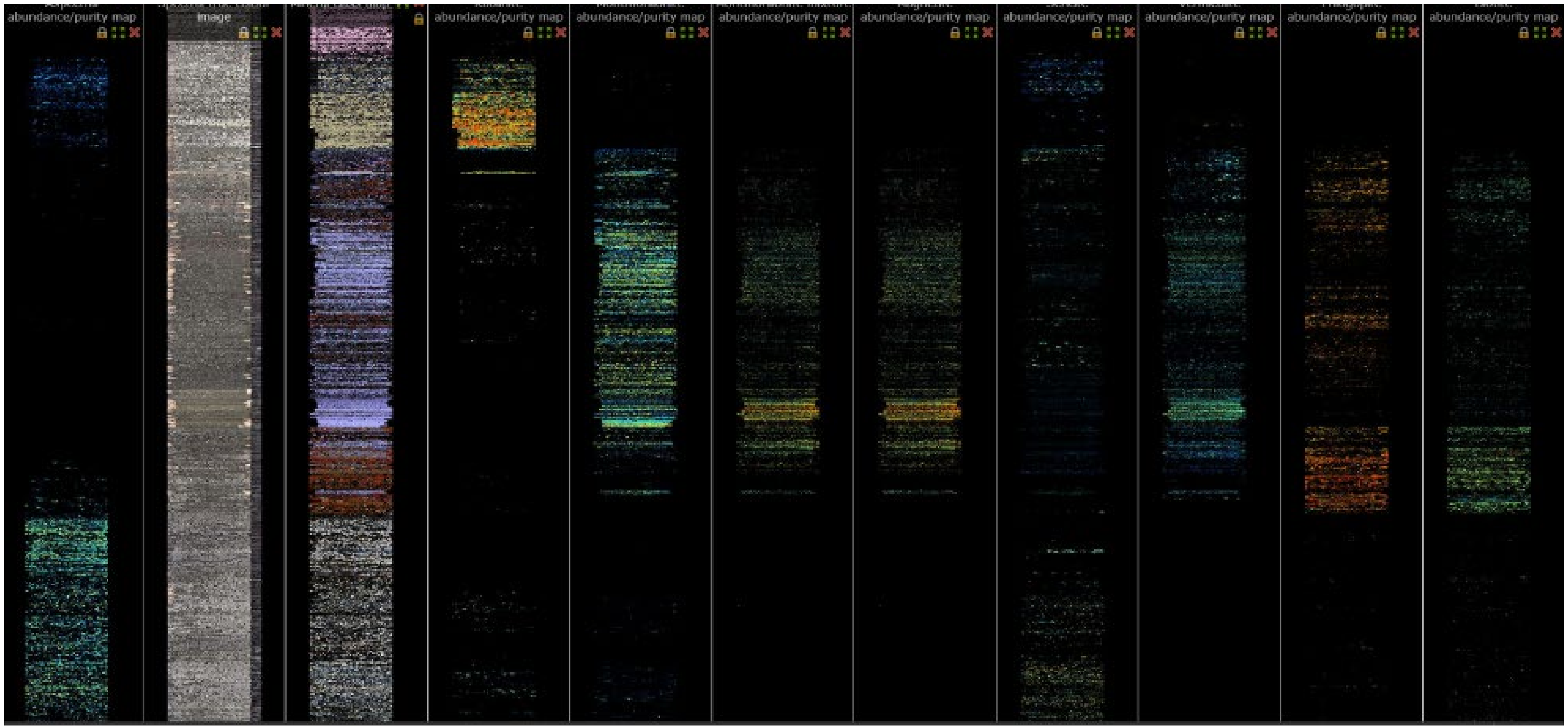




- The absolute value of the cusum at any point is not important
- The gradient of the line over a characteristic period indicates the prevailing mean.

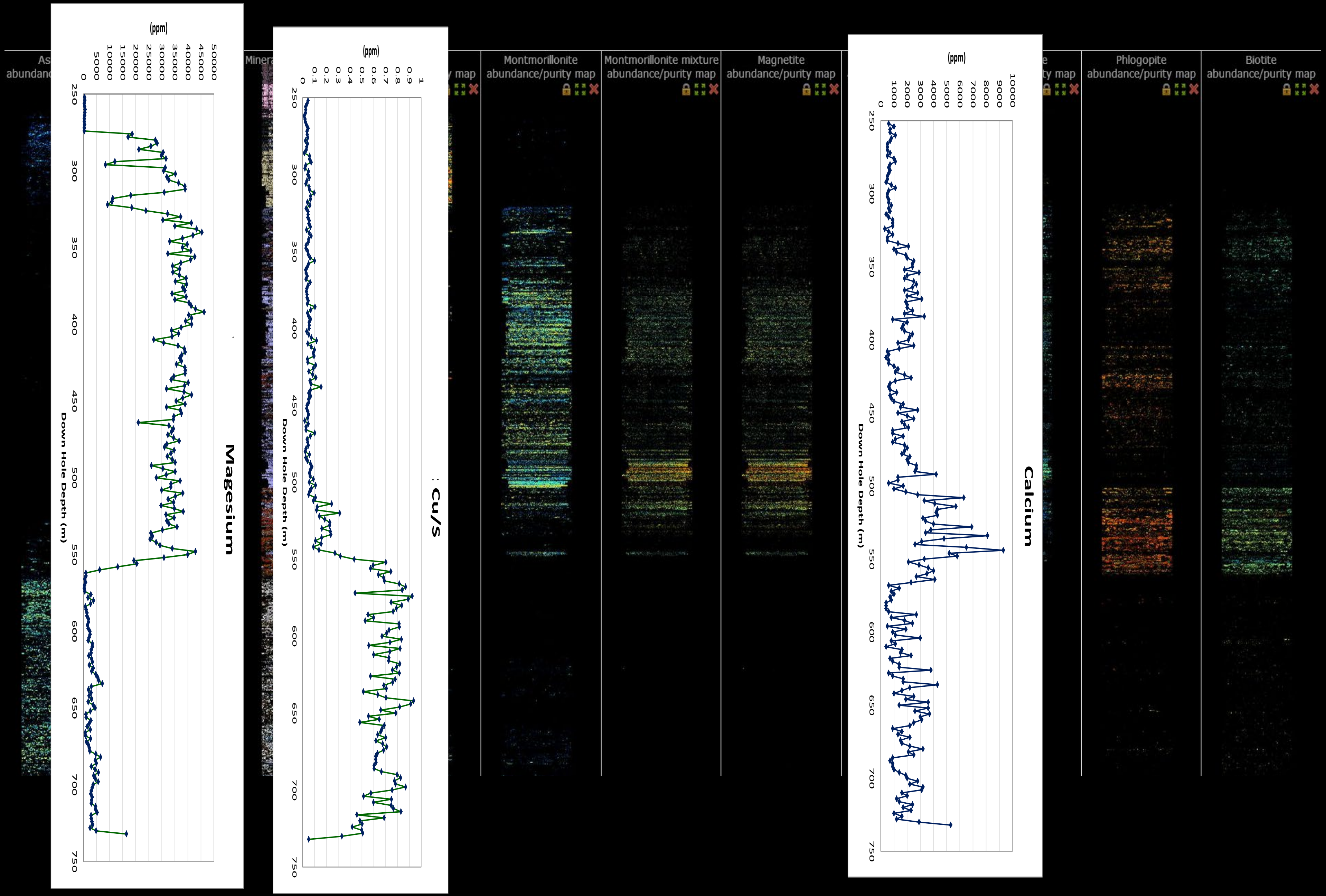
Case Study P

HYPERSPECTRAL IMAGING OF DRILL CORE

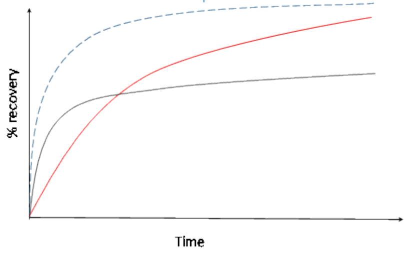


Depth

Each line is 4m of drill core characterised

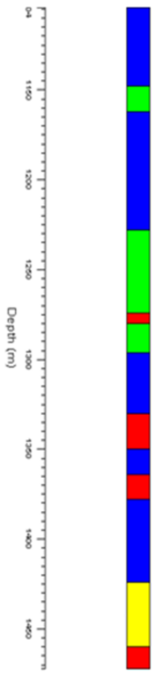

Montmorillonite abundance/purity map
Montmorillonite mixture abundance/purity map
Magnetite abundance/purity map
Phlogopite abundance/purity map
Biotite abundance/purity map
Magesium
Cu/S
Calcium
(ppm)
Down Hole Depth (m)

