Geochemical visualization in the geologist's toolkit

Using micro-XRF and automated mineralogy in the mineral exploration workflow

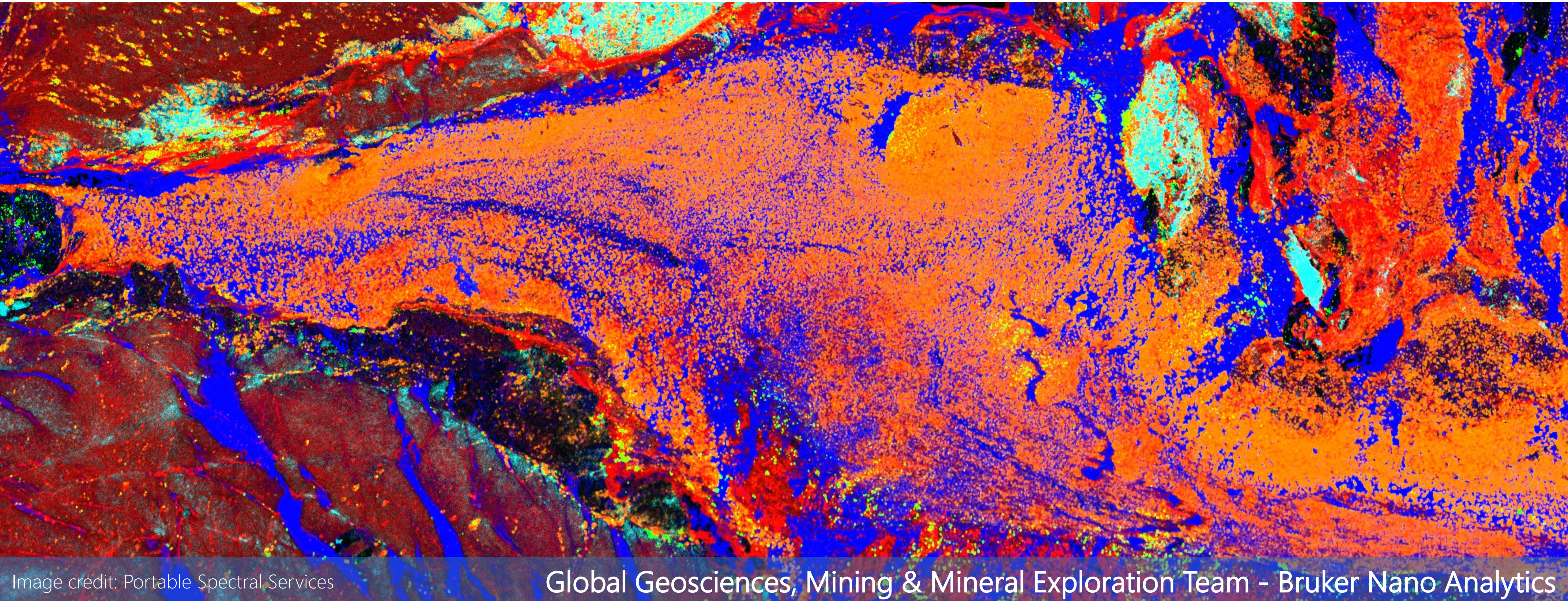

Image credit: Portable Spectral Services

Global Geosciences, Mining & Mineral Exploration Team - Bruker Nano Analytics

Dr. Nigel Kelly
Senior Market Application Scientist, Bruker Nano Analytics

Jonathan Knapp
Market Segment Manager, Bruker Nano Analytics

Bruker's Portfolio

Working across product lines to meet your specific exploration challenges

TRACER 5
Portable XRF with helium and custom calibration software

S1 TITAN
Customizable and rugged portable XRF

CTX
Portable desktop XRF for field or lab

M4 TORNADO
Fast and easy to use large-chamber µXRF

AMICS
Advanced mineral identification and classification for SEM and µXRF

Acknowledgements

Partners and collaborating researchers

Gerda Gloy (BNA Brisbane), Andrew Menzies (BNA Berlin)

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Portable Spectral Services

Erik Tharalson, (Jan) Tadsuda Taksavasu, David Leach, Raul Berruspi,
Garrett Gissler, Thomas Monecke, Katha Pfaff, Kelsey Livingstone
Colorado School of Mines

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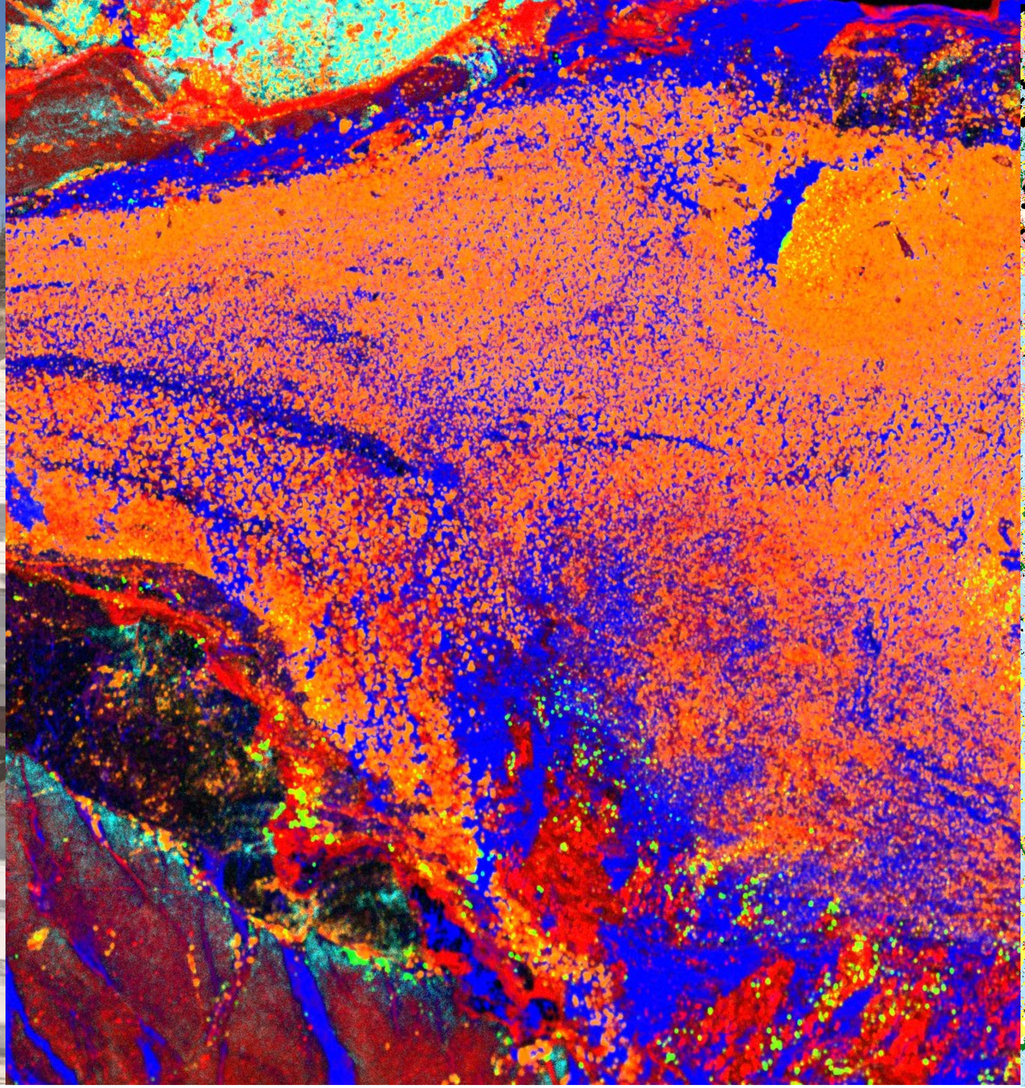
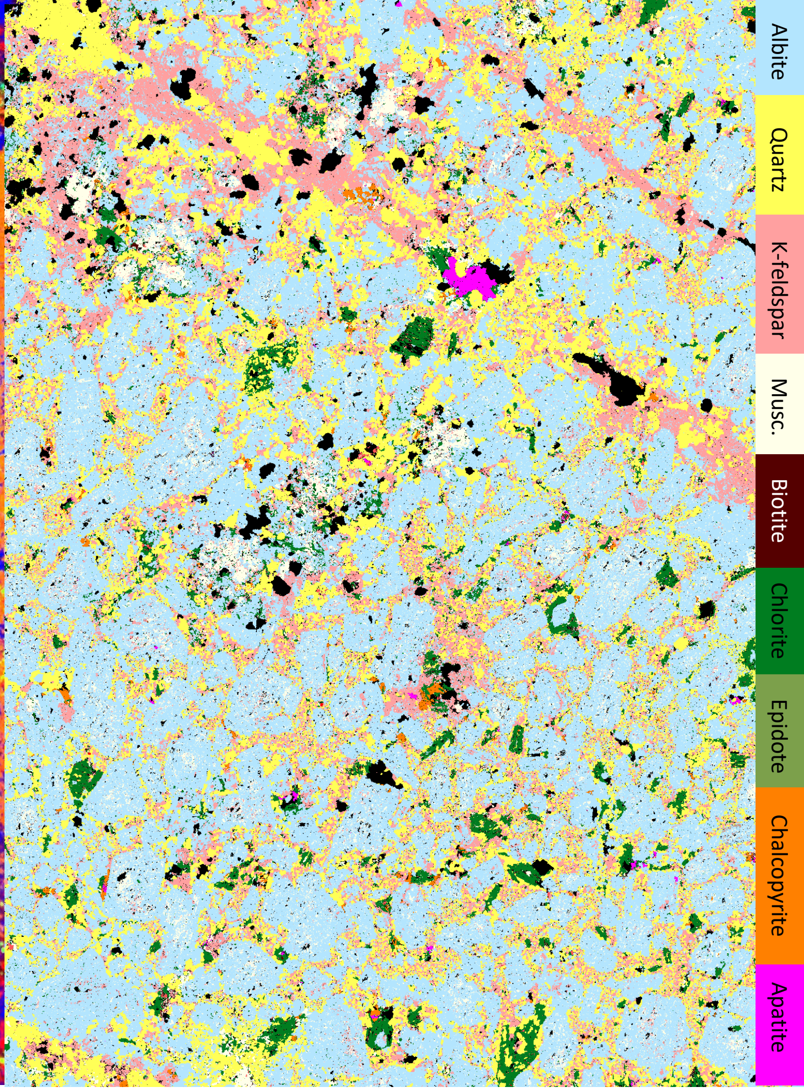




We are in the middle of a revolution in analytical technology for mineral exploration. Geochemical visualization technology has evolved and become affordable. **But how do we apply it?**

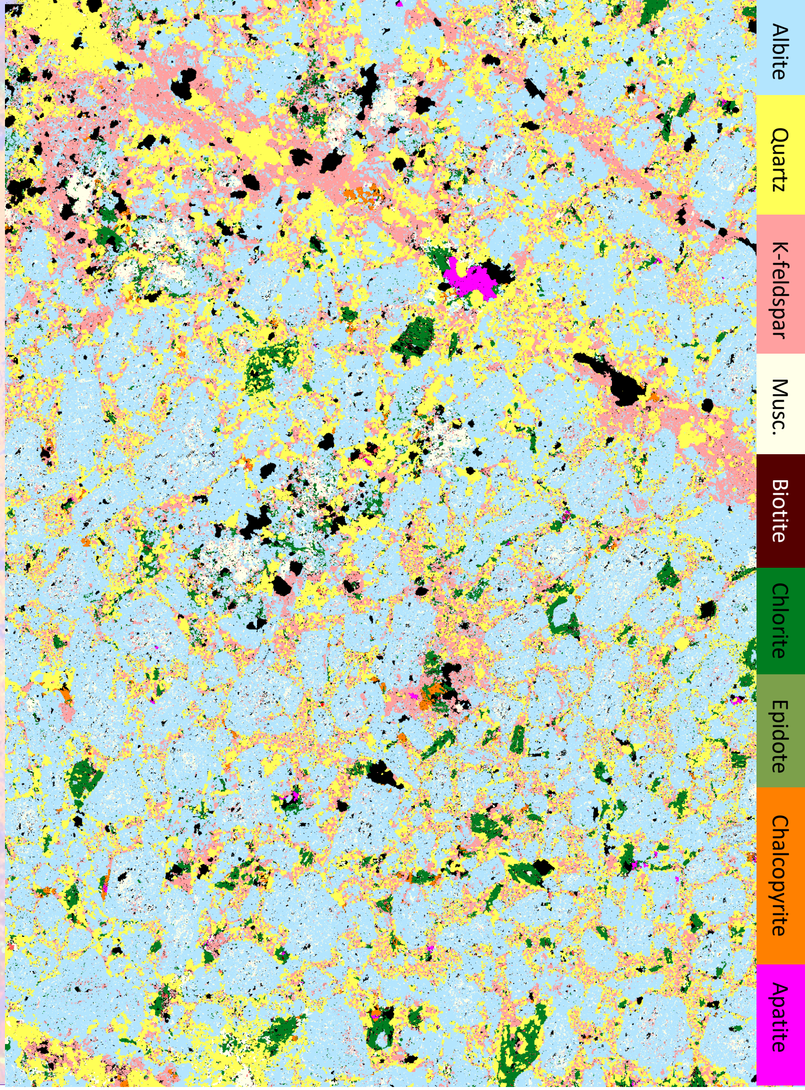
Geochemistry and mineral exploration

Thinking across scales in exploration geochemistry

Field and drill-core scales

Micro-XRF

Scanning Electron Microscopy & Automated Mineralogy



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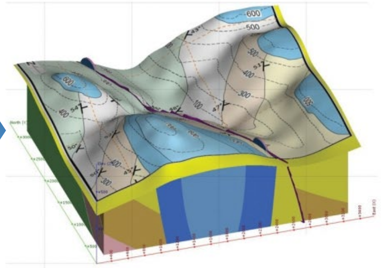
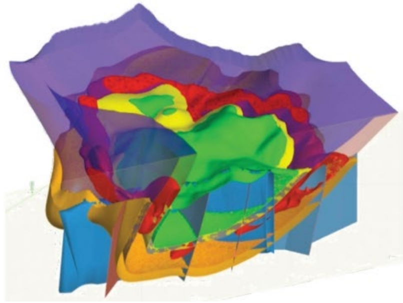
Geochemistry & mineral exploration

Geochemistry in the Exploration Workflow

The Foundation of Exploration is Geochemistry





Surficial Geochemistry

2D Field mapping of soil, sediment, and regolith for exploration targeting

- In-situ primary elements
- Pathfinder elements
- Secondary commodity elements

Lithogeochemistry

3D characterization of rock, drill core, and cuttings for exploration

- Commodity and pathfinder elements
- Rock classification and modal mineralogy
- Modification and vectoring

Modeling and Assessment

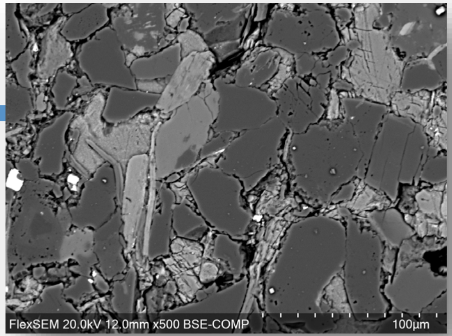
Synthesis of surface and lithogeochemistry from high density drilling in the context of exploration models

- Assessment and feasibility
- Preliminary and advanced geometallurgy

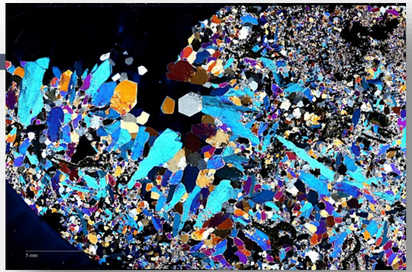
Geochemistry & mineral exploration

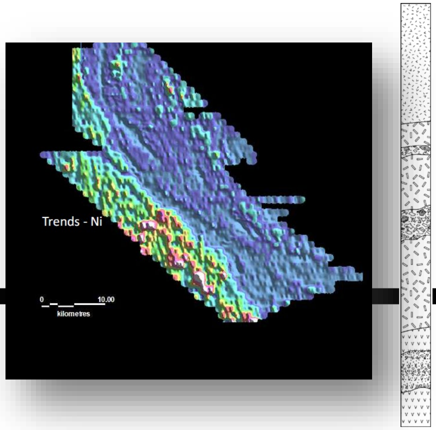
Scales

Micron to Millimeter
SEM, Automated minerology, microprobe, LA-ICP-MS, EBSD, EDS



Centimeter to Kilometer
Bulk geochemistry mapping, field photos, remote sensing, core description and core scanning, hyperspectral





Millimeter to Centimeter
Core and hand sample characterization, µXRF scanning, thin section petrology

10 km | 1000 m 1 km | 100 m | 10 m 1000 cm | 100 cm | 100 mm 10 cm | 10 mm | 1 mm 1000 µm | 100 µm | 10 µm | 1 µm

Geochemistry & mineral exploration

Exploration targeting and assessment

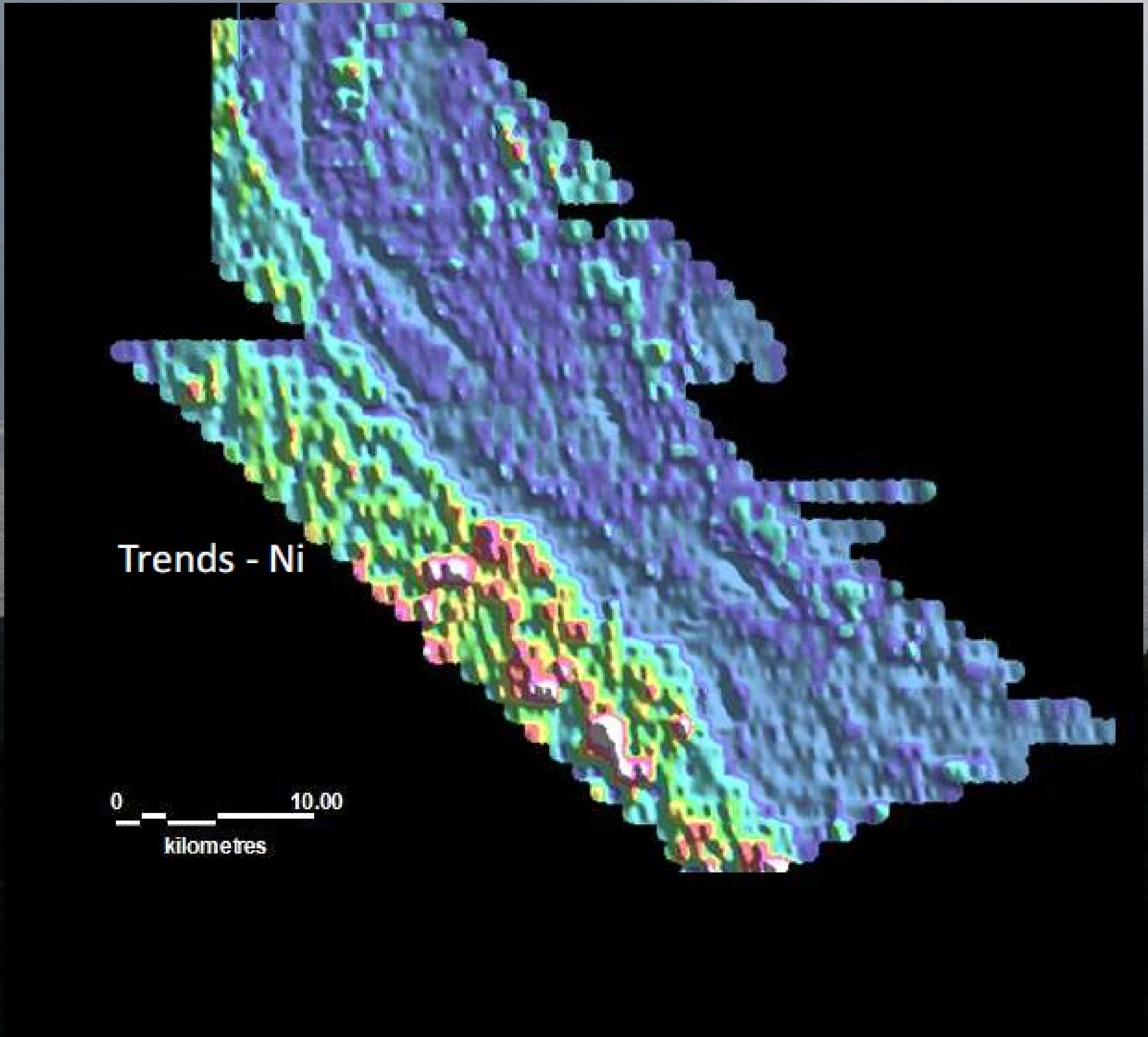
Most geochemistry is "bulk" data collected from rocks, stream sediments, soil, till or regolith

