PECORA 18 Workshop: Advanced Hyperspectral Remote Sensing of the Terrestrial Environment

Hyperspectral Thermal Infrared Remote Sensing – Geological and Environmental Applications

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Overview

PECORA 18: Hyperspectral Thermal Infrared Remote Sensing

- Overview of Hyperspectral Thermal Infrared Remote Sensing

- Geological
  - *Mineral Exploration*
  - *Geothermal Exploration*
  - *Ground Based*
  - *Soils/Transportation Corridor*
  - *Oil and Gas Exploration*
    - Not Discussed
  - *Core Logging*
    - Not Discussed

- Full Spectrum Collections
- Environmental
  - *Acid Mine Drainage*
  - *Vegetation*
  - *Pipeline Monitoring*
  - *Water Temperature*
    - Not Discussed

- Correlation with Rock Properties
  - *Geochemistry – Silica Content*
  - *Correlation with Density and Ultrasonic Velocity*

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Principles – Atmospheric Windows

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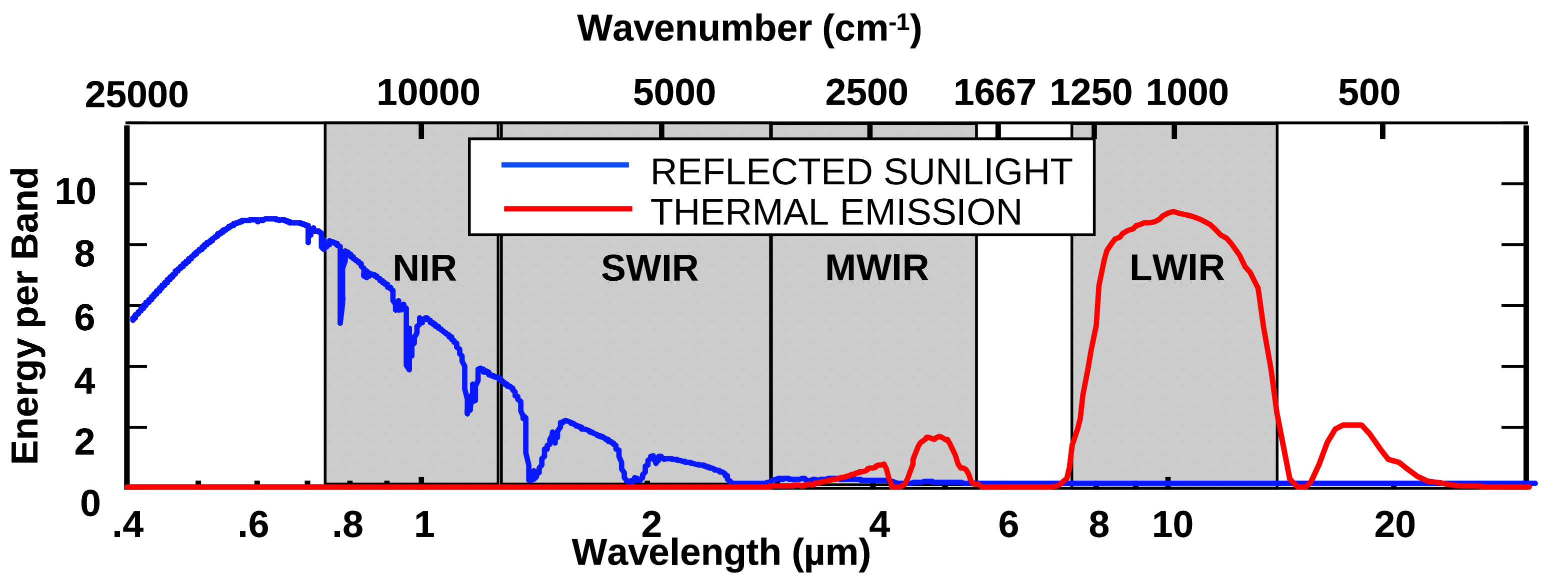

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Principles – Planck's Law

PECORA 18: Hyperspectral Thermal Infrared Remote Sensing

- Planck's Law
  - $\underline{2\pi h_0 c^2_0}$
    $(\lambda^5\ e^{hc0/\lambda k0T}-1)$
- Expansion at longer *wavelengths as* $e^x \approx 1+x$
  - $\underline{2\pi c_0 k_0 T}$
    λ^4
- <u>Simplification of the Equation</u>
  - $\underline{c_1 T}$
    $(\lambda^5\ e^{(c2/\lambda T)}-1)$

  - H_0 *is Planck's constant* $= 6.626 \times 10_{-34}$ *Js*
  - C_0 *is the speed of light* $= 3.00 \times 10^8$ *m/s*
  - K_0 *is Boltzmann's constant* $= 1.381 \times 10^{-23}\ JK^{-1}$
  - $c_1 = 2\pi h_0 c^2_0 = 3.742 \times 10^{-16}$
  - $c_2 = h_0 c_0 / k_0 = 0.1439$ *mK*

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Planck's Law

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$$L(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{\exp(hc/\lambda kT)-1}$$ [Wsr-1m-3]

$$L(\lambda,T)=\frac{1.191006\times10^4}{\lambda^5}\frac{1}{\exp(1.43883\times10^4/\lambda T)-1}$$ [Wcm-2sr-1mm-1]

$$L(\bar{\nu},T)=\frac{1.19101\times10^{-12}\bar{\nu}^3}{\exp(1.4388\bar{\nu}/T-1)}$$ [(Wcm-2sr-1(cm-1)-1)]

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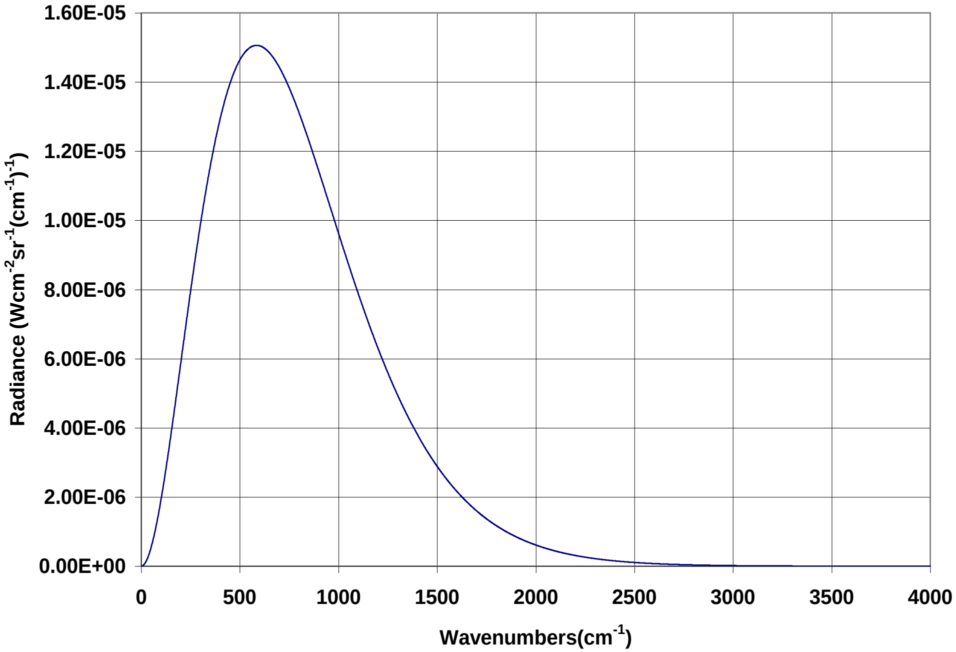
Planck's Law

PECORA 18: Hyperspectral Thermal Infrared Remote Sensing

- Planck's Law
  - $\dfrac{2\pi h_0 c^2_0}{(\lambda^5\, e^{hc0/\lambda k0T} - 1)}$
- Expansion at longer *wavelengths as $e^x \approx 1+x$*
  - $\dfrac{2\pi c_0 k_0 T}{\lambda^4}$
- Simplification of the Equation
  - $\dfrac{c_1 T}{(\lambda^5\, e^{(c2/\lambda T)} - 1)}$



- H_0 is Planck's constant = $6.626 \times 10_{-34}$ Js
- C_0 is the speed of light = 3.00×10^8 m/s
- K_0 is Boltzmann's constant = 1.381×10^{-23} JK^{-1}
- $c_1 = 2\pi h_0 c^2_0 = 3.742 \times 10^{-16}$
- $c_2 = h_0 c_0 / k_0 = 0.1439$ mK

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Planck's Curve

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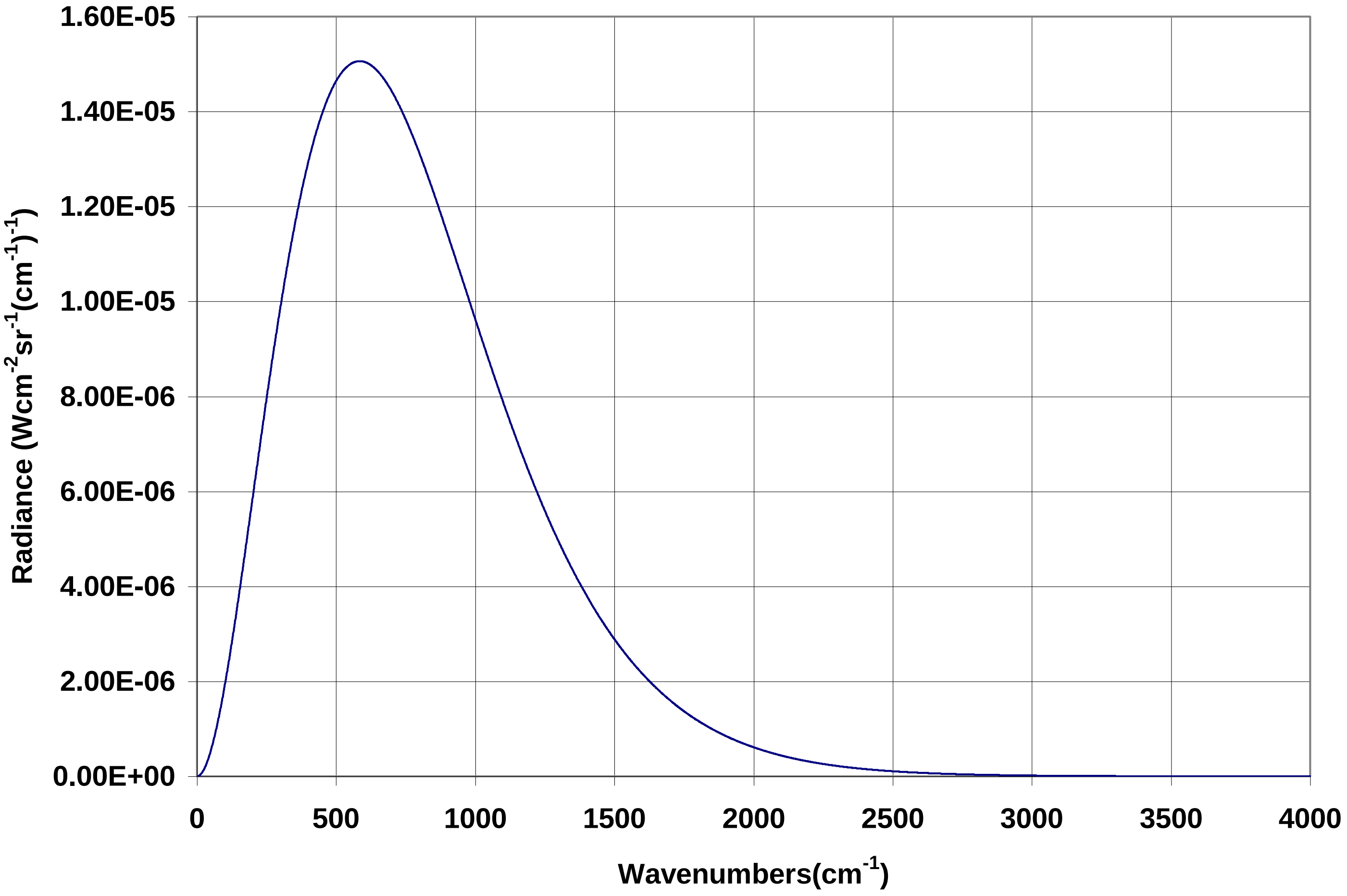

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Principles – Atmospheric Transmission

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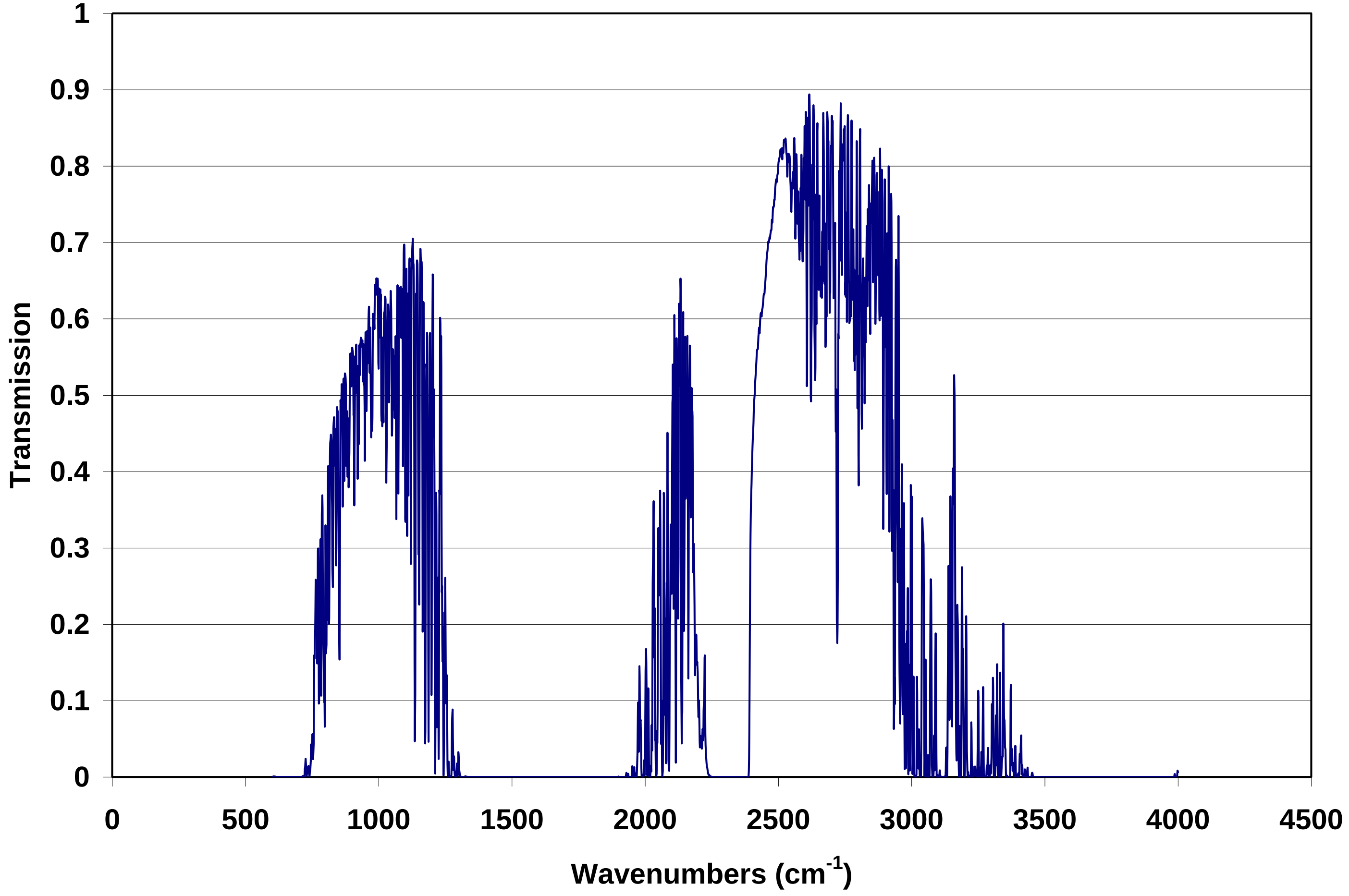

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Principles – Atmospheric Transmission cont.

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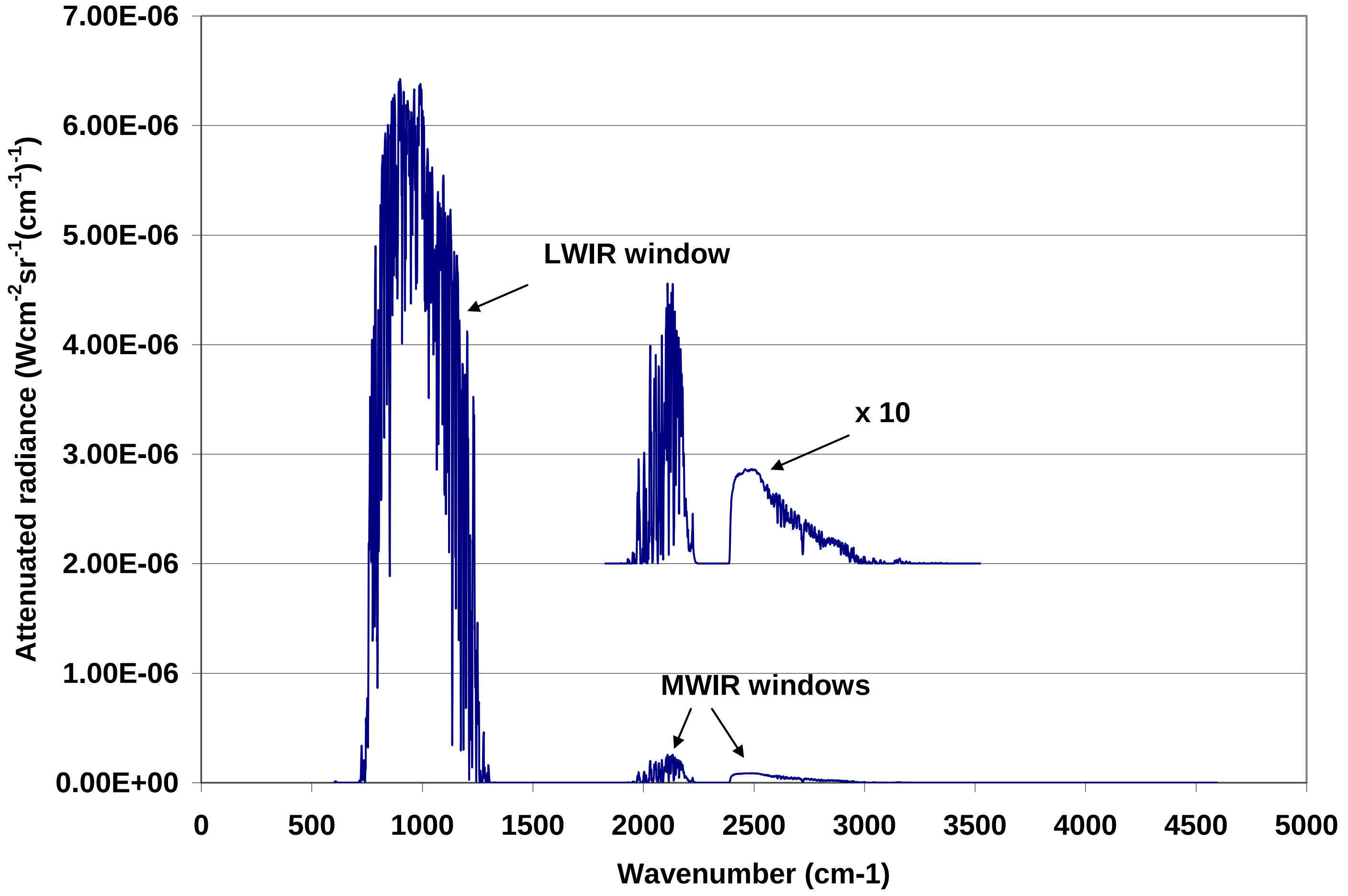

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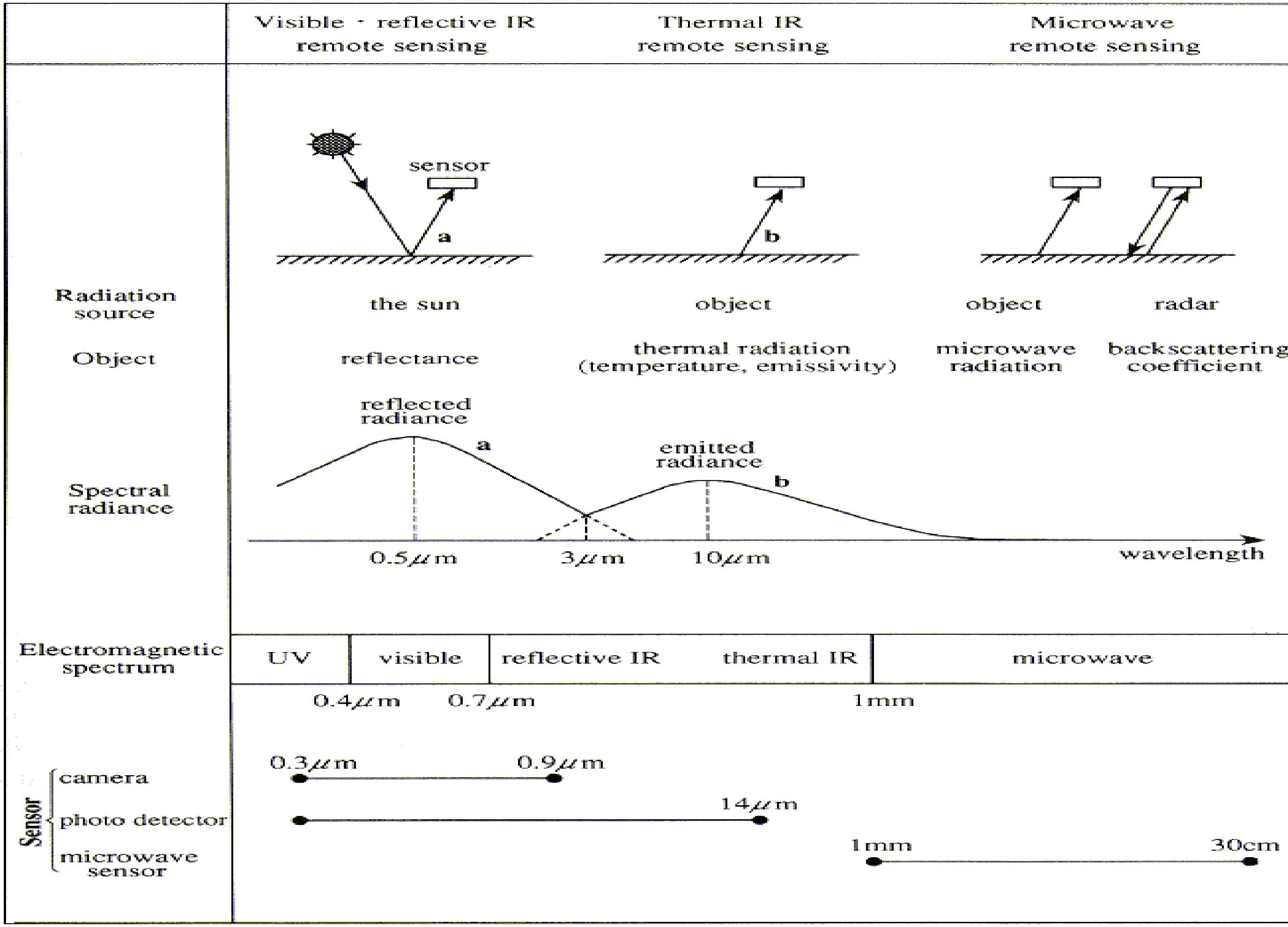

Figure 1.5.1 Three types of remote sensing with respect to wavelength regions

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Remote Sensing Physics

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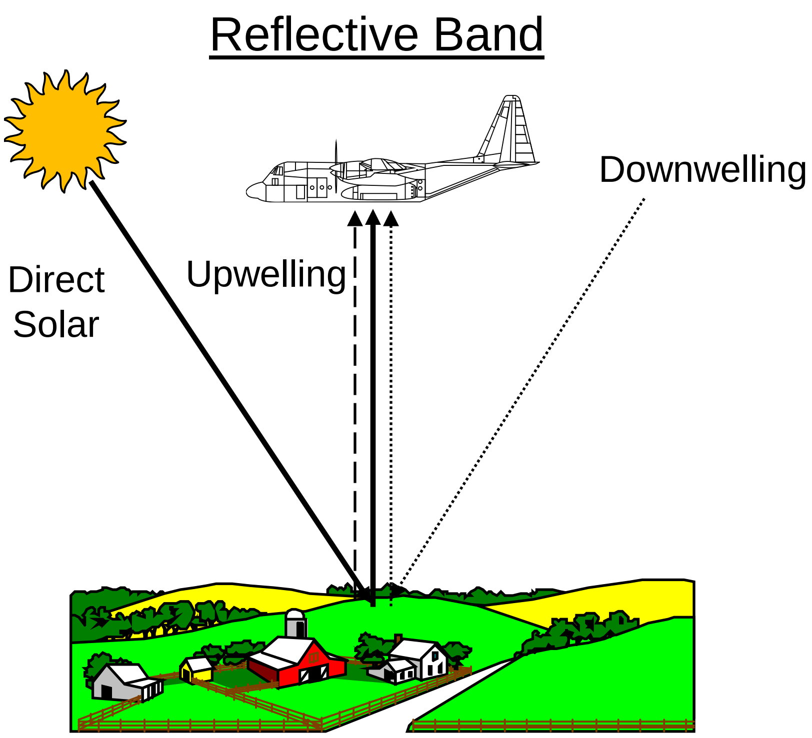

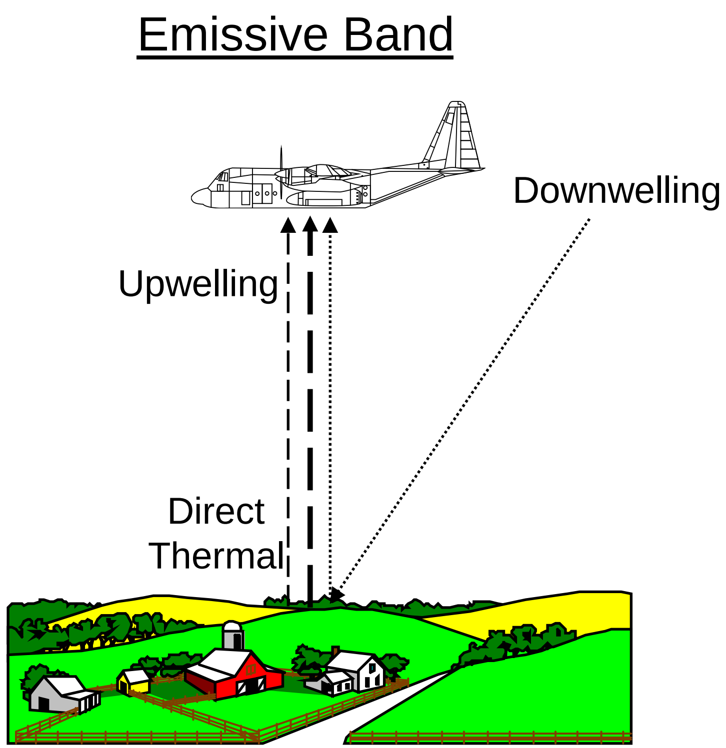

- **Day Operations**
- **Collection near Solar Noon**

- **Day <u>and</u> Night Operations**
- **The spectral peak of most terrestrial objects is in the LWIR**

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Thermal Infrared Sensors

PECORA 18: Hyperspectral Thermal Infrared Remote Sensing

- Airborne Sensors
  - *TIMS (NASA/JPL)*
  - *GEOSCAN (GER)*
  - *MASTER (NASA/JPL)*
  - ***SEBASS (THE AEROSPACE CORPORATION)***
  - *AHI (UNIVERSITY OF HAWAII)*
  - *TASI (ITRES)*
  - *OWL (SPECIM)*
  - ***MAKO (THE AEROSPACE CORPORATION)***
  - ***MAGI (NASA/THE AEROSPACE CORPORATION)***
  - *HyTES (NASA/JPL)*
- Spaceborne Sensors
  - *LANDSAT (NASA)*
  - *MTI (DOE)*
  - *ASTER (NASA/JAPAN)*
  - ***HYSPIRI (NASA)***
  - ***MAGI-L (NASA/THE AEROSPACE CORPORATION)***
- Ground Based Sensors
  - *Designs and Prototype FTIR*
  - *A2Technologies Exoscan*
  - *Aerospace's Vehicles*
    - Tonka, Ram Van, Top Kick, Big Dog

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SEBASS

PECORA 18: Hyperspectral Thermal Infrared Remote Sensing

SENSOR	MWIR / LWIR
Acquisition Altitude (m)	3000 (1.0 VIS – 5.0 LWIR; depending requirements)
# Bands	128 / 128
Spatial Swath (m; @ 3000 m)	422
IFOV (mrad)	1.1
Average Spectral Resolution (µm)	0.025 / 0.050
Spectral Range (µm)	2.5 – 5.3 / 7.6 – 13.5
GSD @ 3000 m (Pixel Size)	3.3
# of Flight Lines / day	20 (depending on requirements for collection, distance from airport)
Flight Lines length (km)	20 (dependent on GSD, and flight conditions)

SEBASS (Push Broom Scanning)

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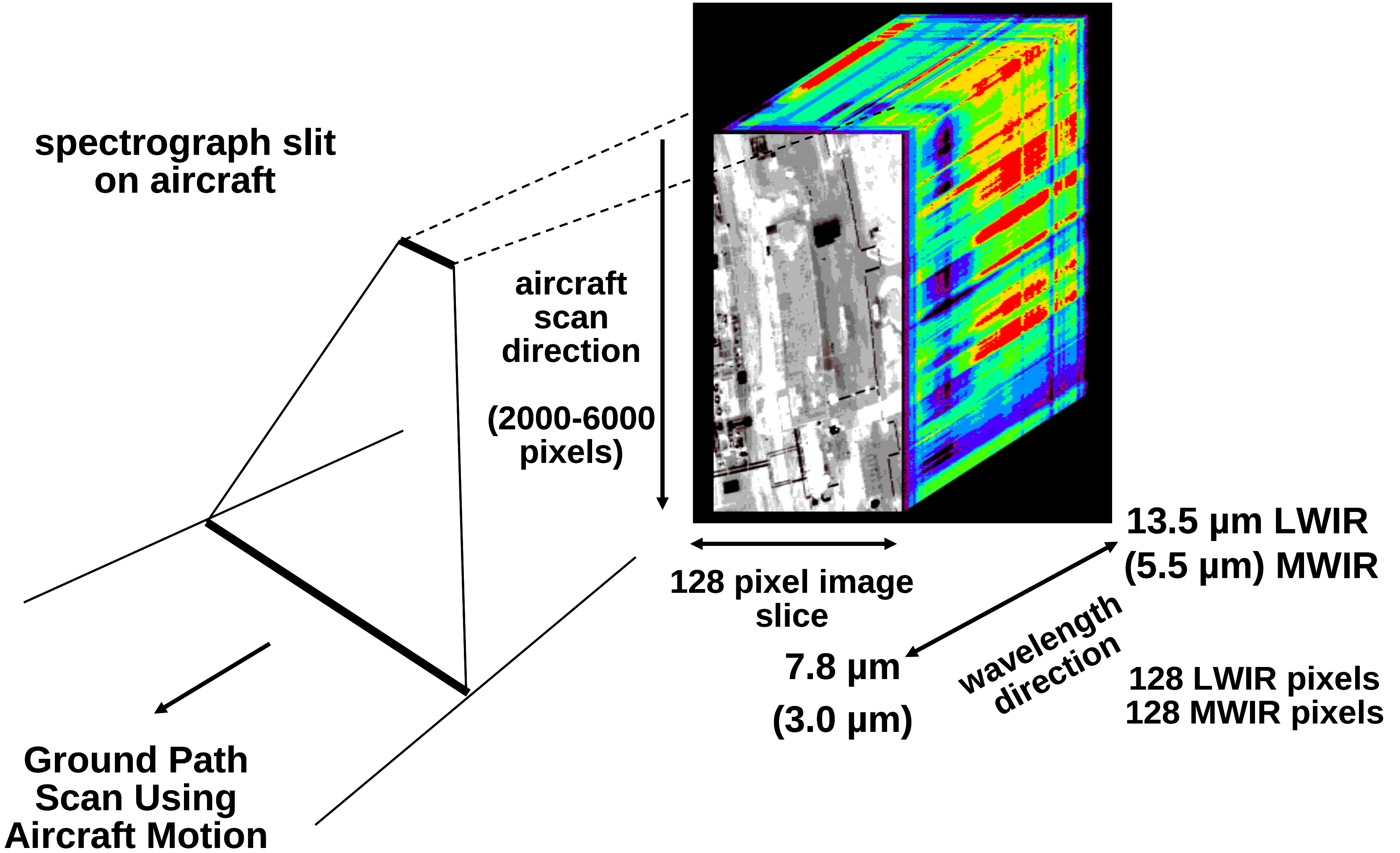

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Sensor Setup in Twin Otter

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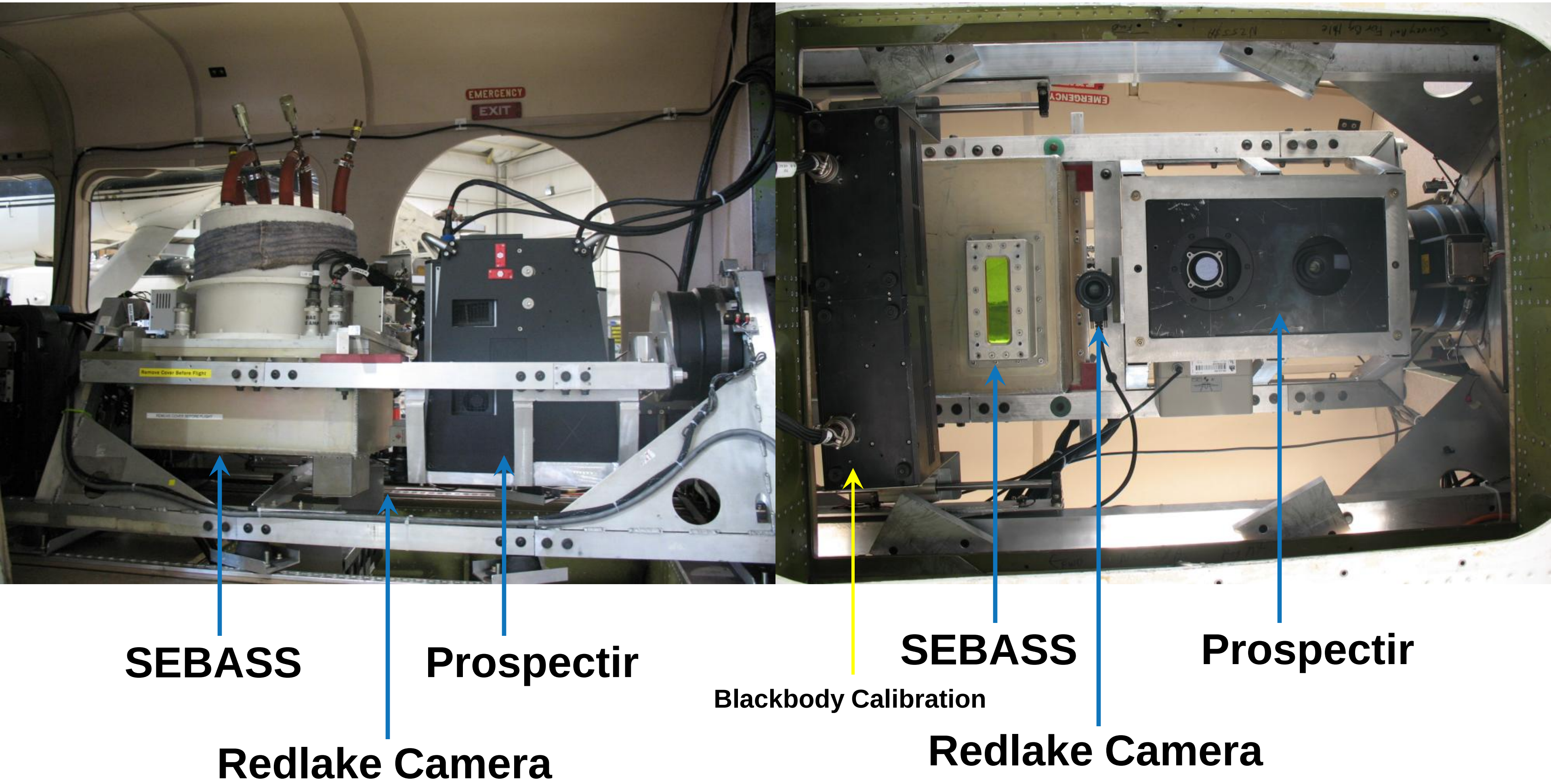

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Sensor Setup Continued

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Ground Targets – Test Flights

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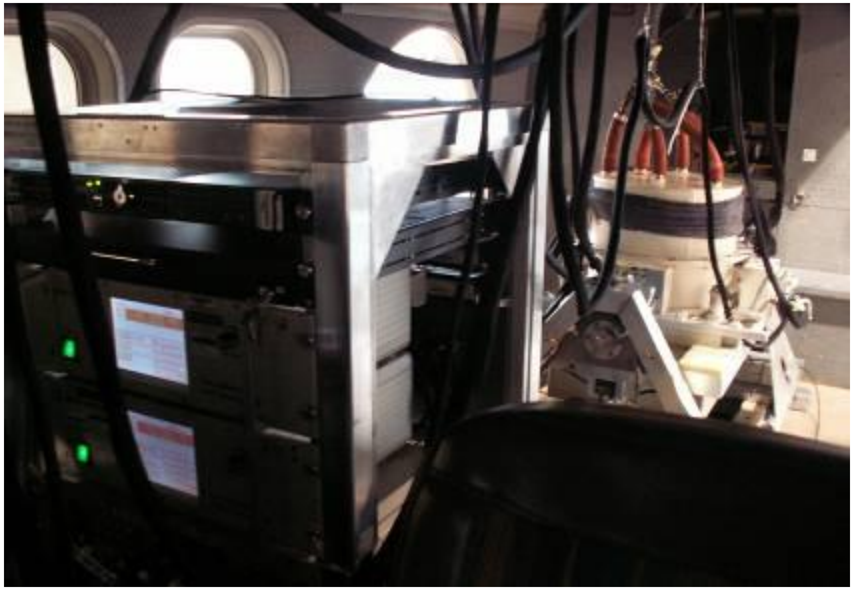
Operator Console

PECORA 18: Hyperspectral Thermal Infrared Remote Sensing

Single-Operator Console



Rack Mount

SEBASS

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Sensor Collection

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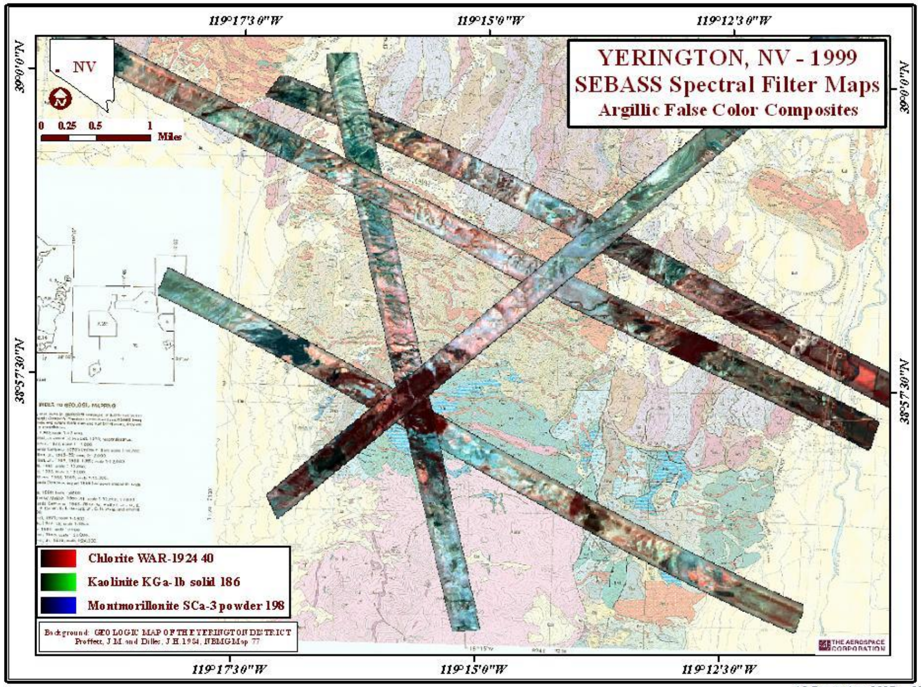
SEBASS

PECORA 18: Hyperspectral Thermal F

- Owned, Built Aerospace in 1996
- Electronics Upgrade in 2005
- Smile Corrected in 2002
- Primary: Operational Research for solids, liquids and gases.