Exploration drill core



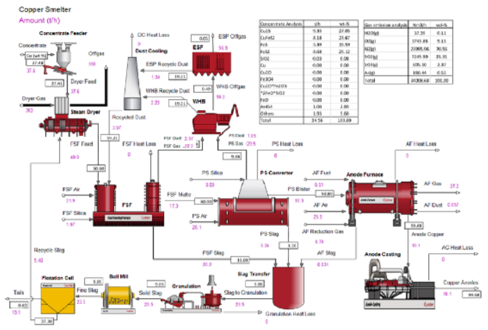
Proxy diagnostic leach tests

Geometallurgy modelling



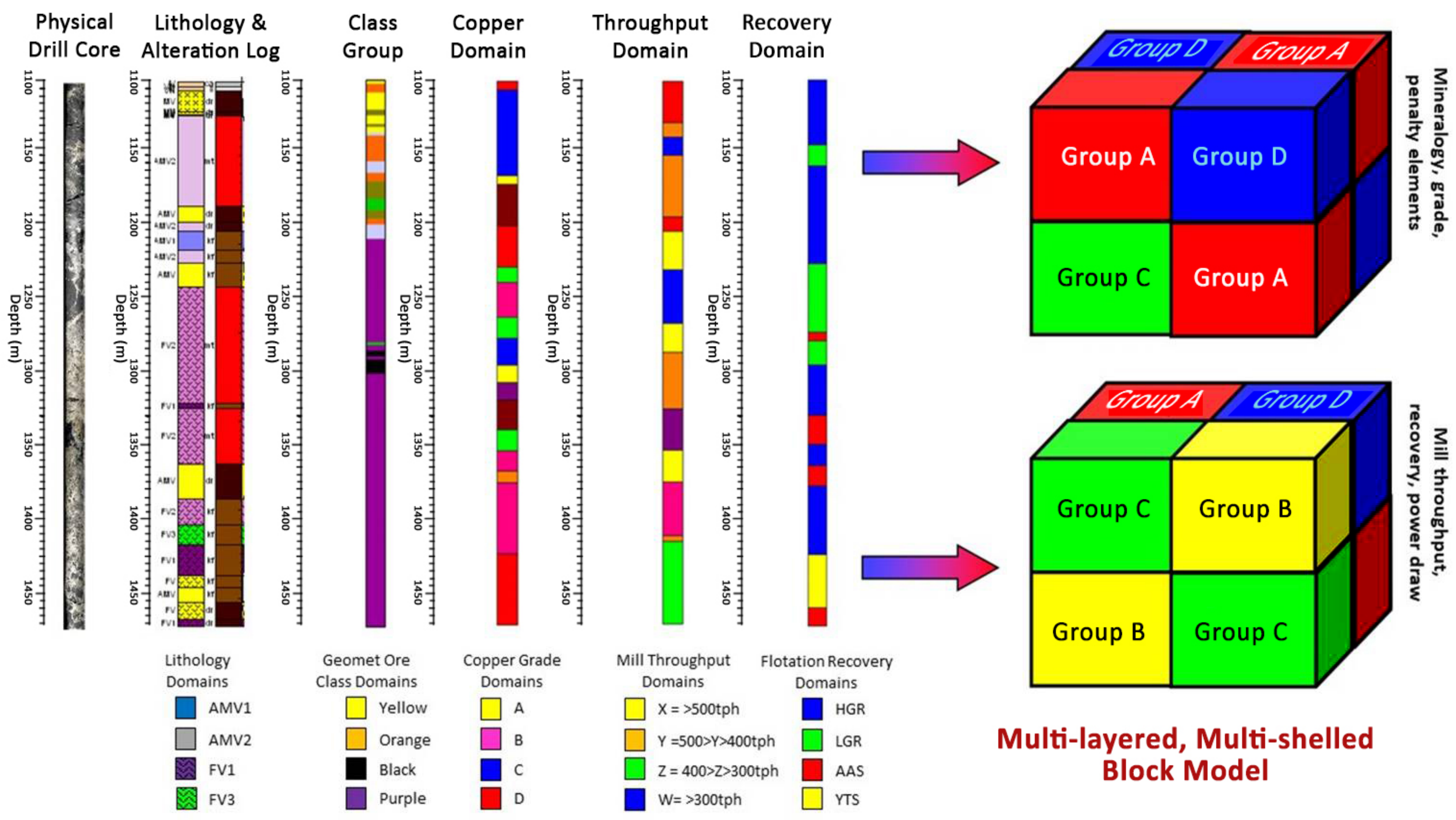
Conventional column leach tests

Feed material much more reliable



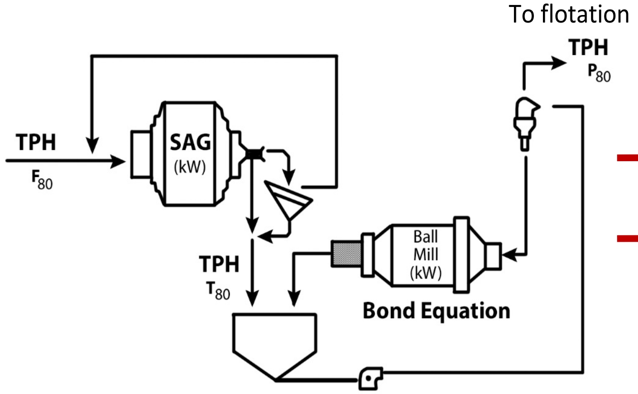
Engineering design

GTK

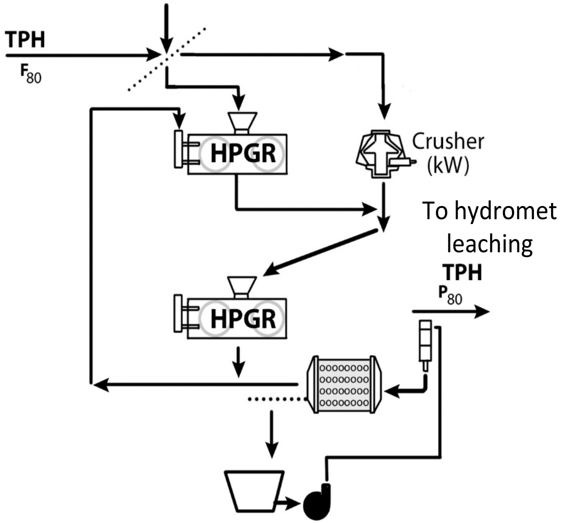


Multi-layered, Multi-shelled Block Model

CIRCUIT A



CIRCUIT B



ORE DOMAINS TO PROCESS

Ore Domain 3

Ore Domain 4

Ore Domain 1

Ore Domain 2

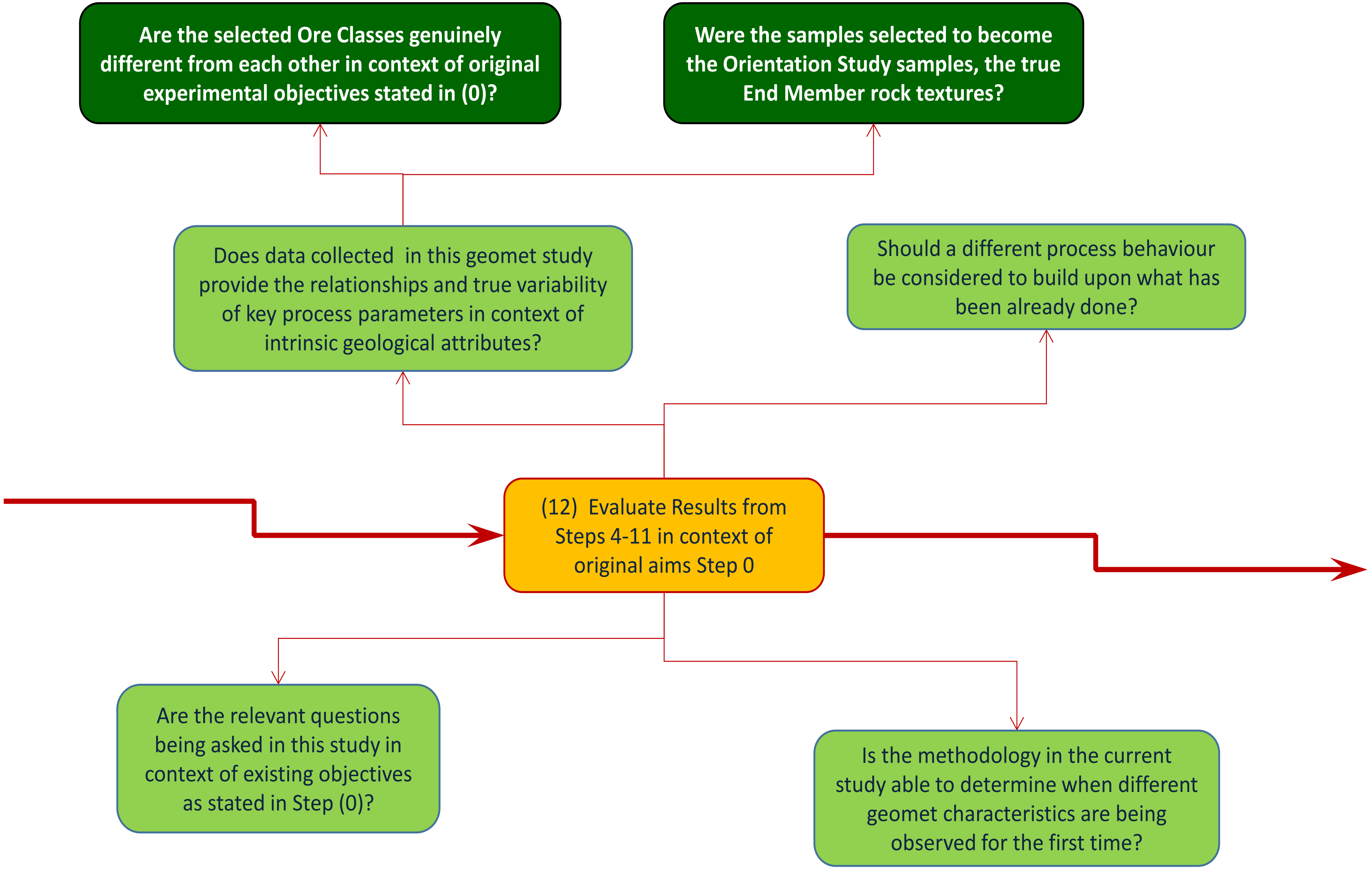
PLANT ECONIMICS

(NPV $ϕ, CAPEX $φ, OPEX $β)

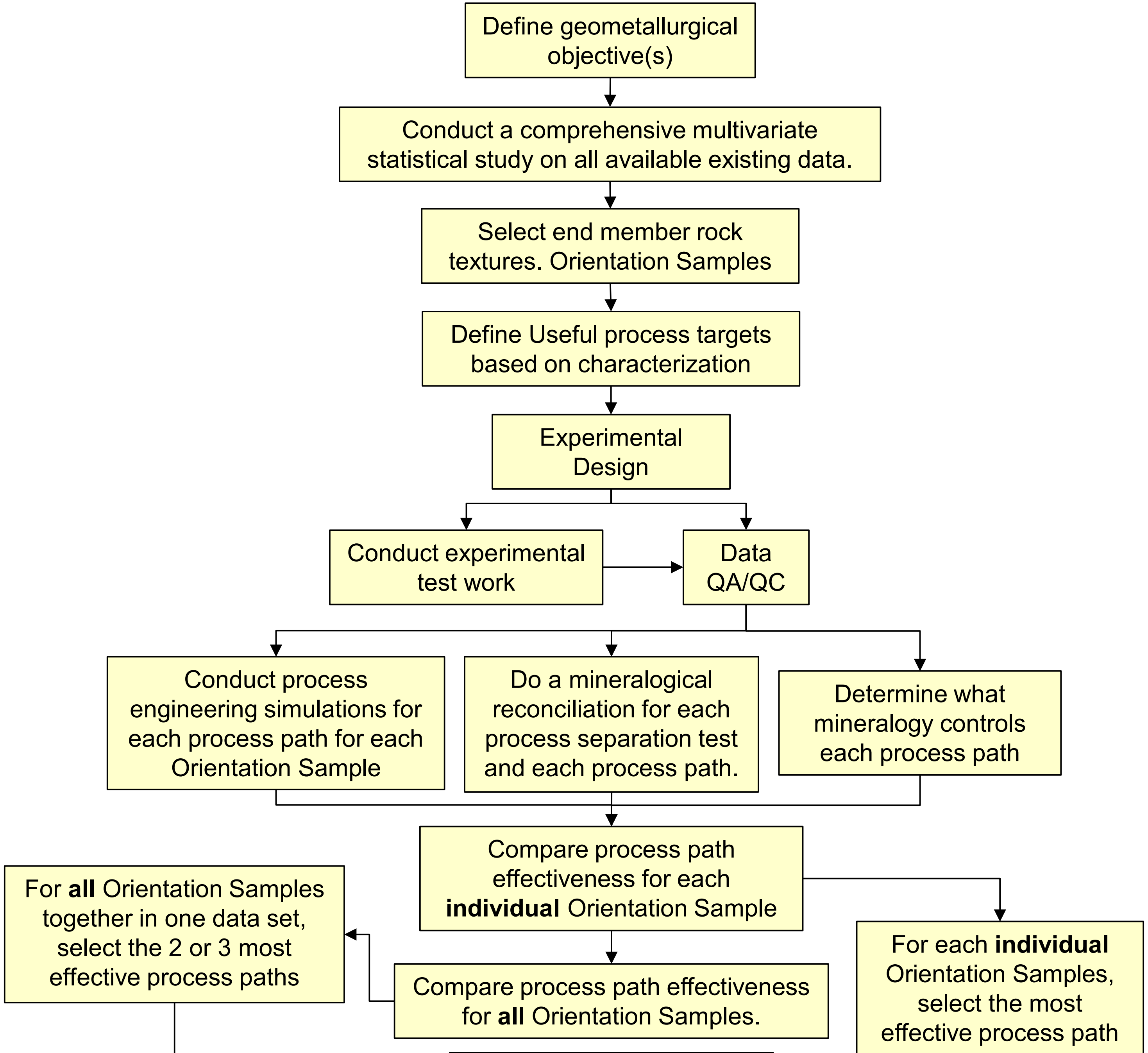
- Net revenue per quarter time period
- Metal produced total
- Metal produced per hour over schedule