Collecting Samples

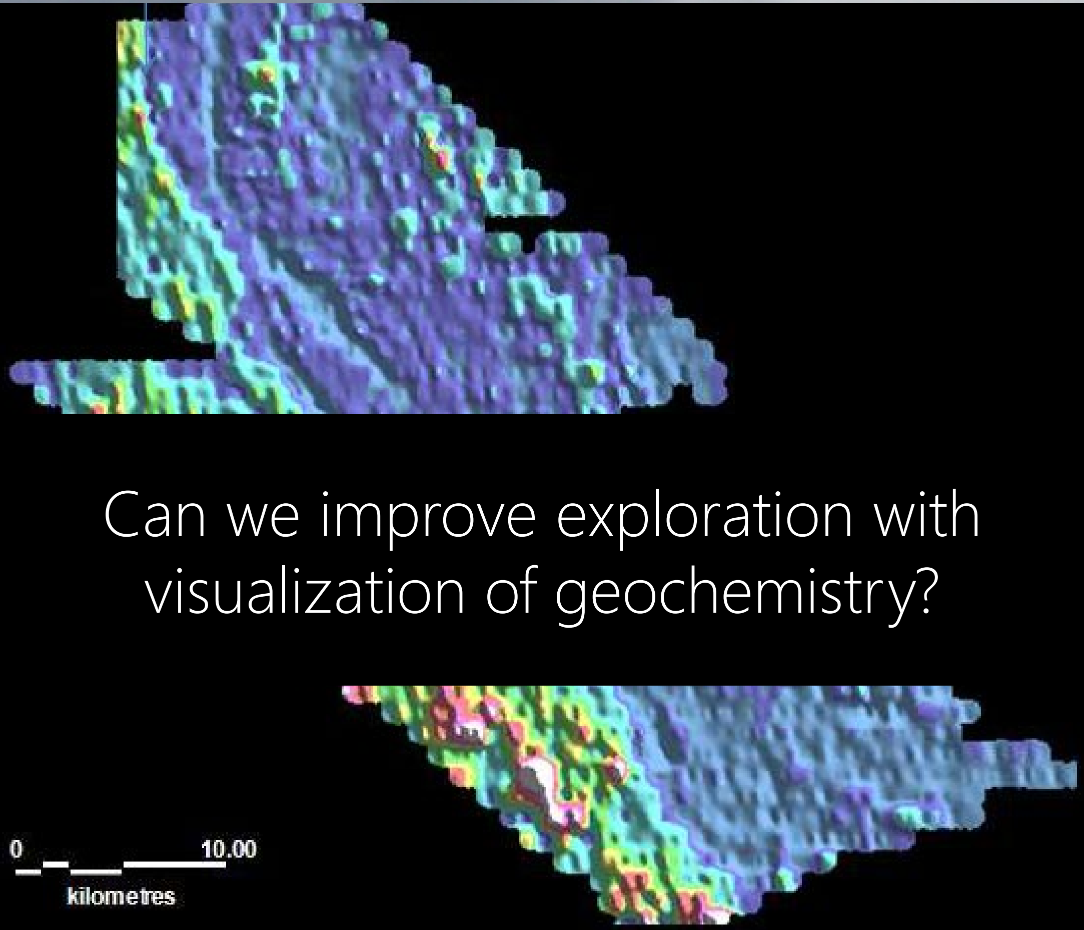
Sample Preparation

Acid Digestion

Instrumental Finish



The data is powerful through force of numbers. However, this is disconnected from the textural information that records the processes of geology.



Can we improve exploration with visualization of geochemistry?

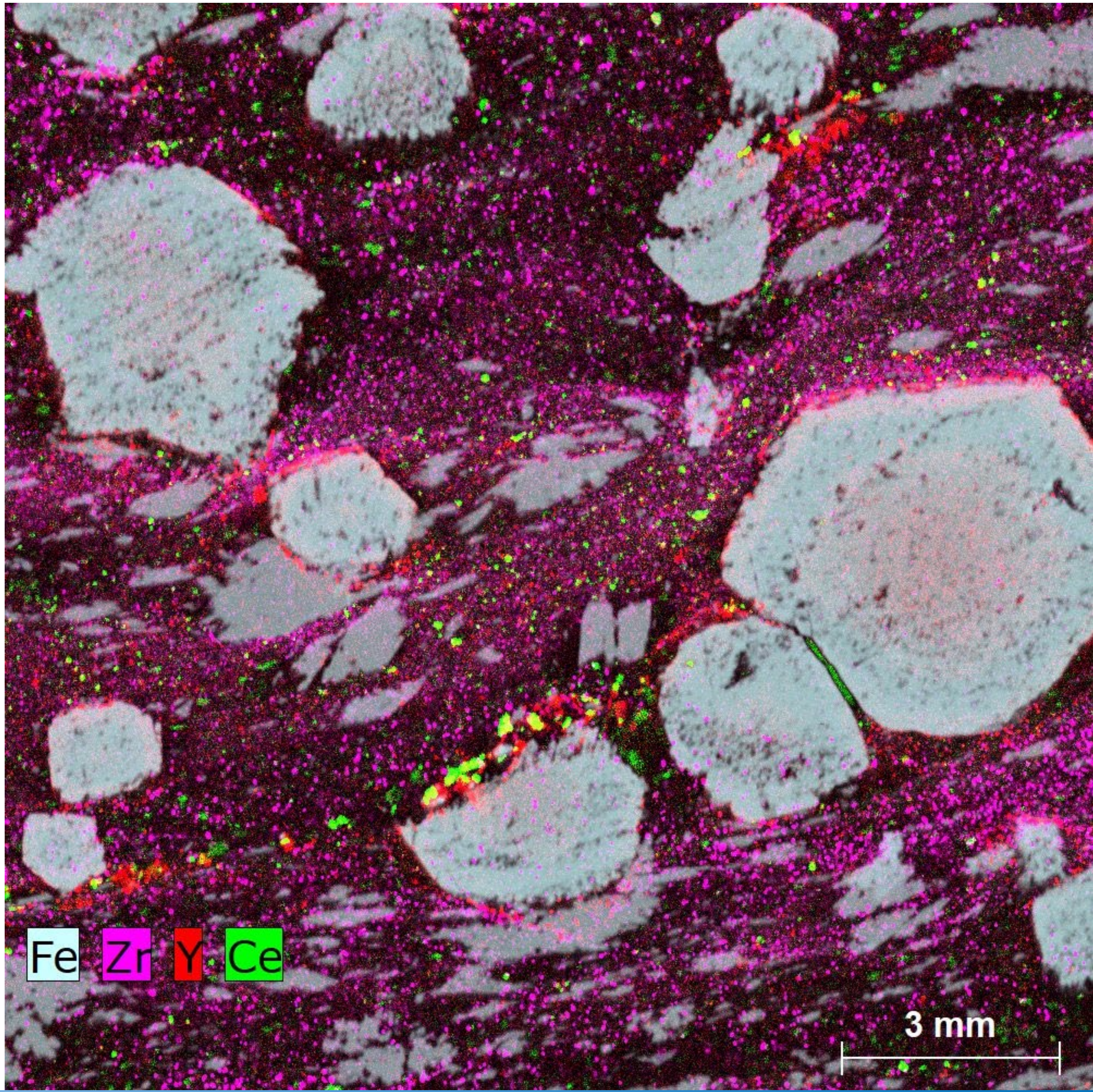
Geochemistry & mineral exploration

What is Visual Geochemistry?

Bulk geochemistry is a reflection of the mineralogy and mineral system processes.

Visual geochemistry is…

- Chemistry in the context of process: mineralization and alteration
- Process deduced from the combination of mineralogy and texture
- Better inputs into existing workflows:
  - Select pathfinder elements with confidence
  - Vectoring and alteration in context of mineral stoichiometric constraints
  - Front end feasibility and geometallurgy



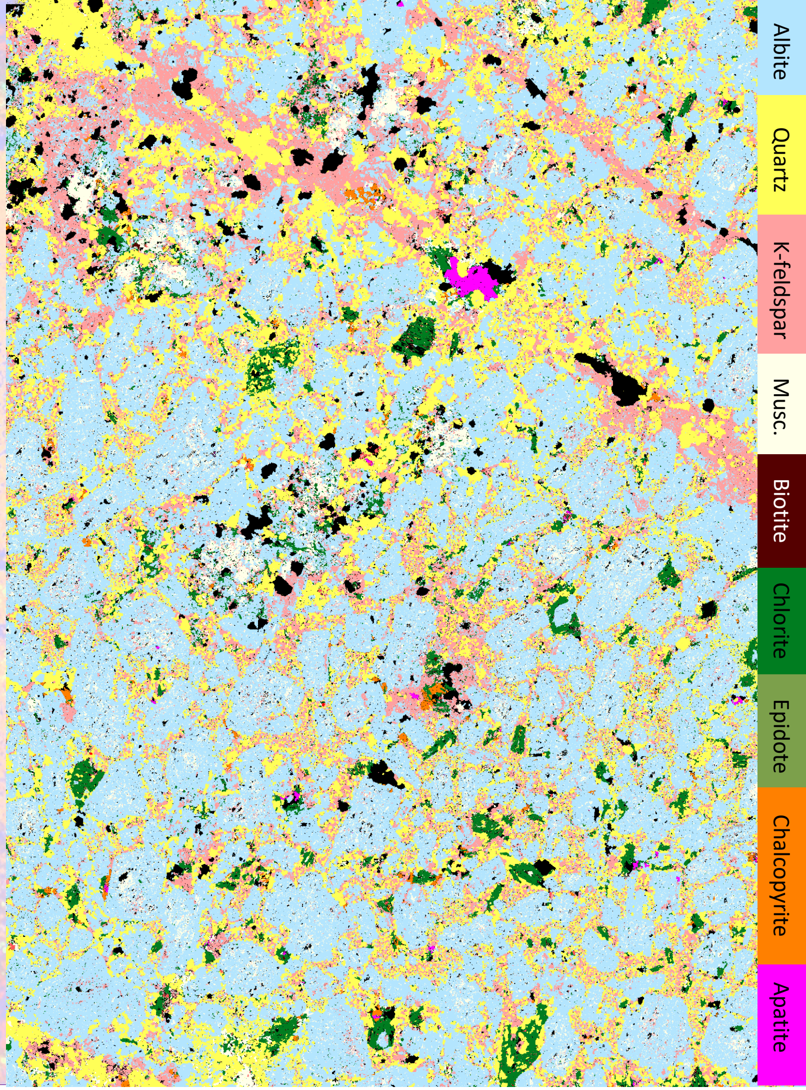
Geochemistry and mineral exploration

Thinking across scales in exploration geochemistry

Field and drill-core scales

Micro-XRF

Scanning Electron Microscopy & Automated Mineralogy



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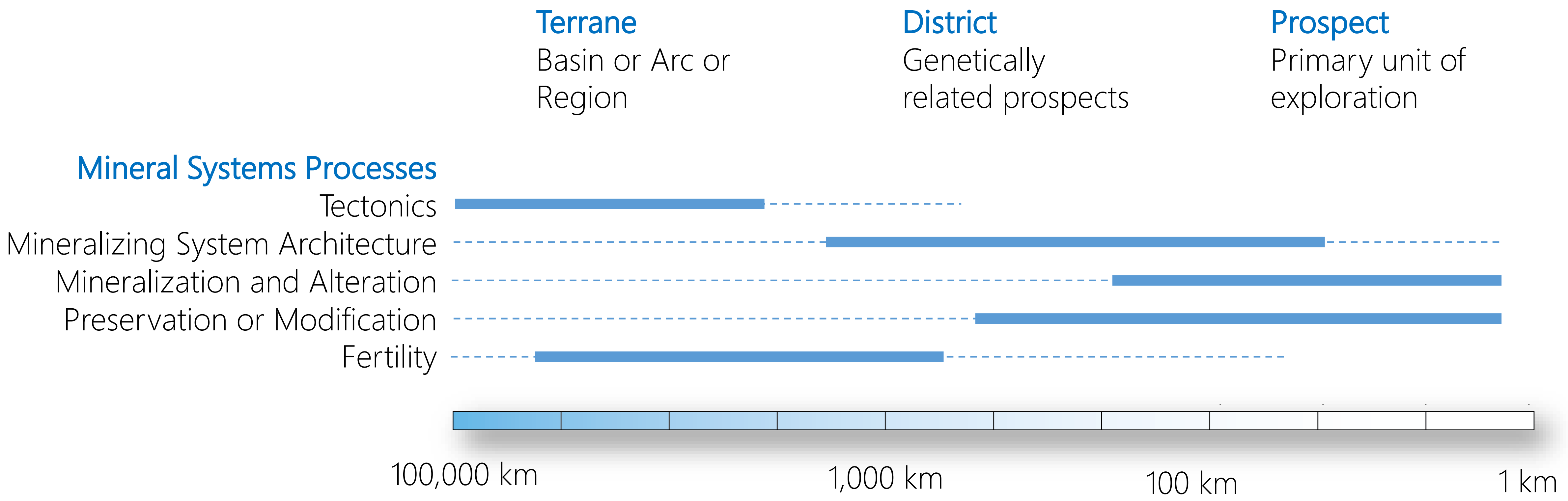
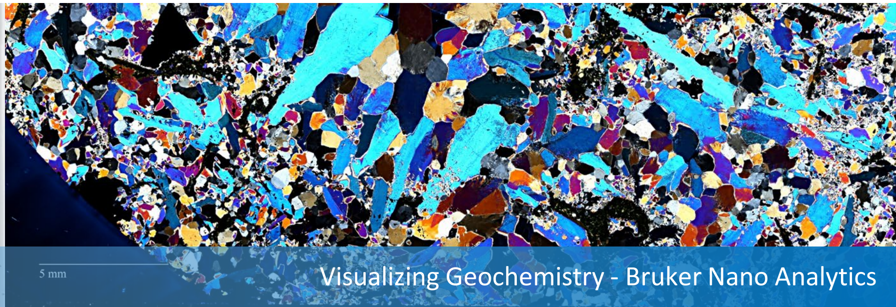
Geochemistry & mineral exploration

Scale in Exploration





Centimeter to Kilometer
Bulk geochemistry mapping, field photos, remote sensing, core description and core scanning, hyperspectral

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Micron to Millimeter
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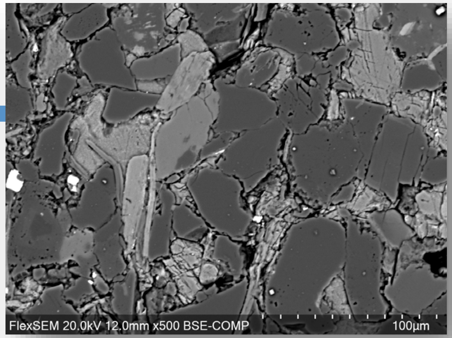

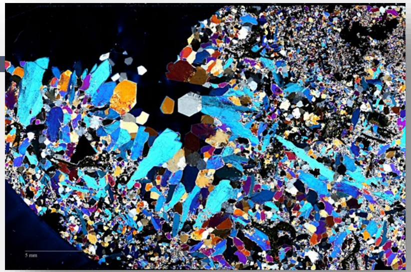

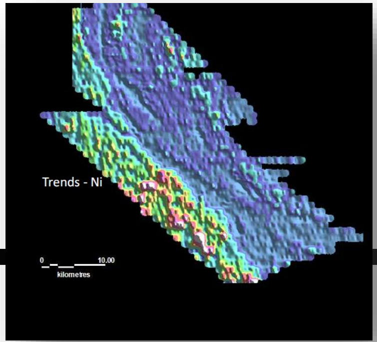

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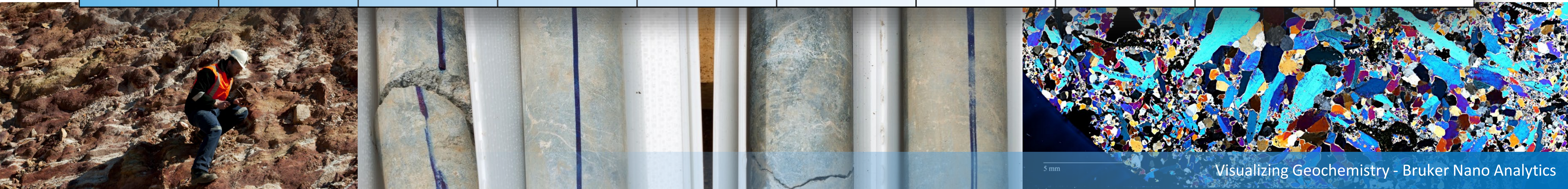
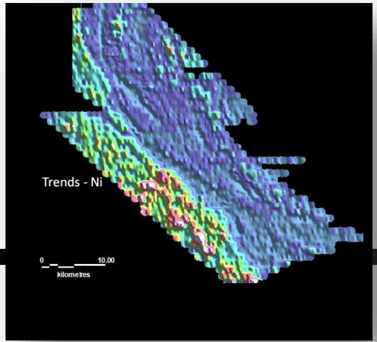
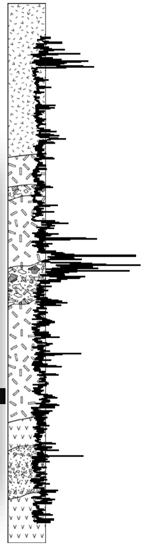


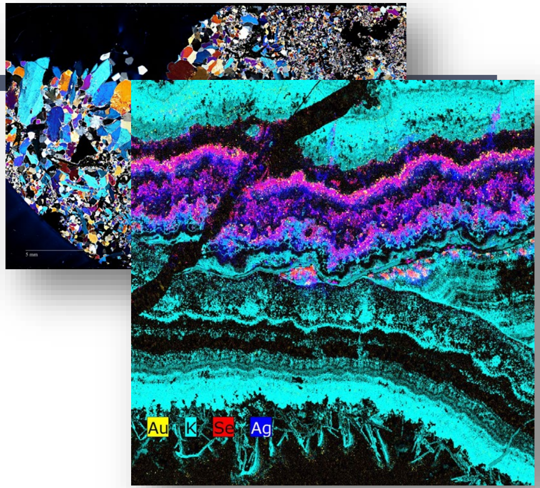
Centimeter to Kilometer
Faster field geochemistry with pXRF and better pathfinder models.

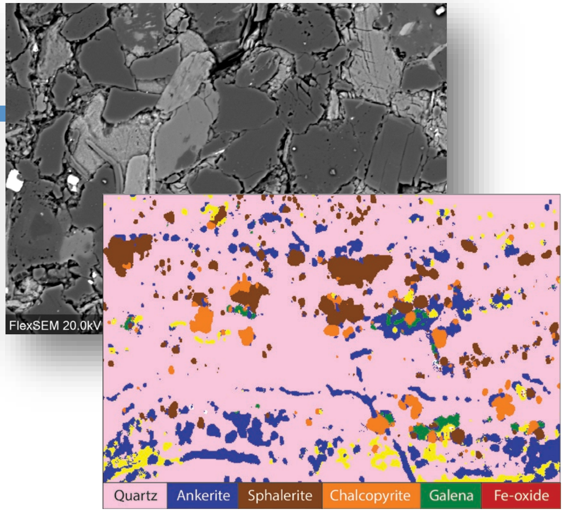
Millimeter to Centimeter
Elemental geochemistry and mineralogy at the scale of optical petrology.

Micron to Millimeter
Faster, automated, and field deployed automated mineralogy









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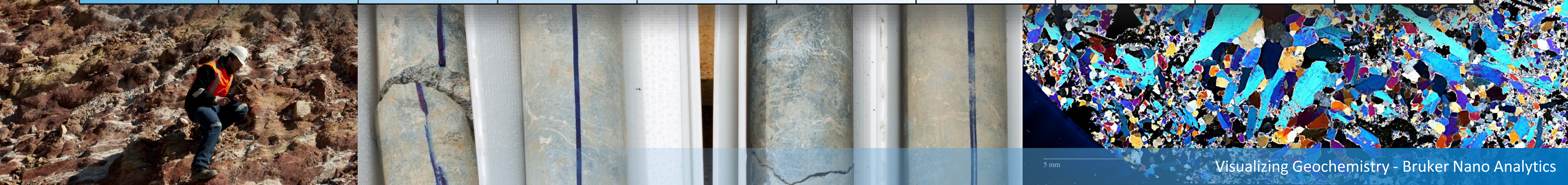


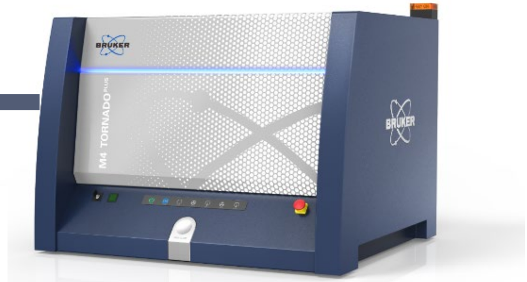
Geochemistry & mineral exploration

Scale in Exploration

Employing a variety of methods with different analytical profiles enables value-added characterization.

