Exploration '17 Post-conference Workshop:
Geochemistry and Infrared Spectral Mineralogical Data Integration for Mineral Exploration
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Integrated Spectral Geology for Mineral Exploration

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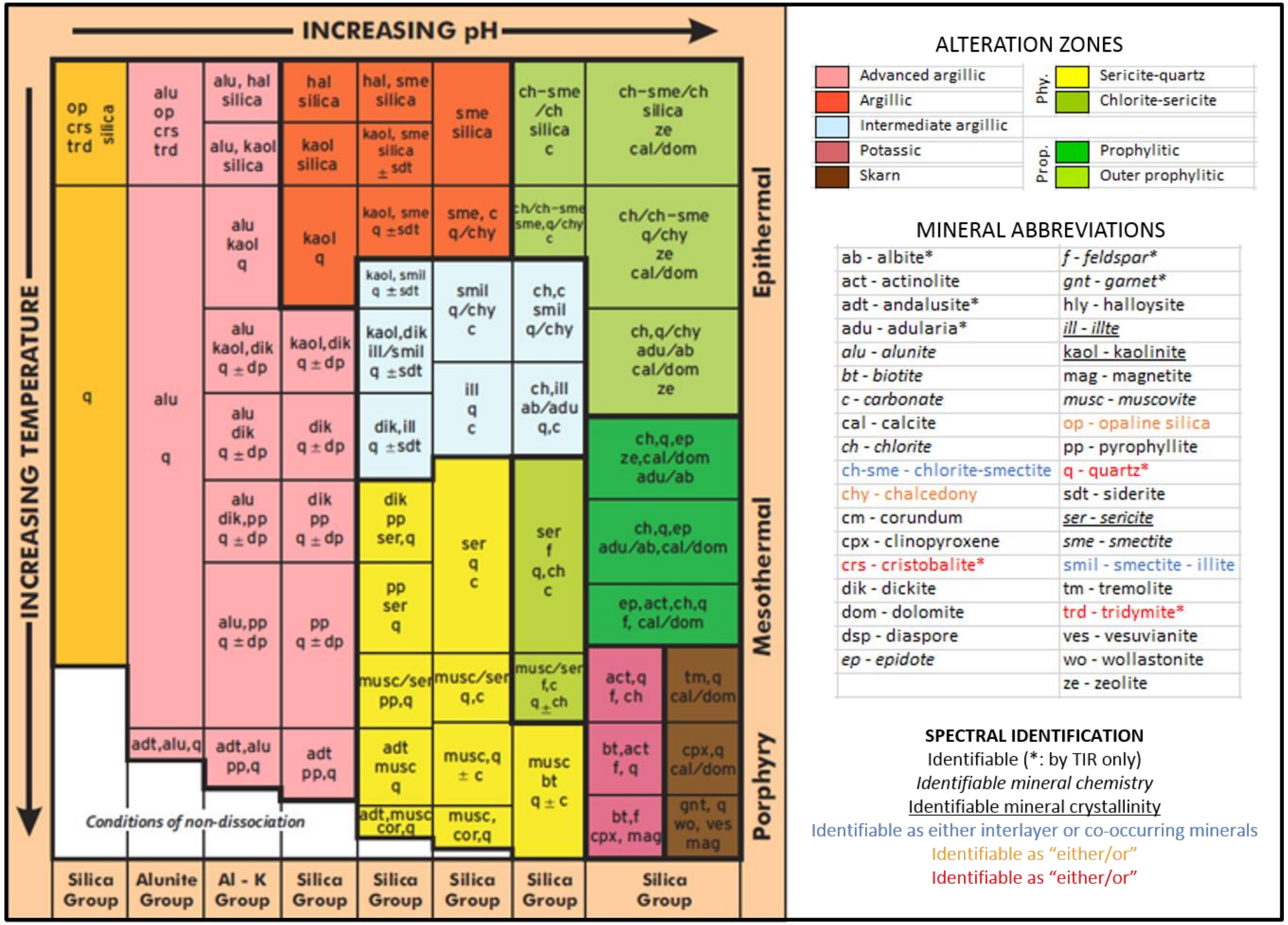
Outline

- **Introduction**
  - The Spectral Tool Box
    - Spectral Mineralogy
    - Instrumentation
  - Field Spectroscopy Workflow
- **Field Examples**
  - Porphyry, Carlin, HS
- **Limitations and Opportunities**
- **Summary**

Spectral Mineralogy – Detection Beyond Naked Eyes



Zhou et al, 2017 (a) Modified from Corbett and Leach, 1998 and Brommecker et al, 2011

- pH – T Gradient
  - Alteration assemblage vs indicator minerals
  - Spectral indices
  - Textures
  - Cryptic zonation
  - Far field footprint
- Target Signal
  - Spectral properties
  - Spectral interferences
  - Host rock effect
  - Overprint
  - Weathering
  - Cover
- Detection Tools
  - System fundamentals
  - Surface detection only
  - Operational constrains
- Integrated workflow
  - Data – Information - Knowledge

Spectral Mineralogy

Diagnostic features: the foundation

Minima position (wavelength), shape (relative depth, slope, doublet etc)

Spectral indices:

Numerical parameters: absorption wv, absorption depth, band ratio etc.

Mineral chemistry: e.g. white mica, alunite, chlorite, carbonates and biotite

Mineral crystallinity: white mica, kaolinite

Relative abundance: e.g. Al hydroxyl group vs carbonates

Spectral mixtures: what to expect

Affects wv, shape and slope; often non-linear

High reflective vs low reflective minerals

Certain diagnostic features persist in all mixtures

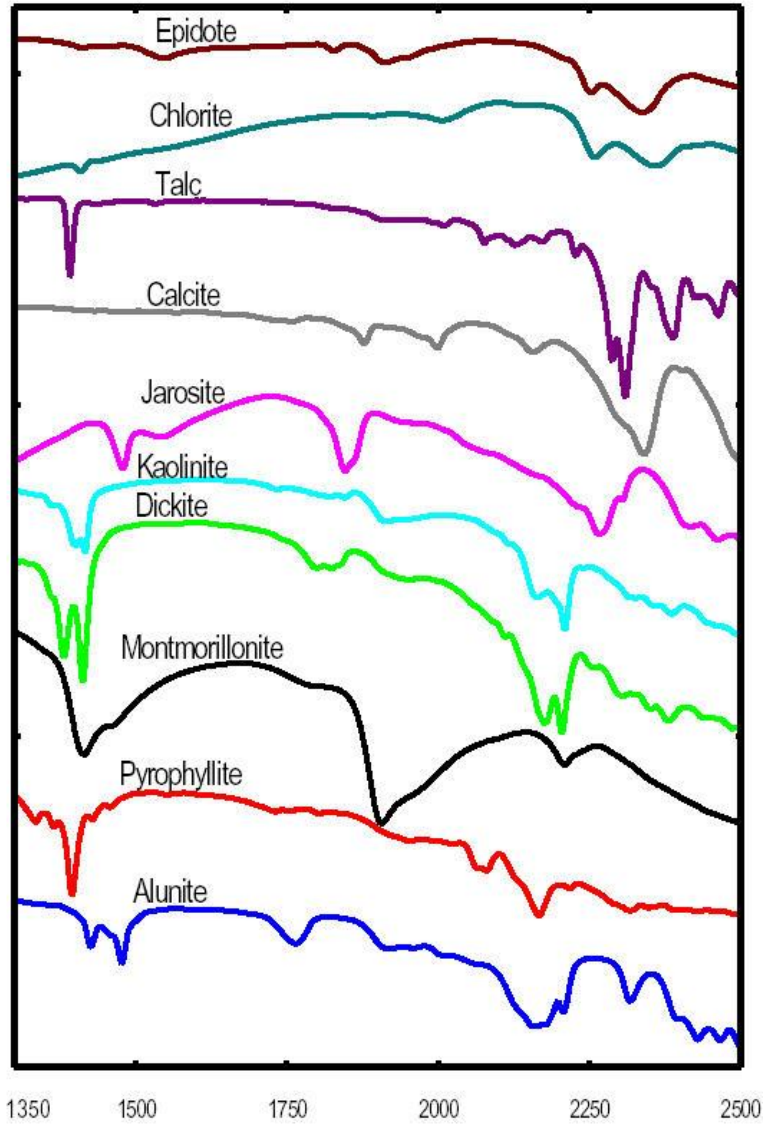
May miss those present in low abundance, especially low reflective minerals

May interfere with mineral id

May interfere spectral index values

Spectral Mineralogy

- Visible - near infrared (VNIR):
  - Iron oxides, iron hydroxide, iron sulfates
- Shortwave infrared (SWIR) →
  - Phyllosilicates
  - Hydroxylated silicates
  - Sulfates
  - Carbonates
  - Ammonium bearing minerals
- Thermal infrared (TIR):
  - Silicates:
    - Quartz, silica,
    - Feldspar, epidote
    - Amphiboles
  - Carbonates