(NPV $A, CAPEX $B, OPEX $C)

- Net revenue per quarter time period
- Metal produced total
- Metal produced per hour over schedule


Are the selected Ore Classes genuinely different from each other in context of original experimental objectives stated in (0)?
Were the samples selected to become the Orientation Study samples, the true End Member rock textures?
Does data collected in this geomet study provide the relationships and true variability of key process parameters in context of intrinsic geological attributes?
Should a different process behaviour be considered to build upon what has been already done?
(12) Evaluate Results from Steps 4-11 in context of original aims Step 0
Are the relevant questions being asked in this study in context of existing objectives as stated in Step (0)?
Is the methodology in the current study able to determine when different geomet characteristics are being observed for the first time?

- The geomet program has been successful in context of original objectives
- The original Orientation Study samples really were samples where the process extremes were observed
- The selected grind size was appropriate
- A viable process flow sheet was developed for each end member rock texture
- An economic signature was developed for each orientation sample
- The mineralogy that controls the favoured process flow sheet was diagnosed, then procedures to map them back in the deposit in a spatial context was developed
- Process defined ore domains were developed across all major geological structures in the deposit
- Sampling is consistent enough to make a production procedure
- A viable link between the geometallurgy campaign and the conventional process modelling characterization was established

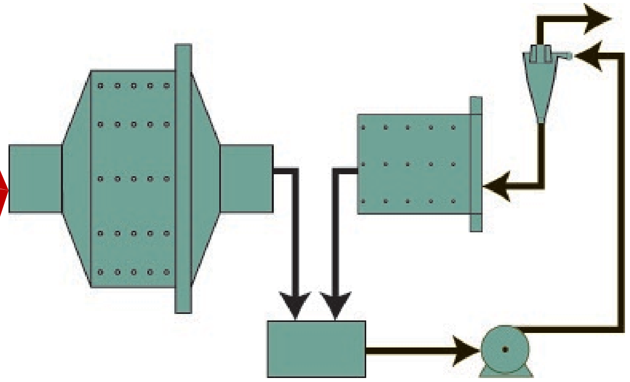

Define geometallurgical objective(s)
Conduct a comprehensive multivariate statistical study on all available existing data.
Select end member rock textures. Orientation Samples
Define Useful process targets based on characterization
Experimental Design
Conduct experimental test work
Data QA/QC
Conduct process engineering simulations for each process path for each Orientation Sample
Do a mineralogical reconciliation for each process separation test and each process path.
Determine what mineralogy controls each process path
Compare process path effectiveness for each **individual** Orientation Sample
For **all** Orientation Samples together in one data set, select the 2 or 3 most effective process paths
Compare process path effectiveness for **all** Orientation Samples.
For each **individual** Orientation Samples, select the most effective process path

GEOMET TO OPERATION

Geometallurgy Laboratory scale

Pilot Scale/Production scale

Mineral signatures	Instrumentation Measurement
Behavior 1	Behavior A
Behavior 2	Behavior B
Behavior 3	Behavior C
Behavior 4	Behavior D
Behavior 5	Behavior E



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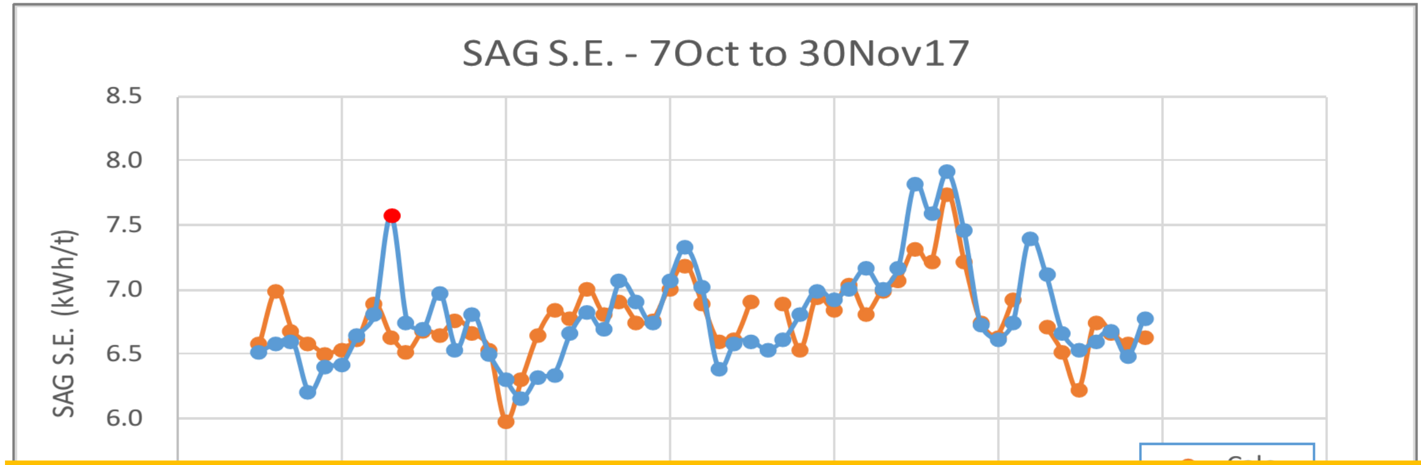
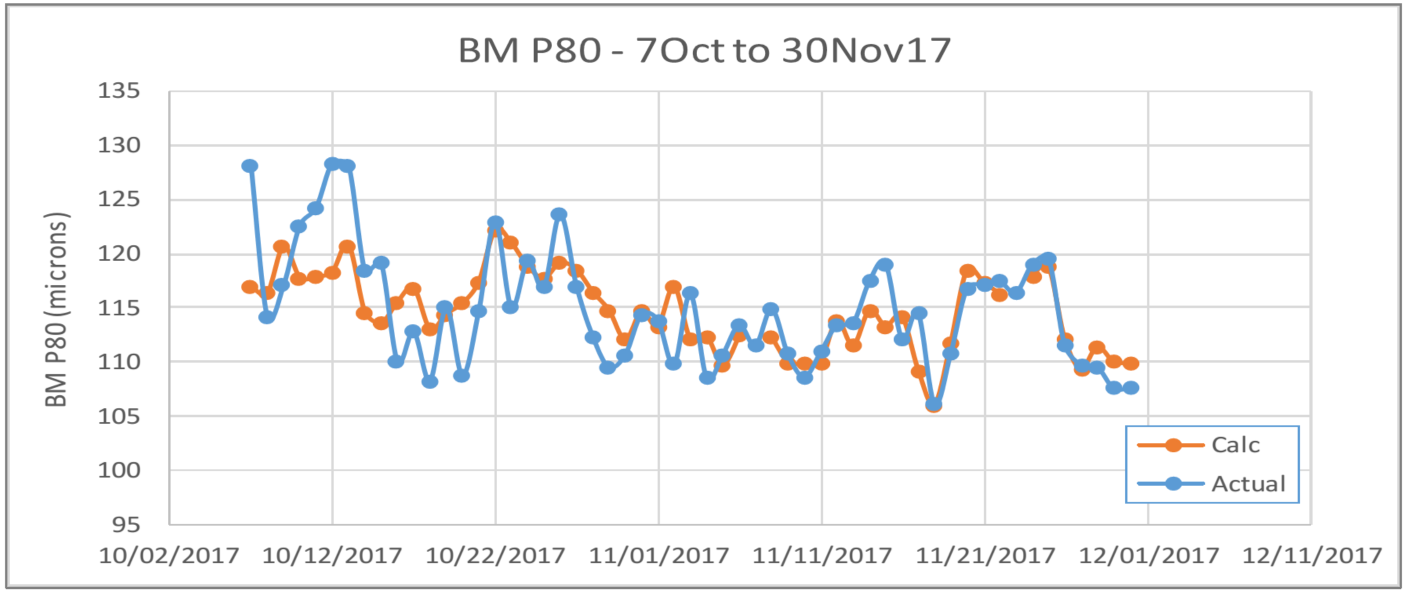
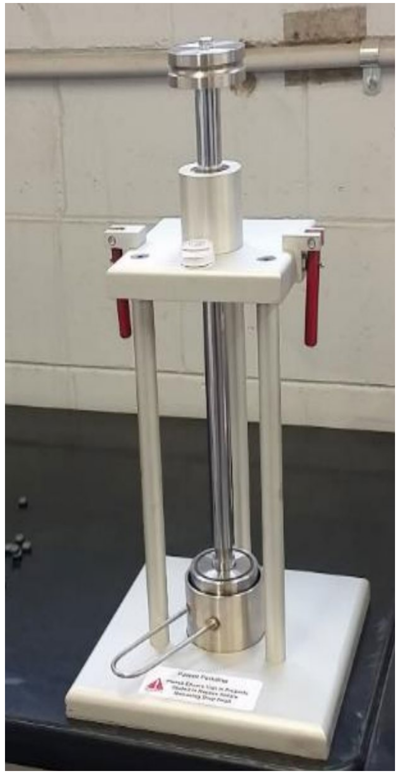


Comparative Comminution Hardness Index Tester HIT

(Toni Kojovic– SimSAGe Pty Ltd)

Kojovic, T., Bergeron, Y. and Leetmaa, K., (2019): *The value of daily HIT ore hardness testing of the SAG feed at the Meadowbank Gold Mine*. Proceedings from SAG2019, Vancouver, September.

