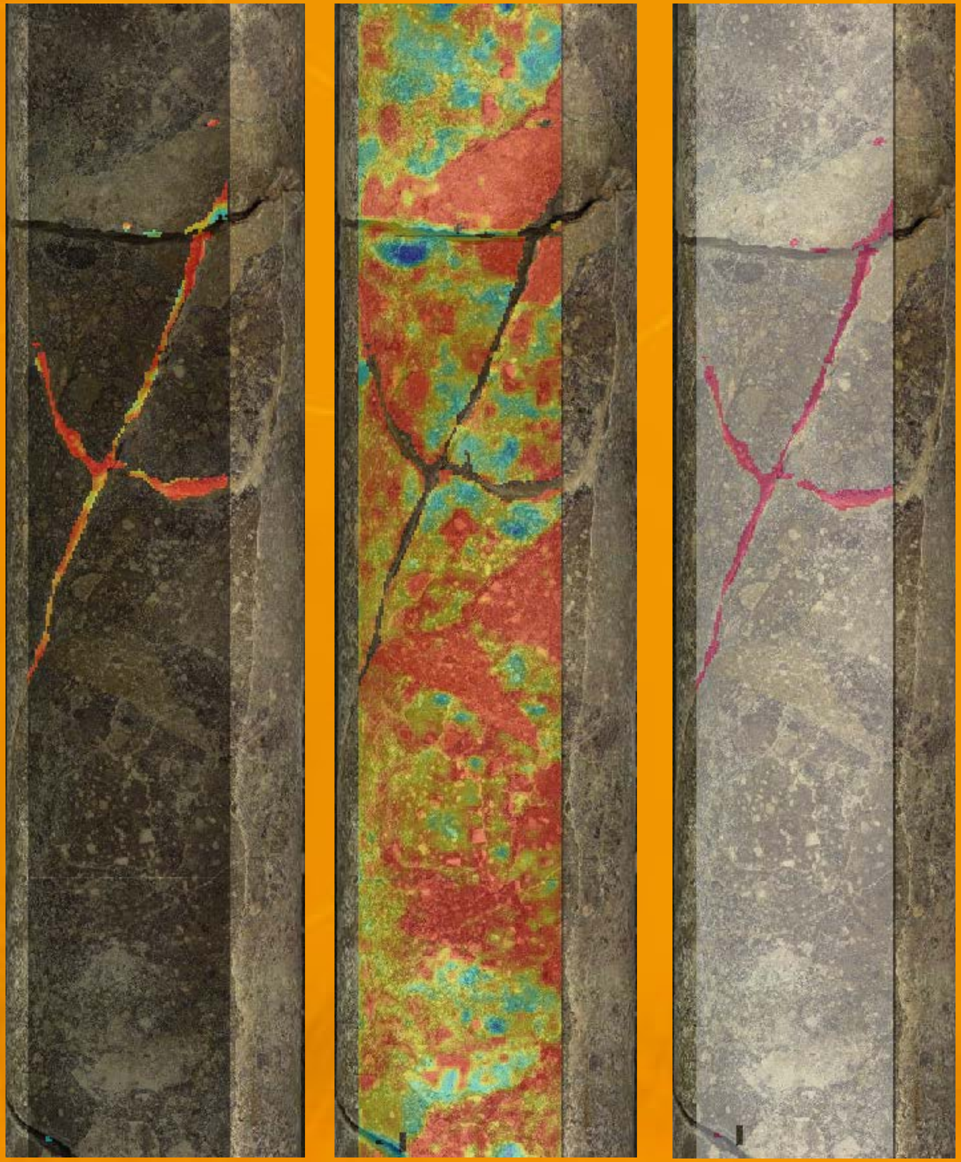

EPITHERMAL ALTERATION FROM CORE TO DEPOSIT SCALE: ASSEMBLAGE, TEXTURE AND PARAGENESIS FROM HYPERSPECTRAL CORE IMAGING

7 SEPTEMBER 2016

Dr. Brigette A. Martini, Dr. Cari Deyell-Wurst,
& Dr. Ronell Carey

Corescan

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Presented at Chile Explore 2016

EPITHERMAL – EXPLORATION AND CHARACTERISATION

Epithermal ore deposits are characterized by alteration mineral assemblages (including clays, micas, chlorite, sulfates, carbonates, etc) that result from interaction of magmatic fluids with host lithologies

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EPITHERMAL – EXPLORATION AND CHARACTERISATION

Individual mineral species can be very difficult to distinguish visually (e.g. *K vs Na alunite*) but subtle variations in mineralogy provides critical information

→ Applications not limited to exploration and type-discrimination (HS vs LS)

→ Also used for the prediction and modelling of mineralisation and ore genesis; ore characterization; waste characterization, and ultimately, deposit viability

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EPITHERMAL – EXPLORATION AND CHARACTERISATION

Hyperspectral imaging technology is a powerful tool to identify mineralogical changes (species variation, chemistry and crystallinity)

→ Textural & mineralogical maps of these variables = PROXY for fluid chemistry (pH, redox) and temperature of formation

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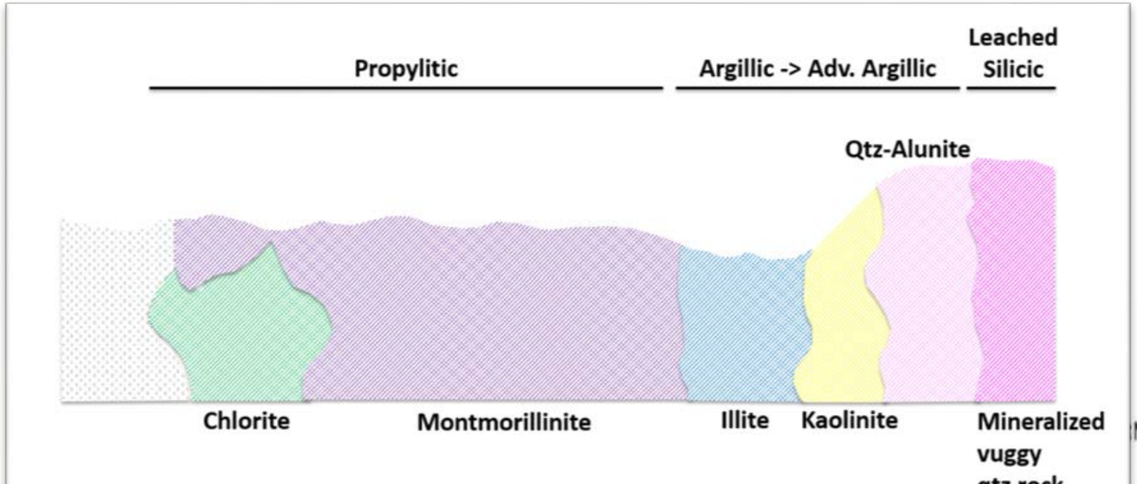
EPITHERMAL – EXPLORATION AND CHARACTERISATION

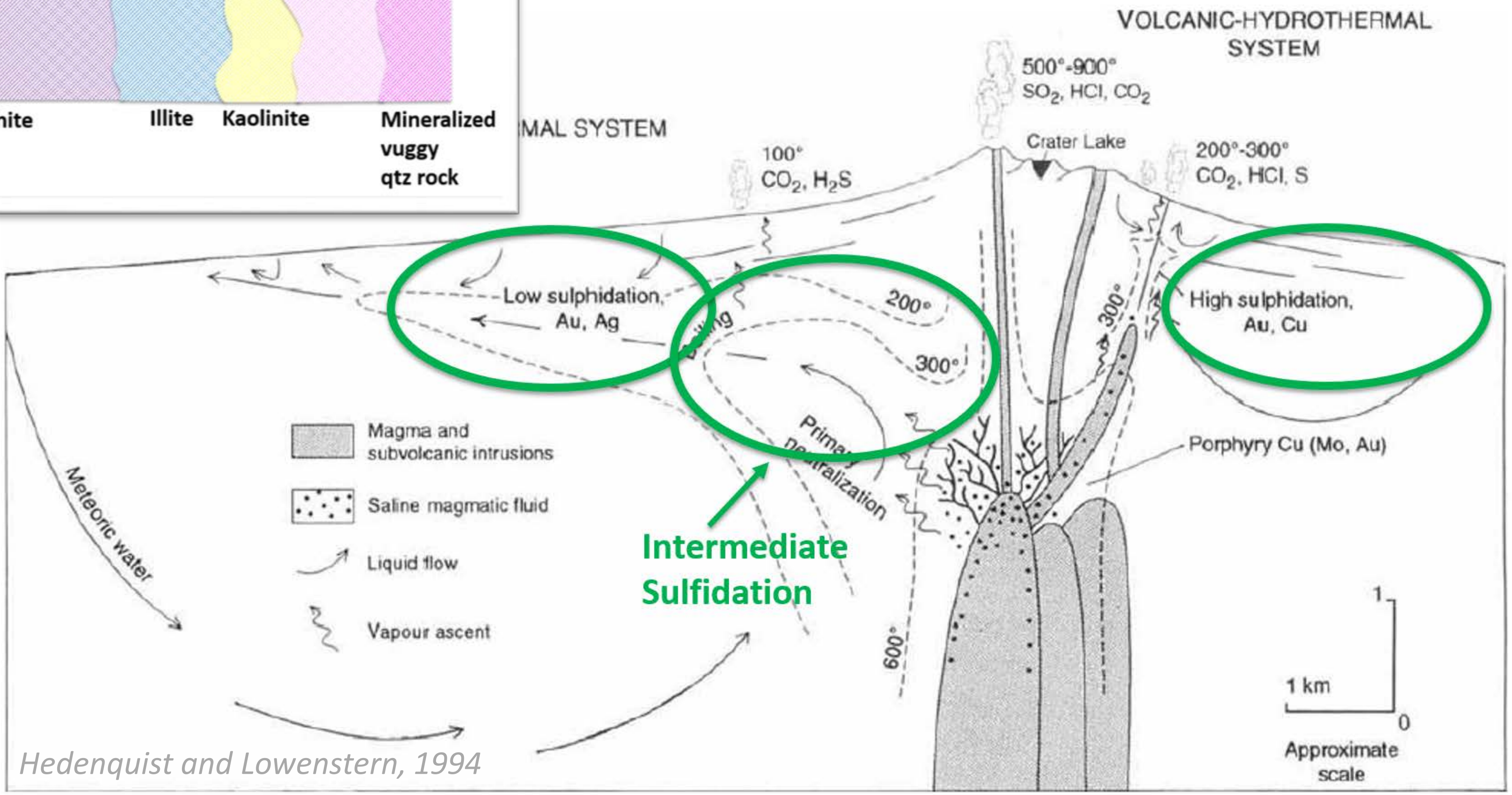
Hyperspectral core imaging provides consistent, accurate and objective mineralogy at continuous, sub-millimetre scales from a single core-box (~1,000,000 points of alteration data) to borehole through to entire deposits (~billions of alteration measurements)

