General Methods and Approaches on Estimation of Mineral Resources –

Reasonable cut-off grades in general and focusing on REE in bauxites

Florian Lowicki| DMT GmbH & Co KG| 15.10.2019

Regional Innovation Scheme

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

CV

- Florian Lowicki; born 10-09-1978 in Berlin; florian.lowicki@dmt-group.com; +49 201 172 1978; +49 170 3376 292
- Dipl.-Ing. (Economic Geology and Applied Geochemistry) at TU Berlin, since 2006
- Resource Geologist for DMT in Essen since 2007
- Mineral projects dealing with commodities as follows,
  - metals (ferrous, base and precious metals)
  - energy (shale oil, tight gas, lignite and coal)
  - heavy mineral sands and REEs
  - bulk minerals (phosphates)
- Registered professional in the field of geology at SACNASP, the South African Council for Natural Scientific Professions, since 2013

DMT at a Glance
As Part of TÜV NORD GROUP

TÜV NORD GROUP

Headquarters in Hannover, Germany

TÜV NORD

Industrial Service,
Mobility, Education

DMT

Business Unit
Natural Resources

ALTER TECHNOLOGY

Aerospace

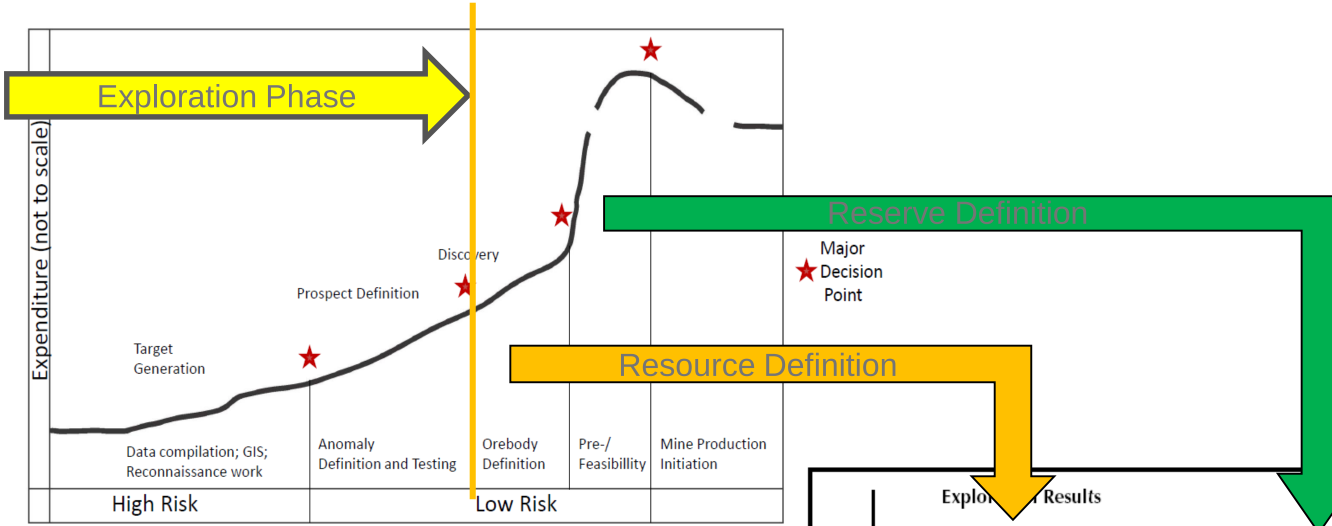
TÜViT

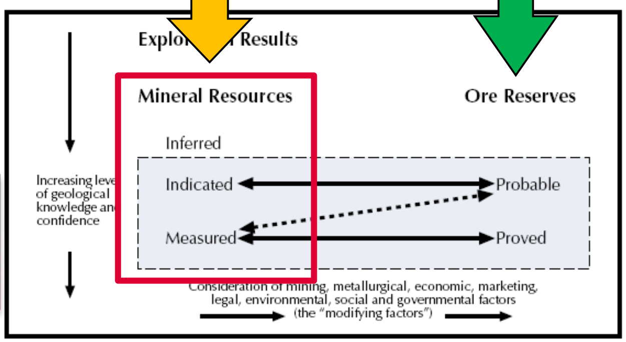
Information Technology

Markets, Customers & Projects
Main Markets

Development of a Mineral Project

From Exploration to Mineral Resource to Mineral Reserve



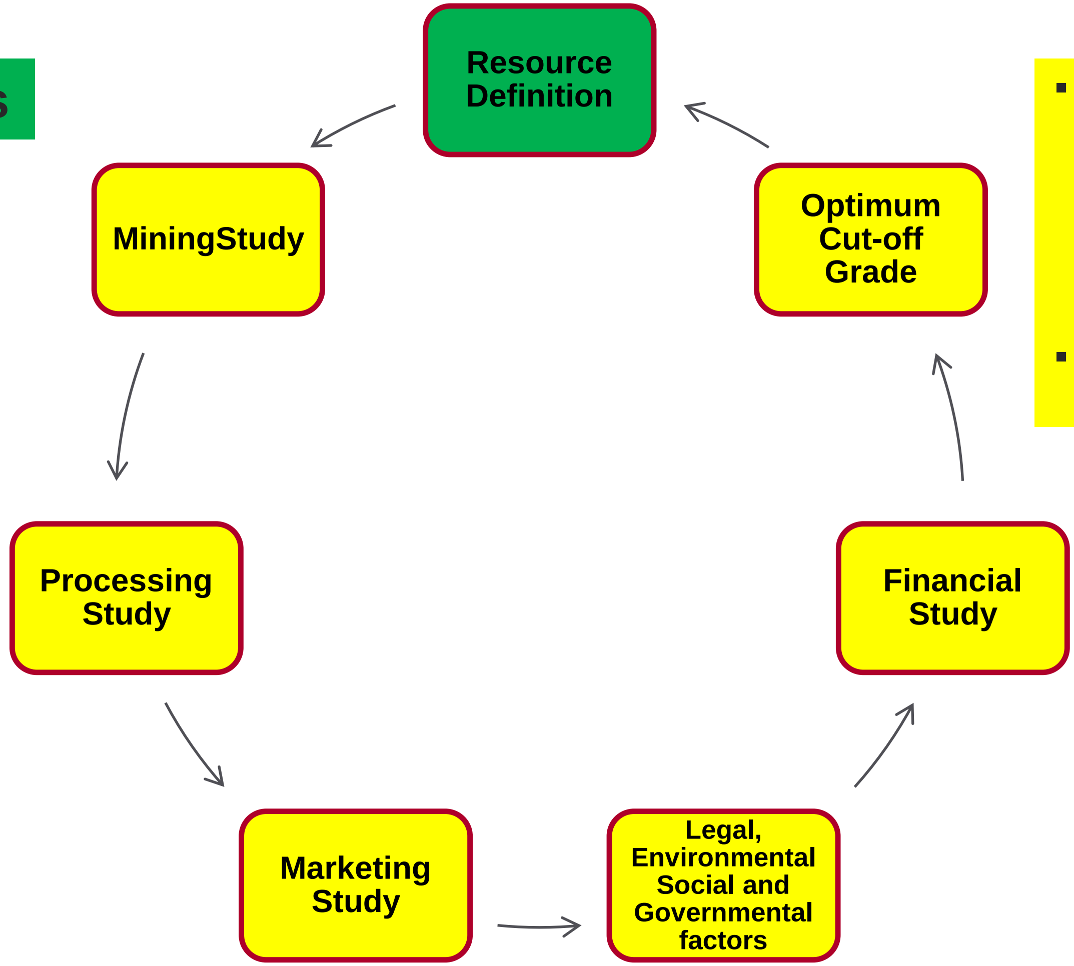


Resource Classification:
Sample spacing (Degree of knowledge/confidence)
<> Complexity of geology and grade continuity

Feasibility Studies for Mineral Projects

From Mineral Resource to Mineral Reserve

Mineral Resources



- at maximum profit
  - Maximum net present value (NPV)
  - Maximum internal rate of return (IRR)
- optimum life of mine (LoM)

Mineral Reserves

Before Exploration

- Business Plan
  - Type of commodity
  - Annual mine production / capacity (Revenues)
  - Lifetime of mine (LoM)

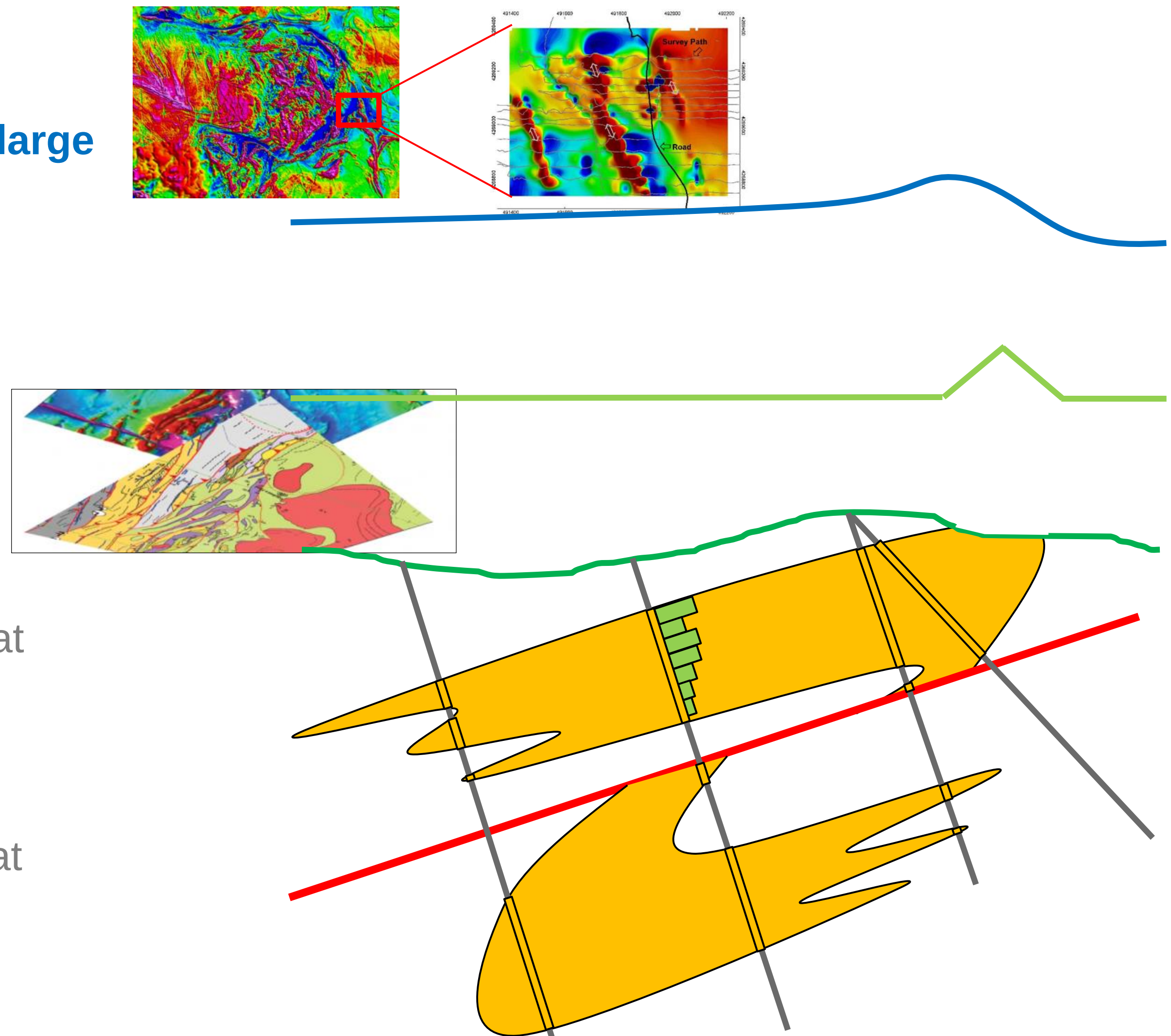
From Business Plan to Desktop Study

- Commodity (Copper; Cu)
- Deposit Model
  - Volcanogenic massive sulphide (high grade but low bulk tonnage = lower commodity tonnage and lower production rate and shorter life of mine = **lower investment costs (CAPEX: start capital)** but higer operating costs (OPEX)
  - Porphyry (low grade but very high tonnage = higher commodity tonnage and higher production rate and longer life of mine = **higher investment costs (CAPEX: start capital)** but lower operating costs (OPEX)
- Geological-structural environment: Overthrusted ocean floor
- Application of large-scaled geophysical methods suitable to find anomalies indicating areas potentially covering propective target
  - for VMS e.g. airborne electro-magnetic (EM) survey

Exploration – From Surface to Underground Investigations

Steps of Exploration

- **Geophysical Exploration (large scale to small scale)**
  > Definition of a **Potential Prospect**
- **Geochemical Exploration**
  > **Prospect**
- **Geological Mapping**
  > **Prospect** (Mineralization at surface)
- **Exploration Drilling**
  > Prospect (Mineralization at subsurface) **- Discovery**



Exploration Risk

- Investment in exploration can reduce your project value from today to tomorrow!!! in the case that new knowledge is bad news.