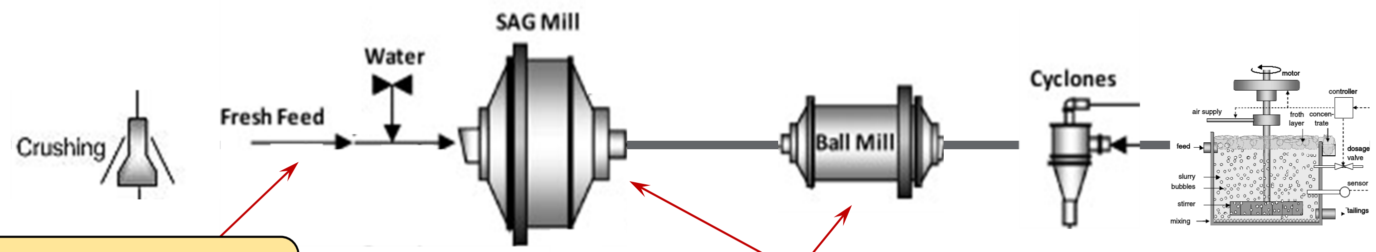




GTK

Comparative Comminution Hardness Test Geopöyrä

(Marcos Bueno – University of Oulu and R. Chandramohan)



Automatic sampling device to feed unit

Optimize together

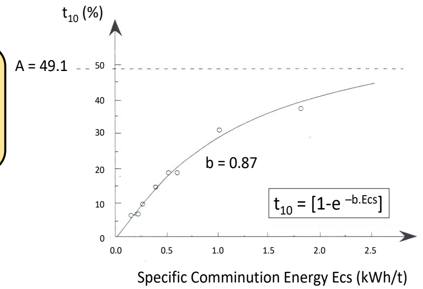
Geopöyrä A*b real time measurement

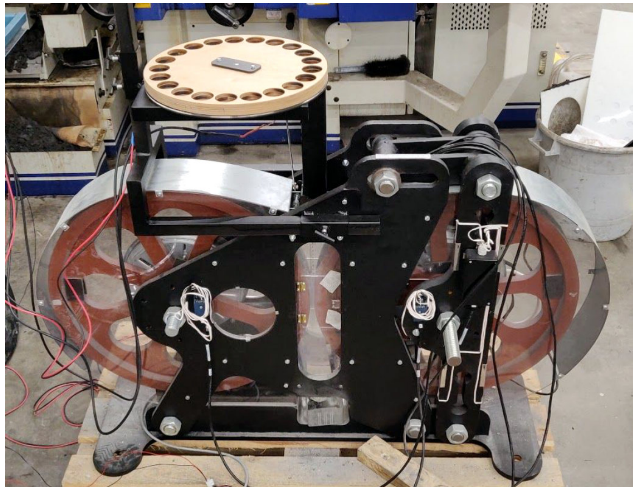
Prediction of SAG mill P_{80} and Specific Energy applied (kWh/t)

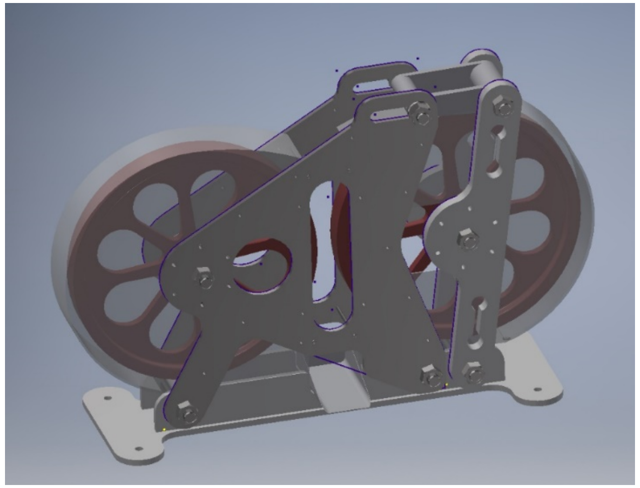
Prediction of ball mill product P_{80}

Broken product real time PSD sizing measurement (optical system)

Calculation of A*b parameter







Torvela, J., Bueno, M., Liedes, T. and Luukkanen, S. (2020): *The Geopyörä Breakage Test*, University of Oulu, Minerals Engineering journal "in press"

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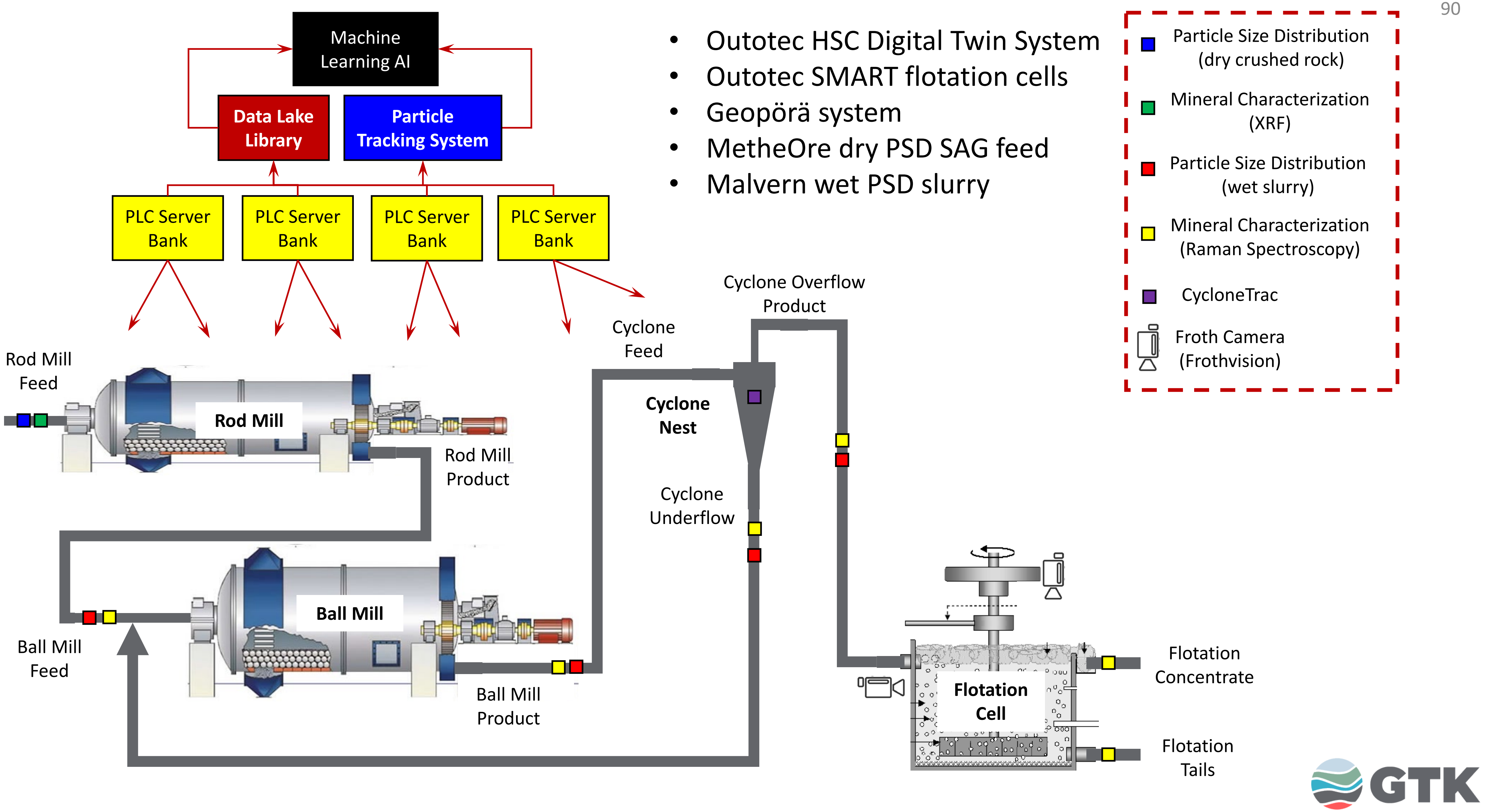
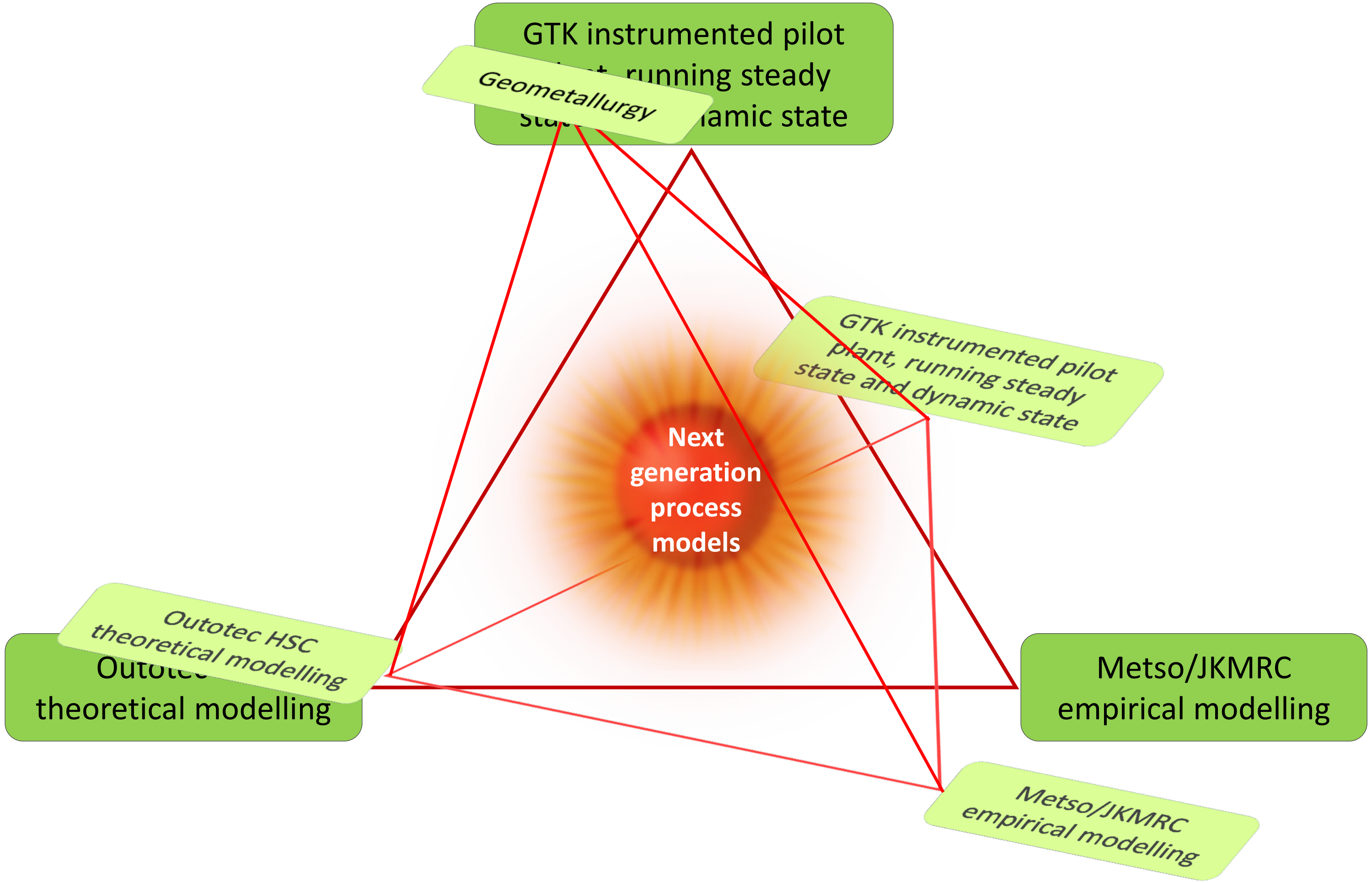
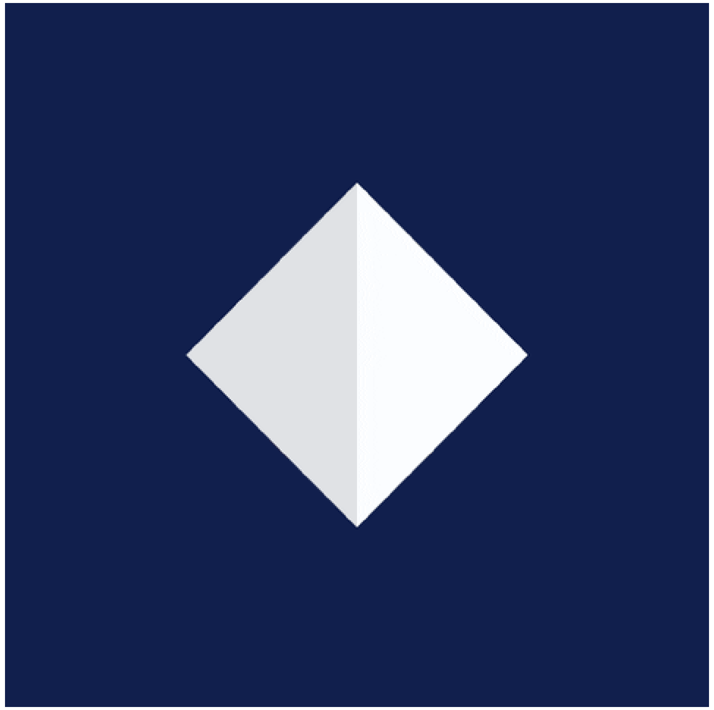
- GTK-Mintec
- 5 tph pilot plant
- Comminution/gravity sep/magnetic sep/flotation