- IFOV = 1.1 mrad
- FOV = 7.9 degrees
- Channels = 128 (LWIR)
- Channels = 128 (MWIR)
- Pushbroom
- Liquid Helium and Liquid Nitrogen Cooled
- Signal to Noise > 1500:1
- NEDT=0.01K
- Reference: 2 thermal blackbodies

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SEBASS – Operating Parameters

PECORA 18: Hyperspectral Thermal Remote Sensing: Current Platform is a Twin Otter

- Operating altitude 1,000 – 19,000 feet
- GSD 0.5 – 5 m (1 - 12.5 feet ;1 milliradian per pixel)
- Push broom nadir view only
- Scan rate linked to aircraft speed
- Real-time roll control

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SEBASS Sensor

PECORA 18: Hyperspectral Thermal Remote Sensing

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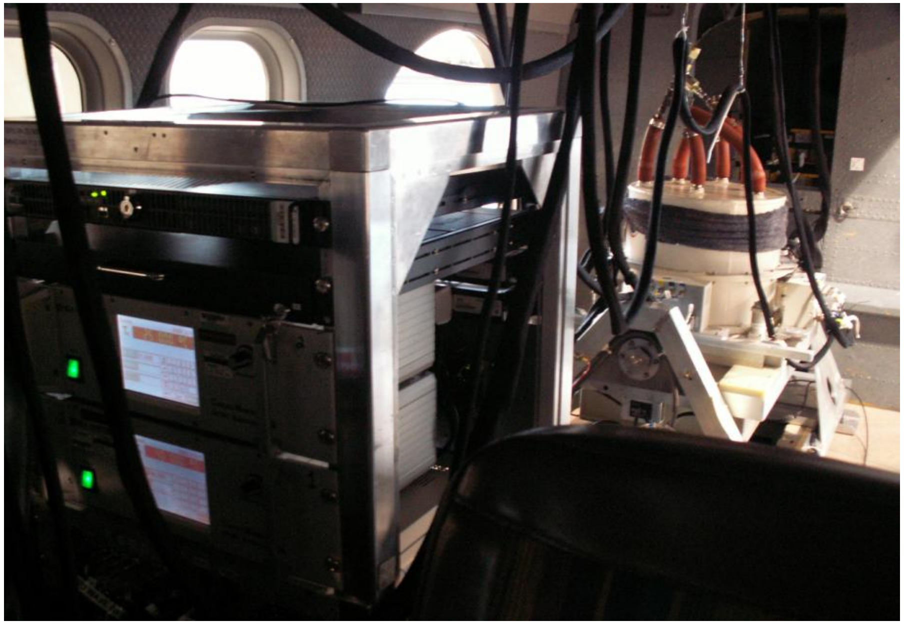
SEBASS – Operator Console – Computer Rack

PECORA 18: Hyperspectral Thermal Remote Sensing

Single-OperatorConsole



Rack Mount

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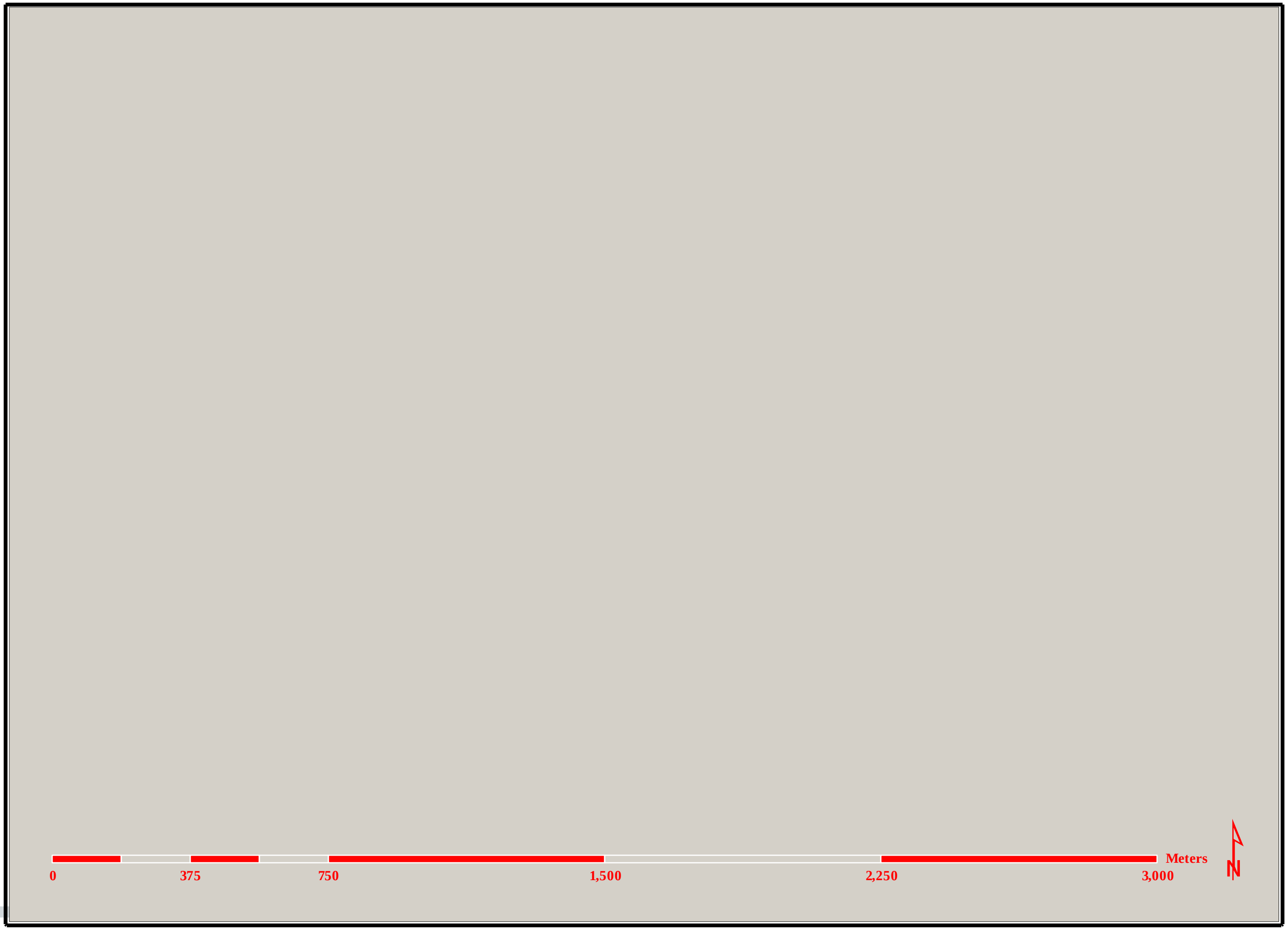
SEBASS Georeferencing Results (<11 m)

PECORA 18: Hyperspectral Thermal Remote Sensing



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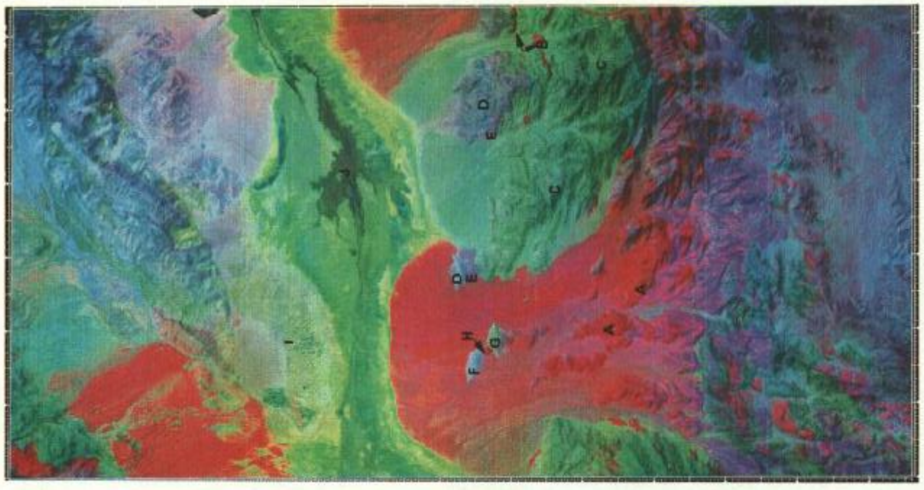
TIMS

PECORA 18: Hyperspectral Thermal Remote Sensing

- Built by Daedalus for JPL in 1980
- Primary: Research applications - rocks, minerals, soils, vegetation, and surface coatings, alteration and weathering. Surface emissivity, porosity, grain size, and roughness. Water surface and forest canopy temperatures. Canopy temperature and levels of green leaf biomass in newly planted clear-cut areas can be determined.



- IFOV = 2.5mrad
- FOV = 76.564 degrees
- Channels = 6 (LWIR)
- Swath Width = 638 Pixels
- Pushbroom
- Roll Corrected
- FPA = HgCdTe
- Reference: 2 thermal blackbodies

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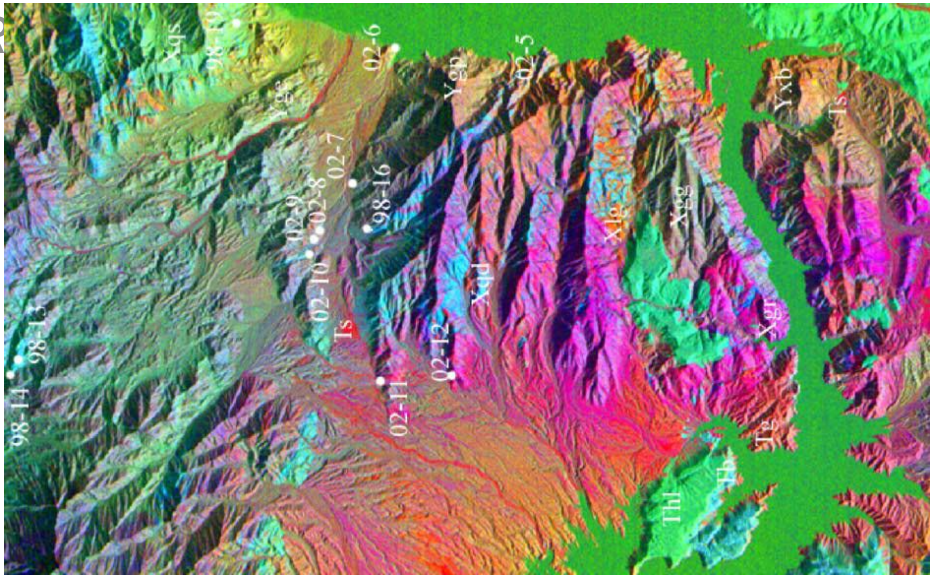
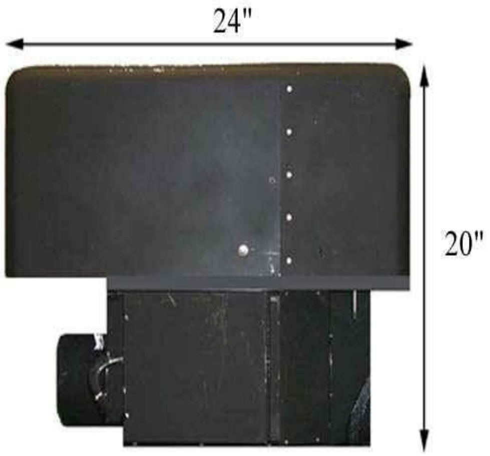
MASTER

PECORA 18: Hyperspectral Thermal R



- Built by JPL 1996
- NASA Airborne Facility, JPL, USGS EROS
- Primary: Support ASTER/MODIS Instrument Teams
- Algorithm Development, Calibration, Validation

- IFOV = 2.5mrad
- FOV = 85.92 degrees
- Channels = 25 (VNIR-SWIR)
- Channels = 15 (MWIR)
- Channels = 10 (LWIR)
- Whiskbroom
- Liquid Nitrogen Cooled



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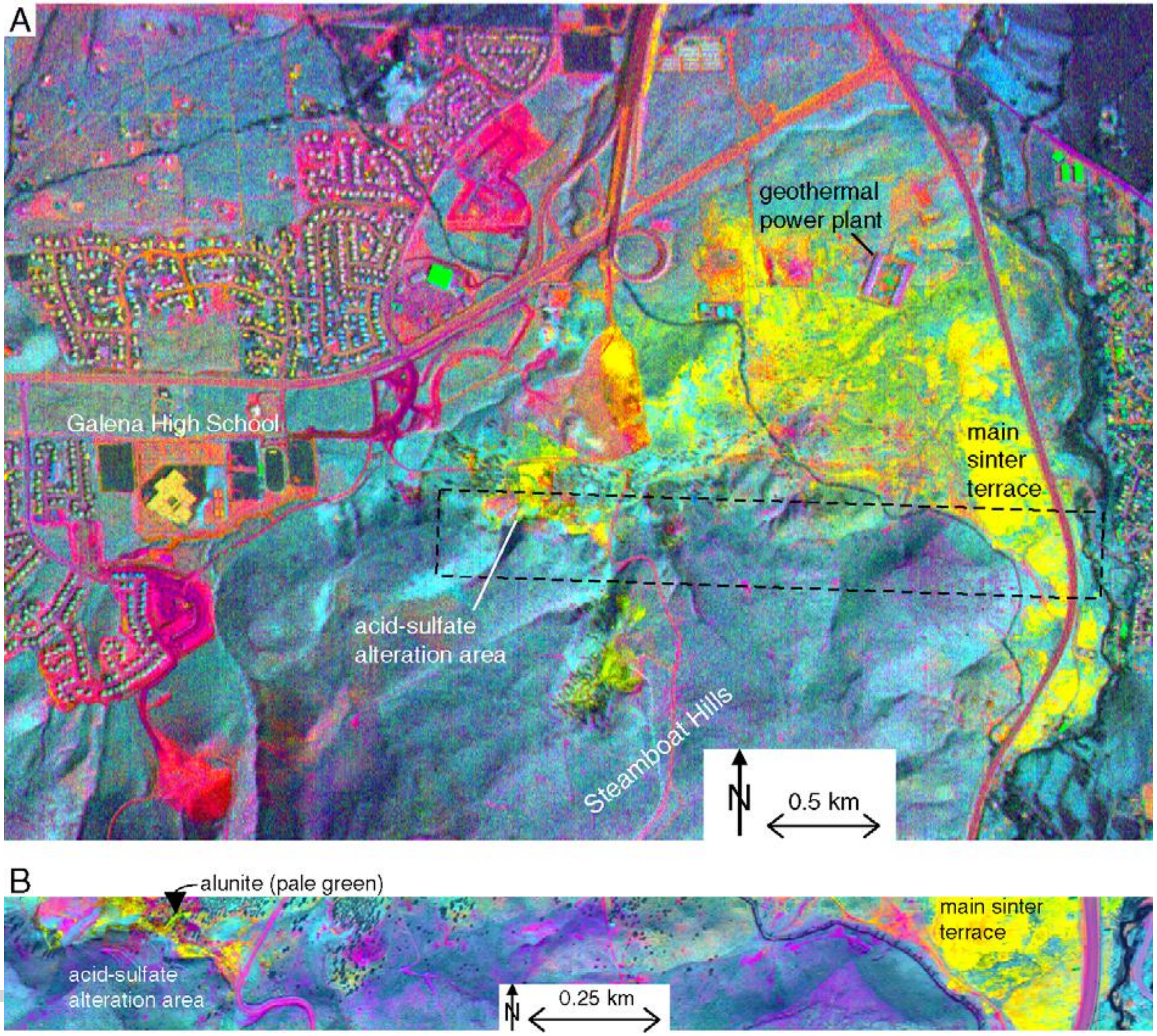
MASTER cont.

PECORA 18: Hyperspectral Thermal Remote Sensing



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MAKO: New Thermal Imager

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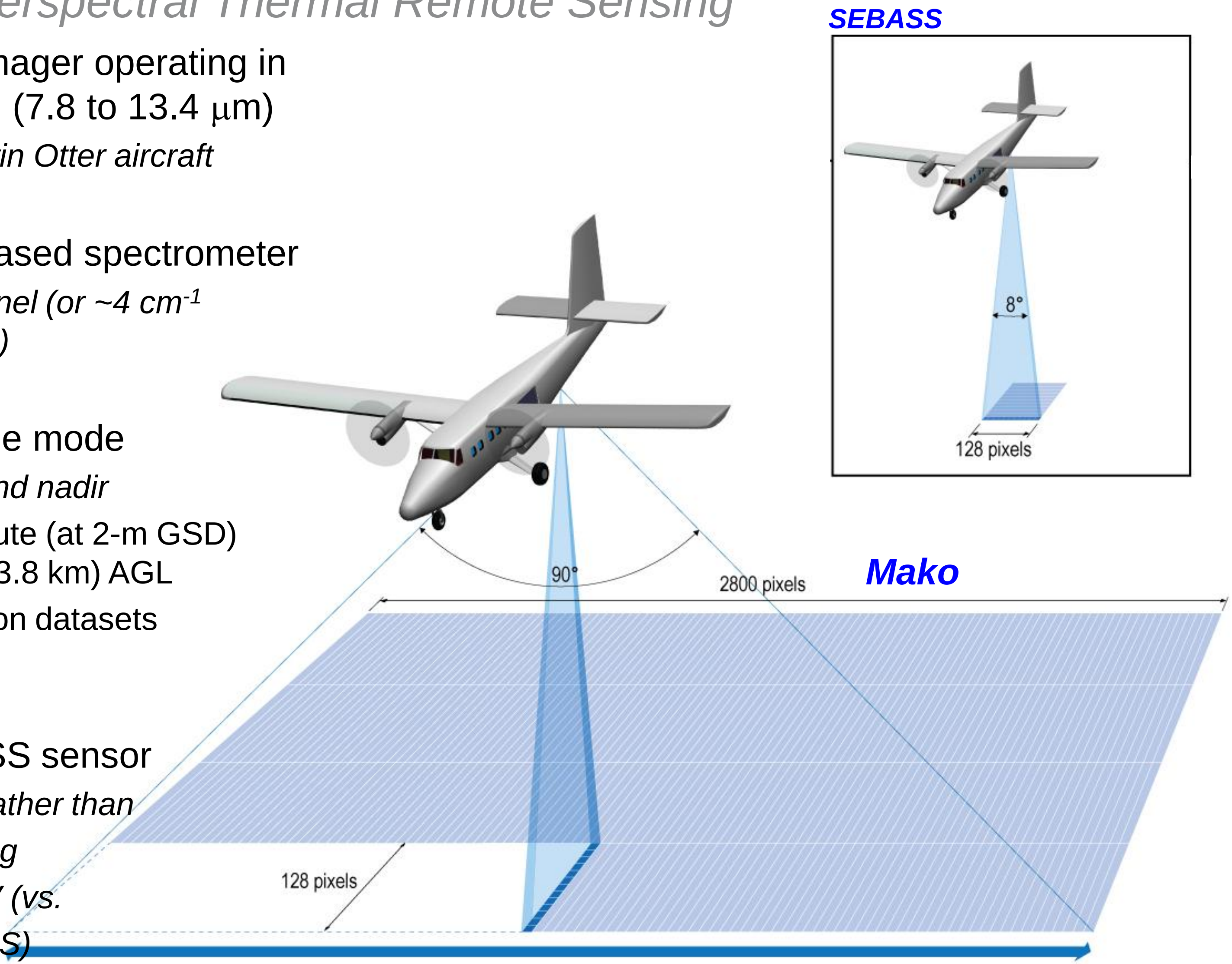
- Airborne spectral imager operating in the thermal infrared (7.8 to 13.4 μm)
  - *Deploys aboard Twin Otter aircraft*
- 128-band grating-based spectrometer
  - *0.044 μm per channel (or ~4 cm^{-1} resolution at 10 μm)*
- Large area coverage mode
  - *Scan to ± 40° around nadir*
    - 20 km^2 per minute (at 2-m GSD) from 12,500 ft (3.8 km) AGL
    - 8-minute duration datasets demonstrated
- Follow-on to SEBASS sensor
  - *Uses whiskbroom rather than pushbroom scanning*
  - *0.5 mrad pixel IFOV (vs. 1.0 mrad for SEBASS)*



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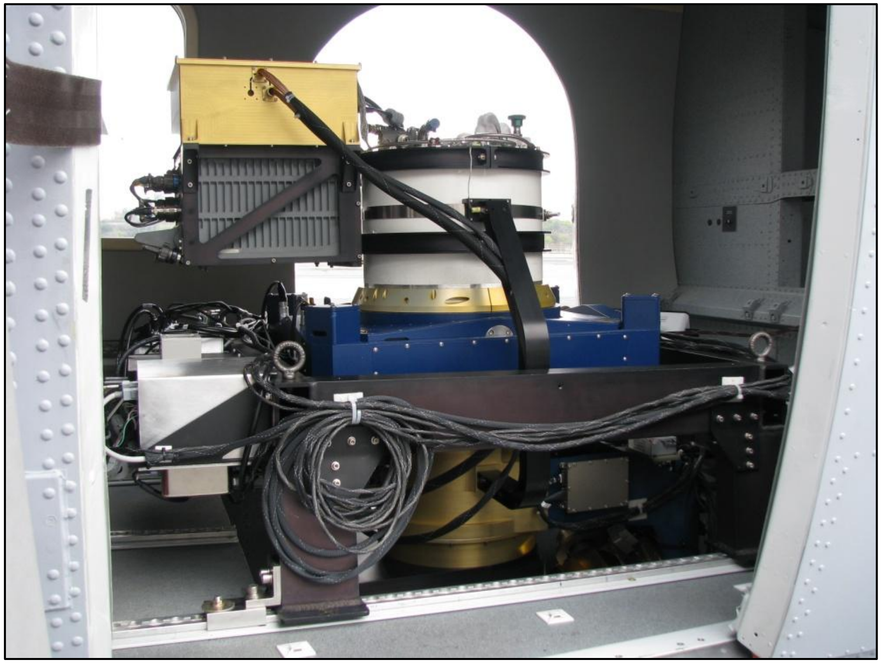
MAKO: New Thermal Imager continued

PECORA 18: Hyperspectral Thermal Remote Sensing

- Uses a commercial 3-axis stabilization mount
  - *Intergraph Z/I mount*
  - *High frequency jitter removed by physical vibration dampeners*
  - *Low frequency jitter removed by active control*
    - Stabilizes up to ±5° range in pitch and roll
  - *Up to ±12° yaw offset can be accommodated in Mako installation*

- Sensor attitude measured with Litton LN-100G INS and KVH DSP-3000 fiber-optic gyros (x3)
  - *Estimated pixel geolocation uncertainty is <10 meters from 12,000 ft AGL*
    - With separate differential GPS

- Gimbal mirror pitch control provides additional capability
  - *Bi-directional whisking*
  - *High-sensitivity (low area coverage) scans (“stare” mode)*



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MAKO: New Thermal Imager Sensor Details

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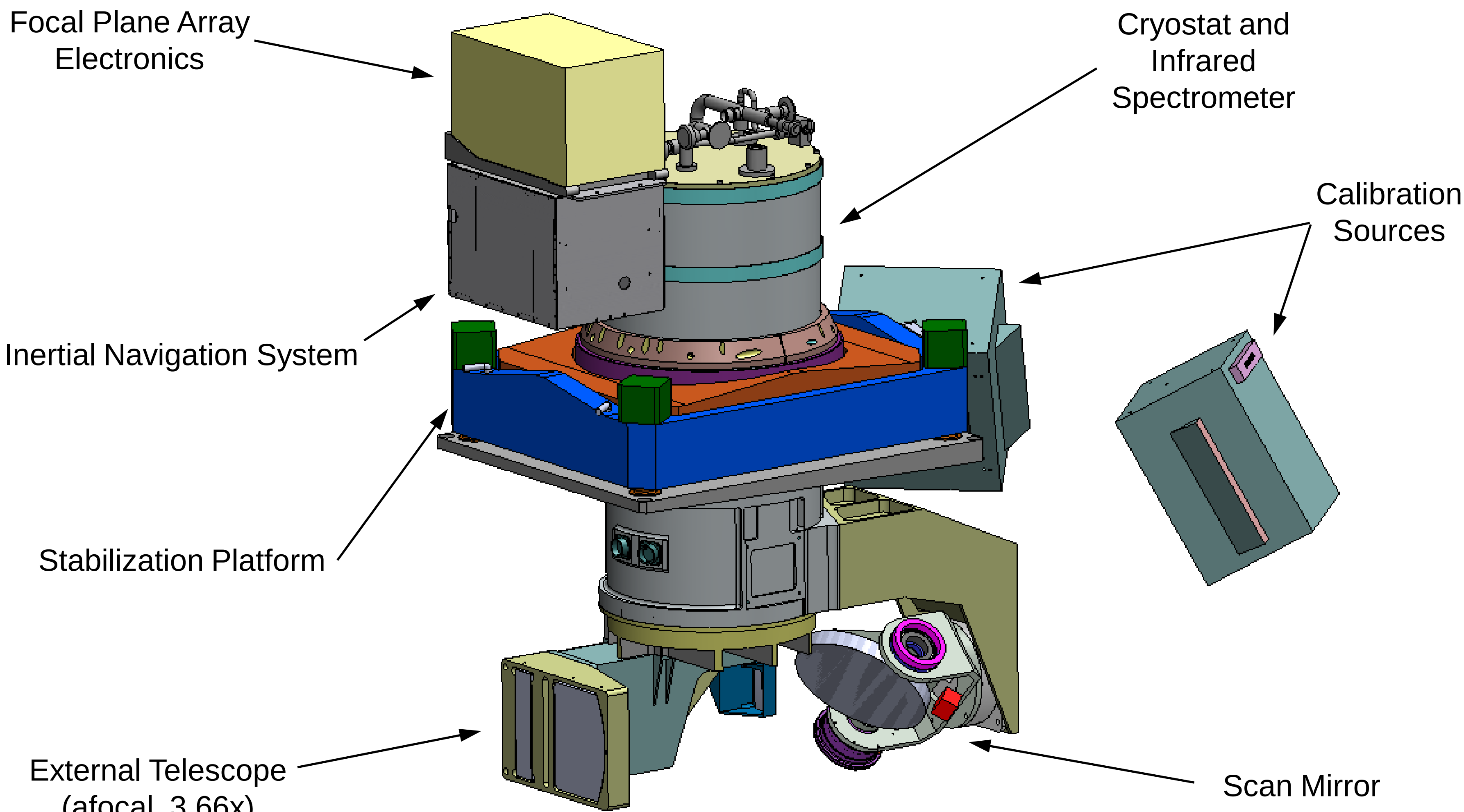

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MAKO: New Thermal Imager Spectrometer Details

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- *Mako* uses a DRS Si:As Blocked Impurity Band 128x128 FPA
  - *75 μm pixels*
  - *Cooled to 10K using LHe*
  - *99.93% operable*
  - *4 kHz max. frame rate (Mako currently at 800 Hz); 16 output taps*

- Spectrometer based on Dyson lens and concave grating
  - *Low distortions (“smile” and “keystone”) at fast f-numbers*
    - *Mako* is an f/1.25 system

- Cooled optics (LHe blow-off) for improved sensitivity and increased dynamic range
  - *48-hour dewar hold time*

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Geological Applications – Ground Based

Mobile Scanning FTIR Sensor

- Vehicle based FTIR's "TONKA or RamVan"
  - *5 vehicles (Van to Large Truck)*
  - *Imaging based laboratory*
- Identify materials
  - *Validate airborne sensor results*
  - *Characterize minimum detectable quantities*
  - *Resolve sampler data*
- Provide ground temperature and emissivity measurements

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Geological Applications – Ground Based

Mobile Scanning FTIR Sensor Capability Summary

- Identifies Solids by measuring the infrared spectrum
- Long-wave infrared hyperspectral imagery system
  - Block 100B FTIR 8-12.5 microns (800-1250cm-1) Spectrometer
  - 181 spectral bands
  - Raster scanning mirror assembly
- Scan period of 0.5 to 2.0 minutes per scene
- IFOV: 0.5 deg
- Real-time data processing to find targets of interest
- On-board calibration sources
- GPS timing & differential location
- Calibrated optical pointing
- 320 deg. azimuth capability
- Co-aligned visible & infrared cameras
- Weather data sensor

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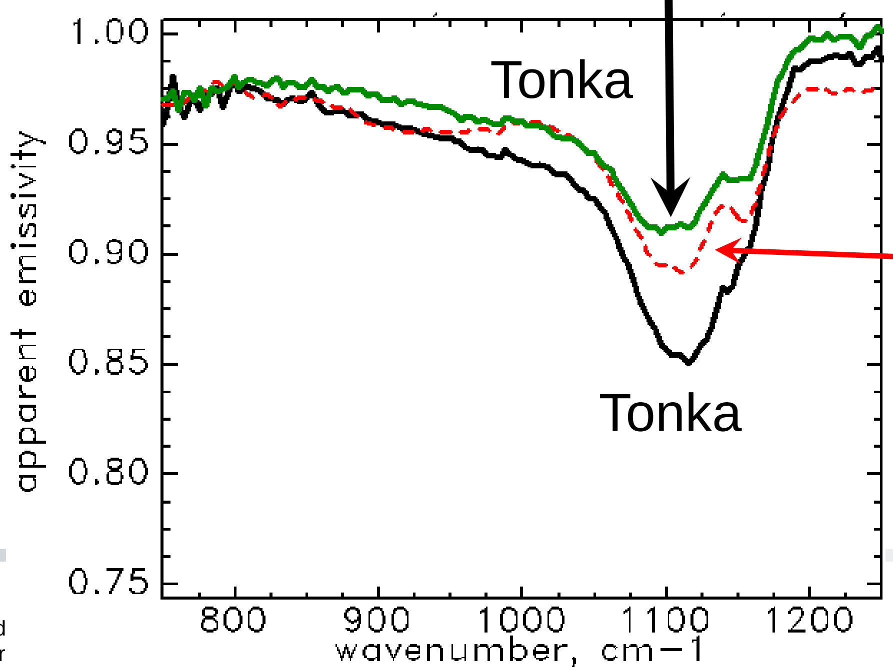
Geological Applications – Ground Based

Mobile Scanning FTIR Sensor – Material Identification

- Each pixel in the Tonka scene is an infrared spectrum
- Materials are identified by matching the measured signatures to the known signature of the gas or solid

Tonka signatures measured of solids in a scene



Materials are identified by matching to a laboratory signature of a known material

lab signature (Mg-sulfate)

Geological Applications – Ground Based

Aerospace Mobile Laboratory

Weather Station

GPS Receiver

Sensor Head Deployed through Roof of Box

Operator Console

Data acquisition computer

Sensor controller

Displays

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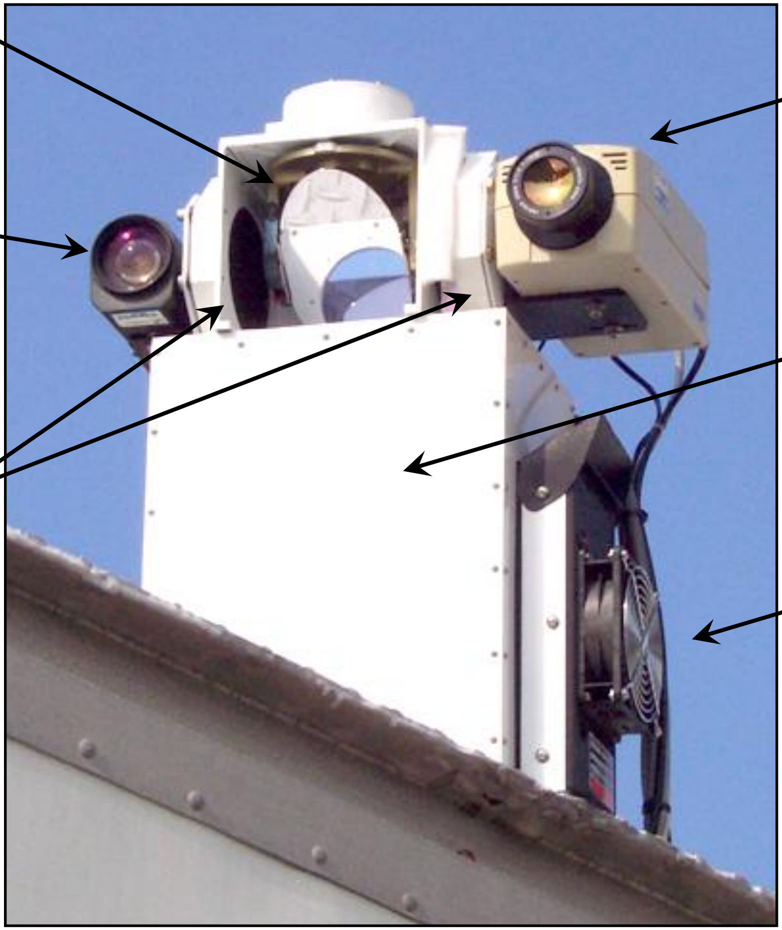
Geological Applications – Ground Based

Tonka FTIR Sensor Components



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Geological and Environmental Remote Sensing

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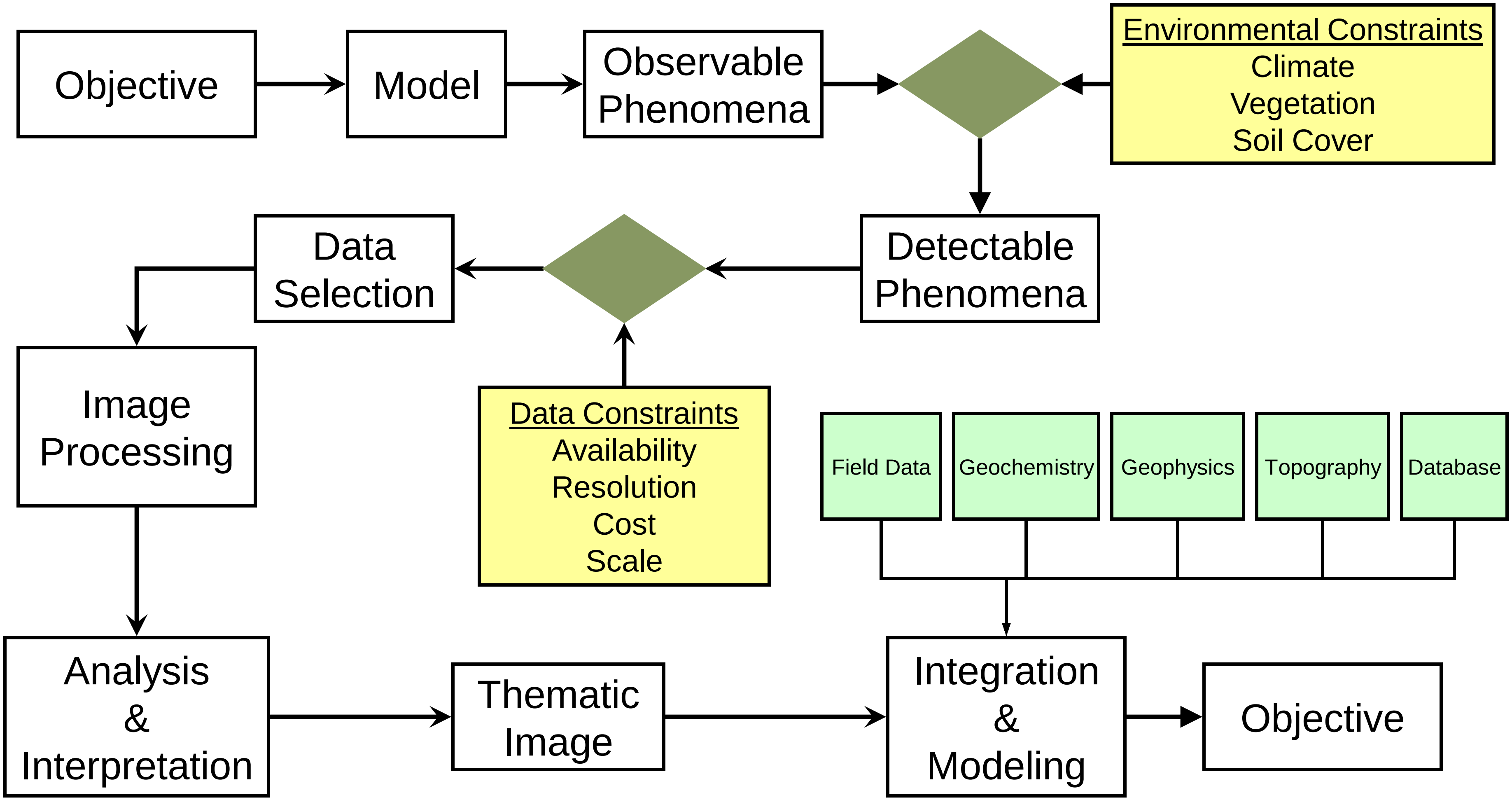

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Geological Applications

Hyperspectral Thermal Infrared Remote Sensing

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Geological Applications – Mineral Exploration

Geology of Yerington, NV – Porphyry Copper Deposit

- Batholith
  - *Biotite, hornblende granodiorite*
  - *Potassium feldspar, porphyritic hornblende, biotite quartz monzonite*
  - *Biotite-hornblende quartz monzonite*
  - *Hornblende-biotite porphyritic quartz monzonite*
- Wall-rock
  - *Quartzitic sandstone*
  - *Gypsum and Anhydrite*
  - *Limestone*
  - *Andesite to dacitic tuff*
  - *Calcareous argillite*
  - *Andesitic and felsitic rocks*
  - *Volcanic Siltstone/Limestone*

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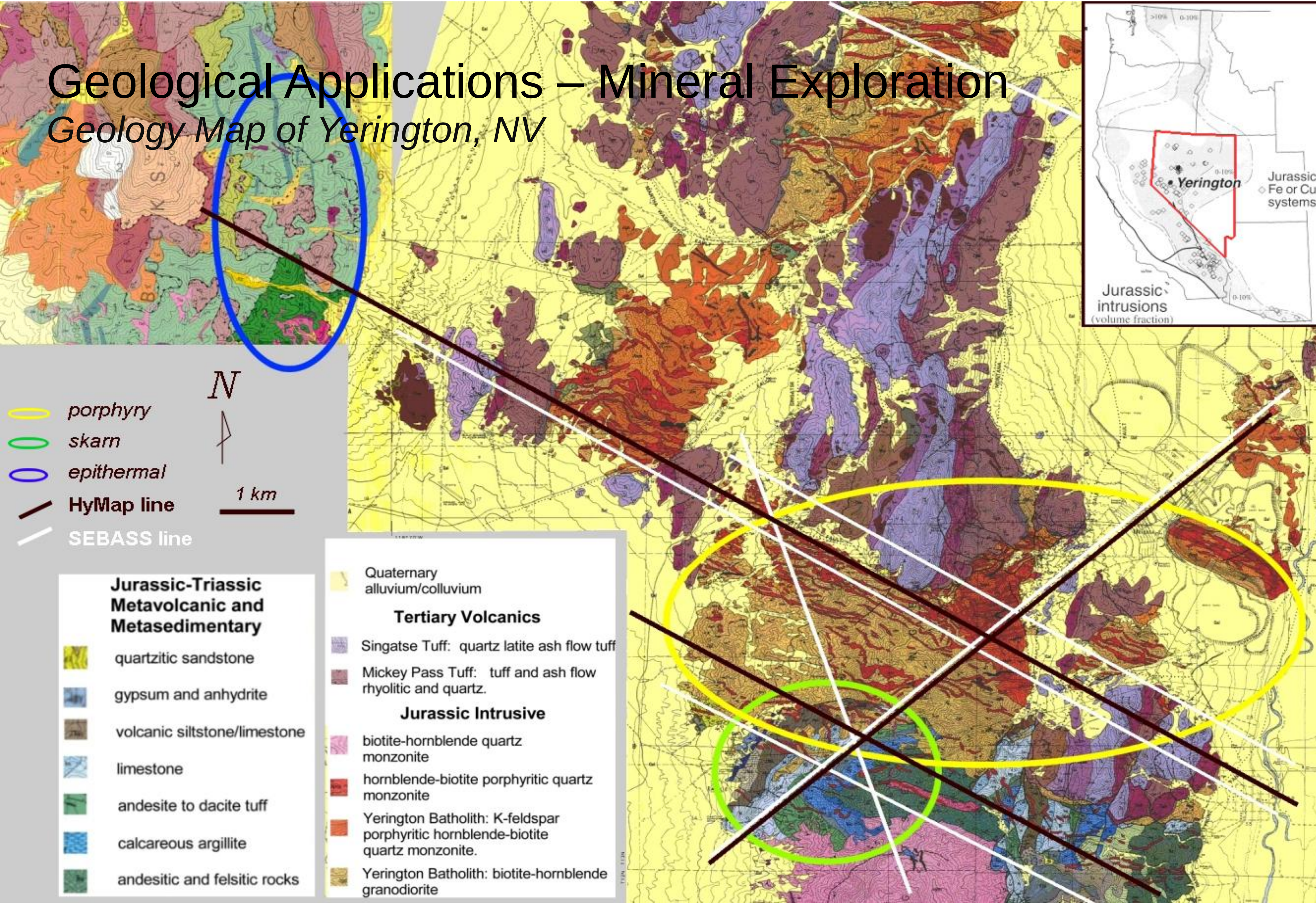
Geological Applications – Mineral Exploration

Geology Map of Yerington, NV



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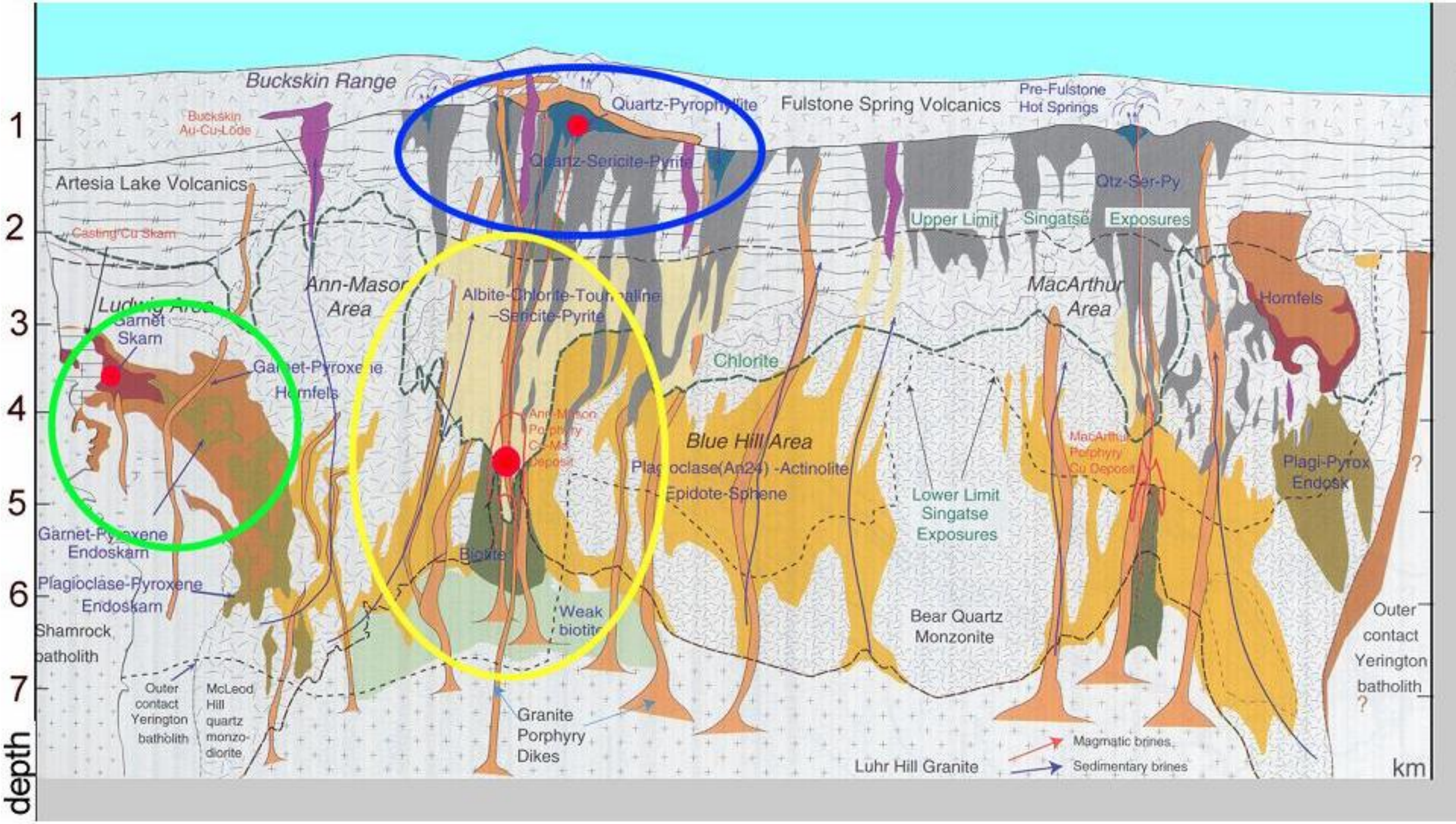
Geological Applications – Mineral Exploration