Discovery:

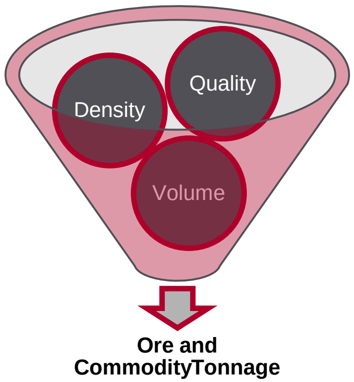
- „…most direct risk faced in mineral exploration is the discovery risk: the low probability – **typically a 1-2 percent chance** – of an economic mineral deposit, given the discovery of a mineral occurence." (Extracted from: Brian Mackenzie, Roy Woodall (2016): Economic Productivity of Base Metal Exploration in Australia and Canada. World Mineral Exploration: Trends and Economic Issues. New York. p. 370 III 1-3)

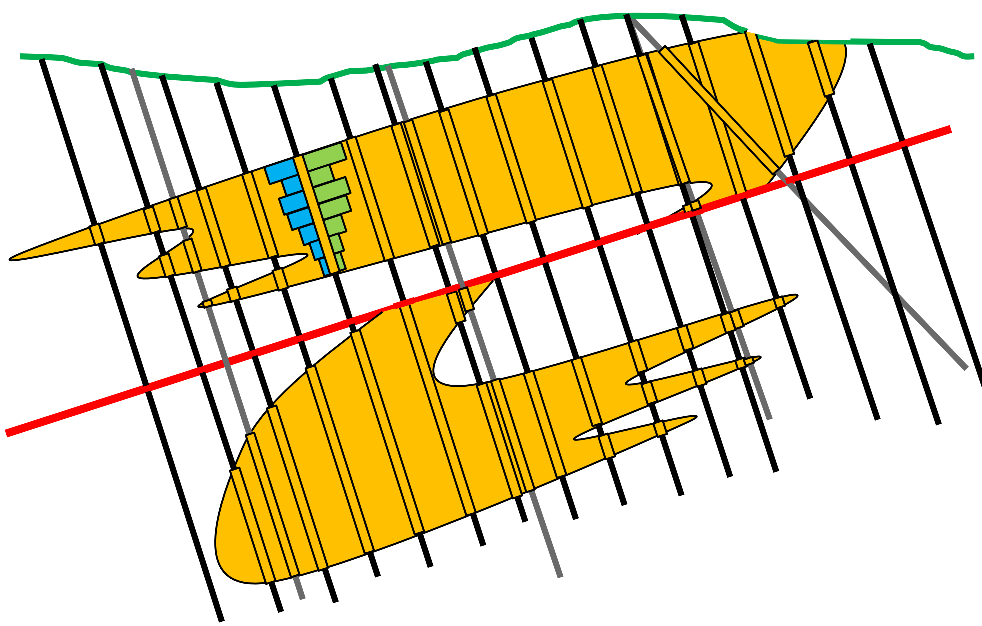
- **Over 90 % of all discoveries** are made by junior companies

From Exploration to Resource Definition

Key parameters of resource definition

- **Geological/geophysical data** (all data relevant for the geometry and orientation of mineralization or coal, e.g. lithology, orientation of bedding, faults etc.)
- **Quality data** (geochemical / mineralogical data or calorific value or other)
- **Density data** (density of mineralized body or coal)

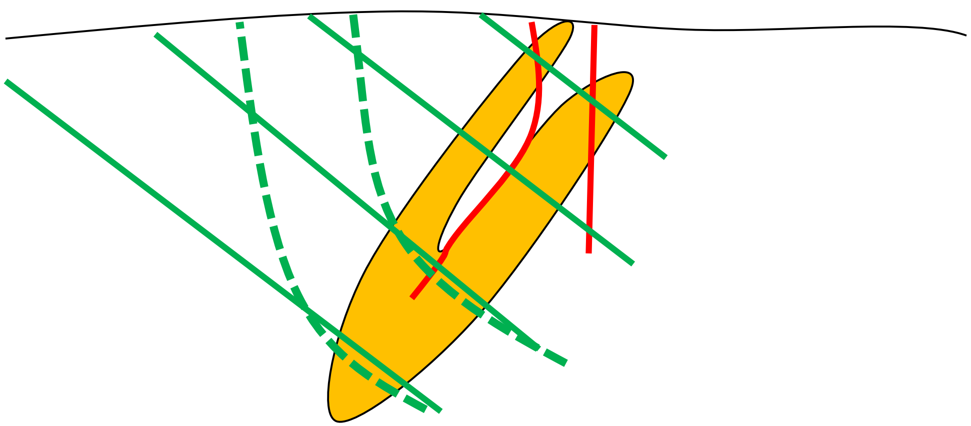


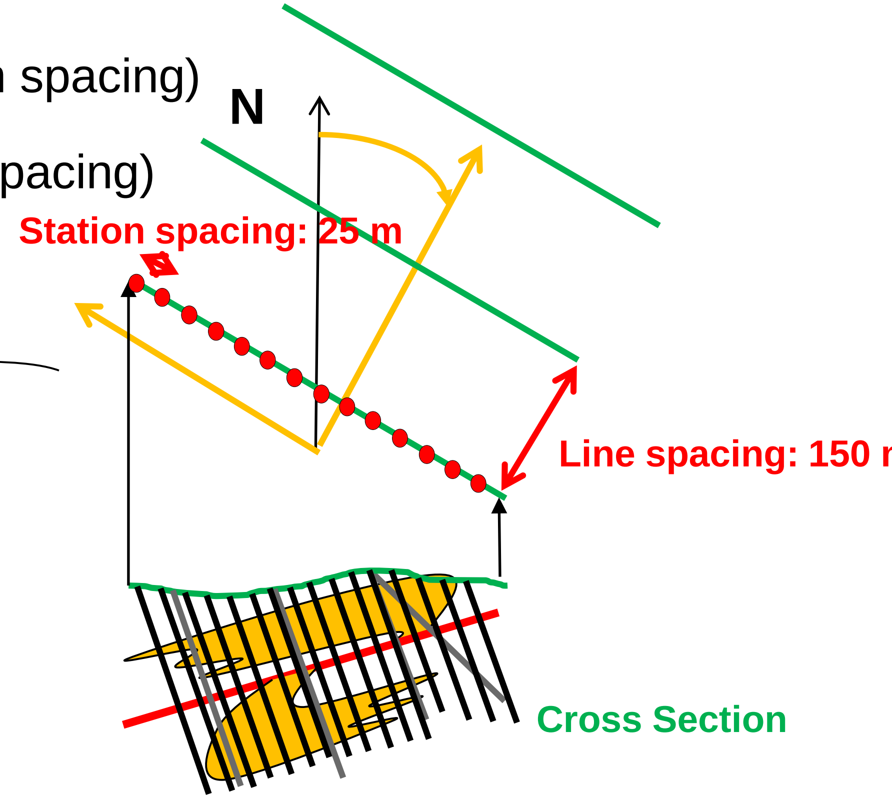


Data acquisition manual – Drilling

Drill grid

- Regular drill pattern
  - Perpendicular to mineralization following direction of…
    - weakest geological continuity (station spacing)
    - strongest geological continuity (line spacing)
  - Station spacing < line spacing





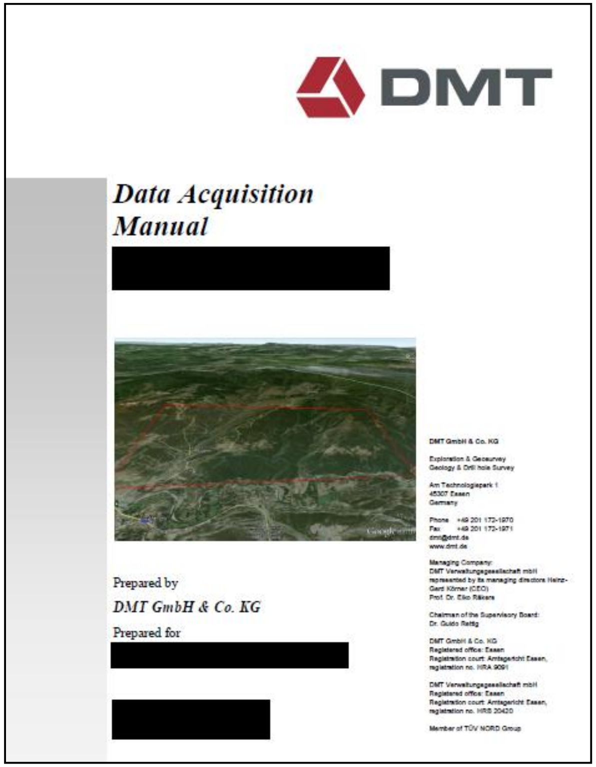
Data acquisition manual – Drilling

Drill grid vs on-site situation

Data Acquisition

Standard Operating Procedures (SOPs)

- **Mapping / units and reference system**
- **Drilling** (Method, diameter, core recovery, collar survey, down hole survey)
- **Logging** (Geology, Determination of mineralized zone)
- **Sampling** (Sample volume, sample preparation method)
- **Sample analysis** (Method of digestion and analysis)
- **Density determination**
- **QA/QC procedures** (Assessement of quality of above procedures and resulting data)


DMT

Data Acquisition Manual

[redacted]