Machine Learning AI
Data Lake Library
Particle Tracking System
PLC Server Bank
PLC Server Bank
PLC Server Bank
PLC Server Bank
• Outotec HSC Digital Twin System
• Outotec SMART flotation cells
• Geopörä system
• MetheOre dry PSD SAG feed
• Malvern wet PSD slurry
Particle Size Distribution (dry crushed rock)
Mineral Characterization (XRF)
Particle Size Distribution (wet slurry)
Mineral Characterization (Raman Spectroscopy)
CycloneTrac
Froth Camera (Frothvision)
Rod Mill Feed
Rod Mill
Rod Mill Product
Cyclone Feed
Cyclone Overflow Product
Cyclone Nest
Cyclone Underflow
Ball Mill
Ball Mill Feed
Ball Mill Product
Flotation Cell
Flotation Concentrate
Flotation Tails
GTK

INTEGRATE FOUR PARADIGMS





Technical outcome exchange across all 4 paradigms

GTK

Geological Survey of Finland
Economic Minerals Unit
Espoo

11.5.2020

GTK Open File Work Report 72/2019

How to Set Up and Develop a Geometallurgical Program

Simon Michaux
Louisa O'Connor

Geologian tutkimuskeskus | Geologiska forskningscentralen | Geological Survey of Finland
Espoo • Kokkola • Kuopio • Loppi • Outokumpu • Rovaniemi
www.gtk.fi • Puh/Tel +358 29 503 0000 • Y-tunnus / FO-nummer / Business ID: 0244680-7

Direct link

http://tupa.gtk.fi/raportti/arkisto/72_2019.pdf

QUESTIONS

?

KIITOS

etunimi.sukunimi@gtk.fi

www.gtk.fi

WHERE MOST CURRENT GEOMET PROGRAMS FALL OVER

Data Collection

- Samples collected without spatial coordinates in the ore body
- Tests done on parcel of rock in non-representative way
- Not enough samples collected
- Test work based on composites that mask variability
- Different tests done on wildly separate parcels of rock with very few or no rock samples with more than one test type (for example A*b and BMWi)
- The wrong hypothesis used to collect data
- No assay data collected with metallurgical testing
- Tests done years apart by different people and laboratories (different methods of reporting)

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WHERE MOST CURRENT GEOMET PROGRAMS FALL OVER

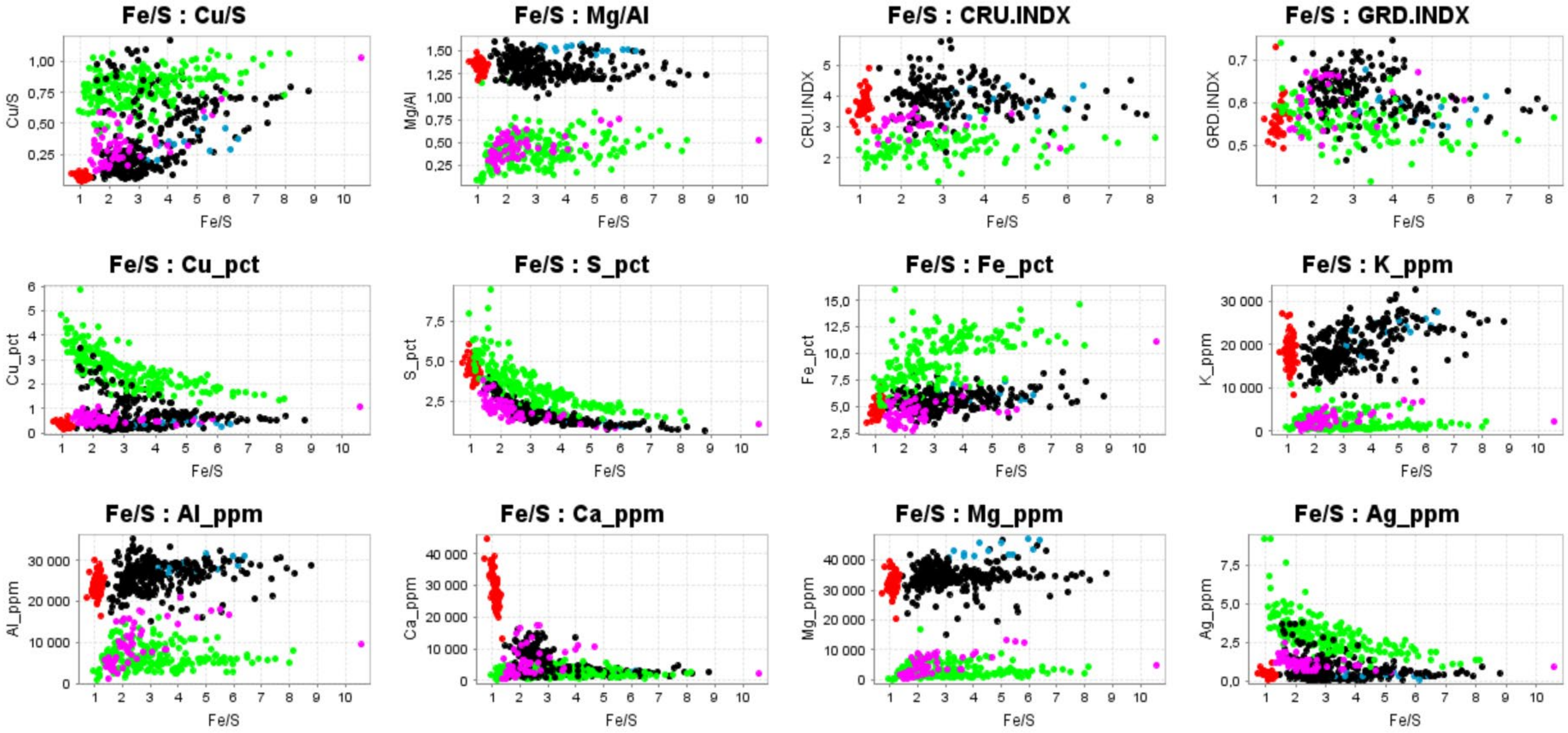
<u>Analysis</u>

- Test data not related to phenomenon being modelled
- Too many things being modelled at once, confusing the outcome
- Analysis done in isolation to the rest of mining process due to mining culture (silo effect)

CONCLUSIONS

- Strong experimental design is a must
- Clear objectives, with clear milestones
- Clear agreement on what success looks like
- Clear agreement on what the scope and budget allocated is
- Project sovereignty has to be defended
- Mission creep can be lethal
  - *Agreeing to change things half way through can lead to running out of budget at the end*
  - *Agreeing to help others who are not invested in the final outcome is the greatest risk for this*
- Regular communication is the key success
- Regular and comprehensive documentation
- ‘Upward’ management and *all* stake holders is required to keep the integrity of the project