EPITHERMAL AU/AG SYSTEMS: HIGH, INTERMED. & LOW SULFIDATION

Near-Surface Alteration

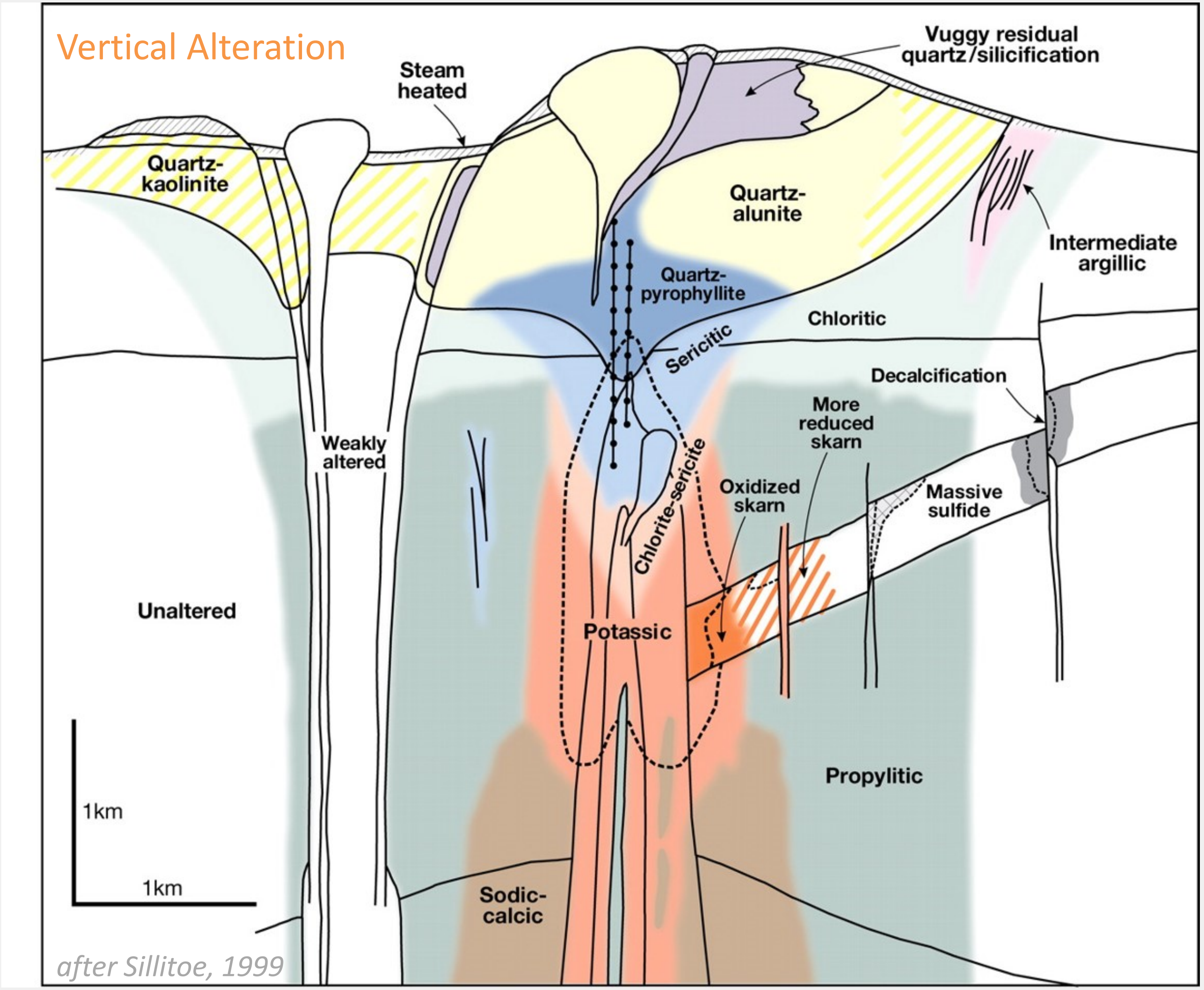


Modified from Steven and Ratte, 1960



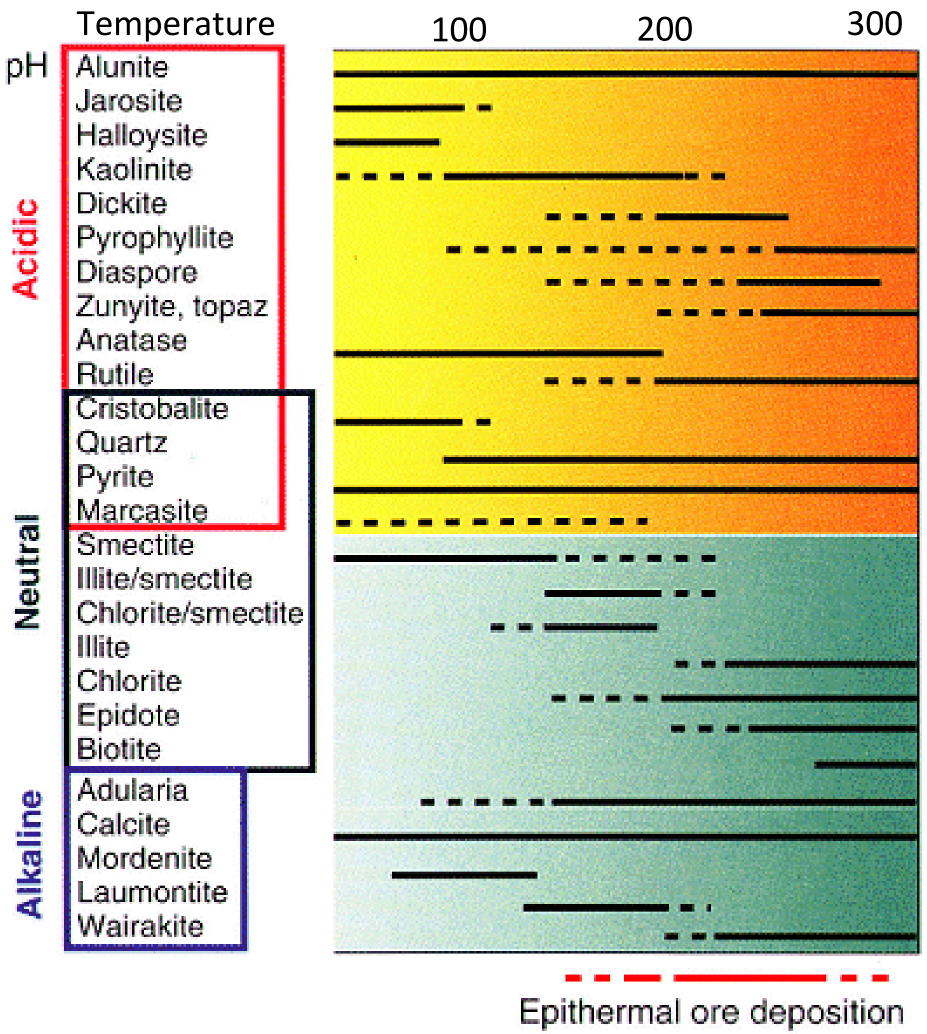
Hedenquist and Lowenstern, 1994

EPITHERMAL AU/AG SYSTEMS: HIGH, INTERMED. & LOW SULFIDATION



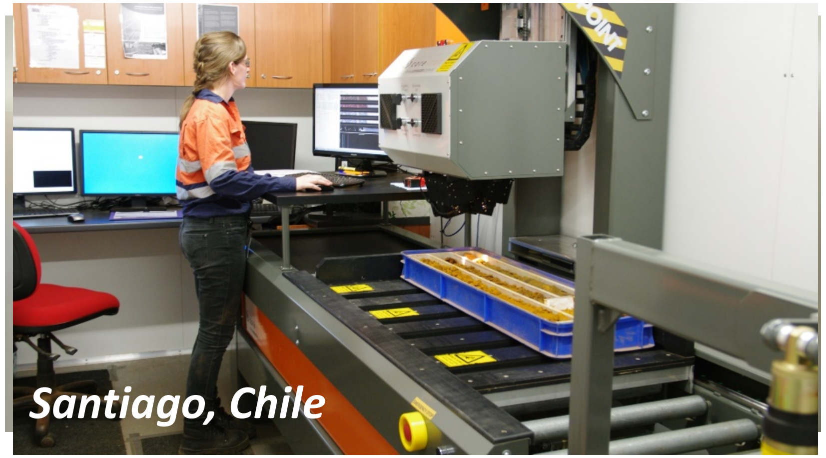
ALTERATION LOGGING WITH HYPERSPECTRAL CORE IMAGING

- Mineralogy
  - Assemblage mapping
  - Minerals as VECTORS - narrow geochemical T and pH ranges can help locate zones of metal deposition
  - Deposit reconstruction (eg. higher T material at surface may suggest erosion of main ore-bearing rock volumes)
  - Input for geometallurgical modeling
  - *Sulfide detection and mapping*
- Texture
  - Pervasive v. Veined
  - Paragenesis; cross-cutting relationships
  - Overprints (this must be distinguished from ore-related alteration)
    - Grade destructive? Enrichment?



(Henley and Ellis, 1983; Reyes, 1990)


Alturas, Chile


Santiago, Chile


Hermosillo, MX

Mobile, Automated, Hyperspectral Core Logging

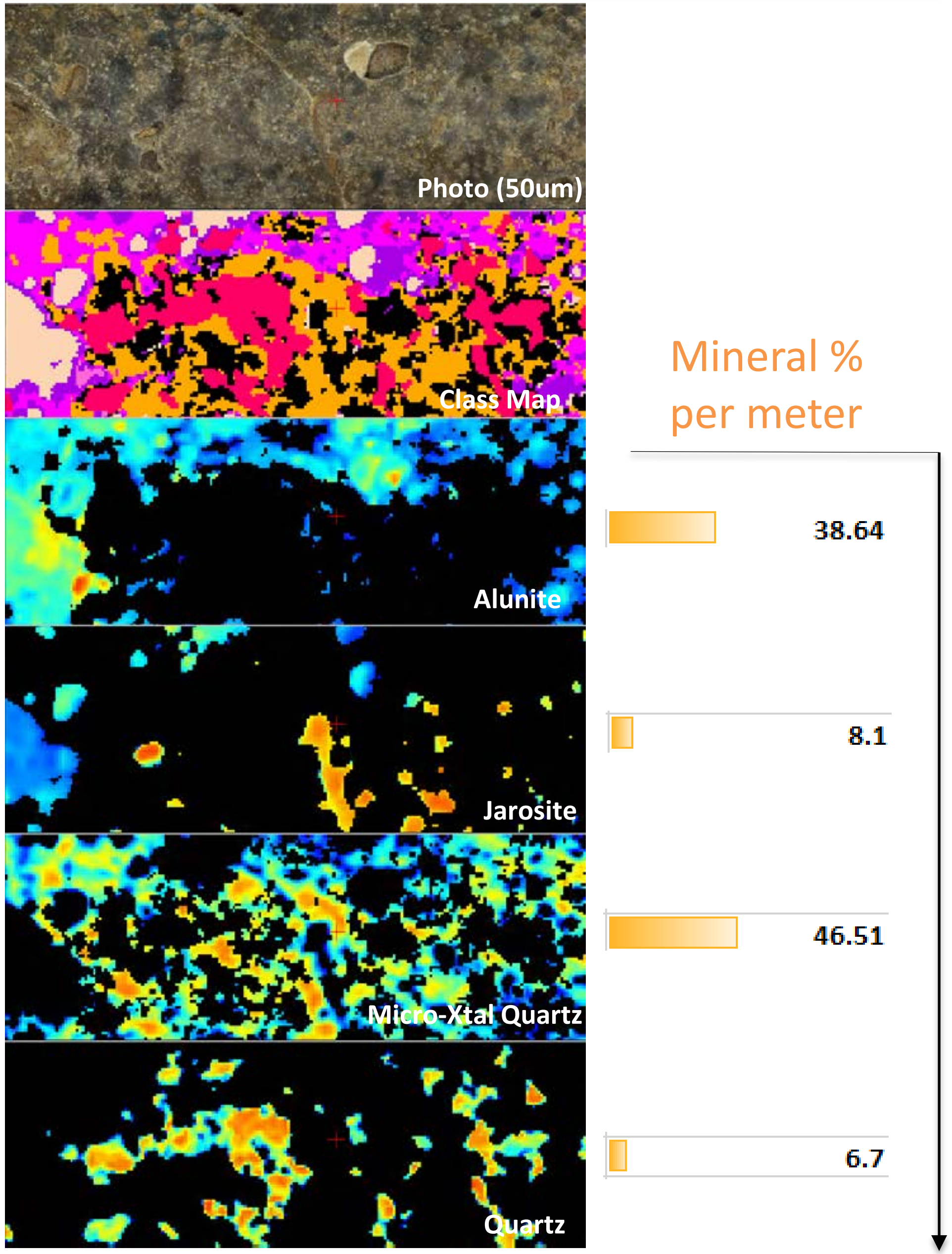
corescan

HCI-3 System Specifications	
Spectrometers	3 (VNIR, SWIR-A, SWIR-B)
Spectral range	450nm - 2500nm
Spectral resolution	~4nm
Scan modes	0.5mm square pixels
Spectral calibration	Detailed full width scan Reconnaissance profile scan
Radiometric calibration	Spectralon reflectance standard, dark current
RGB image resolution	50 µm
Height profile resolution	20 µm
Core tray sizes	Up to 0.6m x 1.5m (WxL)
Scan rates	200m to 1000m per day depending on operational constraints

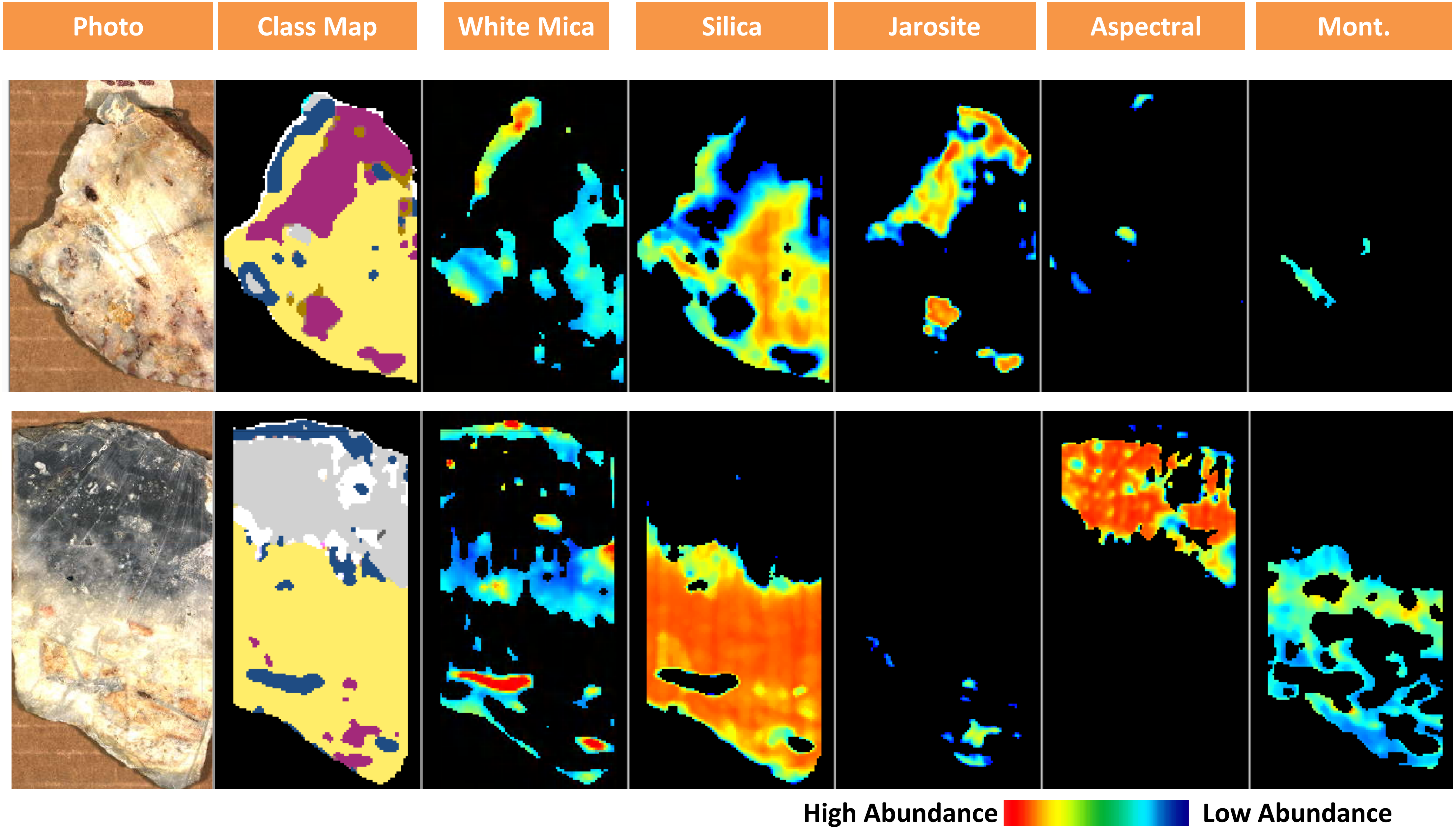
EPITHERMAL GOLD ALTERATION: HIGH SULFIDATION

TYPICAL MINERALOGY LOGGED WITH CORESCAN

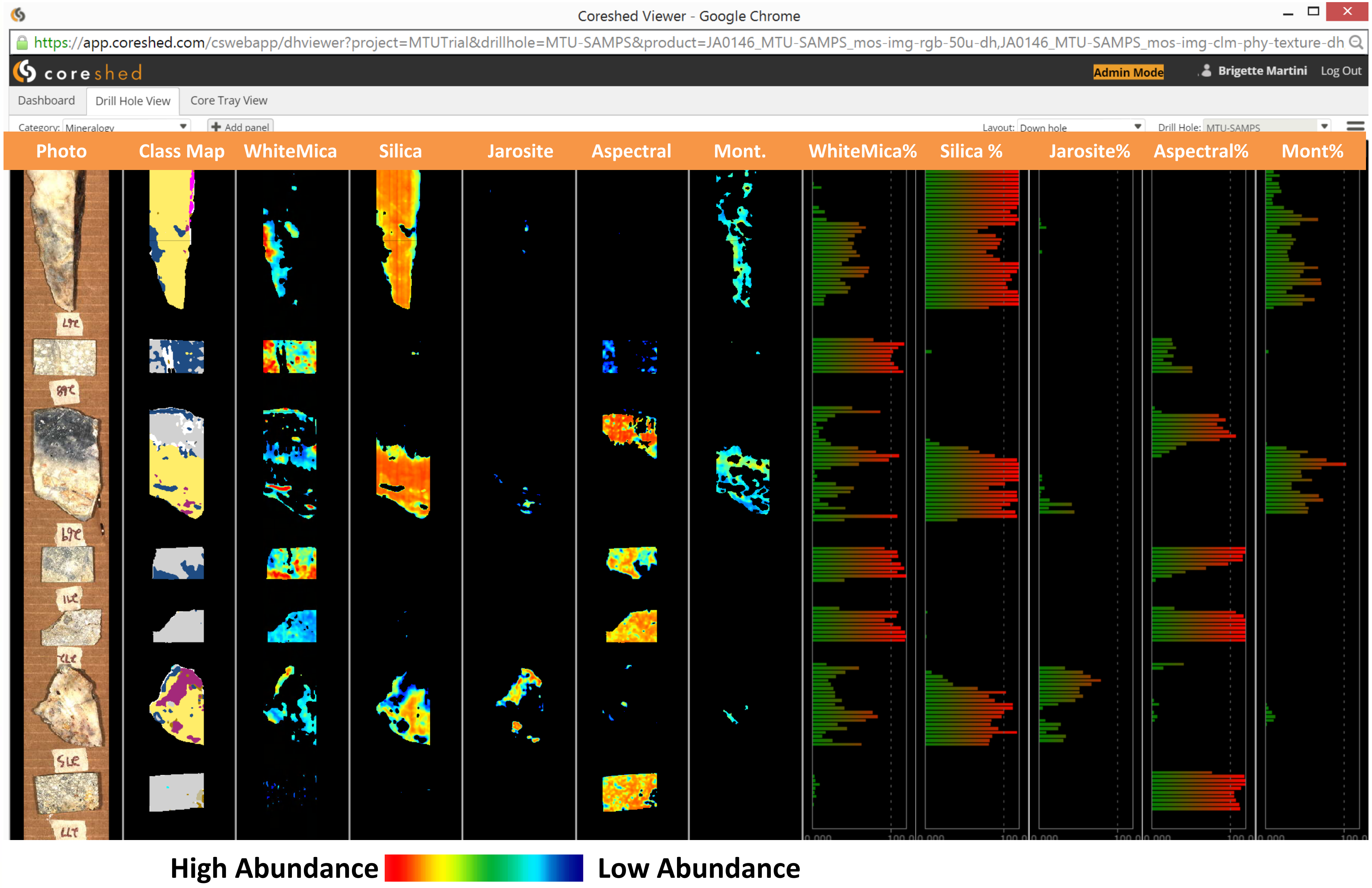
- GANGUE MINERALOGY
  - Quartz and hydrated silica varieties
  - Kaolinite, Dickite, Pyrophyllite
  - Alunite
  - Diaspore
  - Zunyite, Topaz and Andalusite (>260C)
  - APS minerals (Aluminum, Phosphate, Sulfur) eg. woodhouseite-svanbergite; can also be Sr-, Pb- and REE-bearing
  - Illite/sericite
  - Chlorite
  - (a lack of Calcite and Adularia)