SWIR Mineral ID

Absorption features

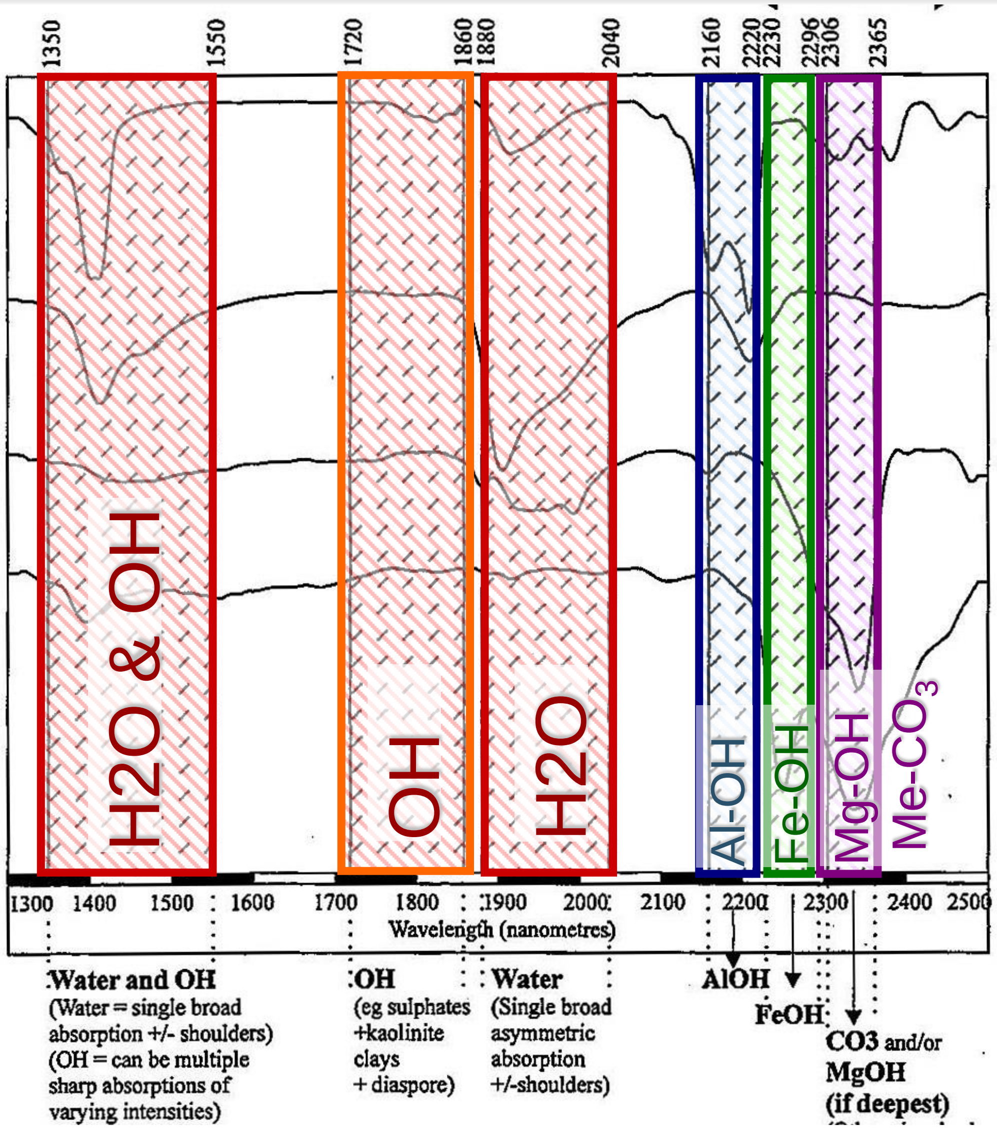
→ Molecular groups

→ Diagnostic features

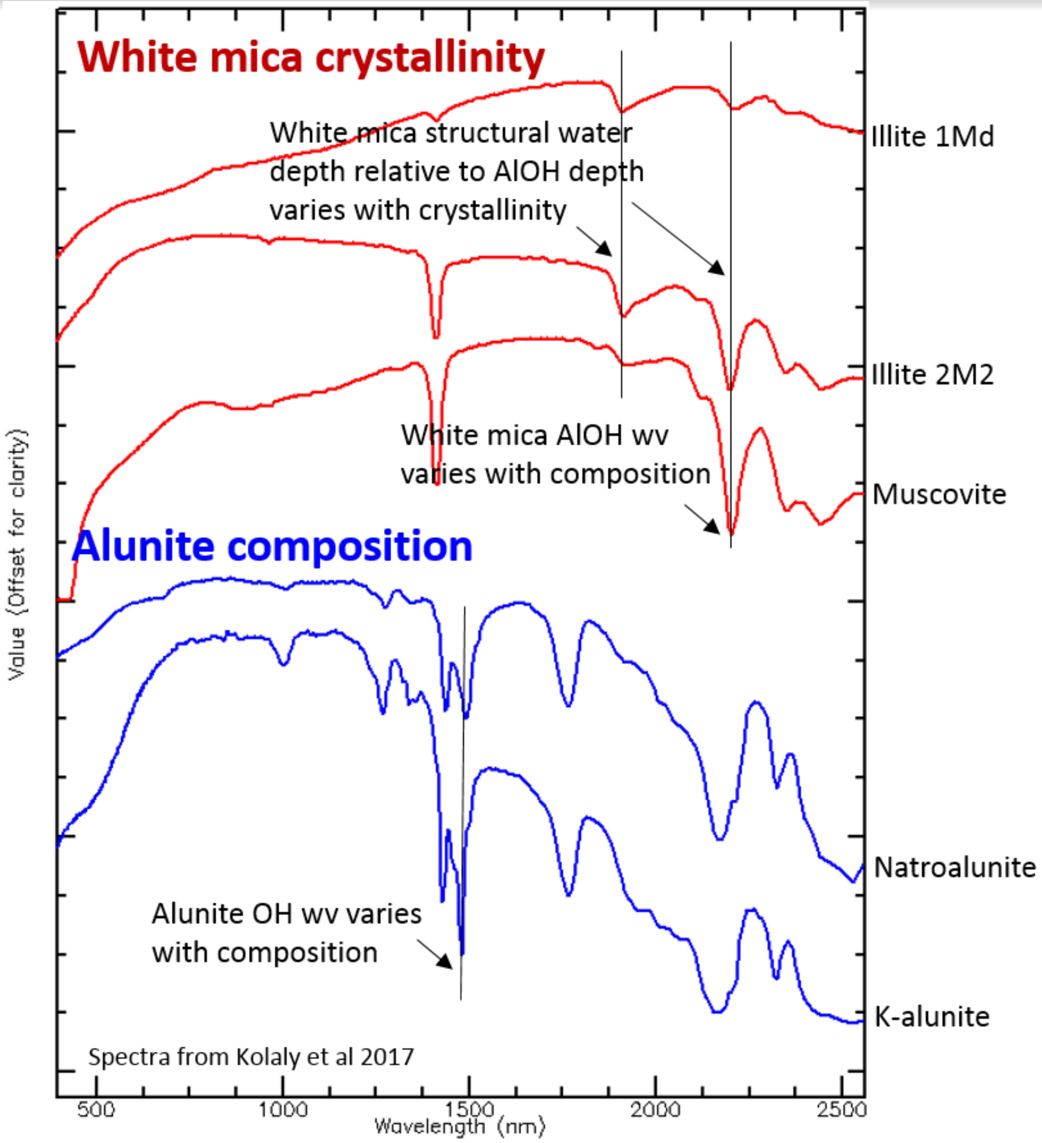
Mineral Identification

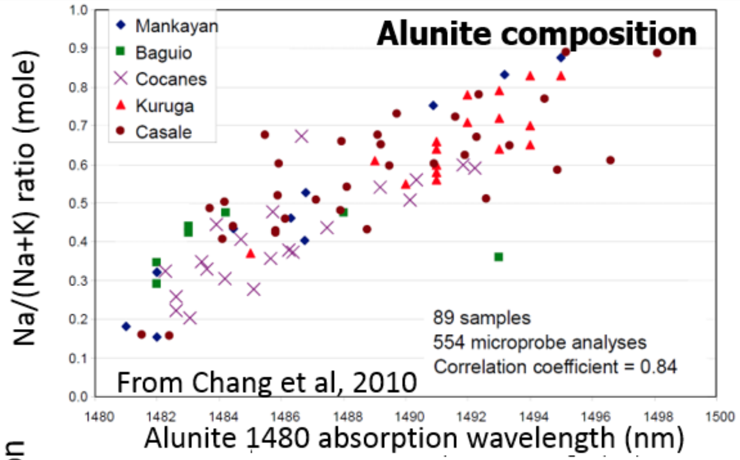
- Al-OH: Sericite & clay
- Mg/Fe-OH: Chlorite, epidote, biotite
- CO_3: Carbonates
- SO_4: Sulfates (alunite)

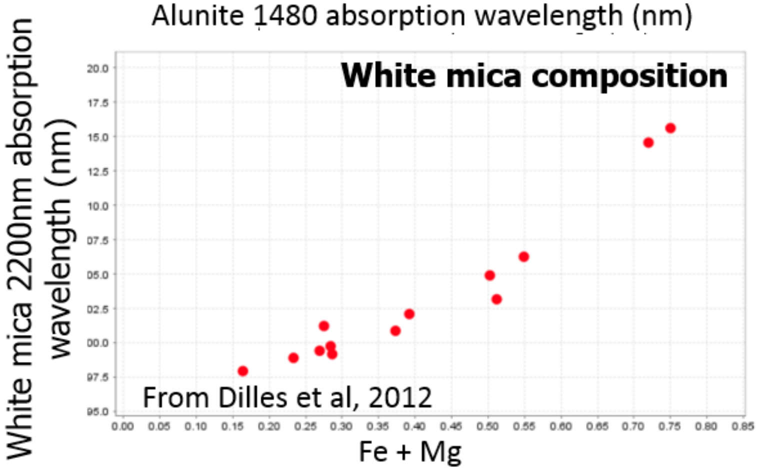
From AusSpec "GMEX", 1997



Spectral Indices







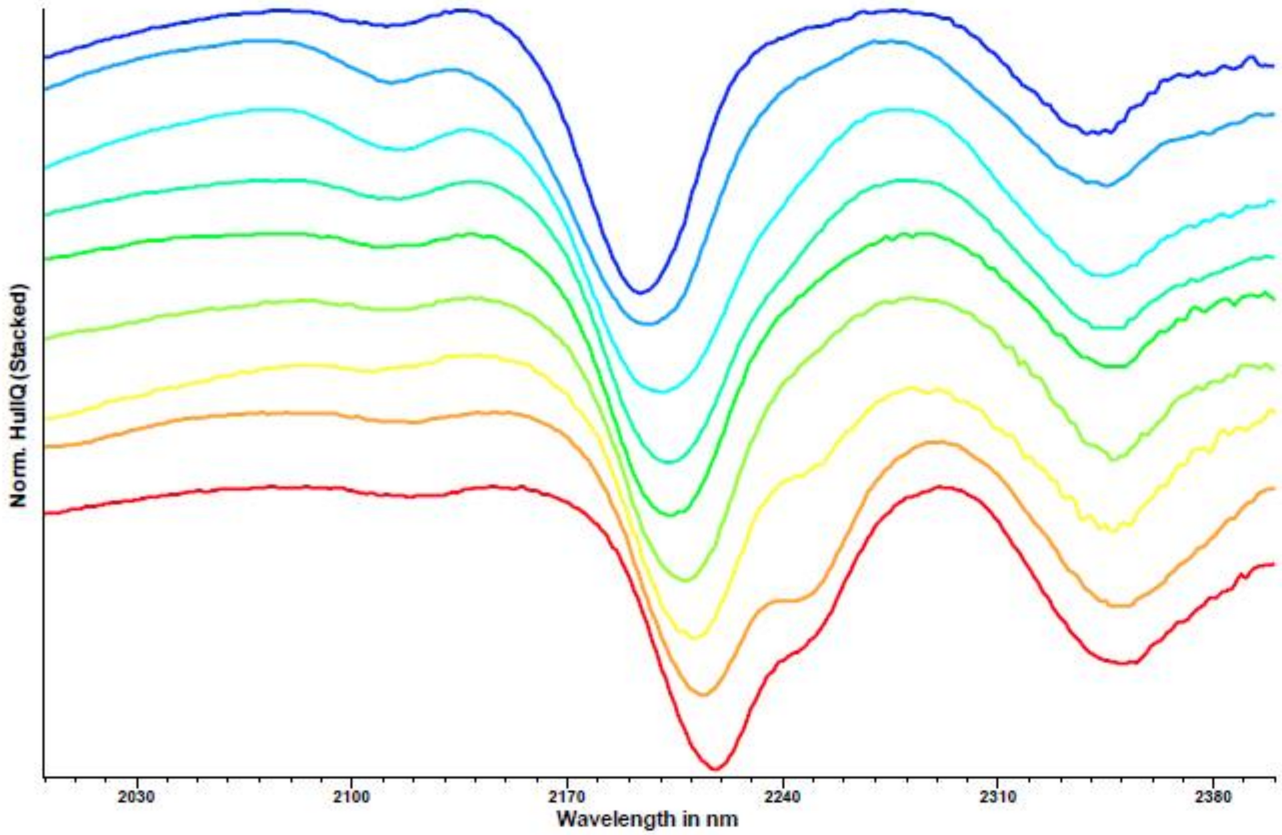
Spectral mineral chemistry indices:

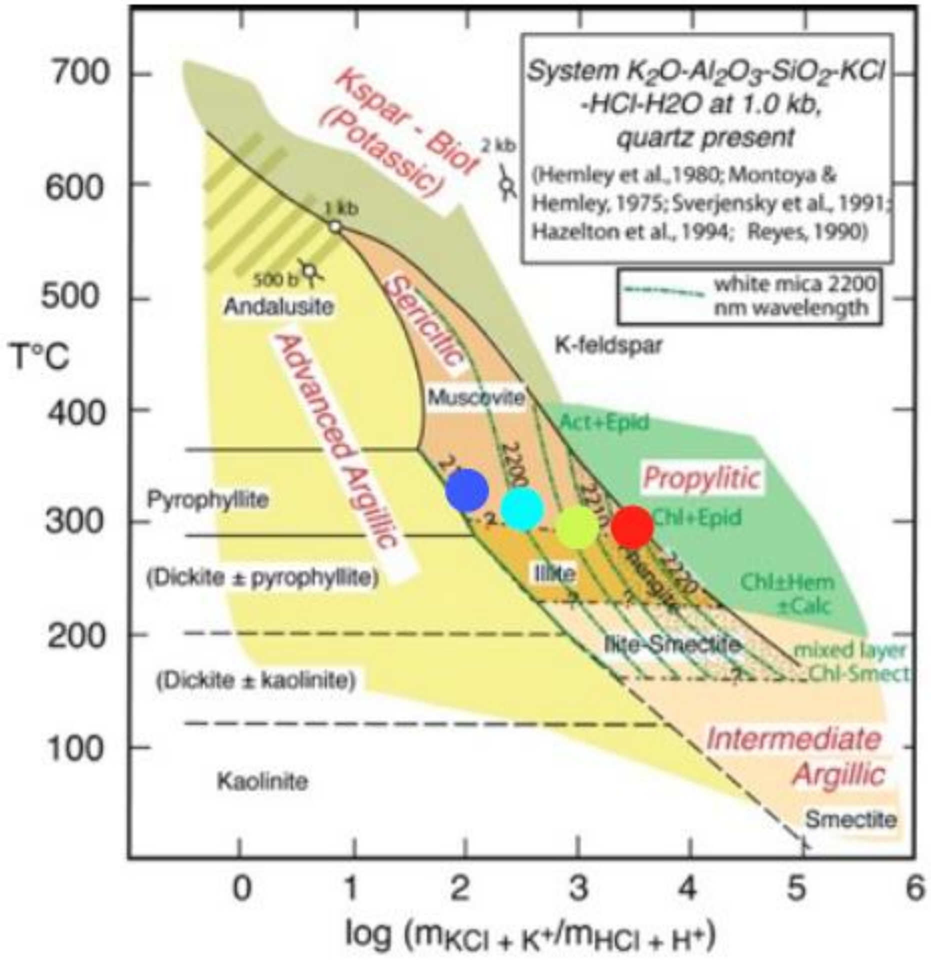
White mica (Scott and Yang, 1997)
2018-20190nm: paragonitic (Na)
2200-2208nm: muscovitic (K)
2216-2228nm: phengitic (Mg-Fe)

Alunite (Thompson et al, 1999)
~1478nm: K alunite
~1496nm: Na alunite
~1510nm: Ca alunite

Zhou et al 2017 (a)

Spectral Indices – White Mica Composition

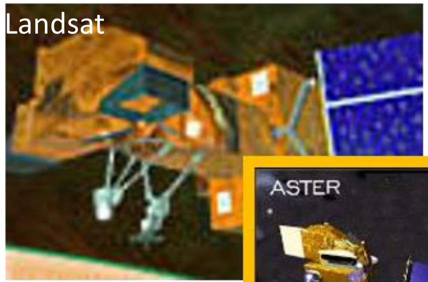


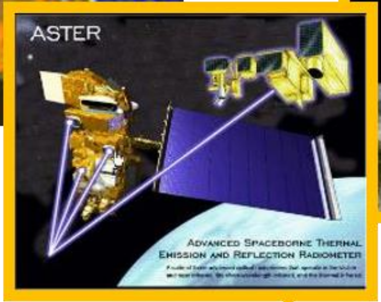


Dilles et al, 2012

Multi-scale Spectral Toolbox: System Fundamentals

Spaceborne — Airborne — Field Spectroscopy: Mobile Lab, Field Portable, Handheld





Probe-1
Hymap
SpecTIR

Hylogger
Corescan
TerraCore

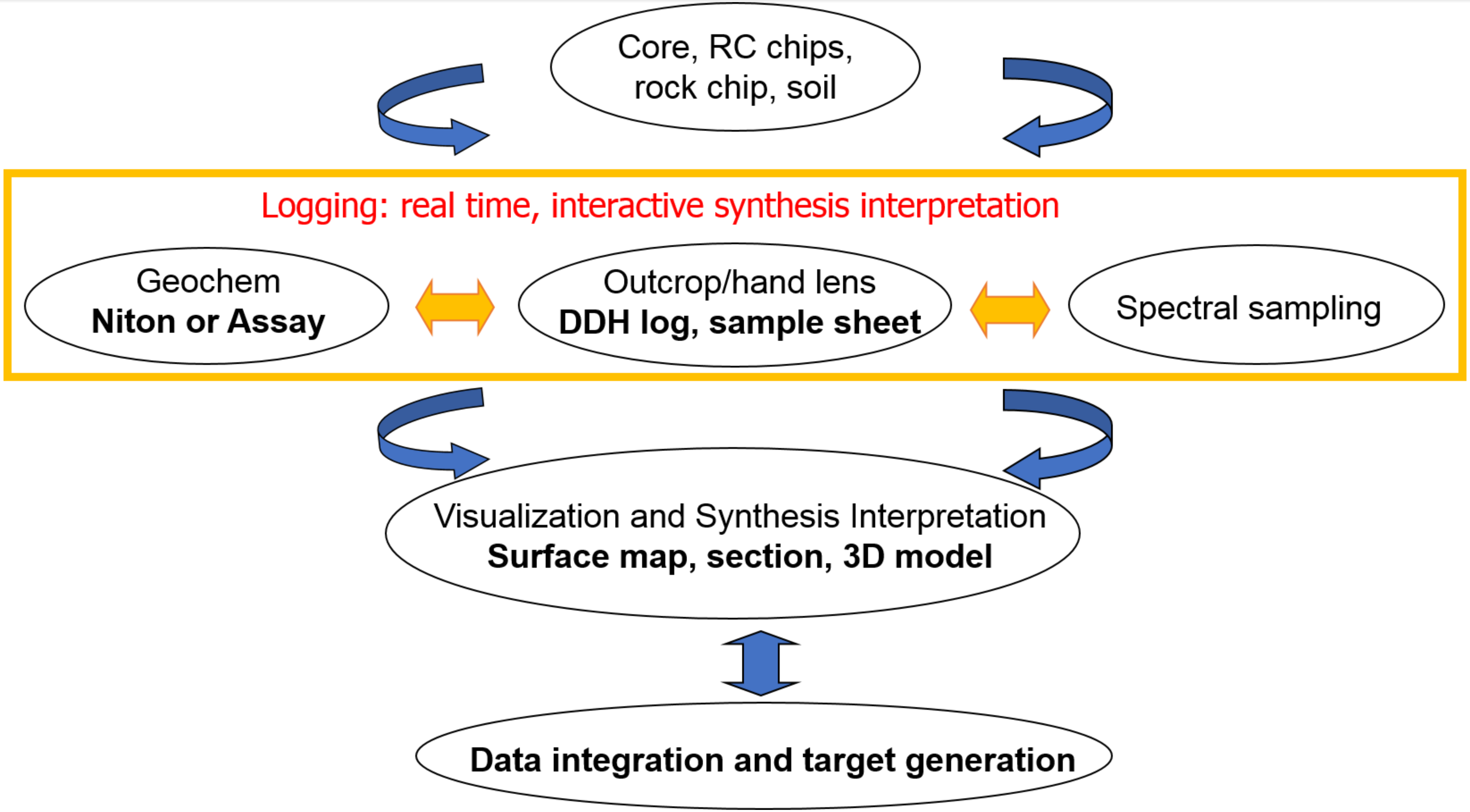
ASD Fieldspec/Terraspec
SE OreExpress

ASD Halo

Instrument		Aster	Wv-3 (2014)	Probe / Hymap	Corescan (2011)	TerraSpec 4
Platform		Spaceborne		Airborne	Mobile lab	Field portable
Sampling		Imaging systems				Point sampling
Spectral Range		VNIR-SWIR-TIR	VNIR-SWIR	VNIR-SWIR hyperspectral		
Spectral Resolution	VNIR @ 700 nm	~ 65 nm	~ 60 nm	15 - 16 nm	2.8 nm	3 nm
	SWIR1 @ 1400 nm	na	na		4.5 nm	10 nm
	SWIR2 @ 2100 nm	~ 40 nm	~ 40 nm	18 - 20 nm		
Spatial resolution		15m/30m/90m	1.2m / 7.5m	3 - 10 m	0.5 mm (0.05 mm*)	~1 - 2 cm

*core photo

Field Spectroscopy Workflow



Field Spectroscopy Workflow, Barrick South America

- Systematic Terraspec sampling on core and rock chip samples,
- Standardized procedures:
  - sampling, spectral interpretation, QAQC
  - Taking into account of textures, styles, intensity, mineral sites
- Team: project geologists, spectral geologists and field technicians.