Alteration Cross-Section of the Yerington District



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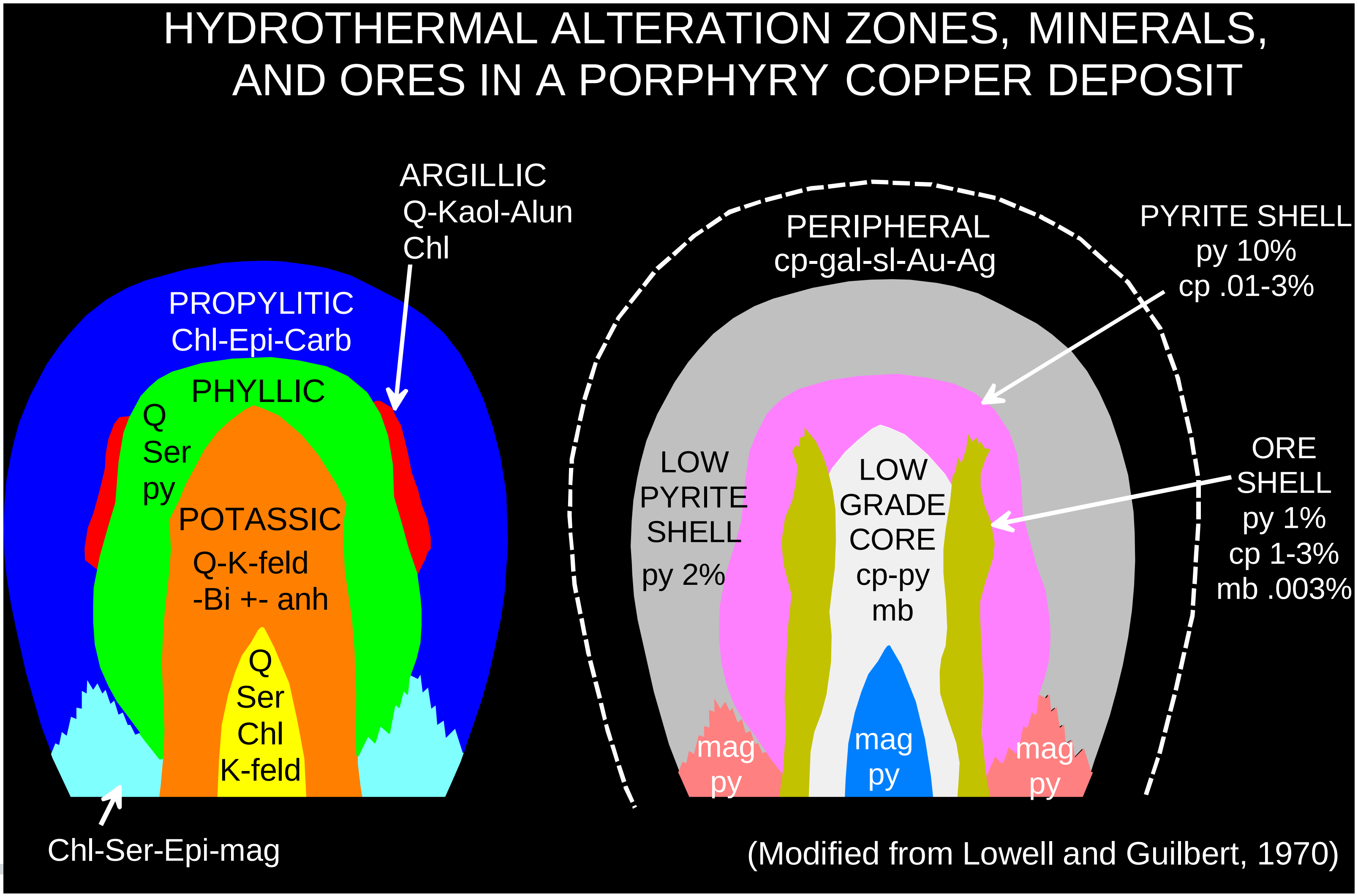
Geological Applications – Mineral Exploration

Generalized Porphyry Copper Deposit Model



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Geological Applications – Mineral Exploration

Porphyry Copper Deposit Model

- Propylitic Alteration
  - *Chlorite*
  - *Epidote*
  - *Carbonate (Calcite)*
  - *Albite*
- Argillic Alteration
  - *Kaolinite*
  - *Chlorite*
  - *Montmorillonite*
- Phyllic Alteration
  - *Quartz*
  - *Sericite*
  - *Pyrite*
  - *Chlorite*
- Potassic Alteration
  - *Orthoclase*
  - *Biotite*
  - *Sericite*
  - *Quartz*
  - *Anhydrite*

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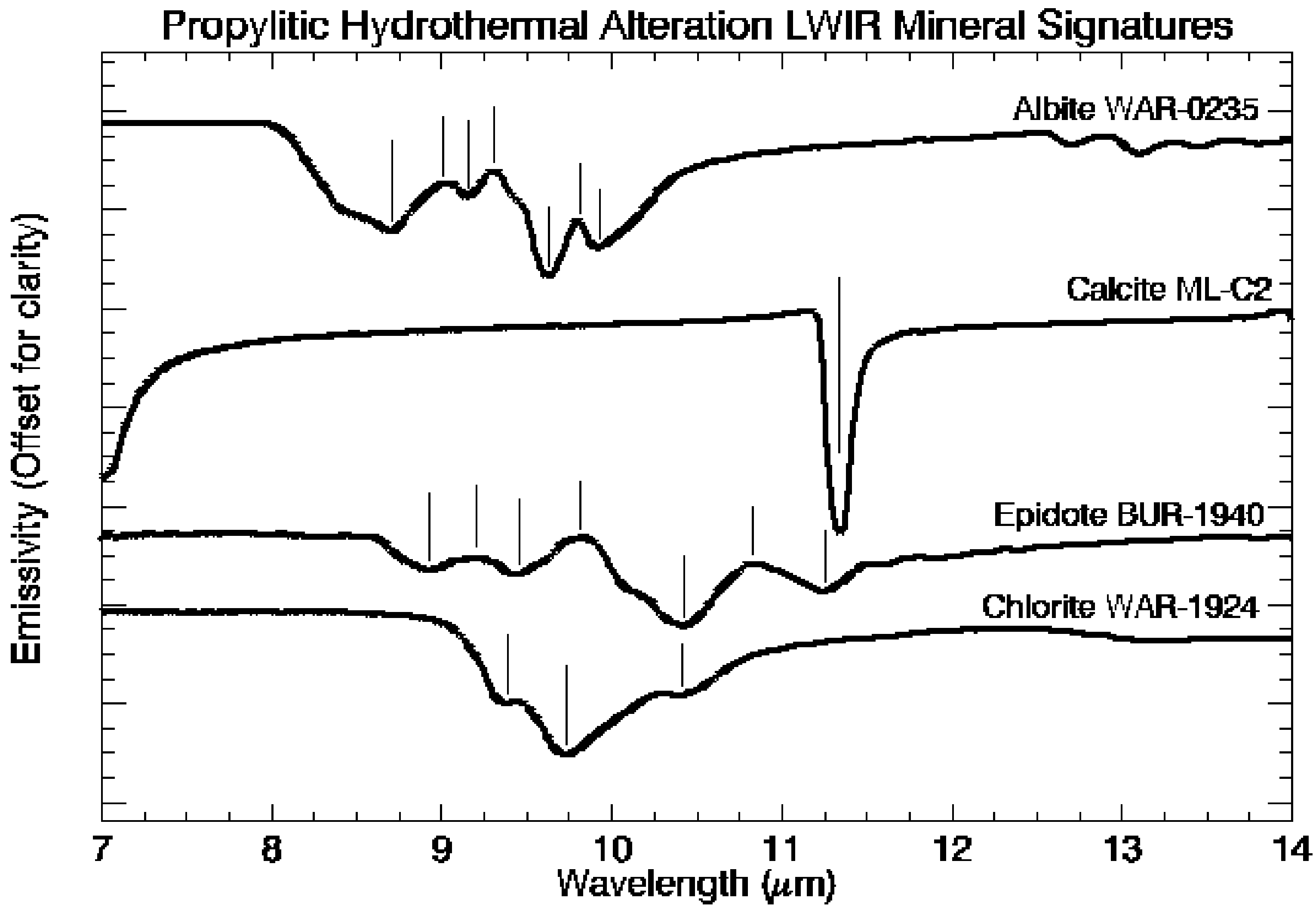
Porphyry Copper LWIR Mineral Signatures



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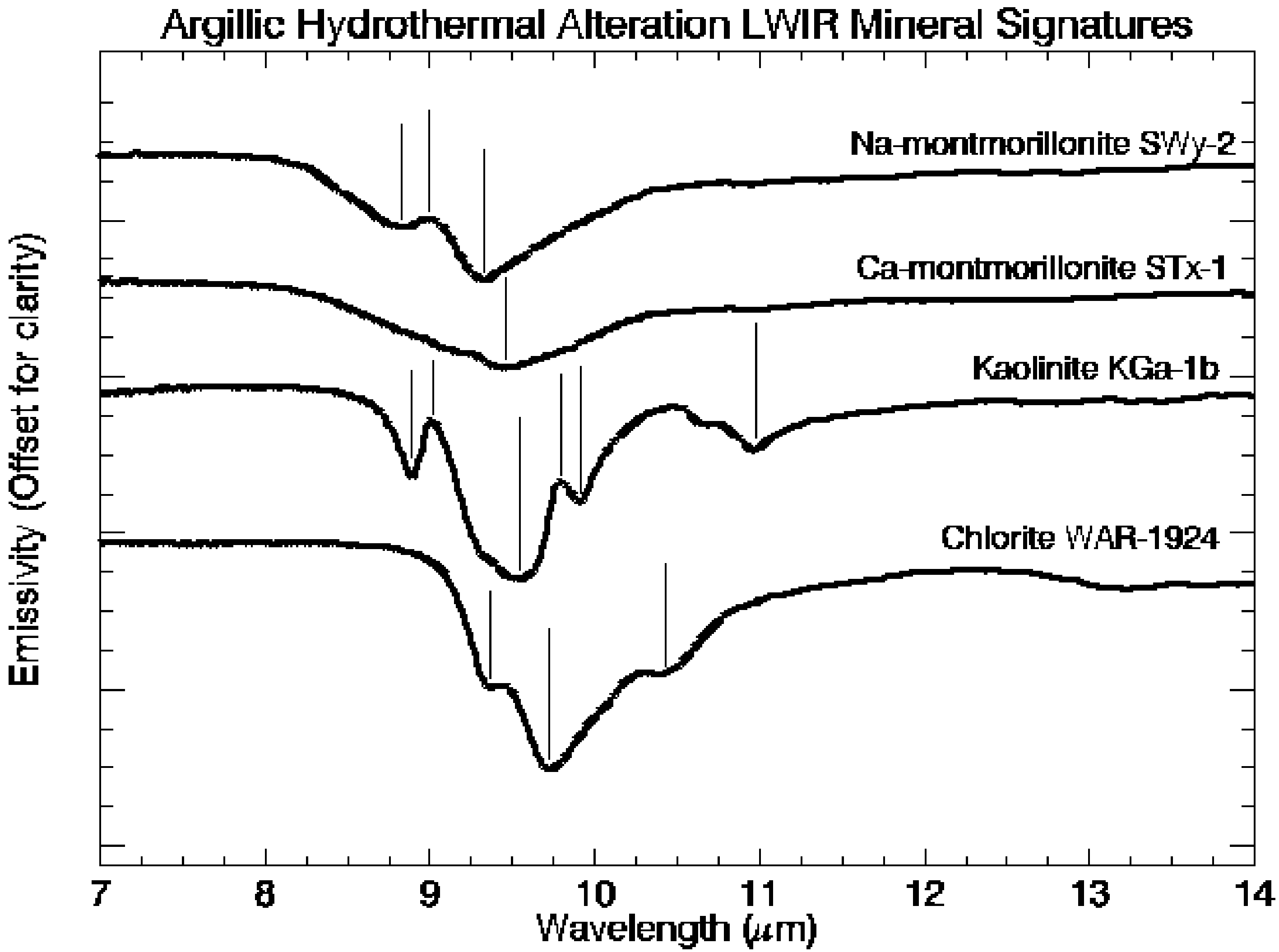
Geological Applications – Mineral Exploration

Porphyry Copper LWIR Mineral Signatures



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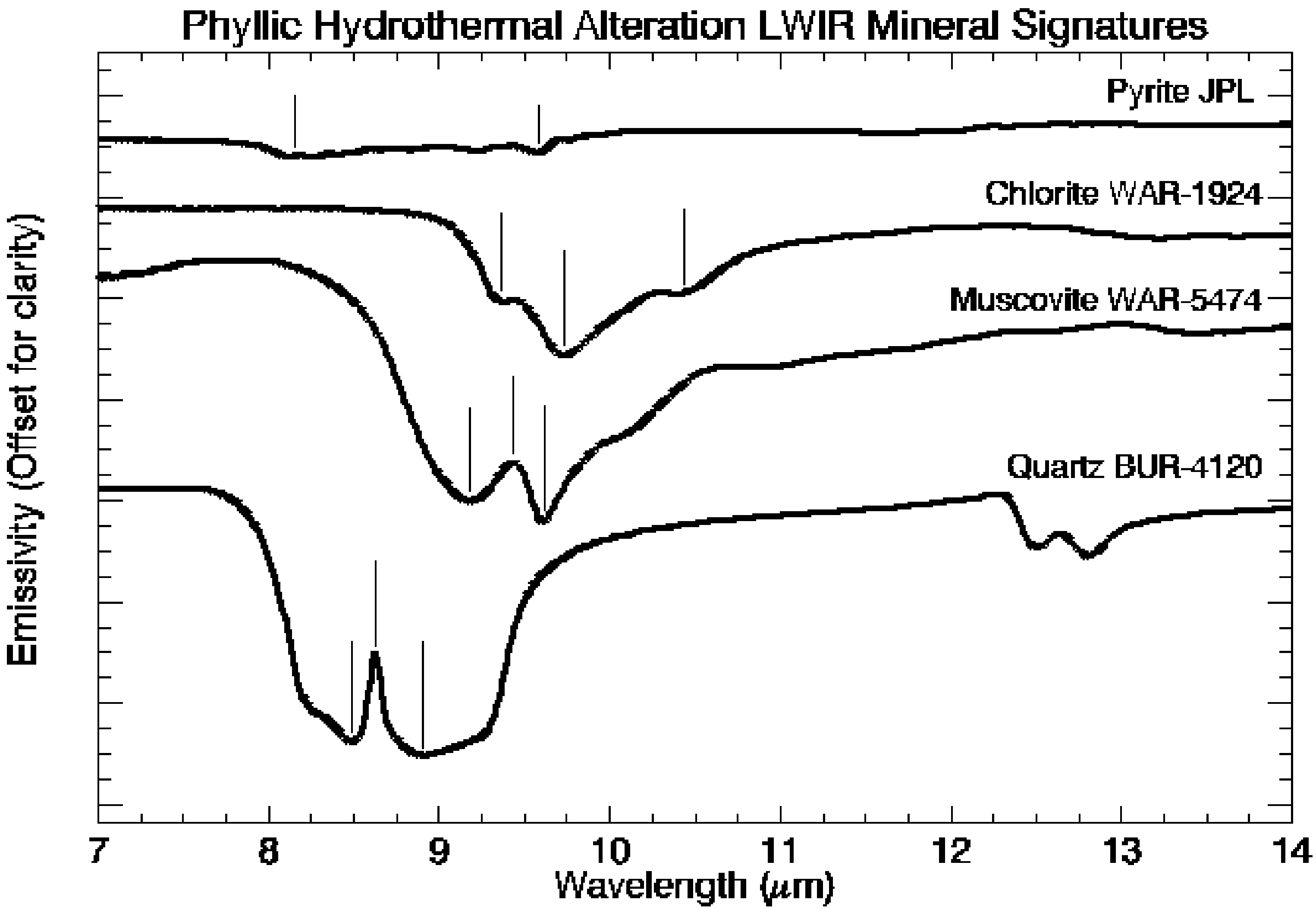
Porphyry Copper LWIR Mineral Signatures



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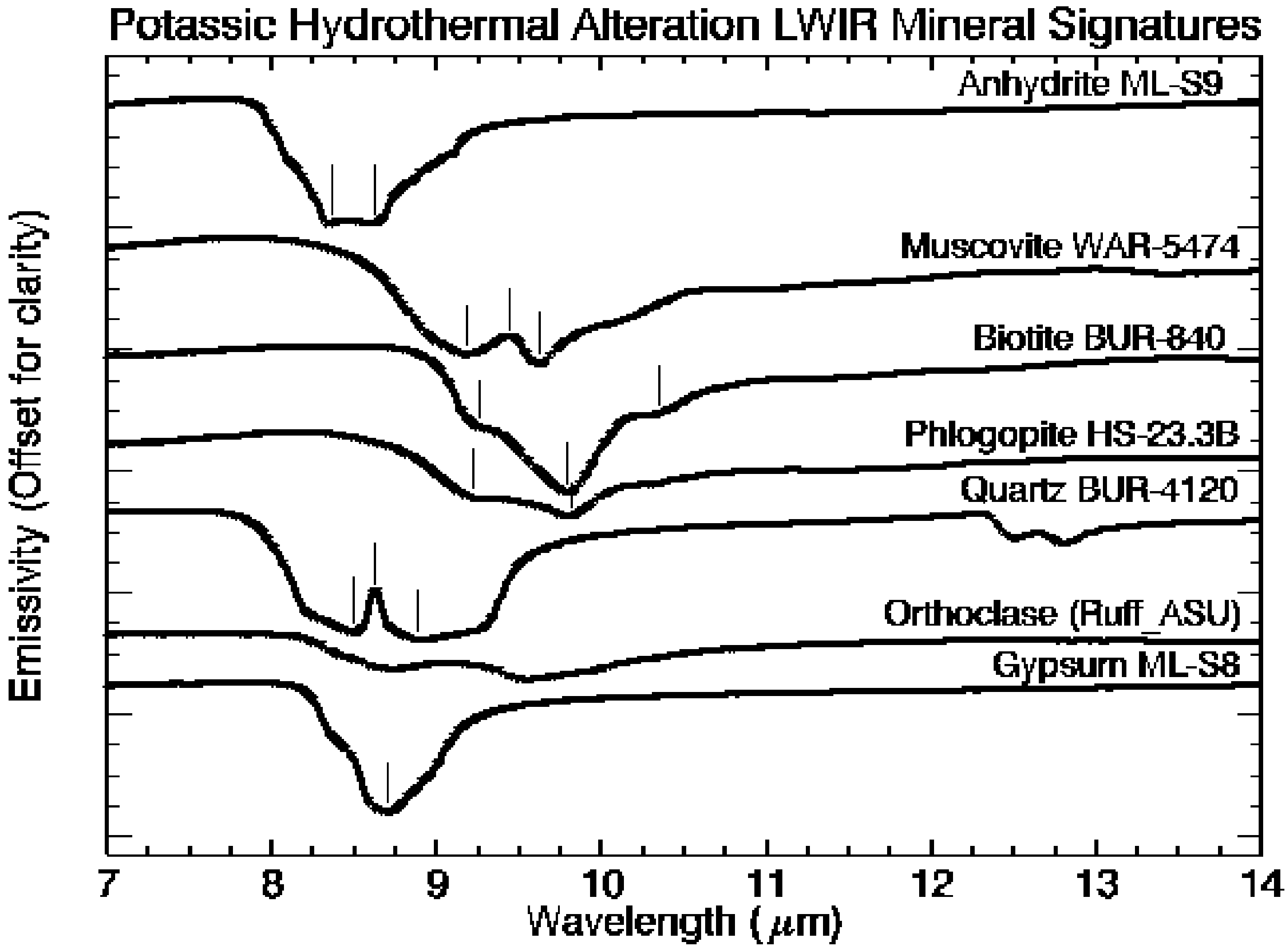
Porphyry Copper LWIR Mineral Signatures



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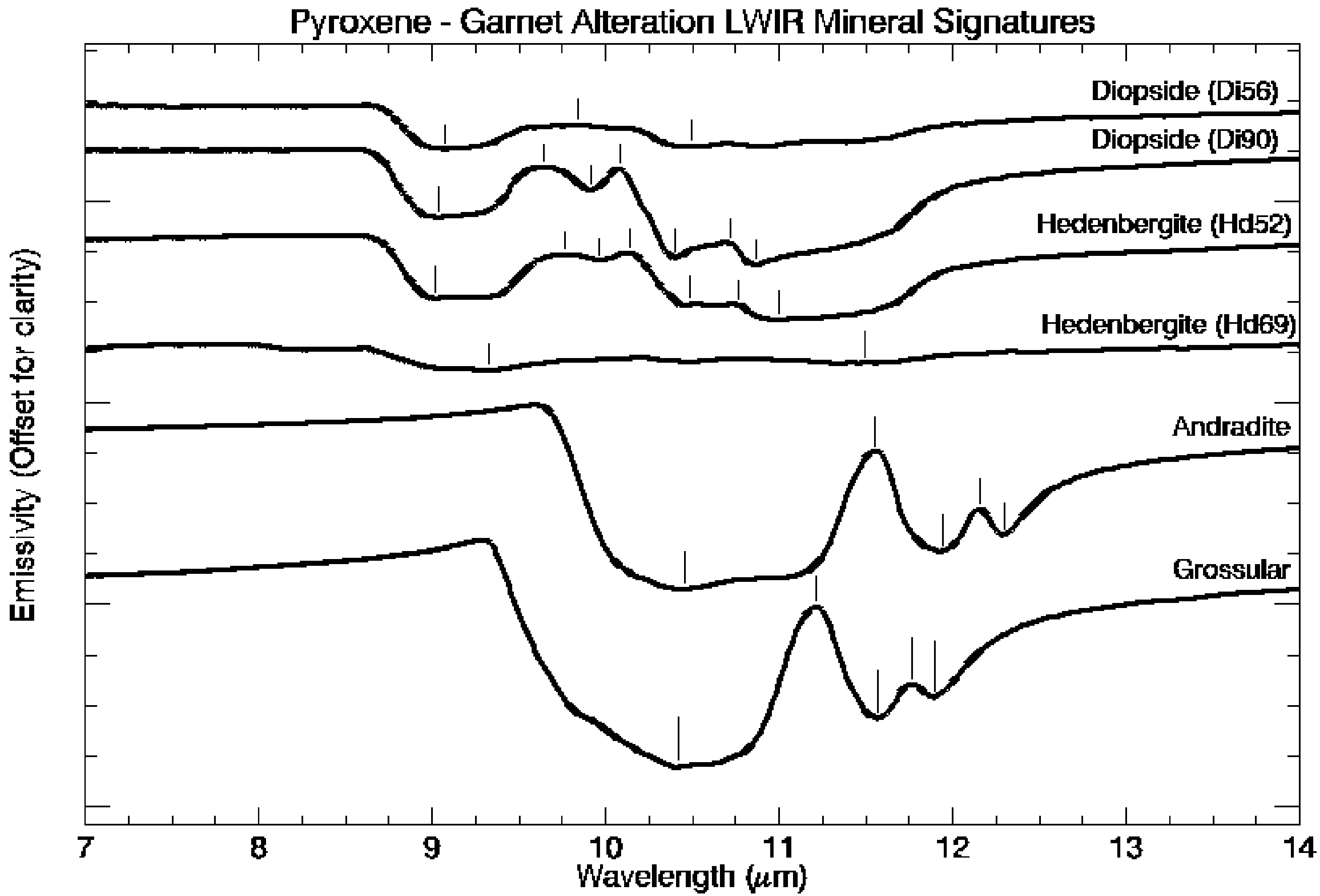
Copper Skarn LWIR Mineral Signatures



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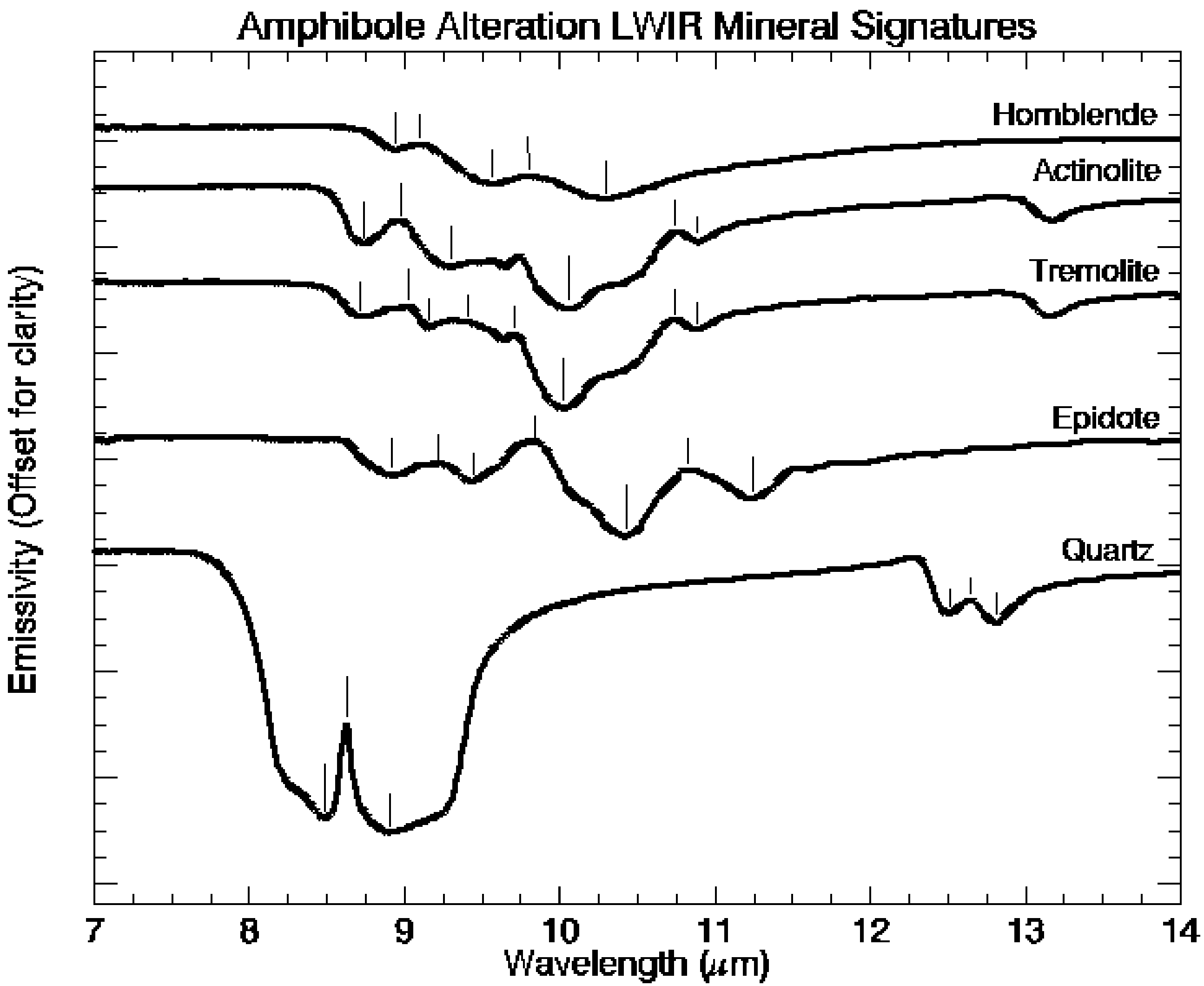
Amphibole LWIR Mineral Signatures



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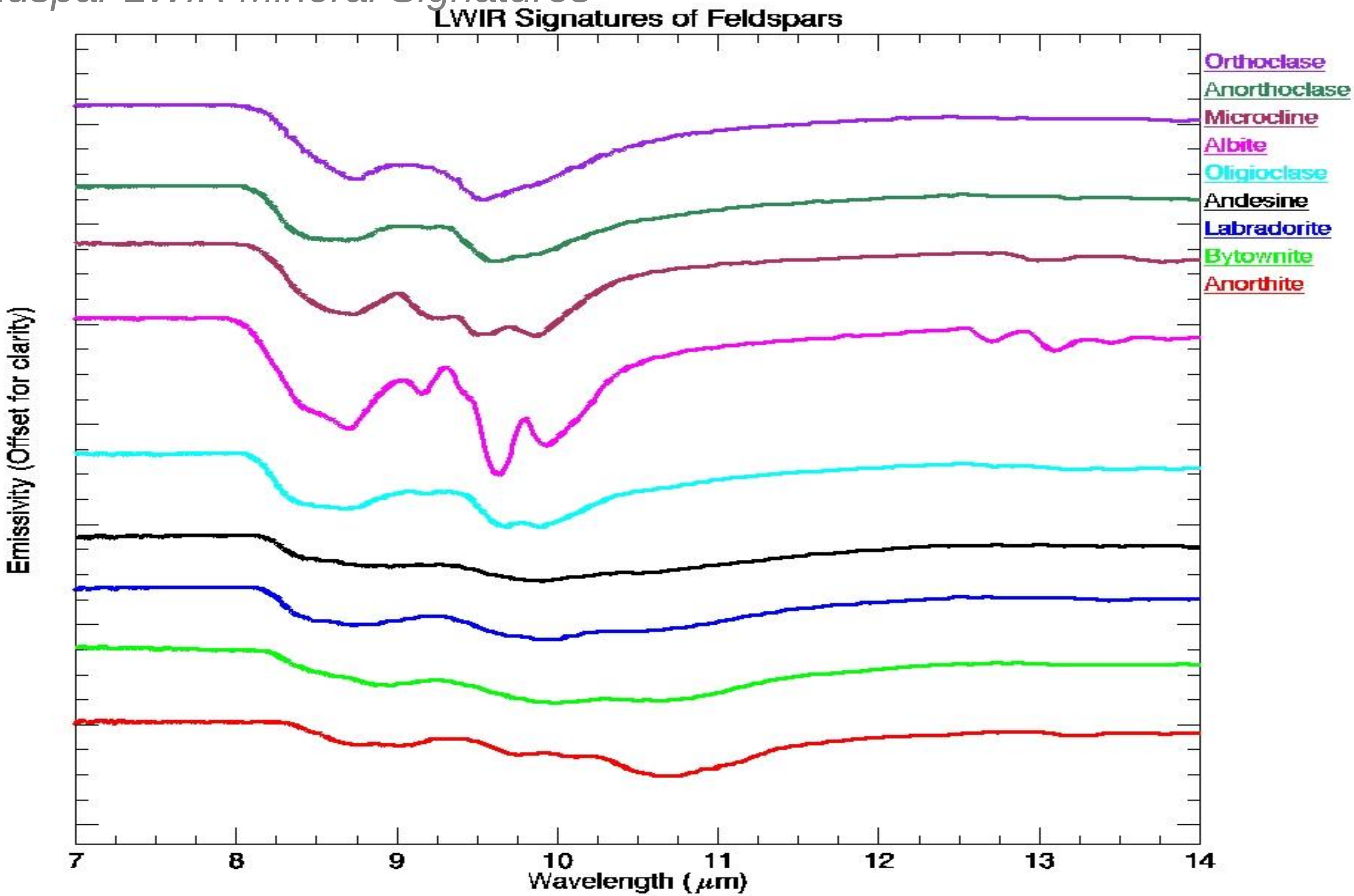
Feldspar LWIR Mineral Signatures



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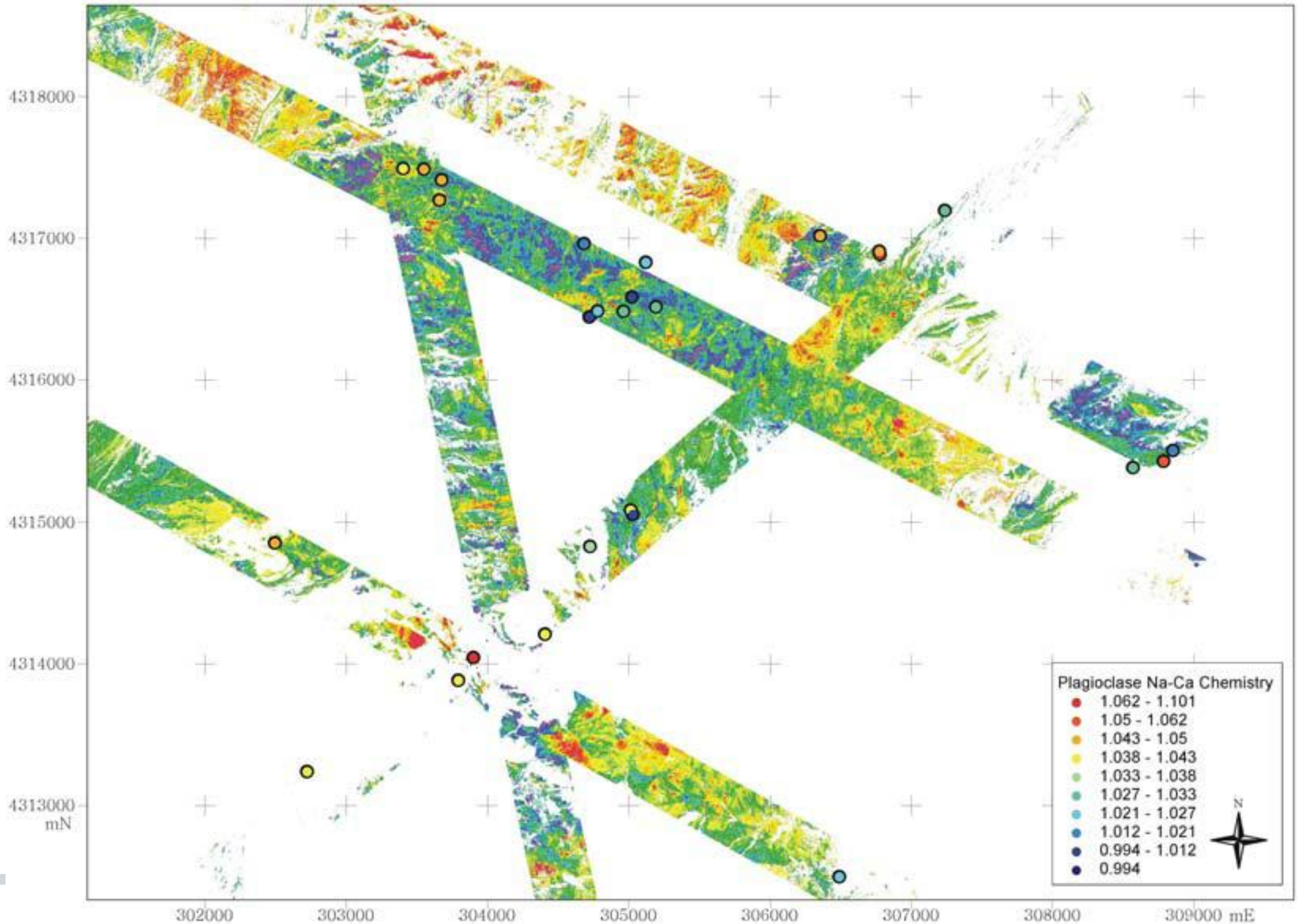
Plagioclase Mineral Chemistry Map



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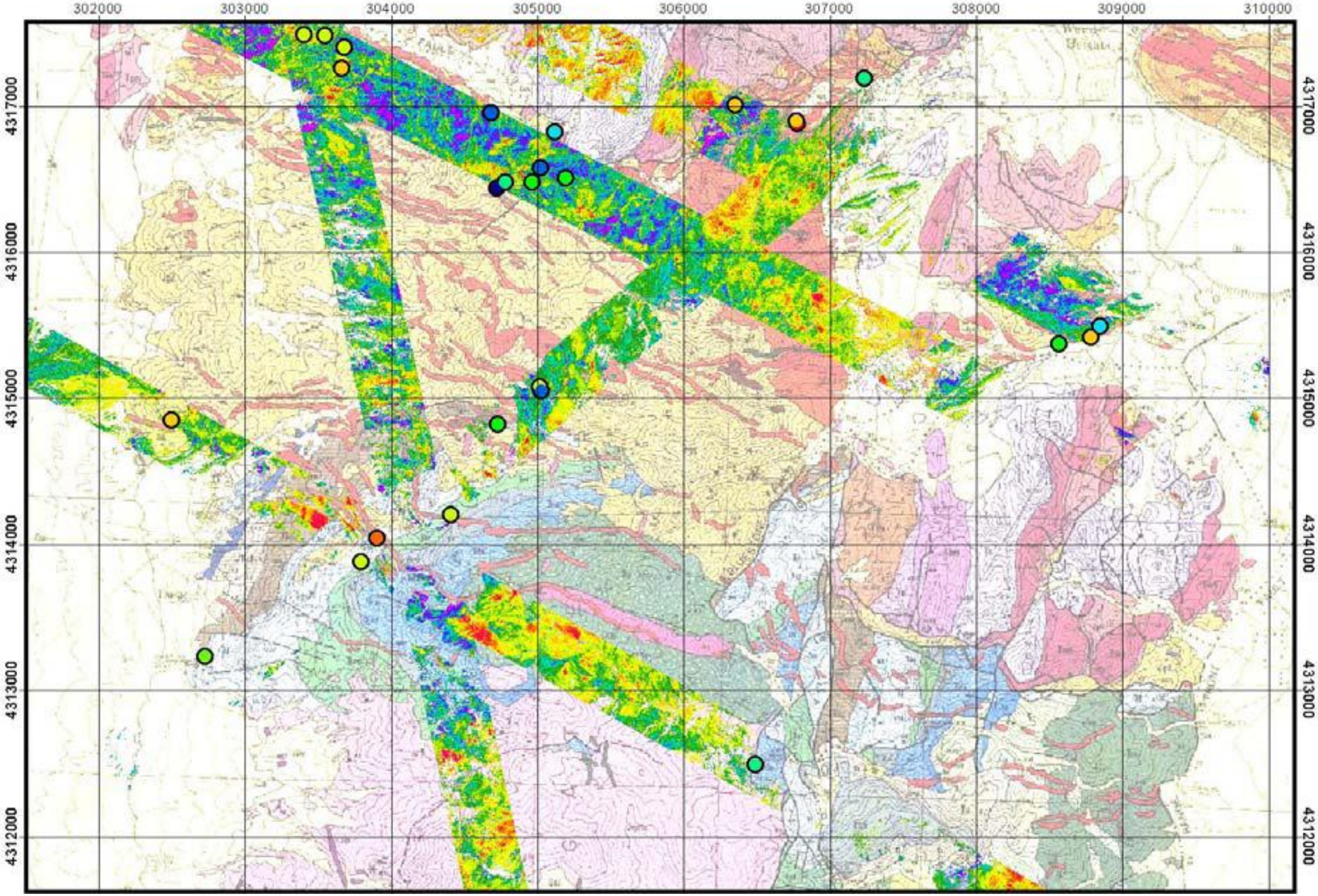

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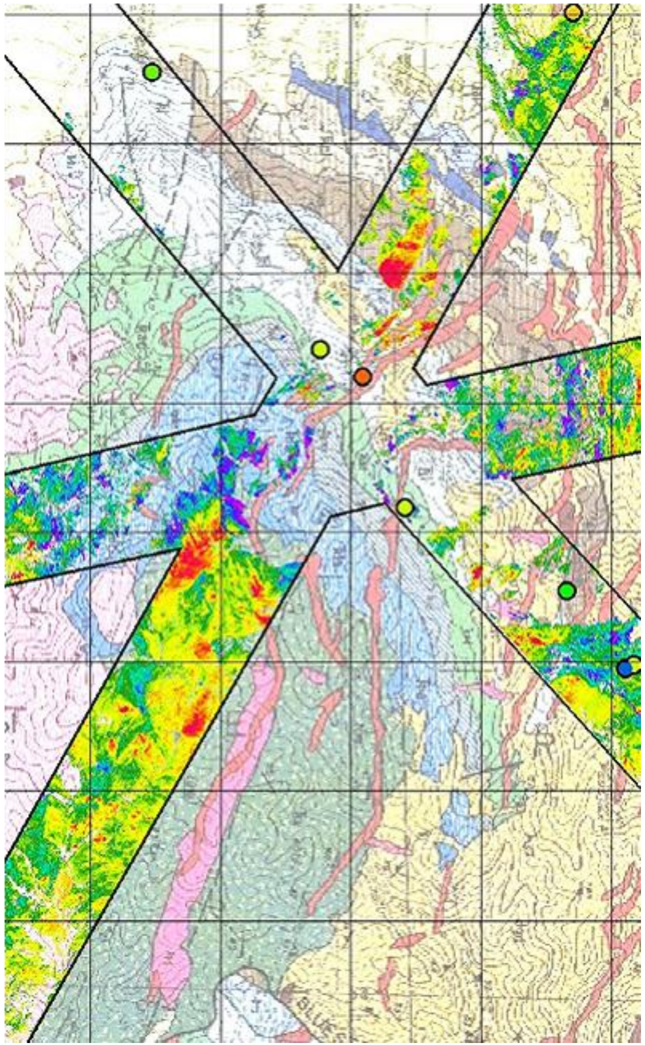
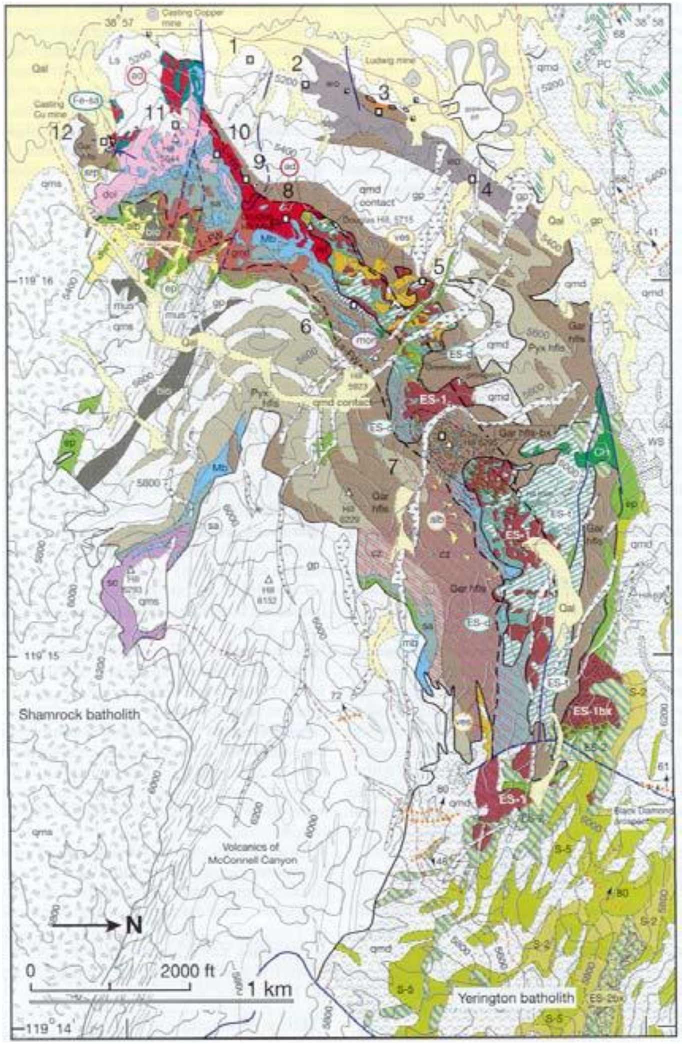
Feldspar Composition Maps