EPITHERMAL GOLD : HS ALTERATION IN HANDSAMPLE

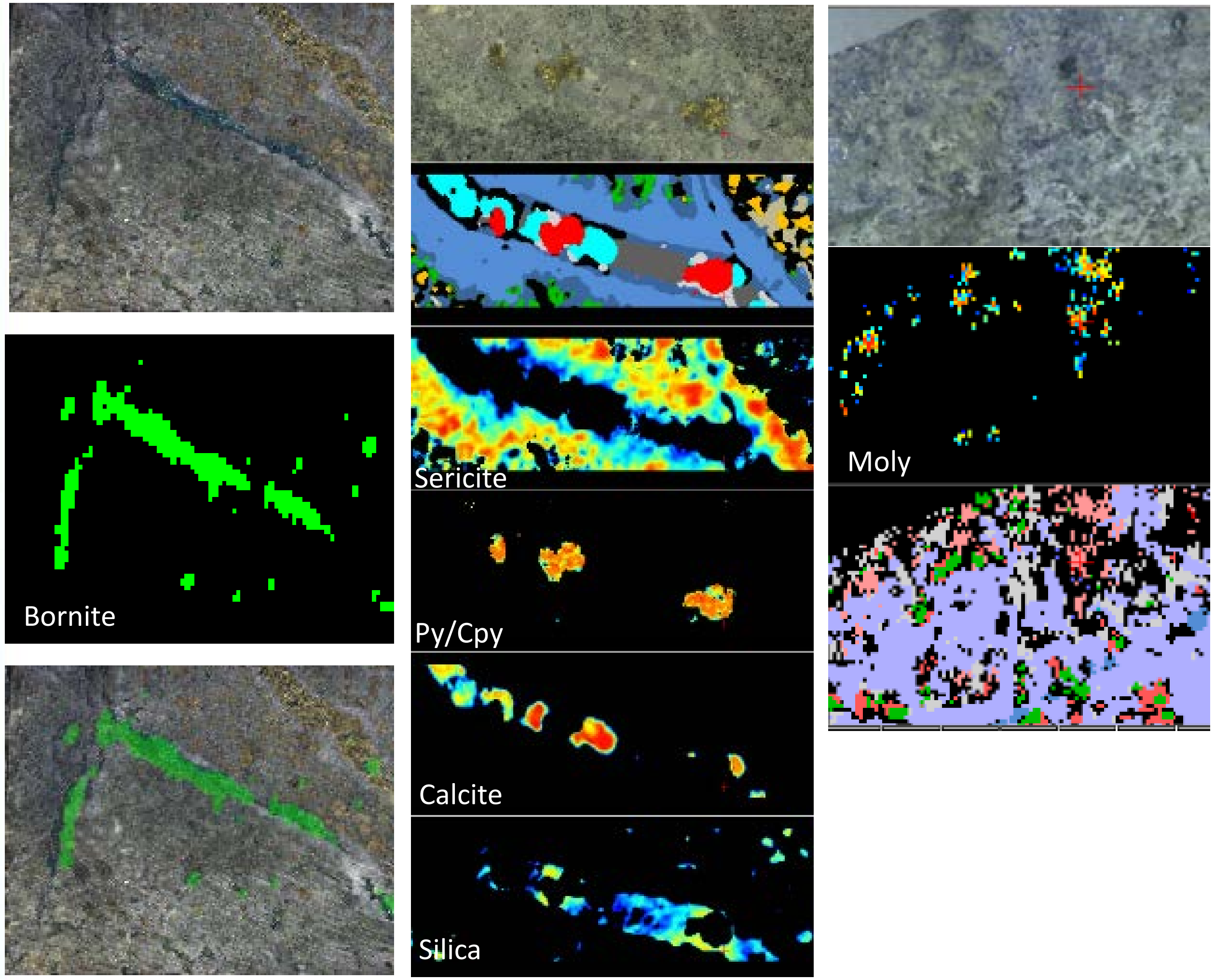


EPITHERMAL GOLD : ASSEMBLAGE MAPPING AND QUANTIFICATION

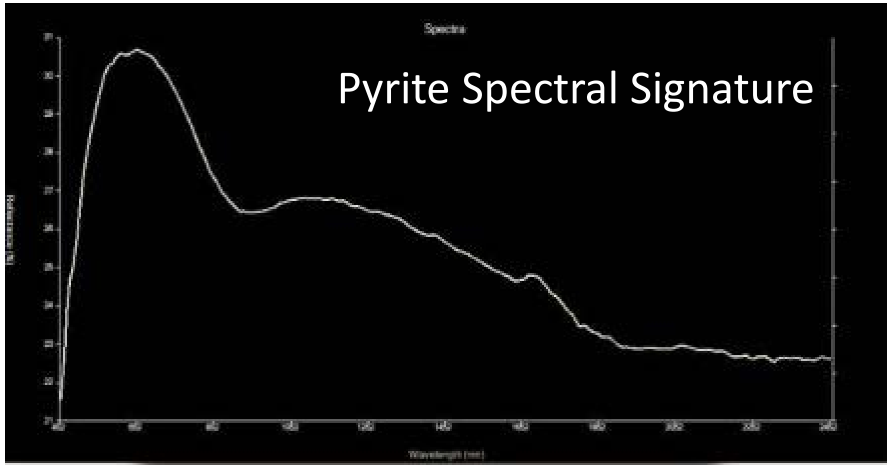


SULFIDE MAPPING

Bornite **Py/Cpy** **Moly**



- It is possible to map sulfides in the VNIR-SWIR spectral range
- *However, unlike typical alteration mineralogy spectra, sulfide signatures are not unique and ambiguity between sulfides can be a problem*
- *Massive sulfide has higher accuracy than finely disseminated sulfides*

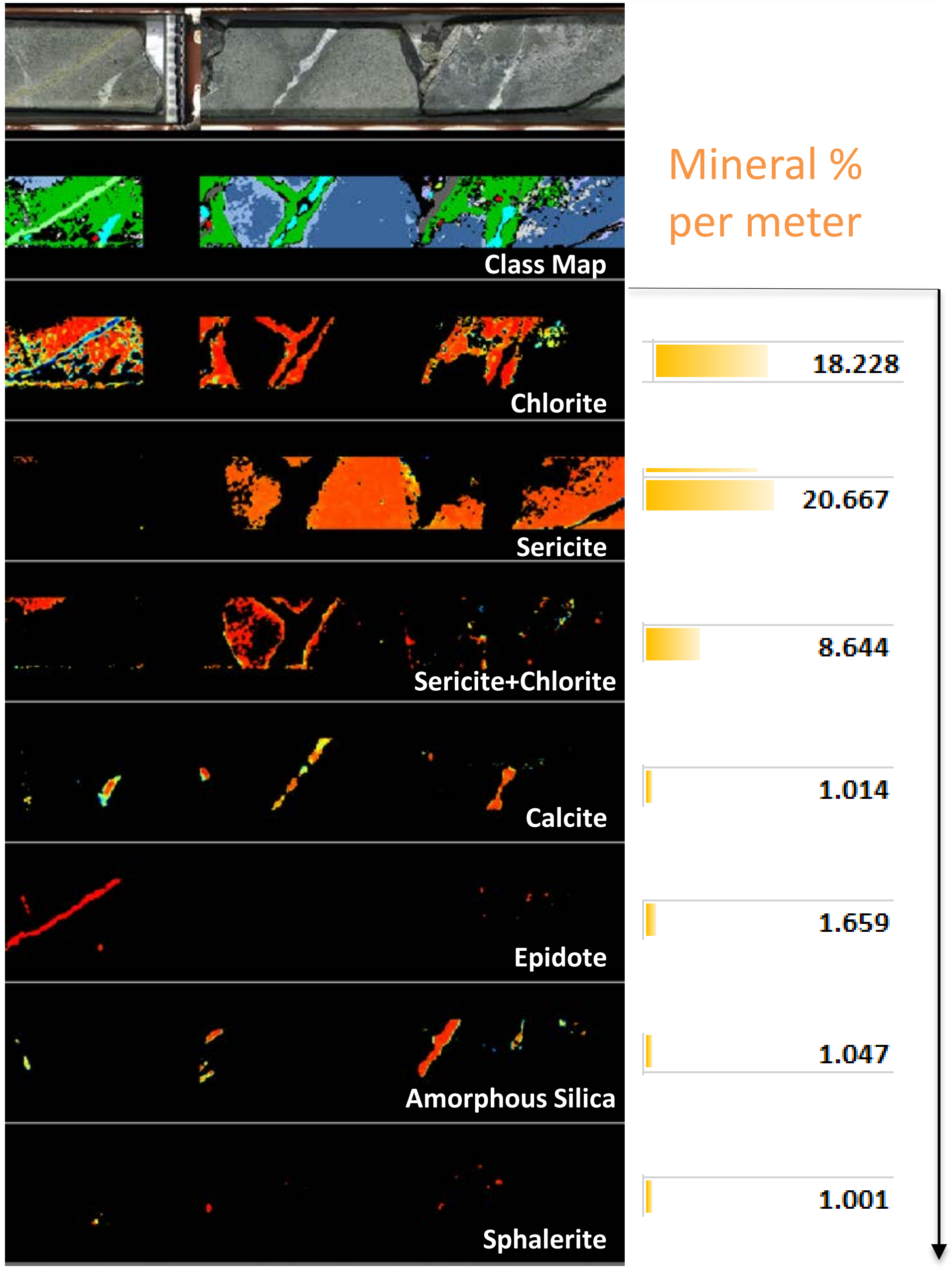


EPITHERMAL GOLD ALTERATION: LOW & INTERMEDIATE SULFIDATION

TYPICAL MINERALOGY LOGGED WITH CORESCAN

- GANGUE MINERALOGY
  - Quartz & hydrated silica varieties
  - Adularia
  - Calcite
  - Illite/Sericite – with inc. T, smectite (stable at <160C) gives way to I/S and then pure llite >220C = clear upward and outward zonation of ore minerals
  - Zeolites (<220C)
  - Chlorite
  - Epidote (stable above 200-240C)
  - Biotite and amphibole (>280C at base of epi env.)

  - *(Lack of alunite and abundant kao-dik-pyl; except as overprint)*

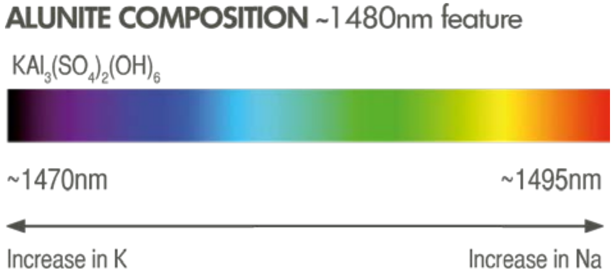


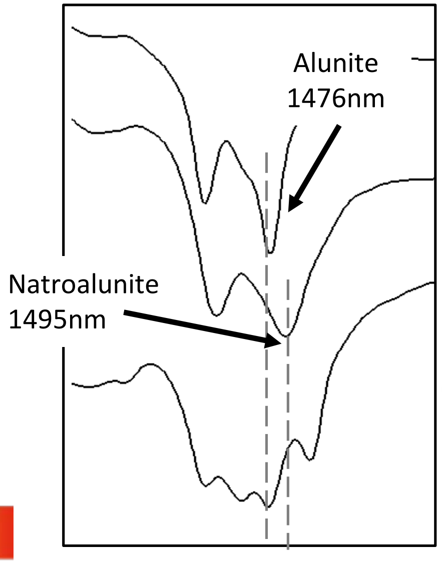
EPITHERMAL GOLD ALTERATION : VECTOR MINERAL(S)

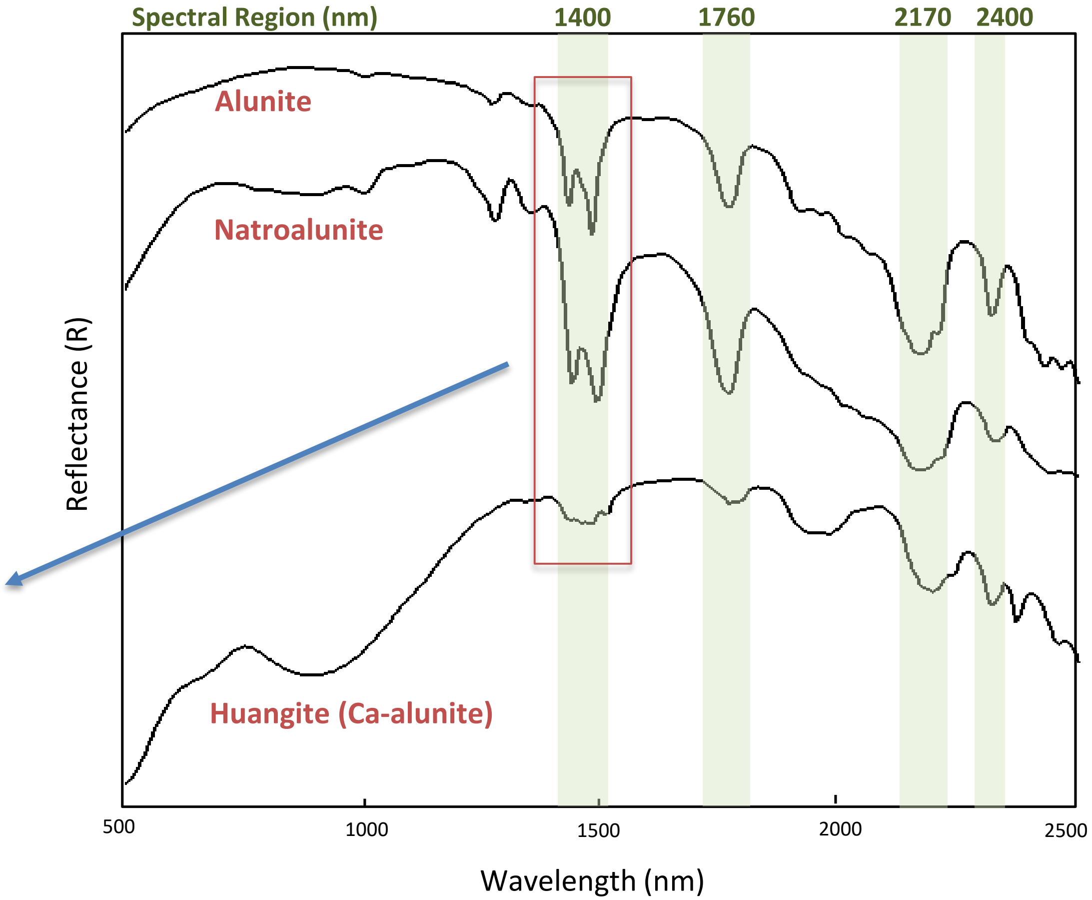
CHARACTERIZATION, ROLE AND SPATIAL DISTRIBUTION OF ALUNITE

$KAl_3(SO_4)_2(OH)_6$

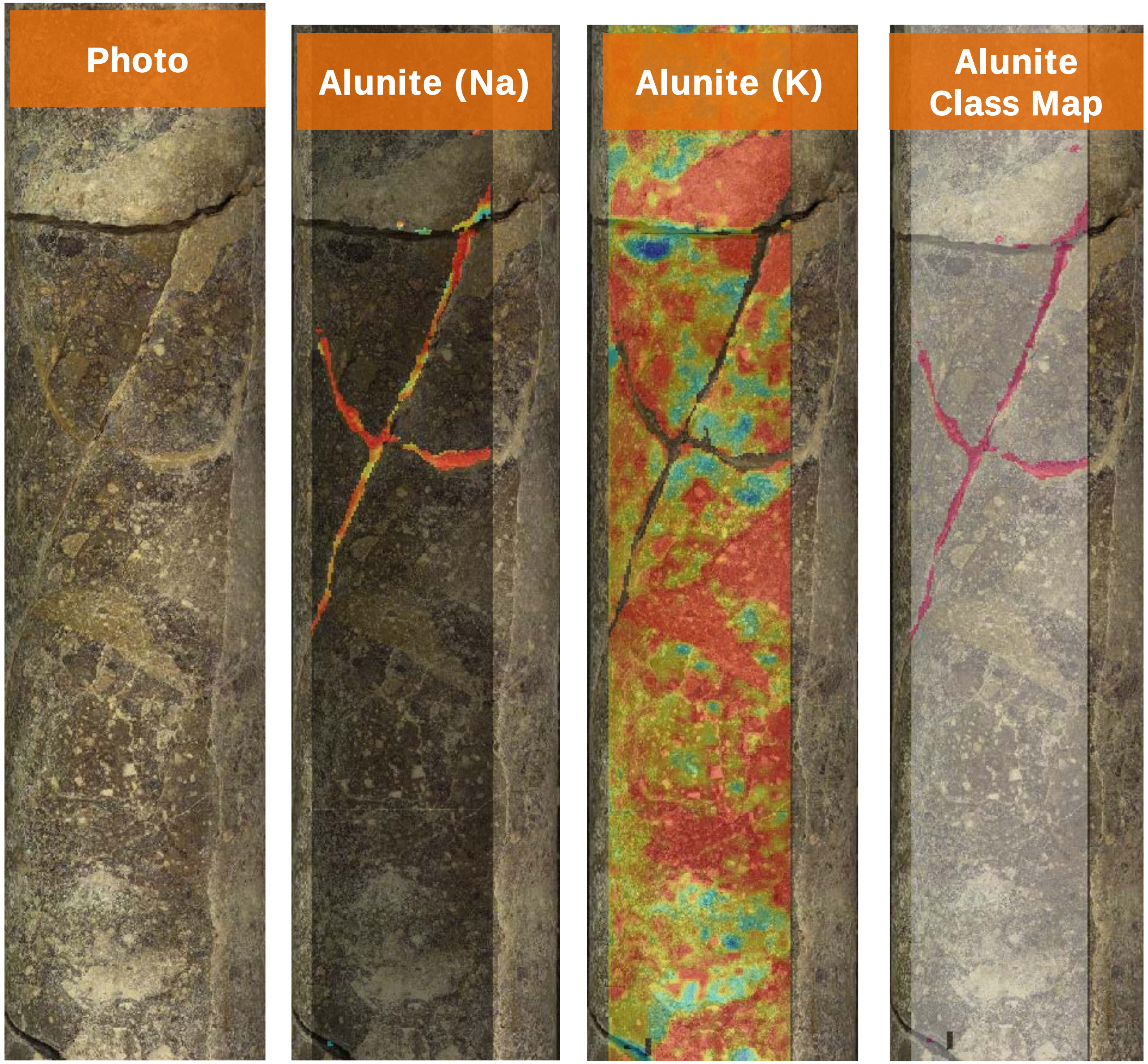
- Substitution of Na for K (natroalunite-alunite solution series) is temperature dependent
- Higher temperatures correlate to an increase in Na *(Arribas et al., 1995; Deyell and Dipple, 2005; Chang et al., 2014)*