Prepared by

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Prepared for

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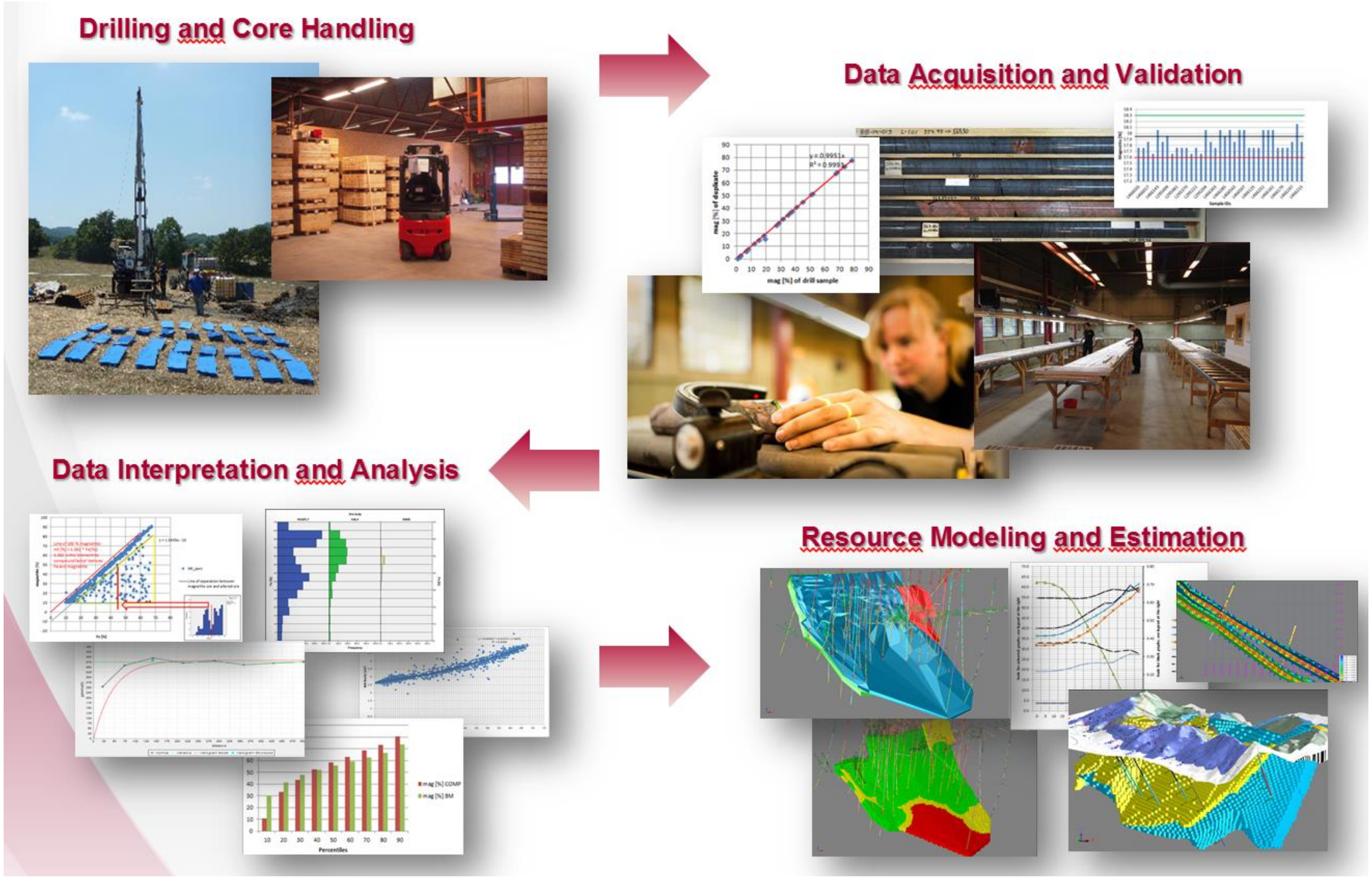
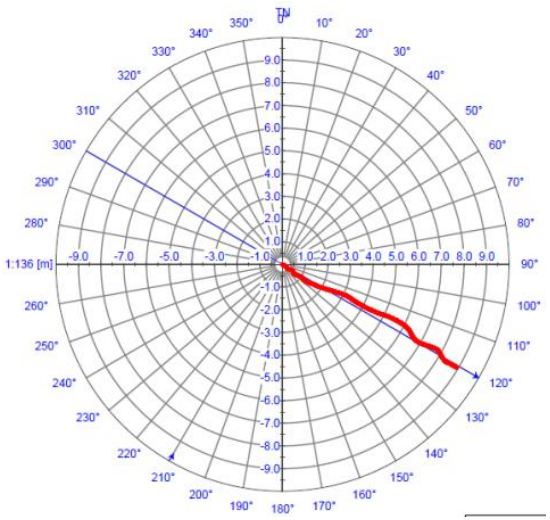
- **Prevent Systematic Errors**
- **Minimize Random Errors**
- **Representive Data set**

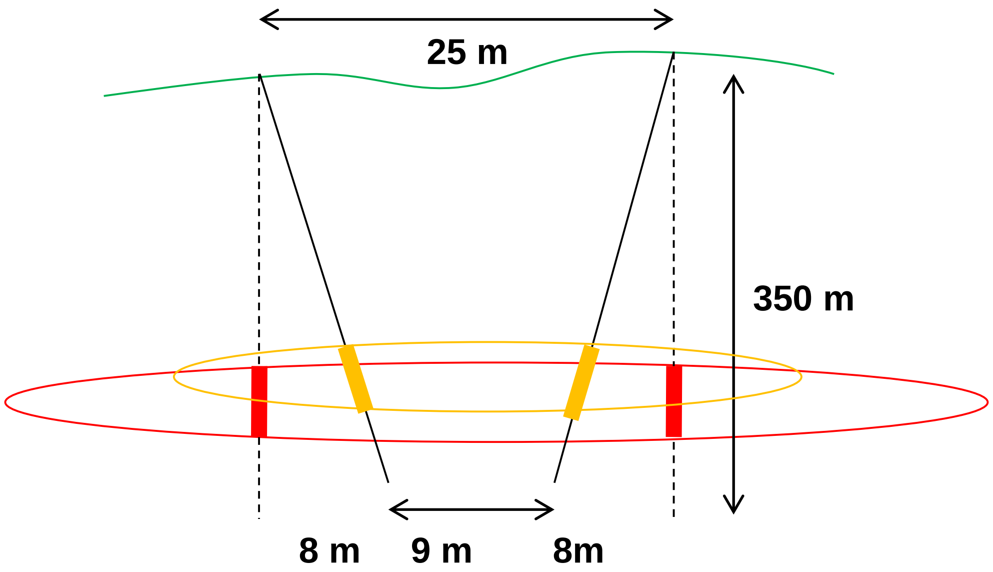
Definition of Mineral Resources



QA/QC – Validation on Data – Drill path

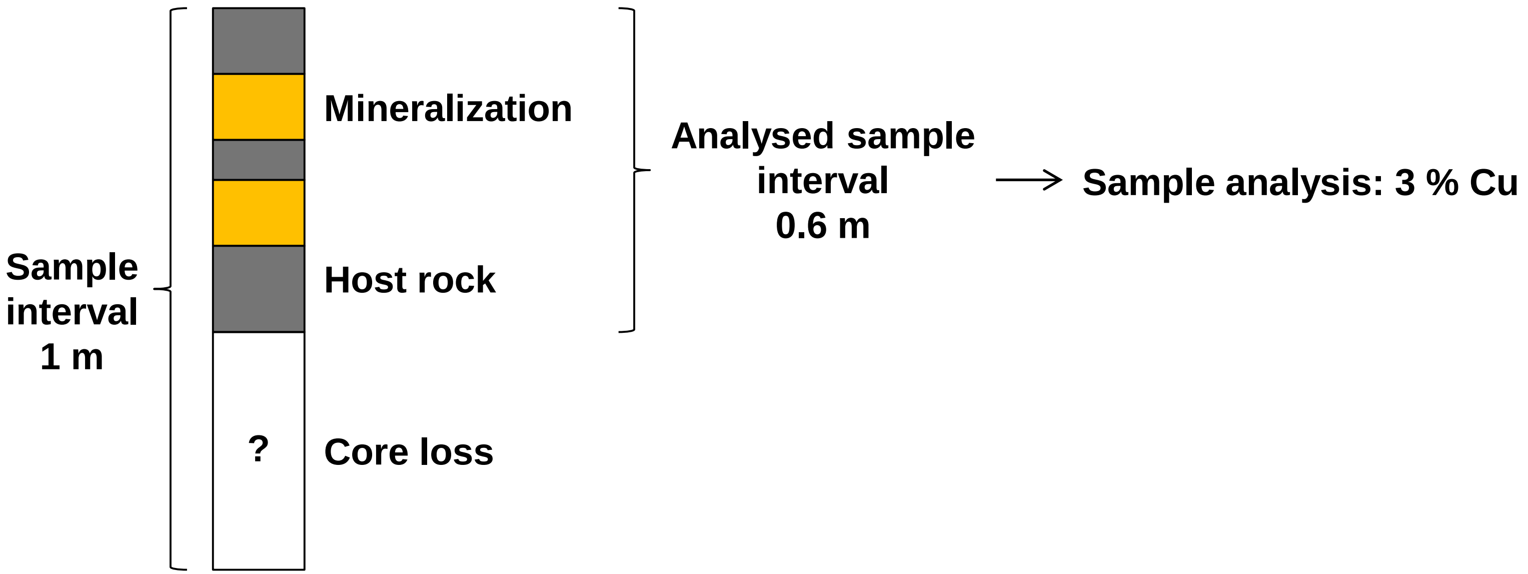
- E.g. Check drill hole deviation from planned path
- α = arctan (deviation [m] /EODH [m]) = arctan (8 m /350 m) = 1.3°
- Measure error: Inclination ± 0.1; Azimuth ±5°; (Depth 350 m: ± 60 cm)





QA/QC – Validation on Data – Drill recovery

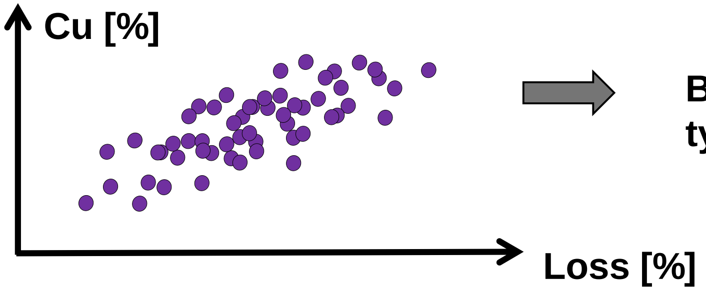
Influence of sample recovery on data from samples and laboratory



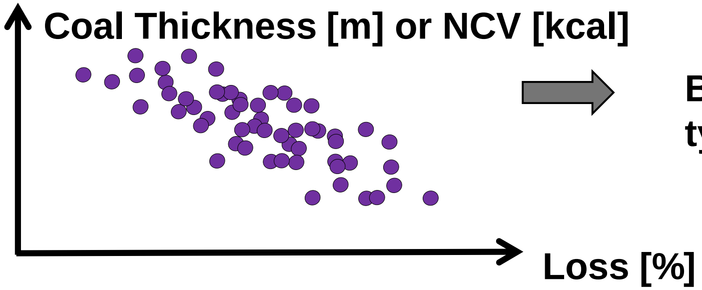
- Geophysial logging demonstrates: Core loss = Host rock
  - $$\mathrm{Cu_{DIL}\%} = \frac{3\ \%\ \mathrm{Cu} * 0.6\ \mathrm{m} + 0\ \%\ \mathrm{Cu} * (1\mathrm{m} - 0.6\mathrm{m})}{1\mathrm{m}} = 1.8\ \%\ Cu$$

QA/QC – Validation on Data – Drill recovery

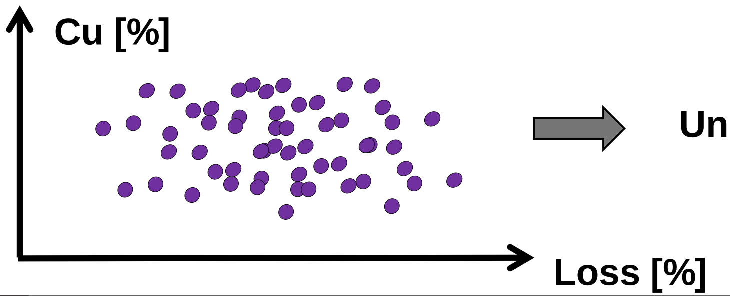
Influence of sample recovery on quality data