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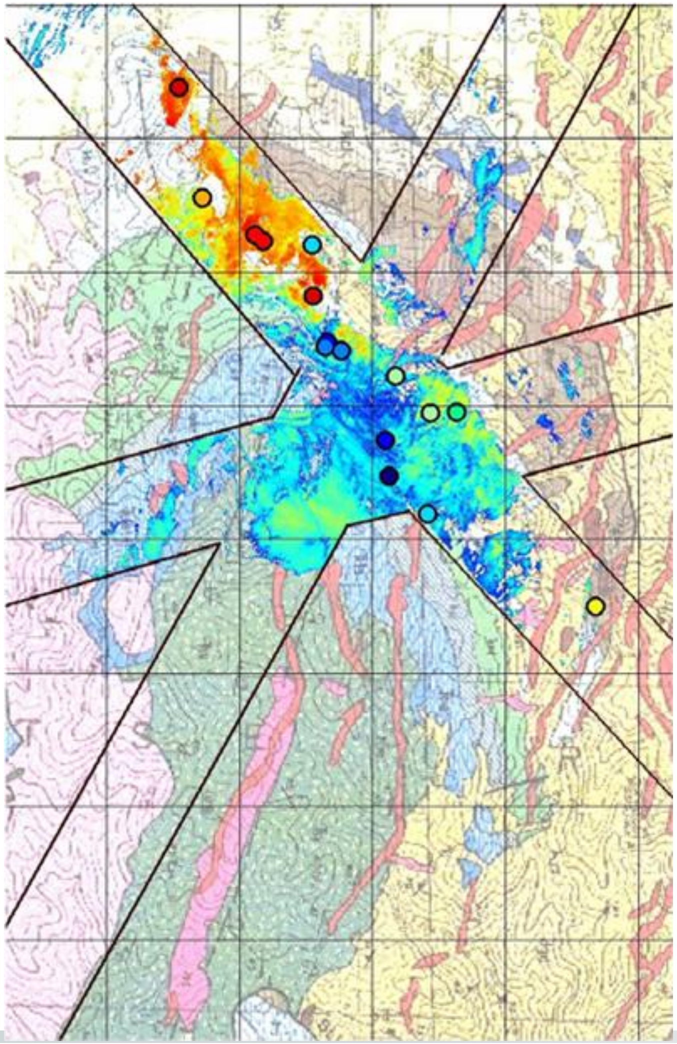
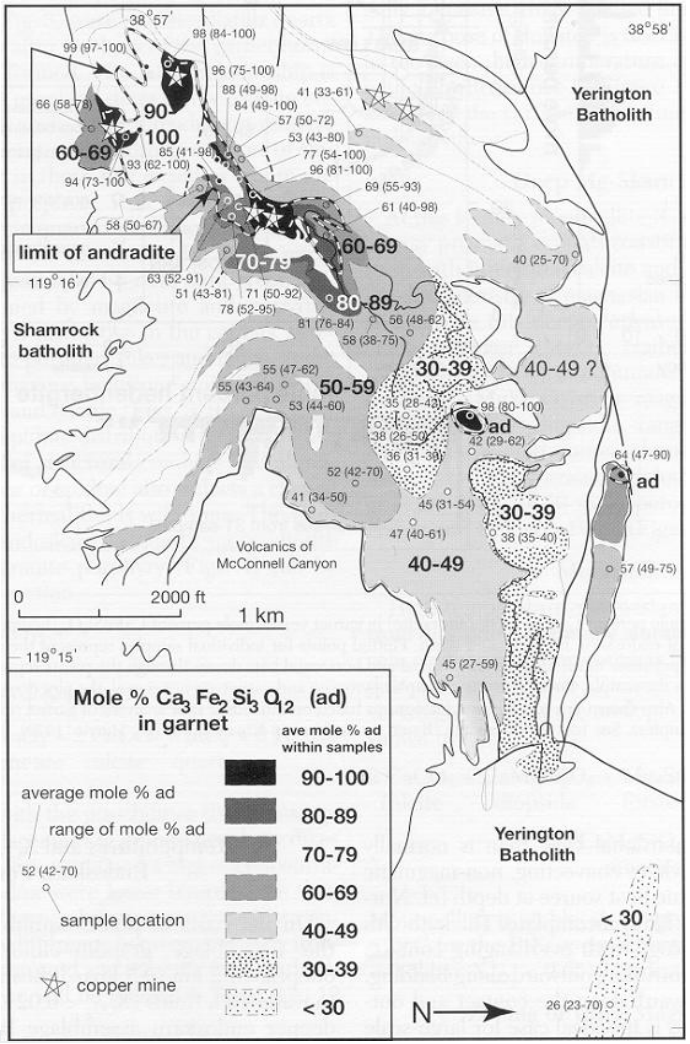
Geological Applications – Mineral Exploration

Garnet Chemistry Maps





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0 0.25 0.5 1
Miles

YERINGTON, NV - 1999
SEBASS Spectral Filter Maps
Feldspar RC2

	Oligioclase BUR-3680 48
	Quartz BUR-4120 55
	Albite WAR-0235 174
	Andesine WAR-0024 175
	Labradorite BUR-3080A 176
	Bytownite WAR-1384 177
	Anorthite BUR-340 178

Background: GEOLOGIC MAP OF THE YERINGTON DISTRICT
Proffett, J.M. and Dilles, J.H. 1984, NBMG Map 77

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YERINGTON, NV - 1999
SEBASS Spectral Filter Maps
Garnet False Color Composites

Andradite_JHU
Grossular_JHU
Pyrope_JHU

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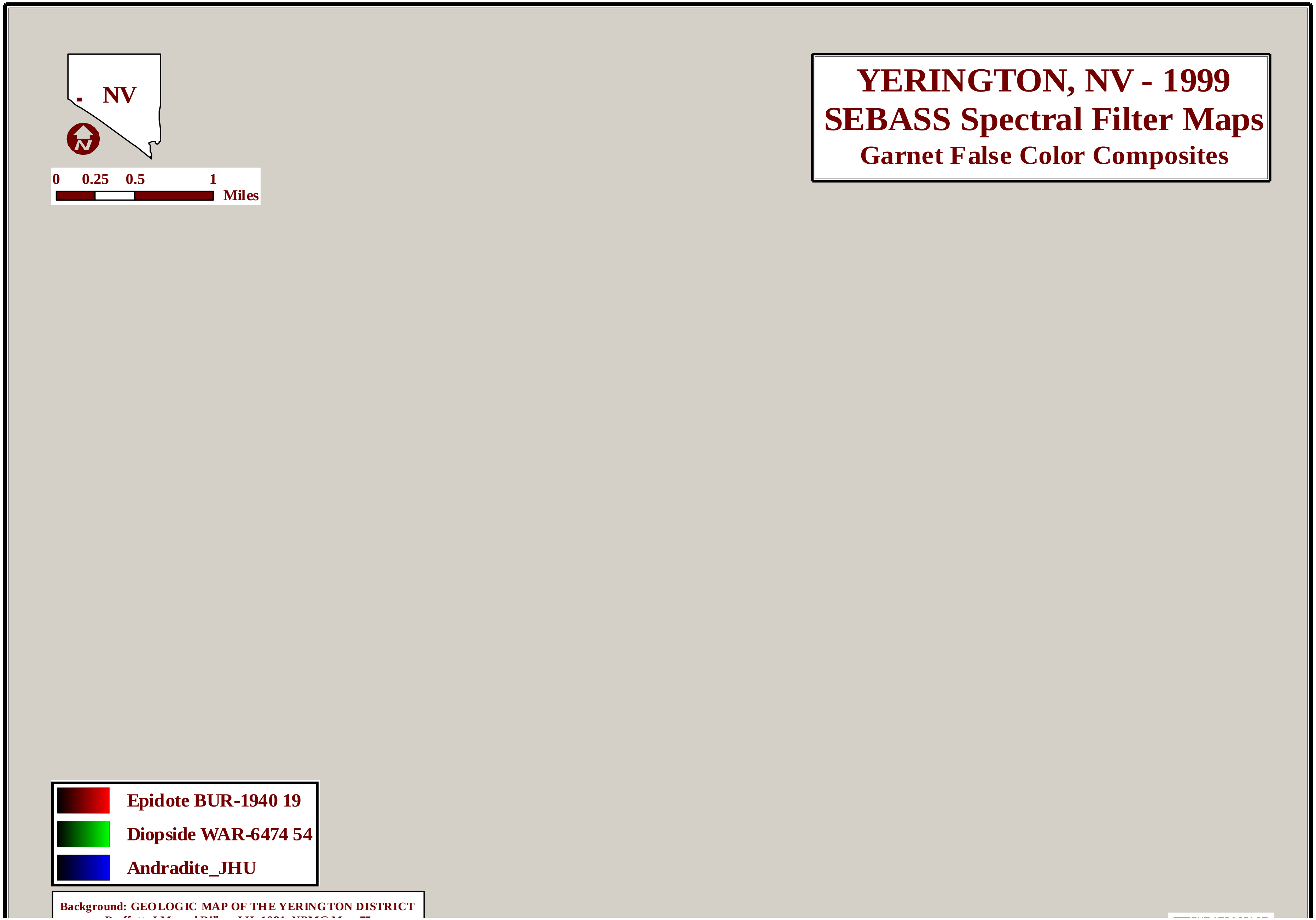

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Miles

YERINGTON, NV - 1999
SEBASS Spectral Filter Maps
Garnet RC2

- Epidote BUR-1940 19
- Diopside NMNH-80819 150
- Hedenbergite HS-104.B 216
- Andradite_JHU
- Grossular_JHU

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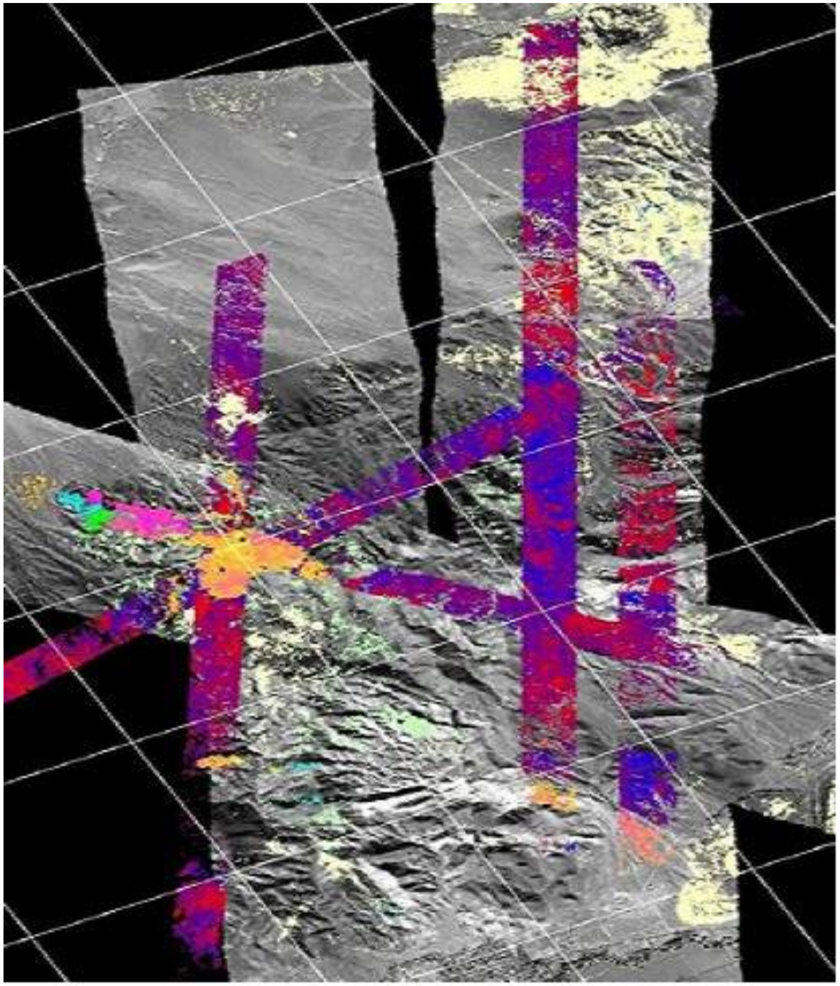
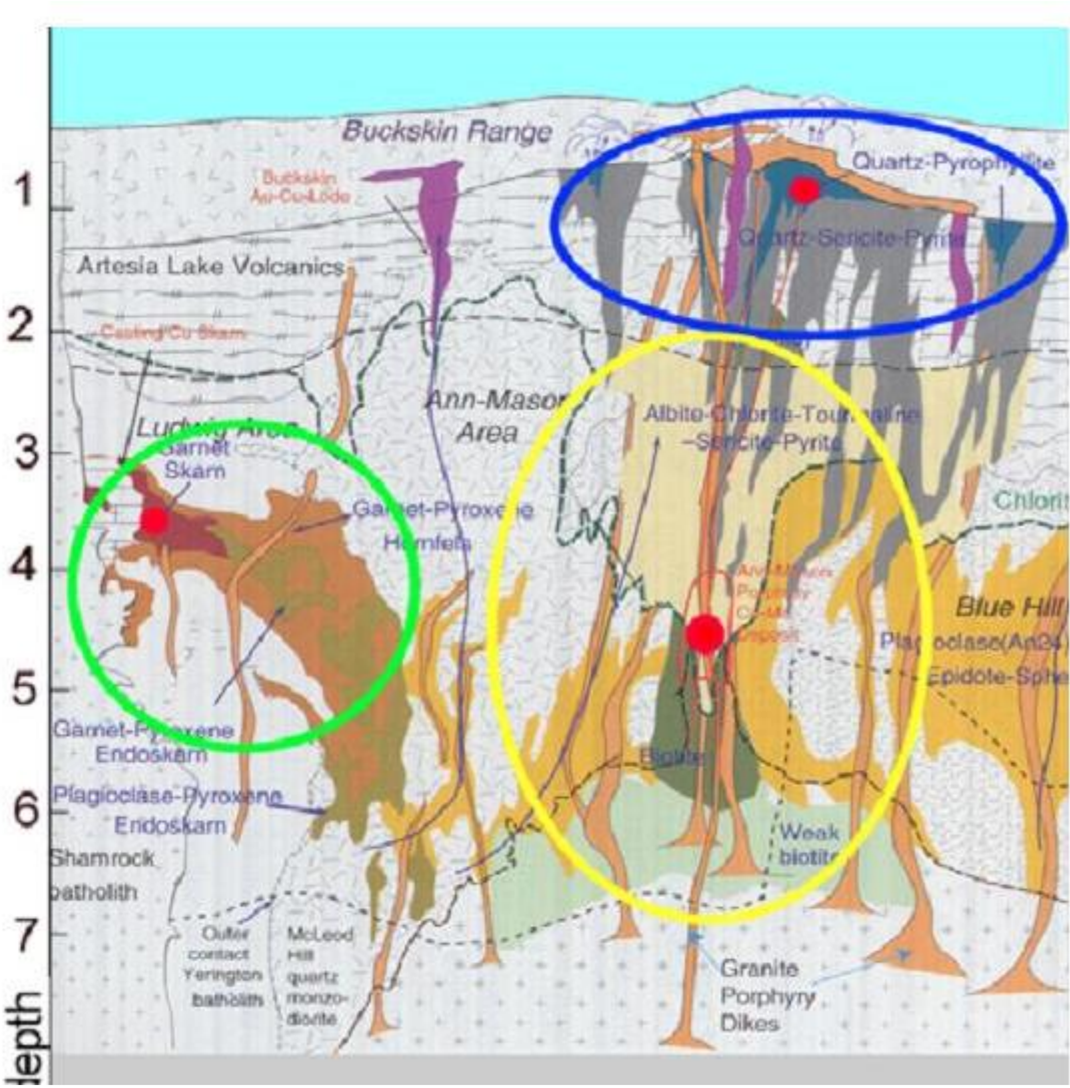
SEBASS Mineral Map and Alteration Cross-Section of Yerington District





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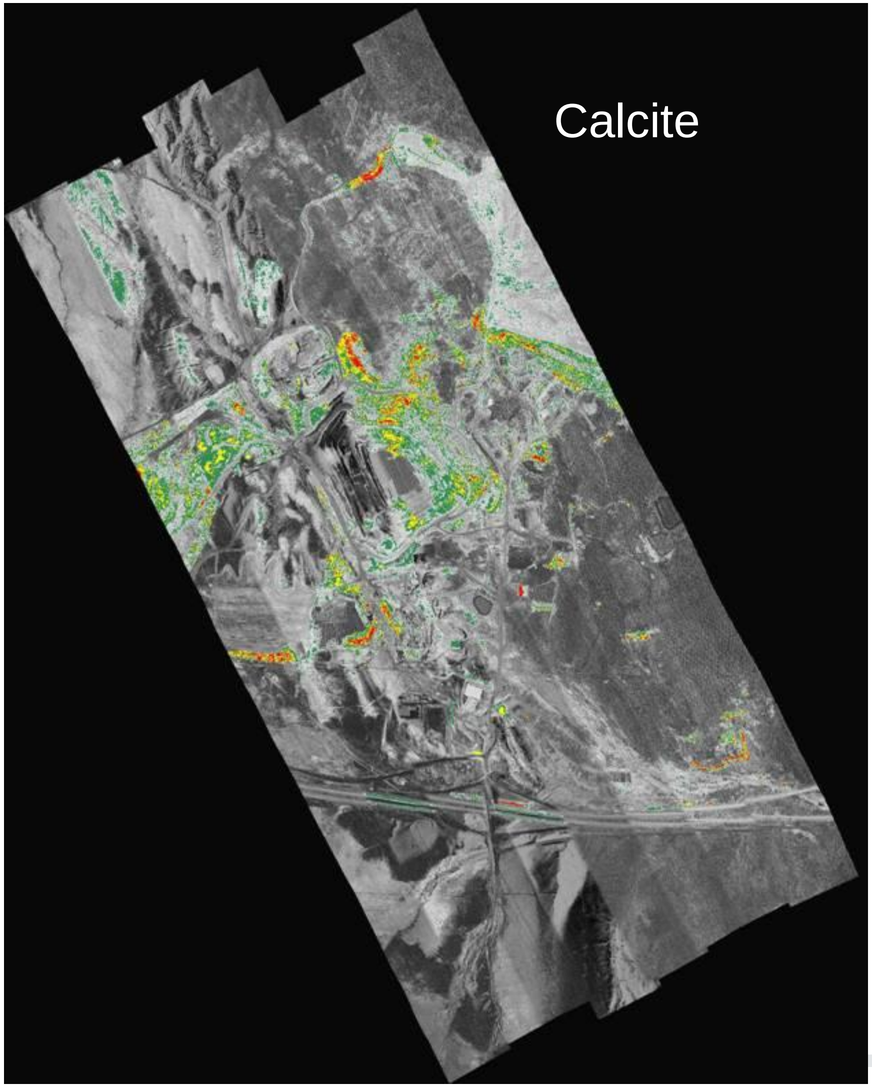
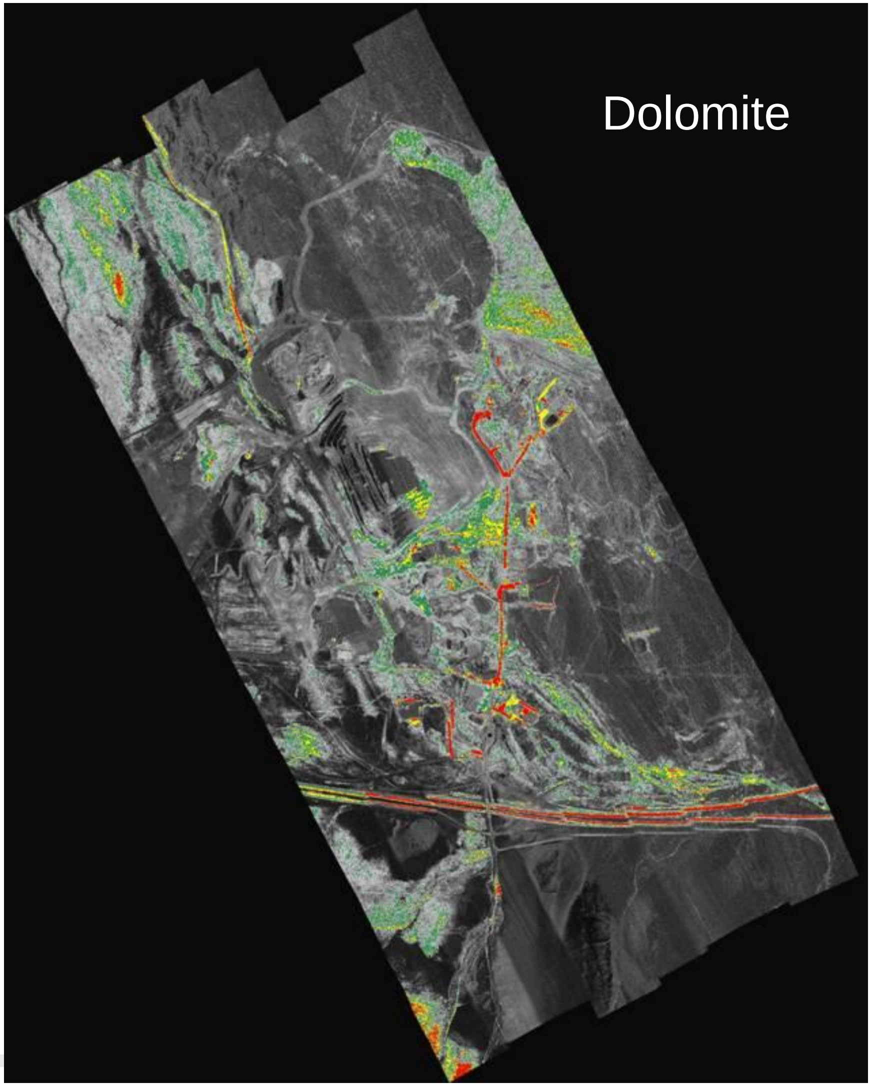
Geological Applications – Mineral Exploration

Carbonate Mapping at Mountain Pass Rare Earth Element Mine





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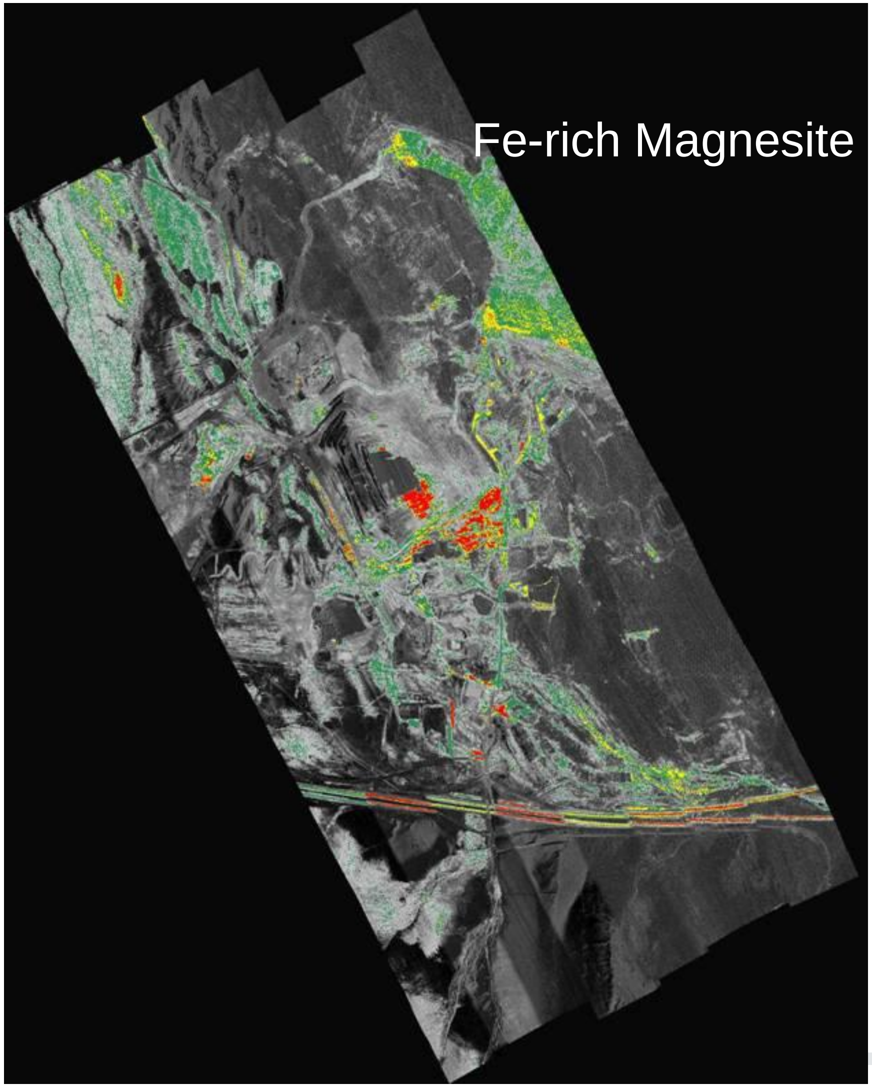

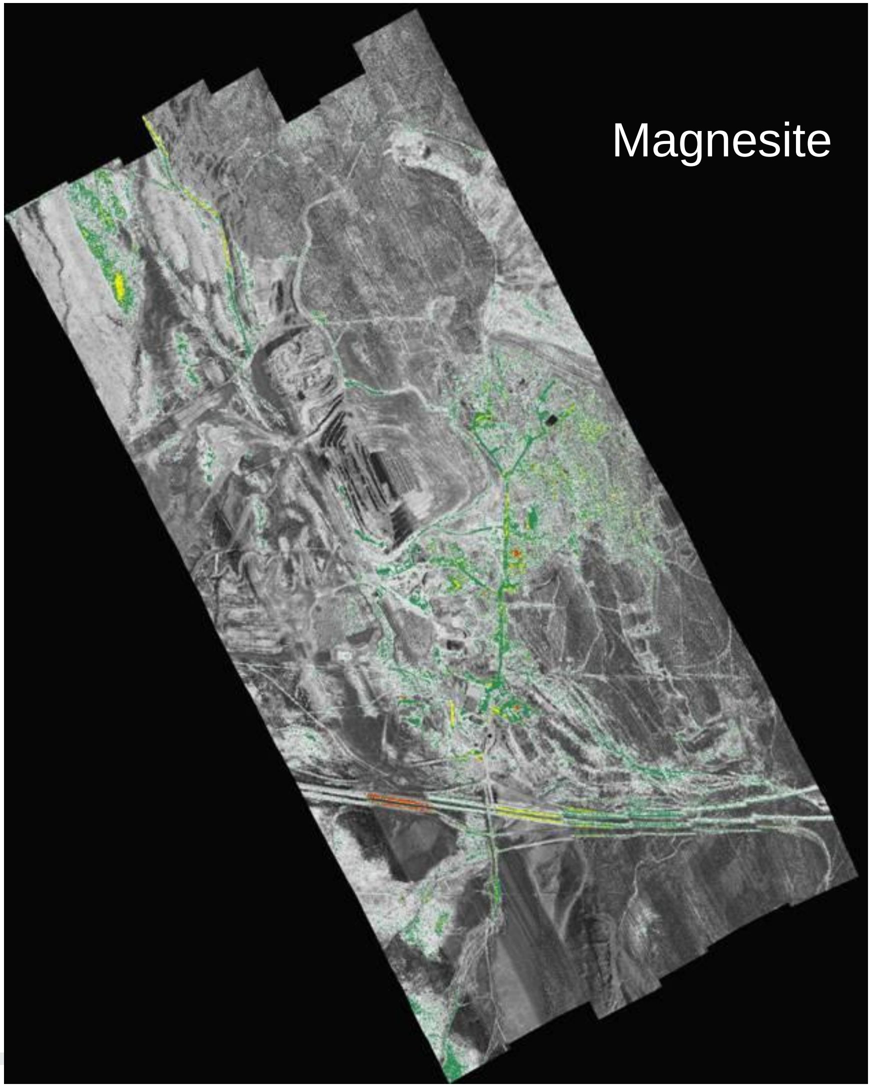

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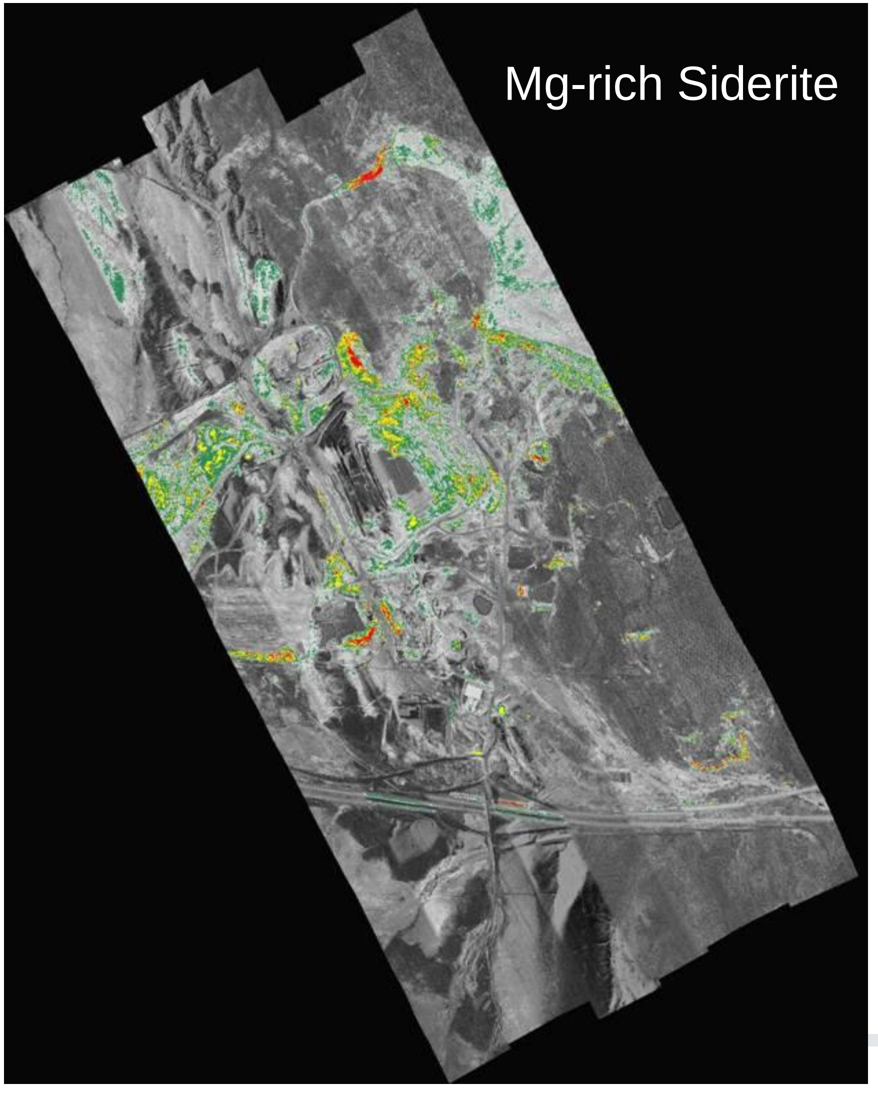

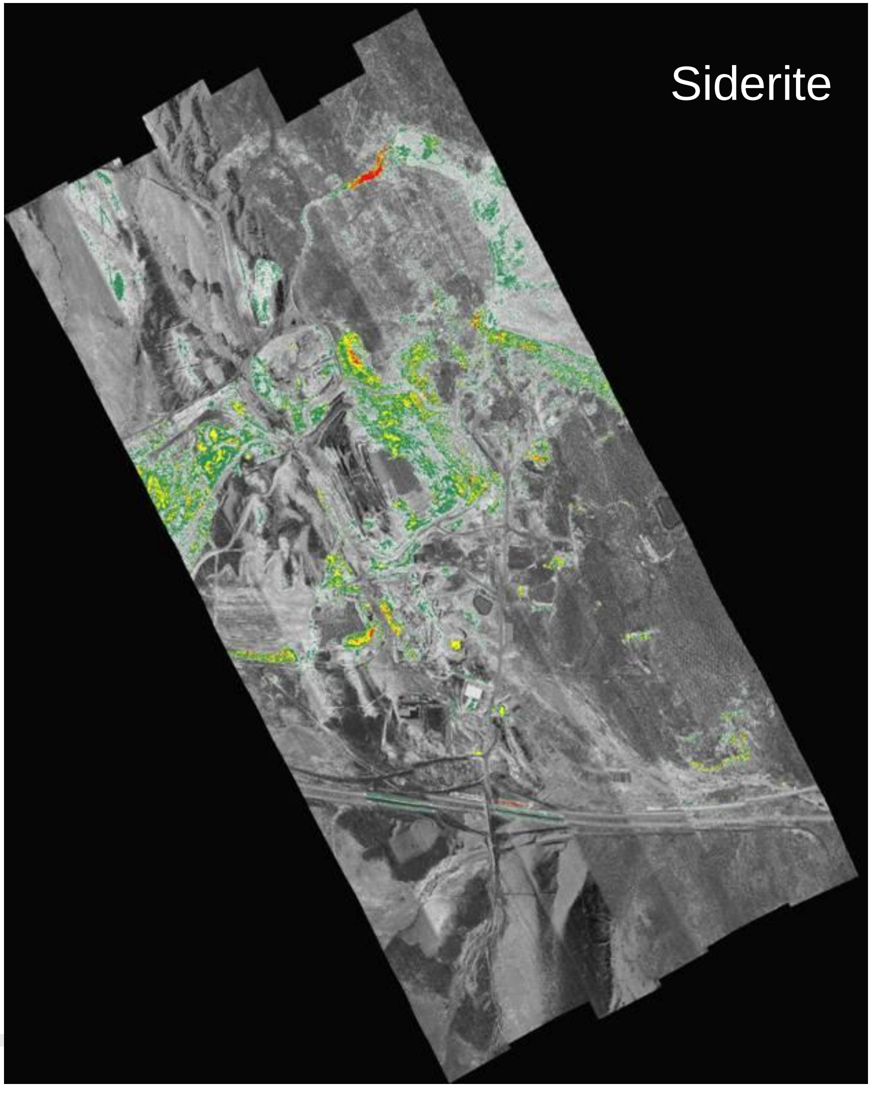

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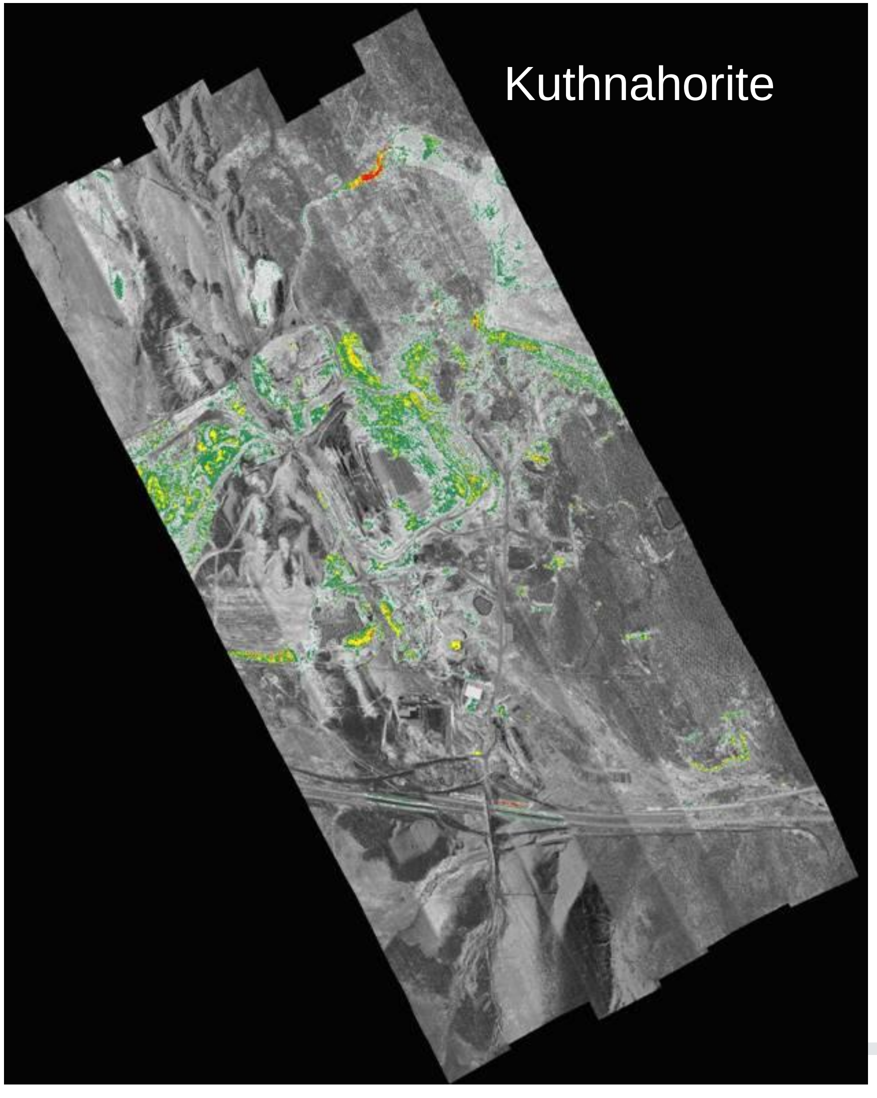
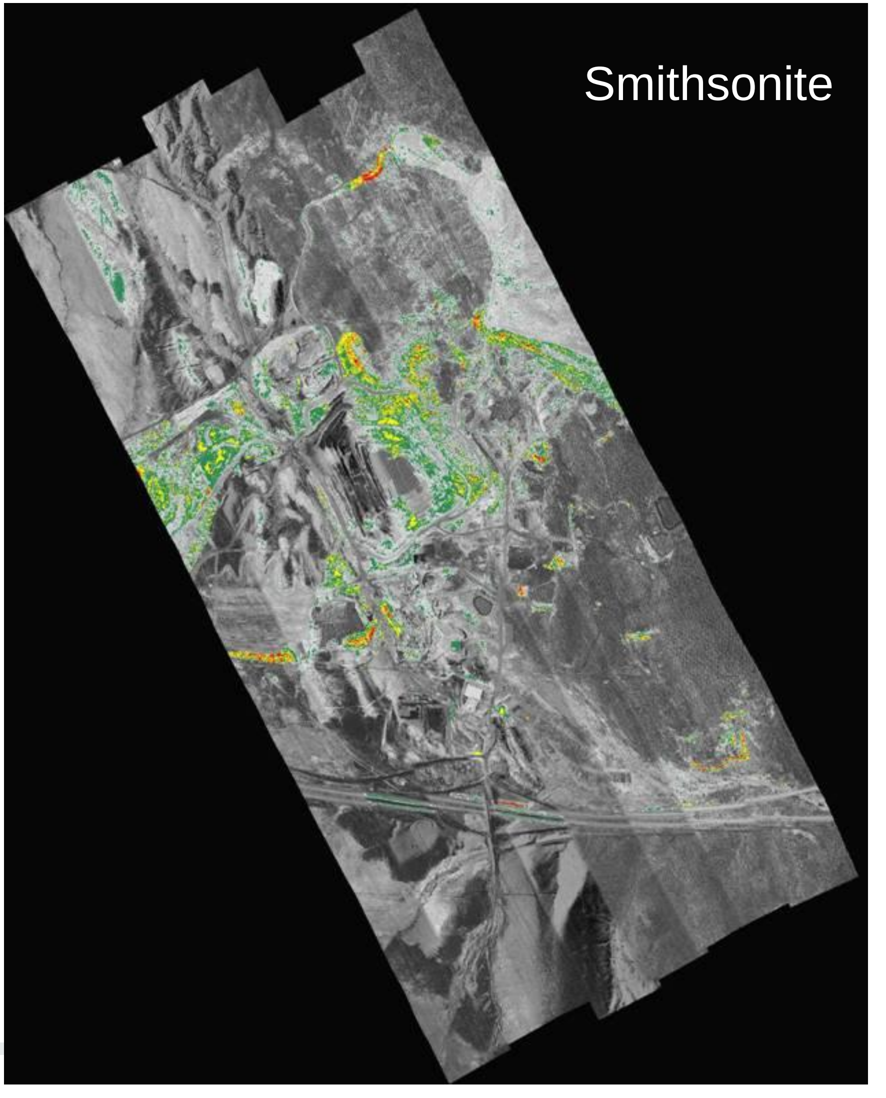
Geological Applications – Mineral Exploration

Carbonate Mapping at Mountain Pass Rare Earth Element Mine





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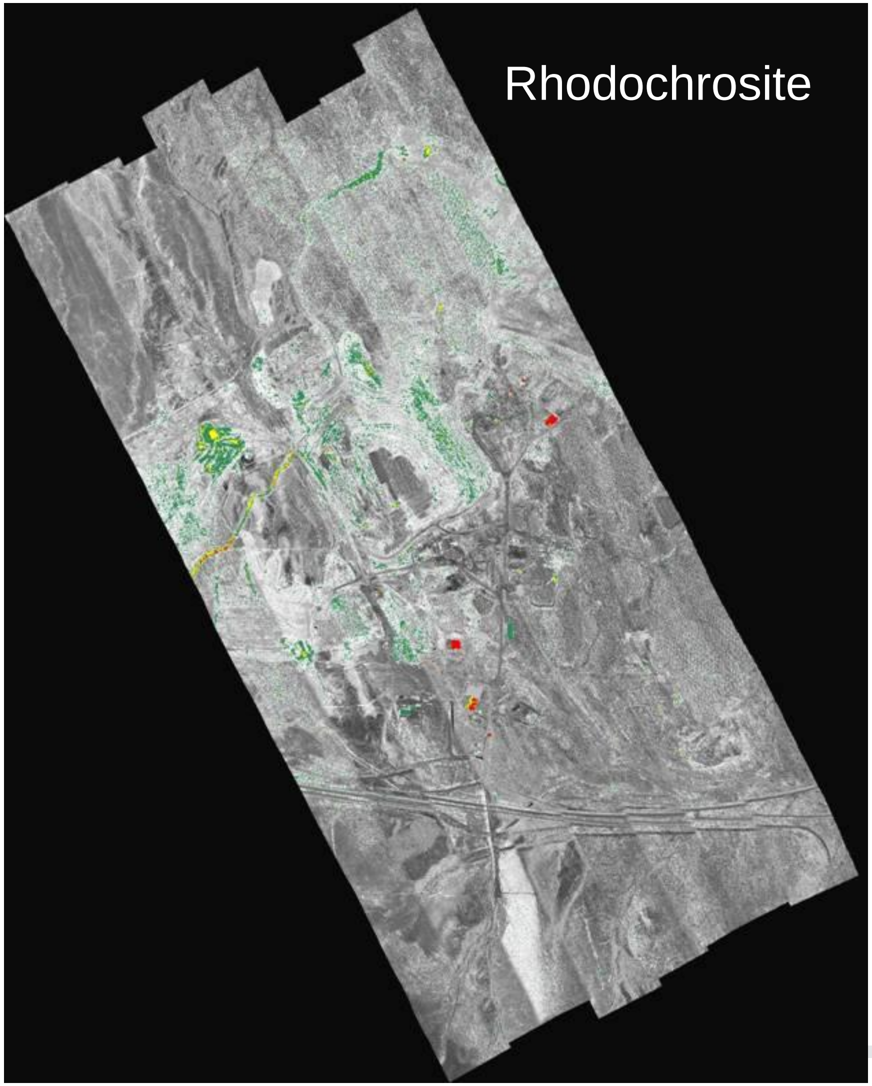
Geological Applications – Mineral Exploration