ALUNITE COMPOSITION - PARAGENESIS

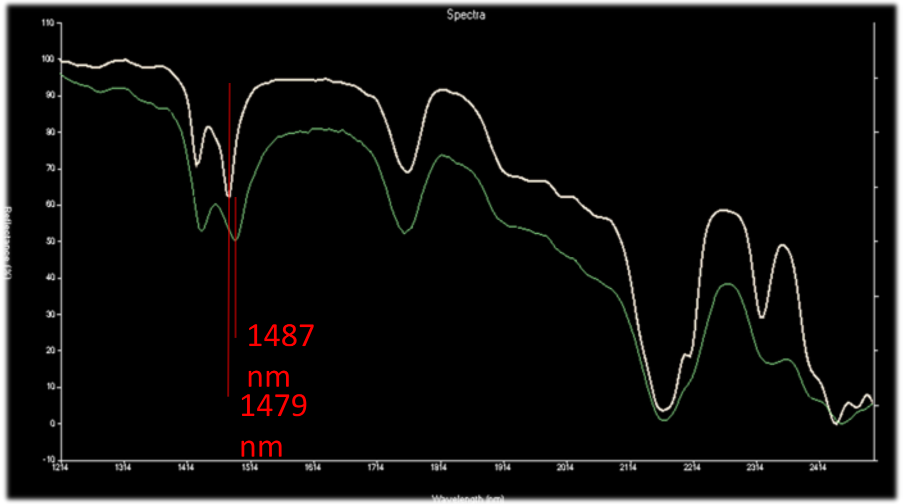


High Abundance — **Low Abundance**

A pervasive K-rich Alunite phase followed by a later stage, vein-hosted, Na-rich Alunite phase

Alunite (Na)

Alunite (K)

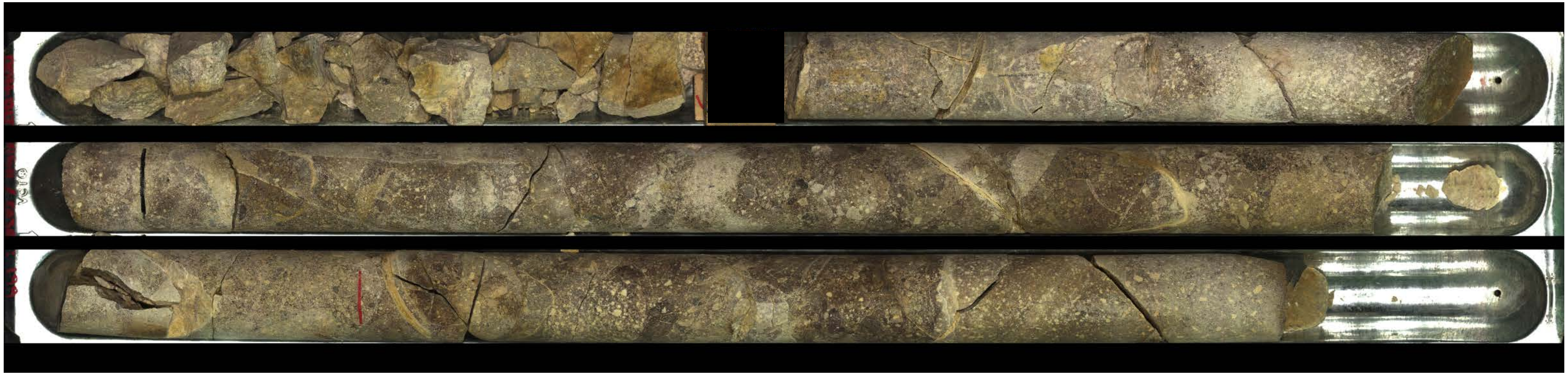


Fine spectral shifts reveal complex alunite chemistry and paragenesis

EPITHERMAL AU – ALUNITE COMPOSITION (AT CORE BOX SCALE)

Photo (50µm)

Fine spectral shifts reveal complex alunite chemistry and paragenesis

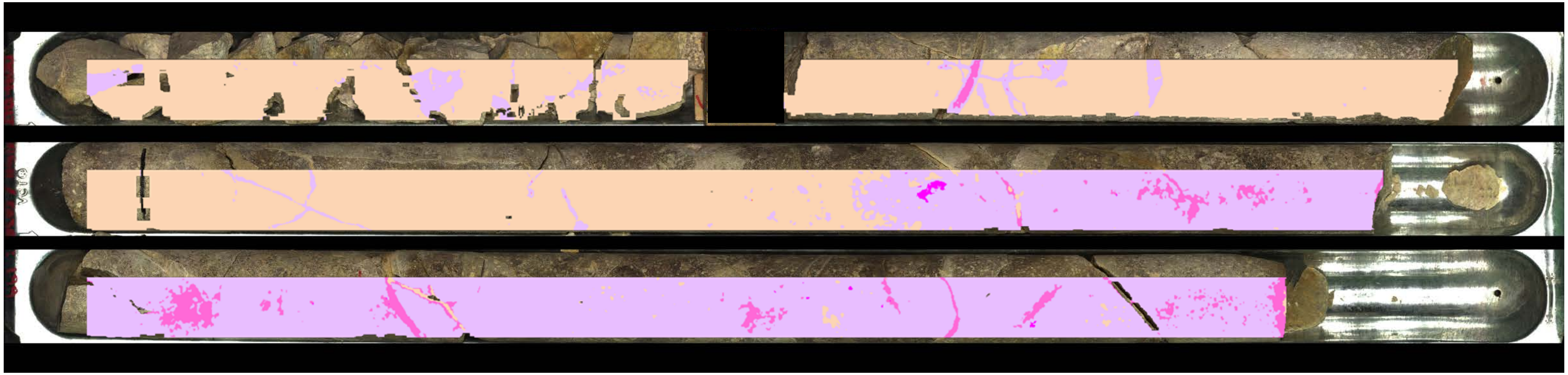


EPITHERMAL AU – ALUNITE COMPOSITION (AT CORE BOX SCALE)

Photo (50µm)

Alunite Class Map

Fine spectral shifts reveal complex alunite chemistry and paragenesis



K-Alunite

K-Alun + Micro-Xtal Quartz

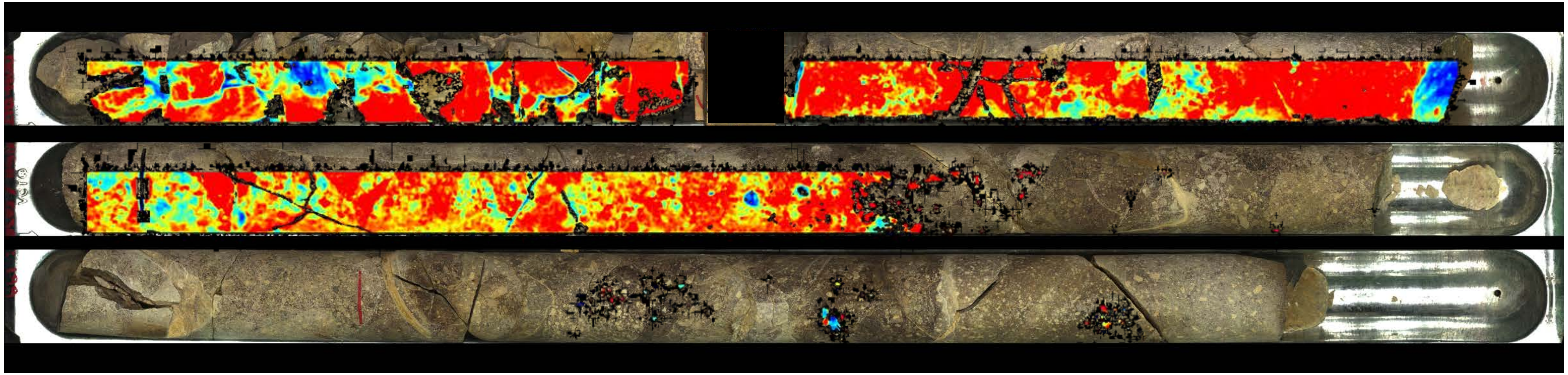
Na-Alunite

EPITHERMAL AU – ALUNITE COMPOSITION (AT CORE BOX SCALE)

Photo (50µm)

Alunite (K)

Fine spectral shifts reveal complex alunite chemistry and paragenesis



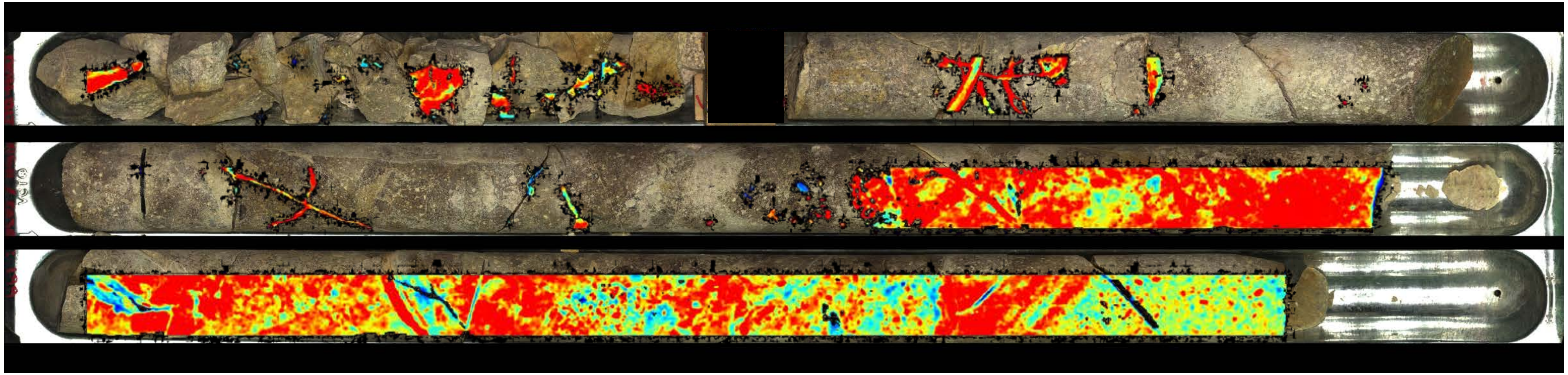
High Abundance – **Low Abundance**

EPITHERMAL AU – ALUNITE COMPOSITION (AT CORE BOX SCALE)

Photo (50µm)

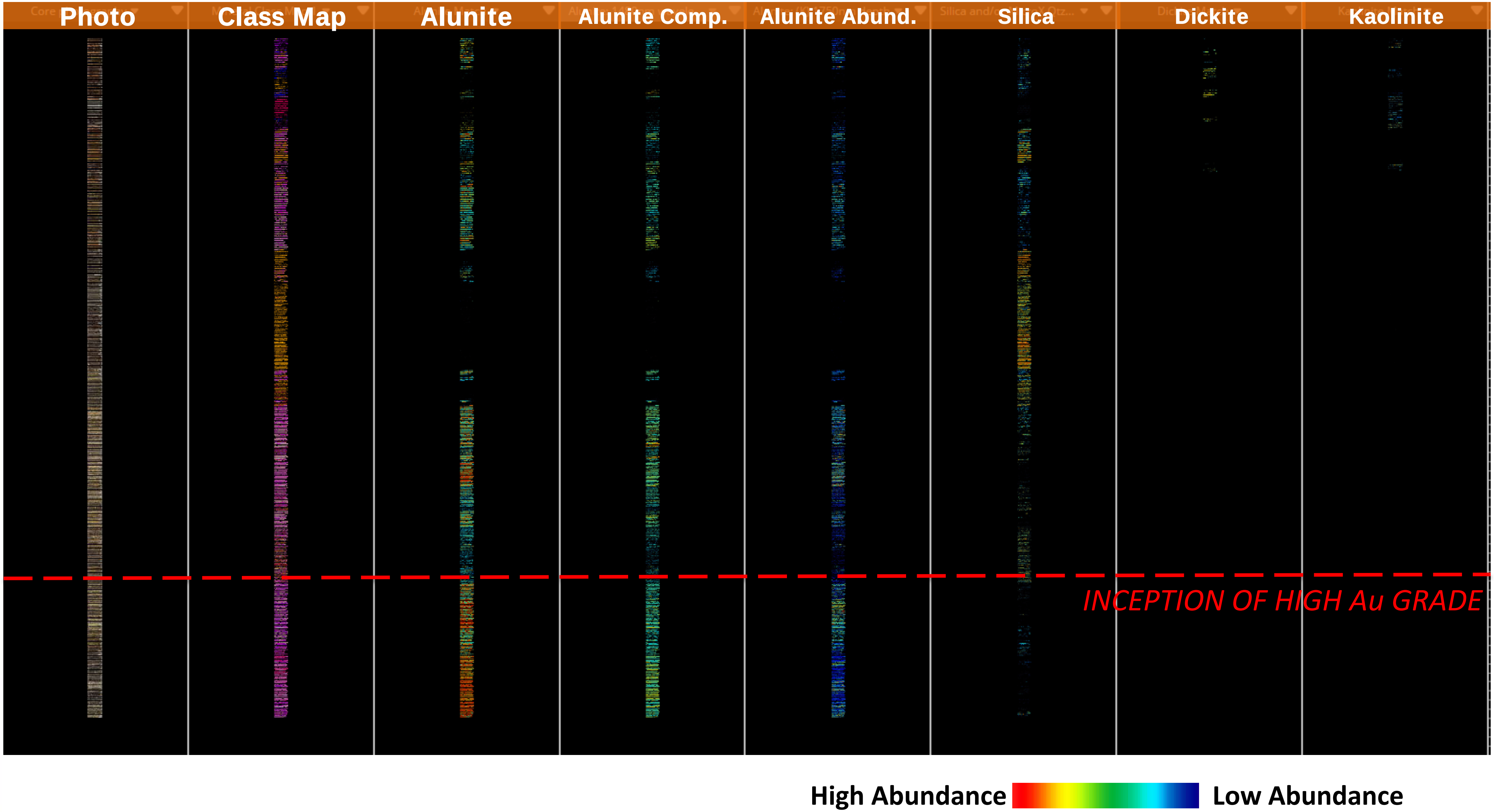
Alunite (Na)

Fine spectral shifts reveal complex alunite chemistry and paragenesis



High Abundance  **Low Abundance**

ALUNITE COMPOSITION – BOREHOLE SCALE



EPITHERMAL GOLD ALTERATION : OVERPRINTING

Epithermal deposits form in dynamic environments
(e.g., island arc volcanics, continental geothermal settings, etc).