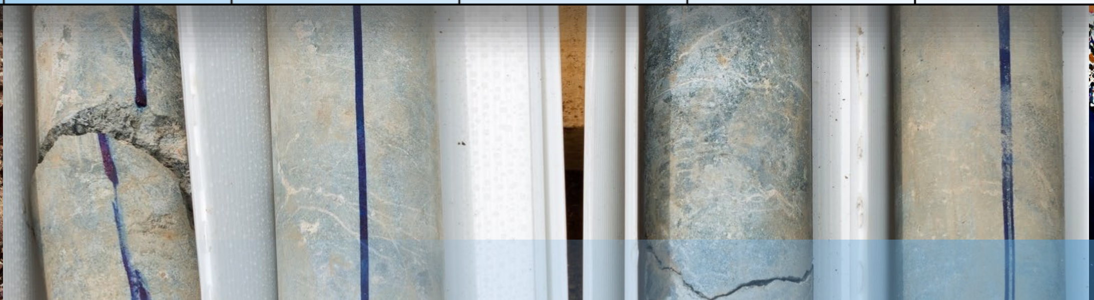
Micron to Millimeter Scale Features

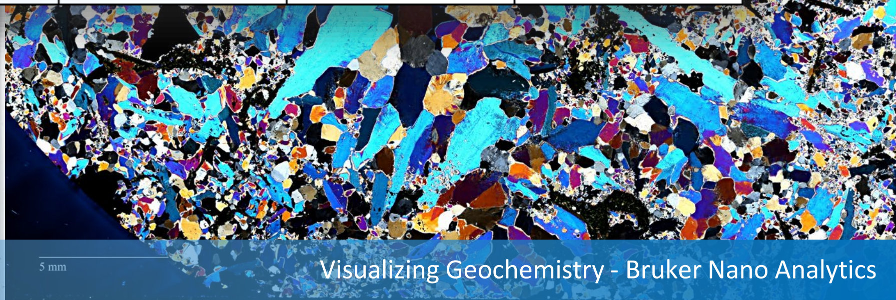
Millimeter to Centimeter Scale Features



Centimeter to Kilometer Scale Features

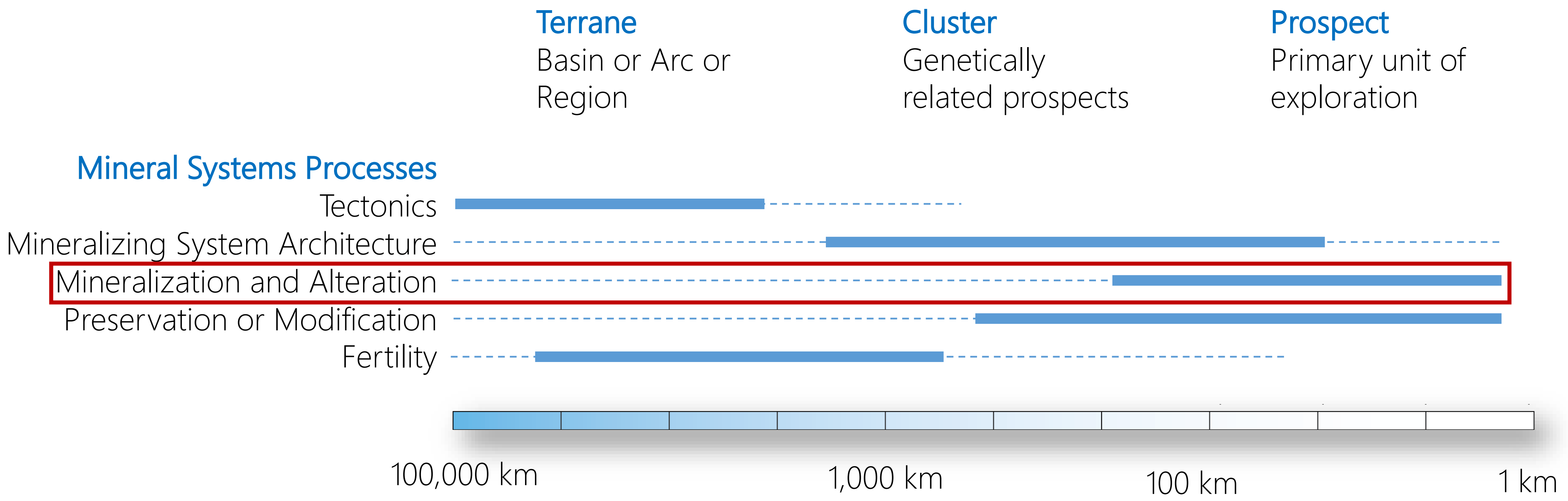
10 km | 1000 m 1 km | 100 m | 10 m 1000 cm | 100 cm | 100 mm 10 cm | 10 mm | 1 mm 1000 µm | 100 µm | 10 µm | 1 µm

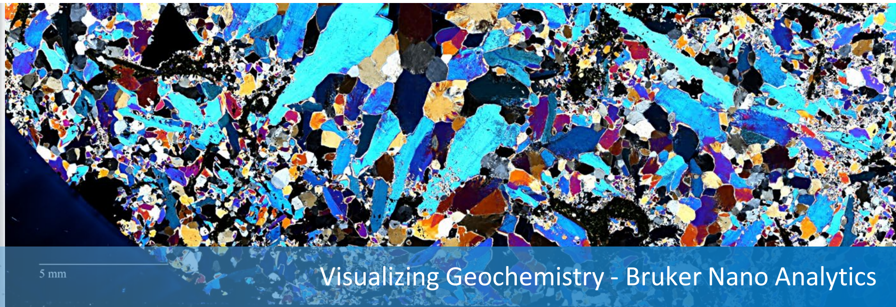




Geochemistry & mineral exploration

Scale in Exploration

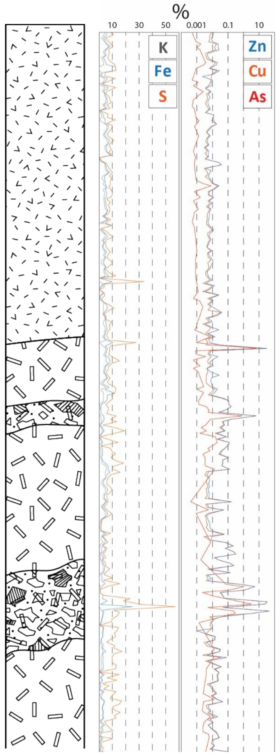




Geochemistry & mineral exploration

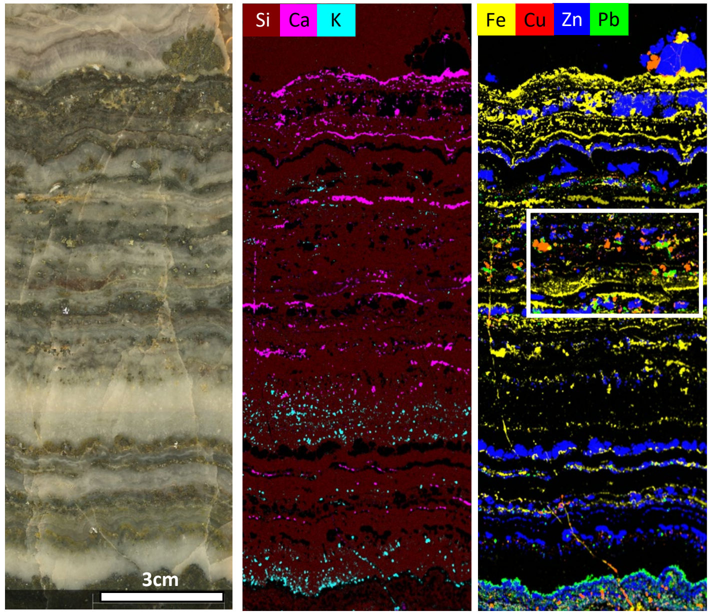
Scale in Exploration

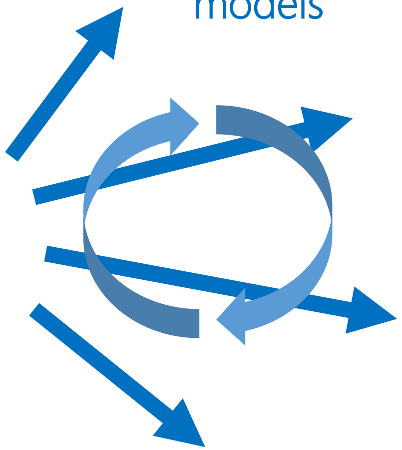
Visual geochemical characterization of process and products informs exploration strategies across scales



Core Scanning and Description

Select units for µXRF – no sample preparation needed

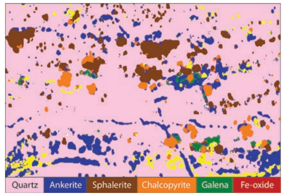




Inputs directly into exploration & deposit models

Development of pathfinder element suites, calibrations for handhelds

Microanalysis Sample Selection



Preliminary grade and recovery estimates, feasibility & design

Intermediate sulfidation epithermal deposit, Arista, Mexico; µXRF images courtesy of Garrett Gissler & Prof. Thomas Monecke, Colorado School of Mines, & Gold Resource Corp.

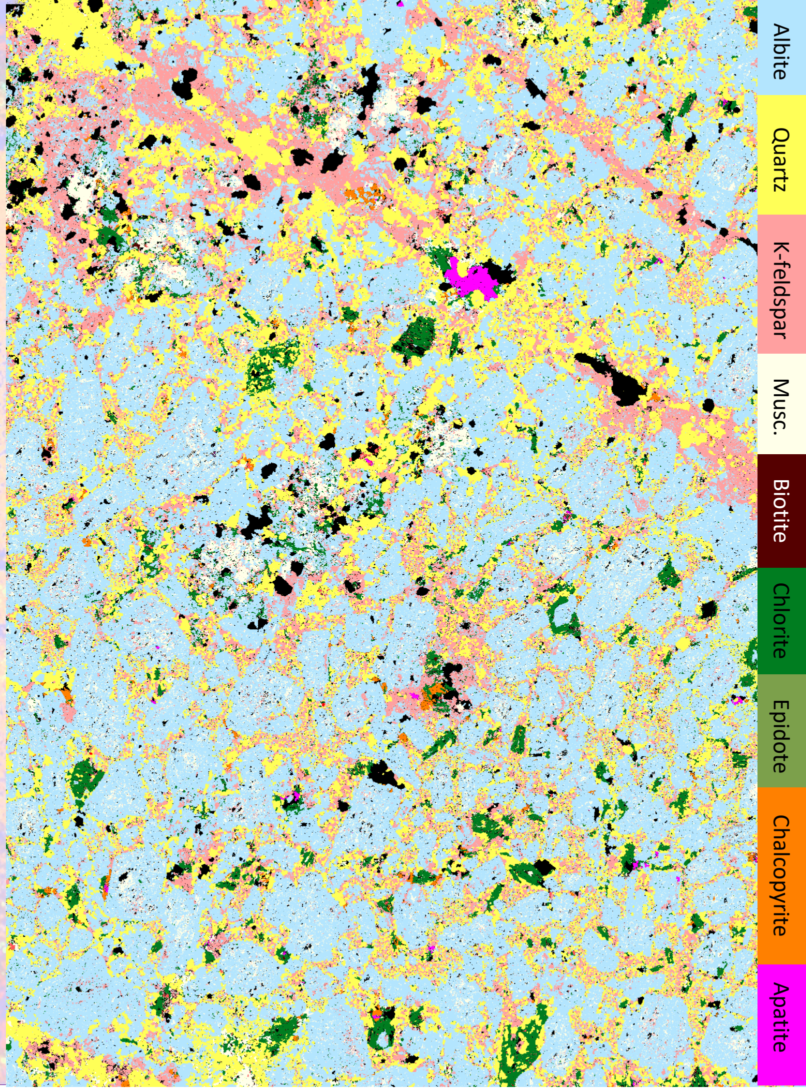
Geochemistry and mineral exploration

Thinking across scales in exploration geochemistry

Field and drill-core scales

Micro-XRF

Scanning Electron Microscopy & Automated Mineralogy



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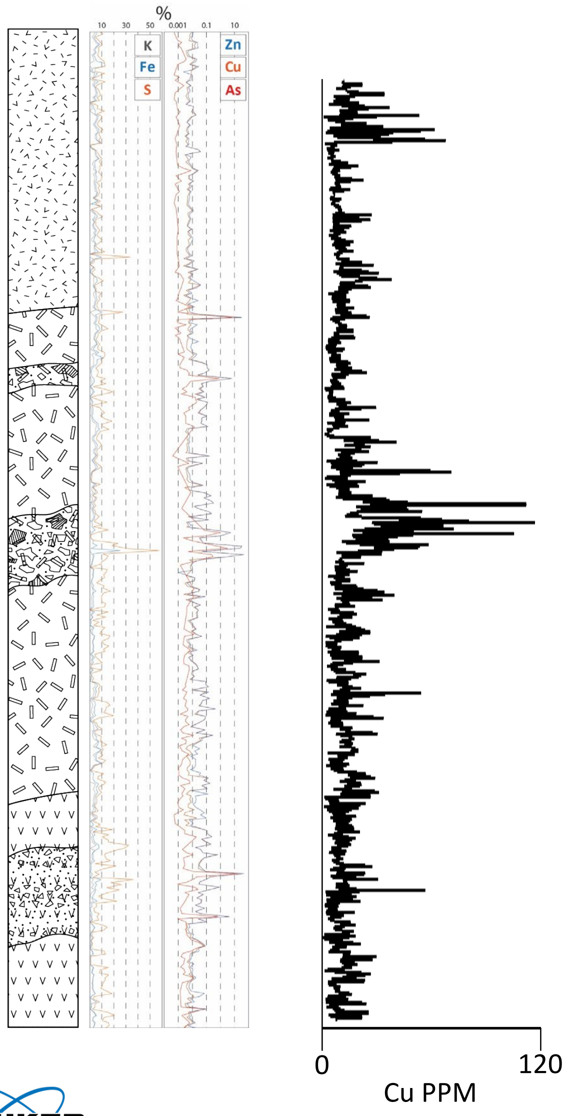
Handheld XRF

Meso-scale geochemistry in the field



Geochemistry at the scale of the drill string

Collect Data anywhere

Titan

Tracer 5g ▲

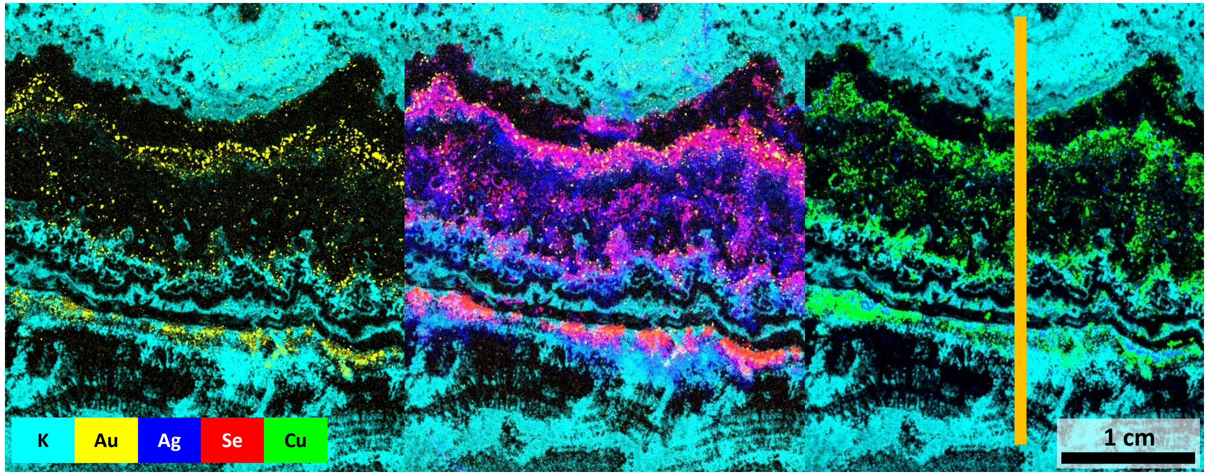
Bruker handheld products

Titan

Tracer 5g ►

Handheld XRF

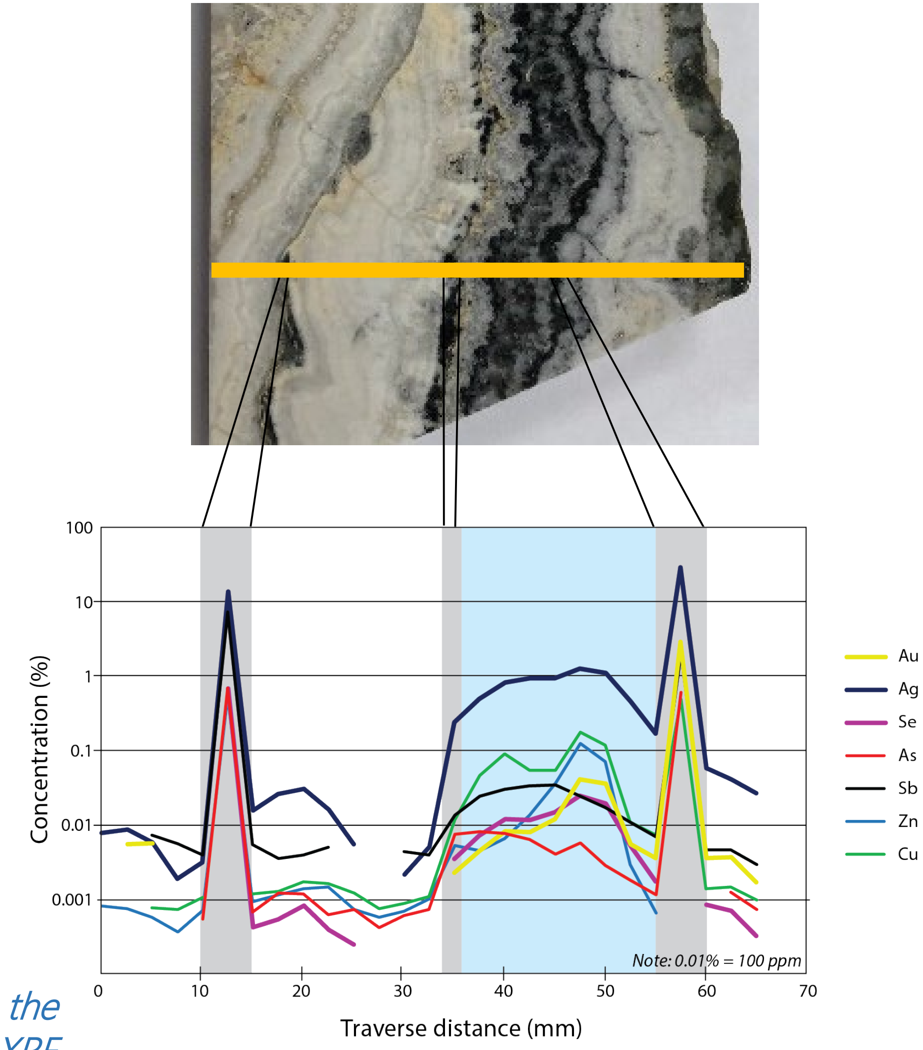
Meso-scale geochemistry in the field



µXRF enables observations made at the finer scale to be linked to those measurable in the core by portable analyzers

- Alteration geochemistry
- Pathfinder element associations
- Development of robust matrix matched calibrations