Biased sampling: upgrading; overestimate; typical for hard comodity (massive ore)



Biased sampling: downgrading; underestimate; typical for weak comodity (coal)

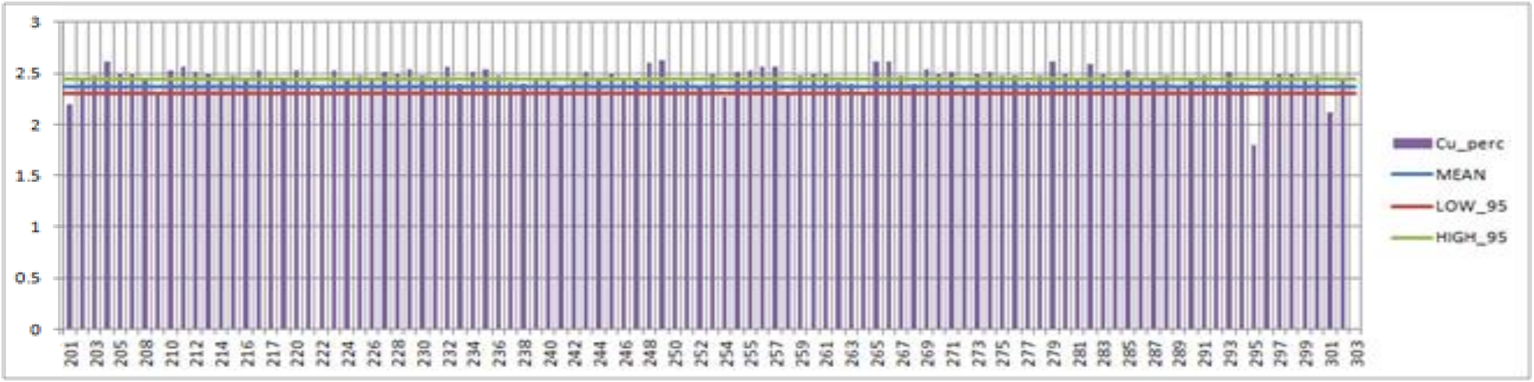


Unbiased sampling

QA/QC – Validation on Data – Laboratory analysis

Representation / Reproduction of quality data

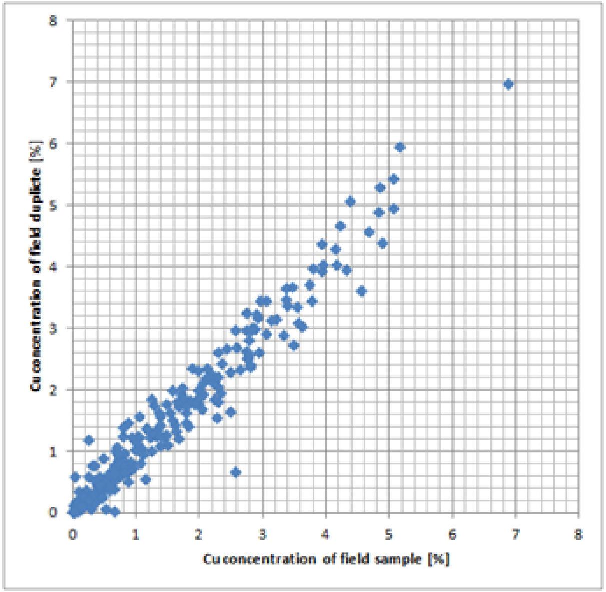
- Certified refererence material (CRM)
  - Material of known concentration of element (ore) or calorific value (coal) etc.
  - Should confirm that applied digestion and analysis method produces representative results
  - CRM should match the mineralization type, matrix, expected range of element concentration and digestion and analysis method



QA/QC – Validation on Data – Data from Laboratory

Representation / Reproduction of quality data

- Second split duplicate
  - The remaining material of last sample split is taken as second split duplicate sample
  - This should confirm the reproduction of sample preparation (splitting) procedure in the field
- Field duplicate
  - The second half of a core
  - This demonstrates short-range variations between samples (nugget effect)



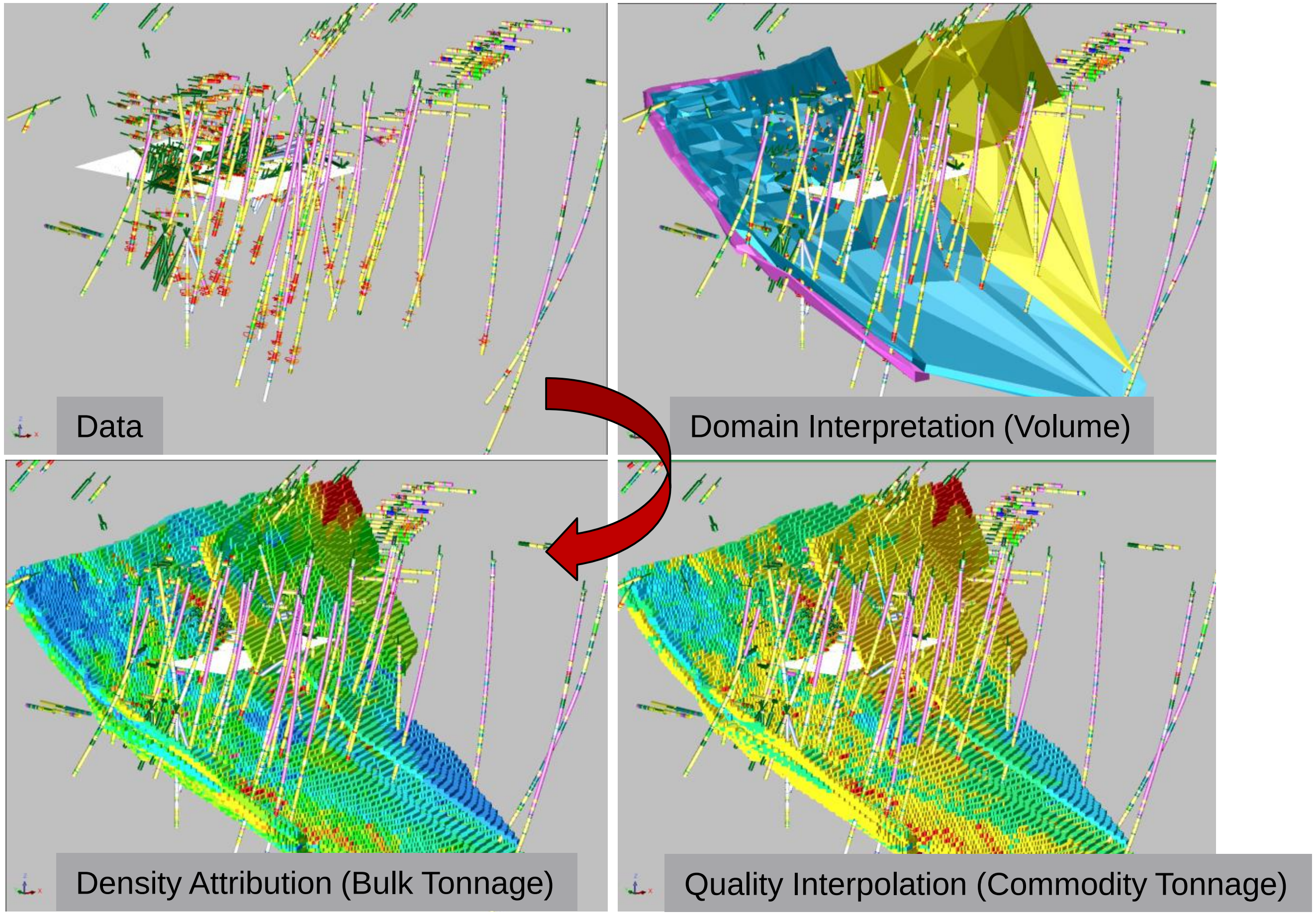
Resource Modelling

Importance of 3D environment:

- **Objective**: Estimation of an average grade representative for the deposit
- **On one side**: Huge data sets need to be checked for spatial consistency (tens to houndreds of thousands of drill meters per project plus data from geology, chemistry, geophysics, density, and many more)
- **On the other side**: These huge data sets are still limited amount of data which the interpretation of mineralization or coal seams must be based on (the vast majority of material is undrilled, univestigated)

Resource Modelling

Generalized Workflow



Data analysis and interpretation – basic statistics

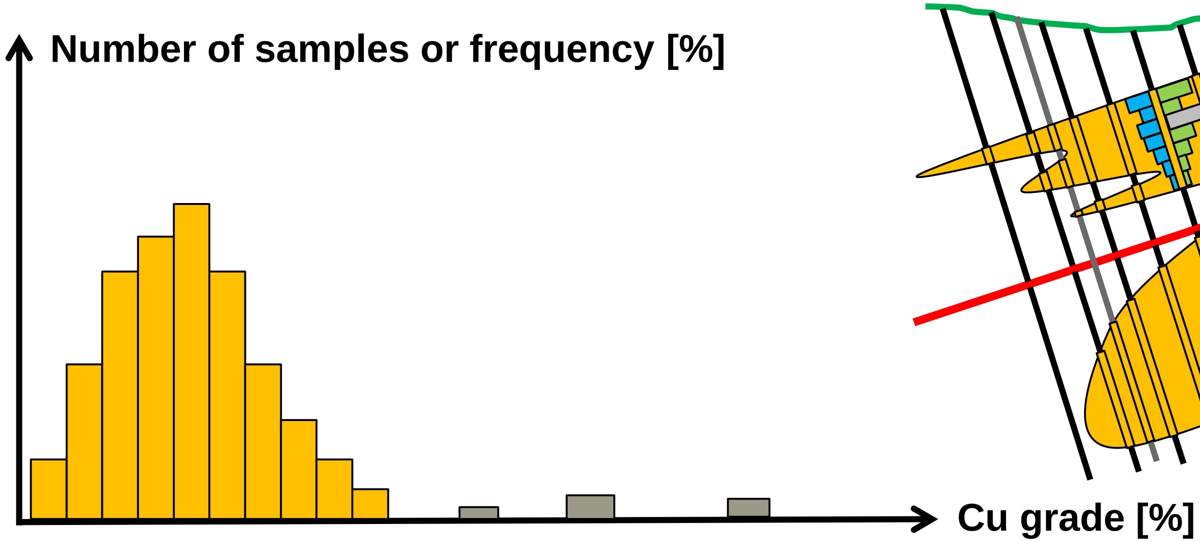
Interpolation needs data, which have…

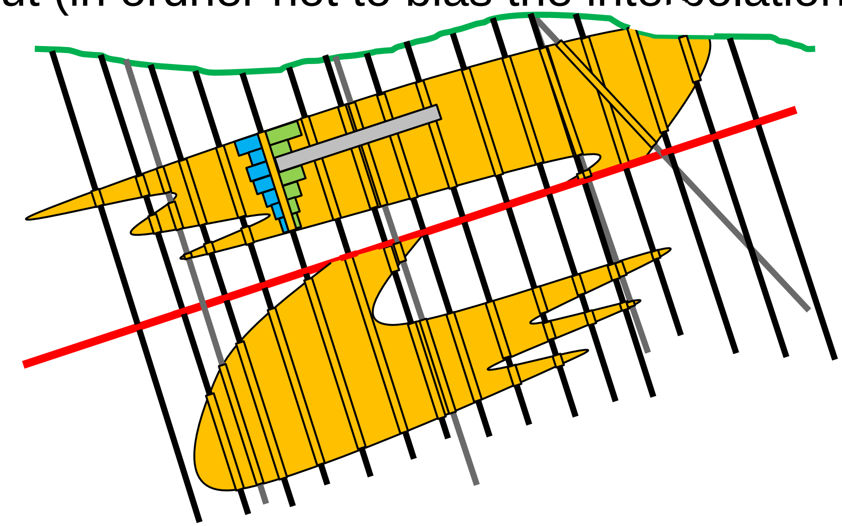
- Normal distribution (following Gauss curve)
- Modal distribution (only one maximum)
- Integrative sample support (equal sample size, spacing and orientation**)**