- Variable flux of magmatic and meteoric fluids, tectonic and structural influences can result in complicated alteration associations.
- Recognition of paragenesis (primary, ore-related alteration vs secondary or overprinting alteration) is critical for exploration success.

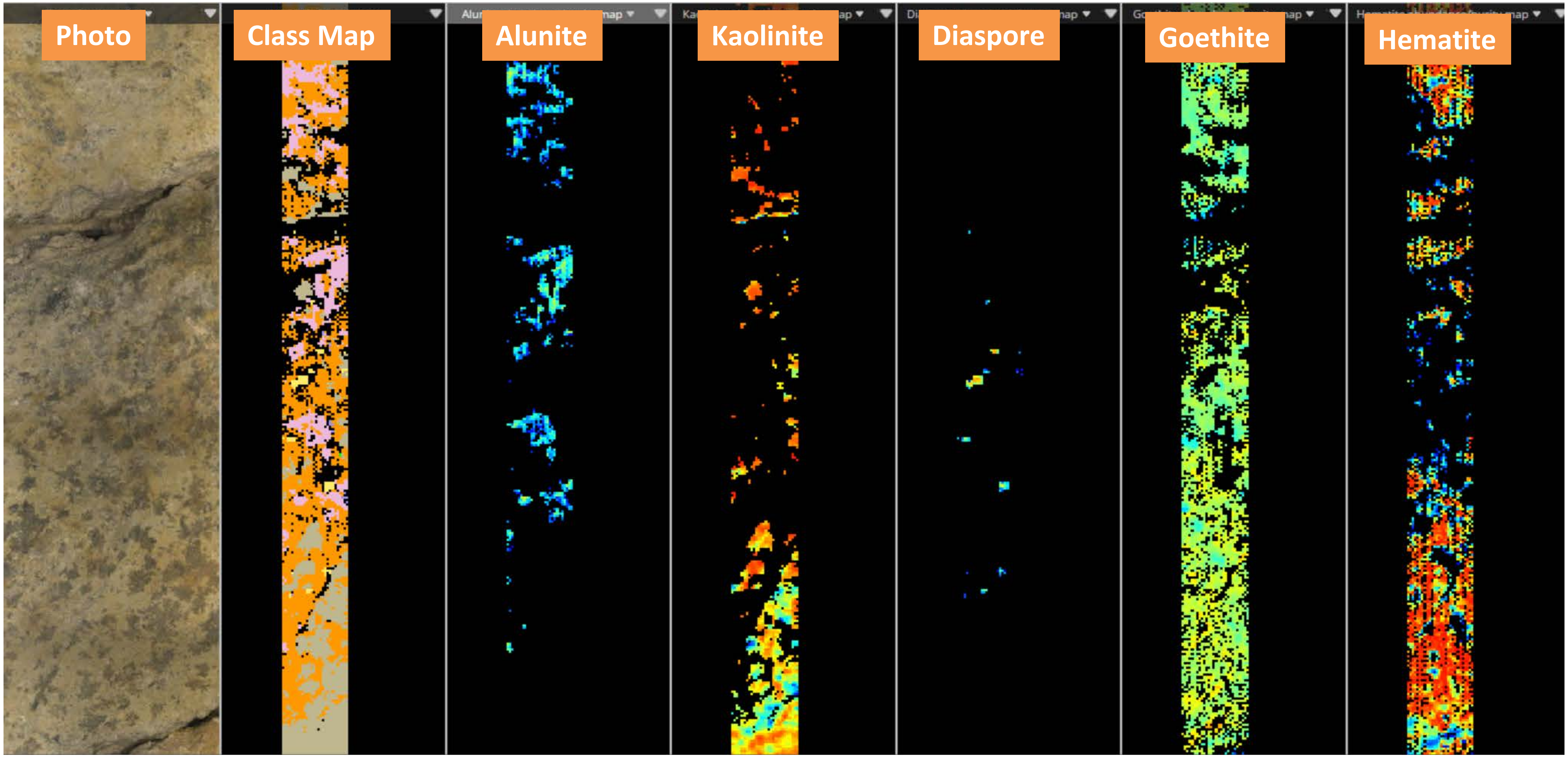
TYPICAL SOURCES OF OVERPRINT

- Steam-heated alteration (from surface)
- Post-hydrothermal weathering of sulphide minerals (supergene)
- Telescoping of hydrothermal systems

Considerations:
→ Secondary enrichment/upgrading?
→ Potential for porphyry-style mineralization at depth?
→ Deleterious clay mineral overprinting?

El Indio Belt, steam-heated alteration

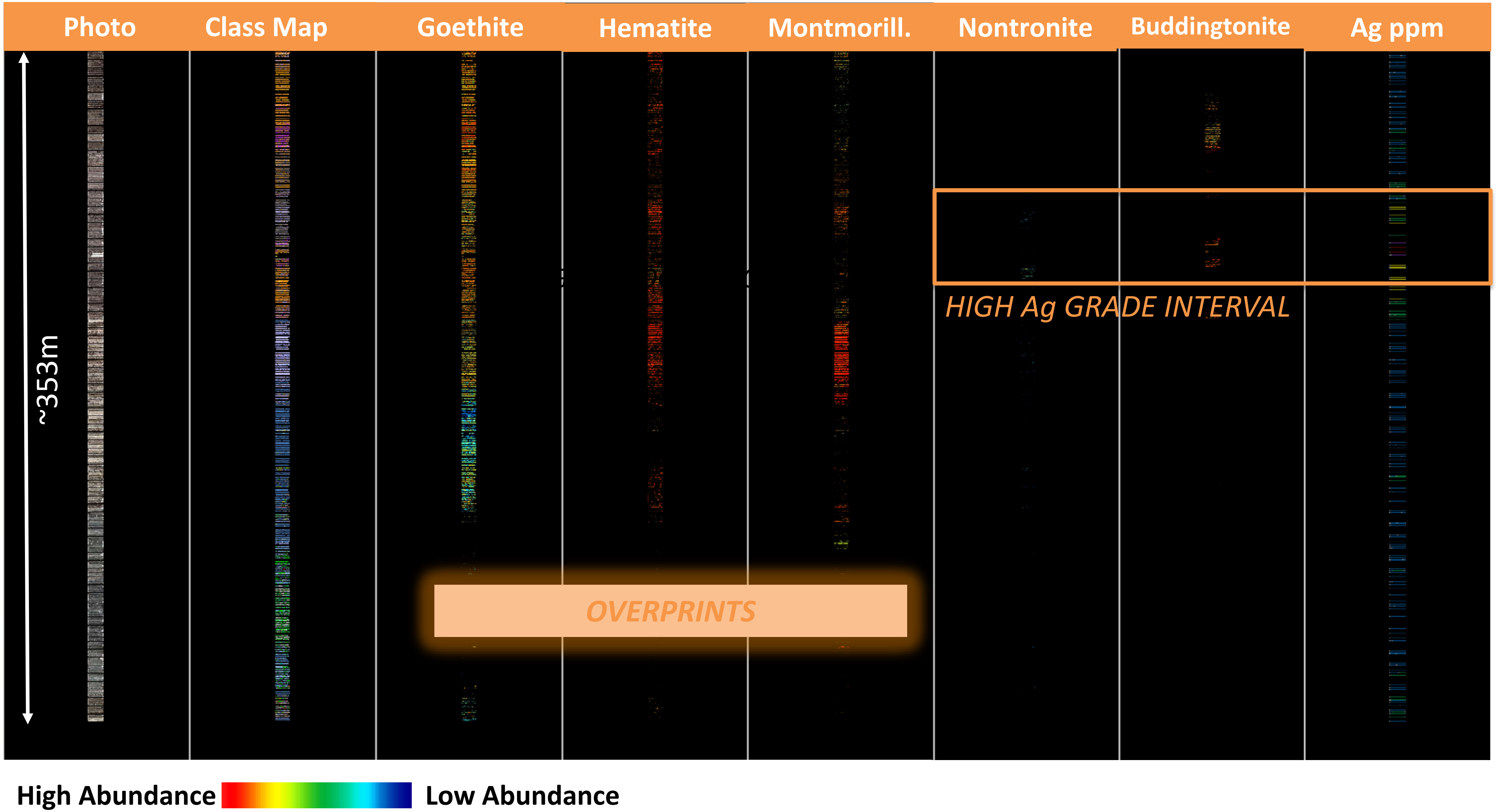
HIGH SULFIDATION: OVERPRINTS



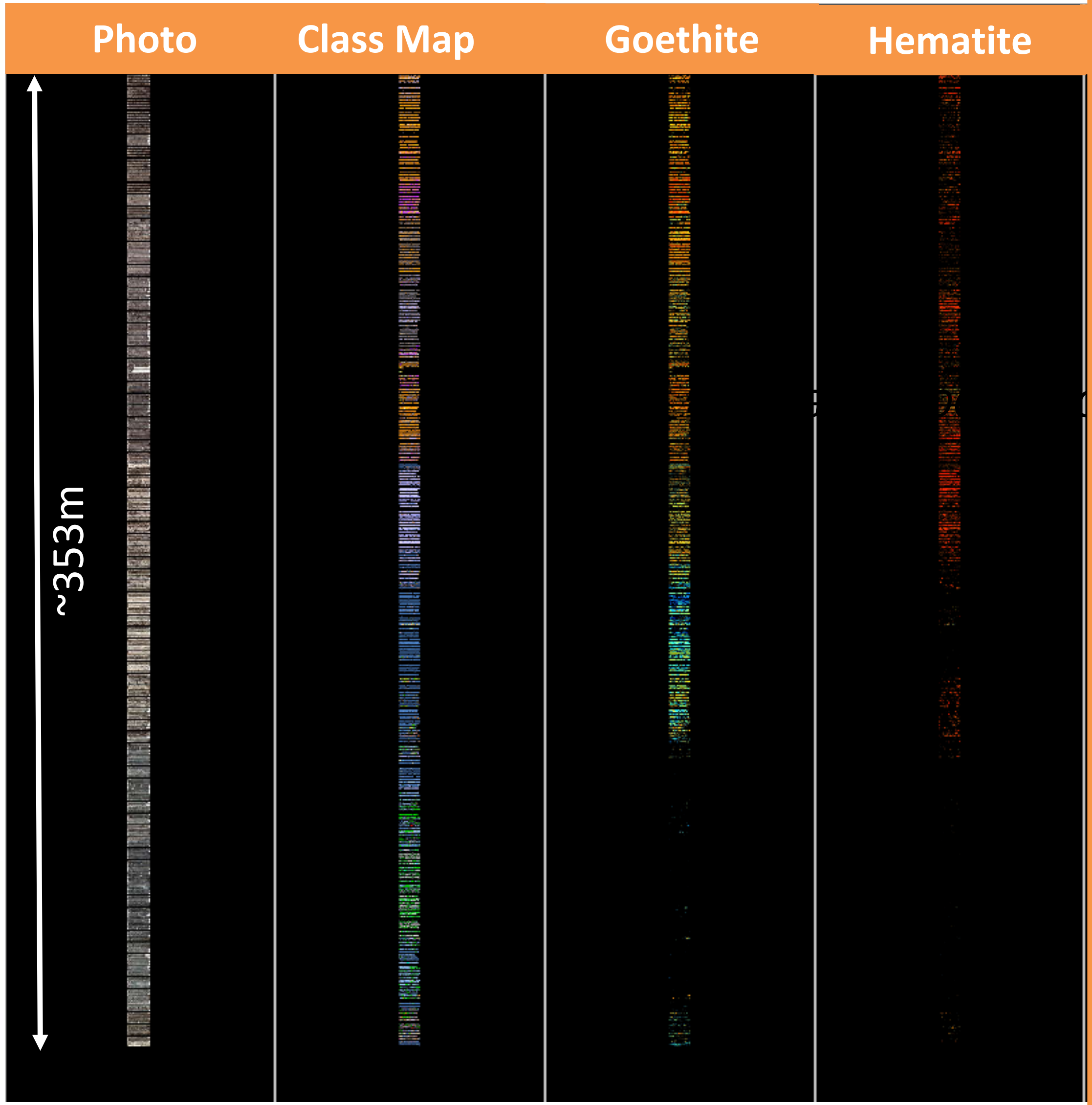
High Abundance **Low Abundance**

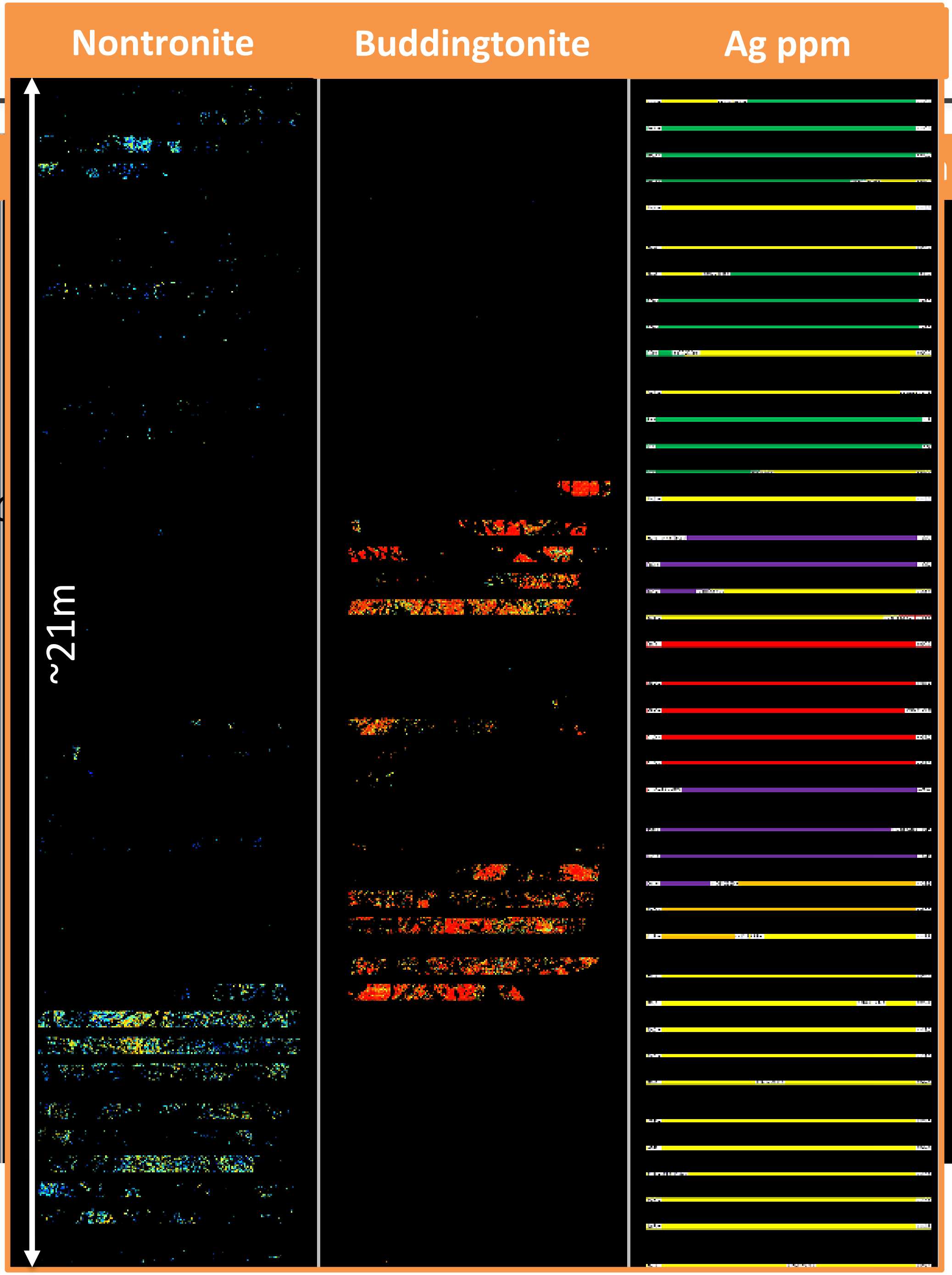
Typical Advanced Argillic assemblage with Goe/Hem overprint