CASE STUDY P


Fe/S : Cu/S
Cu/S
Fe/S
Fe/S : Mg/Al
Mg/Al
Fe/S
Fe/S : CRU.INDX
CRU.INDX
Fe/S
Fe/S : GRD.INDX
GRD.INDX
Fe/S
Fe/S : Cu_pct
Cu_pct
Fe/S
Fe/S : S_pct
S_pct
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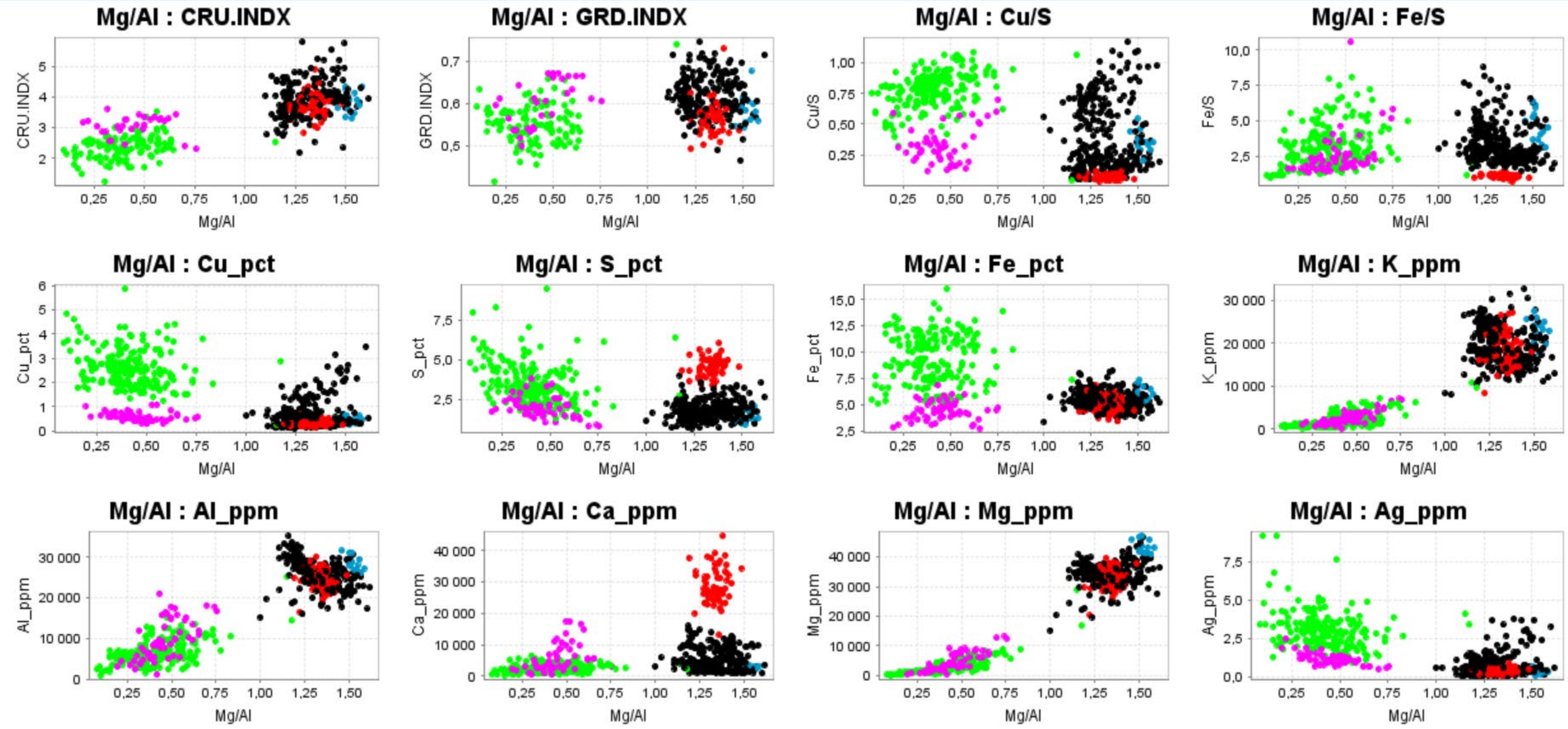
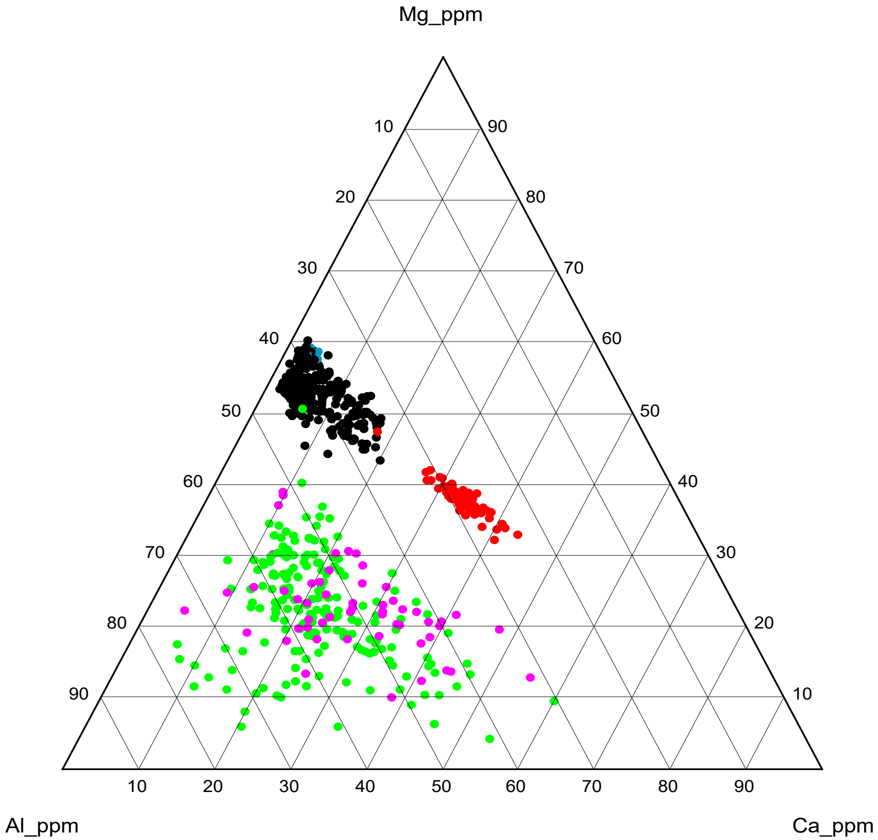
Ag_ppm
Fe/S

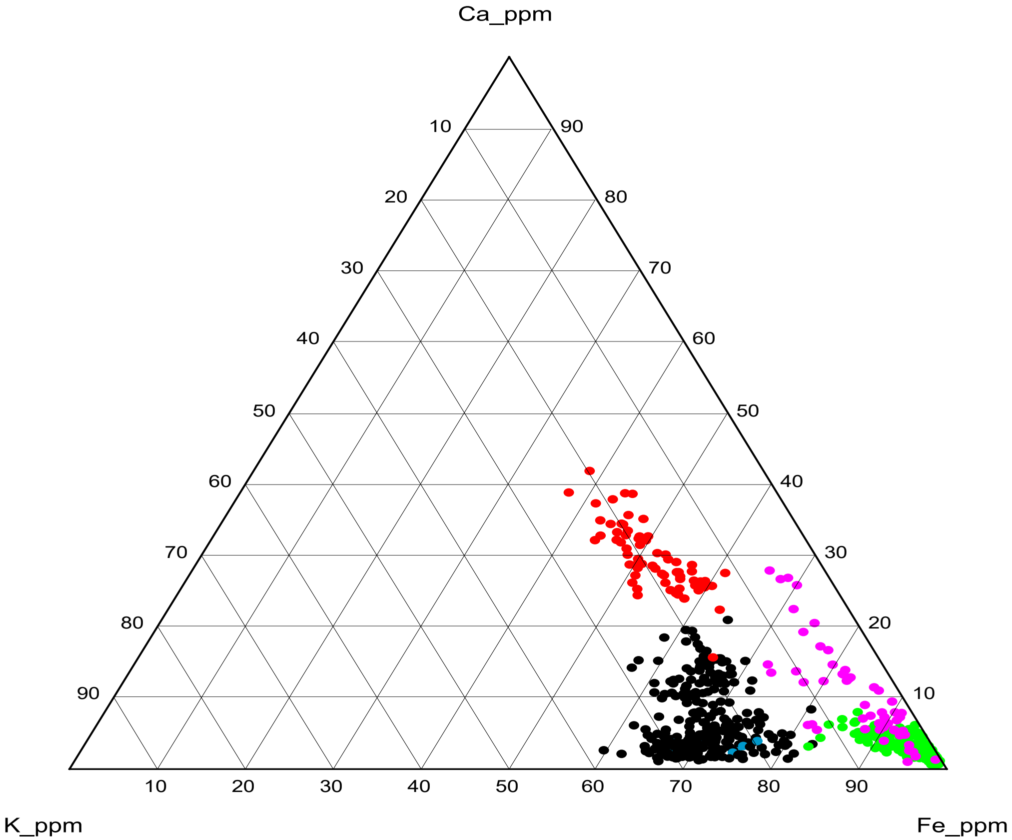
CASE STUDY P



Mg/Al : CRU.INDX
Mg/Al : GRD.INDX
Mg/Al : Cu/S
Mg/Al : Fe/S
Mg/Al : Cu_pct
Mg/Al : S_pct
Mg/Al : Fe_pct
Mg/Al : K_ppm
Mg/Al : Al_ppm
Mg/Al : Ca_ppm
Mg/Al : Mg_ppm
Mg/Al : Ag_ppm