Measurements made with the Bruker Titan 800 handheld XRF



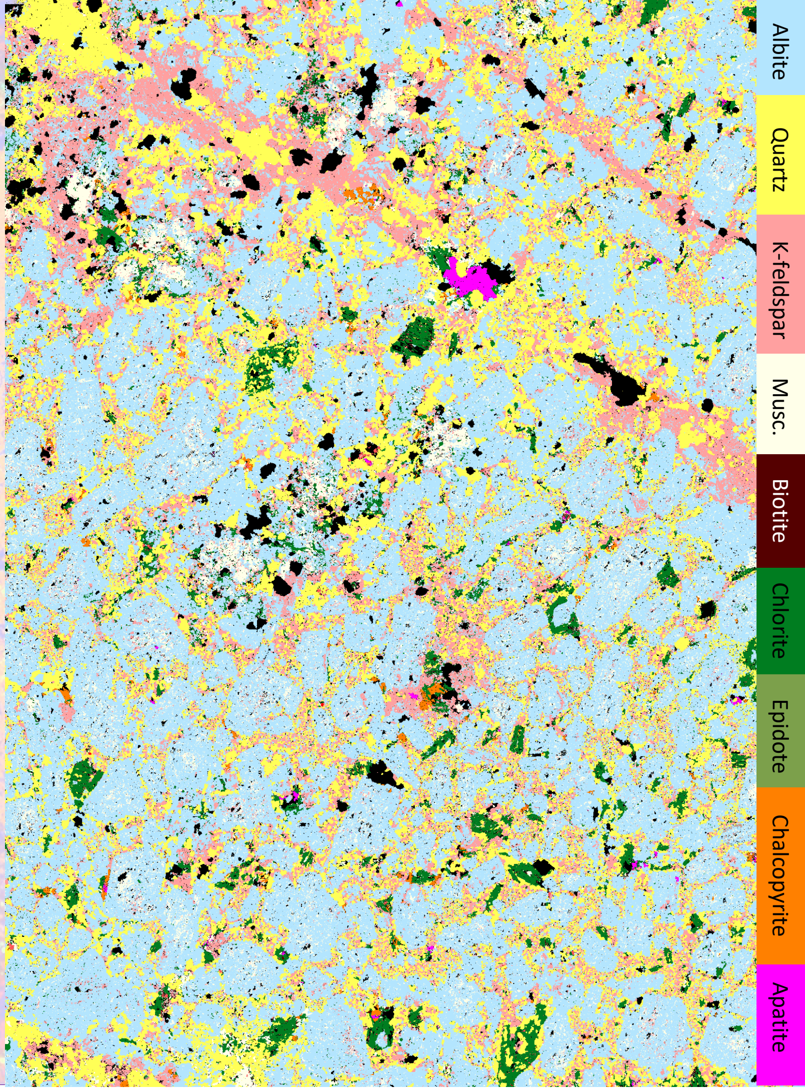
Bulk geochemistry – traditional geochemistry in exploration workflows

Thinking across scales in exploration geochemistry

Field and drill-core scales

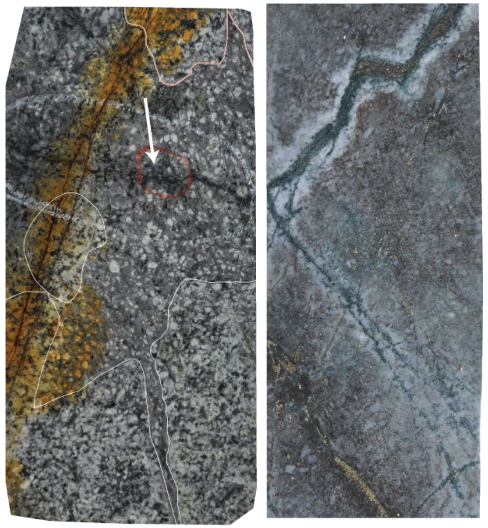
Micro-XRF

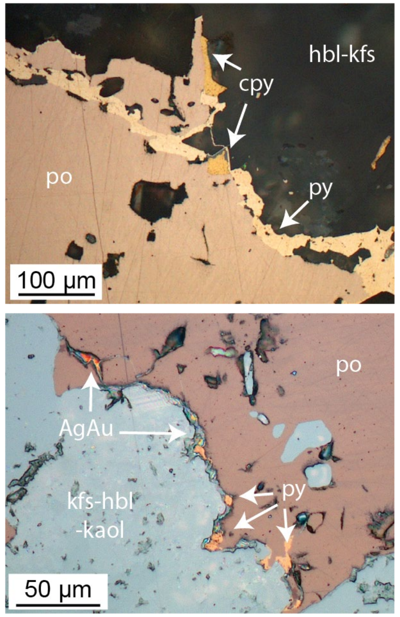
Scanning Electron Microscopy & Automated Mineralogy

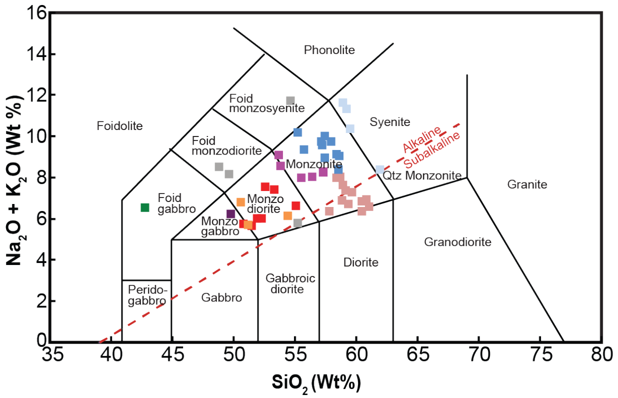


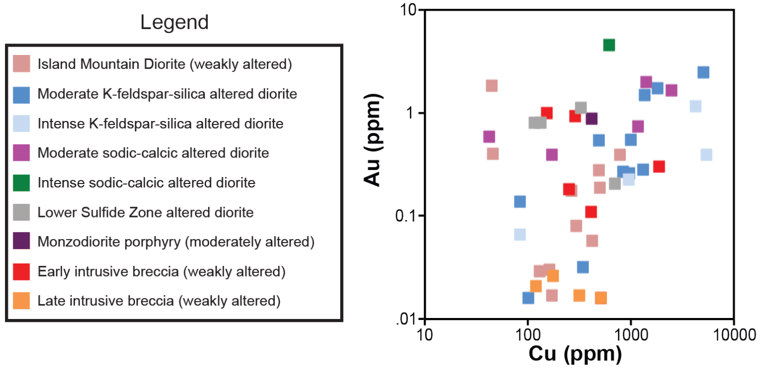
Micro-XRF

Increasing scale – geochemistry at the hand-specimen and hand lens scale









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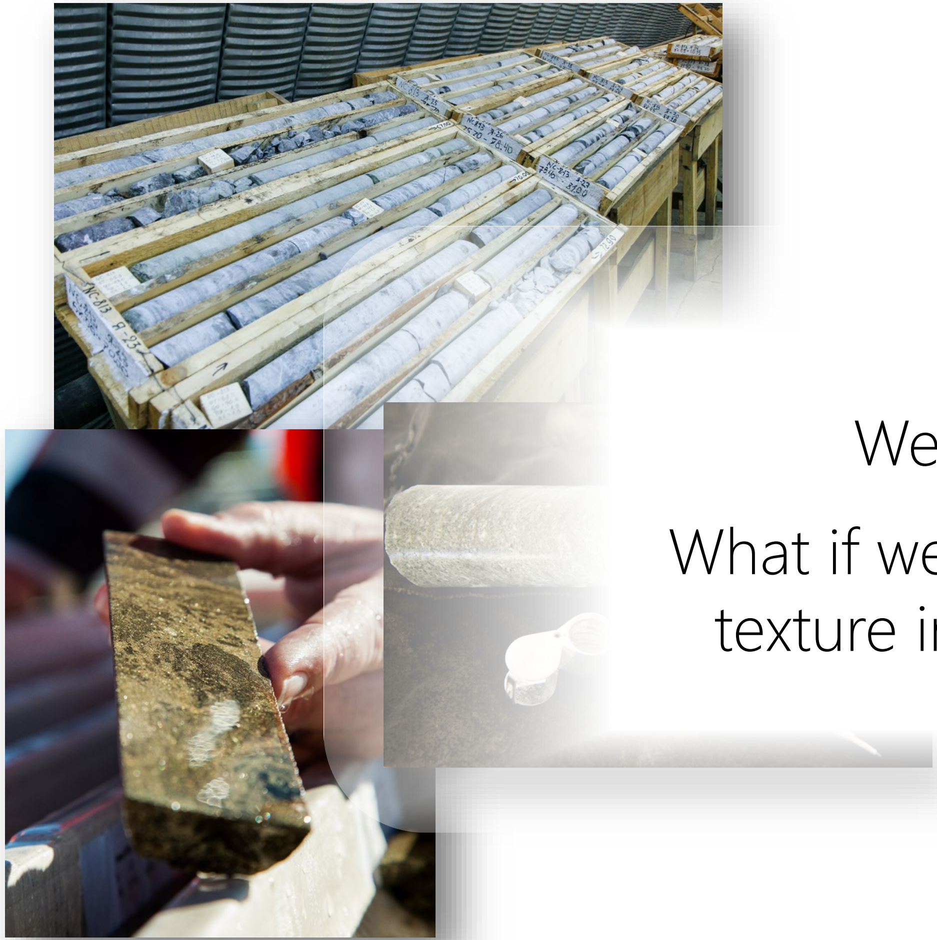
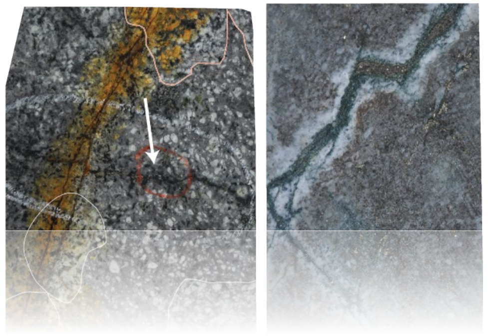
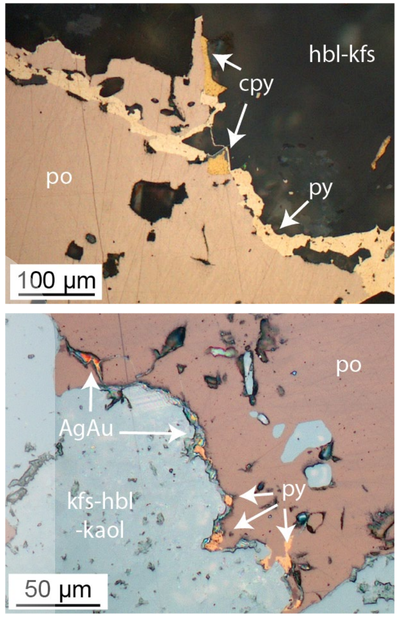
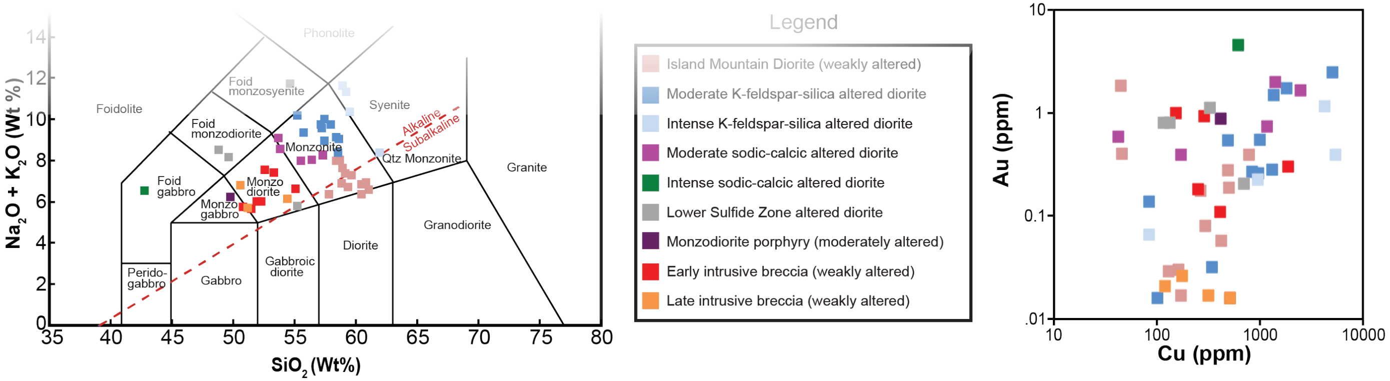






We have a gap in scale.

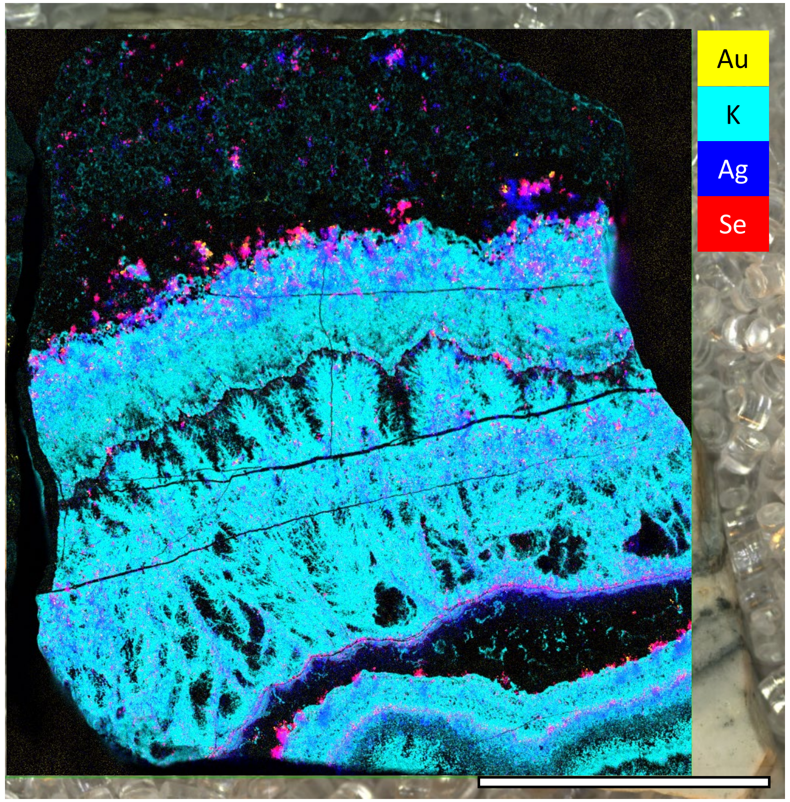
What if we can get geochemistry and texture in one place? And quickly?



Micro-XRF

Increasing scale – geochemistry at the hand-specimen and hand lens scale

Micro-XRF provides texturally constrained geochemistry at hand specimen through to optical microscope scales

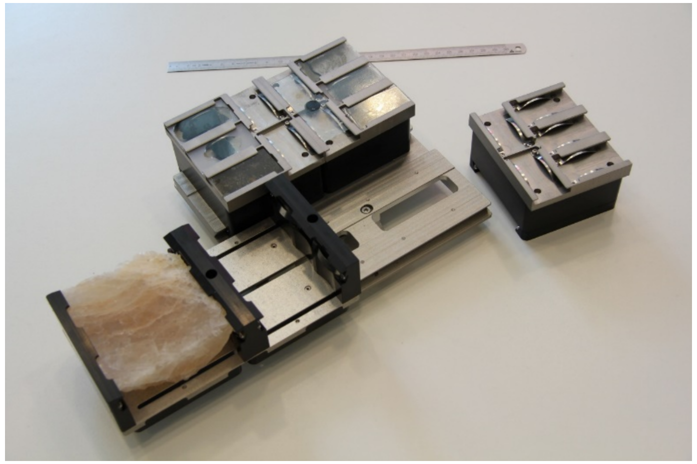


µXRF Images courtesy of Erik Tharalson, Colorado School of Mines
To see more: Tharalson et al. (2019), Minerals, 9.

Micro-XRF

Bruker Nano's M4 Tornado

- Closed chamber, benchtop energy-dispersive micro-XRF
- Spot size of <20 µm, & scanning area up to 19 x 16 cm
- Element range of <Na to U
- Minimal sample preparation – horizontal, planar surface of cut rocks and drill core
- Scan times as fast at a few hours for entire pieces of drill core
- Each pixel represents a full ED spectrum (Hypermap)



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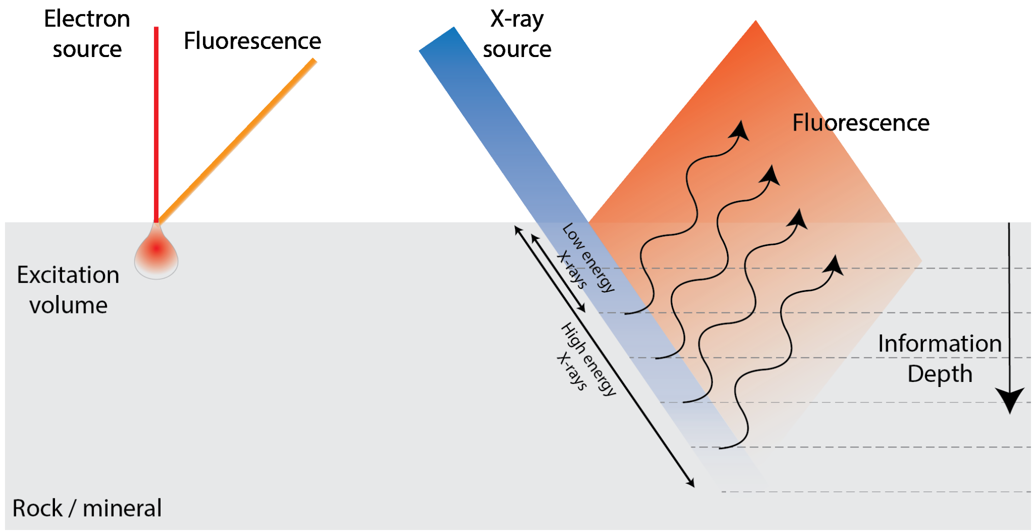
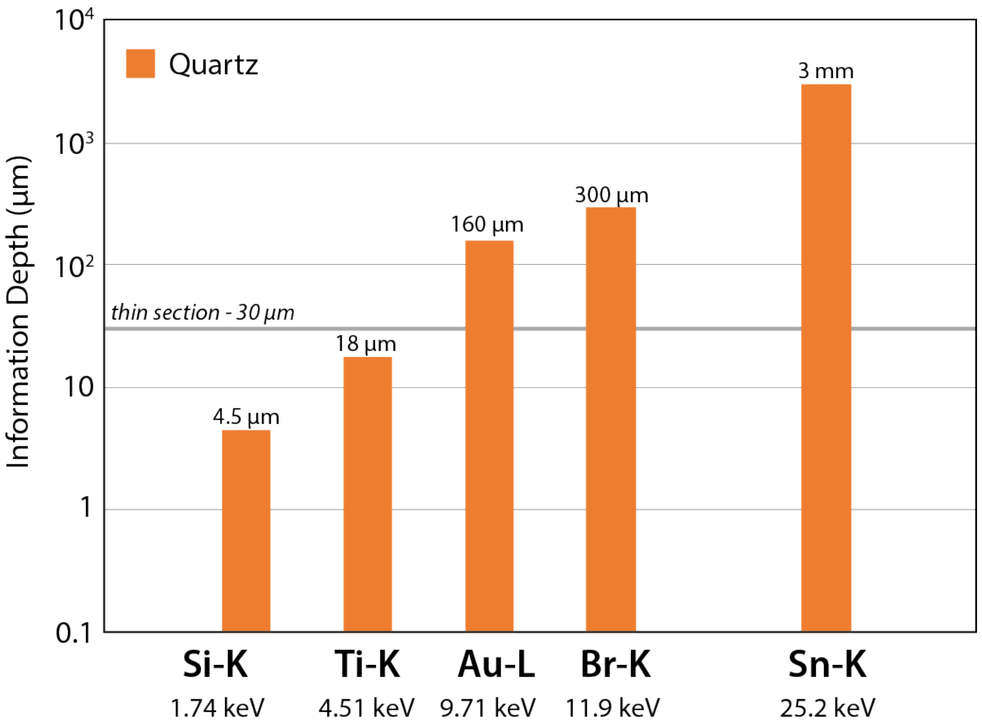
Micro-XRF