LOW SULFIDATION: OVERPRINTS



LOW SULFIDATION: OVERPRINTS

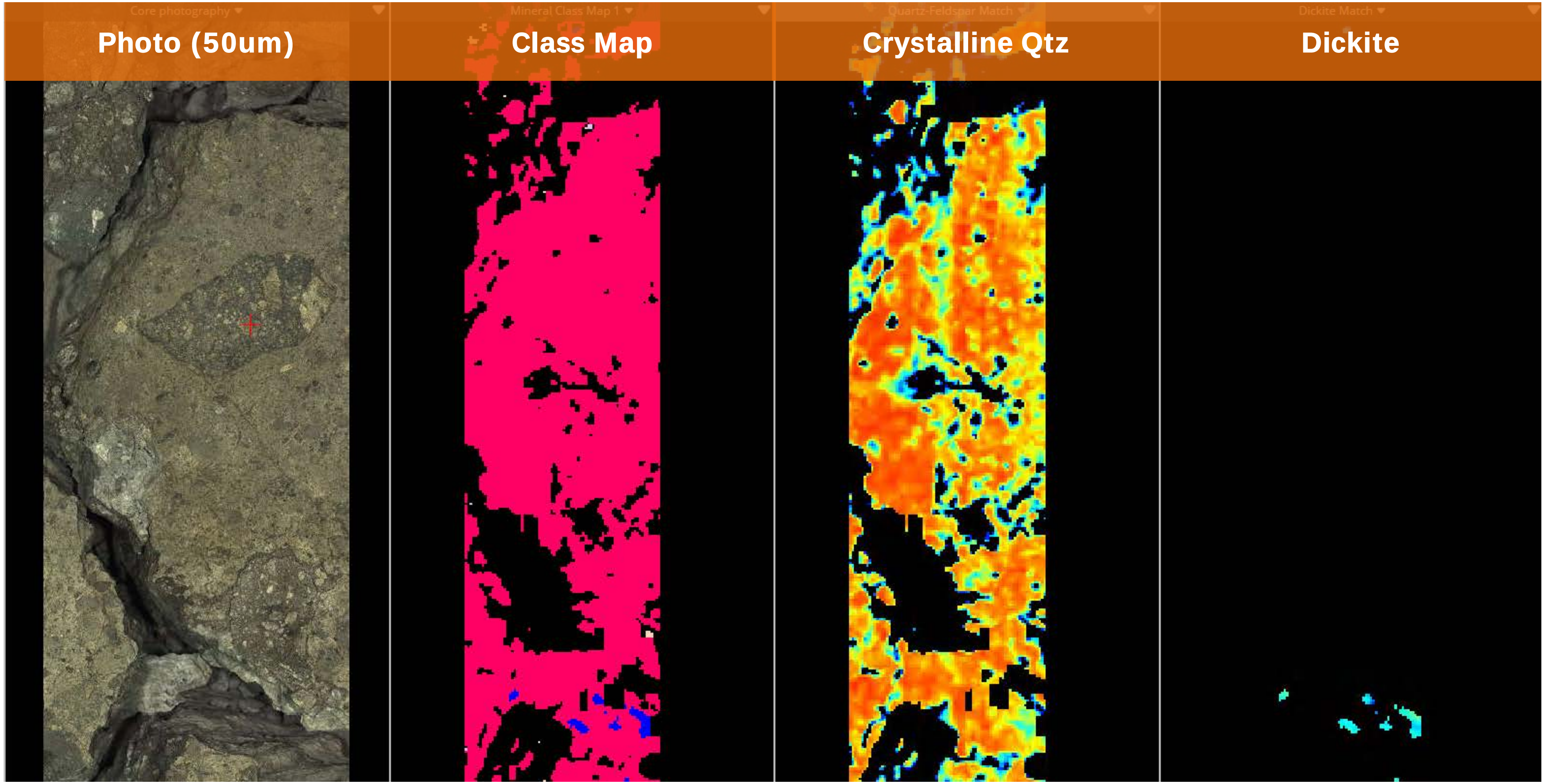




High Abundance — Low Abundance

Higher Ag Grade — Lower Ag Grade

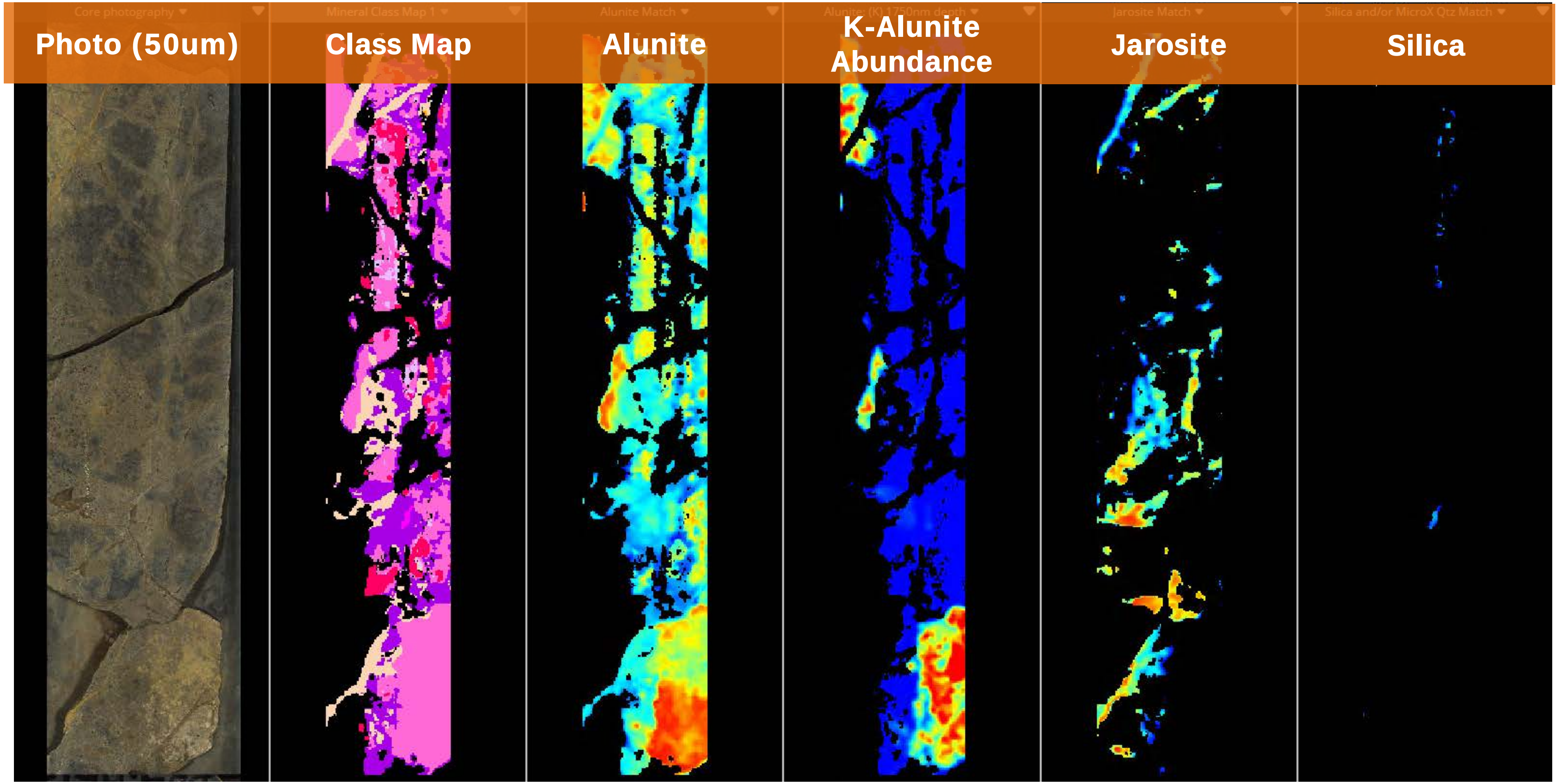
EPITHERMAL ALTERATION WITH GRADE - UNMINERALISED



Xtal Quartz
Dickite

High Abundance — Low Abundance

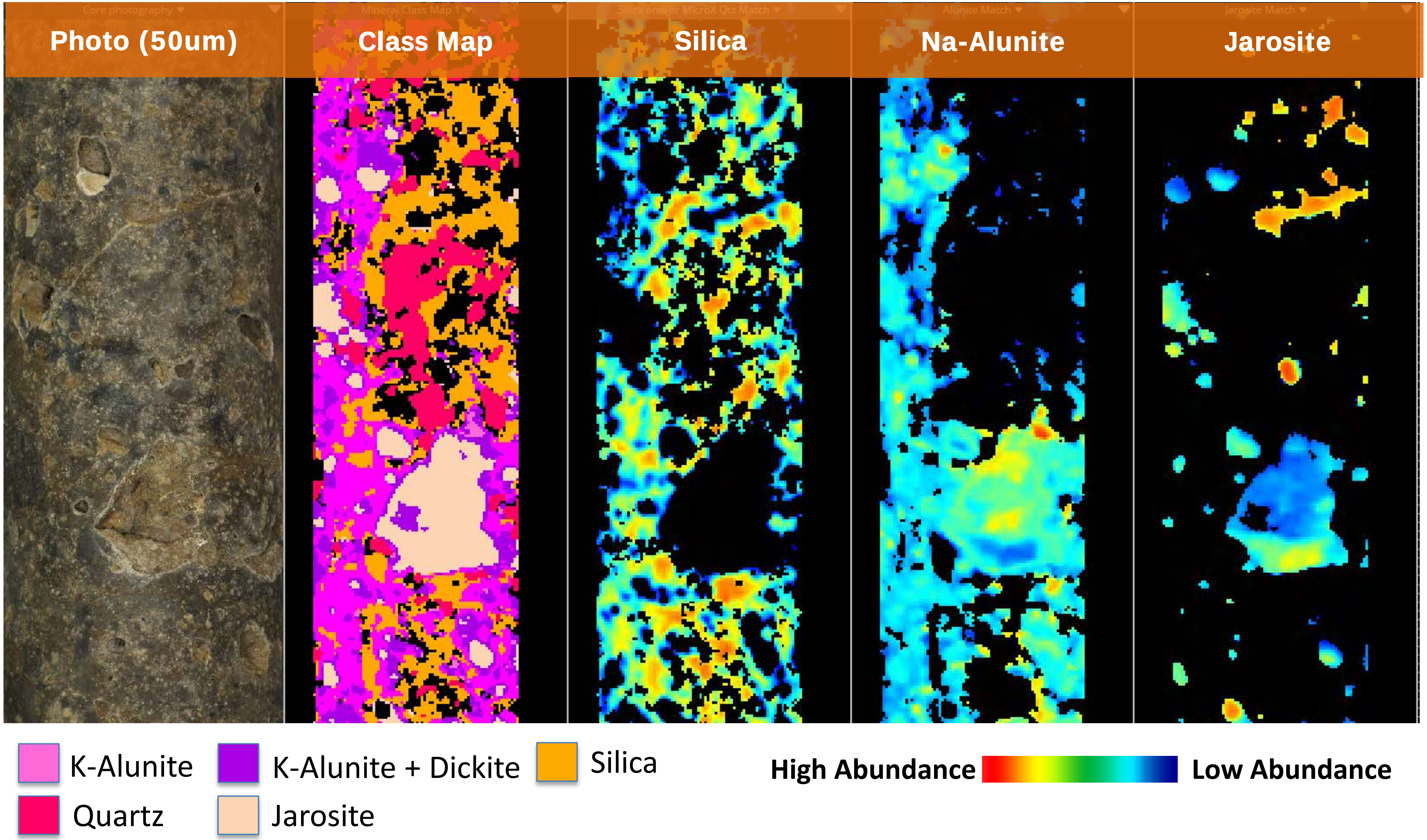
EPITHERMAL ALTERATION WITH GRADE – 2.19 GPT



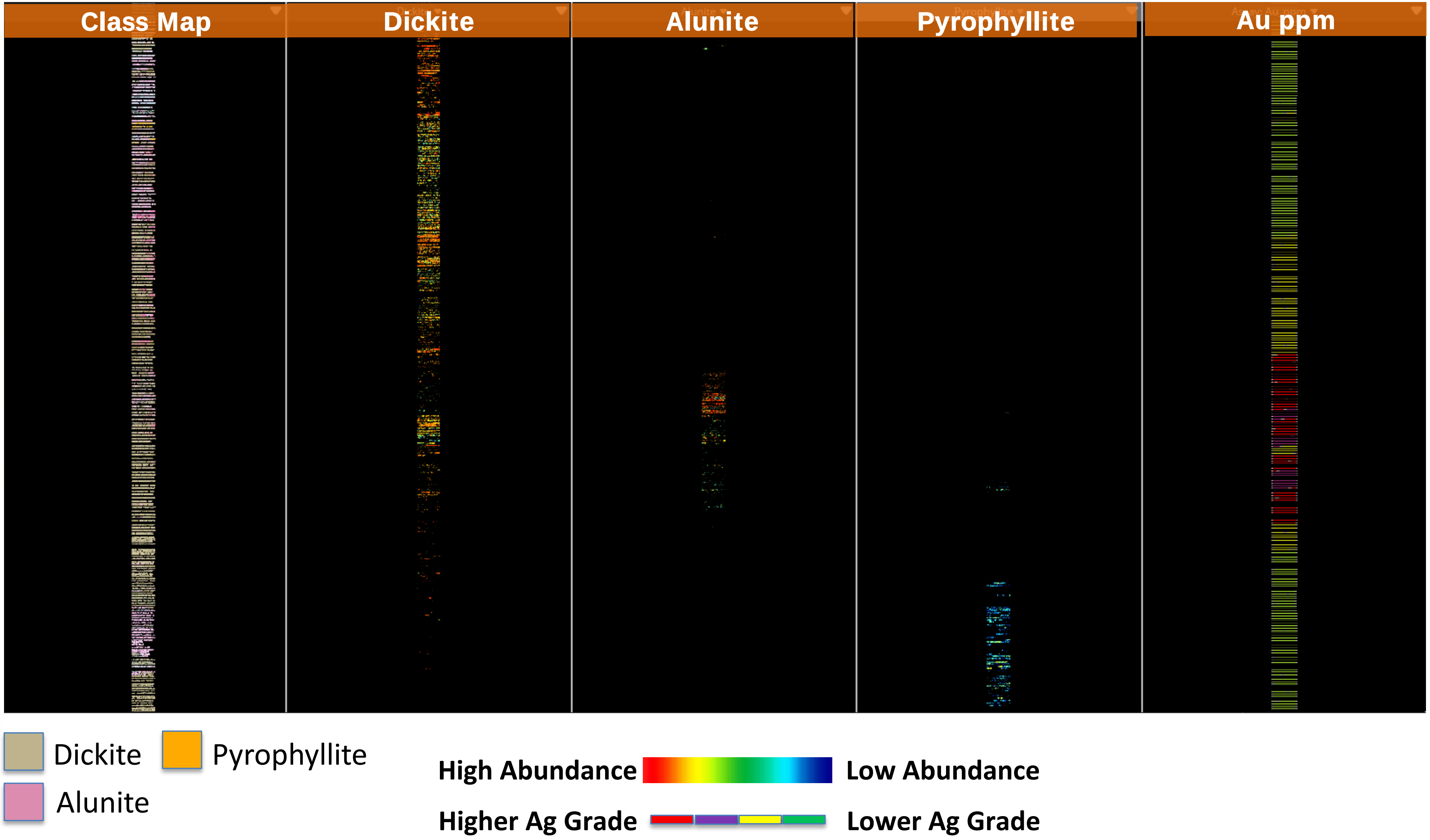
K-Alunite
K-Alunite + Dickite
Quartz
Jarosite