Data analysis and interpretation – basic statistics

Normal distribution

- Investigation by frequency plots (histogram) and cummulated frequency plots
- Check visually for normal distribution (lognormal values should be logarithmized)
- Check for outlier; high grade values which are geologically not undestood (95 percentile; grey colored); upper-grade cut (in ordner not to bias the interpolation

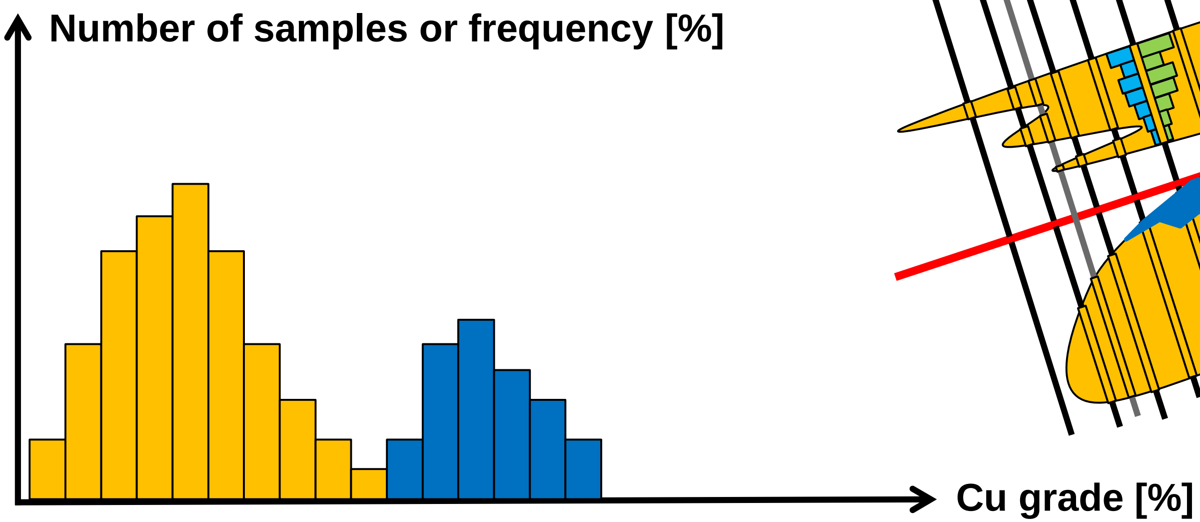


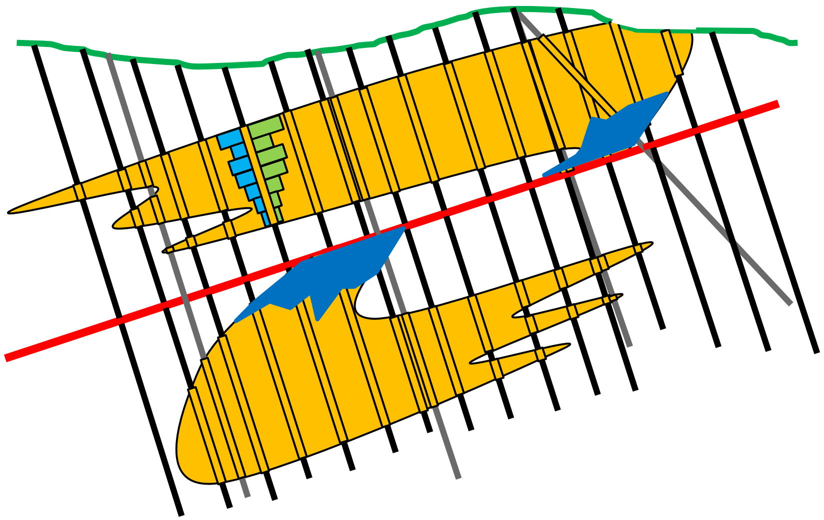


Data analysis and interpretation – basic statistics

Modality

- **Investigation by frequency plots**
- **Check for bi- or multi-modality (different sample populations) and try to find spatial relationship and separate to new domain (new domain?)**





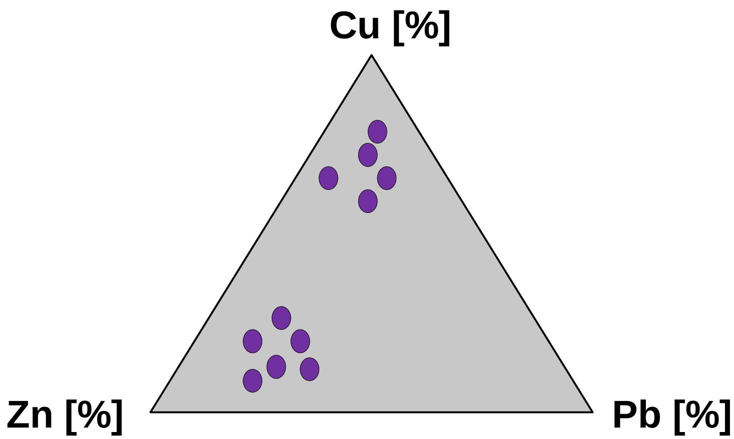
Data analysis and interpretation – basic statistics

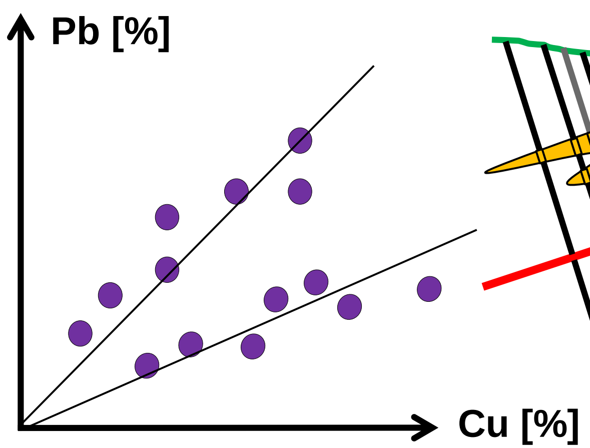
Inter-element relationship

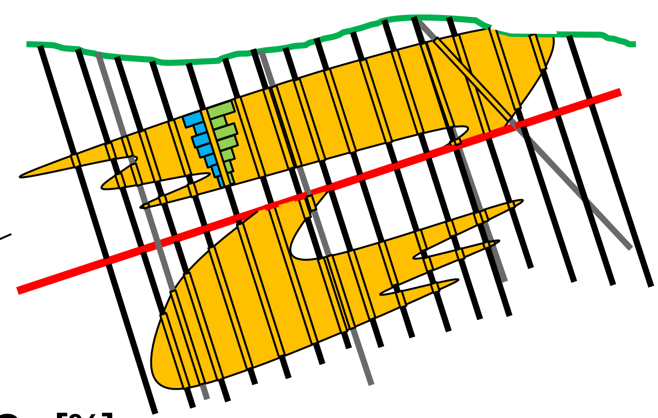
- Check for different compositions of ore (ternary plots) and try to find spatial relationship in order to separated different sample populations (different ore types) in referenc to mineral paragenesis

- Correlation plots finding correlating elements; a significant correlation shows that spatial distribution is similar (see variography, geostatistical interpolation)

- Different trends in correlation



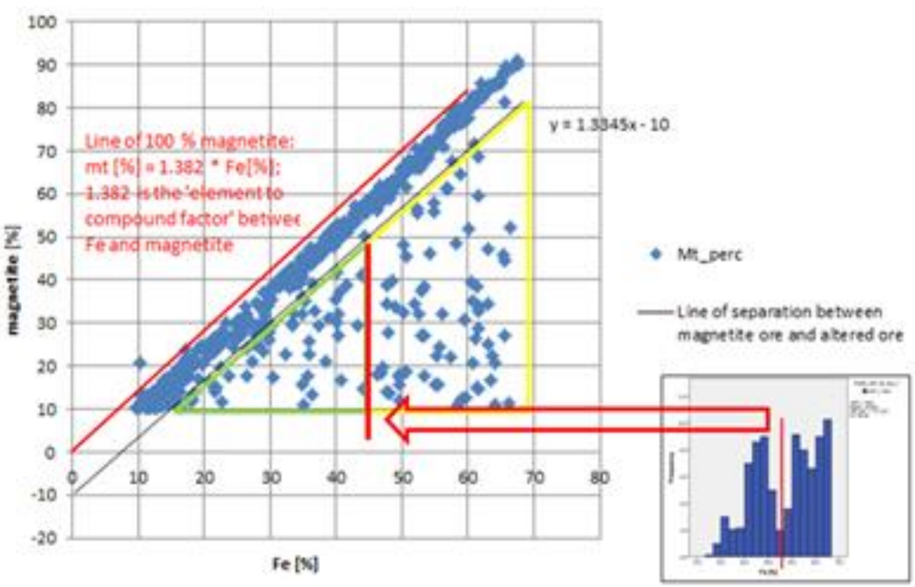


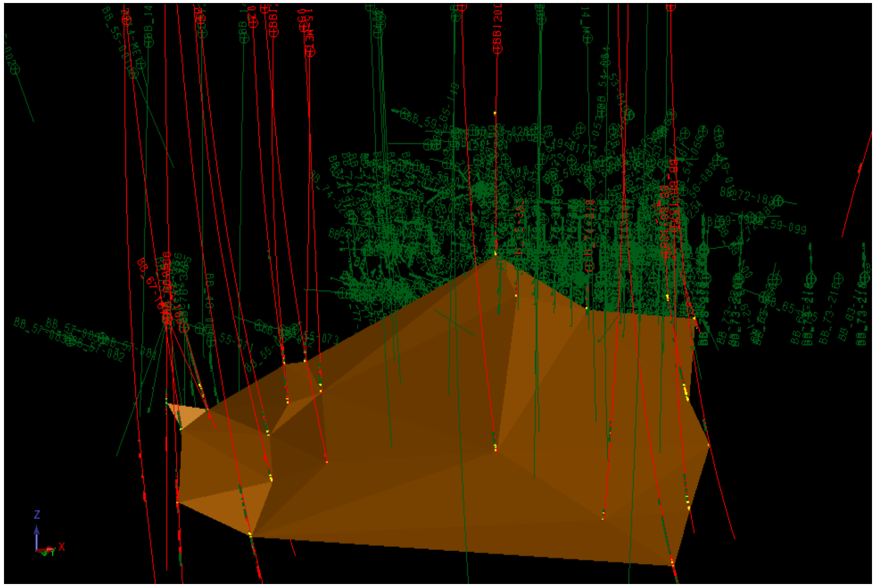


Data analysis and interpretation

Domain interpretation (mineralization geometry and characteristics)