Bruker Nano's M4 Tornado

This is not an SEM

- Larger spot size (~20 um)
- Deeper depth of information



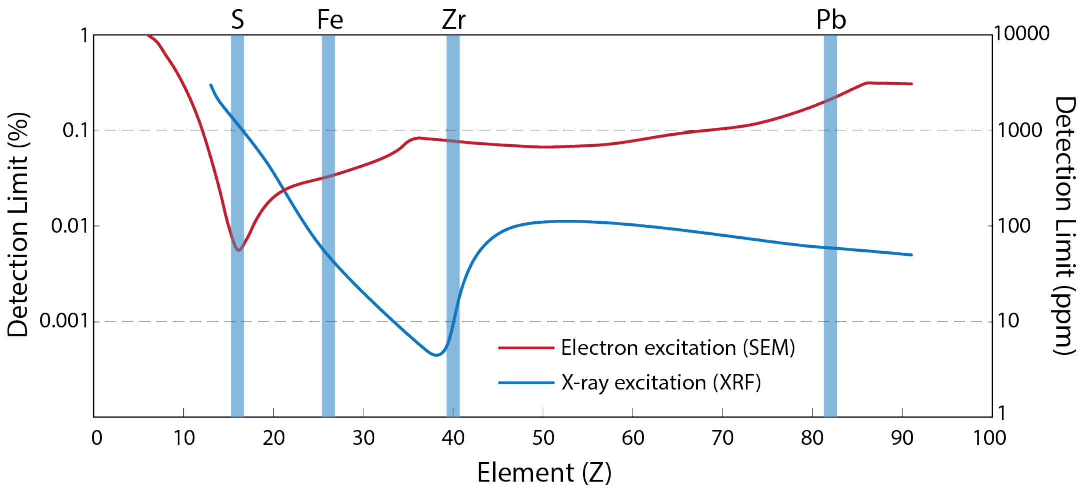


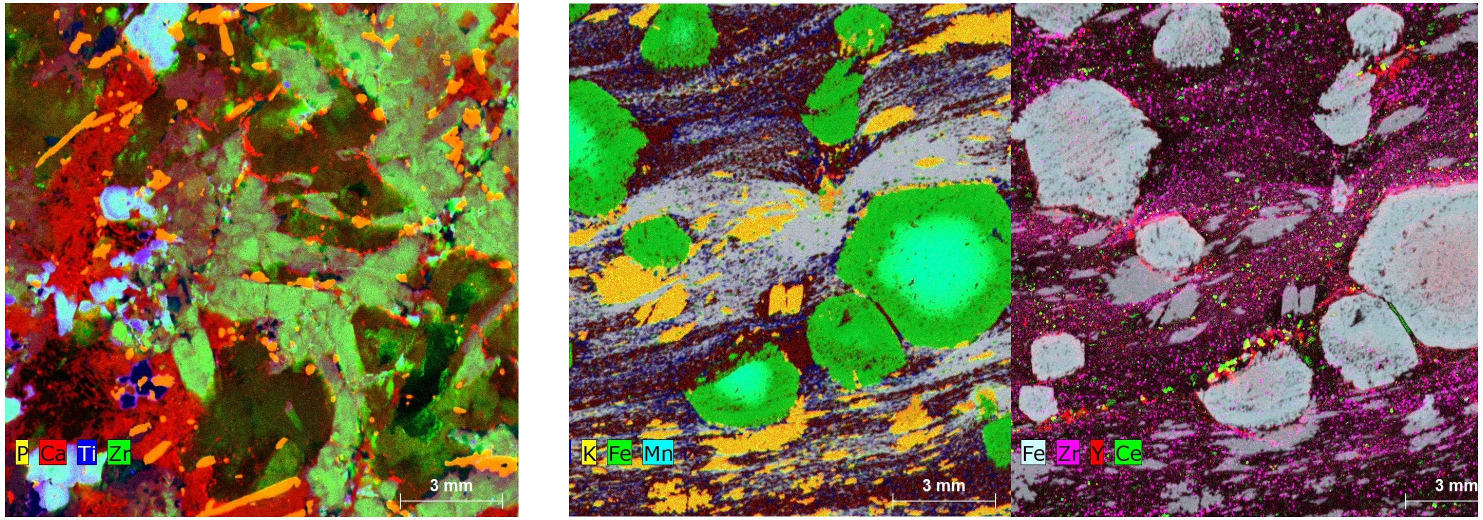
Micro-XRF

Bruker Nano's M4 Tornado

This is not an SEM

- ➢ Larger spot size (~20 um)
- ➢ Deeper depth of information
- ➢ Better excitation in the transition metals and higher energies
- ➢ Lower detection limits = we can map trace elements in minerals

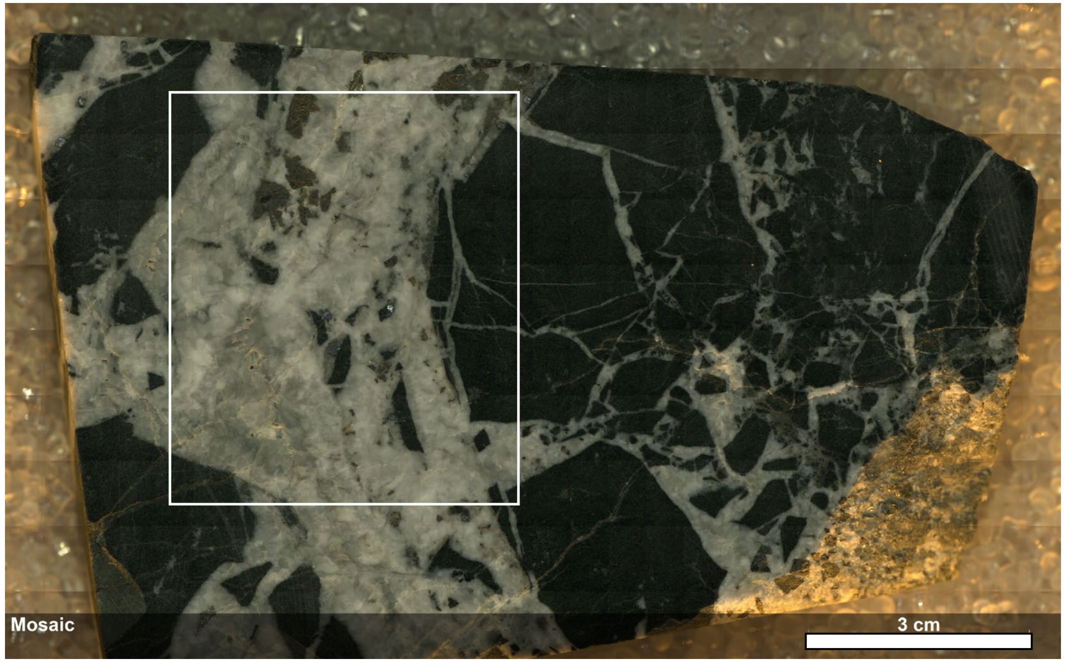




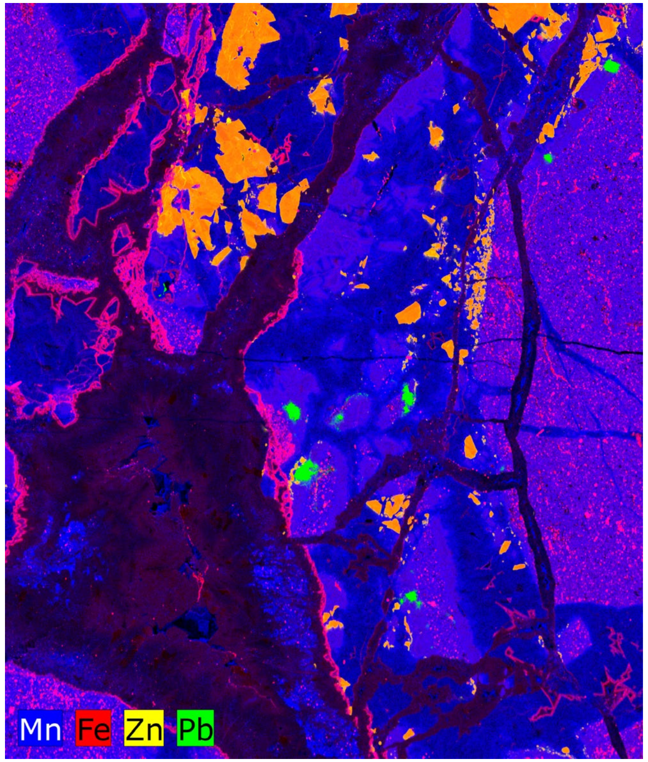
Micro-XRF

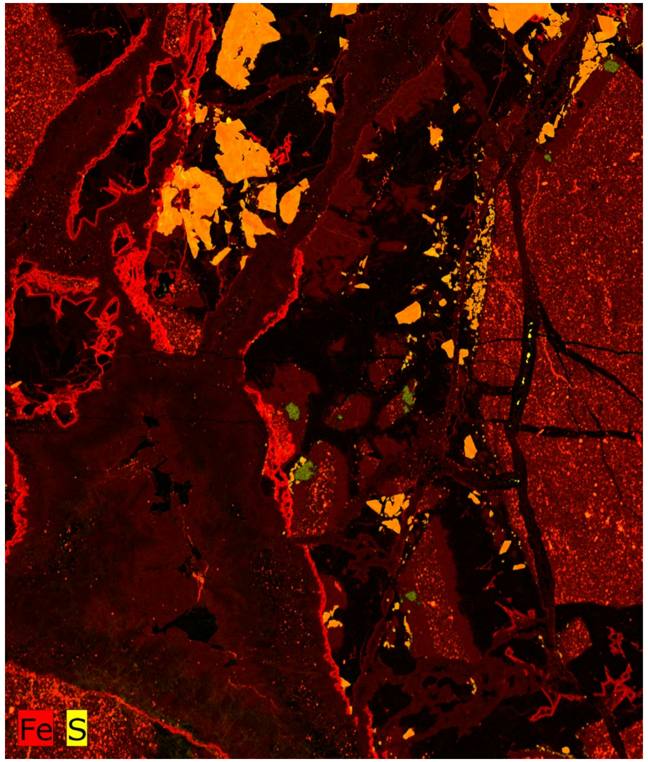
Major, minor and trace element geochemistry in context

What we can "see" with the M4 Tornado?



MVT Zn-Pb mineralization in carbonate host-rock;
Junin, central Peruvian Andes

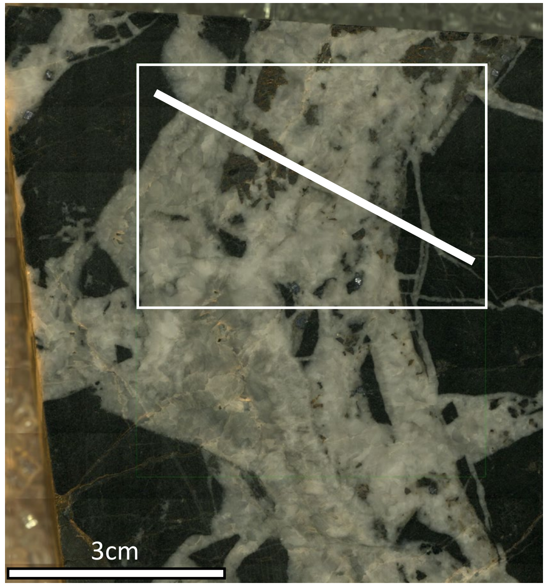


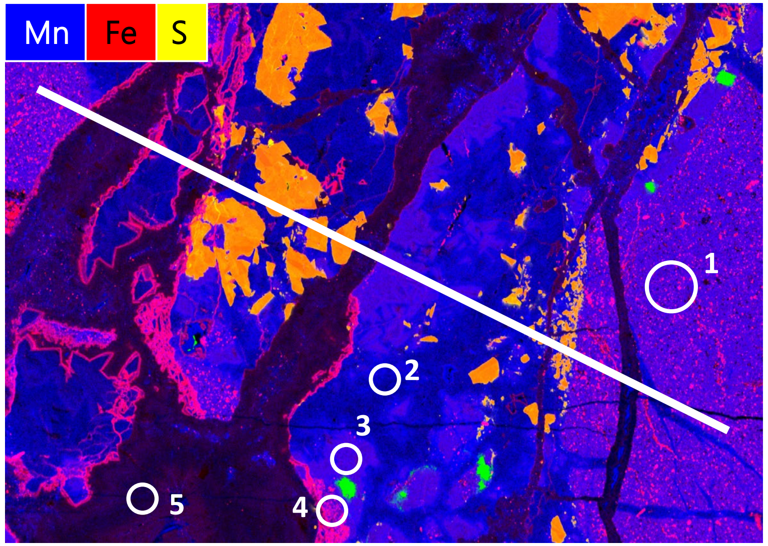


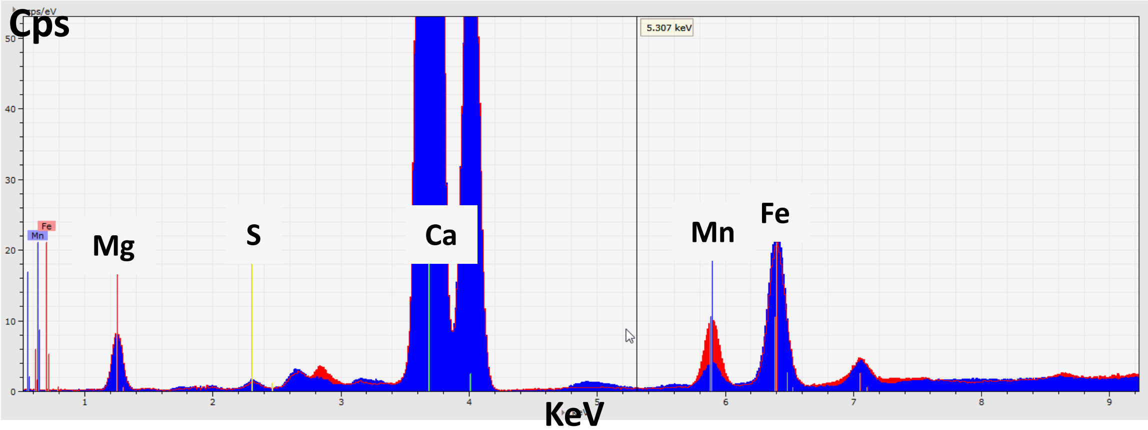
Images & data courtesy of Prof. David Leach & Raul Berruspi, Colorado School of Mines, & Compañía Minera San Ignacio de Morococha S.A.A SIMSA

Micro-XRF

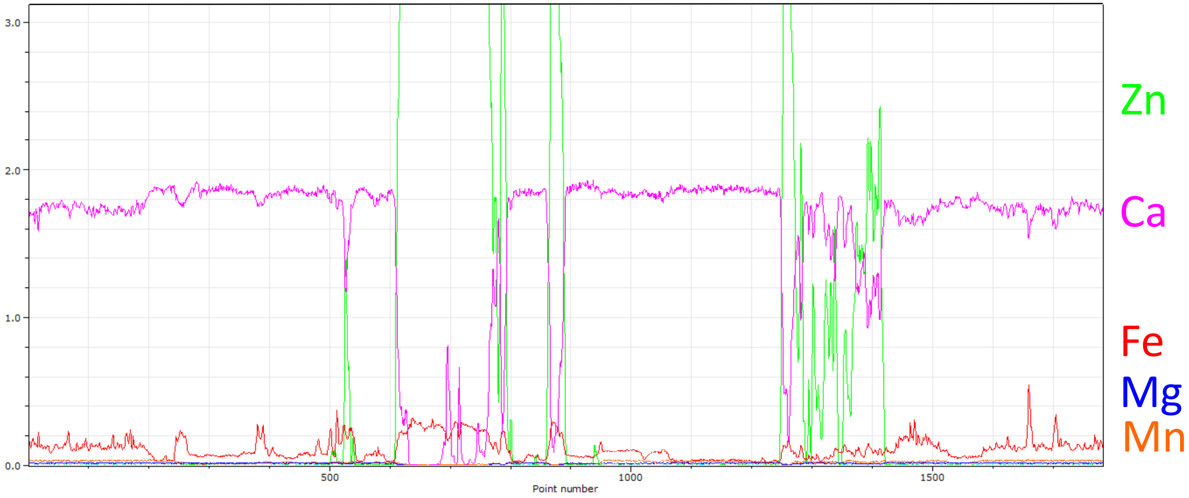
Major, minor and trace element geochemistry in context







Mass%	1	2	3	4	5
Ca	32.32	33.94	33.50	32.07	32.60
Mg	12.55	12.36	12.54	12.91	12.94
Fe	1.33	0.31	0.99	2.69	0.70
Mn	0.37	0.36	0.42	0.29	0.15
Si	1.26	0.00	0.06	0.82	0.03
Al	0.26	0.16	0.12	0.29	0.09
K	0.11	0.02	0.00	0.14	0.03
Ti	0.04	0.00	0.02	0.04	0.00
Sr	0.03	0.02	0.02	0.03	0.03
Ag	0.01	0.01	0.00	0.00	0.00
Zn	0.00	0.01	0.01	0.00	0.01
Pb	0.03	0.01	0.03	0.02	0.03
Ce	0.03	0.05	0.03	0.02	0.01
Cl	0.05	0.13	0.09	0.07	0.08
S	0.28	0.00	0.03	0.44	0.08

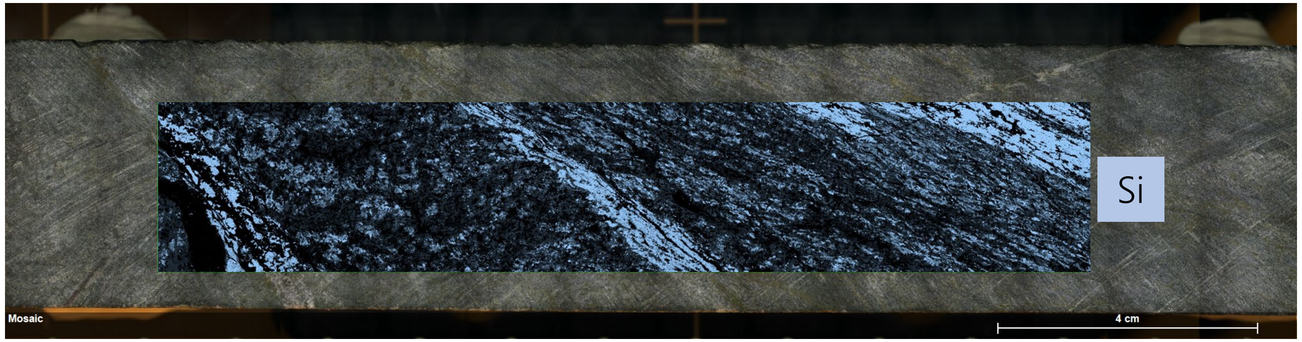


Images & data courtesy of Prof. David Leach & Raul Berruspi, Colorado School of Mines, & Compañía Minera San Ignacio de Morococha S.A.A SIMSA

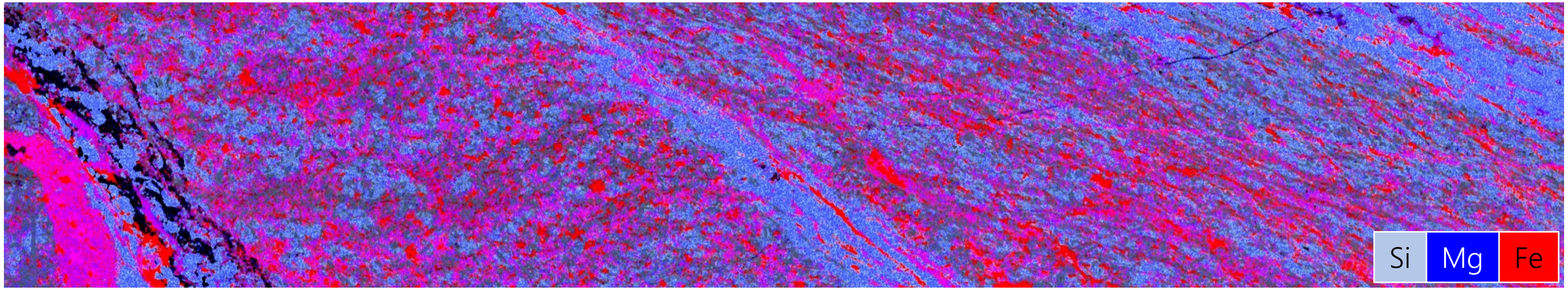
Micro-XRF

Major, minor and trace element geochemistry in context

Altered greenstone, shear-zone hosted orogenic gold

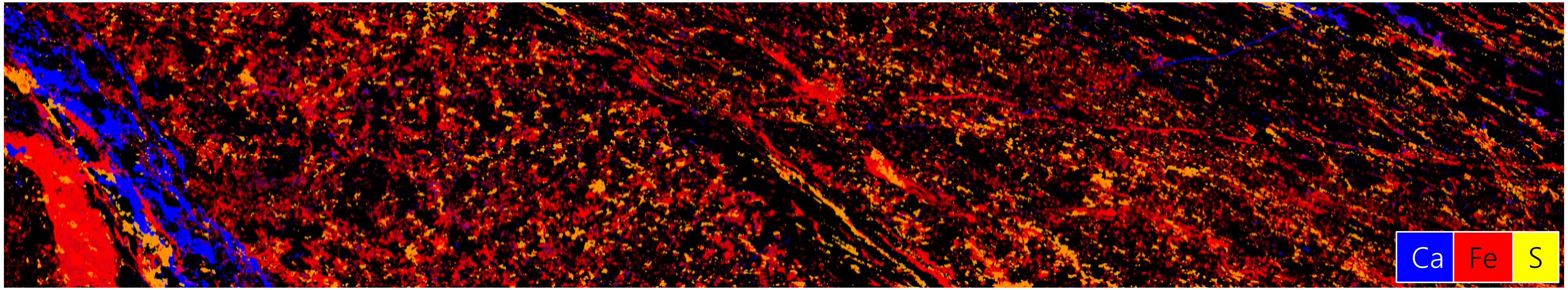


Quartz veining, silicification



Chlorite (pink)