High Abundance Low Abundance

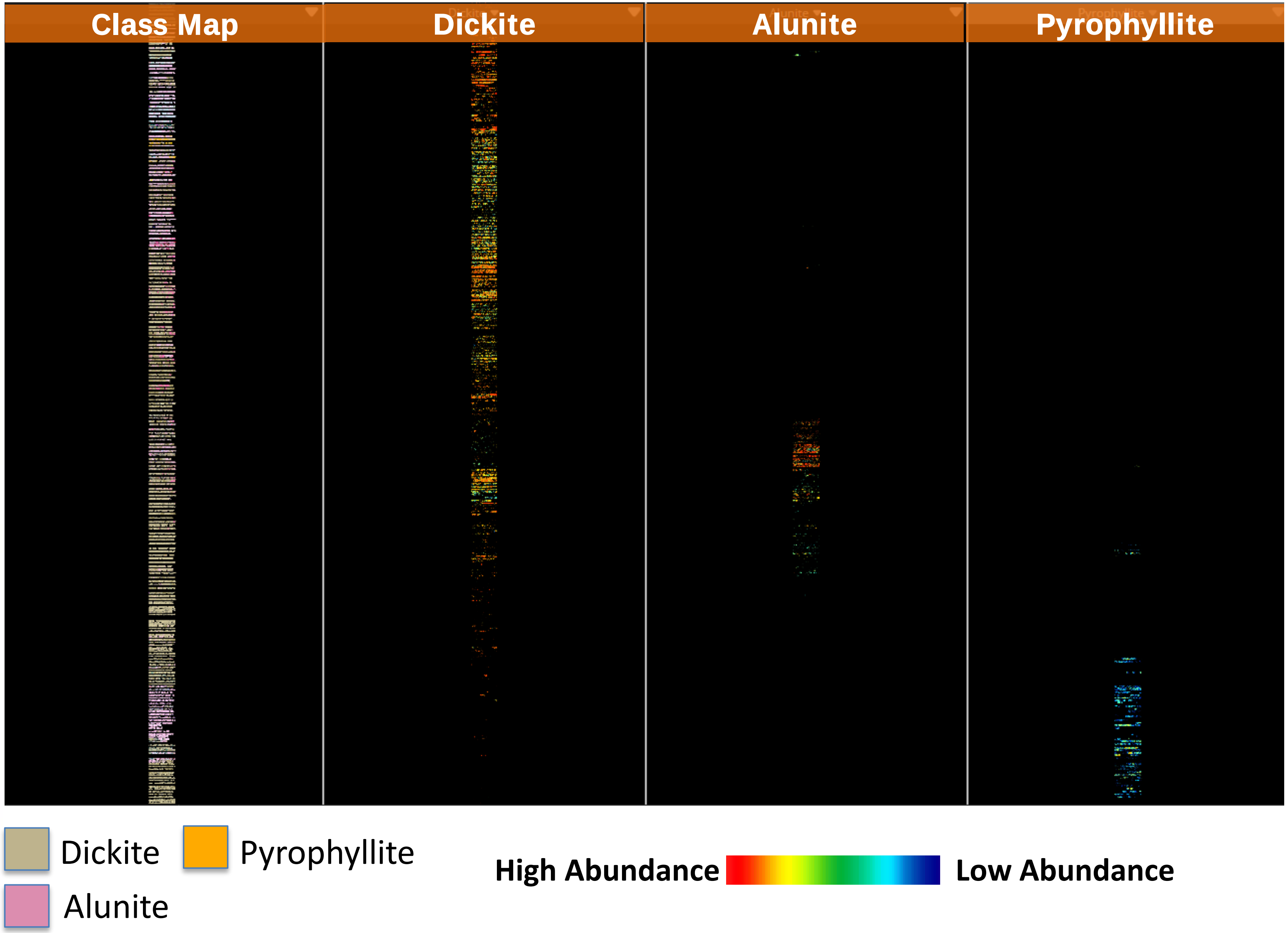
EPITHERMAL ALTERATION WITH GRADE – 17.5 GPT



EPITHERMAL ALTERATION WITH GRADE – BOREHOLE SCALE



EPITHERMAL ALTERATION WITH GRADE – BOREHOLE SCALE



Export to downhole mineral % logs for database and 3D modeling

ASSEMBLAGE ID: MINERAL POINT LOGS

depth_from	depth_to	Aspectral	Bayldonite	Buddingtonite	Carbonate	Chlorite	Epidote	Goethite	Gypsum	Hematite	Kaolinite	Montmorillonite	Montmorillonite-Chlorite
246.3	247.55	0.433	0.000	0.152	0.000	0.000	0.000	19.206	0.000	33.591	0.195	2.874	0.000
247.55	248.8	0.706	0.000	1.622	0.000	0.000	0.000	27.000	0.004	18.775	0.149	1.513	0.000
248.8	250.1	2.856	0.000	0.103	0.000	0.000	0.000	17.721	0.007	30.730	0.047	3.716	0.000
250.1	251.4	2.302	0.000	1.730	0.000	0.000	0.000	25.571	0.010	21.937	0.544	1.226	0.000
251.4	252.85	1.186	0.000	2.706	0.000	0.000	0.000	23.022	0.010	25.687	0.003	6.860	0.000
252.85	254.05	1.883	0.000	2.366	0.000	0.000	0.000	21.782	0.002	22.463	0.052	0.941	0.000
254.05	255.2	5.543	0.000	3.637	0.000	0.000	0.000	26.842	0.008	17.884	0.050	0.967	0.000
255.2	256.3	8.175	0.000	20.646	0.000	0.000	0.000	24.055	0.005	20.216	0.181	0.351	0.000
256.3	257.55	3.370	0.000	3.860	0.001	0.000	0.000	25.668	0.006	25.147	1.212	2.439	0.000
257.55	258.6	7.259	0.000	0.179	0.000	0.000	0.000	19.003	0.004	33.567	2.347	13.982	0.000
258.6	259.1	7.187	0.000	0.166	0.000	0.000	0.000	35.180	0.011	15.300	0.826	1.249	0.000
259.1	260.35	7.027	0.000	0.424	0.000	0.000	0.000	20.403	0.002	35.336	0.061	1.671	0.000
260.35	261.6	10.074	0.000	0.043	0.000	0.225	0.000	24.955	0.000	11.382	0.000	1.748	0.052
261.6	262.9	4.325	0.000	0.017	0.003	0.067	0.000	29.332	0.002	7.469	0.008	3.499	0.002
262.9	264.7	1.480	0.015	0.003	0.013	28.120	0.000	33.583	0.000	14.949	0.317	6.570	4.981
264.7	266.65	0.238	0.000	0.002	0.006	34.724	0.000	32.016	0.000	19.153	0.260	4.416	2.636
266.65	268.6	0.272	0.000	0.001	0.000	19.584	0.000	19.471	0.000	41.784	0.080	8.440	0.201
268.6	270.6	0.740	0.010	0.002	0.000	20.713	0.000	32.497	0.000	23.476	0.097	13.024	1.488
270.6	272.6	1.211	0.000	0.018	0.001	4.463	0.000	12.949	0.000	72.871	0.025	3.943	0.007
272.6	274.6	0.953	0.000	0.033	0.000	0.232	0.000	15.061	0.000	78.341	0.000	0.865	0.000
274.6	276.6	1.463	0.000	0.041	0.006	5.677	0.000	14.329	0.002	67.520	0.022	1.794	0.000
276.6	278.6	1.525	0.000	0.027	0.000	3.251	0.000	19.093	0.000	65.310	0.000	1.868	0.000
278.6	280.6	3.091	0.000	0.036	0.003	1.916	0.000	33.104	0.000	50.668	0.034	3.064	0.030
280.6	282.2	2.293	0.000	0.012	0.006	5.582	0.000	25.289	0.000	48.303	0.000	8.918	0.036
282.2	283.35	0.785	0.000	0.000	0.001	2.567	0.000	20.933	0.000	32.700	1.569	36.769	0.233
283.35	285.15	0.002	0.000	4.348	0.000	0.004	0.000	6.881	0.000	47.003	0.739	27.548	0.000
285.15	287.15	0.002	0.000	0.000	0.000	0.000	0.000	12.237	0.000	44.383	1.213	16.784	0.000
287.15	289.1	0.045	0.000	0.000	0.000	0.000	0.000	9.523	0.000	54.753	0.658	26.562	0.000
289.1	291.05	0.004	0.000	0.000	0.000	0.000	0.000	3.282	0.001	54.812	0.541	38.636	0.000

Consistent, high resolution mineral point logs reveal basic (and sometimes subtle) mineral assemblages

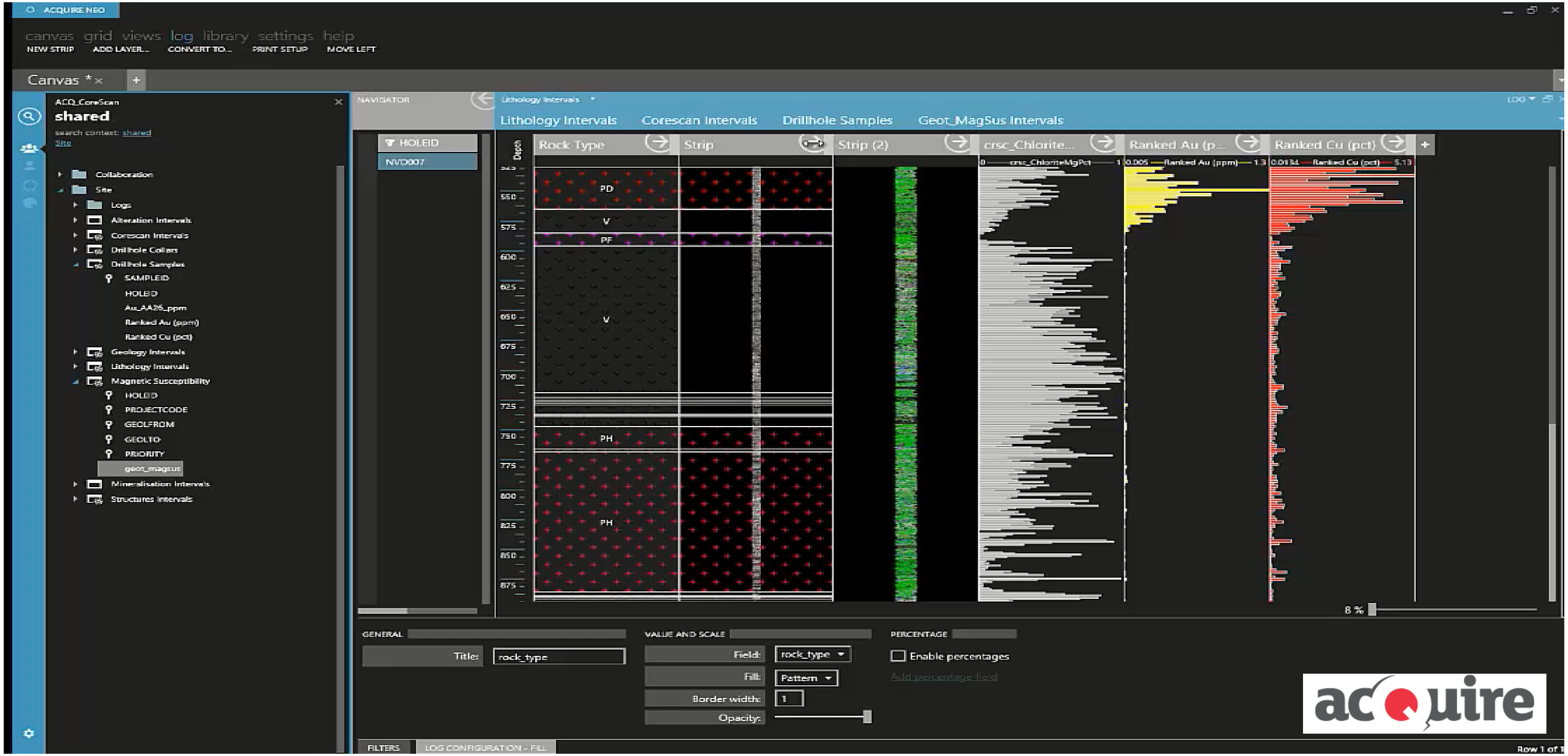
MINERAL POINT LOGS: RANKING OF ABUNDANCE AND ASSEMBLAGE ID

depth_from	depth_to	Name	Value (%)	2nd Mineral Name	Value (%)	3rd Mineral Name	Value (%)	4rd Mineral Name	Value (%)
227.35	228.95	Goethite	31.74	Hematite	28.79	Silica/Quartz	22.96	Aspectral	11.07
228.95	230.85	Goethite	29.63	Hematite	29.53	Silica/Quartz	25.17	Buddingtonite	6.99
230.85	232.8	Hematite	40.49	Silica/Quartz	28.69	Goethite	23.07	Montmorillonite	3.43
232.8	234.65	Hematite	41.48	Silica/Quartz	20.30	Goethite	19.77	Montmorillonite	6.74
234.65	236.55	Silica/Quartz	32.11	Goethite	24.24	Hematite	21.37	Aspectral	13.13
236.55	238.45	Silica/Quartz	43.10	Hematite	25.42	Goethite	21.86	Aspectral	5.17
238.45	240.15	Silica/Quartz	39.18	Goethite	28.77	Hematite	13.92	Aspectral	10.12
240.15	241.75	Silica/Quartz	39.01	Aspectral	17.63	Goethite	16.33	Buddingtonite	12.81
241.75	242.9	Silica/Quartz	44.82	Goethite	20.73	Hematite	15.14	Unclassified pixels	5.95
242.9	243.85	Silica/Quartz	35.52	Goethite	25.31	Hematite	19.36	Montmorillonite	14.96
243.85	245.05	Silica/Quartz	35.85	Goethite	26.44	Hematite	18.27	Buddingtonite	13.27
245.05	246.3	Silica/Quartz	39.69	Goethite	21.91	Hematite	20.98	Buddingtonite	9.52
246.3	247.55	Silica/Quartz	42.89	Hematite	33.59	Goethite	19.21	Montmorillonite	2.87
247.55	248.8	Silica/Quartz	48.57	Goethite	27.00	Hematite	18.77	Unclassified pixels	1.66
248.8	250.1	Silica/Quartz	43.88	Hematite	30.73	Goethite	17.72	Montmorillonite	3.72
250.1	251.4	Silica/Quartz	44.89	Goethite	25.57	Hematite	21.94	Aspectral	2.30
251.4	252.85	Silica/Quartz	39.73	Hematite	25.69	Goethite	23.02	Montmorillonite	6.86
252.85	254.05	Silica/Quartz	48.41	Hematite	22.46	Goethite	21.78	Buddingtonite	2.37
254.05	255.2	Silica/Quartz	42.65	Goethite	26.84	Hematite	17.88	Aspectral	5.54
255.2	256.3	Goethite	24.06	Silica/Quartz	22.54	Buddingtonite	20.65	Hematite	20.22
256.3	257.55	Silica/Quartz	34.92	Goethite	25.67	Hematite	25.15	Buddingtonite	3.86
257.55	258.6	Hematite	33.57	Silica/Quartz	21.85	Goethite	19.00	Montmorillonite	13.98
258.6	259.1	Silica/Quartz	36.98	Goethite	35.18	Hematite	15.30	Aspectral	7.19
259.1	260.35	Hematite	35.34	Silica/Quartz	33.34	Goethite	20.40	Aspectral	7.03
260.35	261.6	Silica/Quartz	47.95	Goethite	24.95	Hematite	11.38	Aspectral	10.07
261.6	262.9	Silica/Quartz	52.61	Goethite	29.33	Hematite	7.47	Aspectral	4.33
262.9	264.7	Goethite	33.58	Chlorite	28.12	Hematite	14.95	Montmorillonite	6.57
264.7	266.65	Chlorite	34.72	Goethite	32.02	Hematite	19.15	Montmorillonite	4.42
266.65	268.6	Hematite	41.78	Chlorite	19.58	Goethite	19.47	Montmorillonite	8.44
268.6	270.6	Goethite	32.50	Hematite	23.48	Chlorite	20.71	Montmorillonite	13.02
270.6	272.6	Hematite	72.87	Goethite	12.95	Chlorite	4.46	Montmorillonite	3.94
272.6	274.6	Hematite	78.34	Goethite	15.06	Unclassified pixels	2.28	Silica/Quartz	1.49
274.6	276.6	Hematite	67.52	Goethite	14.33	Unclassified pixels	7.32	Chlorite	5.68
276.6	278.6	Hematite	65.31	Goethite	19.09	Unclassified pixels	6.55	Chlorite	3.25
278.6	280.6	Hematite	50.67	Goethite	33.10	Unclassified pixels	5.12	Aspectral	3.09
280.6	282.2	Hematite	48.30	Goethite	25.29	Montmorillonite	8.92	Chlorite	5.58
282.2	283.35	Montmorillonite	36.77	Hematite	32.70	Goethite	20.93	Chlorite	2.57
283.35	285.15	Hematite	47.00	Montmorillonite	27.55	Silica/Quartz	7.79	Goethite	6.88
285.15	287.15	Hematite	44.38	Unknown-2360nm	24.67	Montmorillonite	16.78	Goethite	12.24
287.15	289.1	Hematite	54.75	Montmorillonite	26.56	Goethite	9.52	Unknown-2360nm	7.55
289.1	291.05	Hematite	54.81	Montmorillonite	38.64	Goethite	3.28	Silica/Quartz	1.67
291.05	292.95	Hematite	44.05	Montmorillonite	35.56	Silica/Quartz	11.04	Goethite	7.32
292.95	293.95	Hematite	31.79	Goethite	23.28	Montmorillonite	18.78	Unknown-2360nm	14.00
293.95	294.3	Goethite	31.67	Hematite	15.23	Montmorillonite	13.99	Silica/Quartz	13.11