ASD Real-time Spectral Logging, Barrick Cortez Study

+ Hand lens !

Spectral log, DDH geol-geochem log

Cortez real-time integrated synthesis interpretation during spectral data collection

- Stratigraphy: logging and pit mapping
- Structure: logging and pit mapping
- Geochemistry: assay + Niton
- Alteration assemblage:
  hand lens + ASD Fieldspec/Terraspec
  texture, mineralogy and
  illite composition index

Close collaboration with Cortez geologists

Corescan On-site Real Time Workflow, Barrick Alturas Project

Drill Rig

Sample Cleaning-drying

Check Properly labeled (#, depths)

Corescan Onsite Lab

Scanning

Real time viewing/ monitoring

On-site Real Time Processing and QA/QC

Within ~5min/meter, all data ready for viewing, **technicians test all data for spectral integrity as well as correct labeling and data storage**

Corescan

Barrick El Indio camp

Barrick

(Corescan Indio)
RAW data and processing server

(Corescan Indio)
Spectral data & images & 1m numerical log
Realtime

Bi-weekly courier

(Corescan Perth)
Coreshed.com
Images & sample interval numerical log
(bi-weekly update)

(Corescan Indio)
Elndio.coreshed.com
Updated daily

(Barrick)
Internet browser
blog
Coreshed.com

(Barrick Indio)
WIFI Internet browser (Corescan indio wifi)
Core Tray Viewer (Barrick indio wifi)
(geologos Ful Login)

Weekly acQuire Database Update

QA/QC

(Barrick specialist). Provide quick feedback to CoreScan processing - IMPROVE THE FINAL RESULT

Data access

- On-line Coreshed
- Barrick aQuire db: numerical logs
- GV Mapper: numerical logs

Real time logging with Corescan

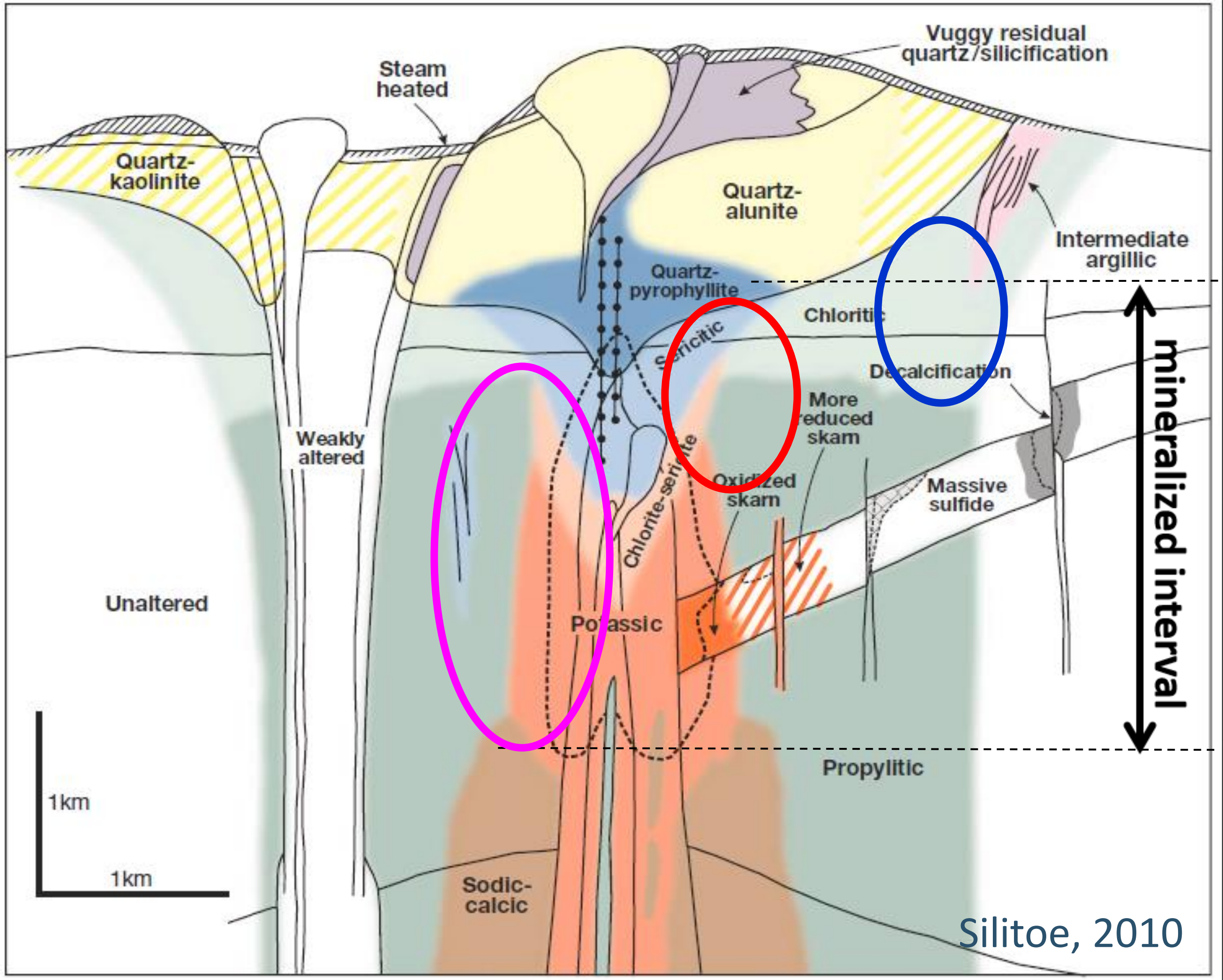
On-site Real Time Coreshed Data Access and Visualization

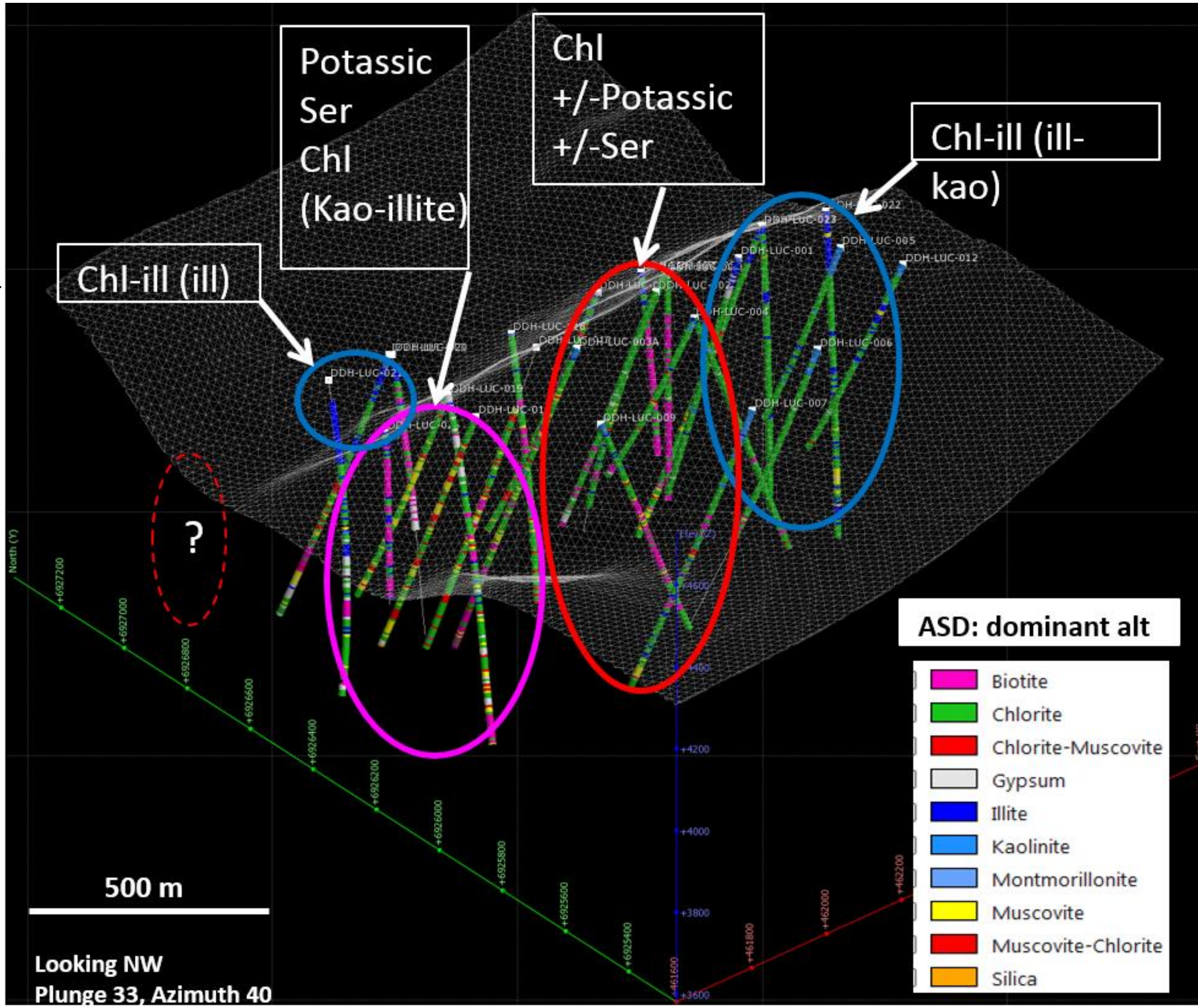
Zhou et al, 2017 (b), “Alturas Corescan Case History”