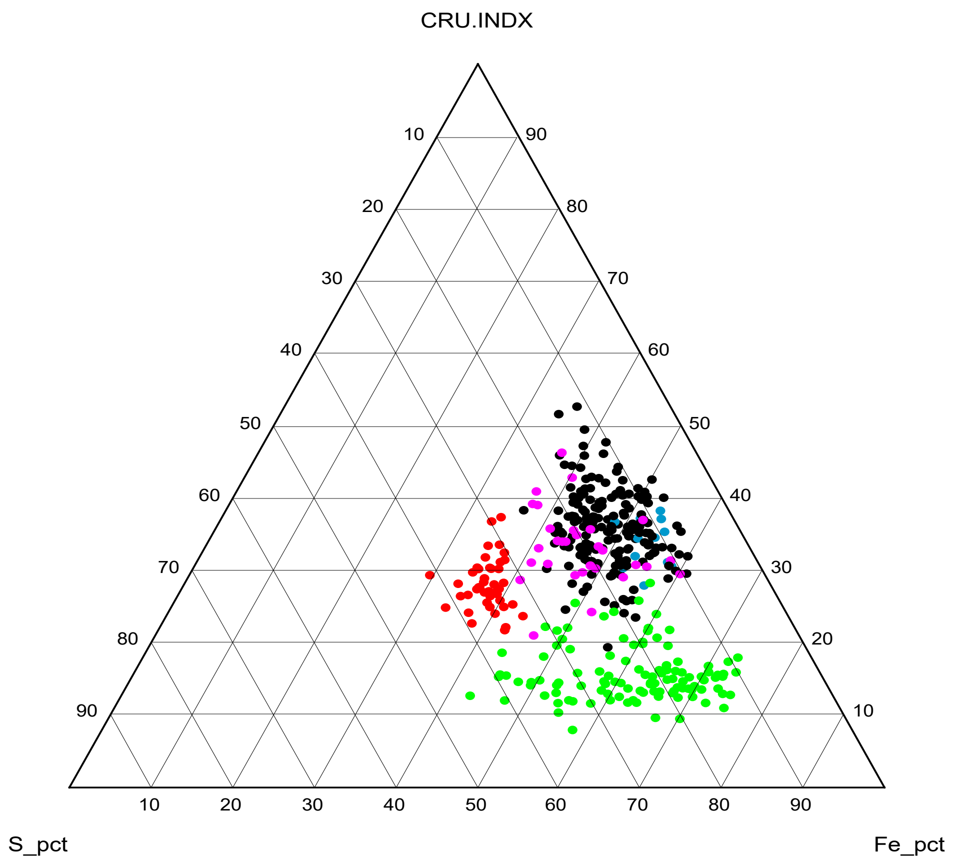
CASE STUDY P





GTK

CASE STUDY P



CRU.INDX
10
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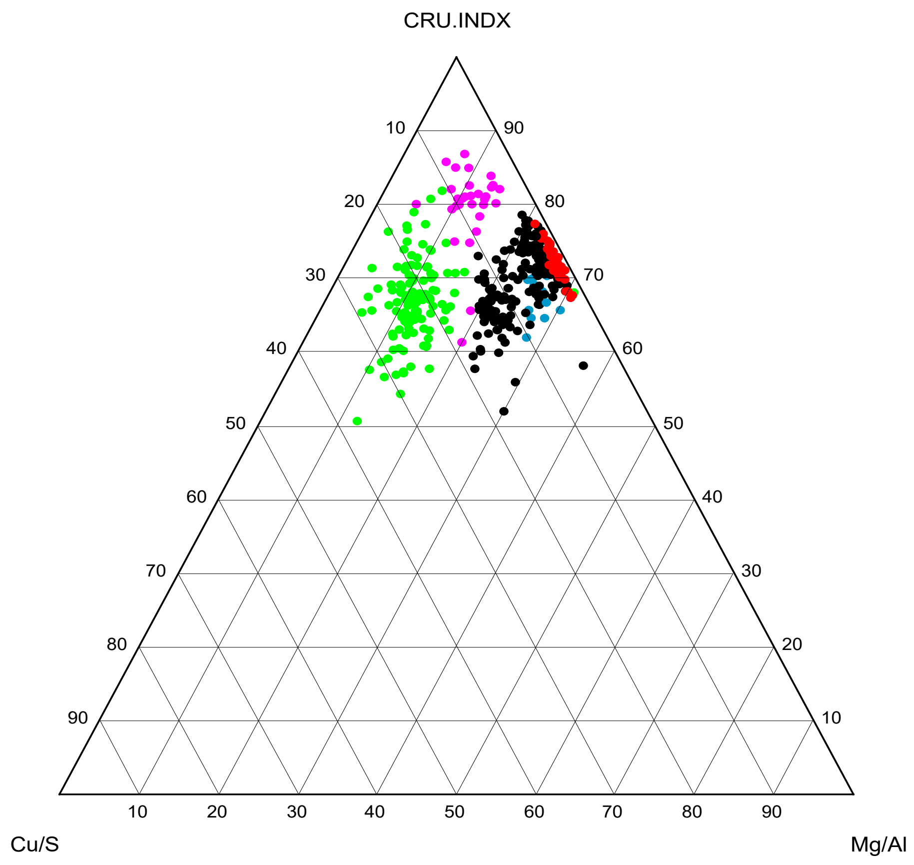
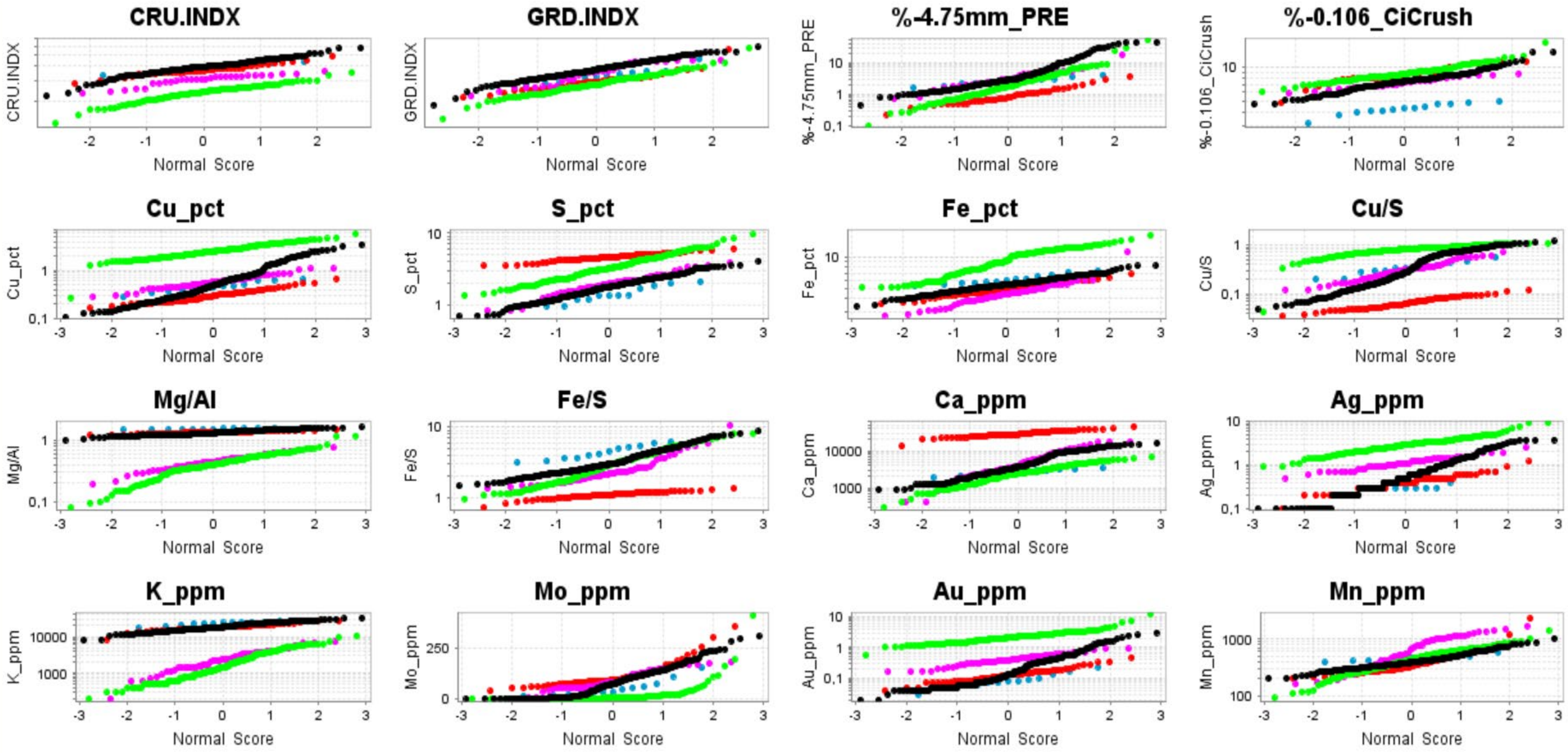
70
80
90
S_pct
Fe_pct

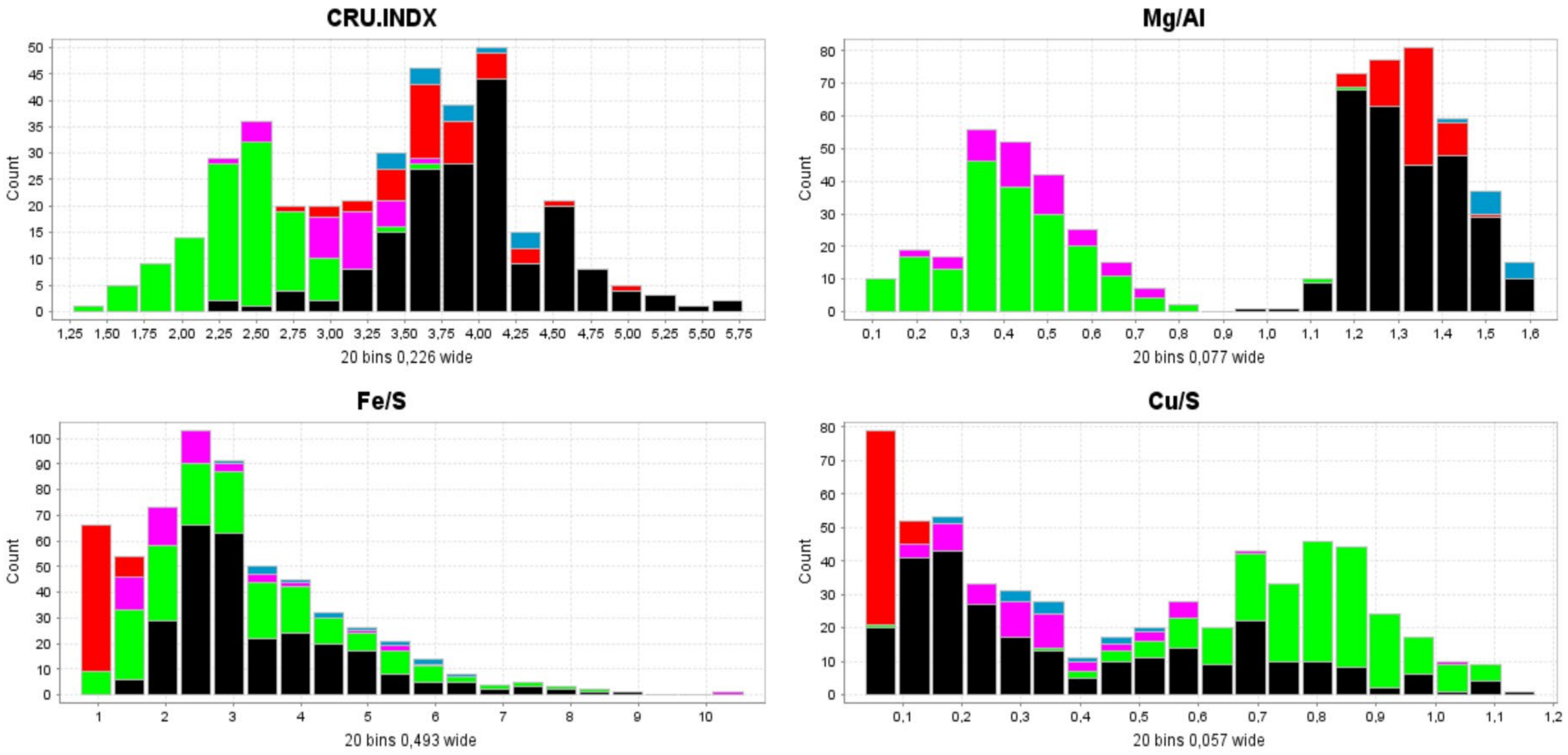


CRU.INDX
10
20
30
40
50
60
70
80
90
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
90
Cu/S
Mg/Al