Ranking of mineral occurrence within each measured interval reveals assemblage and vertical alteration zonation

SYNTHESIS/ANALYSIS OF HYPERSPECTRAL POINT DATA

Imagery, mineral maps and mineralogical point data from Corescan can be integrated with historical lith logs, assay and other downhole data (eg. mag sus) in a variety of geospatial database environments

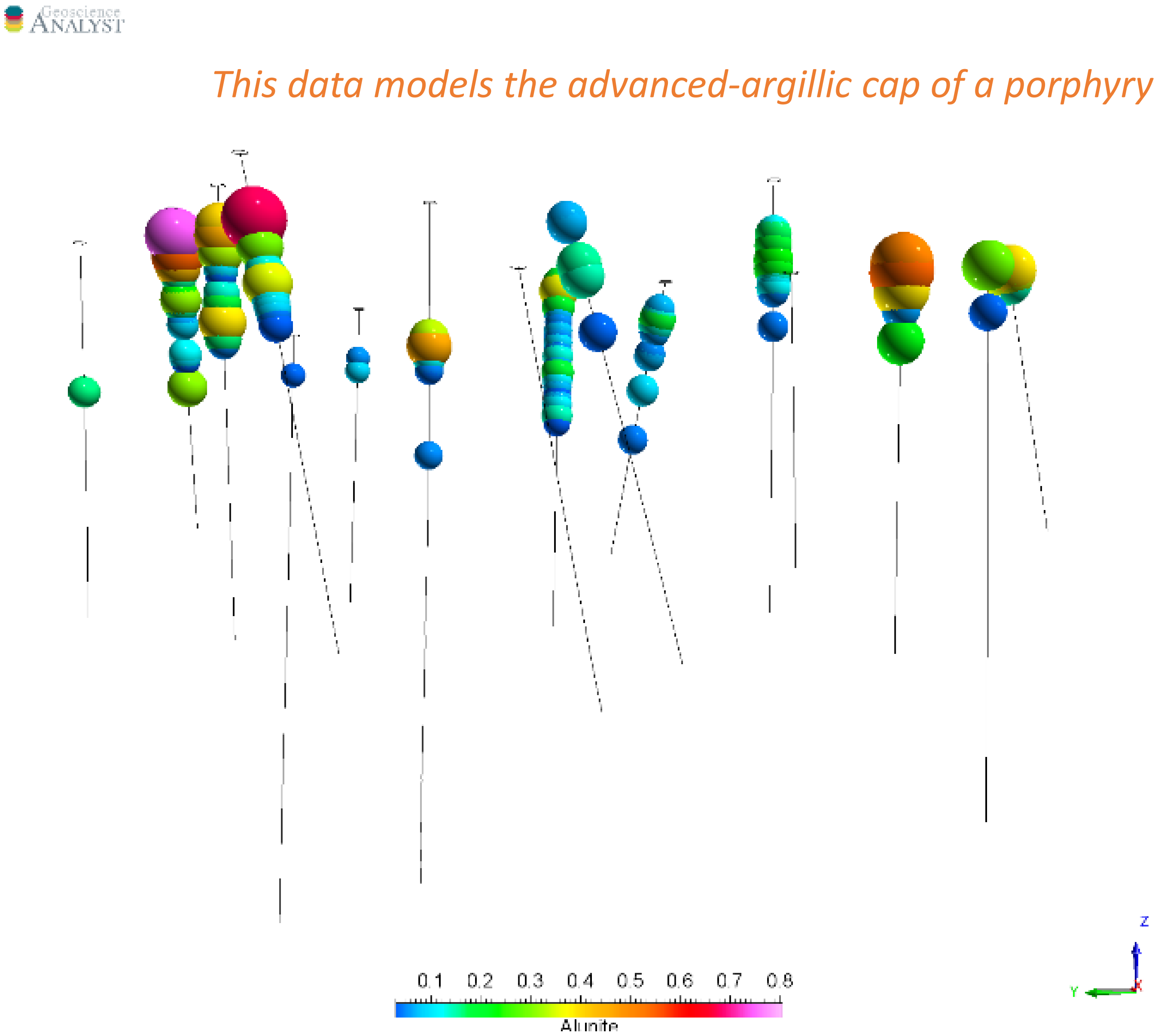


DEPOSIT-SCALE ALTERATION DOMAINS: ALUNITE

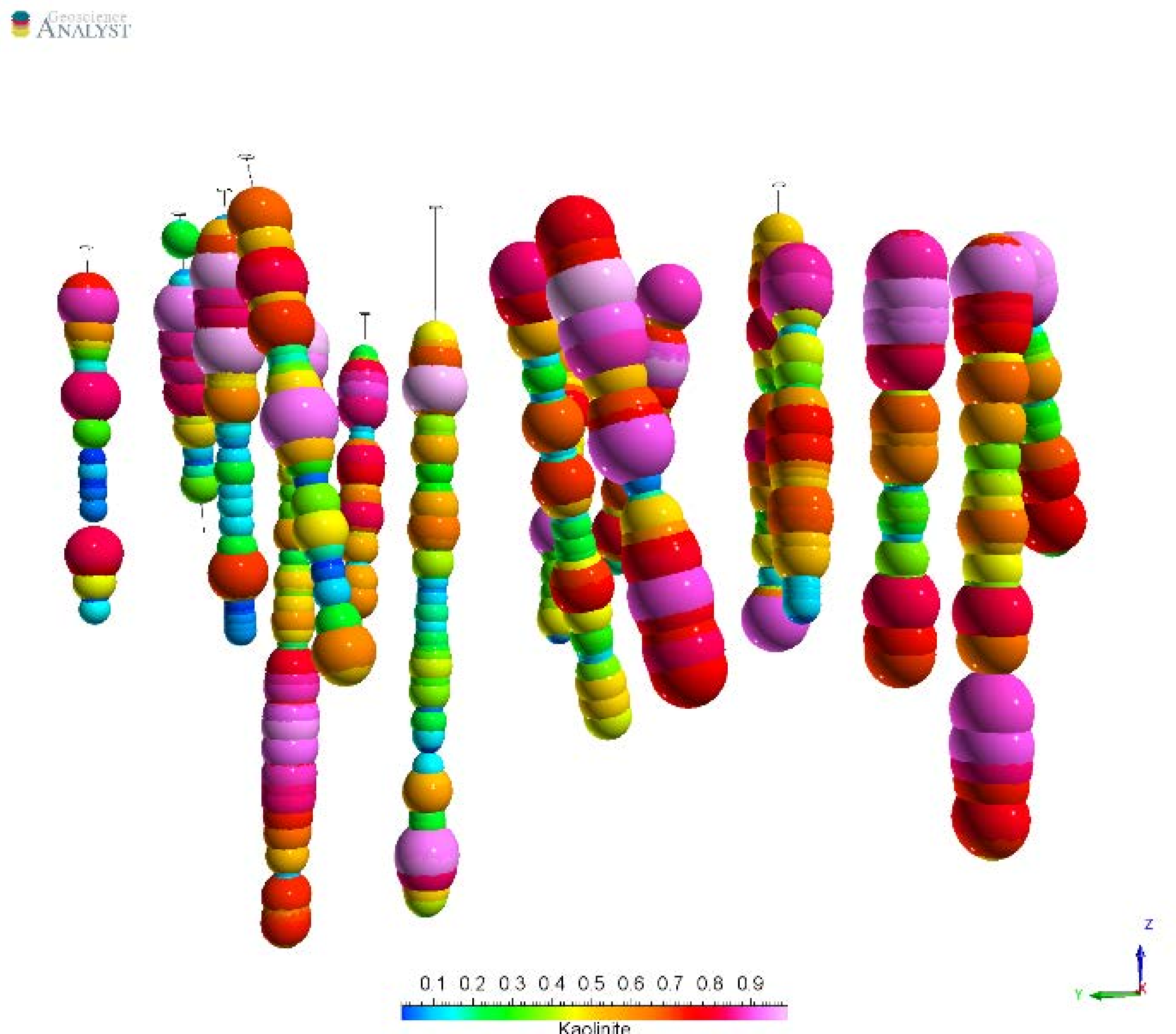
Alteration % point data brought into simple 3D models (e.g. Gocad, Leapfrog, Target, MineSight, Vulcan, etc.)

- Point data represents % of minerals counted downhole, in specific depth intervals
- This model was created with 1m interval data which represents ~200,000 pixels/signatures per meter of core
- Color of model spheres relates to purity or 'goodness' of fit to verified mineral spectral signatures
- Size of model spheres also relates directly to purity of the identified mineral

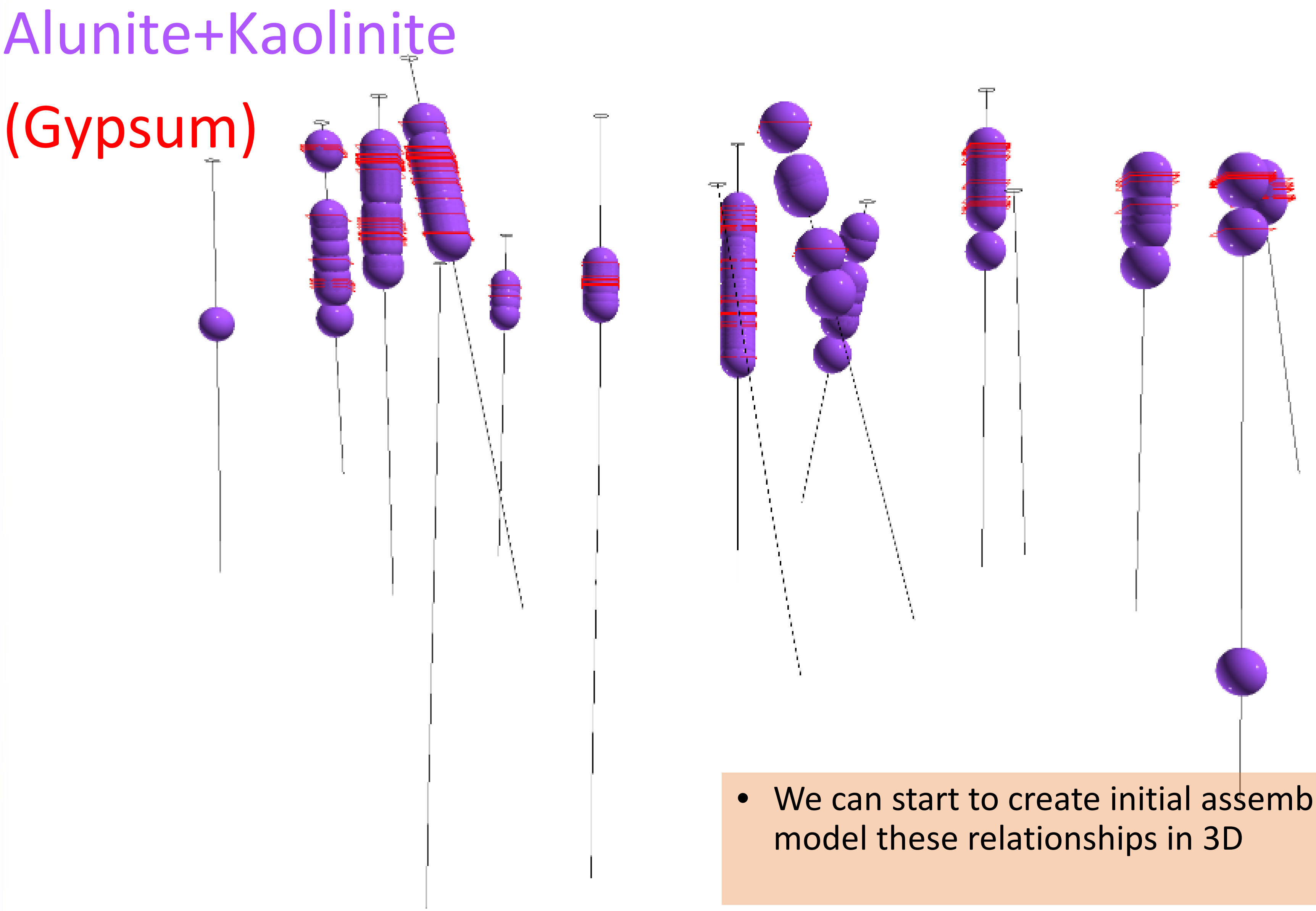
This data models the advanced-argillic cap of a porphyry system



DEPOSIT-SCALE ALTERATION DOMAINS: KAOLINITE

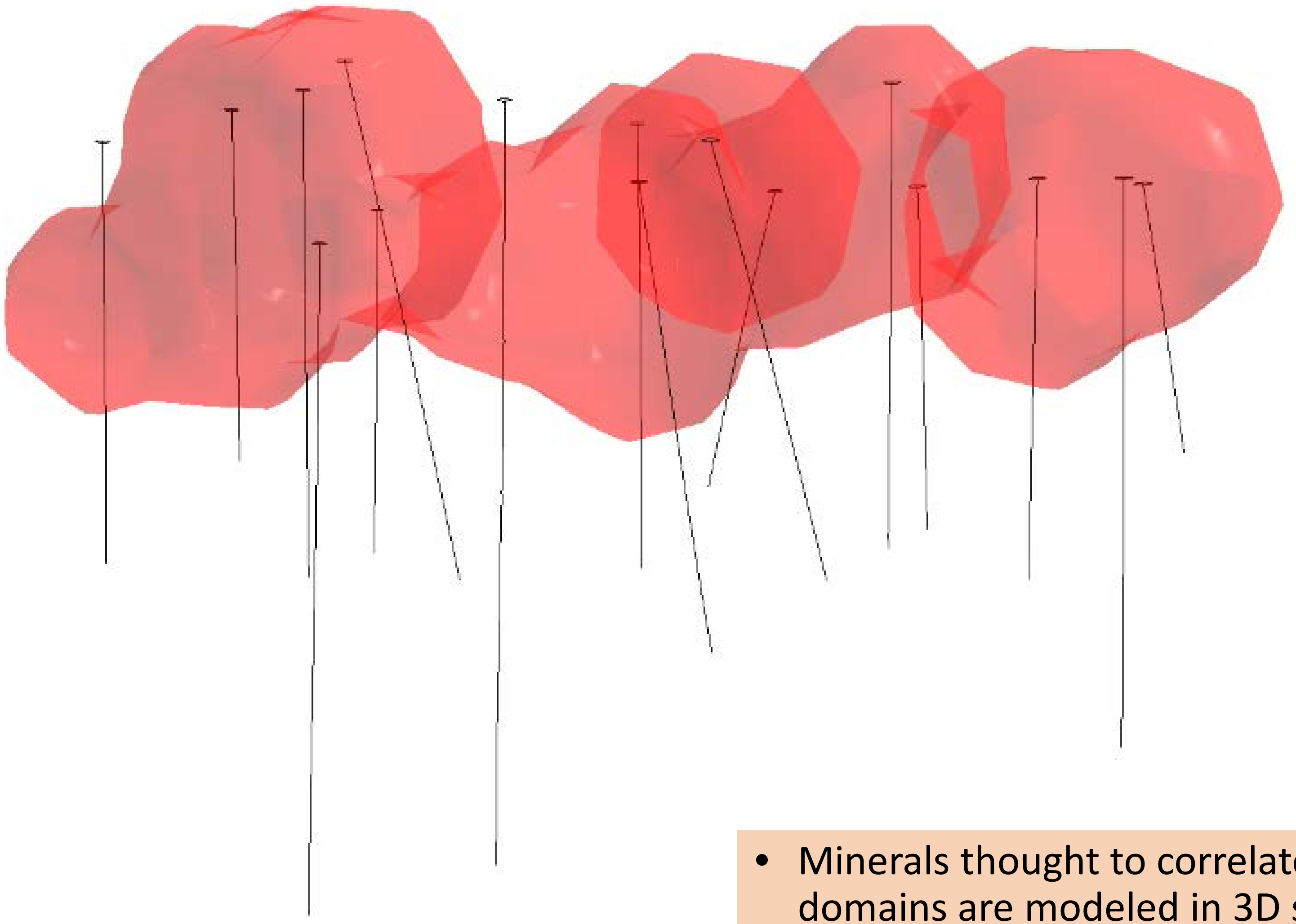


DEPOSIT-SCALE ALTERATION DOMAINS: ALUN+KAOL (+GYP)



- We can start to create initial assemblage classifications and model these relationships in 3D

DEPOSIT-SCALE ALTERATION DOMAINS: ADVANCED ARGILLIC



- Minerals thought to correlate to particular alteration domains are modeled in 3D space

"FROM MICRONS TO KILOMETERS"