Spectral Geology

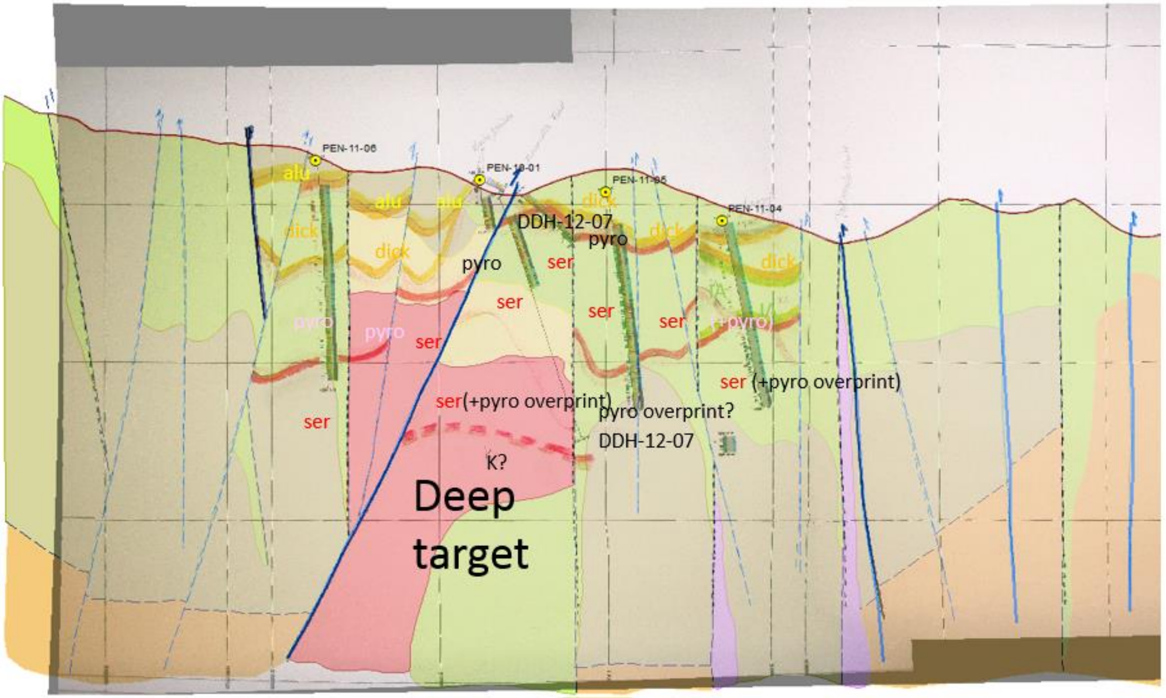
- Spectral Mineralogy Beyond Naked Eyes
  - Cryptic zonation
  - Far field footprint
  - Objective
  - Non-destructive
- Fluid-rock interaction: pH, T, redox, fluid/rock ratio etc
  - Zonation of alteration assemblages
    - Predicative models: Corbett and Leach (1998), Silitoe (2000 and 2010)
  - Zonation of mineral composition, crystallinity and intensity
    - Spectral indices
  - "Noises" and "constrains":
    - Host rock lithology, supergene/hypogene overprinting effect
    - Spectral "mixing" and interferences etc.
- Structural Mapping

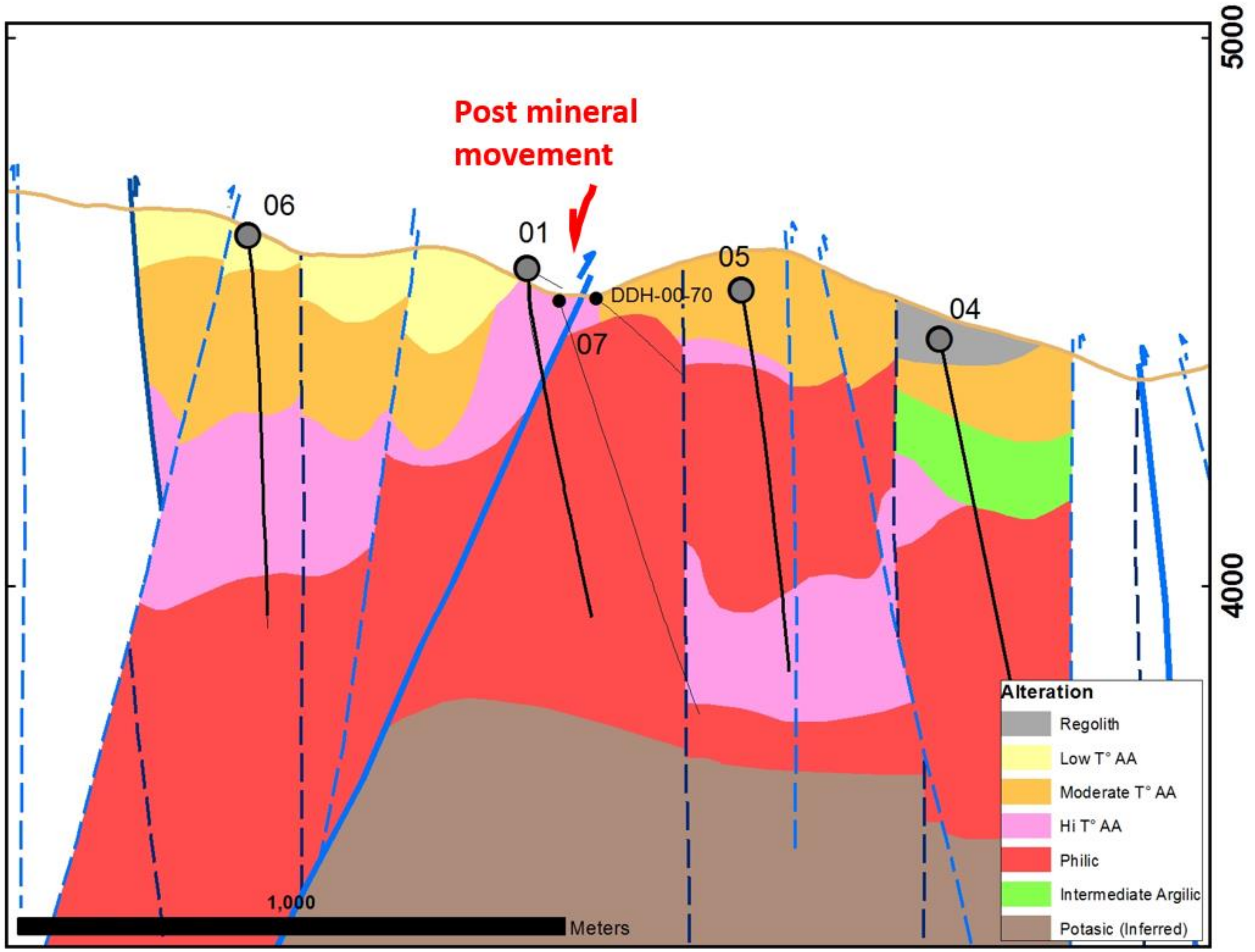
Field Examples: Luciano Porphyry Deposit, Casale District