Siderite + Fe-sulfides (red)



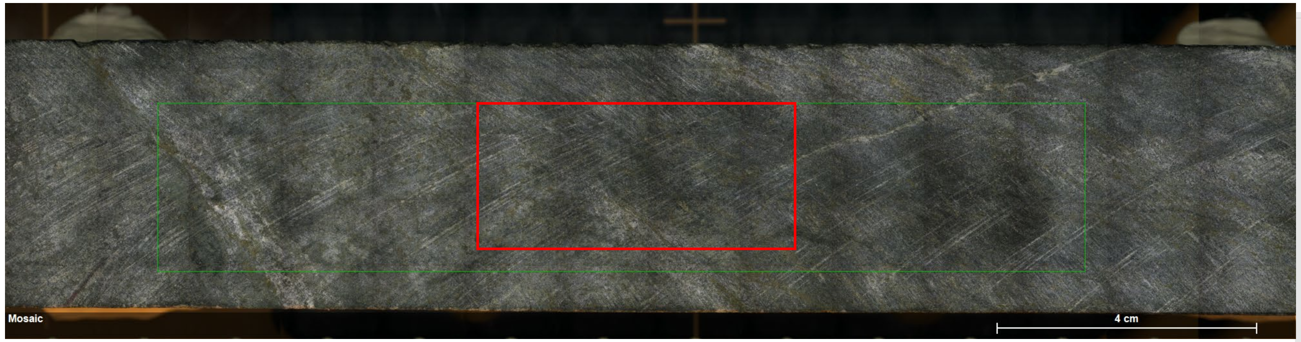
Fe Sulfides (orange)

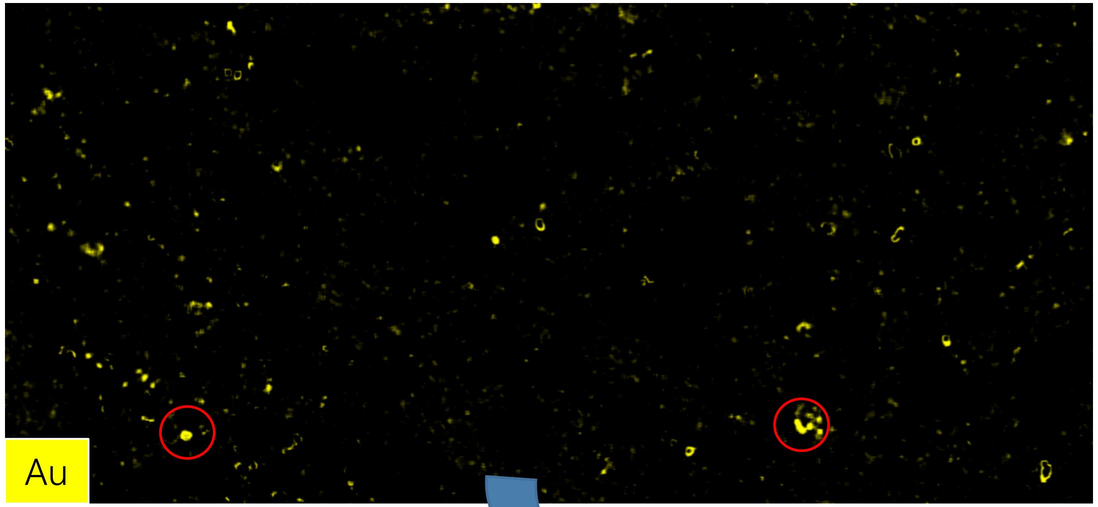
Calcite (blue), Siderite & other Ca-Fe carbonates (red in veins)

Images & data courtesy of Ardiden Ltd & Portable Spectral Services (Perth, Aus)

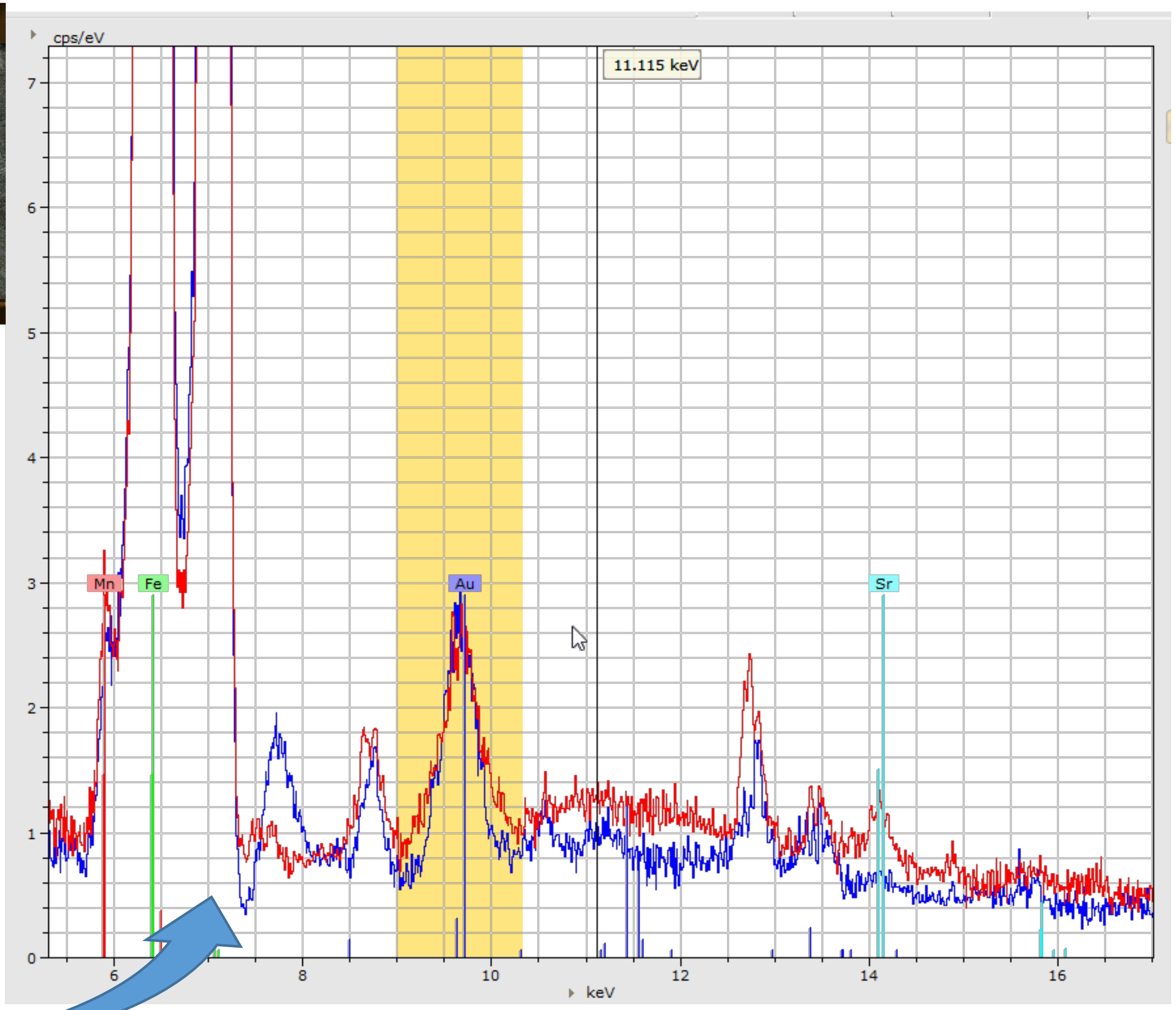
Micro-XRF

Major, minor and trace element geochemistry in context





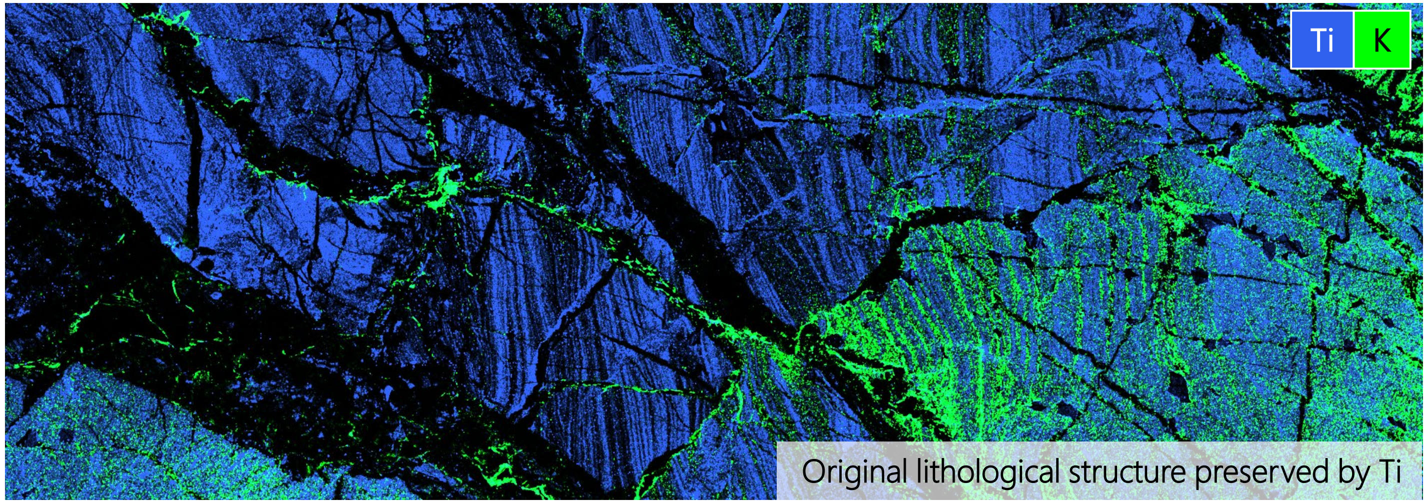
Visualizing the gold



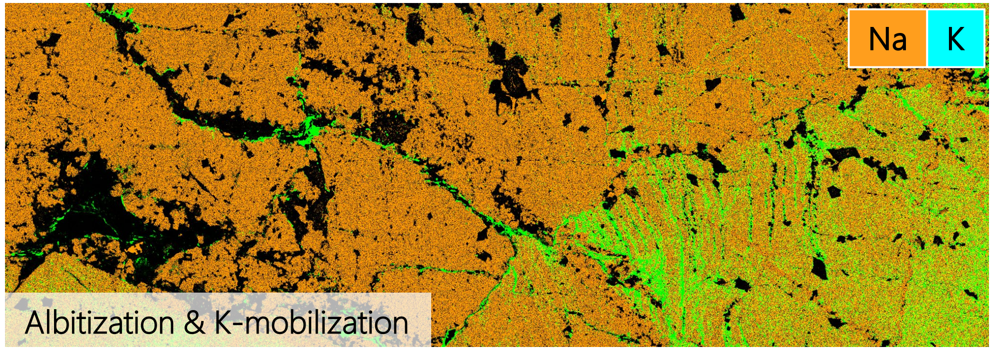
Images & data courtesy of Ardiden Ltd & Portable Spectral Services (Perth, Aus)

Micro-XRF

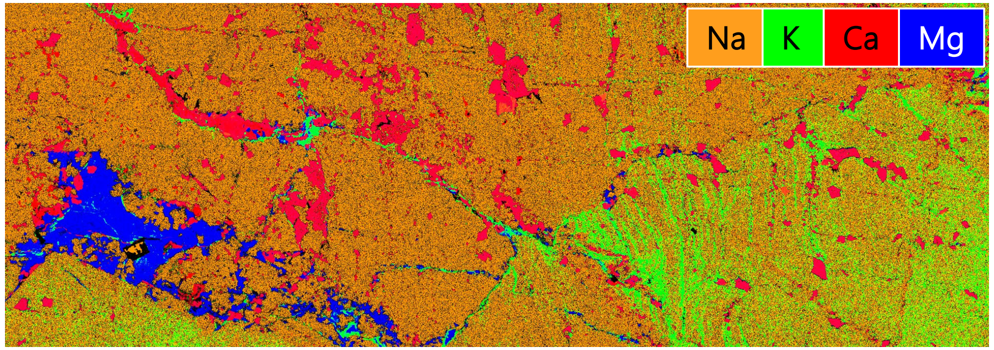
Major, minor and trace element geochemistry in context

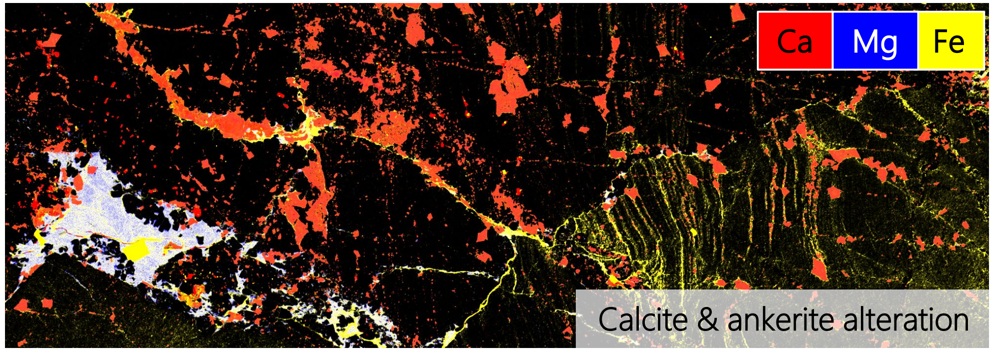


Original lithological structure preserved by Ti



Albitization & K-mobilization





Calcite & ankerite alteration

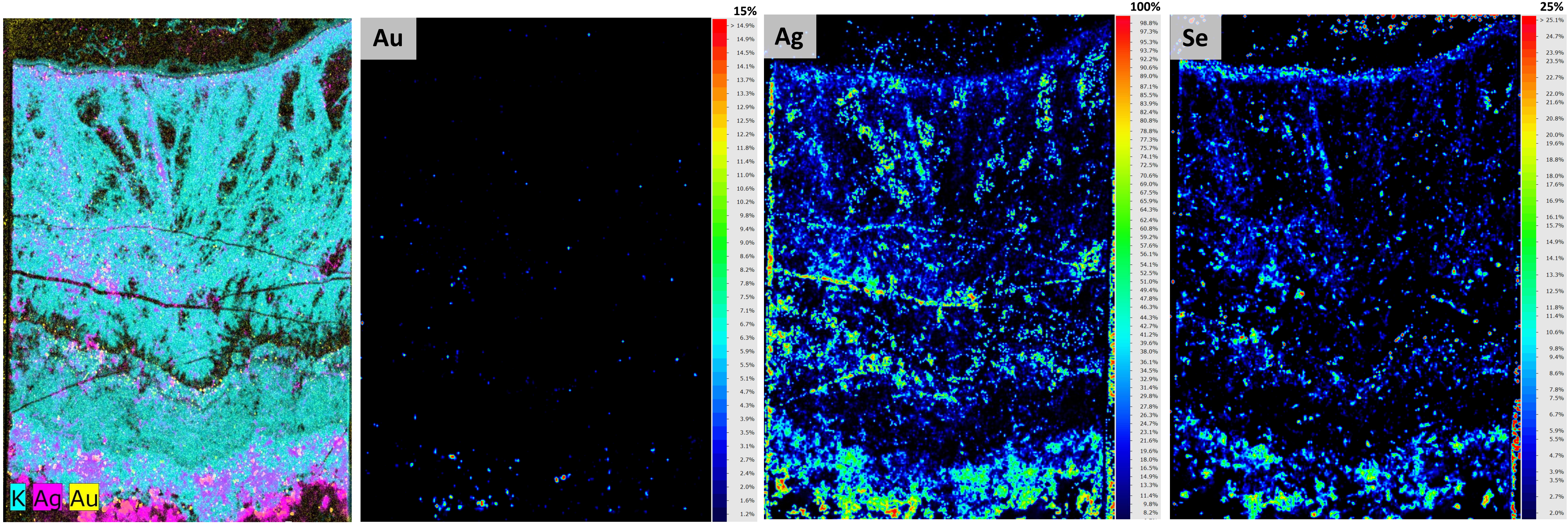
Albitized sedimentary host rocks to Au-Co mineralization, Kuusamo, Finland.

Images & data courtesy of Dr. Andrew Menzies (Bruker Nano), Drs. Alan Butcher & Peter Sorjonen-Ward, GTK

Micro-XRF

Quantification – points, traverses, areas, and whole maps

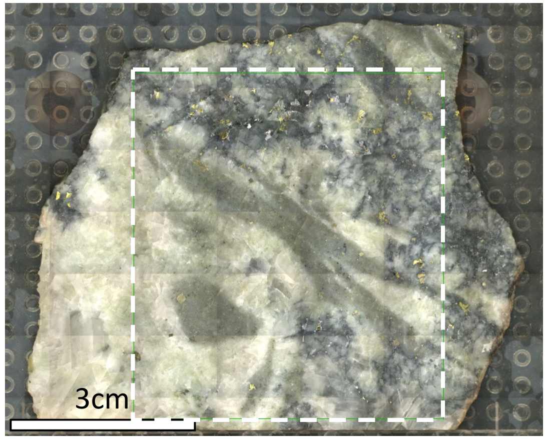
Full quantification can applied to entire maps, pixel by pixel



Quantification aided by matrix specific type standardization and may be exported for further analysis

Micro-XRF

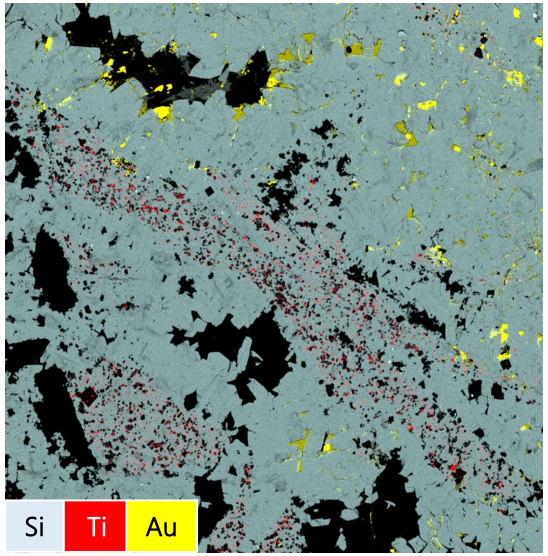
Quantification – points, traverses, areas, and whole maps

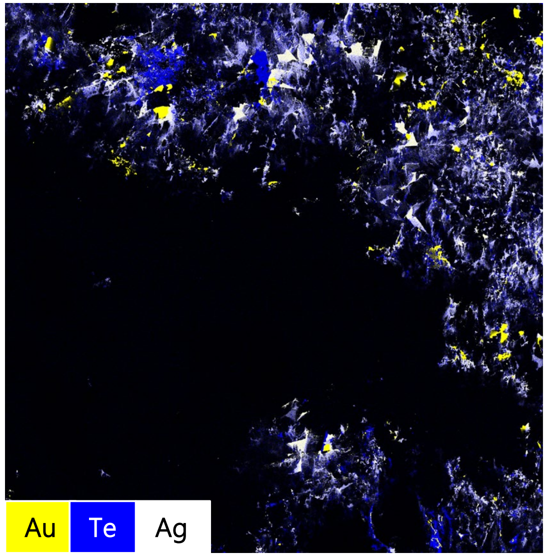


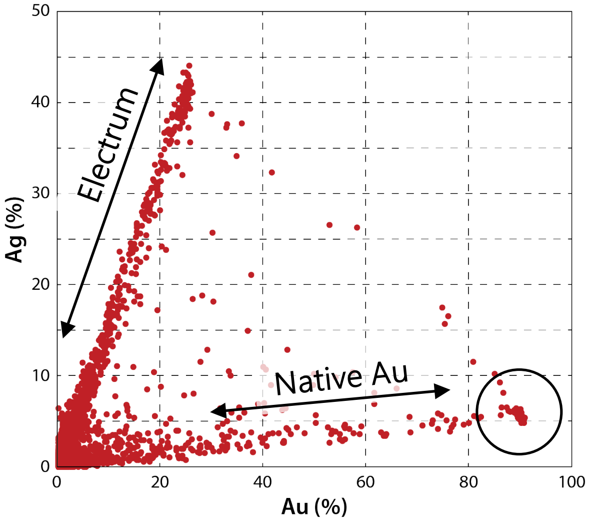
Assessing gold-silver-tellurium mineralization relationships in hydrothermal quartz veins