Carbonate Mapping at Mountain Pass Rare Earth Element Mine



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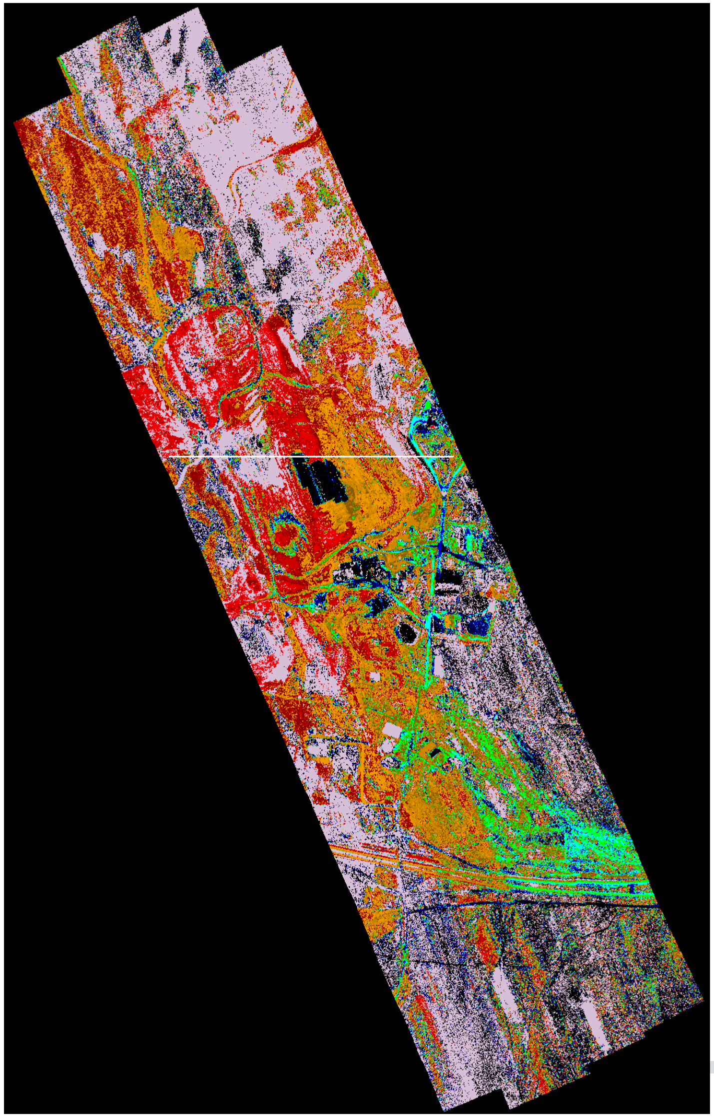
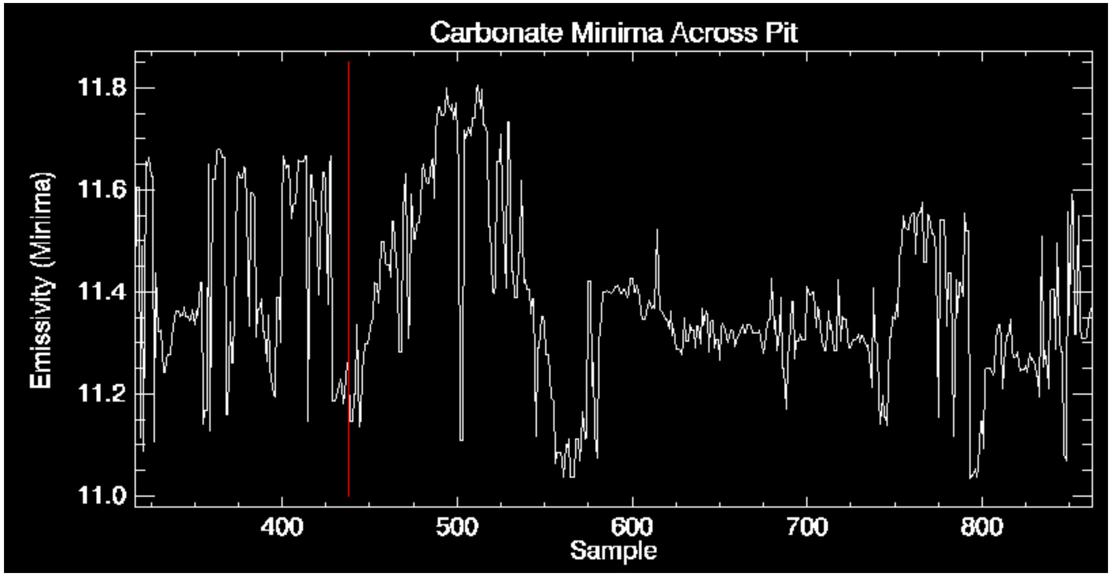
Spectral Minima Mapping for Carbonates at Mountain Pass REE Mine





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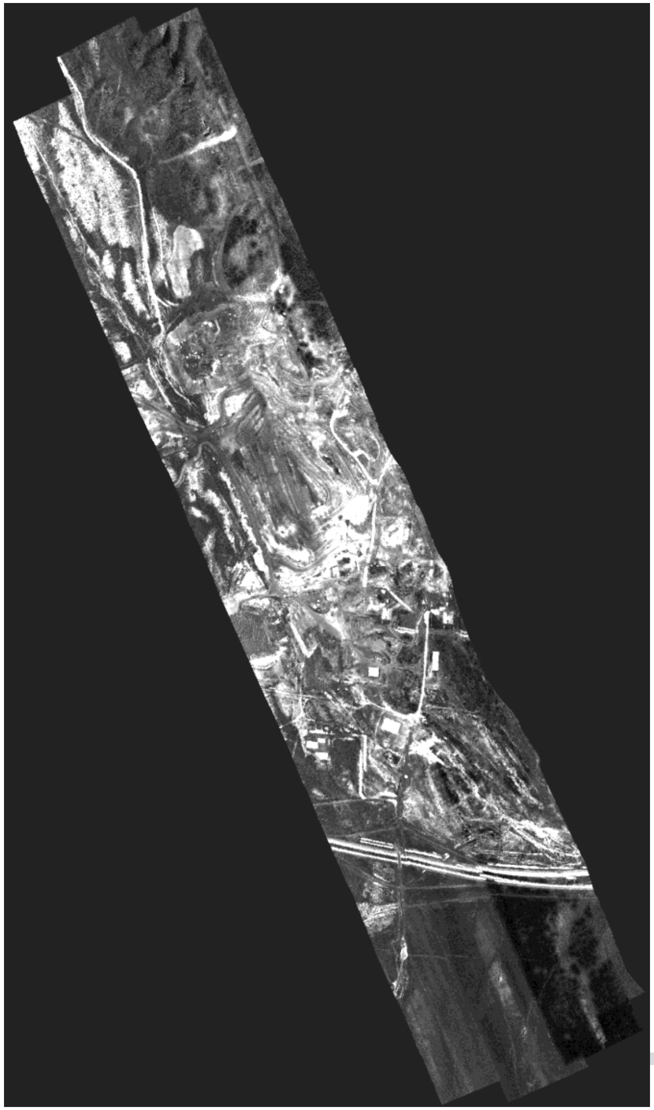
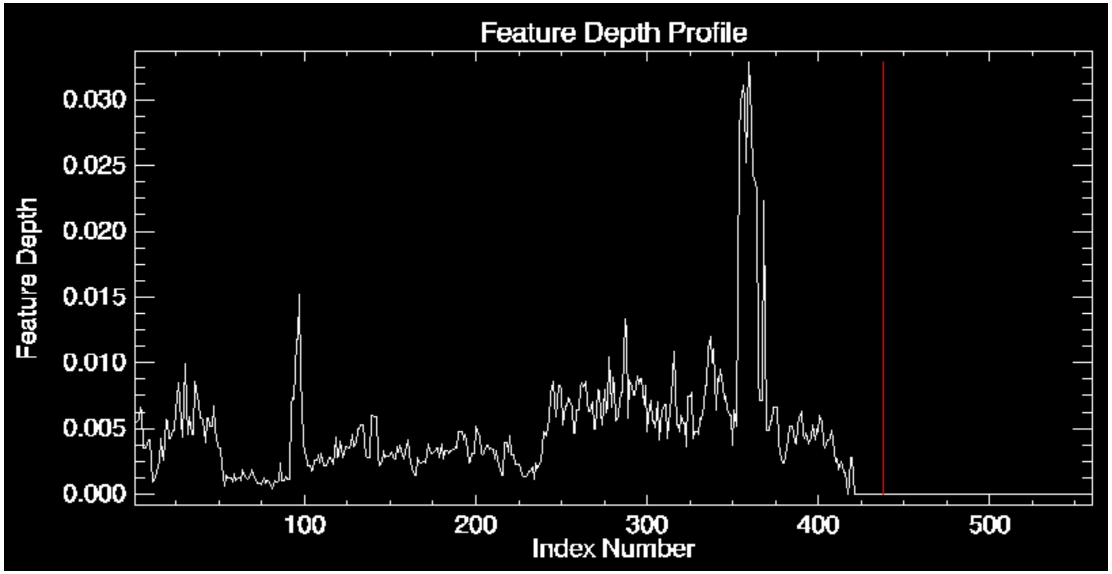
Geological Applications – Mineral Exploration

Feature Depth Mapping for Carbonates at Mountain Pass REE Mine





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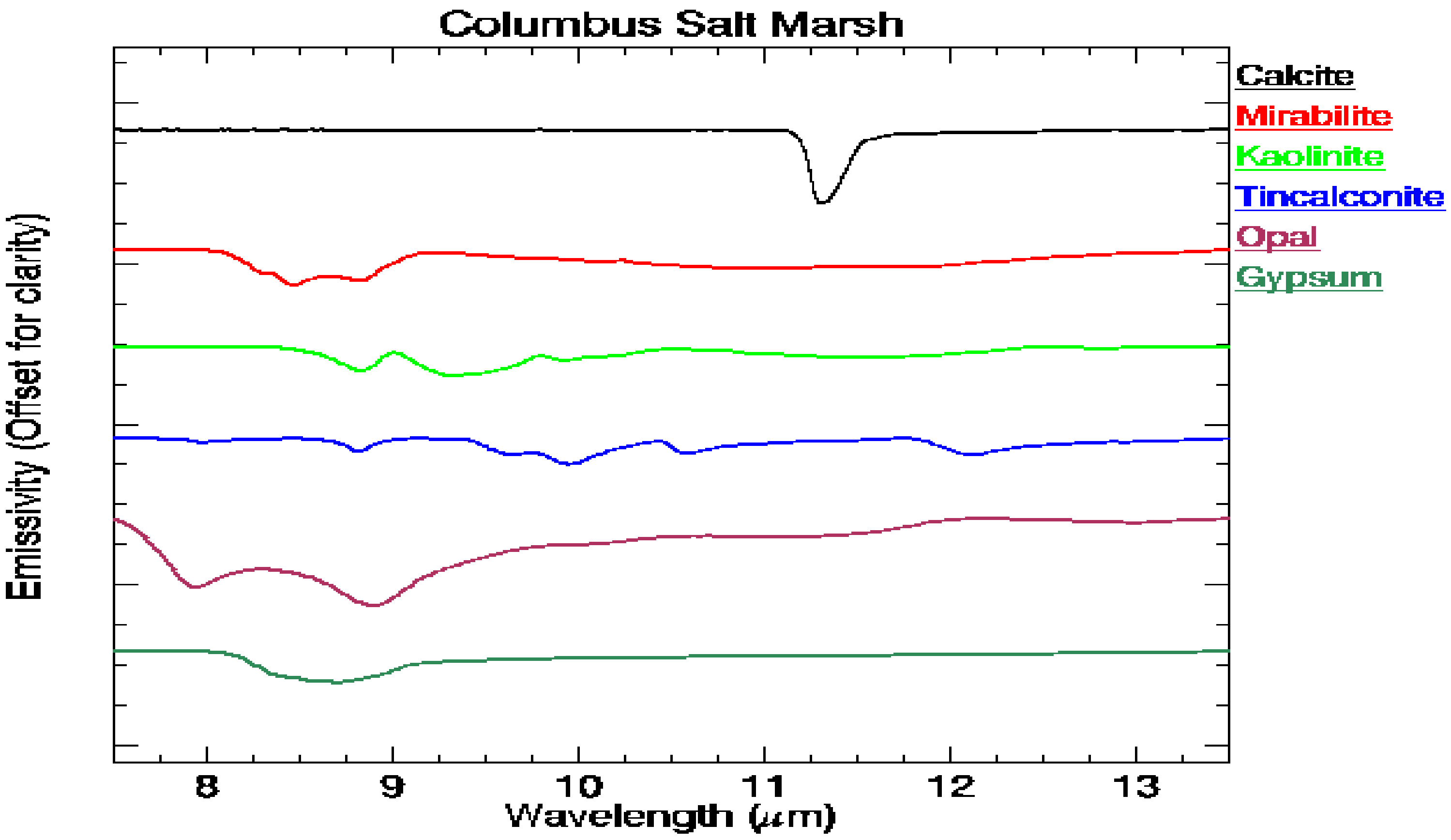
Geological Applications – Geothermal Exploration

Columbus Marsh – Applicable Library Signatures



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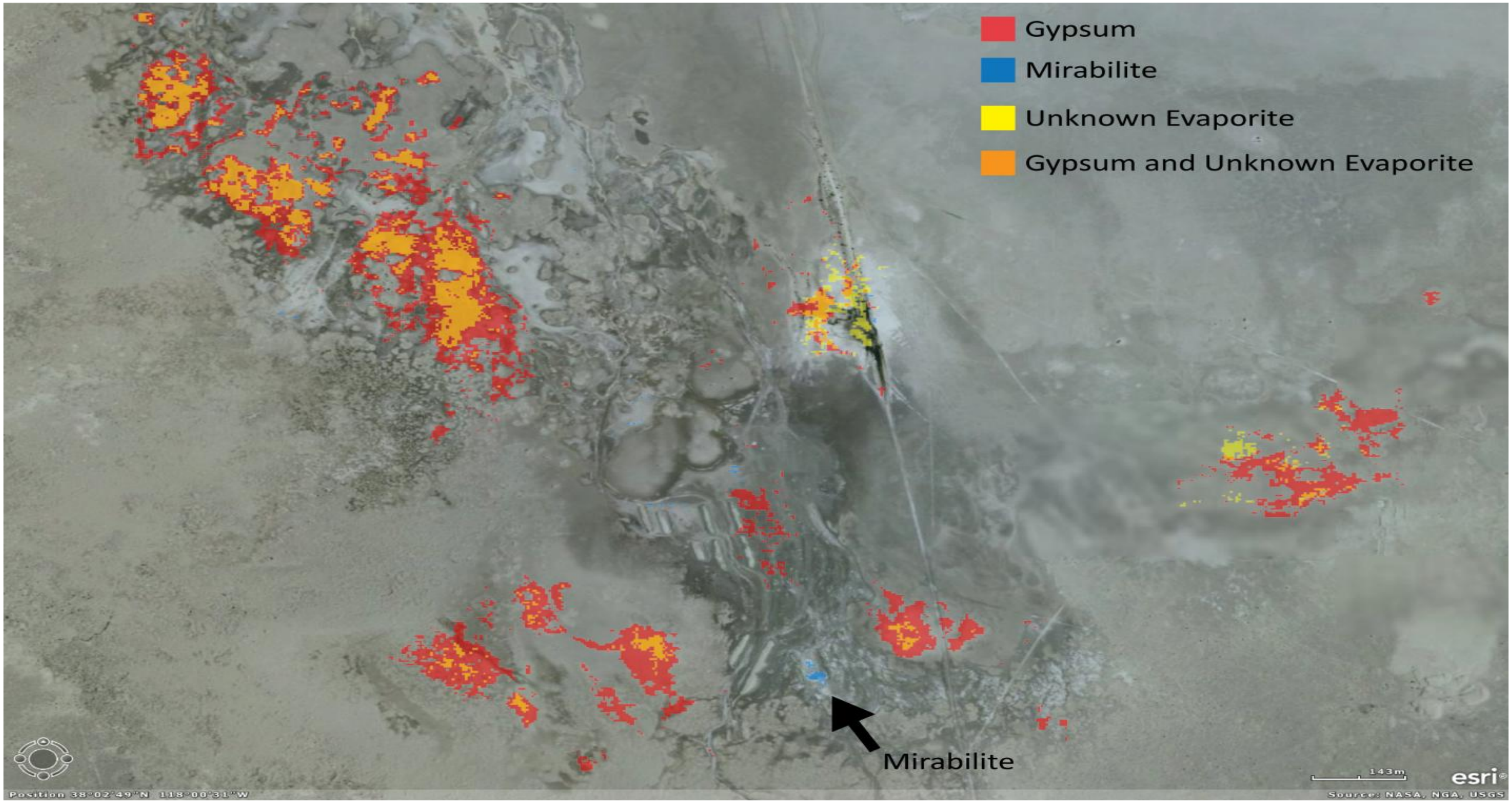
Geological Applications – Geothermal Exploration

Geothermal Exploration – Columbus Marsh



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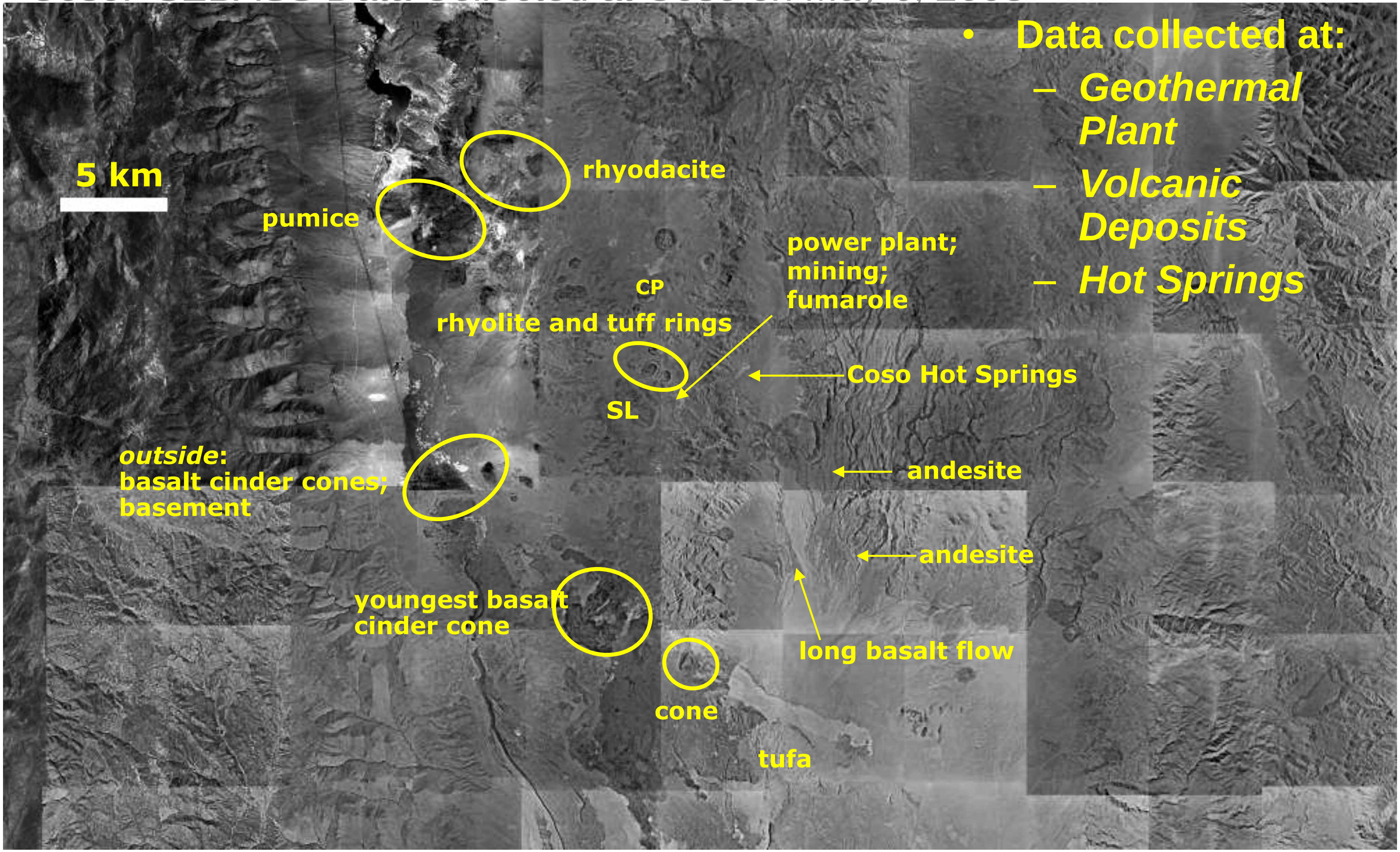
Geological Applications – Geothermal Exploration

Coso: SEBASS Data Collected at Coso on May 6, 2005



- **Data collected at:**
  - ***Geothermal Plant***
  - ***Volcanic Deposits***
  - ***Hot Springs***

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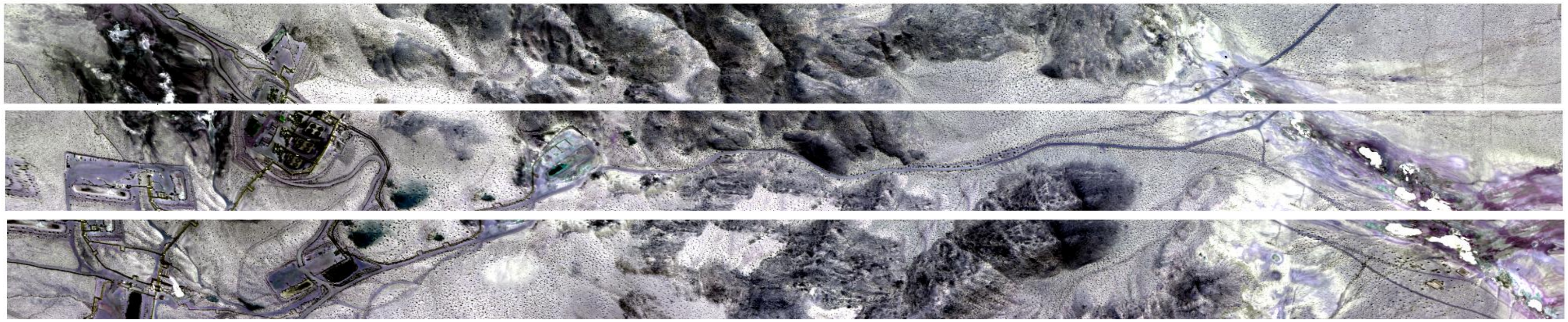
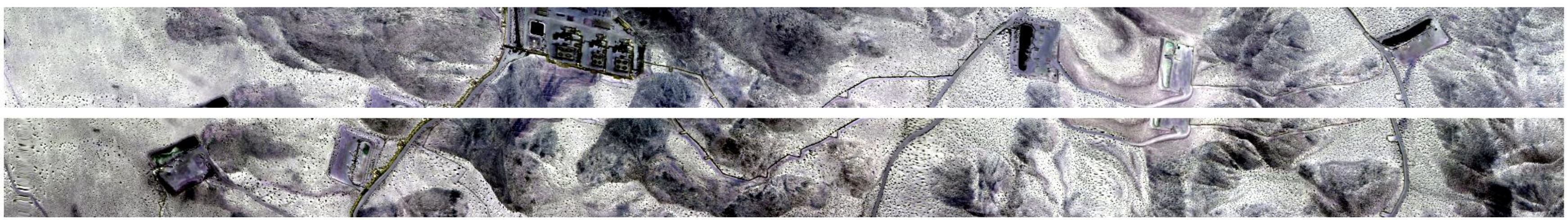
Geological Applications – Geothermal Exploration

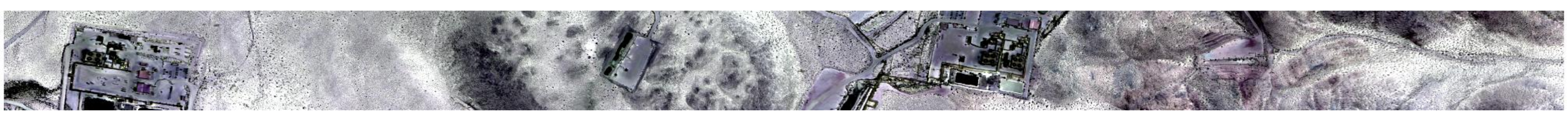
Coso – Geothermal Plants: SEBASS LWIR



Plant “A”



Plant “B”



Plant “C”

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Geological Applications – Geothermal Exploration

Geothermal Plant: Photography from Aircraft

Plant “A”

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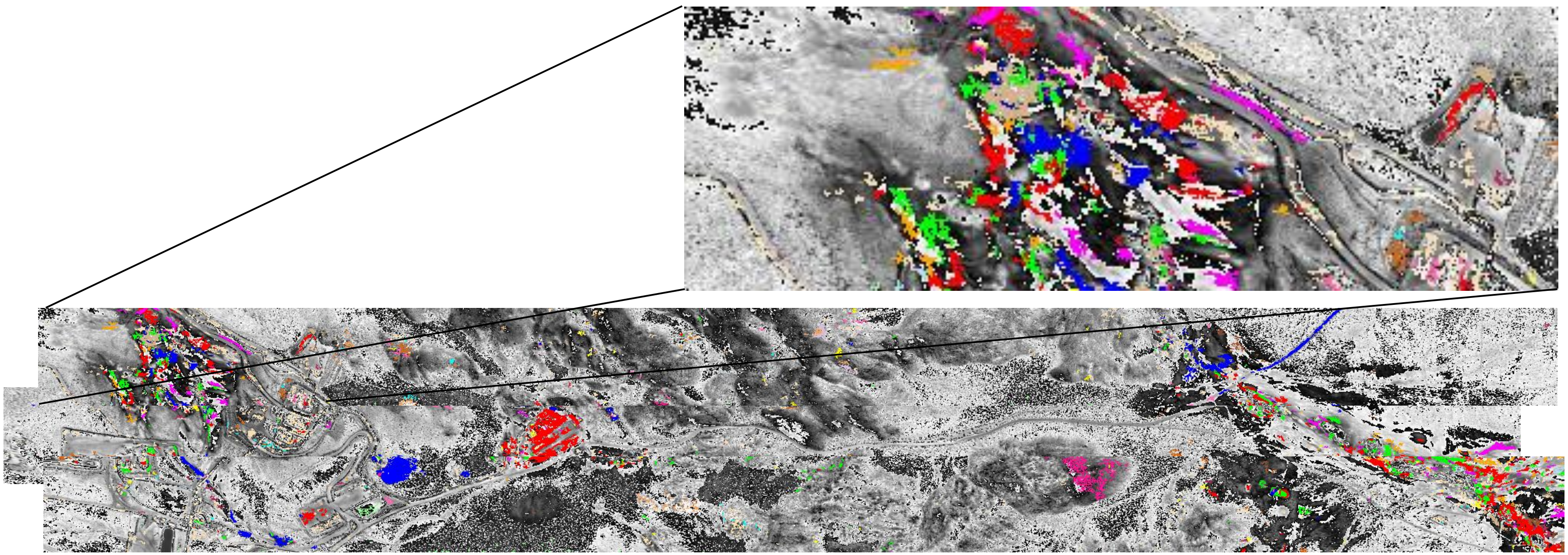
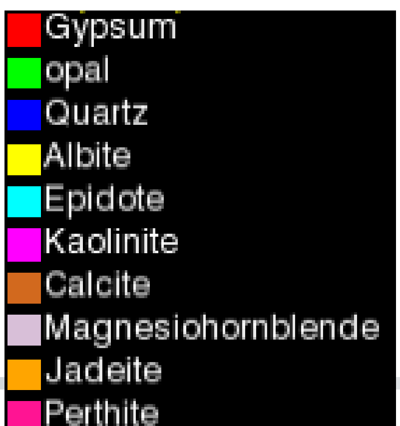
Geological Applications – Geothermal Exploration

Coso Geothermal Plant "A"



Mineral Spectral Identification
Overlaid onto Thermal Imagery



3 flight lines
128 x 2000 pixels
3-m GSD

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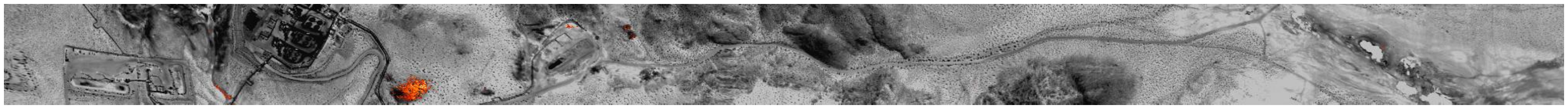
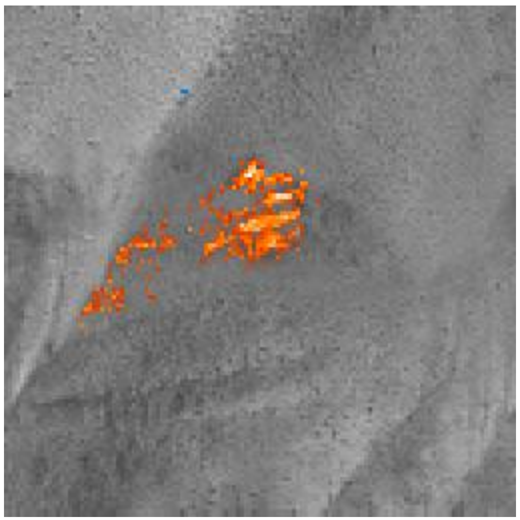
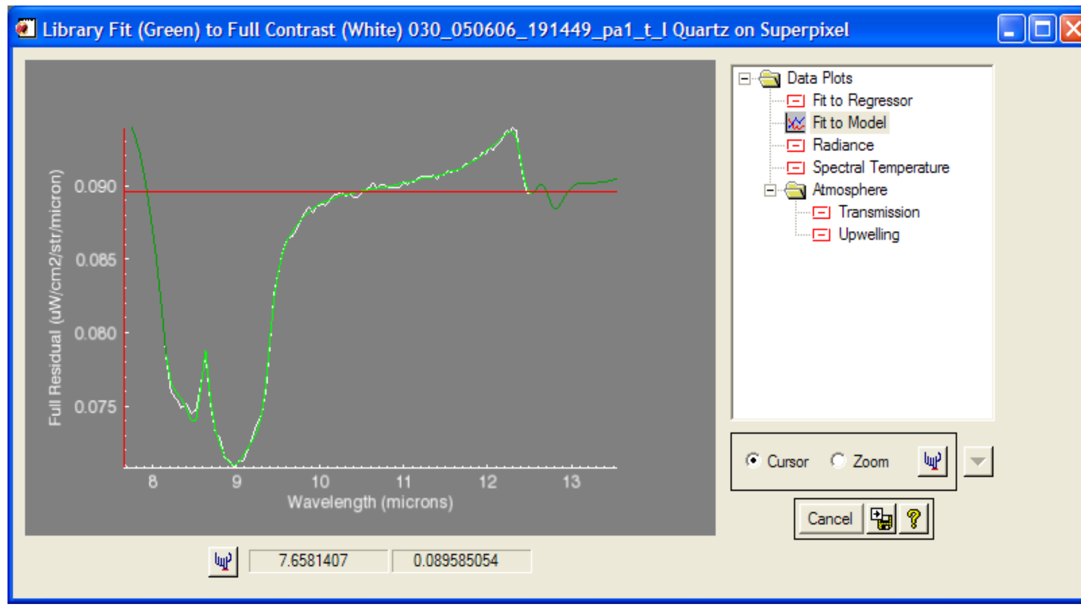
Geological Applications – Geothermal Exploration

Coso Geothermal Plant "A" - continued







Quartz: Spectral Fit Has High Confidence

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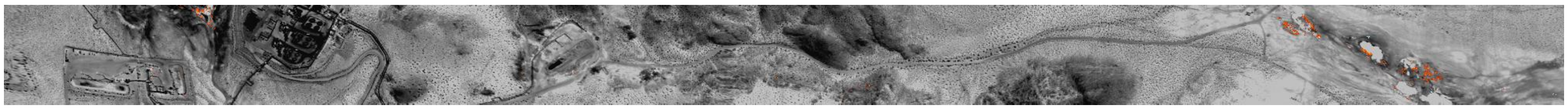
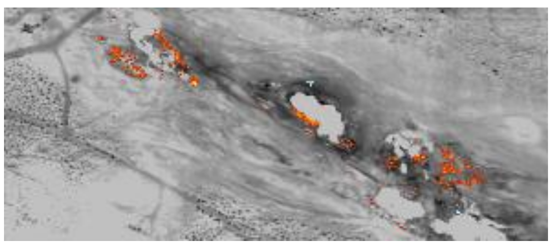
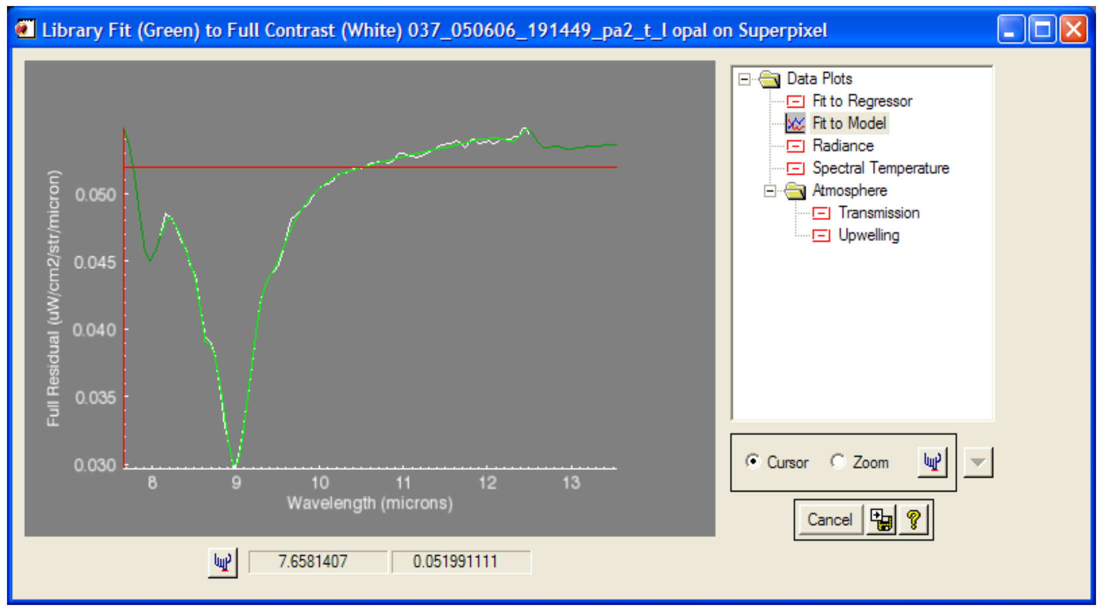
Geological Applications – Geothermal Exploration

Coso Geothermal Plant "A" - continued







Opal: Spectral Fit Has High Confidence

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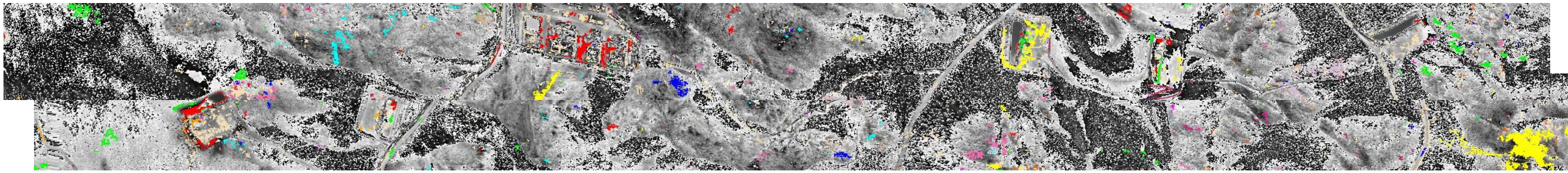
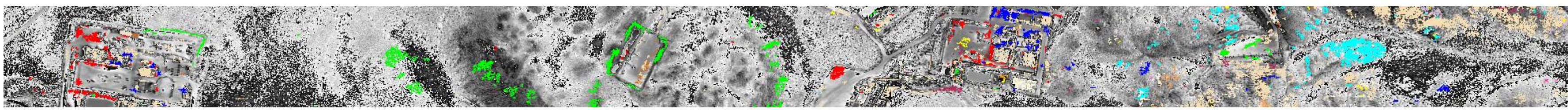
Geological Applications – Geothermal Exploration

Coso Geothermal Plants "B" and "C"



Plant "B"



Plant "C"

Mineral Spectral Identification
Overlaid onto Thermal Imagery

2 flight lines for Plant "B"
1 flight line for Plant "C"

128 x 2000 pixels
3-m GSD

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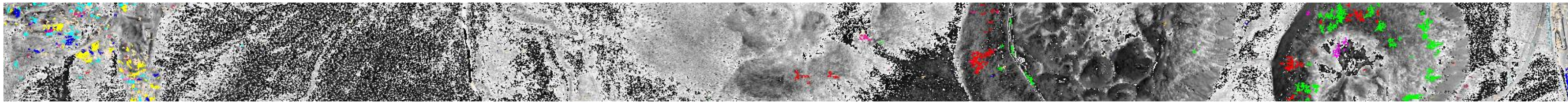
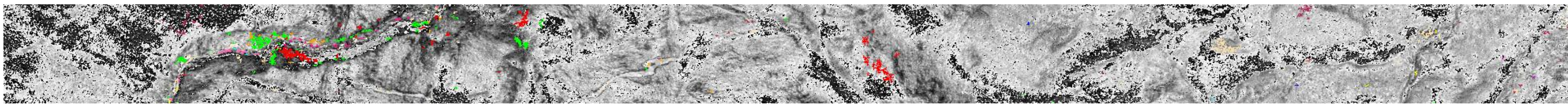
Geological Applications – Geothermal Exploration

Other Coso Geothermal Sites



Pumice Site



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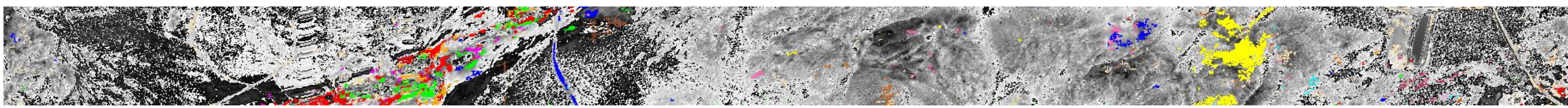
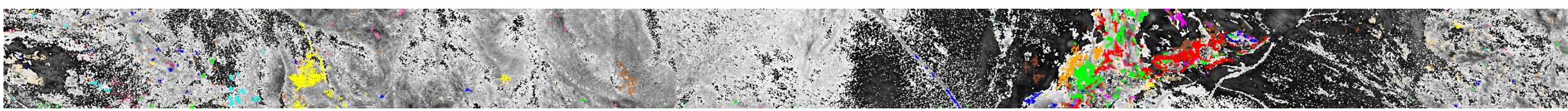
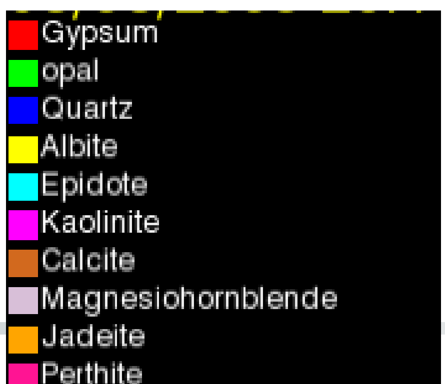