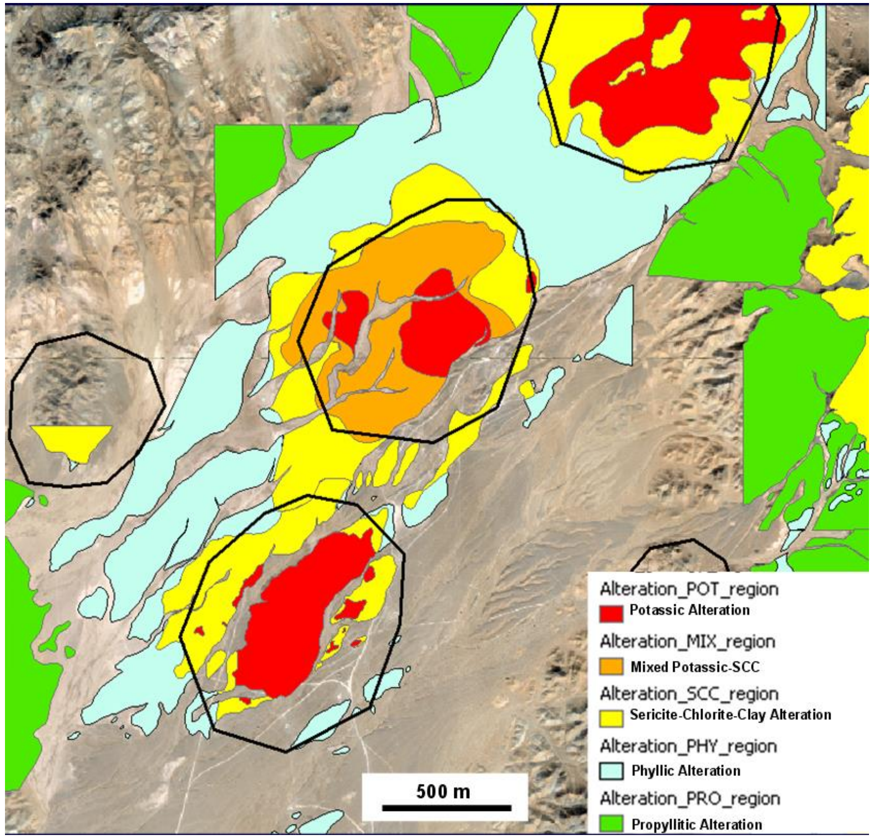
Field Example: Penelope, Argentina

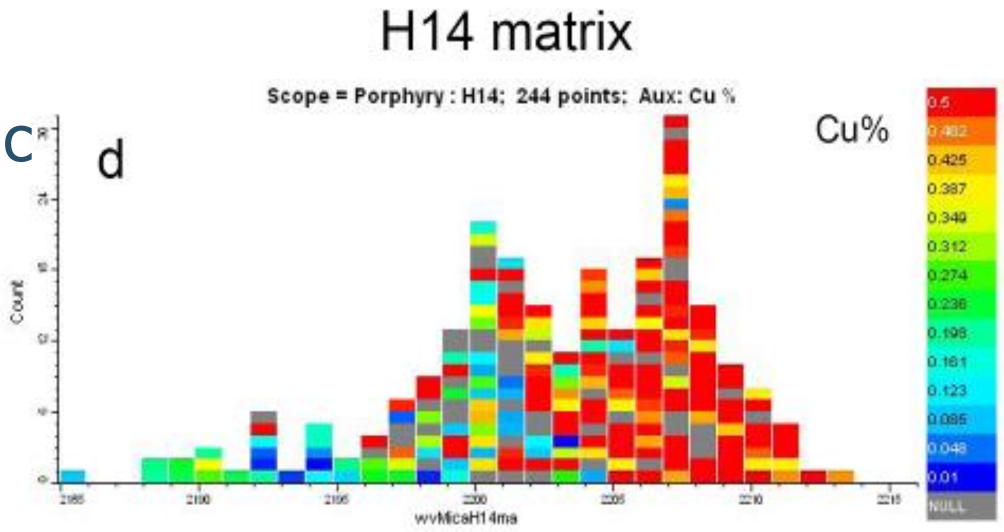


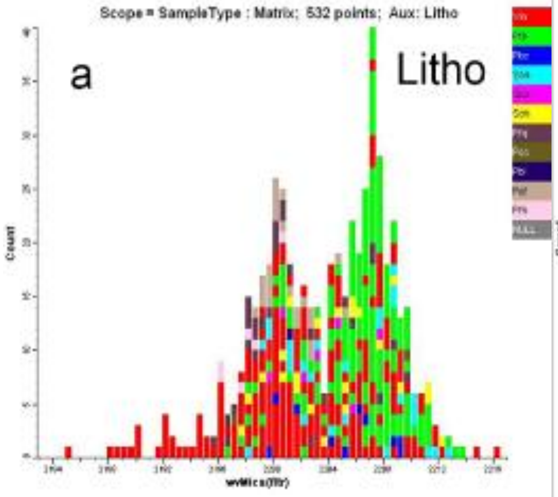


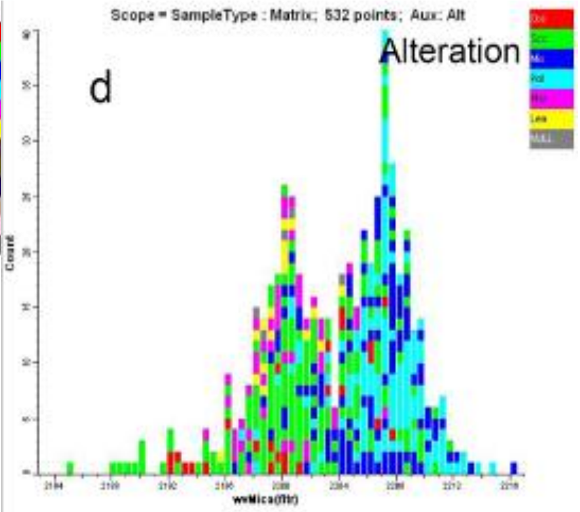
Field Examples: Reko Diq, Pakistan

- Porphyries - potassic: phengitic sericite
- Volcanics - SCC & phyllic: potassic sericite
- pH gradient, lithology or mineral site specific







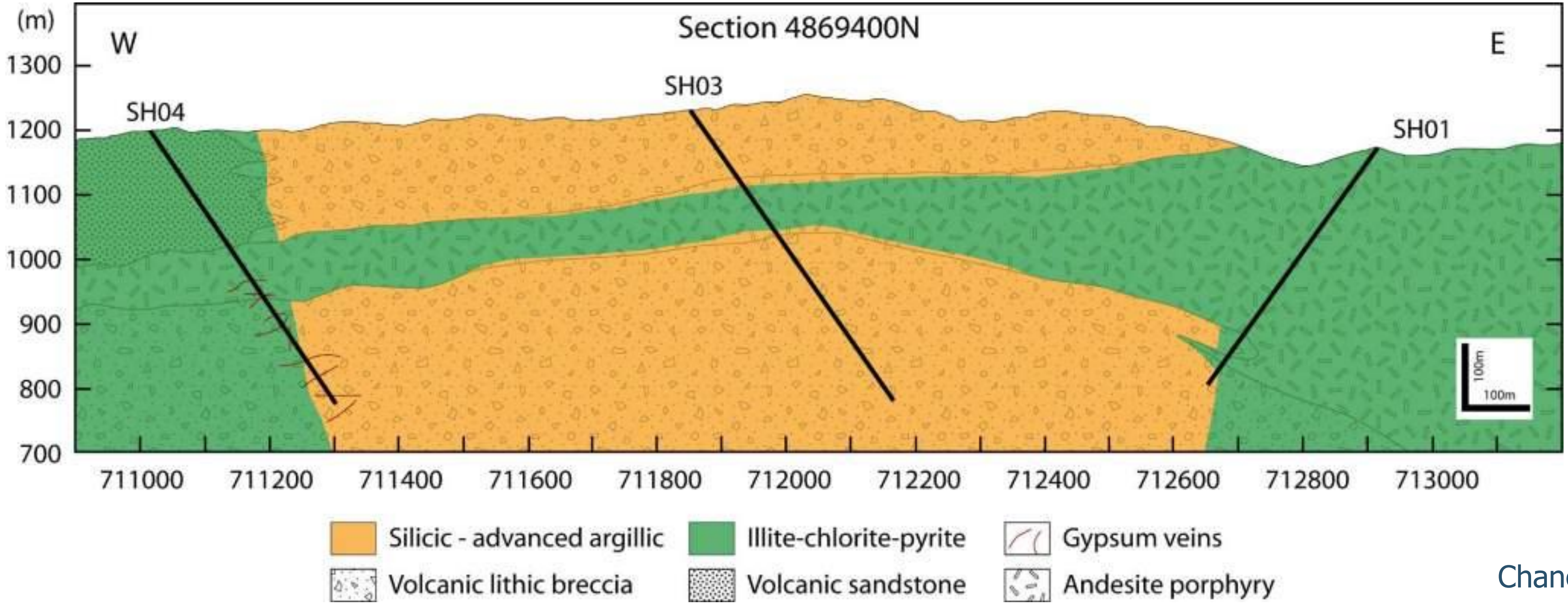


Field Examples: Shuteen, Far East, Philippines

Multiple layers of lithocap

Alteration strongly controlled by protolith

- Volcanic lithic breccia → silicic – advanced argillic alteration
- Andesite porphyry → Illite – chlorite – pyrite alteration

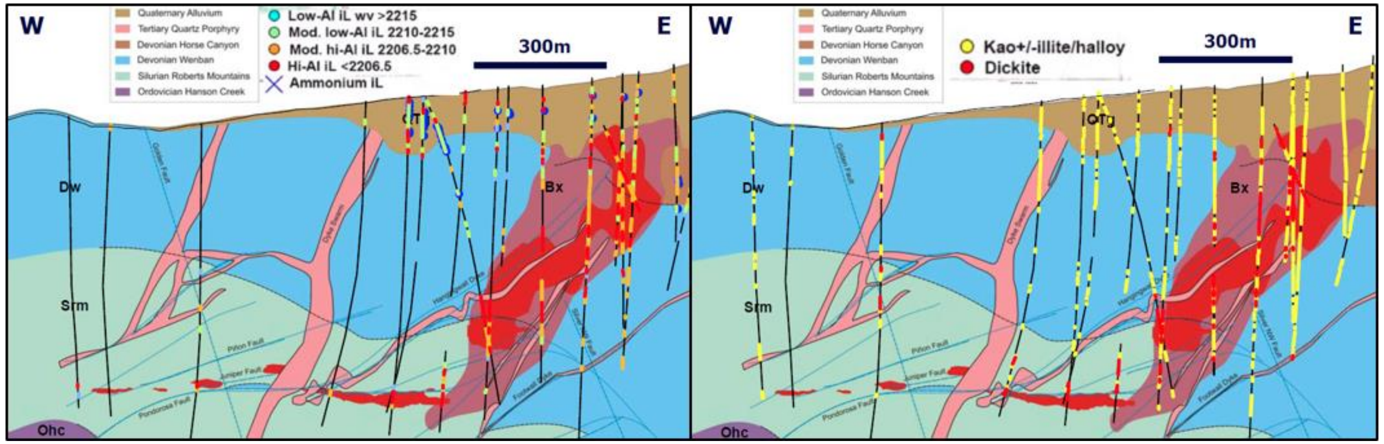


Chang et al, 2010

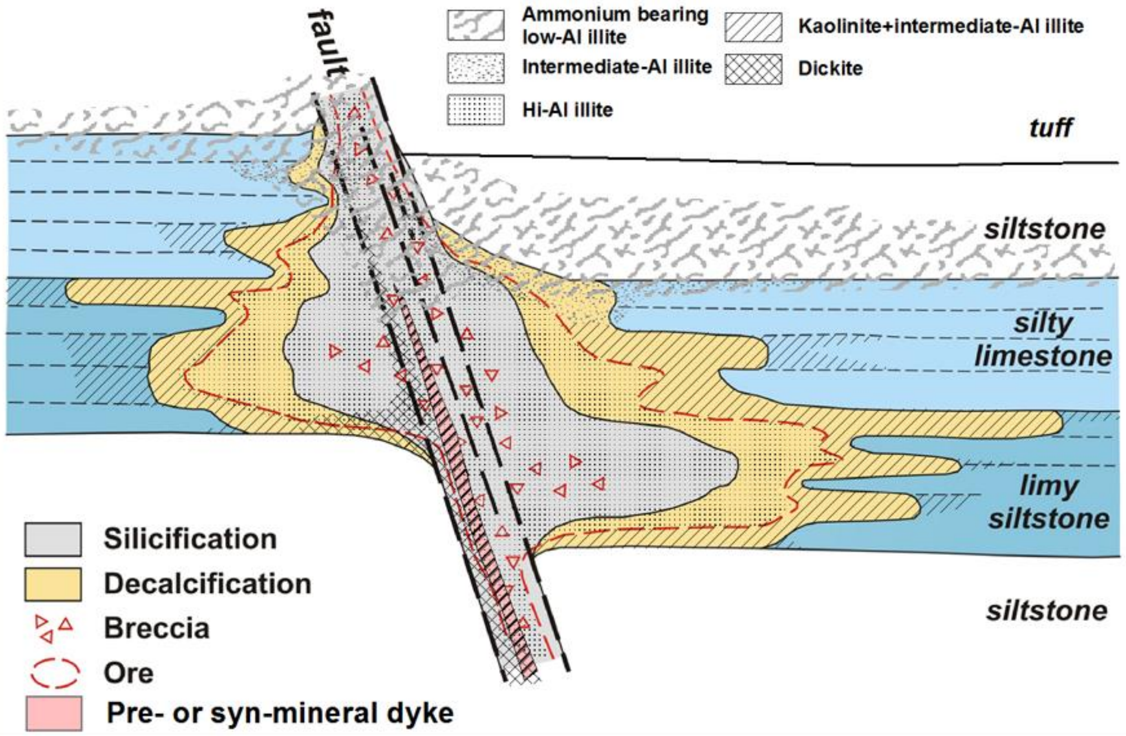
Field Examples: Cortez, Nevada, U.S.