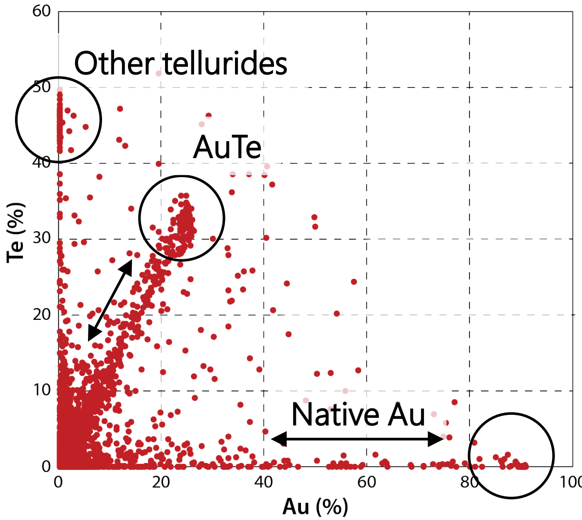
Gold occurs in association with Ag and Te

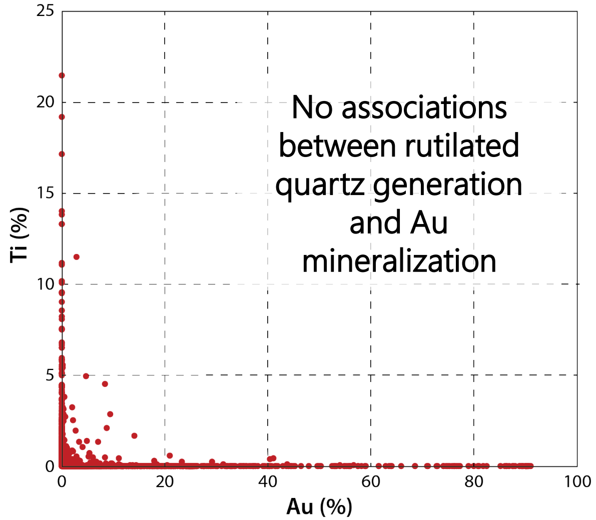
- Native Au
- Electrum
- Au-tellurides











Images & data courtesy of Portable Spectral Services (Perth, Aus)

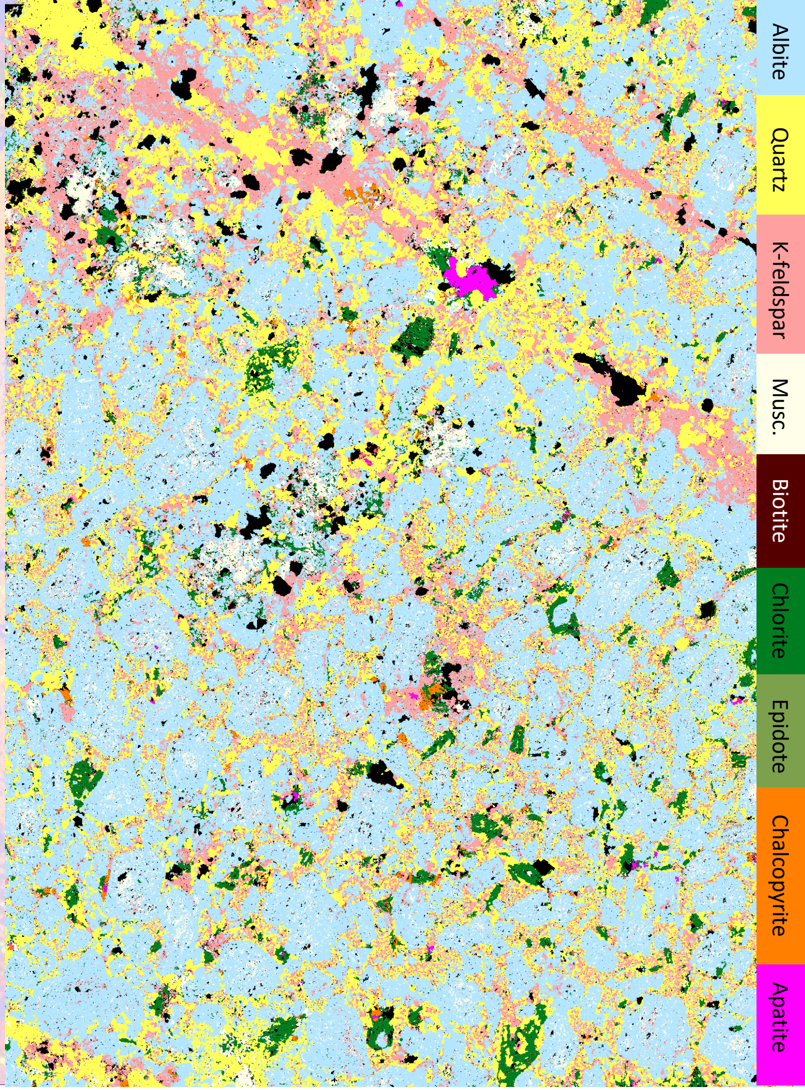
Geochemistry and mineral exploration

Thinking across scales in exploration geochemistry

Field and drill-core scales

Micro-XRF

Scanning Electron Microscopy & Automated Mineralogy

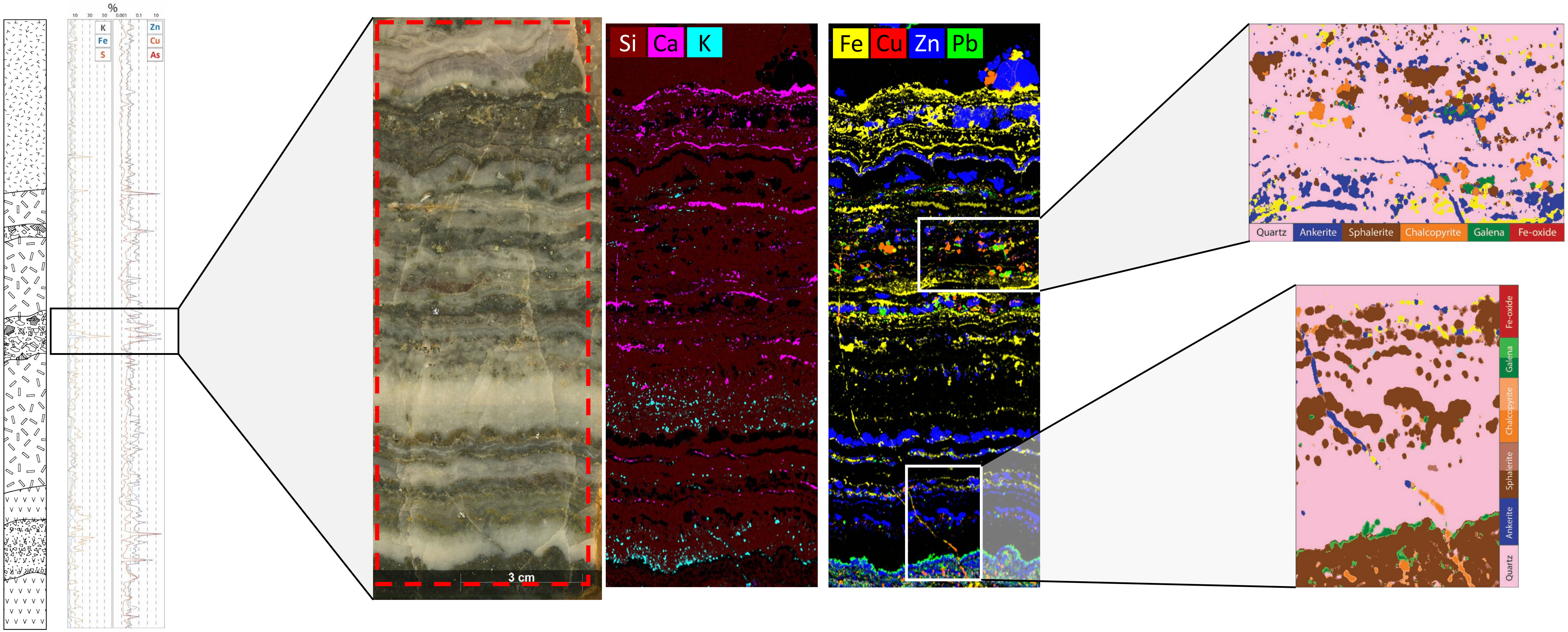


BRUKER

Scanning electron microscopy

Linking the micro to the macro

Where is SEM in the exploration workflow today?



Intermediate sulfidation epithermal deposit, Arista, Mexico; µXRF images courtesy of Garrett Gissler & Prof. Thomas Monecke, Colorado School of Mines, & Gold Resource Corp.

Scanning electron microscopy

Linking the micro to the macro

Scanning electron microscopy and automated mineralogy

- Doesn't comprise a large footprint in exploration
- Perceived cost
- Perceived scalability issues

Provides the most detailed view and brings the mineralogy back to geochemistry

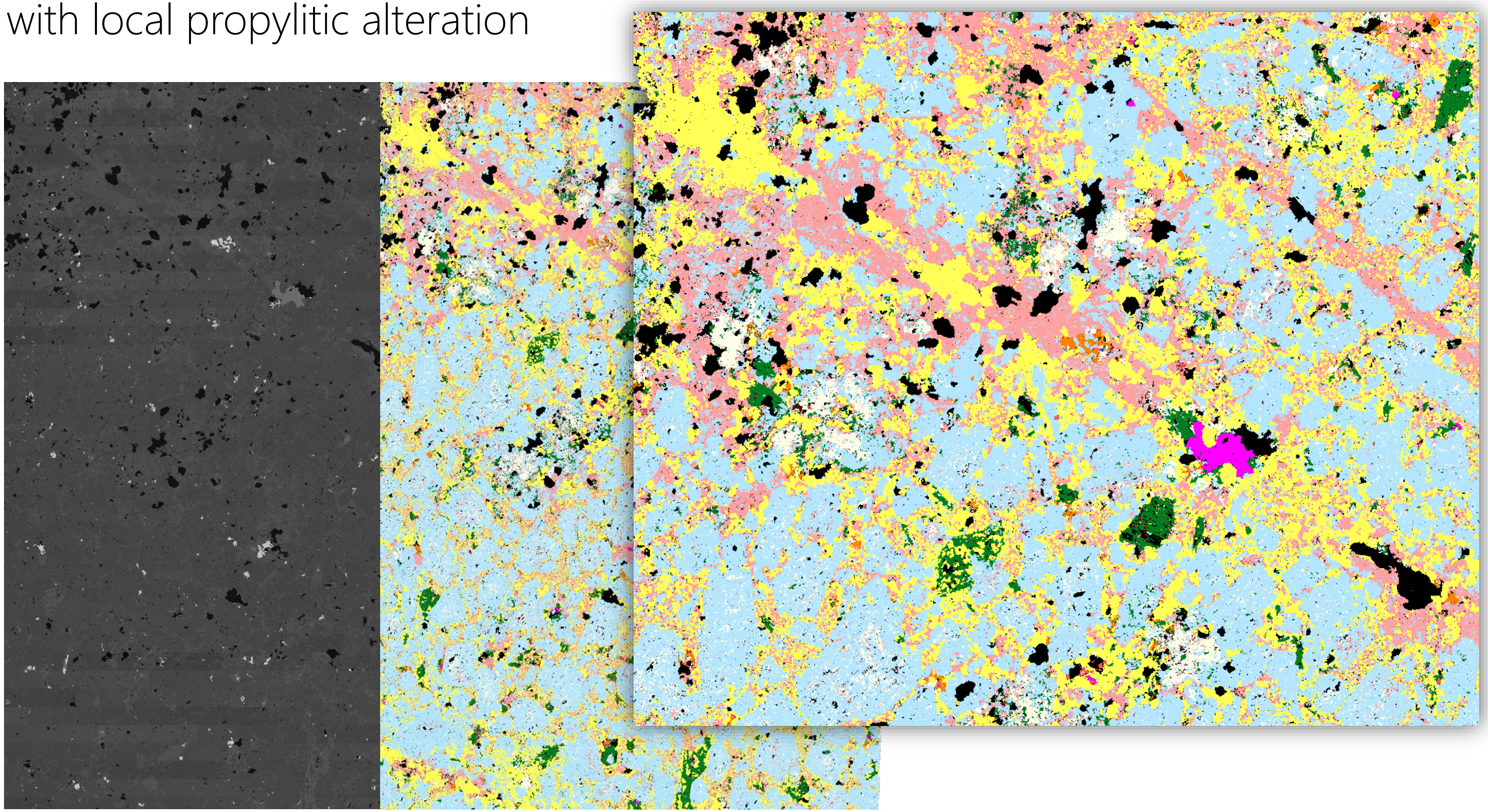
- More accessible than ever (small footprint, field deployable SEMs)
- Sample target refinement by other techniques (µXRF, hyperspectral core scanning)

Hitachi FlexSEM 1000

AMICS – Advanced Mineral Identification & Characterization System

Bruker's advanced automated mineralogy solution

Qtz-Kfs veins in a copper porphyry
with local propylitic alteration

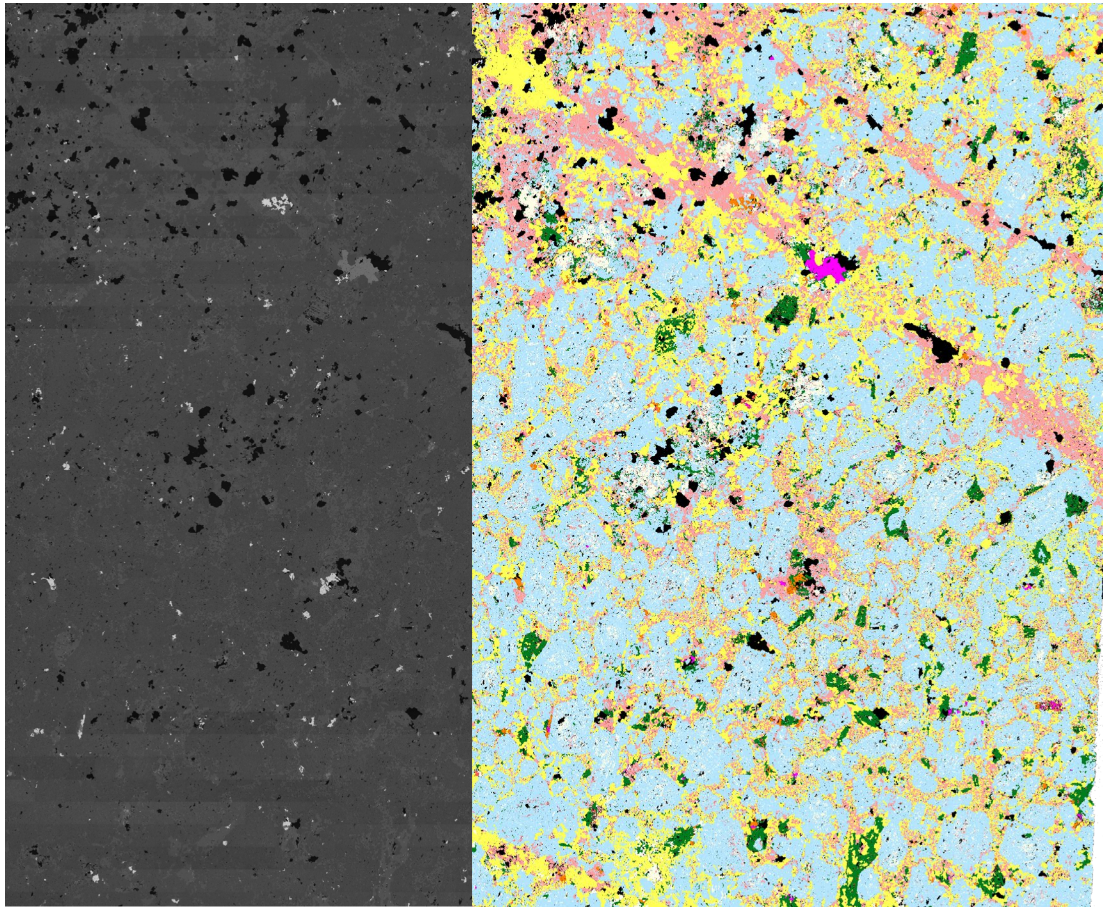


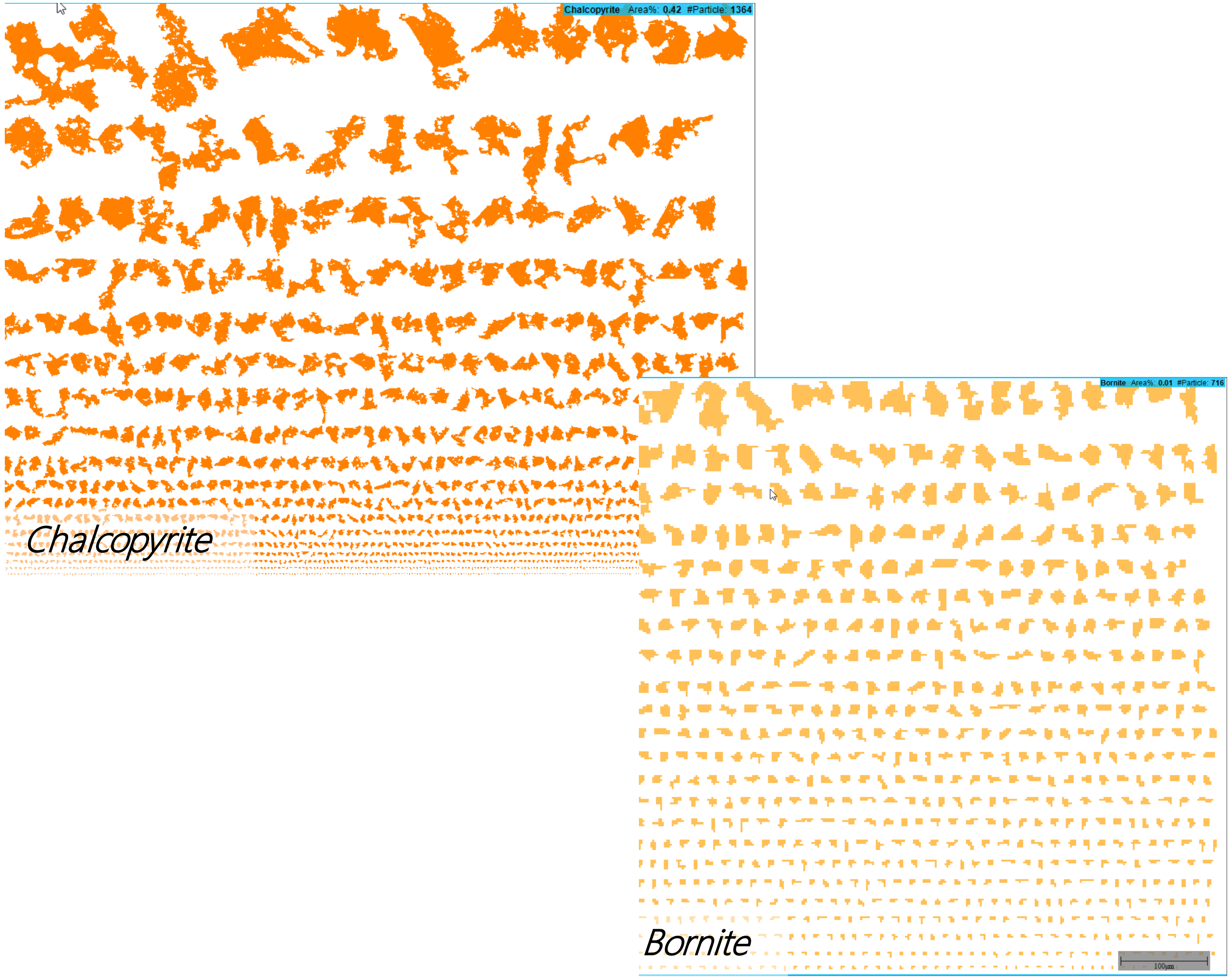
	Wt%	Area%	Area (µ2)
Albite	47.42	46.11	405507536
Quartz	22.66	22.04	193803843
Orthoclase	15.40	15.32	134766216
Muscovite	7.17	6.48	56969081
Chlorite	4.16	3.78	33251880
Epidote	0.00	0.00	8590
Biotite	0.14	0.12	1053071
Kaolinite	0.02	0.02	132321
Zircon	0.01	0.01	52563
Apatite	0.24	0.19	1691494
Other Accessory Minerals	0.28	0.17	1485786
Pyrite	0.00	0.00	5924
Chalcopyrite	0.70	0.42	3735439
Chalcocite	0.00	0.00	459
Bornite	0.02	0.01	83475
Other (pores, fractures)	1.78	5.32	46826622