- Statistics for domain interpretation

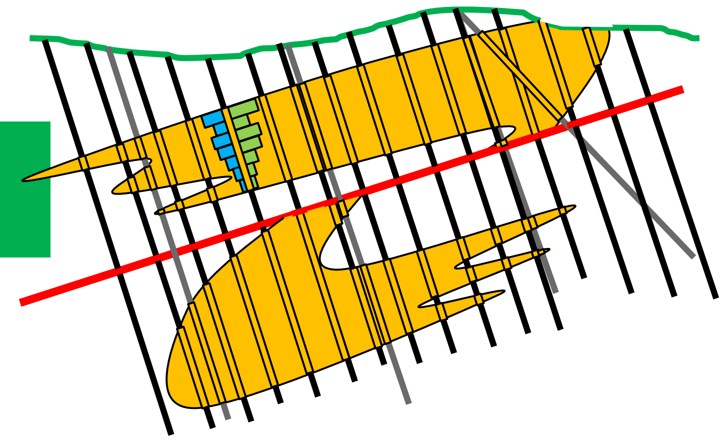




Data analysis and interpretation

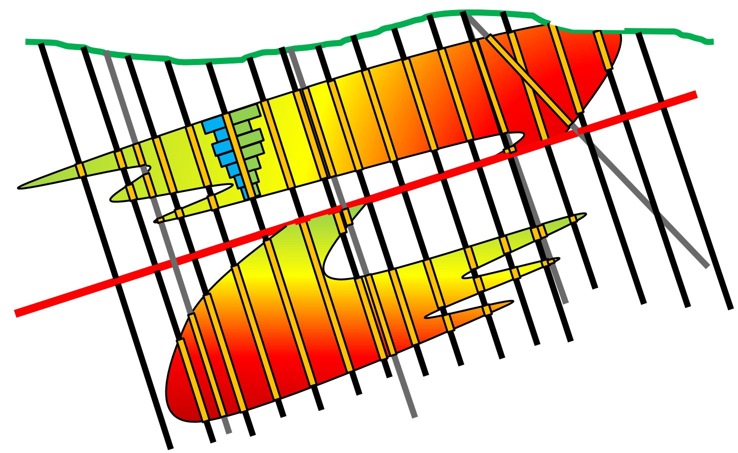
Basic parameters for ore tonnage estimate

$$T_{Min} = V_{Ore} * MD_{Min} @ MG_{Min}$$



Gological-structural interpretation in sections following a geological concept about geometry and orientation of mineralization

Finding a representative mean density and mean grade by interpolation

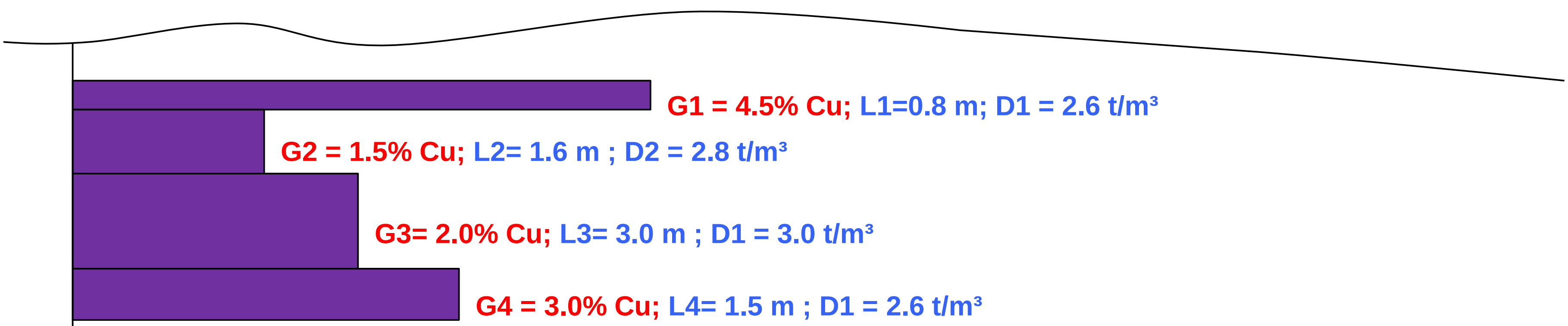


Data analysis and interpretation – before interpolation

Sample support / weighting

- Correct weighting of grade (G) to consider sample length (L) and sample density (D)
- Under dry condition

$$\frac{\sum_{i=1}^{n} G_i * L_i * D_i}{\sum_{i=1}^{n} L_i * D_i}$$



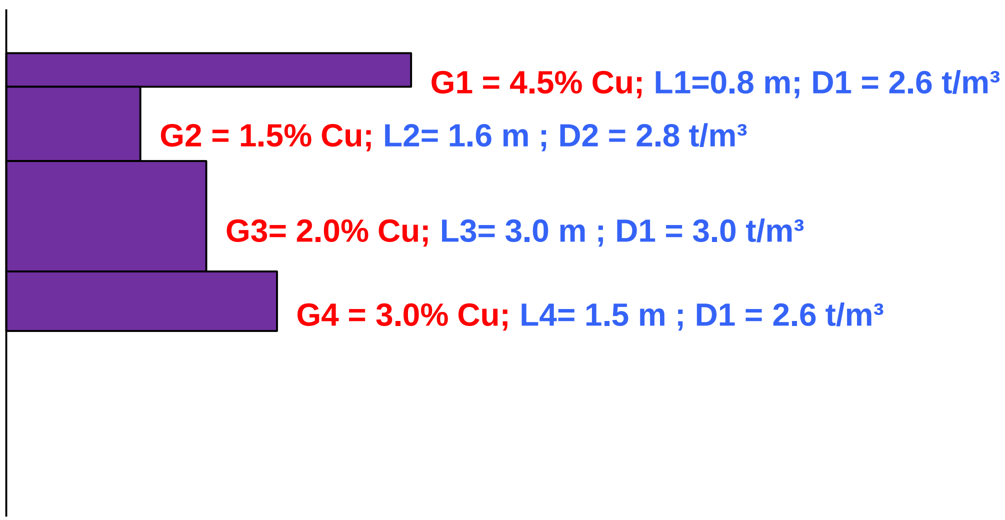
$$MG_{DH} = \frac{4.5\% * 0.8m * 2.6t/m^3 + 1.5\% * 1.6m * 2.6t/m^3 + 2.0\% * 3.0m * 2.6t/m^3 + 3.0\% * 1.5m * 2.6t/m^3}{0.8m * 2.6t/m^3 + 1.6m * 2.6t/m^3 + 3.0m * 2.6t/m^3 + 1.5m * 2.6t/m^3}$$

$$MG_{DH} = \frac{G1 * L1 * D1 + G2 * L2 * D2 + G3 * L3 * D3 + G4 * L4 * D4}{L1 * D1 + L2 * D2 + L3 * D3 + L4 * D4}$$

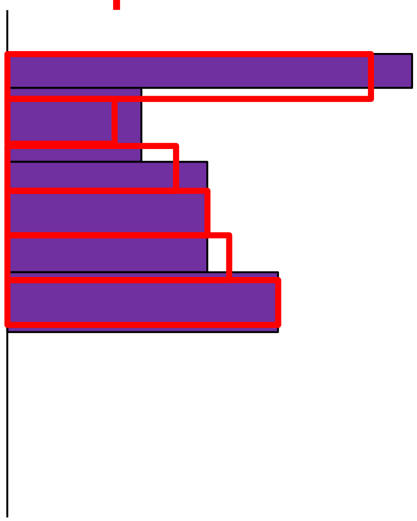
Data analysis and interpretation – interpolation

Sample compositing

- Weighting to composite samples (red) in order to consider vertical inhomogenities



1 metre composites:

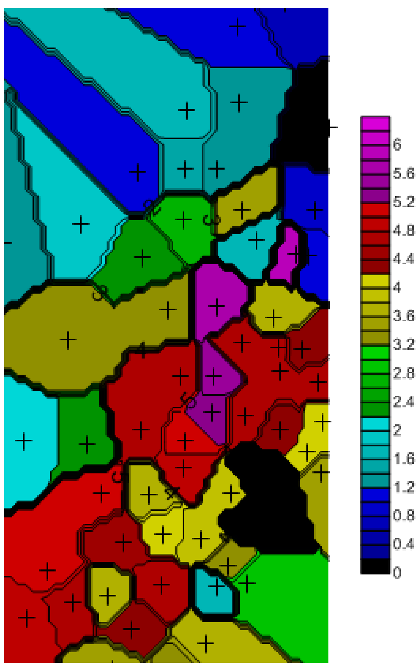


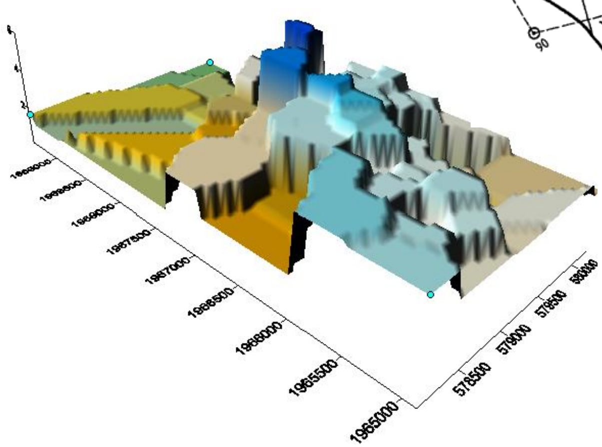
Data analysis and interpretation – interpolation

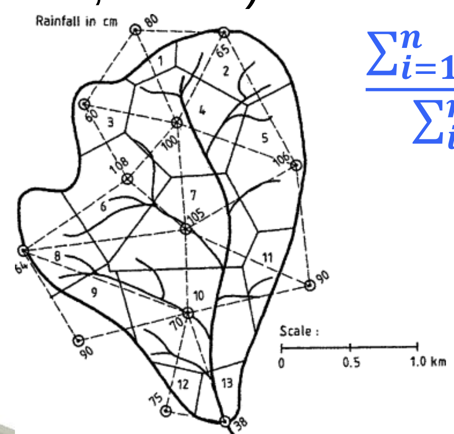
Weighting laterally inbetween sample points by interpolation in 2D or 3D

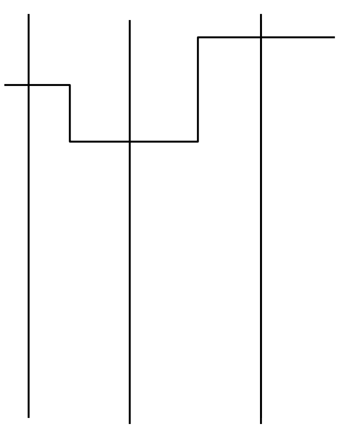
- 2D Example (Polygonal method) = Nearest Neighbour Interpolation
- Arithmetic average weighted by area of polygon (A) = Arithmetic average of gridded (interpolated) grades (Grid, e.g. X=2m, Y=2m)

$$\frac{\sum_{i=1}^{n} G_i * A_i}{\sum_{i=1}^{n} A_i}$$









Data analysis and interpretation - interpolation methods

Geometrical interpolation methods

- Natural neighbour interpolation (Voronoi, Thiessen, Polygonal method)
- Nearest neighbour interpolation (Delaunay, Triangulation)
- Inverse Distance Weighting (IDW)