Outcrop and hand lens observations

ASD Spectral Logging



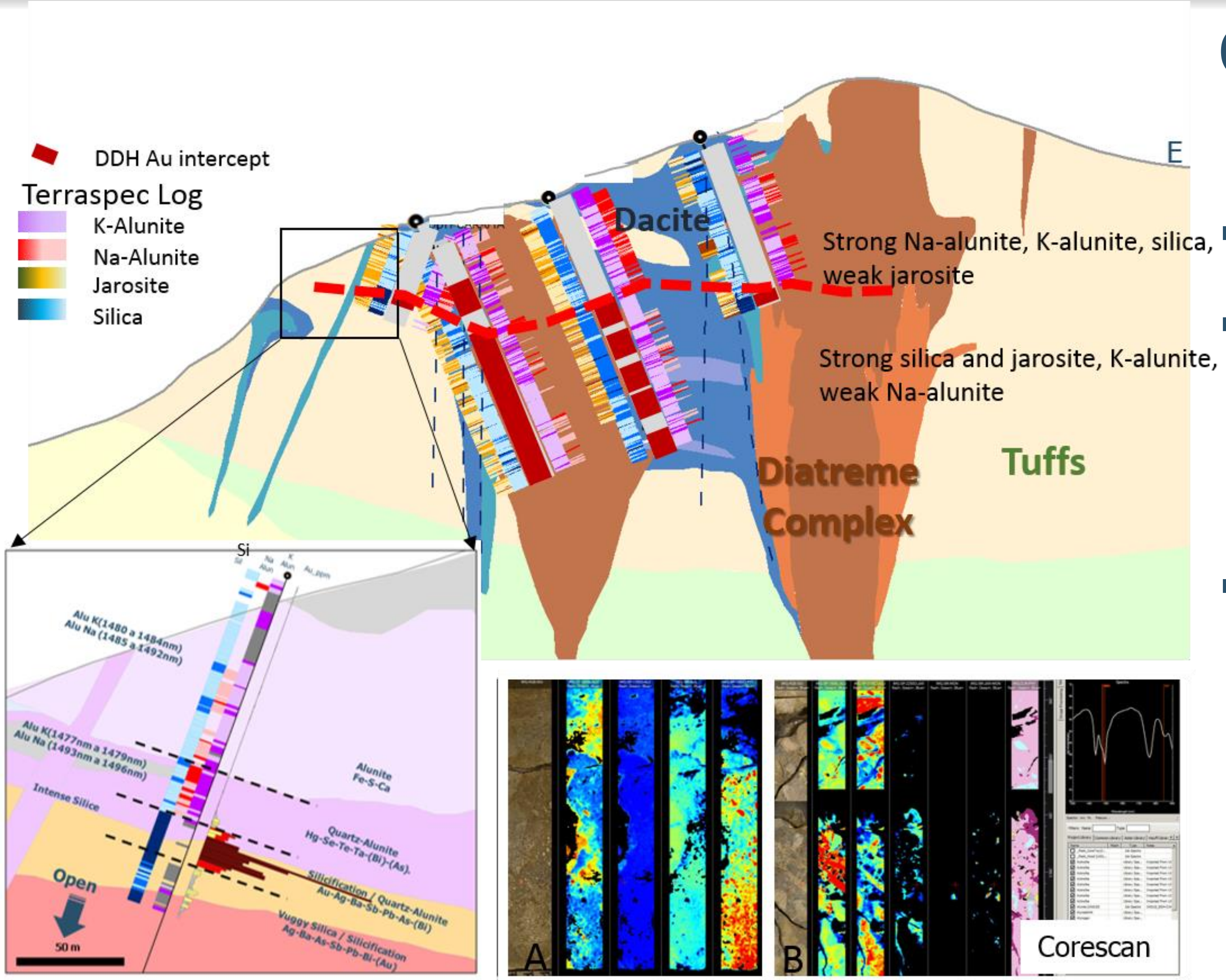
Generalized Carlin Alteration Model



Modified from Robert et al 2007 and Zhou 2009

Zhou el al, 2017 (a)

Field Examples: Alturas, Chile

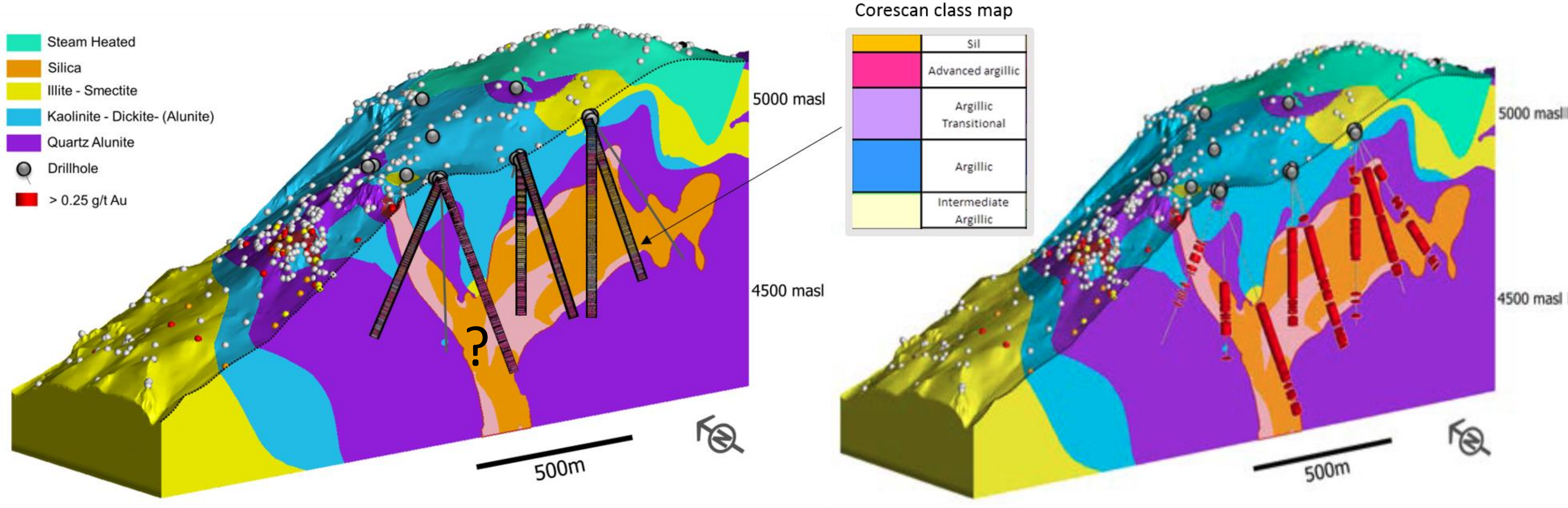


Zhou el al, 2017 (a)

Corescan high resolution hyperspectral imaging

- Semi quantitative mineralogy + texture
- Alteration assemblages and timing relation
  - ➢ Apparent alunite composition zoning with pre-mineral Na-alunite
- Improved logging consistency, accuracy and efficiency
  - ➢ Robust 2D and 3D alteration model
  - ➢ More informed real time decision
  - ➢ New insights for synthesis analysis

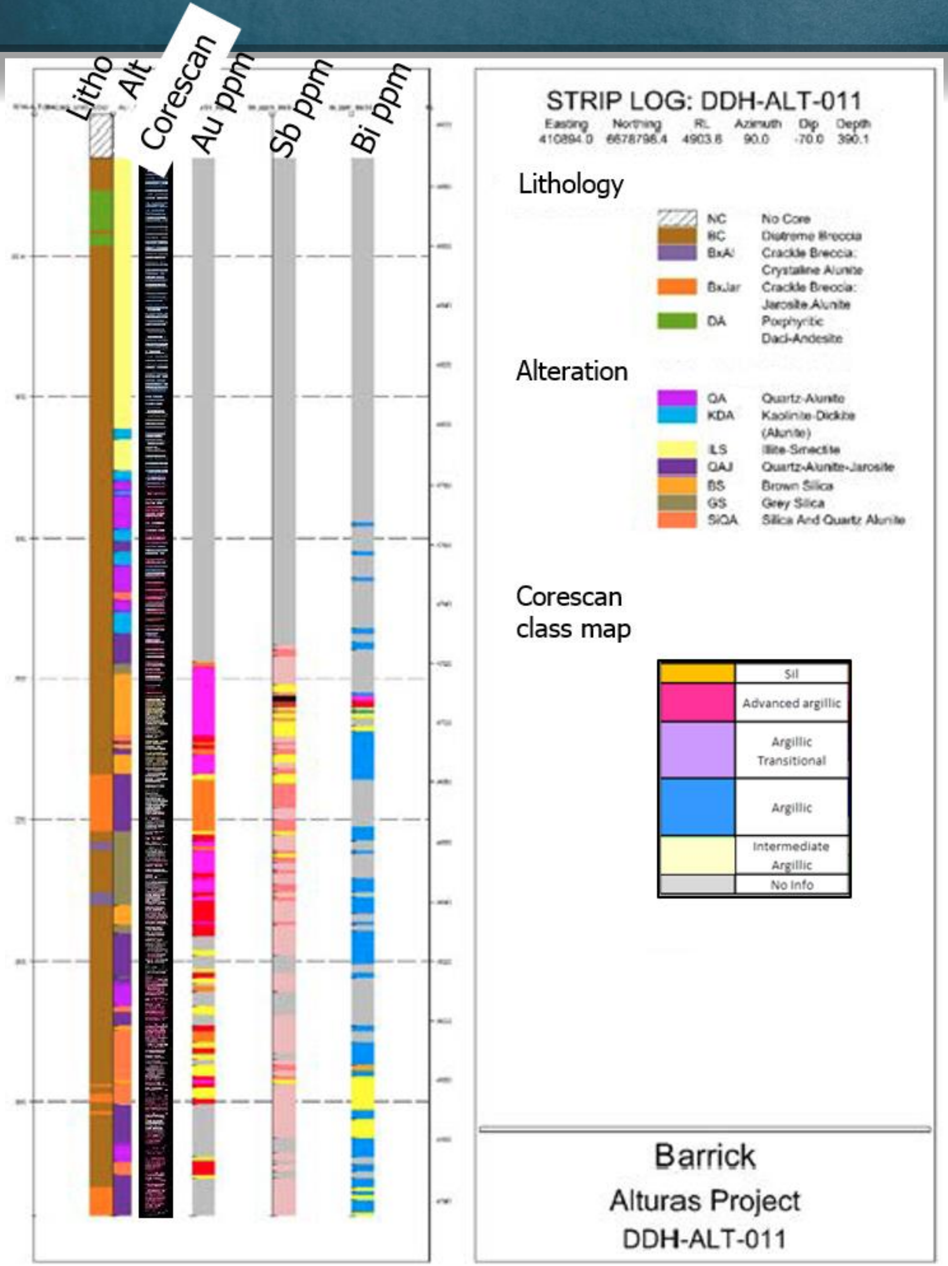
Field Examples: Alturas, Chile



Zhou et al, 2017 (b)