Hot Springs 1



Hot Springs 2



All lines:
128 x 2000 pixels
3-m GSD

Mineral Spectral Identification
Overlaid onto Thermal Imagery

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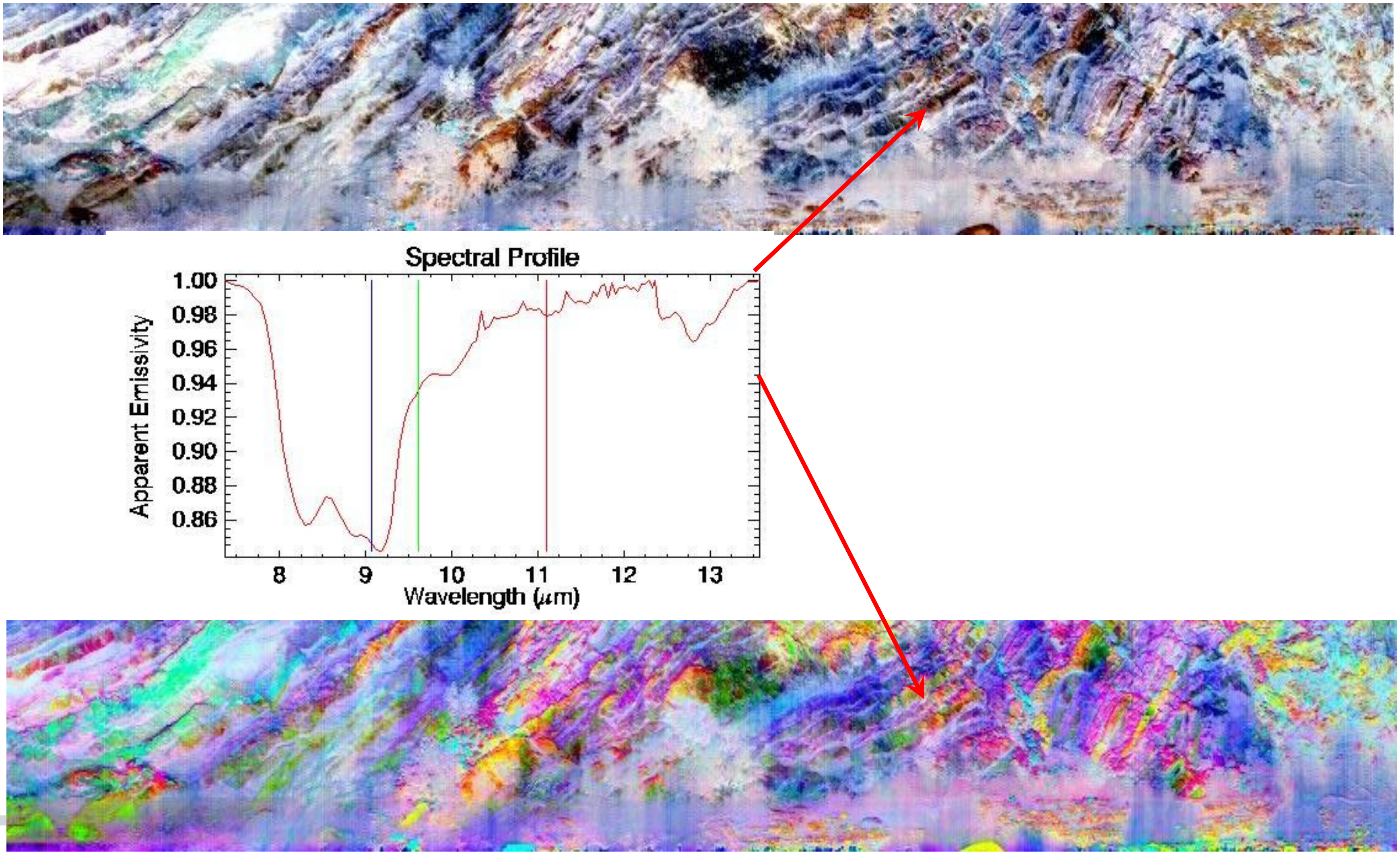
Geological Applications – Ground Based

SEBASS – Hells Gate, CA



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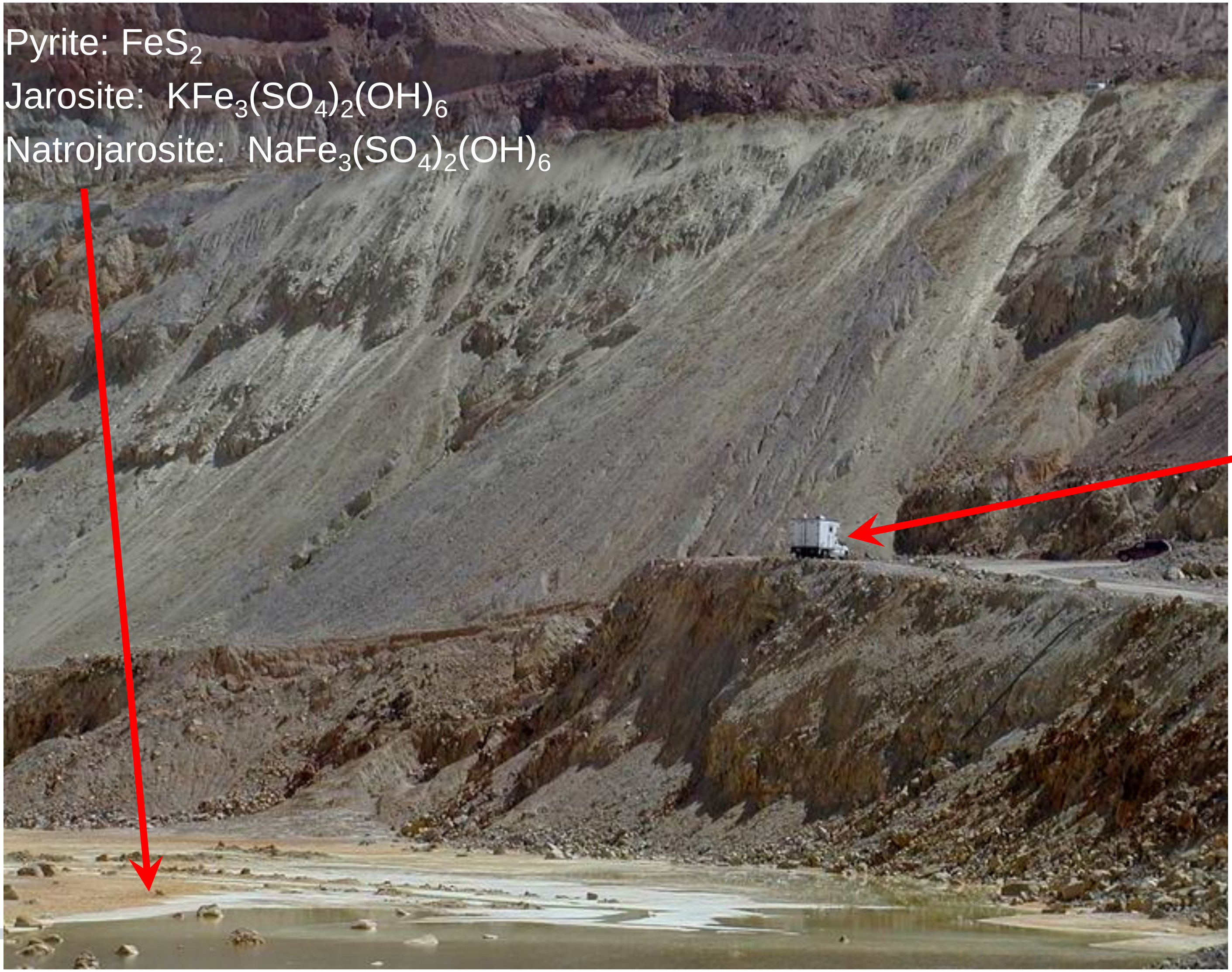
Geological Applications – Ground Based

Copper Mine in Arizona



Tonka

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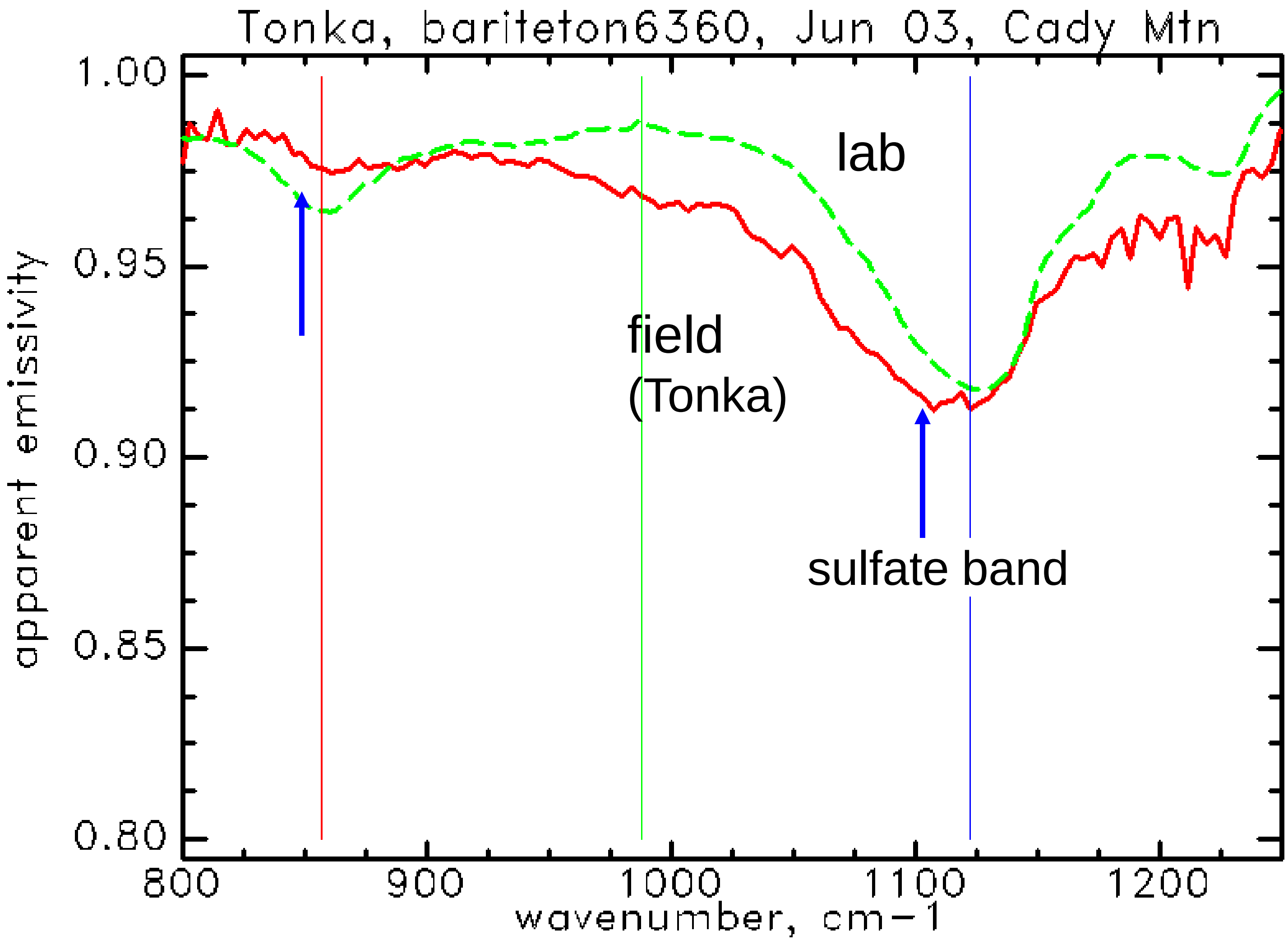
Geological Applications – Ground Based

Example Spectra: Tonka and Laboratory



Barite is a sulfate, $BaSO_4$, and has a distinct sulfate band.

Lab: ASTER sample so03ac, 125–500 μm particle size

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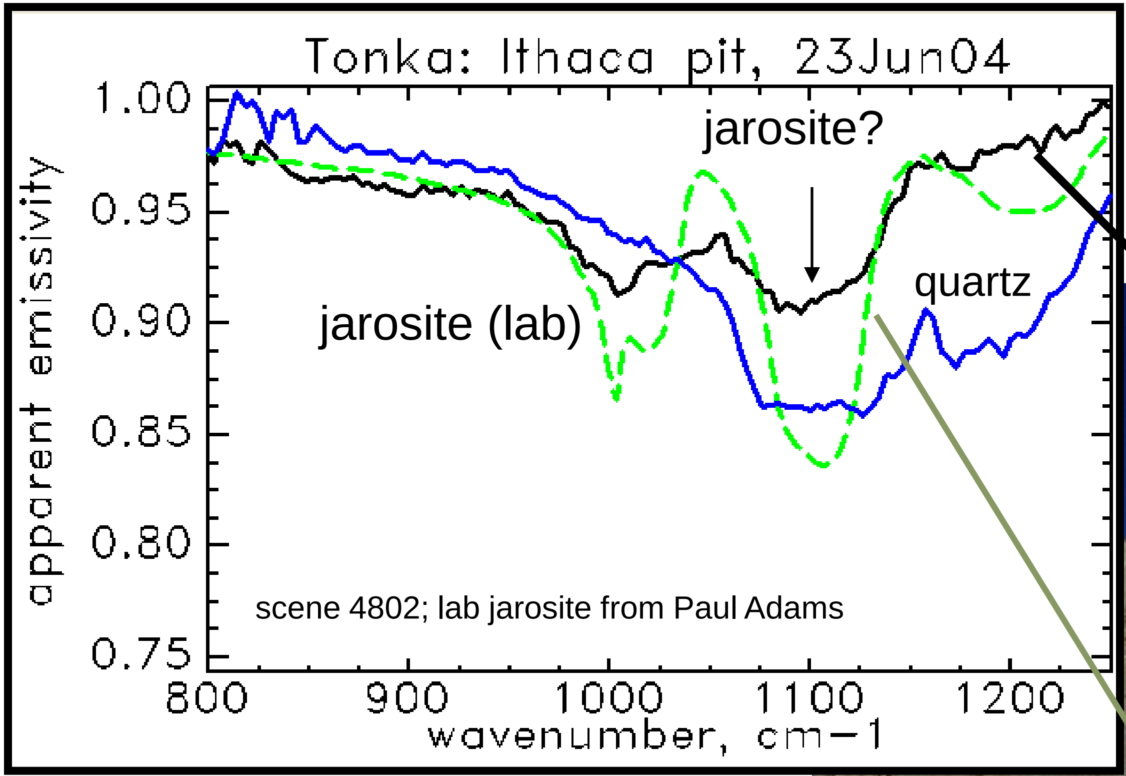
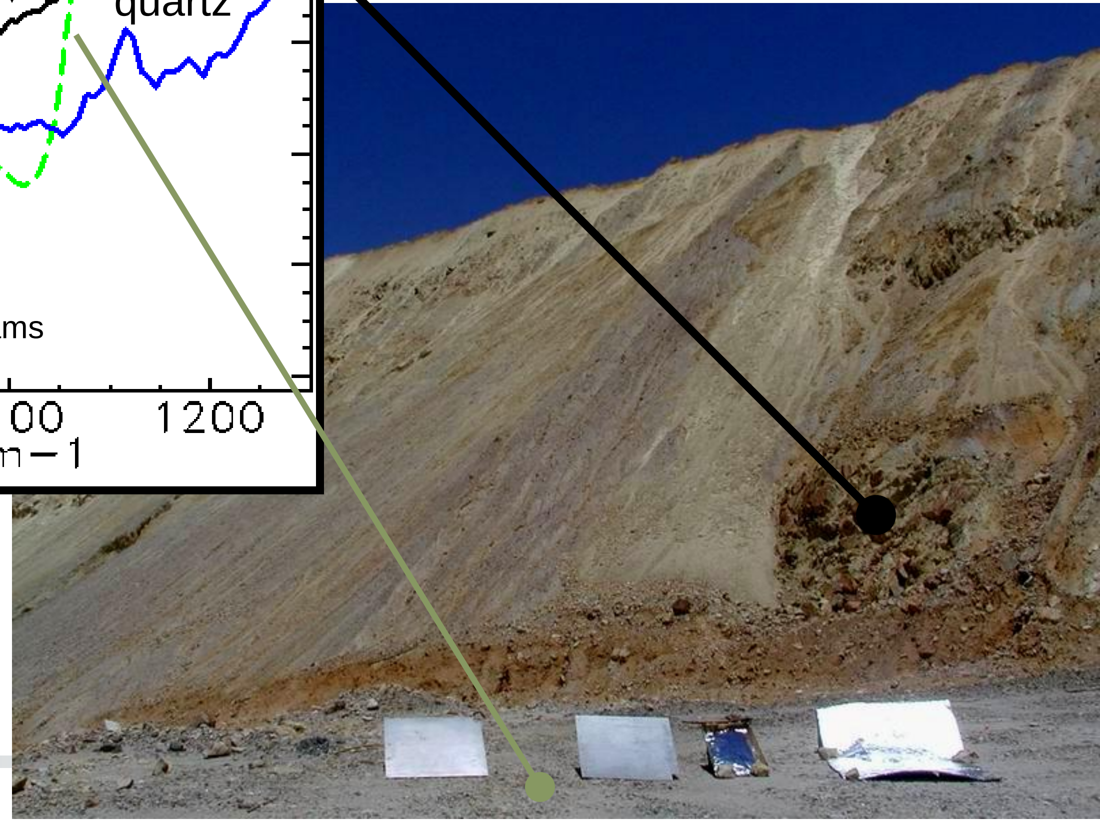
Geological Applications – Ground Based

Open Pit Tailings Pile





Older material is a darker yellow-orange, and shows a stronger jarosite feature

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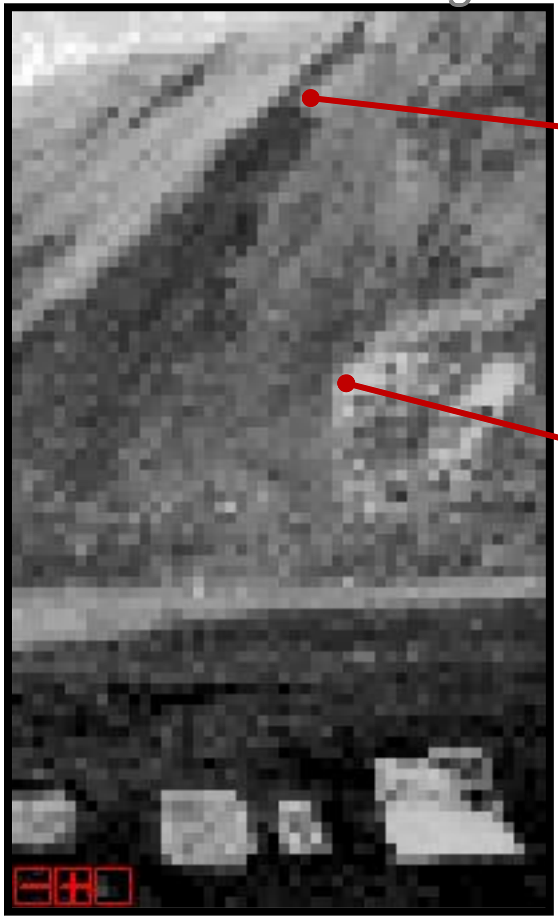
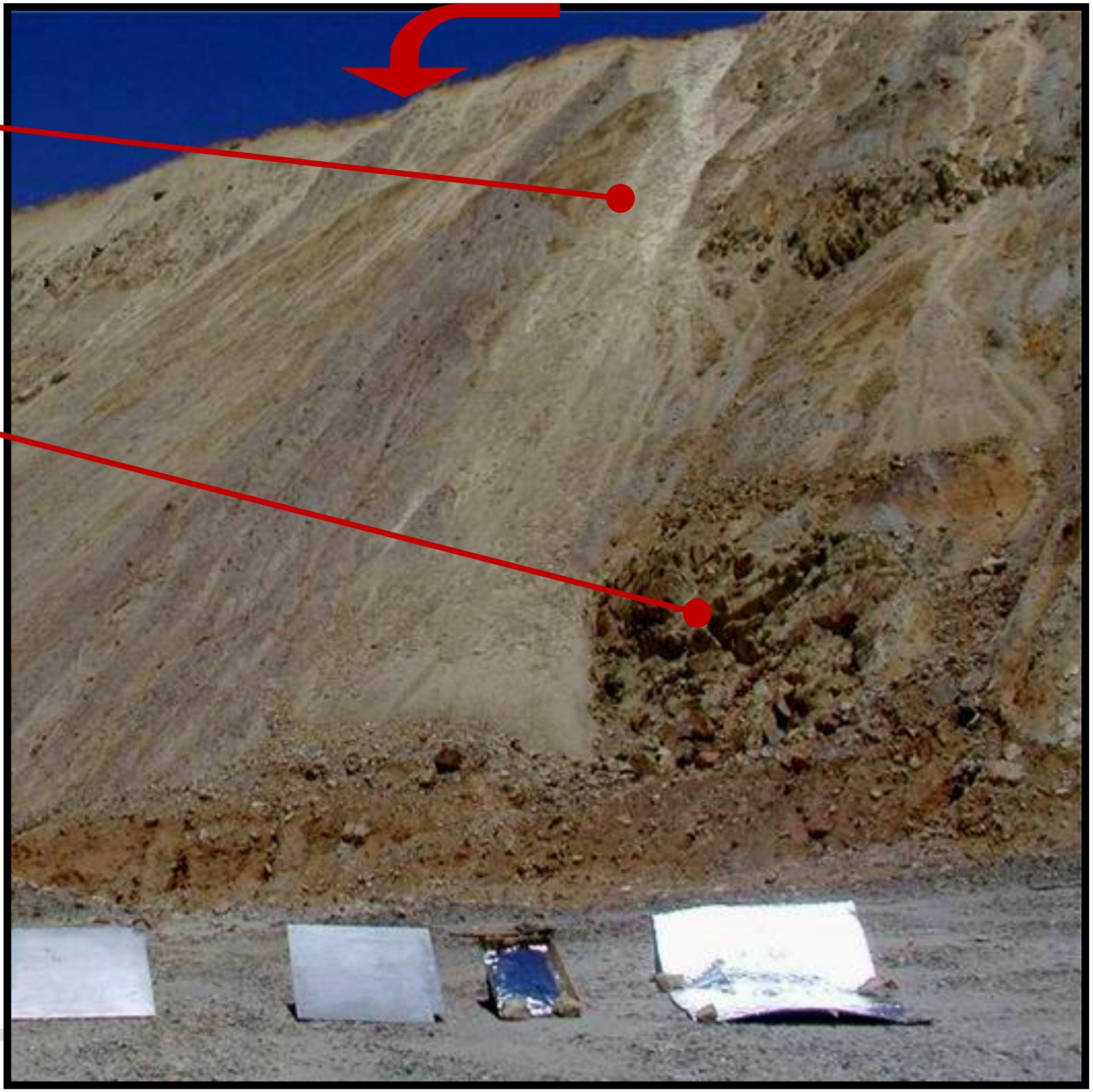
Geological Applications – Ground Based

Open Pit Fresh Tailings



Linear mixture model of Tonka image: Brighter indicates stronger jarosite band (Scene 4802)



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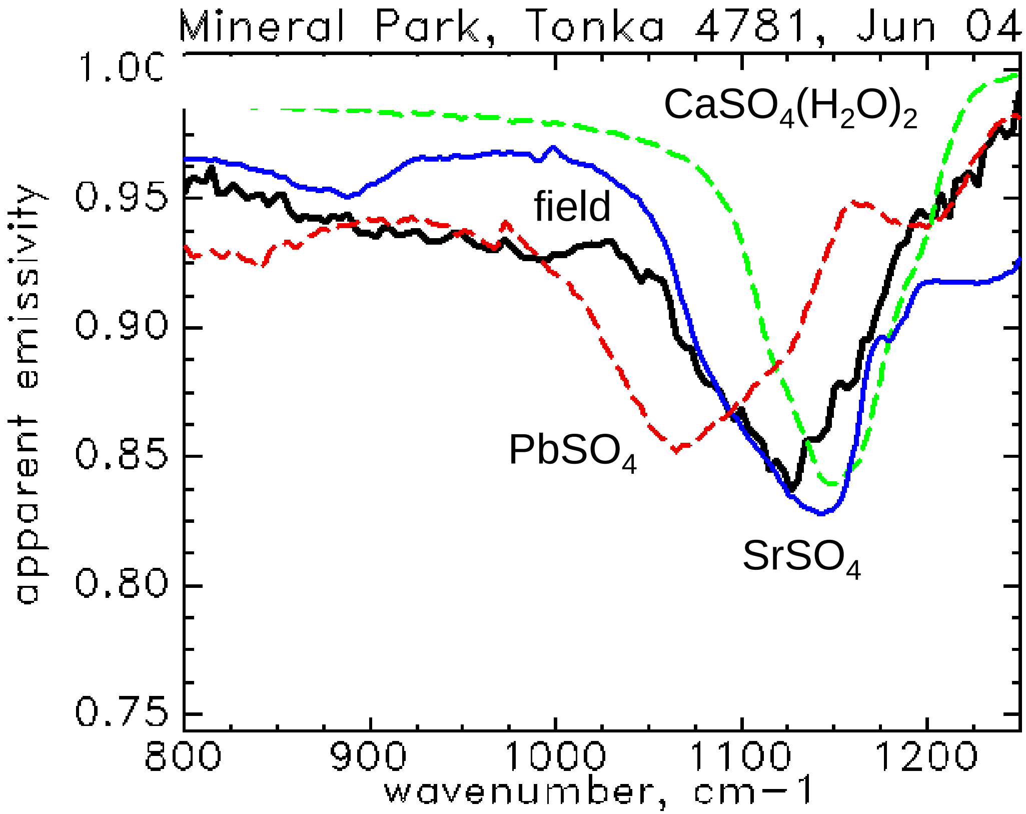
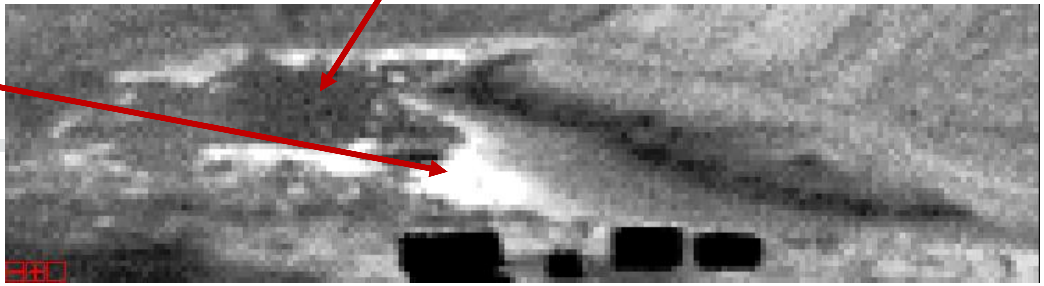
Geological Applications – Ground Based

Sulfates – Different band center wavelengths



water

Linear mixture map of celestite



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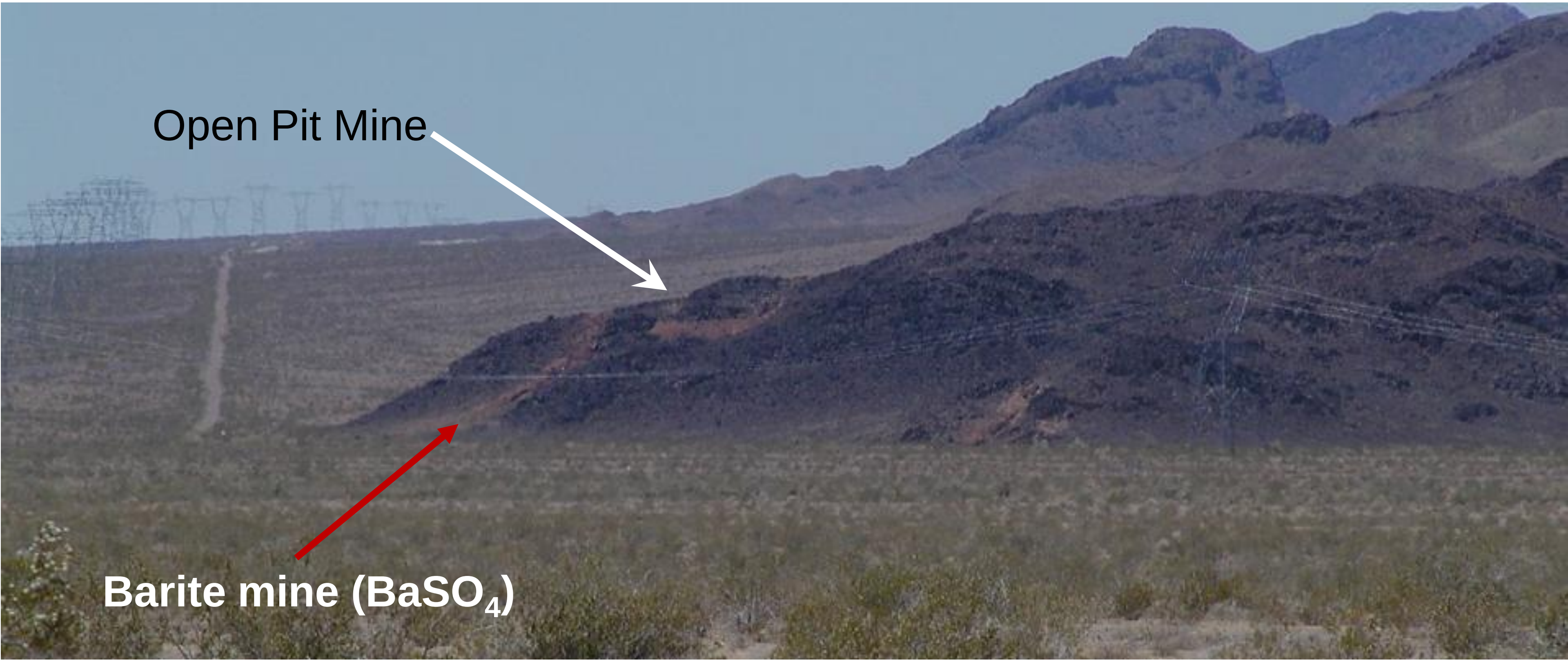
Geological Applications – Ground Based

Abandoned Barite Mine Near Ludlow



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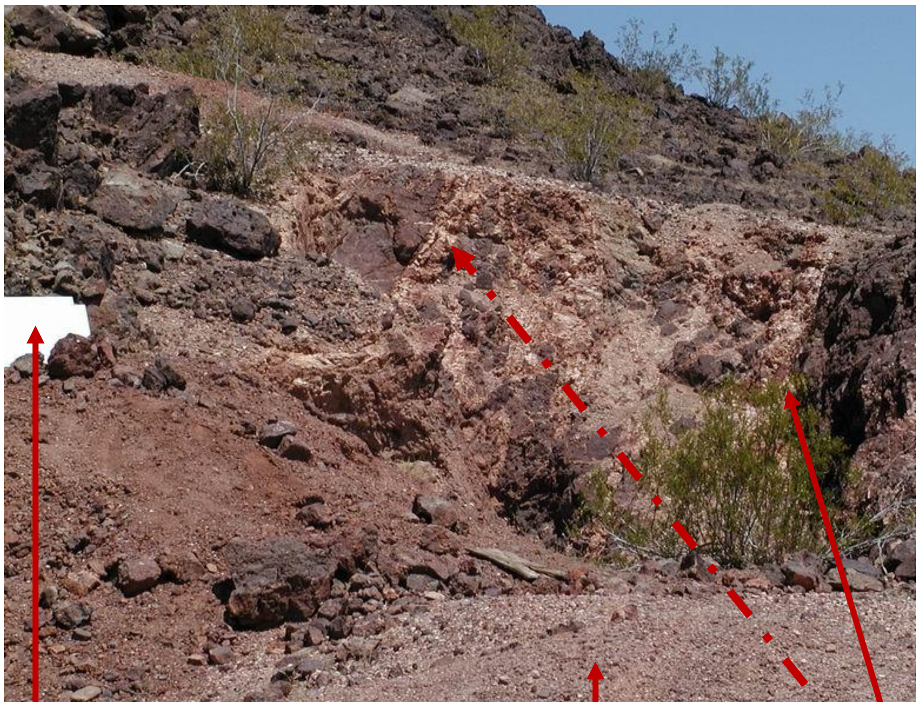
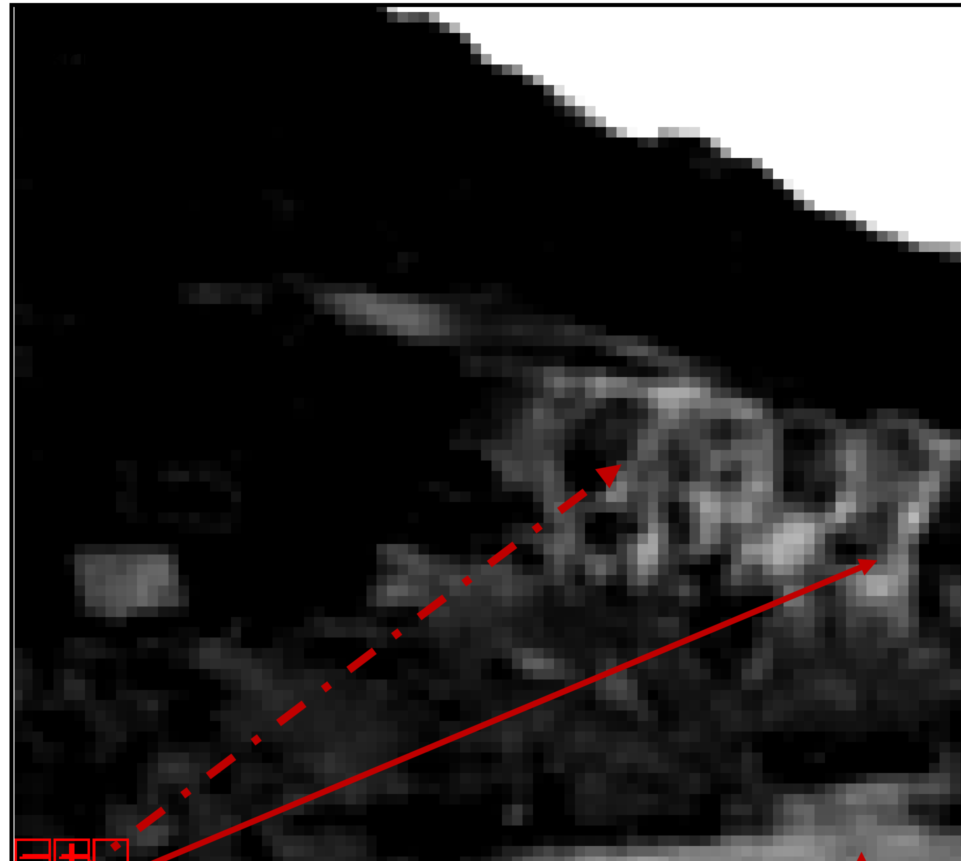
Geological Applications – Ground Based

Mapping Barite On-Site

Visible Image





Al target

Fine tailings

Barite veins (arrows mark the same location in each image)

Fine tailings

Tonka: Linear Mixture Map of Barite

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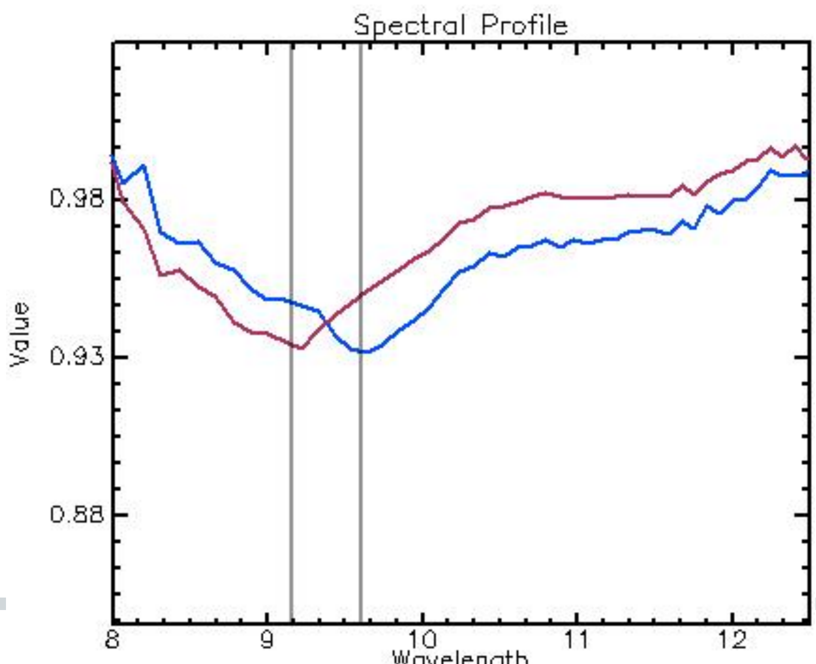
bariteton6360, June 2003

Geological Applications – Transportation Corridor

Zeolites



Zeolite solid solution series

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Environmental Applications

Hyperspectral Thermal Infrared Remote Sensing

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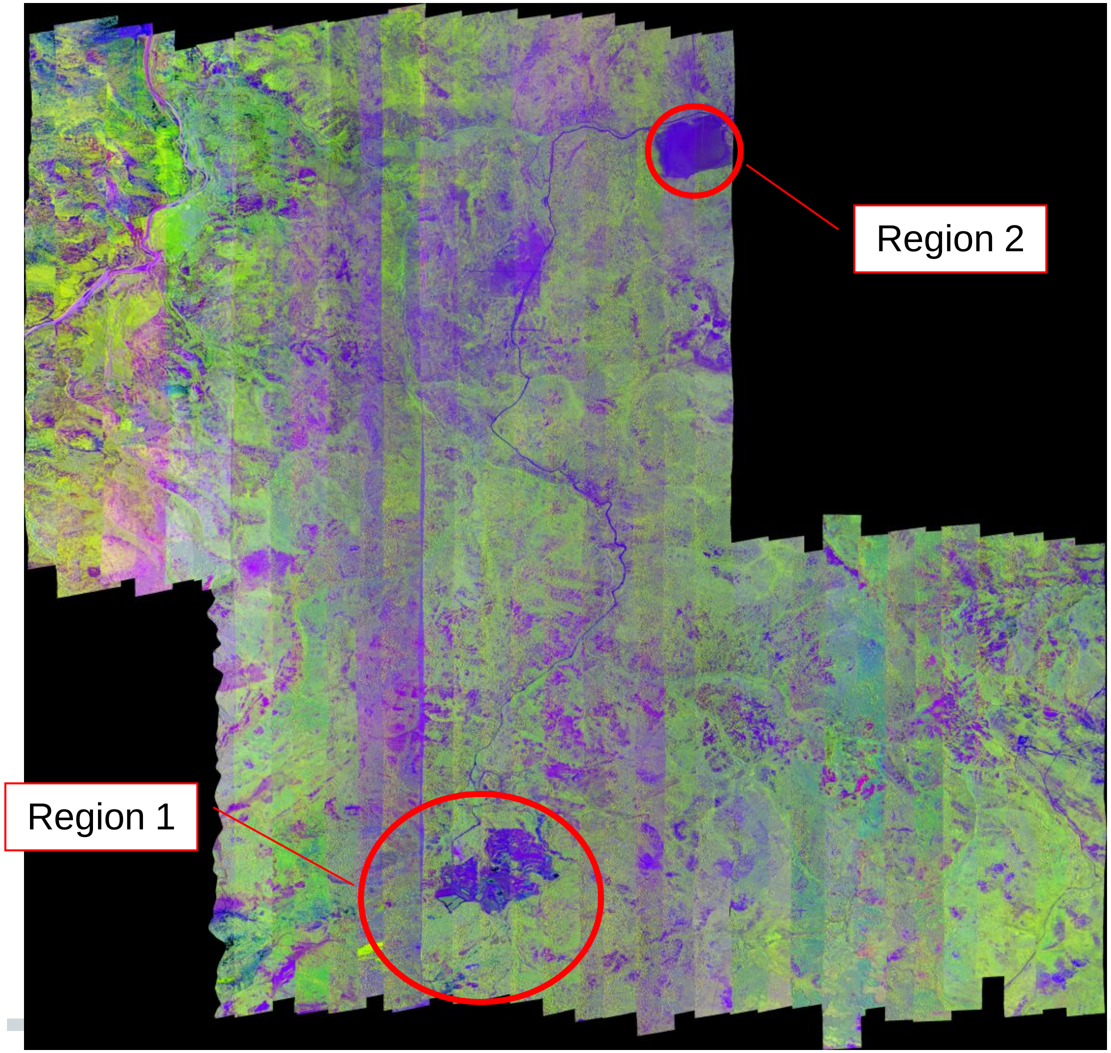
Environmental Applications – Acid Mine Drainage

Leviathan: Anomaly Map



- SEBASS "Anomaly" Map of Leviathan—Shows Potential Spectral Regions of Interest
- Georeferenced mosaic of PICTS results for Leviathan. Note that each strip is generated independently, hence the colors between strips are not exactly the same. Distinctions within a strip point to regions that should be further investigated, such as the highlighted regions

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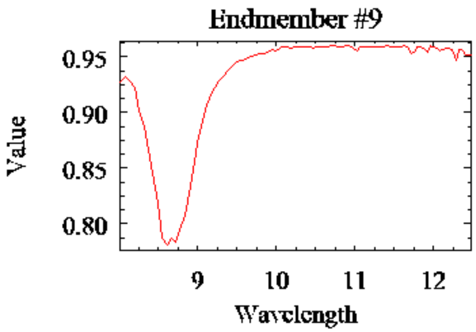
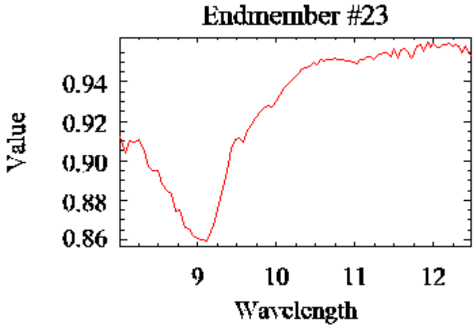
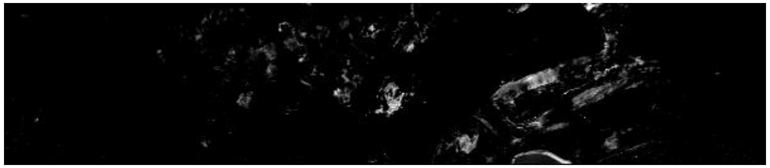
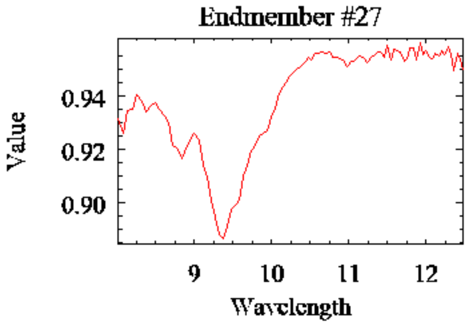
Environmental Applications – Acid Mine Drainage

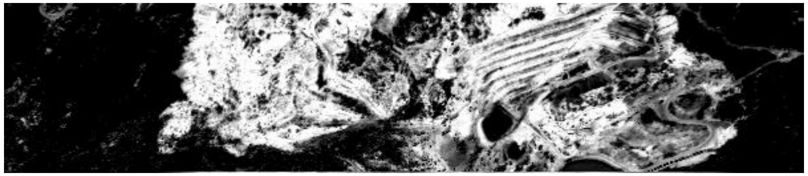
Leviathan: Emissivity Material Maps--Unmixed Abundance Planes











Abundance planes for unmixed emissivity image using non-negative least squares. Note the strong abundance for endmember 9, not as strong for endmembers 23 and 27. The latter two appear to be mixtures of different endmembers to some extent.