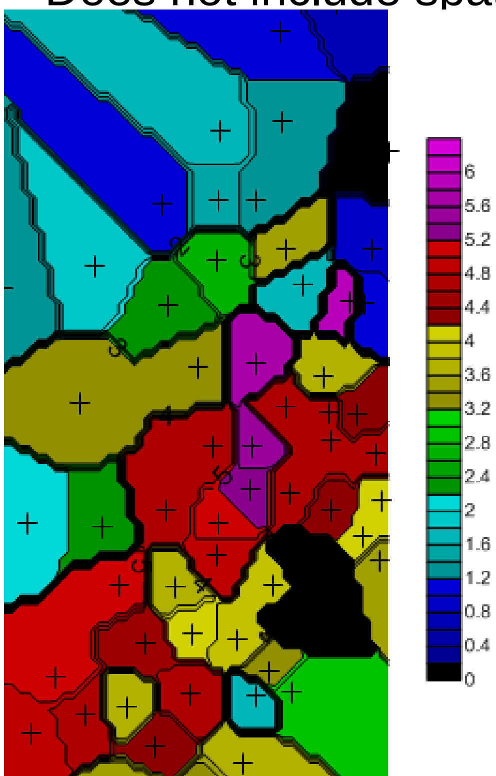
Geometrical interpolation methods

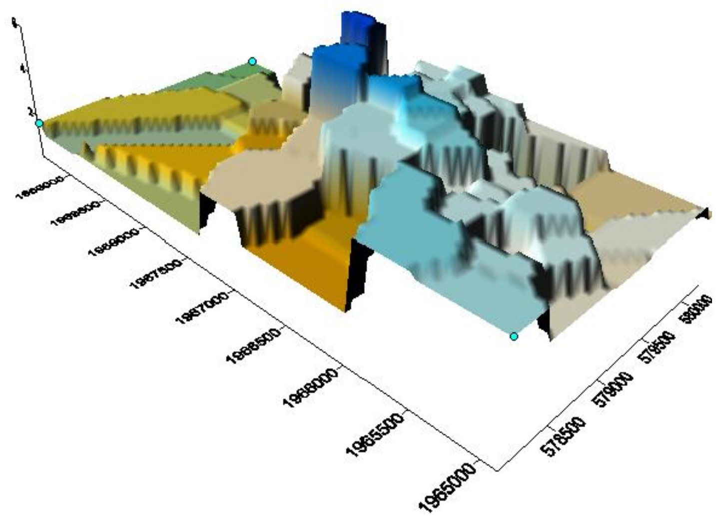
- Kriging considering trends in spatial distribution
- Precondition: all data are attributed to their domain, are normal distributed in their domain without outlier and have an integrative sample support

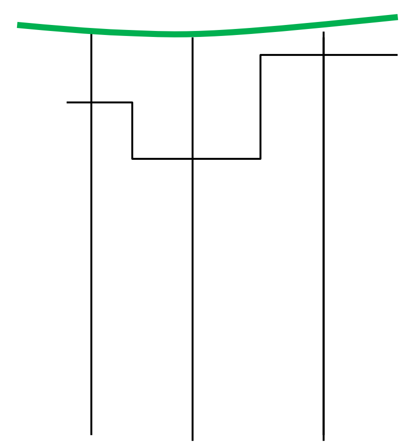
Data analysis and interpretation - interpolation methods

Nearest neighbour interpolation (Voronoi, Thiessen, Polygonal method)

- Transparent method, often used at early stage projects (data constraints)
- Does not include spatial trends in grade distribution (anisotropy)



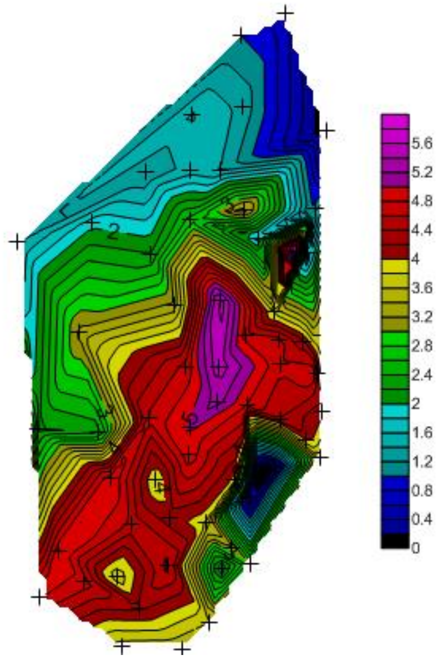


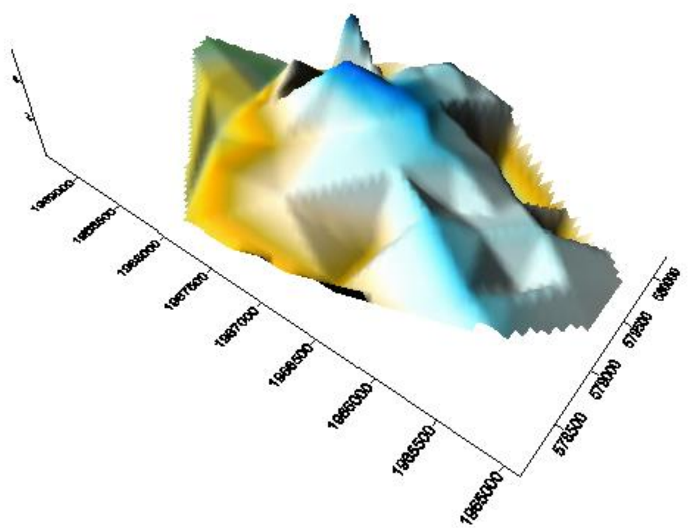


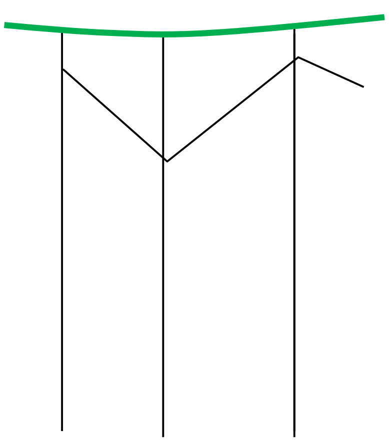
Data analysis and interpretation - interpolation methods

Delauney triangulation

- Transparent method, often used at early stage projects (data constraints)
- Does not include spatial trends in grade distribution (anisotropy)



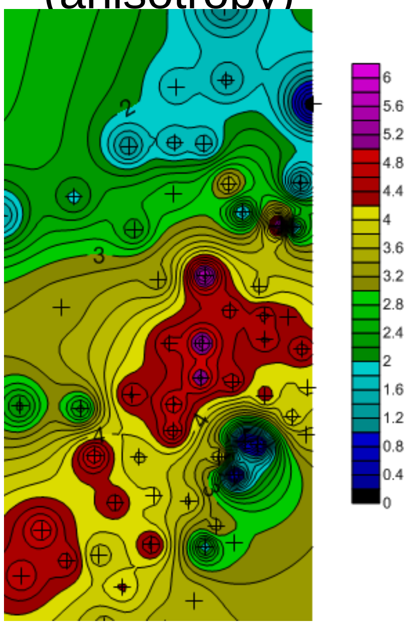


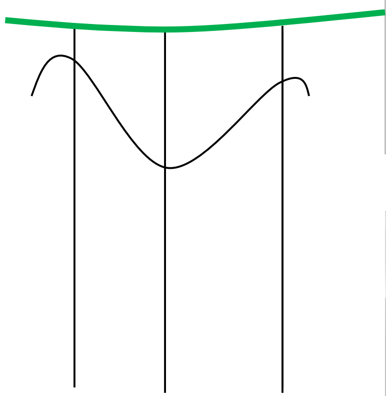


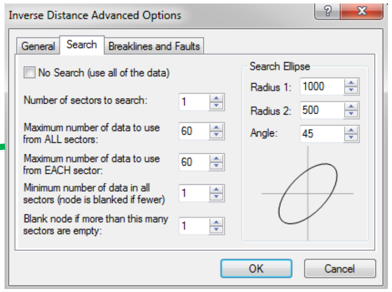
Data analysis and interpretation - interpolation methods

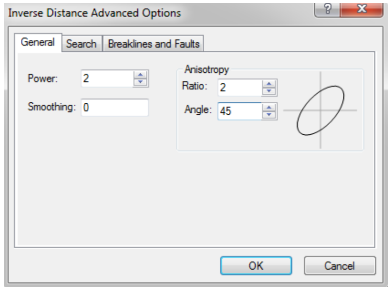
Inverse Distance Weighting (IDW)

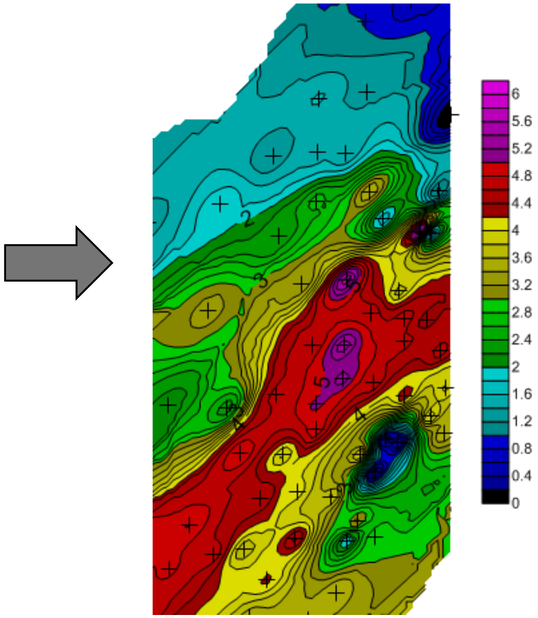
- IDW assumes that each measured point has a local influence that diminishes with distance (or distance to the power of q > 1), and weighs the points closer to the prediction location greater than those farther away; therefore the name inverse distance weighted; can include spatial trends in grade distribution (anisotropy)







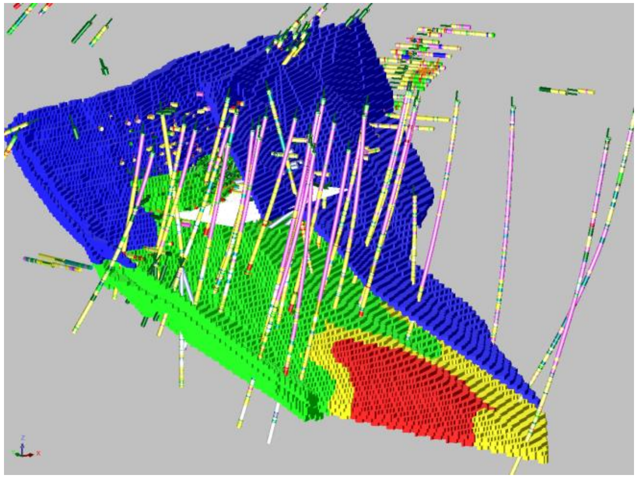


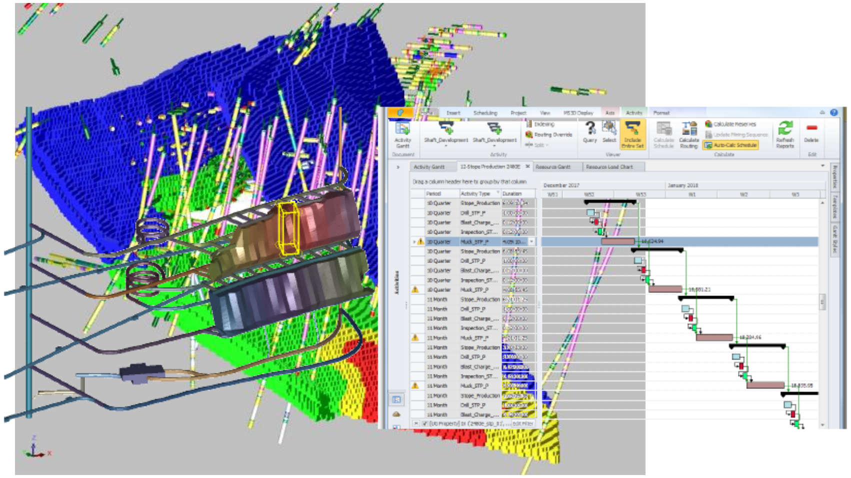


Resource classification

Resource Classification considering geological and grade continuity

- Complexity of deposit and degree of investigation
- Hand-over for mine planning and other studies