Astorga et al, 2017

Field Examples: Alturas



Geochem – spectral integration

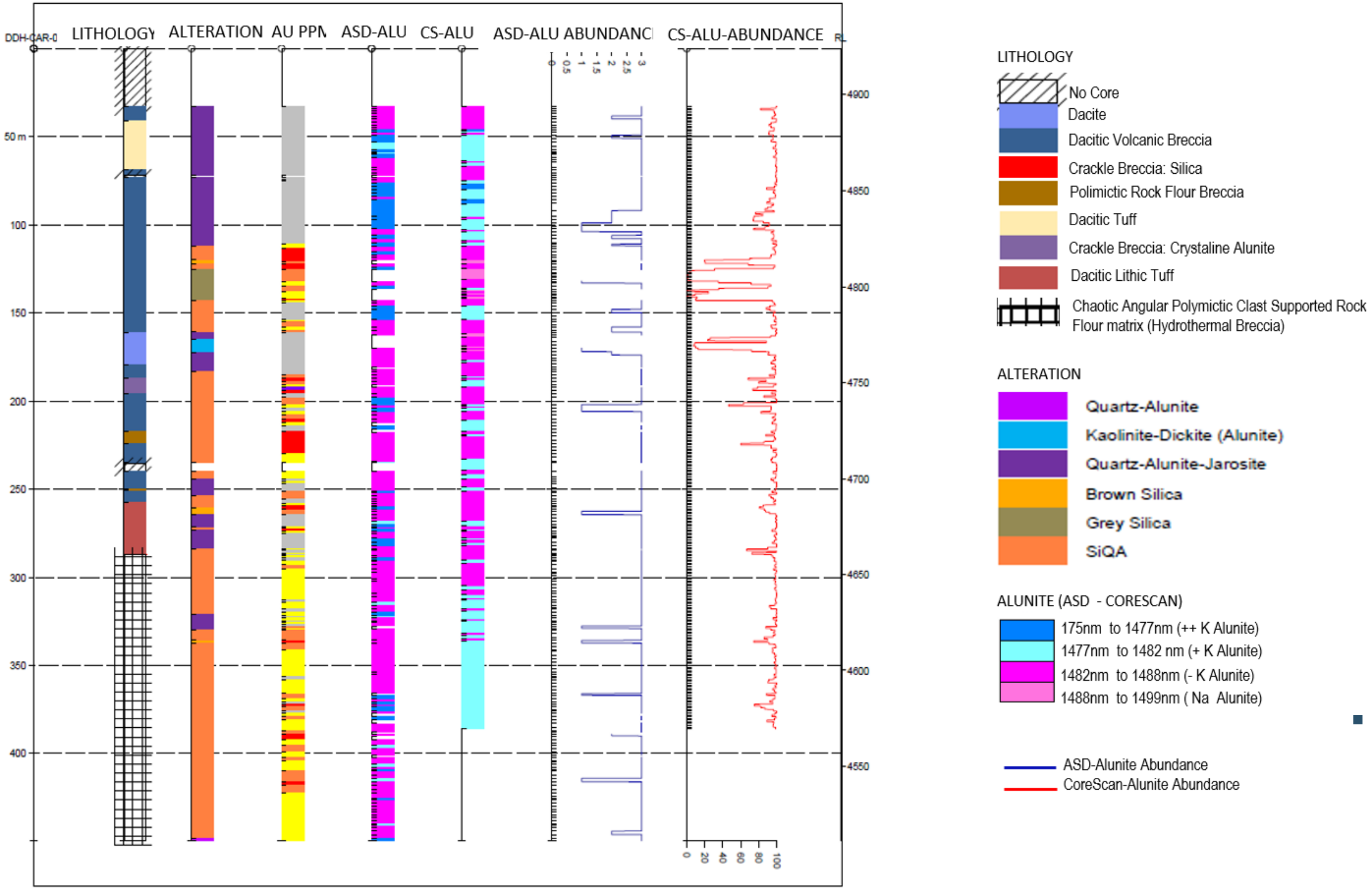
Data compatibility

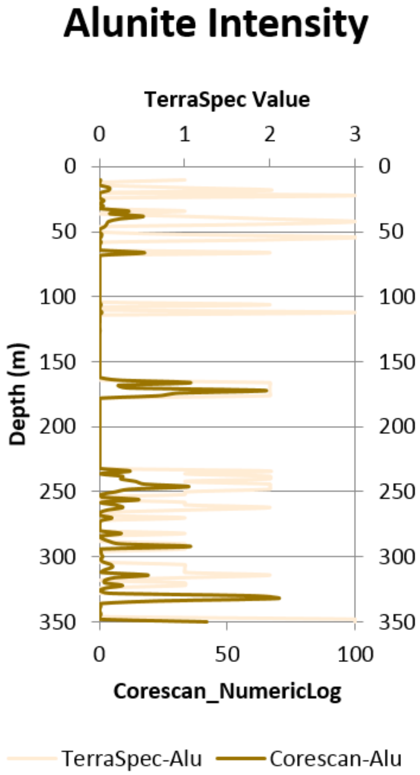
- ASD point data vs high res imaging
- Bulk geochem vs surface mineralogy

Complimentary

Modified from Astorga et al, 2017

Data compatibility: Continuous vs. Point sampling





- Corescan provides more reliable estimates of alunite composition and intensity

IR Limitations and Opportunities

LIMITATIONS

- Mineral id vs. alteration assemblages →
  - Phase separation and timing relation
- Interference by carbon, abundant sulfides →
- Surface detection only →
- Effect of lithology →
- Effect of mineral sites →

OPPORTUNITIES

- See beyond naked eyes
- Mineralogy + texture
- Real time
- Objective, none destructive, fast,
- High sampling density
- Semi-quantitative
- Outcrop + hand lens + IR oversampling
  - Hi res hyperspectral core imaging
- TIR, geochemistry
- Bulk assay geochemistry
- Geology and geochemistry: protolith
- Hand lens and micro XRF

Geochem – Spectral Integration: the Goal

Logging and Mapping Consistency, Accuracy and Efficiency

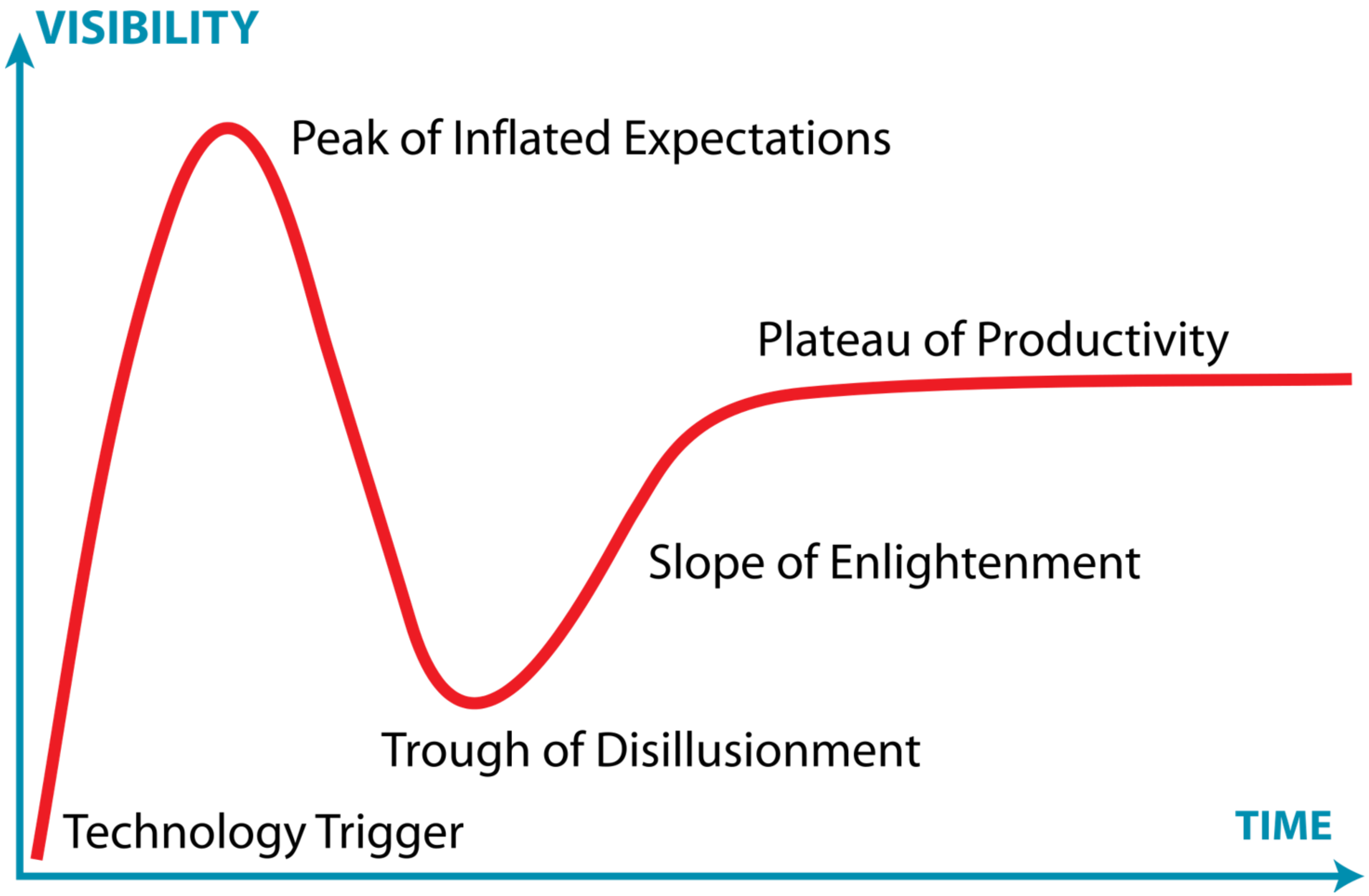
Predictability

- Alteration assemblage and timing relation to ore
- Far field, subtle cryptic alteration footprint

Cost effective:

- Time/man-hour
- Sampling density
- Turn-around time
- Data re-usability (e.g. down stream application)

No Silver Bullet But… the devil is in the details



Reference: Gartner Hype Cycle from Gartner.com

Summary

A vast array of spectral tools

- From microscopic resolution, drill hole, to regional and continental scale mapping
- Mineralogy and spectral indices: see beyond naked eyes
- Objective, non-destructive and fast
- New and evolving technologies

System technical fundamentals

- Capabilities, limitations

Multi-scale, integrated approach throughout exploration process

- From data collection – data processing - synthesis to integrated targeting
- Field driven, real time, interactive

New opportunities

- Hi res hyperspectral imaging: pattern + process; downstream, LOM applications
- Improved data compatibility for integration with geochem

Acknowledgments

Barrick Gold Corporation is thanked for permission to present field examples from Reko Diq, Luciano, Penelope, Cortez and Alturas.

Thanks are extended to many colleagues for their contribution to the projects discussed in this presentation.