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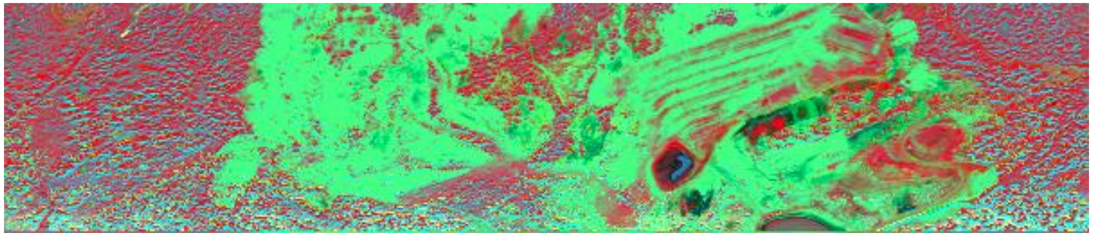
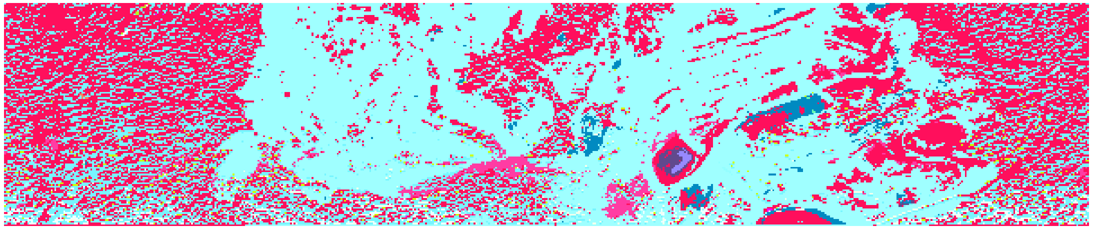
Environmental Applications – Acid Mine Drainage

Leviathan: Endmember Maps--Unmixing

"Abundance" Product



Thematic Product



- Each extracted endmember is assigned a color
- Abundance of the endmember is used to build this three color map.
- The lower image is a thematic map created from the endmember set using only the highest abundance endmember of each pixel to determine the color triplet for that pixel.
- These maps provide an overview of the mineral content of the scene

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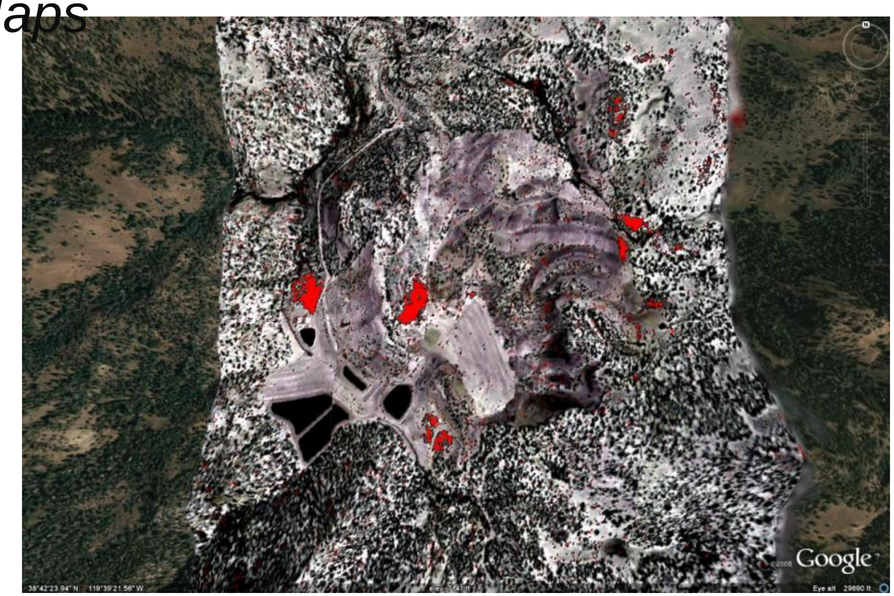
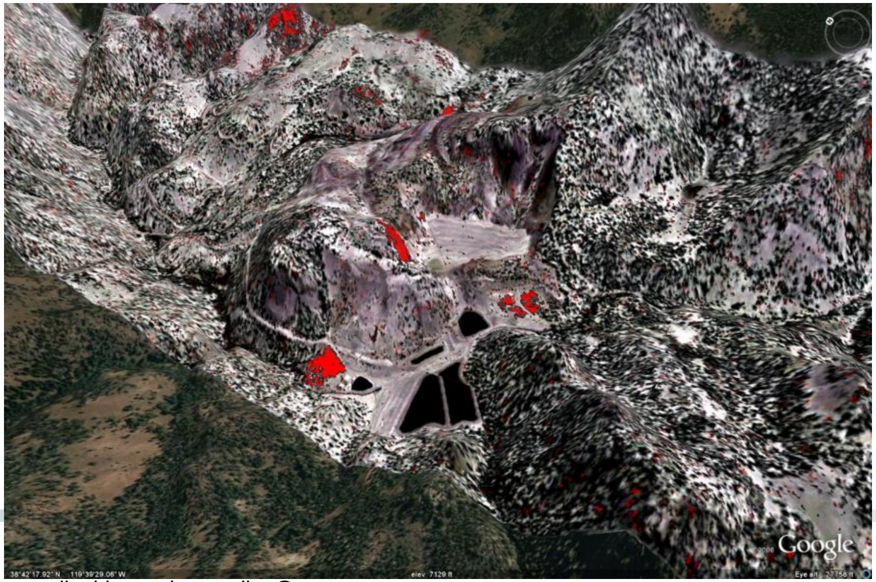
Georeferenced Mosaicked Mineral Maps





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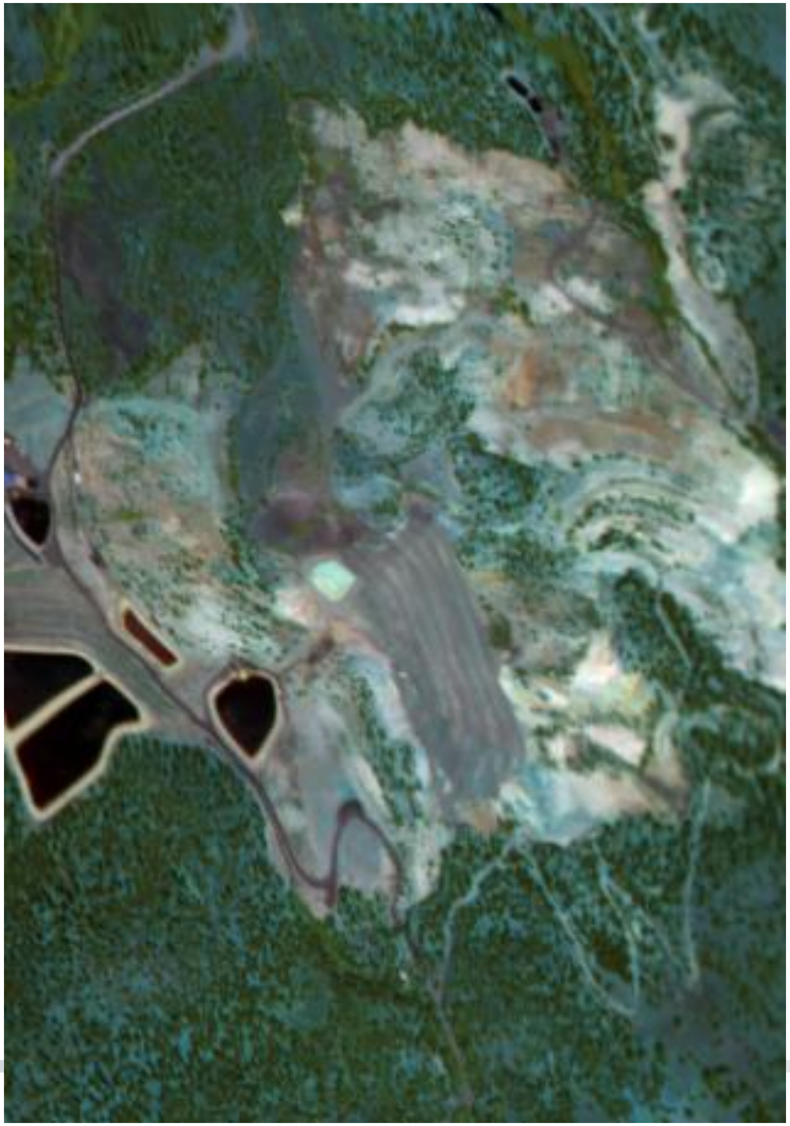
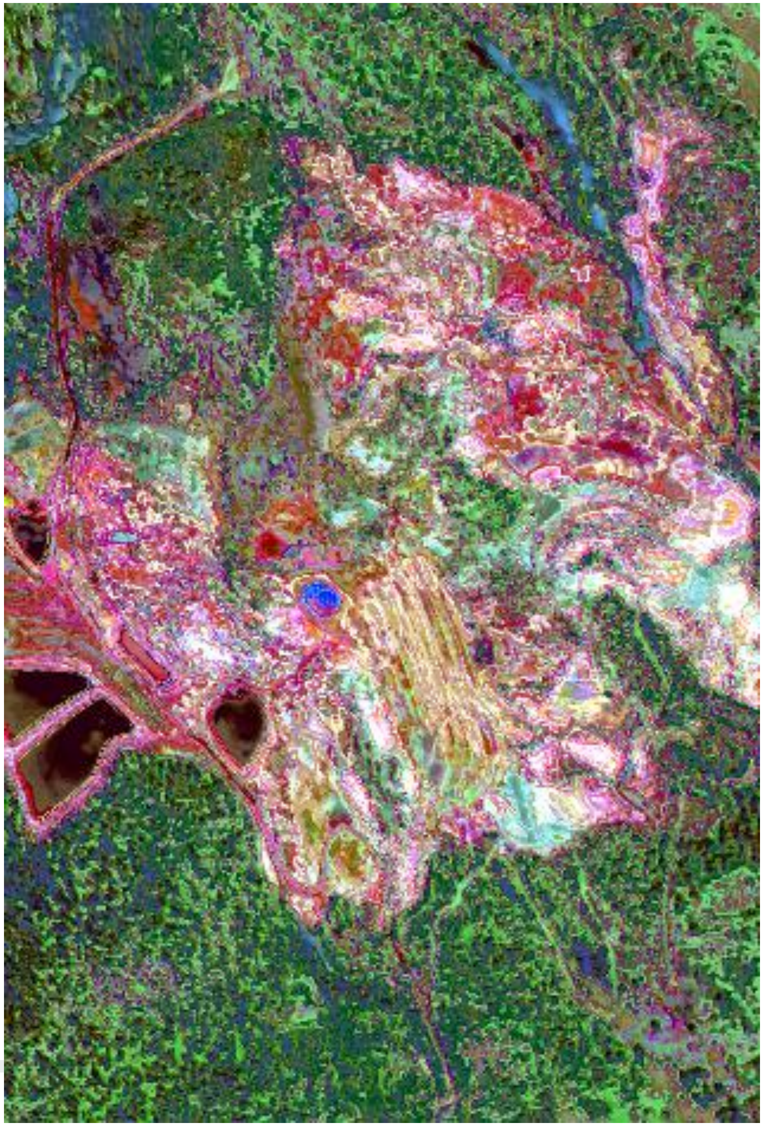
Anomaly Image and Endmember Material Image – All Wavelengths





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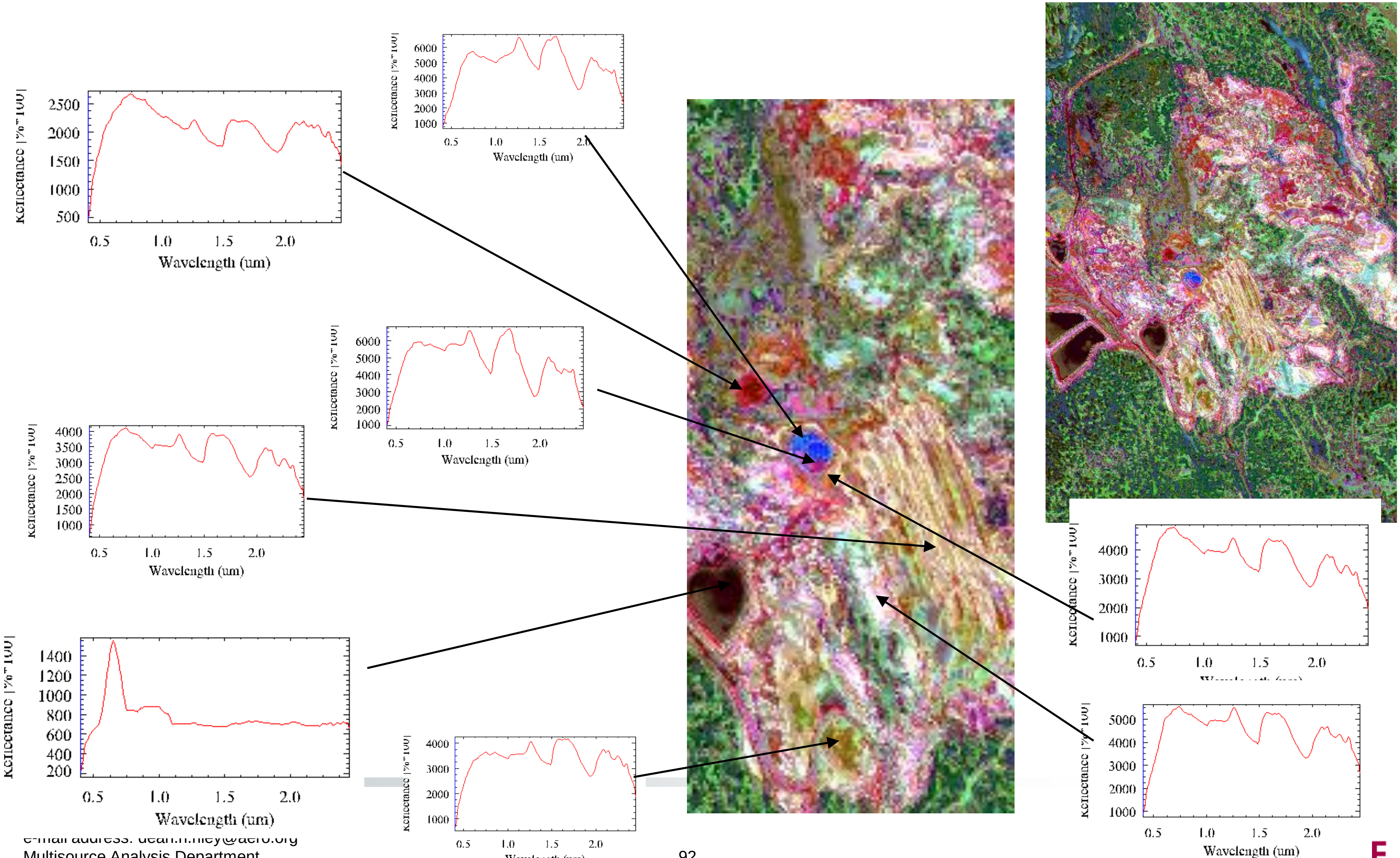
Environmental Applications – Acid Mine Drainage

Reflectivity Map – Reveals Diversity of Spectral Content



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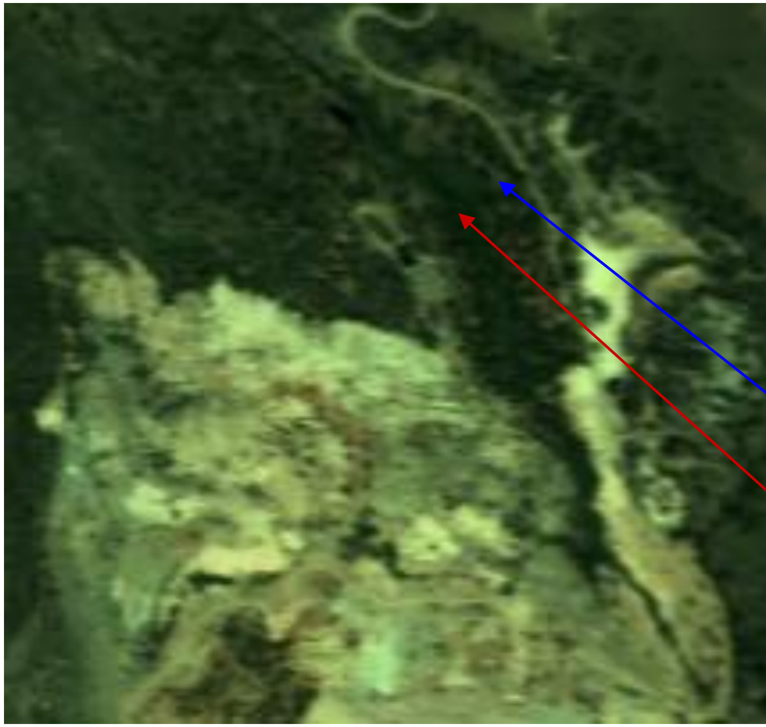
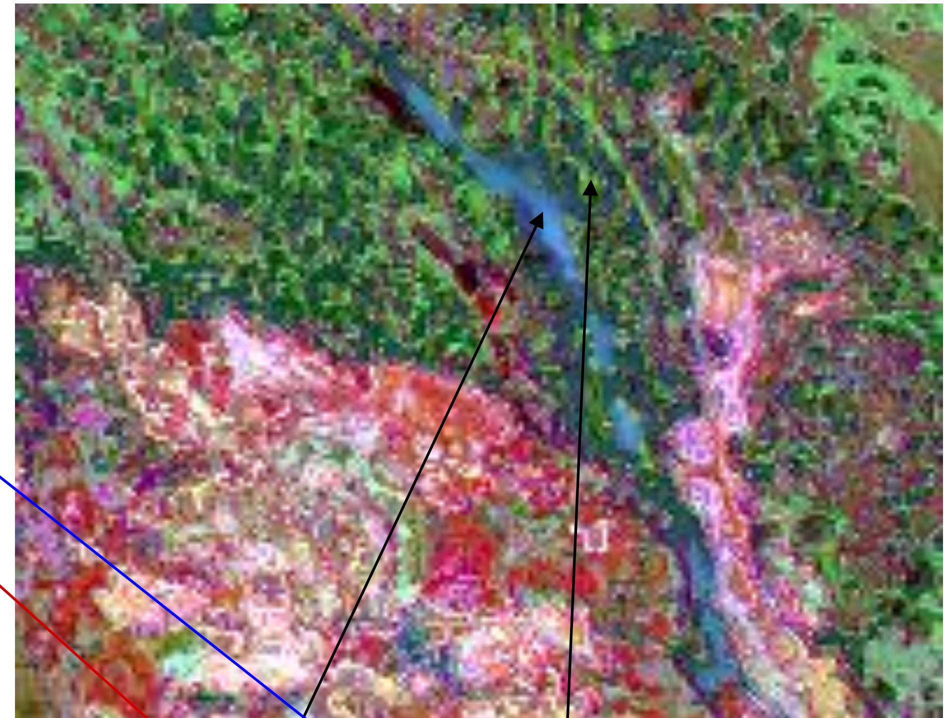
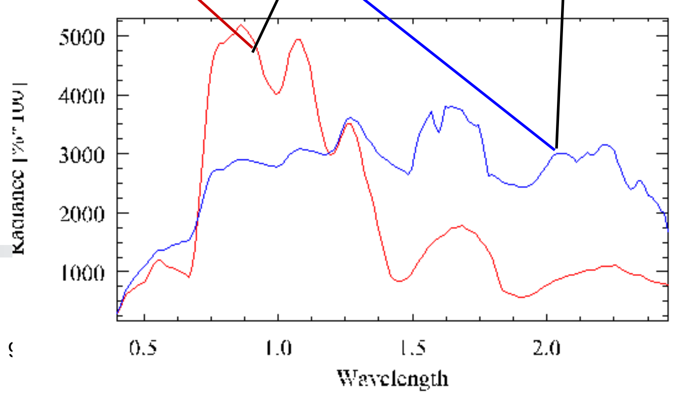
Environmental Applications – Acid Mine Drainage

Reflectivity Map of Vegetation Region





Why is this region spectrally distinct?



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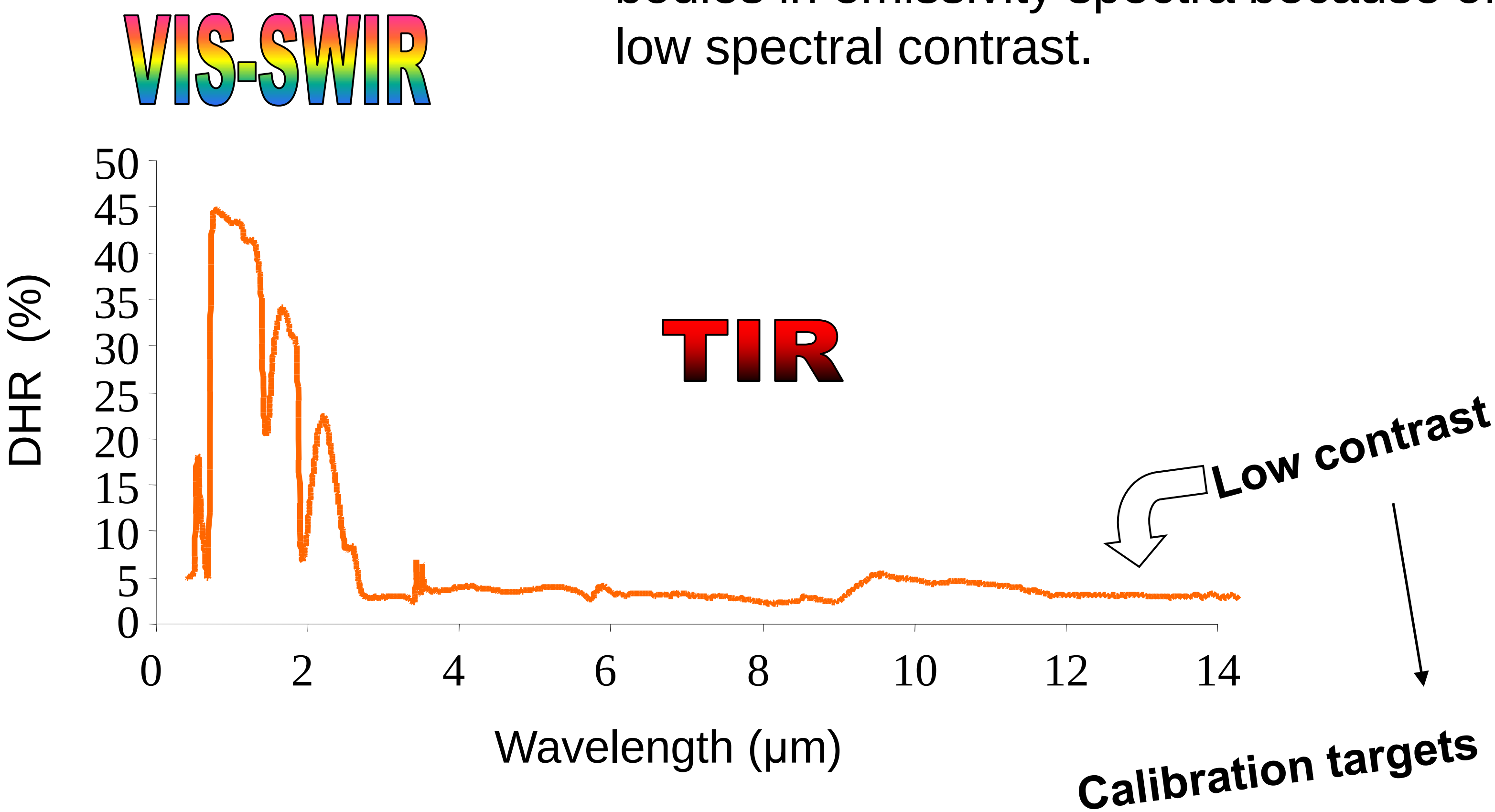
Environmental Applications – Vegetation

Virginia Arboretum – Vegetation Mapping in the LWIR

Plants have long been considered as gray bodies in emissivity spectra because of low spectral contrast.



Fagus grandifolia (Beech)

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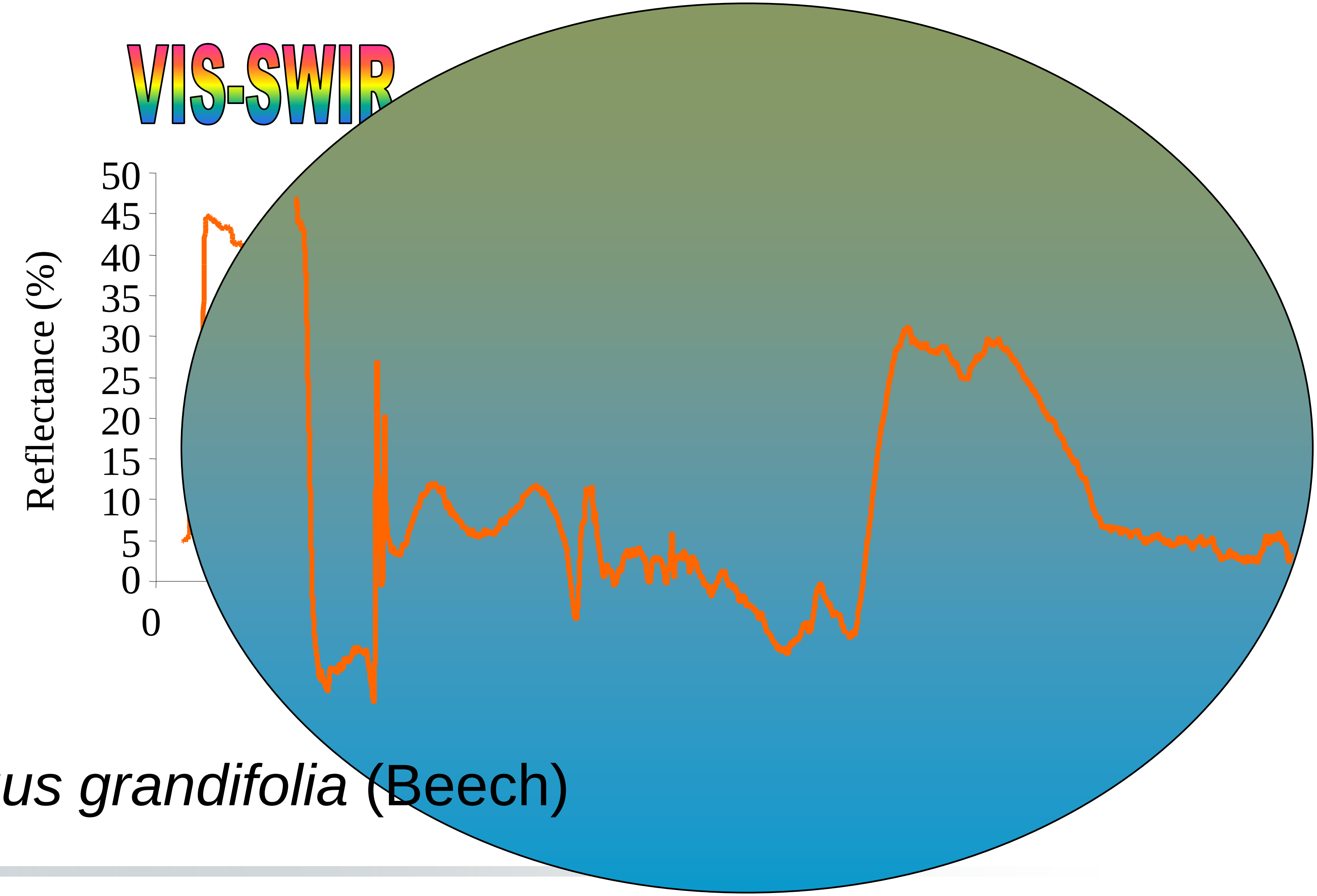
Environmental Applications – Vegetation

Virginia Arboretum – Vegetation Mapping in the LWIR



Fagus grandifolia (Beech)

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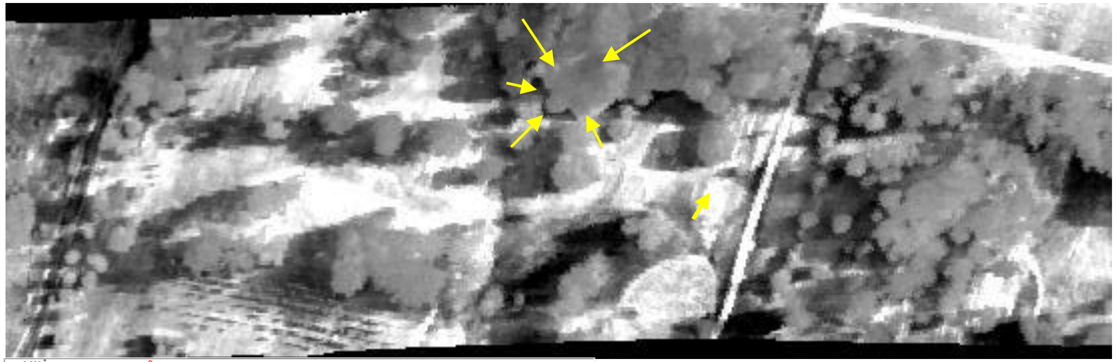
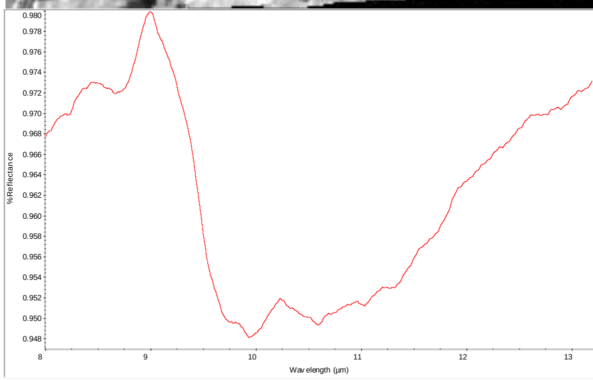
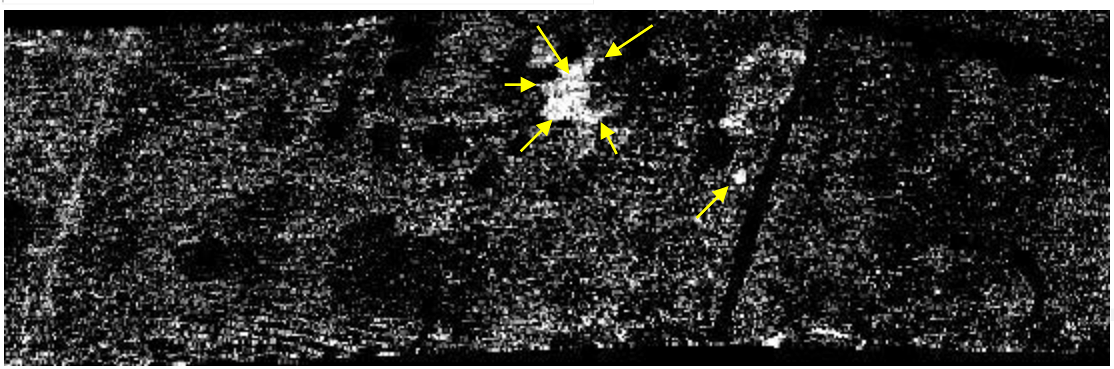
Environmental Applications – Vegetation

Virginia Arboretum – Acer palmatum Japanese maple



Emissivity





Match

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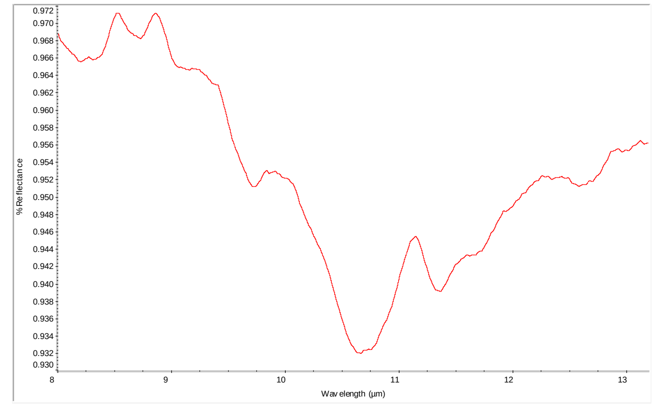
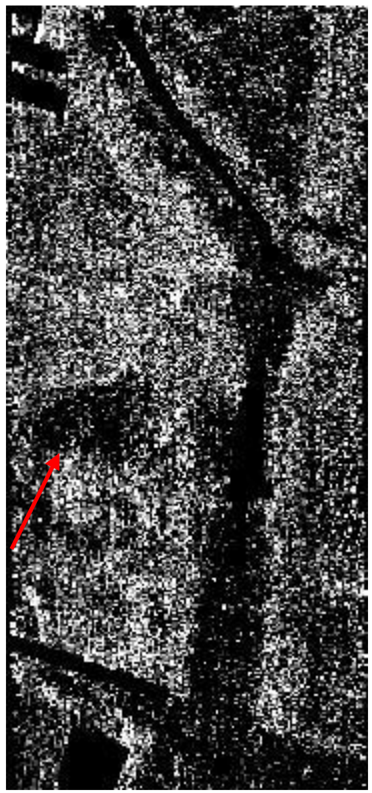
Environmental Applications – Vegetation

Virginia Arboretum – Graminea Grass



Emissivity

Match



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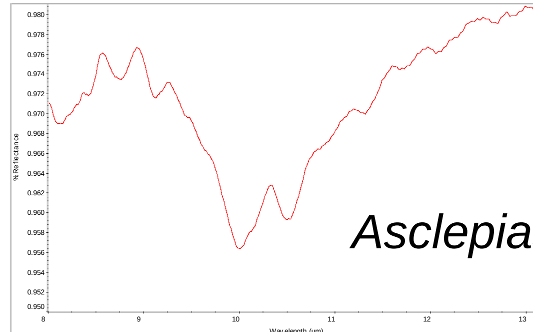
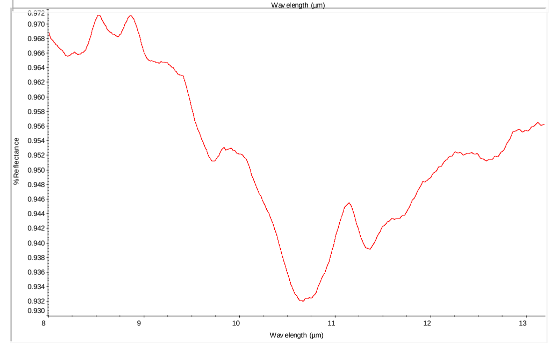
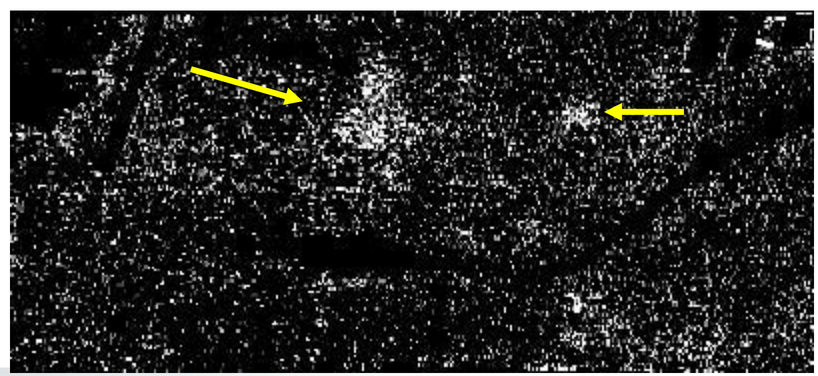
Environmental Applications – Vegetation

Virginia Arboretum – Graminea Grass and Milk Weed



Asclepias sp Milk weed





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Environmental Applications – Gaseous Emissions

Hyperspectral Thermal Infrared Remote Sensing

- La Brea, California
  - *SEBASS*
  - *Methane*

- San Joaquin, California
  - *MAKO*
  - *Ammonia*

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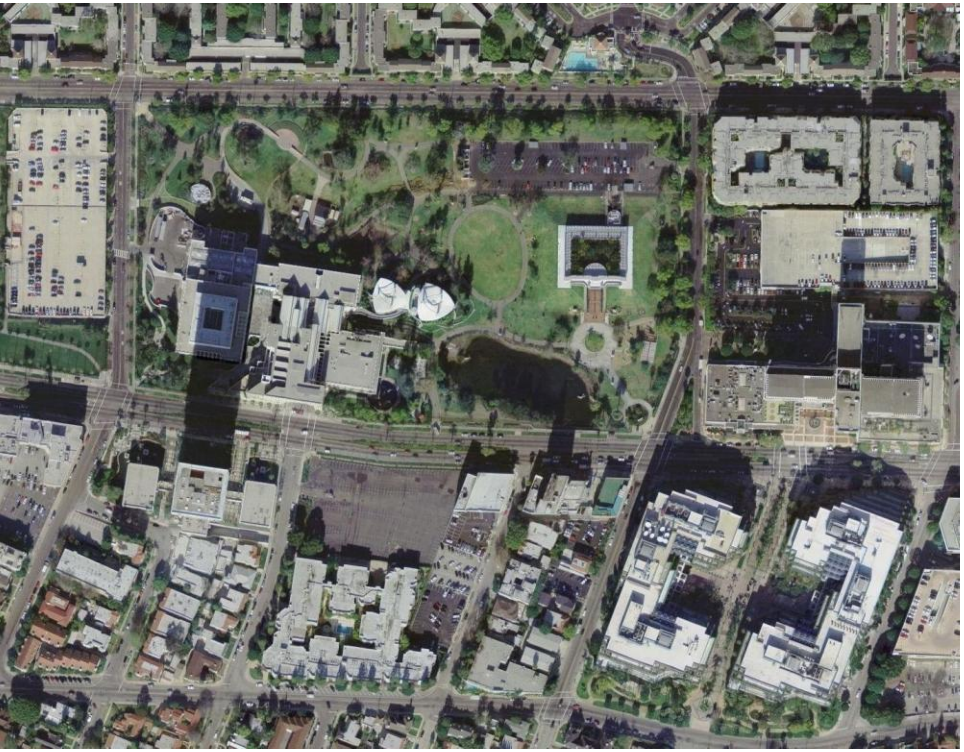
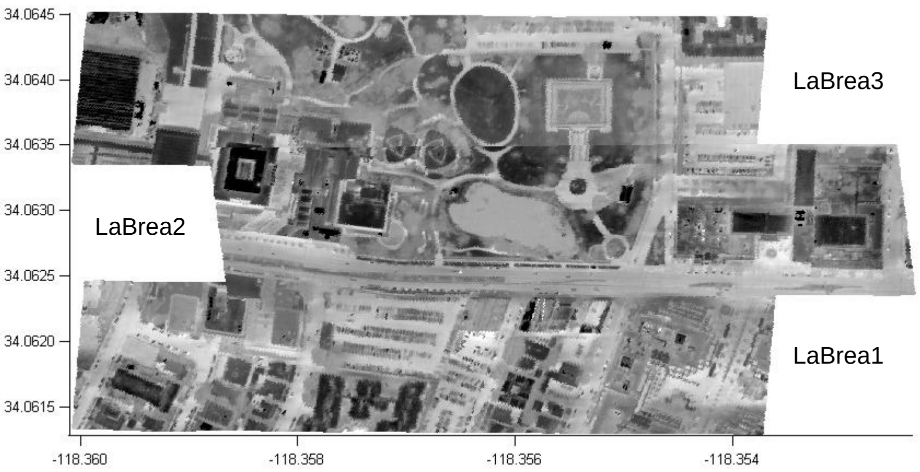
Environmental Applications – Gaseous Emmissions

Methane Monitoring La Brea, California



TerraServer Image



Geo-rectified
SEBASS Quick-look
Images- Bin 64

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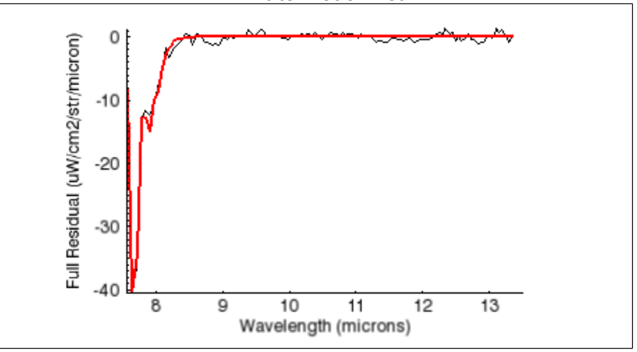
Environmental Applications – Gaseous Emissions

Methane Monitoring La Brea, California

Fit-to-Model Plot



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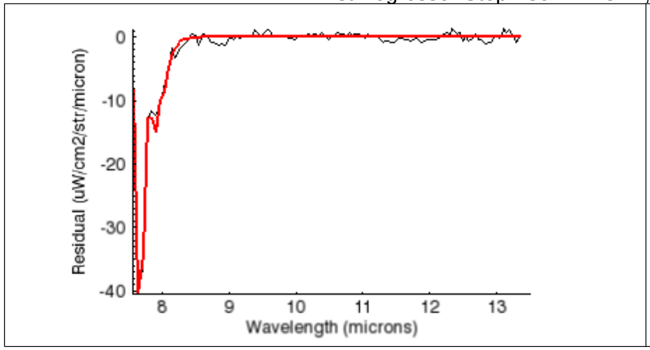

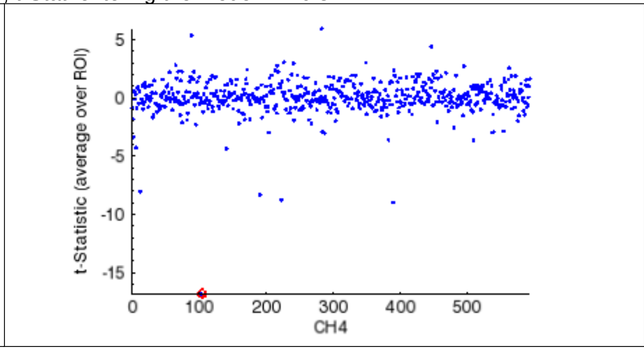

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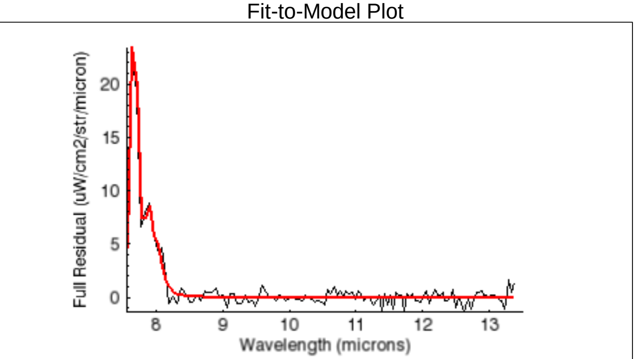
Environmental Applications – Gaseous Emissions