CASE STUDY P

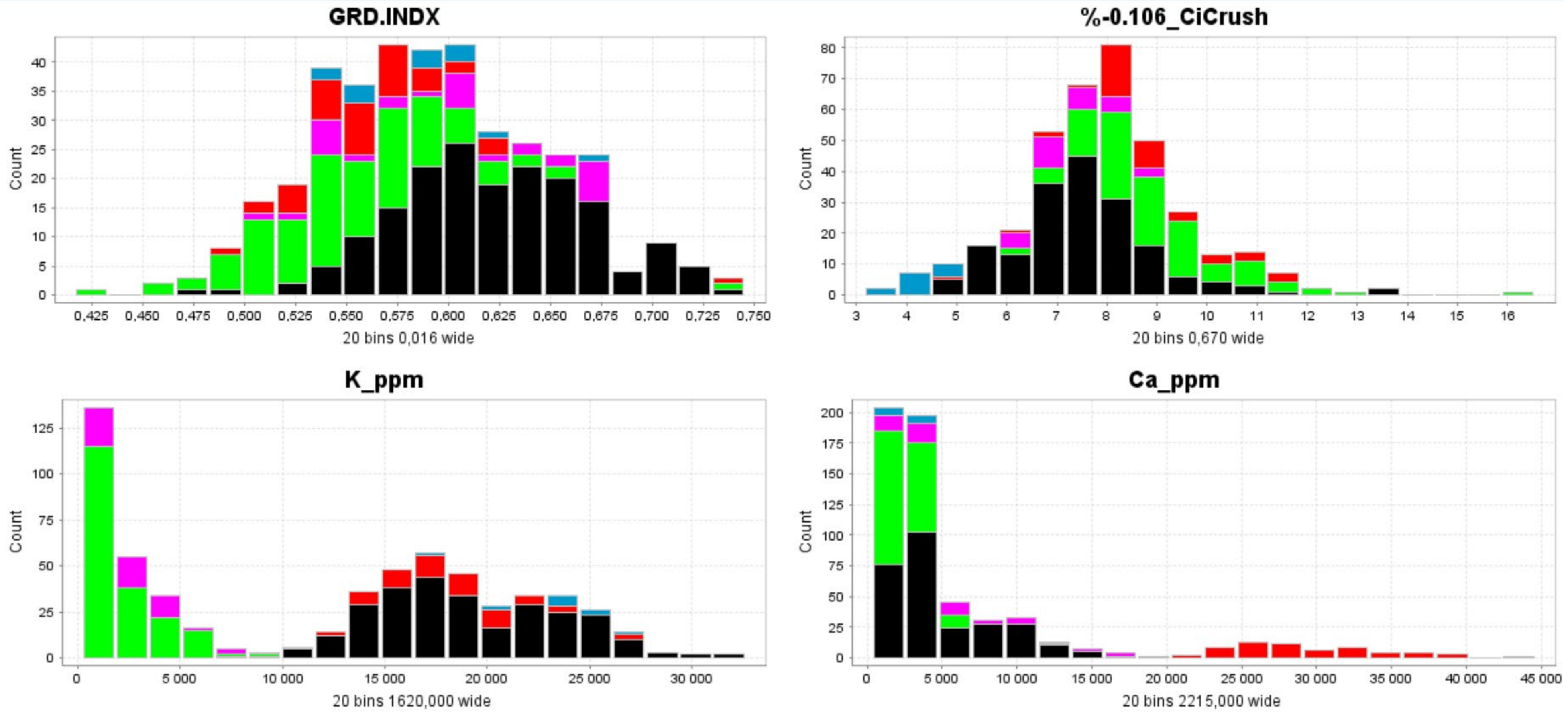

CRU.INDX
GRD.INDX
%-4.75mm_PRE
%-0.106_CiCrush
Cu_pct
S_pct
Fe_pct
Cu/S
Mg/Al
Fe/S
Ca_ppm
Ag_ppm
K_ppm
Mo_ppm
Au_ppm
Mn_ppm
Normal Score

CASE STUDY P



GTK

CASE STUDY P



GTK

PRINCIPLE COMPONENT ANALYSIS (PCA)

- The PCA approach is to spatially model classes created during principal component analysis:
  - *Each class has a given distribution.*
  - *Assign processing response and variability to each block by association.*

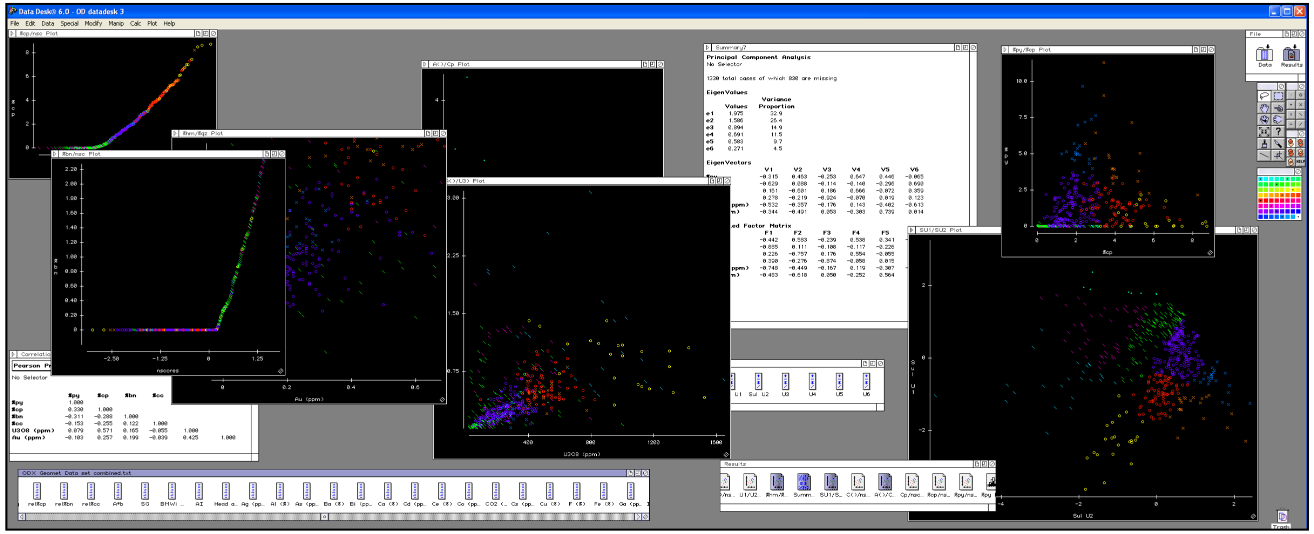
- Problem/Issues:
  - *Class based characterisation has been set up to group based on fundamental controls, not on constraining the processing response.*
  - *This can potentially result in large variability within classes that may cover the entire distribution of processing performance results.*

PRINCIPLE COMPONENT ANALYSIS (PCA)

- Principal Component Analysis (PCA) is a mature statistical technique that is widely used for finding patterns in data of multiple dimensions.

- PCA finds a set of orthogonal dimensions, which account for all the variance in a particular dataset, by reducing the dimensionality of a complex system of correlations into a smaller number of dimensions.

- First principal component accounts for as much data variance as possible and each subsequent principal component accounts for remaining data variance.



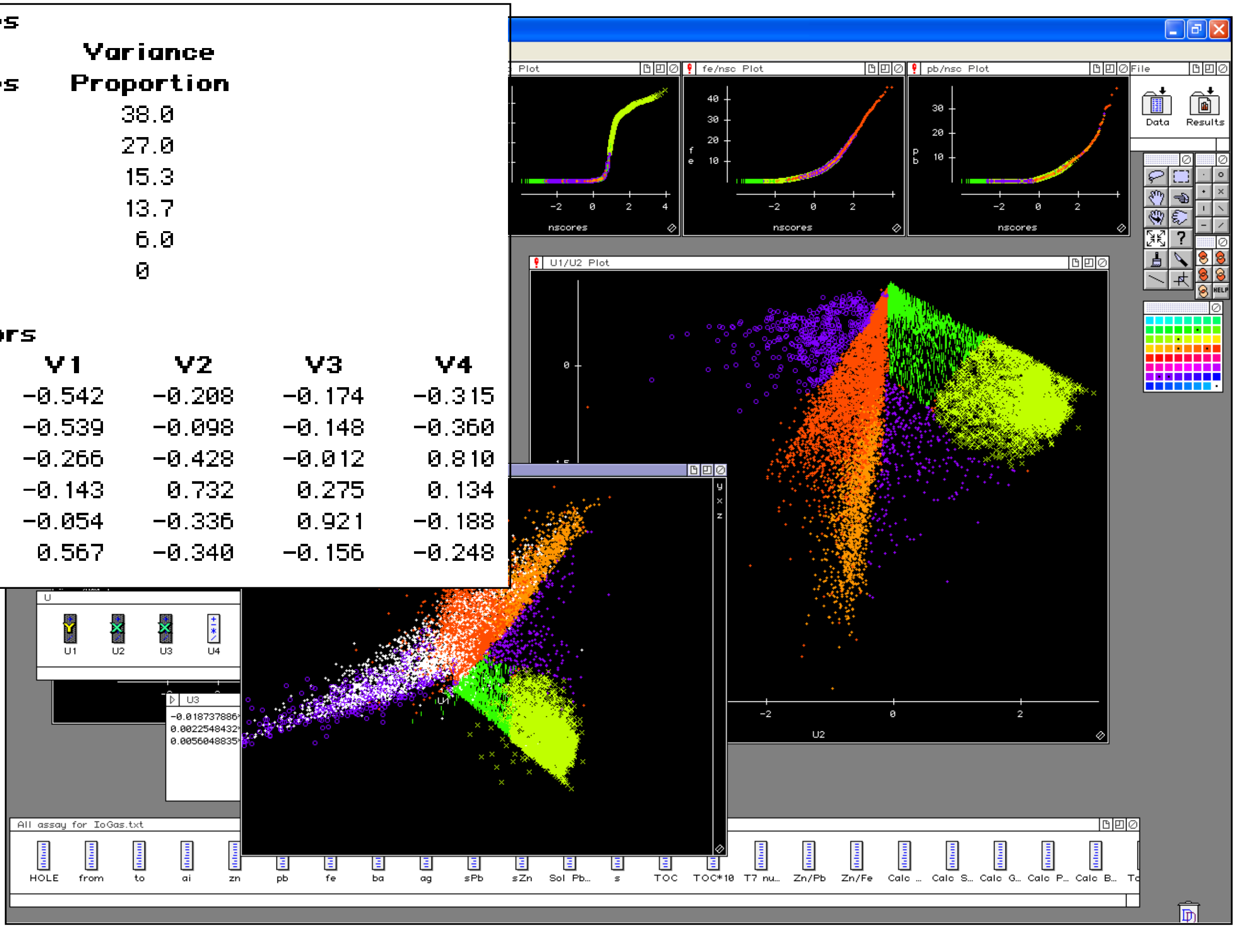
PRINCIPLE COMPONENT ANALYSIS (PCA) – EXAMPLE A

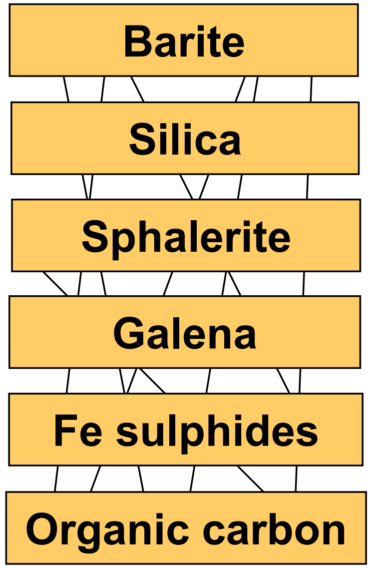
EigenValues

	Values	Variance Proportion
e1	2.278	38.0
e2	1.620	27.0
e3	0.921	15.3
e4	0.820	13.7
e5	0.360	6.0
e6	0	0

EigenVectors

	V1	V2	V3	V4
zn	-0.542	-0.208	-0.174	-0.315
pb	-0.539	-0.098	-0.148	-0.360
fe	-0.266	-0.428	-0.012	0.810
ba	-0.143	0.732	0.275	0.134
TOC*10	-0.054	-0.336	0.921	-0.188
Calc Qtz	0.567	-0.340	-0.156	-0.248





N=20,250

Data Desk software

Mineralogy calculated from assays for a massive sulphide system

GTK