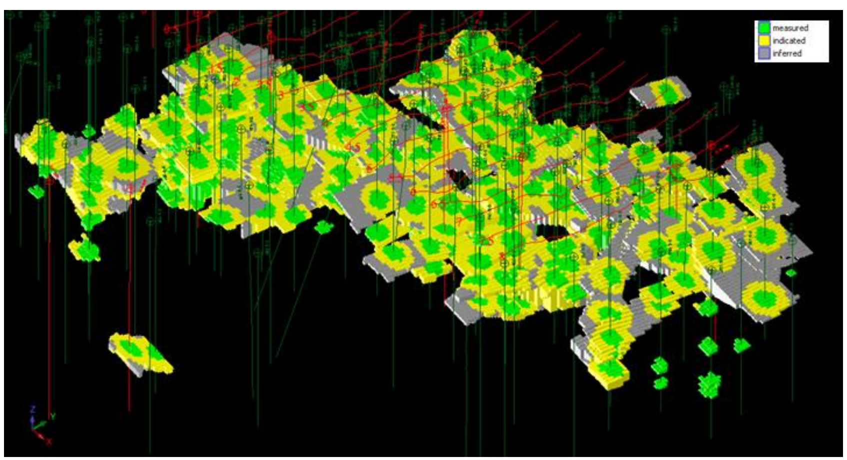


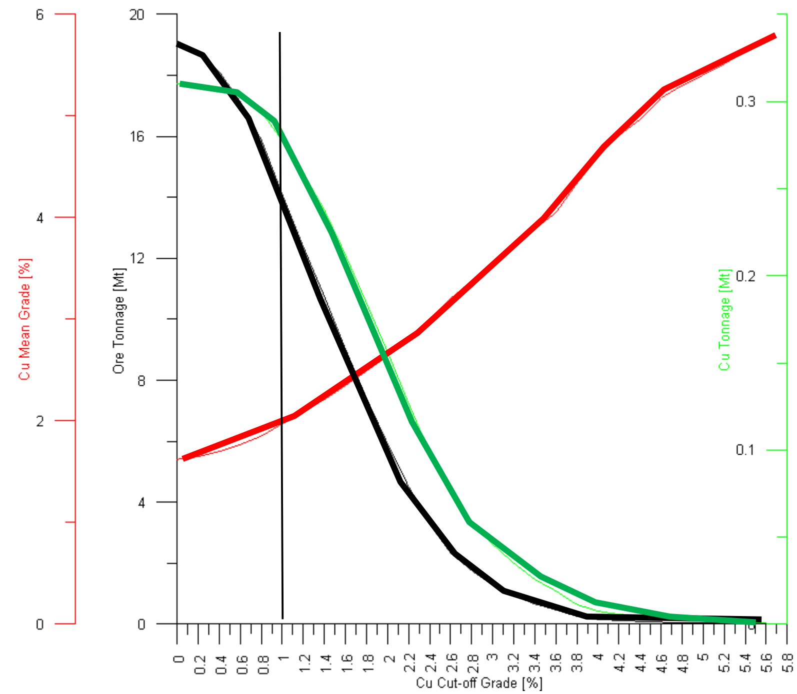


Resource Classification and Estimate

Parameter Relevant for Resource Estimate

- **Bulk Tonnage [t]** = Bulk Volume [m³] * Average Density [t/m³]
- Commodity Tonnage [t] = Bulk Tonnage [t] * **Average Grade [%]**
- **Grade-Tonnage Curve (Classified Resources)**





Resource Classification and Estimate

Parameter Relevant for Resource Estimate

Block model (data from drill holes and trenches)					
TFe Cutoff [%]	Volume [Mm³]	Tonnage [Mt]	Density [t/m³]	TFe mean grade [%]	Magnetite [%]
0	1815	5607	3.09	10.29	3.12
0.5	1815	5607	3.09	10.29	3.12
1	1815	5607	3.09	10.29	3.12
1.5	1815	5607	3.09	10.29	3.12
2	1815	5606	3.09	10.29	3.12
2.5	1815	5606	3.09	10.29	3.12
3	1815	5605	3.09	10.29	3.12
3.5	1814	5603	3.09	10.30	3.12
4	1813	5601	3.09	10.30	3.12
4.5	1812	5596	3.09	10.30	3.12
5	1807	5581	3.09	10.32	3.13
5.5	1796	5551	3.09	10.35	3.15
6	1783	5510	3.09	10.38	3.17
6.5	1760	5443	3.09	10.43	3.20
7	1721	5326	3.09	10.51	3.26
7.5	1660	5141	3.10	10.63	3.36
8	1576	4884	3.10	10.78	3.50
8.5	1465	4547	3.10	10.97	3.69
9	1326	4122	3.11	11.20	3.94
9.5	1163	3621	3.11	11.46	4.26
10	985	3074	3.12	11.77	4.64
10.5	804	2513	3.13	12.11	5.08
11	638	1997	3.13	12.46	5.56
11.5	494	1550	3.14	12.82	6.06
12	**374**	**1177**	**3.14**	**13.16**	**6.55**
12.5	273	861	3.15	13.50	7.04
13	189	596	3.15	13.84	7.53
13.5	119	374	3.16	14.20	8.05
14	63	199	3.16	14.60	8.63
14.5	29	92	3.17	15.05	9.25
15	12	38	3.18	15.52	9.90
15.5	5	15	3.18	15.98	10.50
16	2	6	3.19	16.40	11.02
16.5	1	2	3.19	16.84	11.53
17	0	0	3.20	17.31	12.02
17.5	0	0	3.20	17.74	12.43

Resource Definition – Cut-off Grade – Break Even Point

Operating Cut-off grade Determination for Iron Ore

- Break-Even is the Point when Costs = Revenues = No Profit and No Loss
- An underground mine will produce iron ore concentrate of 62 % Fe, the price for 1 ton of this concentrate is 100 USD; Dilution 10 %, Processing recovery 90 %; costs for mining and processing to produce concentrate is 20 USD/ton of ore . What is the operating cut-off grad?

Item	Cost/Revenue
Costs for mining plus processing [US$/t ore]	20
Price of concentrate [US$/t conc]	100
Fe grade of concentrate [Fe[%]/t conc]	63
Dilution [fraction]	0.1
Processing recovery [fraction]	0.9

$$\frac{\text{Costs for mining plus processing [US\$/t ore]}}{\left(\frac{\text{Price of concentrate [US\$/t conc]}}{\text{Fe grade of concentrate [Fe[\%]/t conc]}}\right)} * \frac{1 + \text{Dilution}\left[\text{fraction}\right]}{\text{Processing recovery}\left[\text{fraction}\right]} = Fe\ Cutoff\ grade$$

REE in Bauxites – Cut-off Grade

Operating Cut-off grade

Table 3. Trace element composition of the samples. Error is given as one standard deviation of a duplicate measurement.

Element	Karst Bauxite Greece	Lateritic BauxiteGhana	Bauxite ResidueGreece, AoG
	ICP-MS	INAA	ICP-MS
	(mg/kg)	(mg/kg)	(mg/kg)
La	57 ± 7	19.1 ± 1.3	130 ± 1
Ce	206 ± 8	34 ± 1	480 ± 26
Pr	15 ± 1	n/a	29 ± 2
Nd	53 ± 6	13 ± 1	107 ± 0
Sm	9.8 ± 1.0	2.0 ± 0.2	19.4 ± 0.2
Eu	2.4 ± 0.9	0.8 ± 0.2	4.6 ± 1.1
Gd	10.6 ± 0.6	n/a	22.0 ± 0.3
Tb	2.3 ± 0.5	<0.5	3.3 ± 0.0
Dy	9.8 ± 0.3	n/a	20.1 ± 0.1
Ho	2.1 ± 0.1	n/a	4.1 ± 0.1
Er	7.2 ± 0.8	n/a	13.3 ± 0.3
Tm	<2	n/a	<2
Yb	7.0 ± 0.4	2.5 ± 0.3	13.8 ± 0.3
Lu	<2	0.4 ± 0.0	2.2 ± 0.0
Y	48 ± 2	n/a	108 ± 2
Nb	55 ± 9	n/a	100 ± 1
Th	51 ± 2	22.7 ± 2.3	105 ± 2
ΣLn [1]	382.3		854.4
ΣREE [2]	430.6		962.5

[1] Sum of lanthanides; [2] Sum of lanthanides and yttrium.

REE in Bauxites – Cut-off Grade

Operating Cut-off grade

- Can we mine red mud and extract (process) REE out of the red mud for less than 17 EUR? (Just as an example to show way of assessment, numbers will change)

	Bauxite Residue REEs Greece	Conversion factor REE to REO	Bauxite Residue REOs Greece	Price	In-situ Value
	ppm (g/t)		ppm (g/t)	USD /t REO	USD/ t Red mud
Lanthanium	**130.0**	1.1728	**152.5**	3000	**0.46**
Cerium	**480.0**	1.1713	**562.2**	3000	**1.69**
Praseodymium	**29.0**	1.1703	**33.9**	55600	**1.89**
Neodymium	**107.0**	1.1664	**124.8**	49000	**6.12**
Samarium	**19.4**	1.1596	**22.5**	1825	**0.04**
Europium	**4.6**	1.5825	**7.3**	47000	**0.34**
Gadolinium	**22.0**	1.1423	**25.1**	18250	**0.46**
Terbium	**3.3**	1.1510	**3.8**	444000	**1.69**
Dysprosium	**20.1**	1.1477	**23.1**	180000	**4.15**
Holmium	**4.1**	1.1455	**4.7**		**0.00**
Erbium	**13.3**	1.1664	**15.5**	22200	**0.34**
Thulium	**2.0**	1.1421	**2.3**		**0.00**
Ytterbium	**13.8**	1.1387	**15.7**		**0.00**
Lutetium	**2.2**	2.2916	**5.0**	2750	**0.01**
Yttrium	**108.0**	1.2699	**137.1**		**0.00**
Niobium	**100.0**	1.1544	**115.4**		**0.00**
Thorium	**105.0**	1.1379	**119.5**		**0.00**
				SUM	**17.19**

REE in Bauxites – Processing – Technical Feasibility

Operation

- Mining is common practice

- EURARE project finished in 2017

(Davris et al., 2018). The REE were then stripped from the ionic liquid using acid, and the ionic liquid regenerated and reused (Figure 10).

Figure 10 *Ionic liquid leaching of Rødberg bastnäsite ore and red mud (or bauxite residue) (Balomenos et al., 2017). ©NTUA.*

Processing of REE-bearing ore

The current state-of-the-art processes for REE extraction require complex, energy and resource intensive technologies. These include a beneficiation stage for the production of a rare earth-rich concentrate, leaching/purification to produce mixed rare earth compounds, separation into individual high purity rare earth solutions, precipitation as individual rare earth compounds, and finally production of rare earth metals or alloys through metallothermic reduction or fused-salt electrowinning. A European REE industry will require cost-effective, and resource-efficient processing methods that are appropriate for European primary REE resources and for European health, safety, and environmental standards. Currently, Europe does not have industrial-scale REE beneficiation or leaching, but has some capability for REE separation: this includes the Solvay plant at La Rochelle in France, and the Silmet plant in Estonia (Guyonnet et al., 2015). At the time of writing, activities at both plants are limited, due to the concentration of the REE separation industry in China (Wall et al., 2017). A new demonstration plant for REE separation is currently under construction in Norway by the company REEtec, which has previously carried out REE separation at pilot-scale.

Thank You for Your Attention!