AMICS – Advanced Mineral Identification & Characterization System

Bruker's advanced automated mineralogy solution

Qtz-Kfs veins in a copper porphyry
with local propylitic alteration



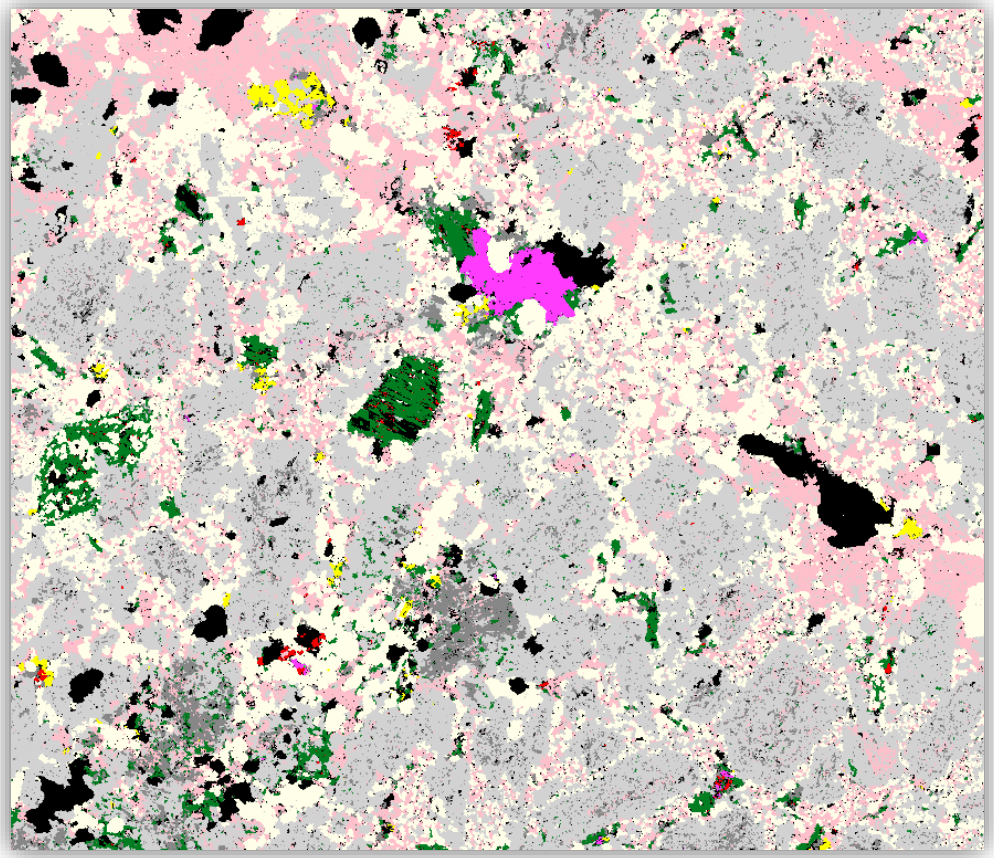


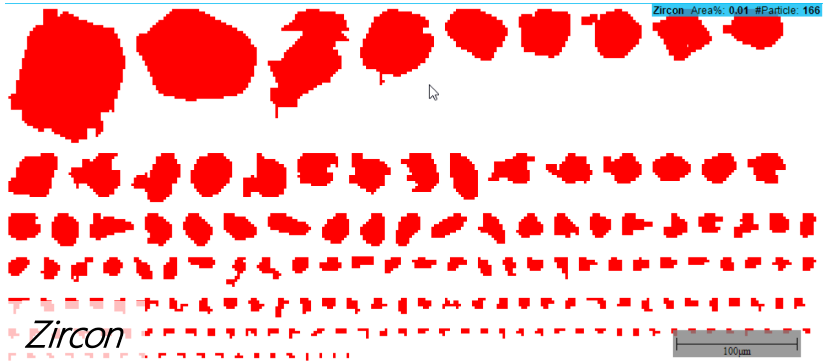
AMICS – Advanced Mineral Identification & Characterization System

Bruker's advanced automated mineralogy solution

Qtz-Kfs veins in a copper porphyry
with local propylitic alteration

- Quartz
- Orthoclase
- Biotite
- Chlorite
- Other Silicates
- Sulfides
- Apatite
- Rutile
- Zircon
- Titanite
- Epidote_2
- Monazite_Ce
- Other





Textural context of accessory minerals – tracing fertility at intrusion, district and arc scales

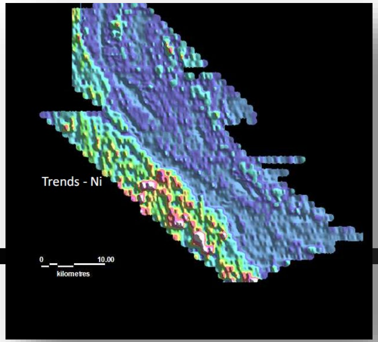
Linking back across scales

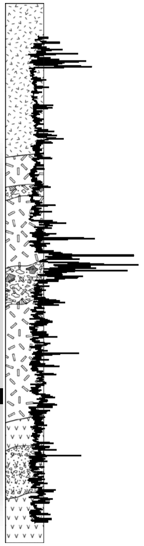
Summary

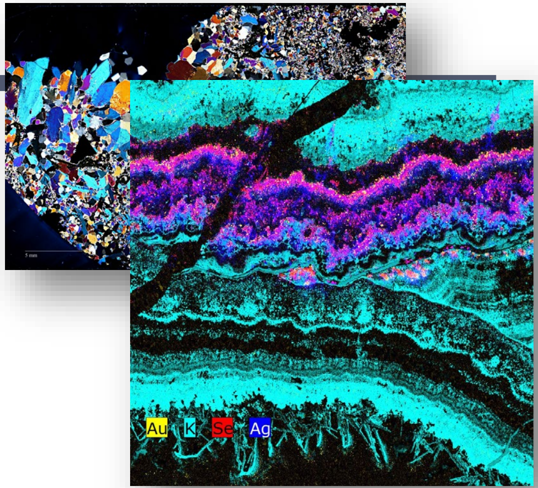
Centimeter to Kilometer
Faster field geochemistry with pXRF and better pathfinder models.

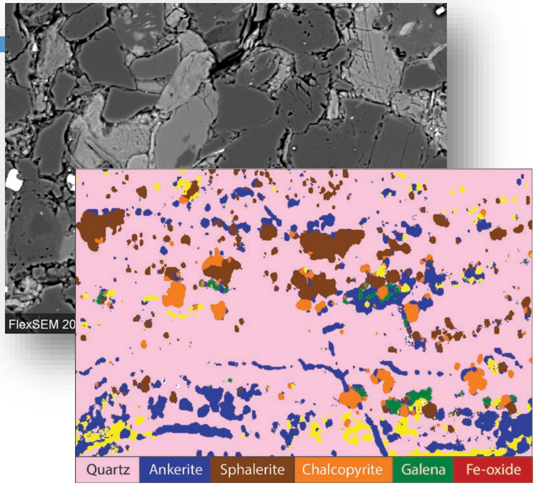
Millimeter to Centimeter
Elemental geochemistry and mineralogy at the scale of optical petrology.

Micron to Millimeter
Faster, automated, and field deployed automated mineralogy





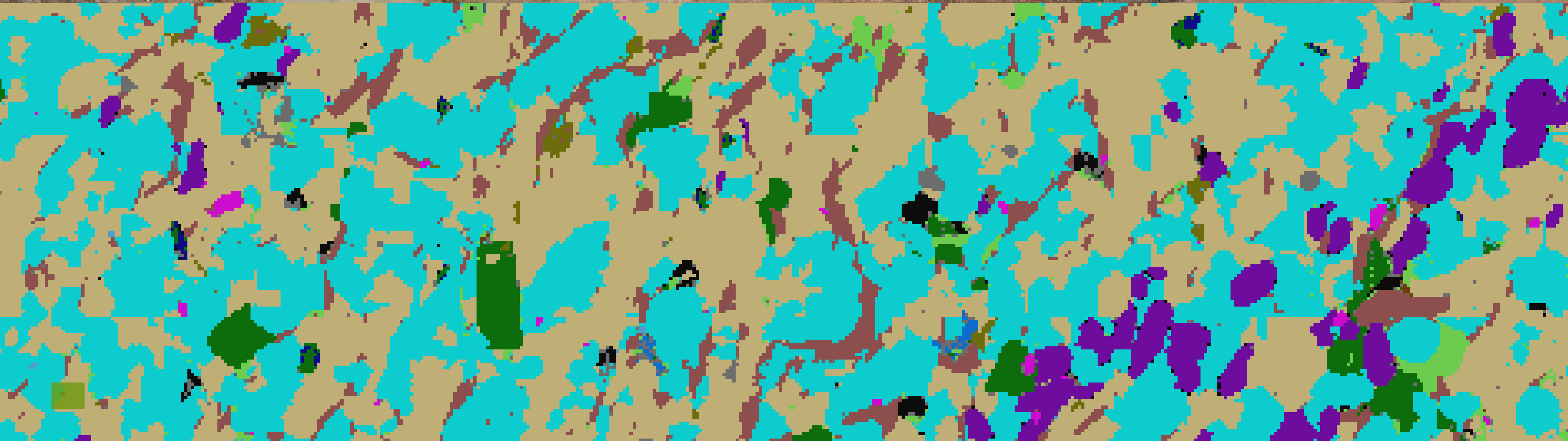




1000 m | 100 m | 10 m | 100 mm | 10 mm | 1 mm

10 km | 1 km | 1000 cm | 100 cm | 10 cm | 1000 µm | 100 µm | 10 µm | 1 µm


Questions?



M4 Technical Specs

Subtitle

30 W micro-focus Rh tube with polycapillary lens
for excitation spot sizes < 20 µm (for Mo-Kα)

Optional 40 W micro-focus W tube with collimator
for excitation of 'heavy' elements, embedded in lighter matrices

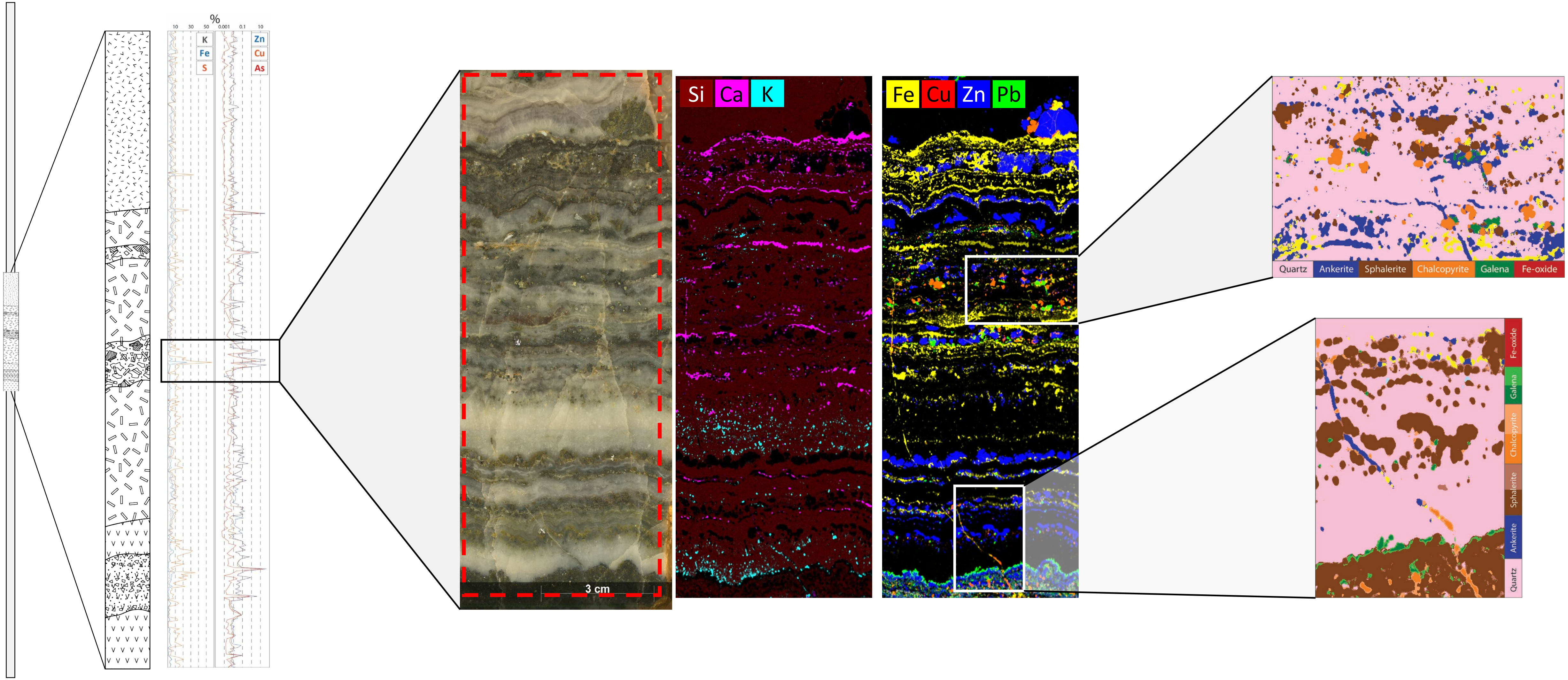
Up to two Silicon drift detectors (SDD)
with 30 or 60 mm² active area each
energy resolution < 145 eV
(for Mn-Kα @ 130 kcps throughput)
Optional light element window (LEW)

Sealed sample chamber with adjustable pressure between 1 mbar and atmospheric pressure for detecting elements down to Na (down to C with LEW)

Sample stage with measureable area of 200 mm x 160 mm, maximum sample height 120 mm, maximum sample weight 7 kg, and sample stage speed up to 100 mm/s, minimum step size 4 µm

Geochemistry & mineral exploration

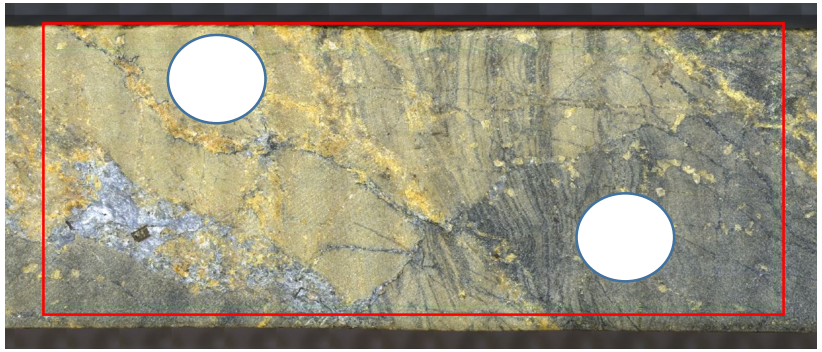
Where does Bruker fit?



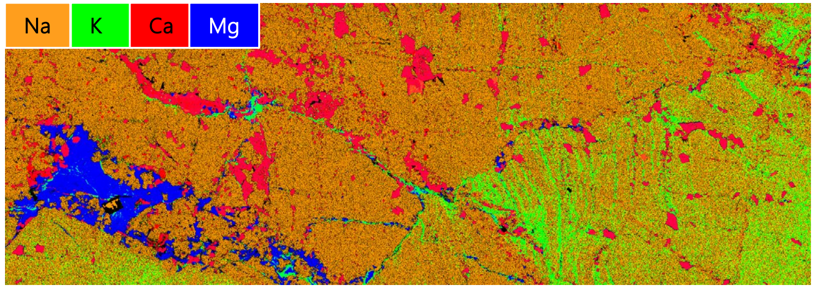
µXRF images & data courtesy of Garrett Gissler & Prof. Thomas Monecke, Colorado School of Mines

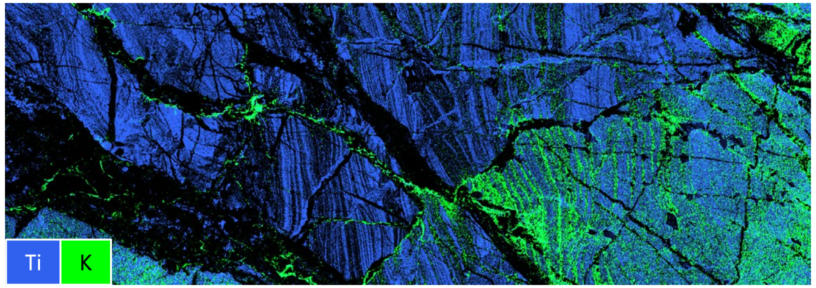
Micro-XRF

Quantification – points, traverses, areas, and whole maps

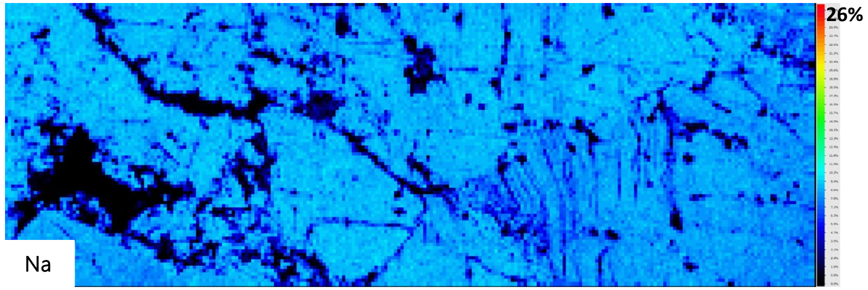


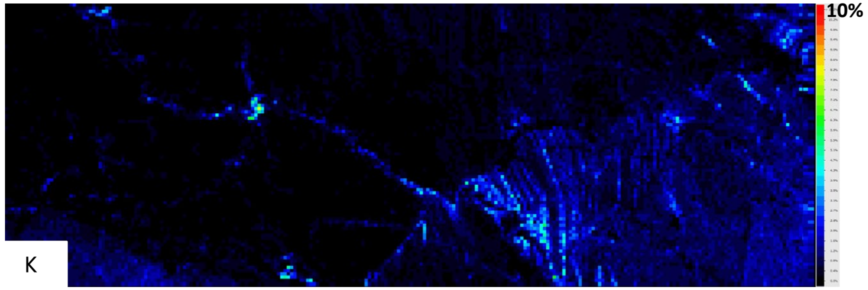
Fully quantified compositions can be used on the pixel (mineral) scale or bulk (area) scale



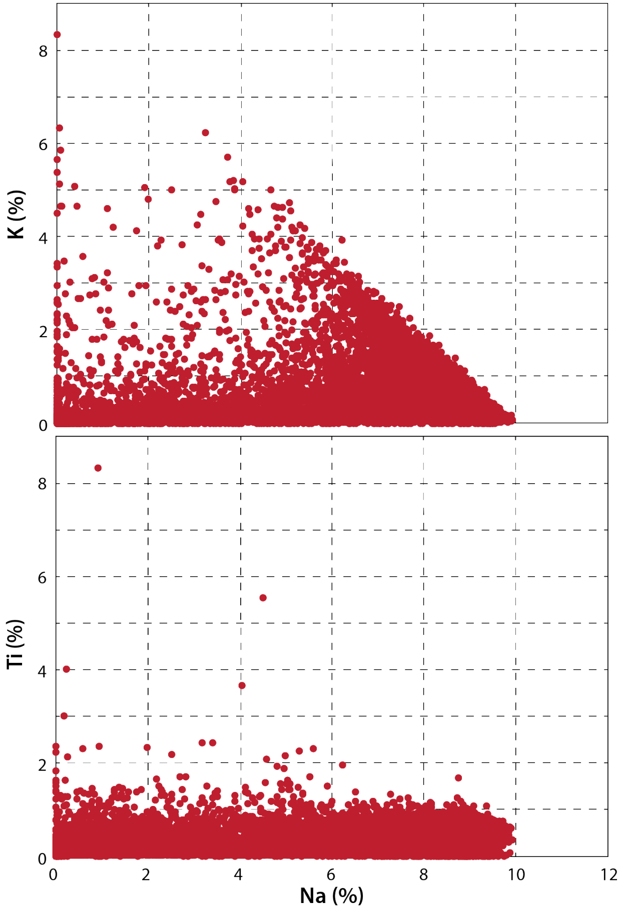


Element map (count intensity)





Quantified maps (%)



Element composition (%) for each pixel