Methane Monitoring La Brea, California

Fit-to-Model Plot



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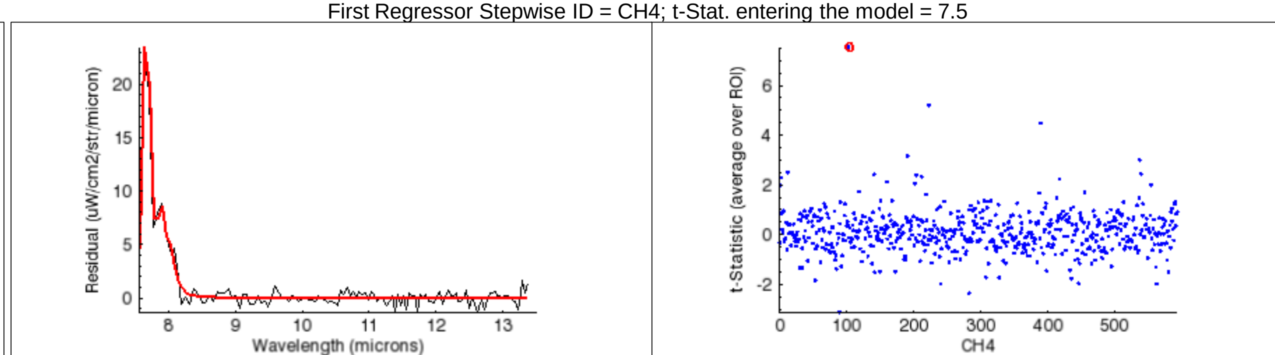

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Environmental Applications – Gaseous Emissions

Ammonia Monitoring, Salton Sea, California

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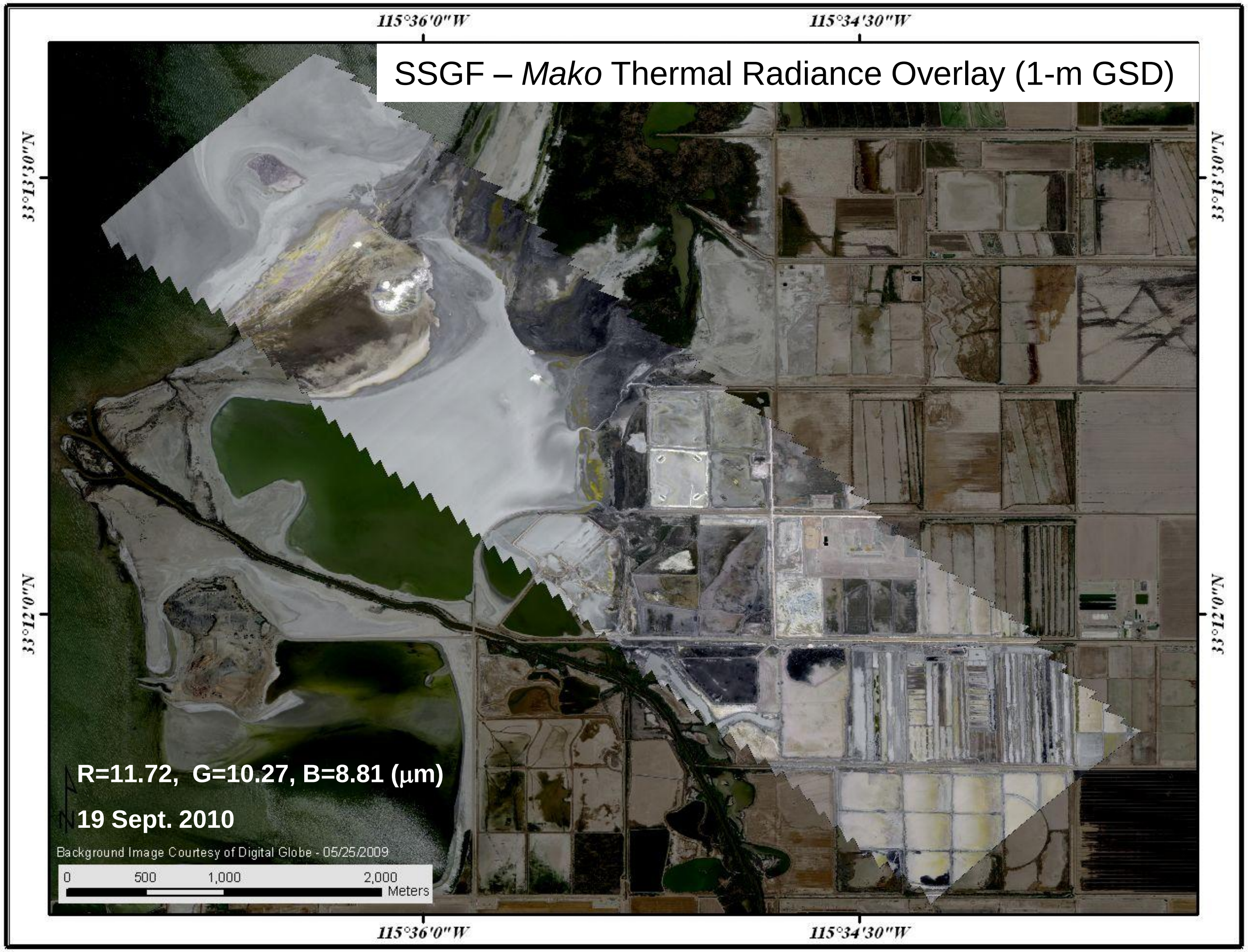
Environmental Applications – Gaseous Emissions

Ammonia Monitoring, Salton Sea, California



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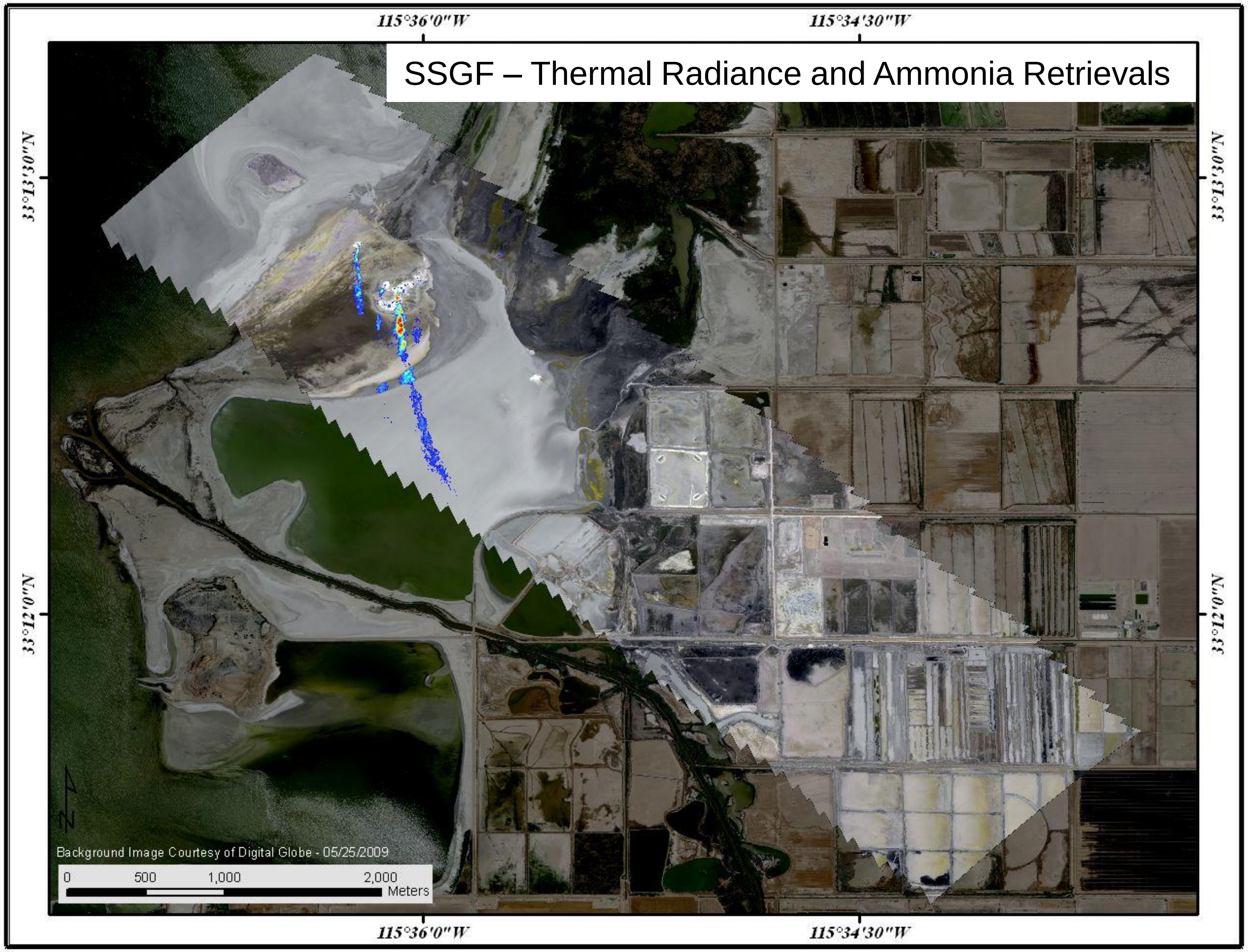
Environmental Applications – Gaseous Emissions

Ammonia Monitoring, Salton Sea, California



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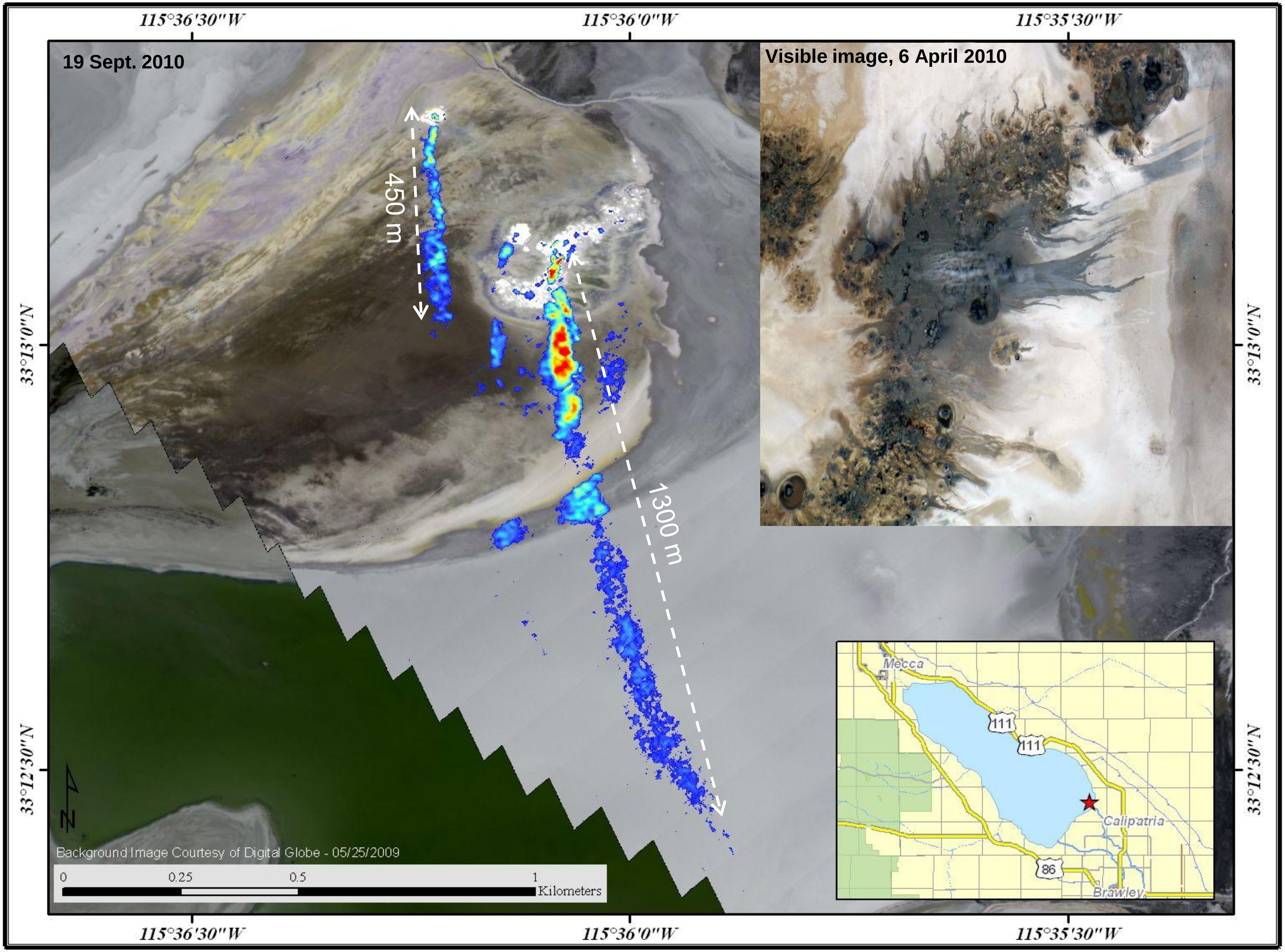
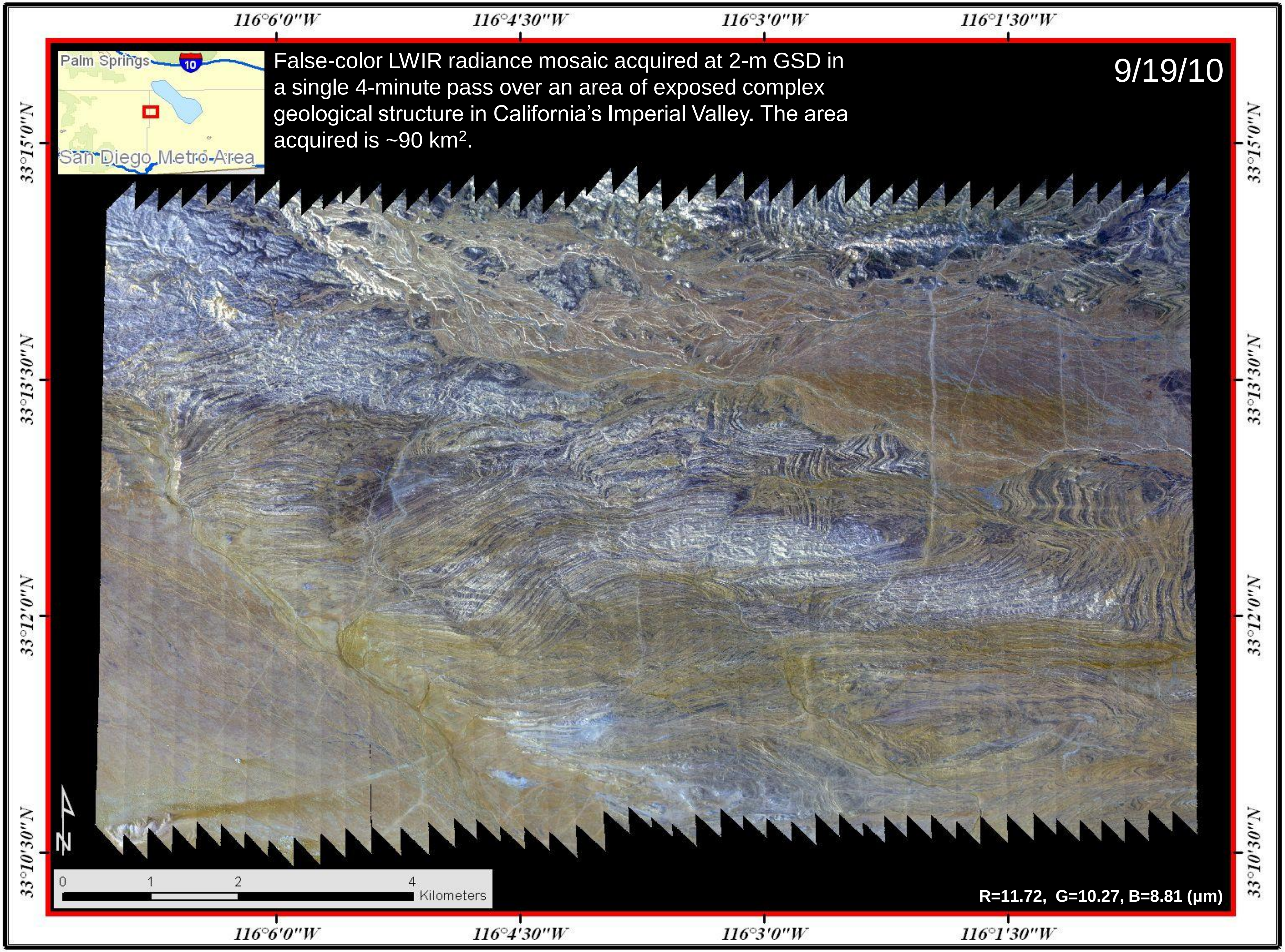


115°36'30"W
115°36'0"W
115°35'30"W
19 Sept. 2010
Visible image, 6 April 2010
450 m
1300 m
33°13'0"N
33°12'30"N
Mecca
111
111
Calipatria
86
Brawley
Background Image Courtesy of Digital Globe - 05/25/2009
0
0.25
0.5
1
Kilometers
N

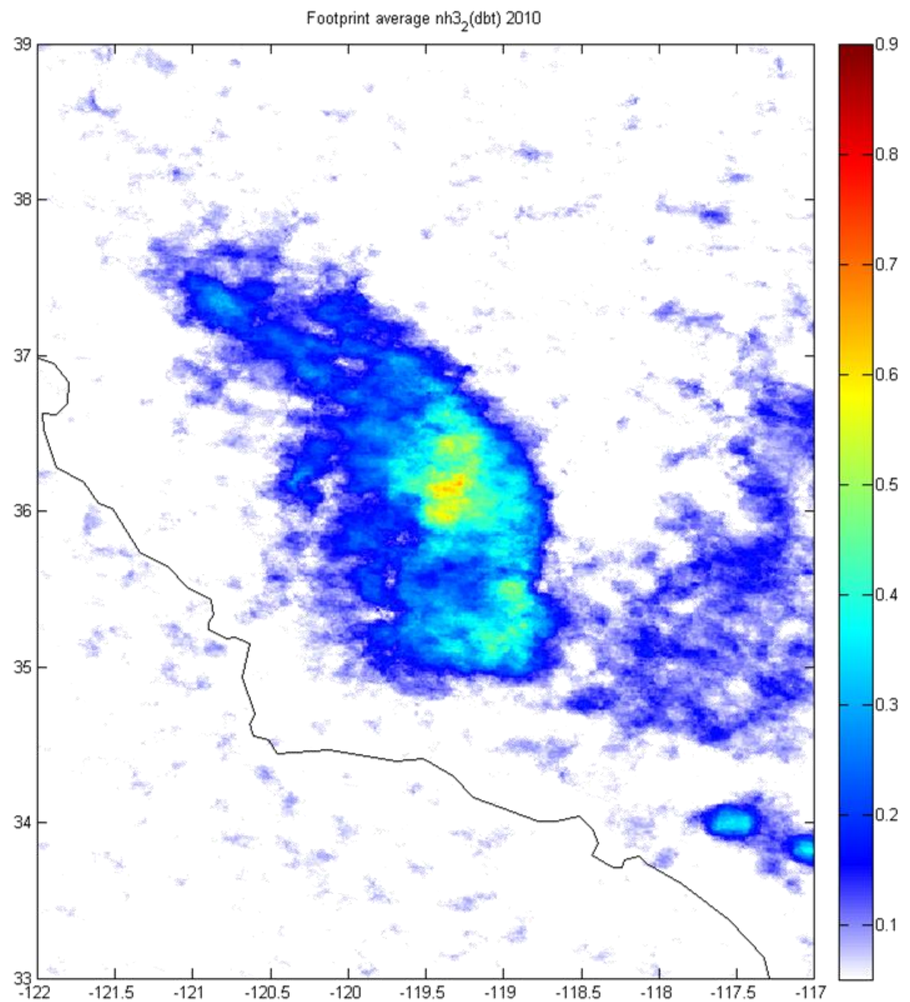

116°6'0"W
116°4'30"W
116°3'0"W
116°1'30"W
33°15'0"N
33°13'30"N
33°12'0"N
33°10'30"N
Palm Springs
10
San Diego Metro Area
False-color LWIR radiance mosaic acquired at 2-m GSD in a single 4-minute pass over an area of exposed complex geological structure in California's Imperial Valley. The area acquired is ~90 km^2.
9/19/10
N
0
1
2
4
Kilometers
R=11.72, G=10.27, B=8.81 (μm)

Environmental Applications – Gaseous Emissions

Agricultural Ammonia in the San Joaquin Valley

- *Mako* was flown over California's Central Valley on 17 Sept. 2010
- Flights were conducted in Tulare and Kings Counties primarily between the towns of Visalia and Delano
- Altitude was 3.8 km AGL → 2-m GSD
- Collections coordinated with overflights of the European IASI (Infrared Atmospheric Sounding Interferometer) sensor aboard Europe's MetOp-A
- Integrated ammonia column densities in the dairy farm regions near Visalia varied between 25 and 45 ppm-meters
- The airborne data clearly showed prominent plumes of ammonia emanating from some of the dairy facilities

This work being done in collaboration with the IASI team based at *l'Université Libre de Bruxelles* in Belgium



IASI annual average for 2010

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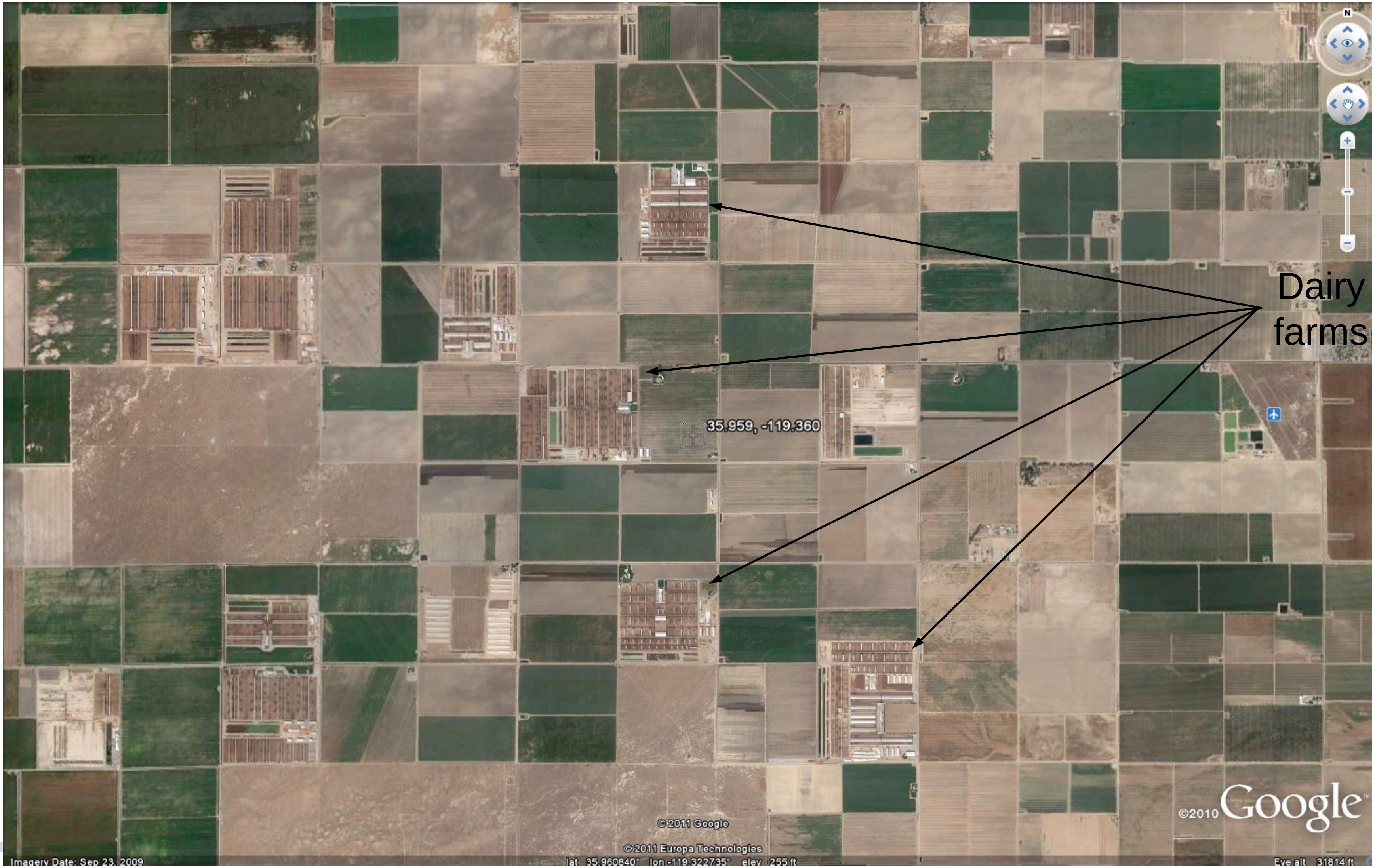
Environmental Applications – Gaseous Emissions

Google Earth Image for Flight CV01



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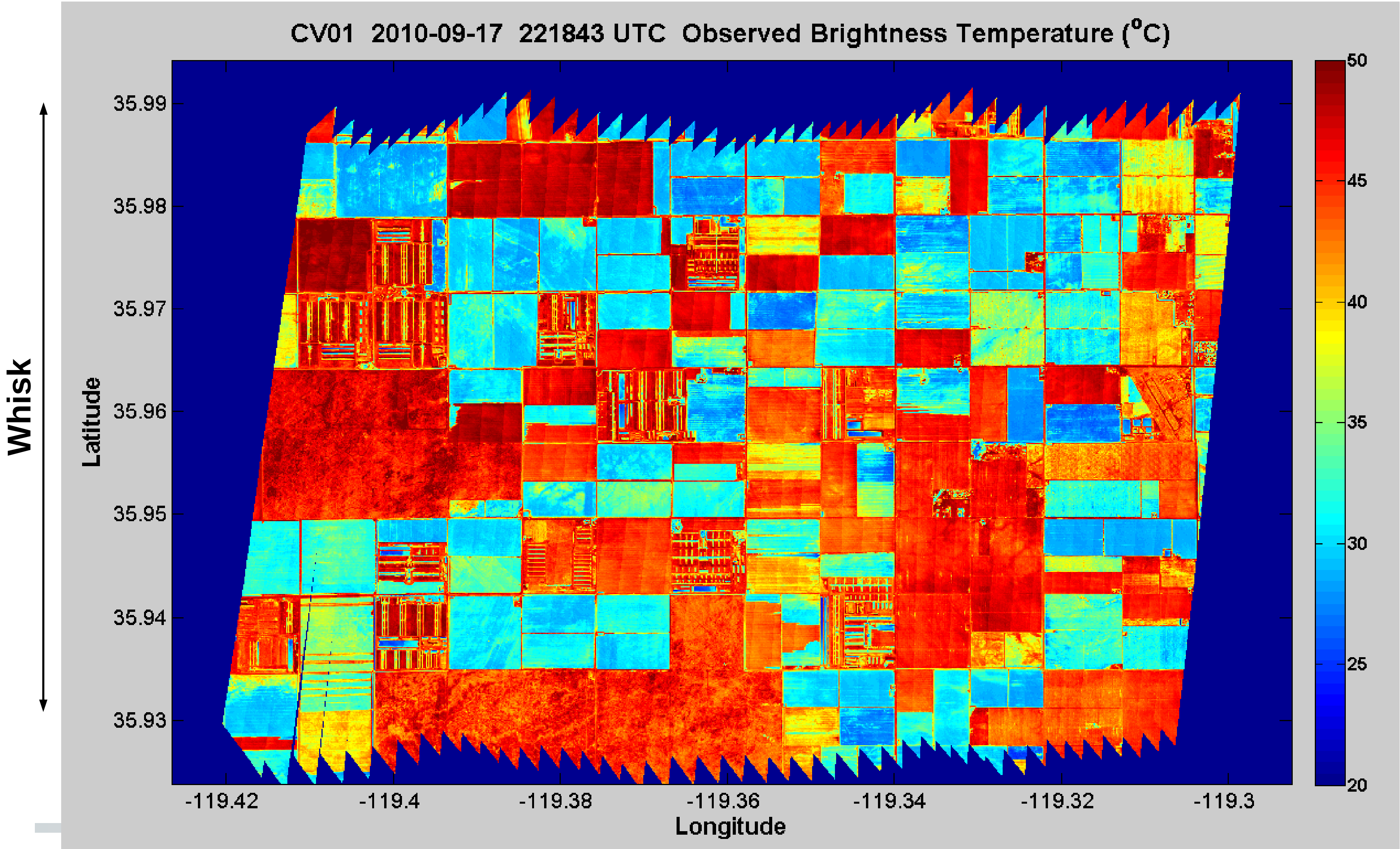
Environmental Applications – Gaseous Emissions

CV01 – Brightness Temperature Map



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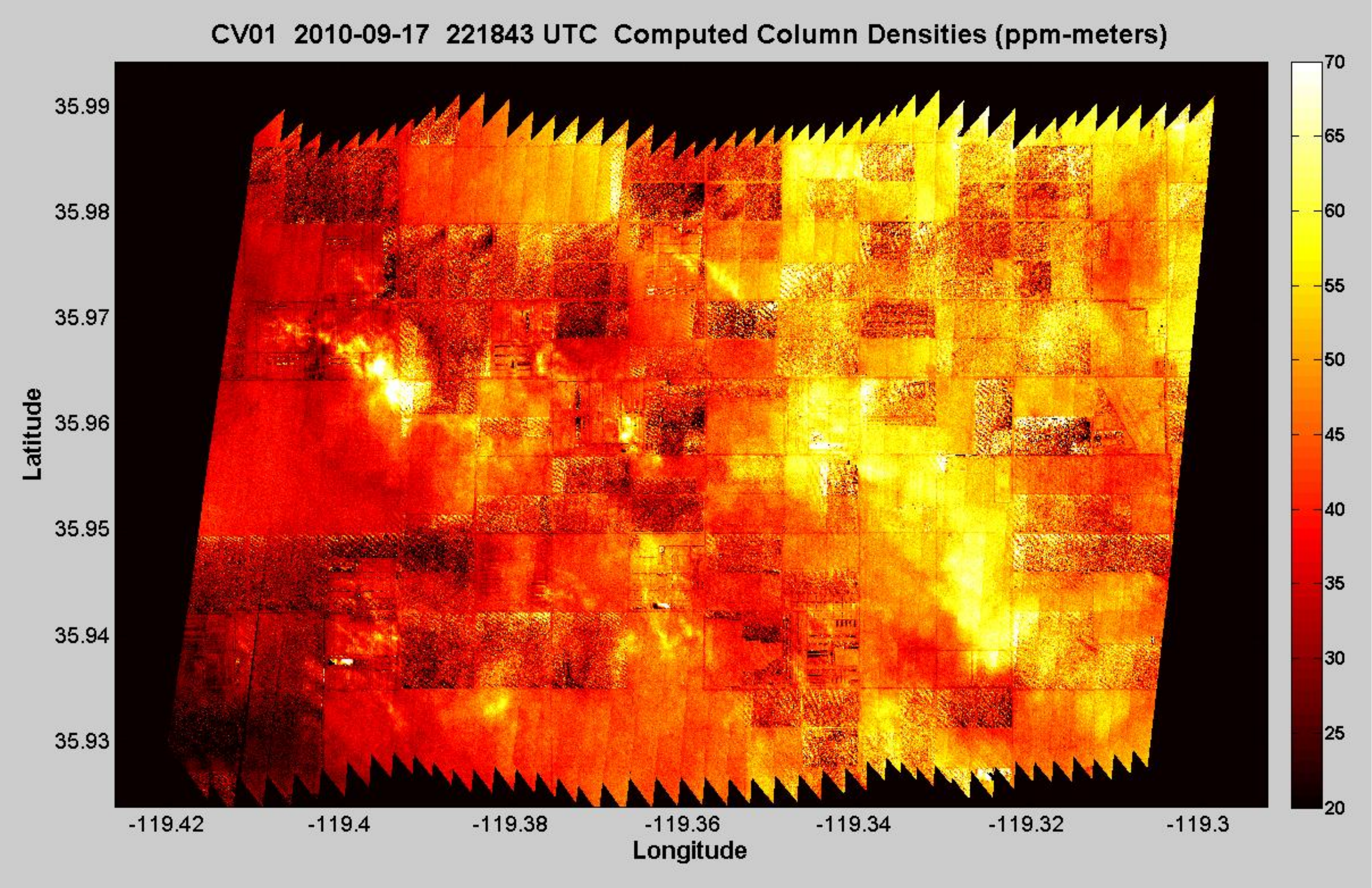
Environmental Applications – Gaseous Emissions

CV01 – Computed Column Density Map



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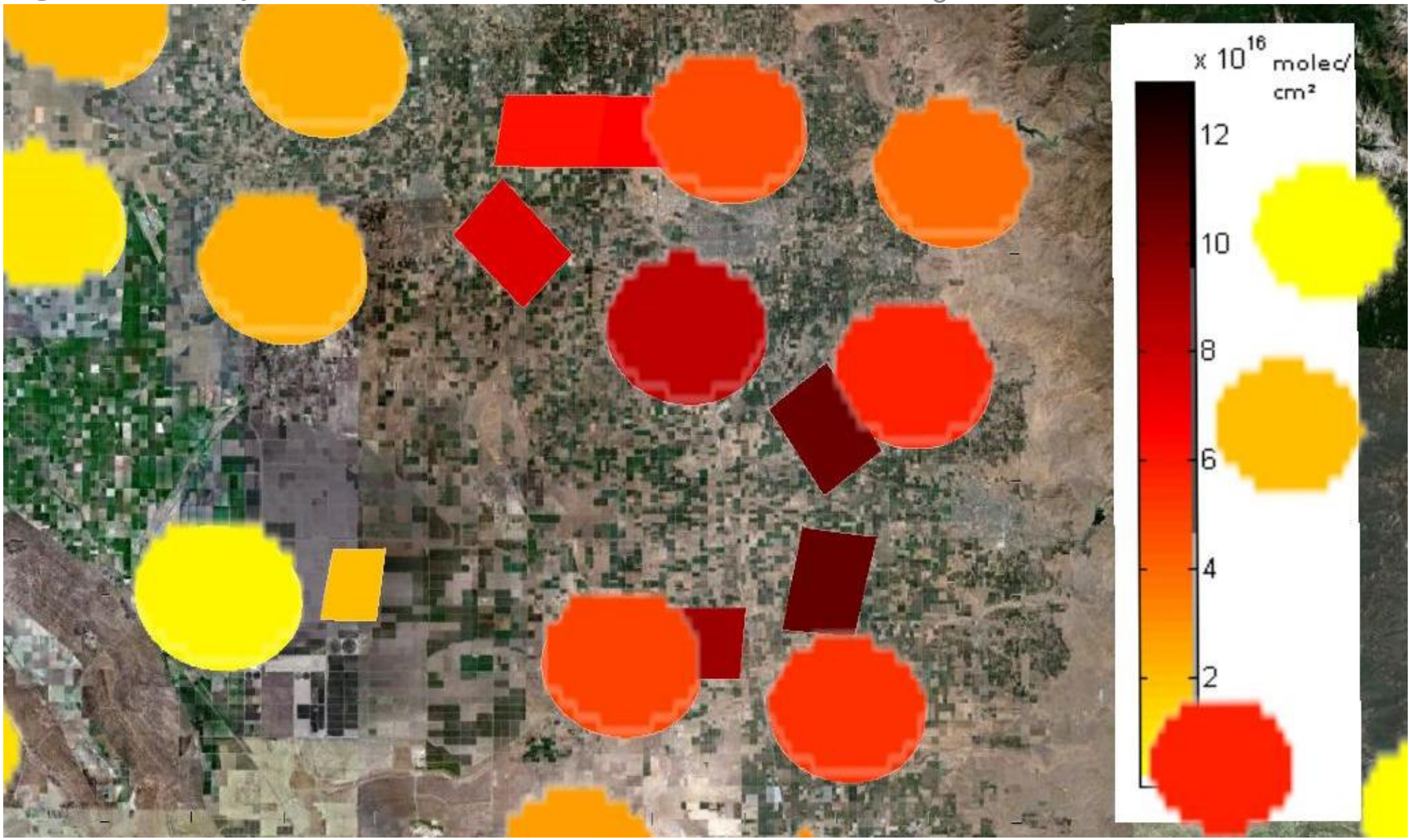
Environmental Applications – Gaseous Emissions

Regional comparison between IASI and Mako NH_3



IASI: Polka dots
Mako: Parallelograms

(*L. Clarisse, M. Van Damme*)

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Rock’s Physical, Chemical, & Mechanical Properties: Correlation with Thermal Infrared Spectroscopy and Remote Sensing

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Physical, Chemical, Mechanical Modeling

Chemical – SiO_2 Prediction

- Introduction
  - *Few studies focused on the use of thermal infrared (8-13 µm)*
  - *Differences in Si-O bonding manifest as shifts in the emissivity minimum*
  - *Variations in silicate mineralogy useful for geological mapping*
- Modeling Techniques
  - *Mixture modeling (Gillespie, 1992; Bandfield, 2002; Ramsey and Christensen, 1998)*
  - *Gaussian fitting (Sabine, 1994; Hook et al, 2005)*
  - *Partial Least Squares Regression (current approach)*
- Importance
  - *Core and Hand Samples*
  - *LWIR and VNIR-SWIR Airborne HSI data*
  - *Classifying igneous, sedimentary, and metamorphic rocks*

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Physical, Chemical, Mechanical Modeling

Theoretical Framework

- Different Si-O bonded structures vary interaction in 8-13µm
- Emissivity minimum occurs at shorter wavelengths (~8.5 µm) for framework silicates (quartz and feldspars)
- Emissivity minimum occurs at longer wavelengths (~9.5 – 10.5 µm) for sheet, chain, and isolated tetrahedral structures (micas, clays, amphiboles, pyroxenes, olivines, and garnets.
- Framework silicates dominate felsic igneous rocks (rhyolites, granites)
- Chain silicates dominate mafic igneous rocks (basalts, gabbros)
- Emissivity minimum of the Si-O stretching region moves to longer wavelengths as wt.% SiO_2 decreases.

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Physical, Chemical, Mechanical Modeling

Experimental Setup and Design

- Spectral Data
  - *FTIR (Igneous Rocks, 60 samples)*
- Wt.% SiO_2
  - *ALS Chemex (Igneous Rocks, 60 samples)*
- Partial Least Squares Regression
  - *X-variable (Spectral Data)*
  - *Y-variable (Wt.% SiO_2)*
  - *Same samples*
- Partial Least Squares Result
  - *Coefficients that can be to applied to specific instrumentation with same wavelengths to predict Wt.% SiO_2 from laboratory analysis.*
- Spectral Resampling
  - *SEBASS 8-12*
    - resample FTIR Hemispherical Reflectanc data to band centers of SEBASS's 128 channels,
    - subset to 8.0 -12.0 µm

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Partial Least Squares Regression

- Evolved from Chemometrics
- Wold, 1981
- Matlab implementation
  - *[1] de Jong, S., "SIMPLS: An Alternative Approach to Partial Least Squares Regression," Chemometrics and Intelligent Laboratory Systems, vol. 18, 1993, pp. 251-263.*
  - *[2] Rosipal, R. and N. Kramer, "Overview and Recent Advances in Partial Least Squares," in Subspace, Latent Structure and Feature Selection: Statistical and Optimization Perspectives Workshop (SLSFS 2005), Revised Selected Papers (Lecture Notes in Computer Science 3940), Springer-Verlag, 2006, pp. 34-51.*

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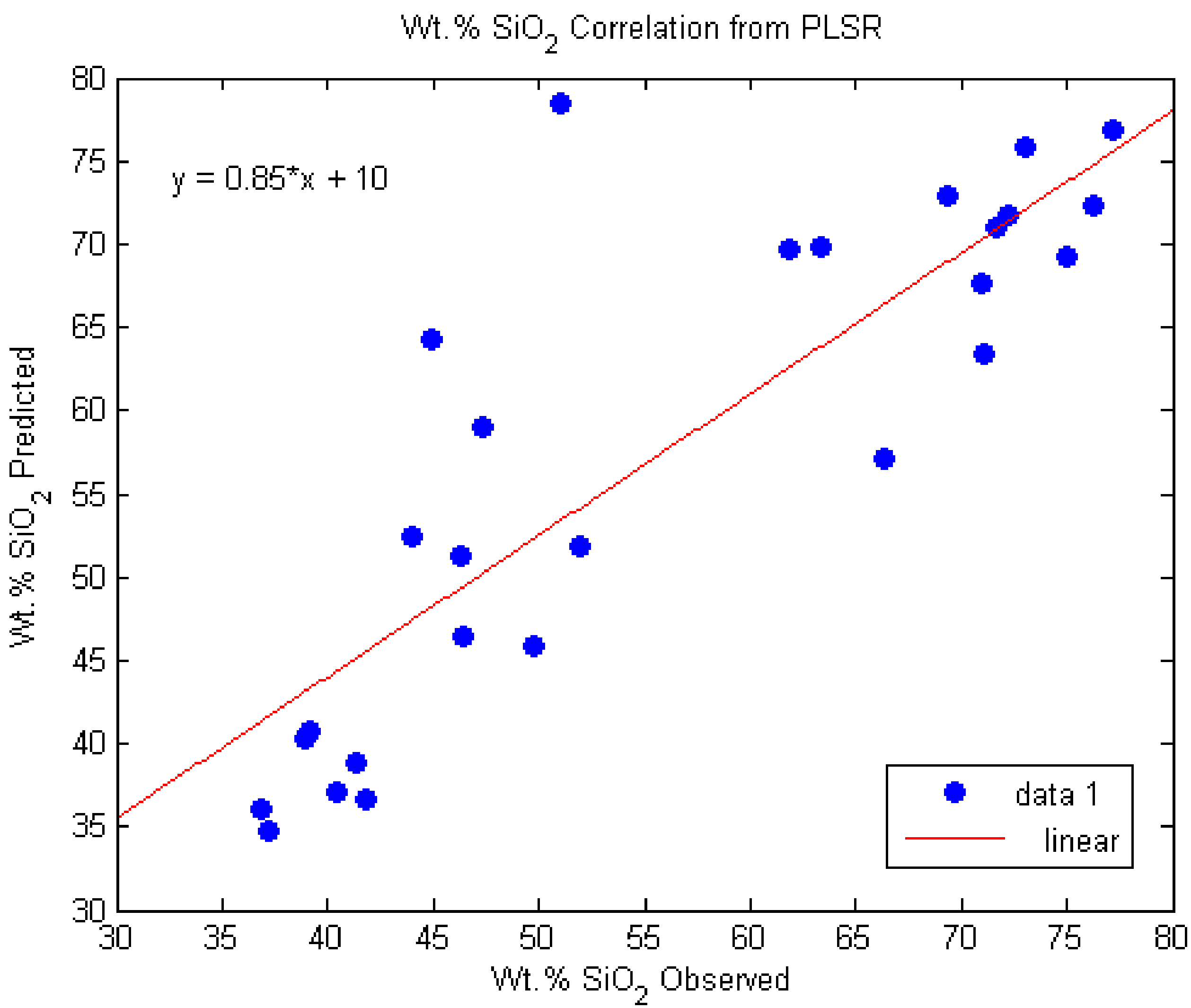
Physical, Chemical, Mechanical Modeling

Chemical – SiO_2 Prediction Wt% (27 PLS Factors)



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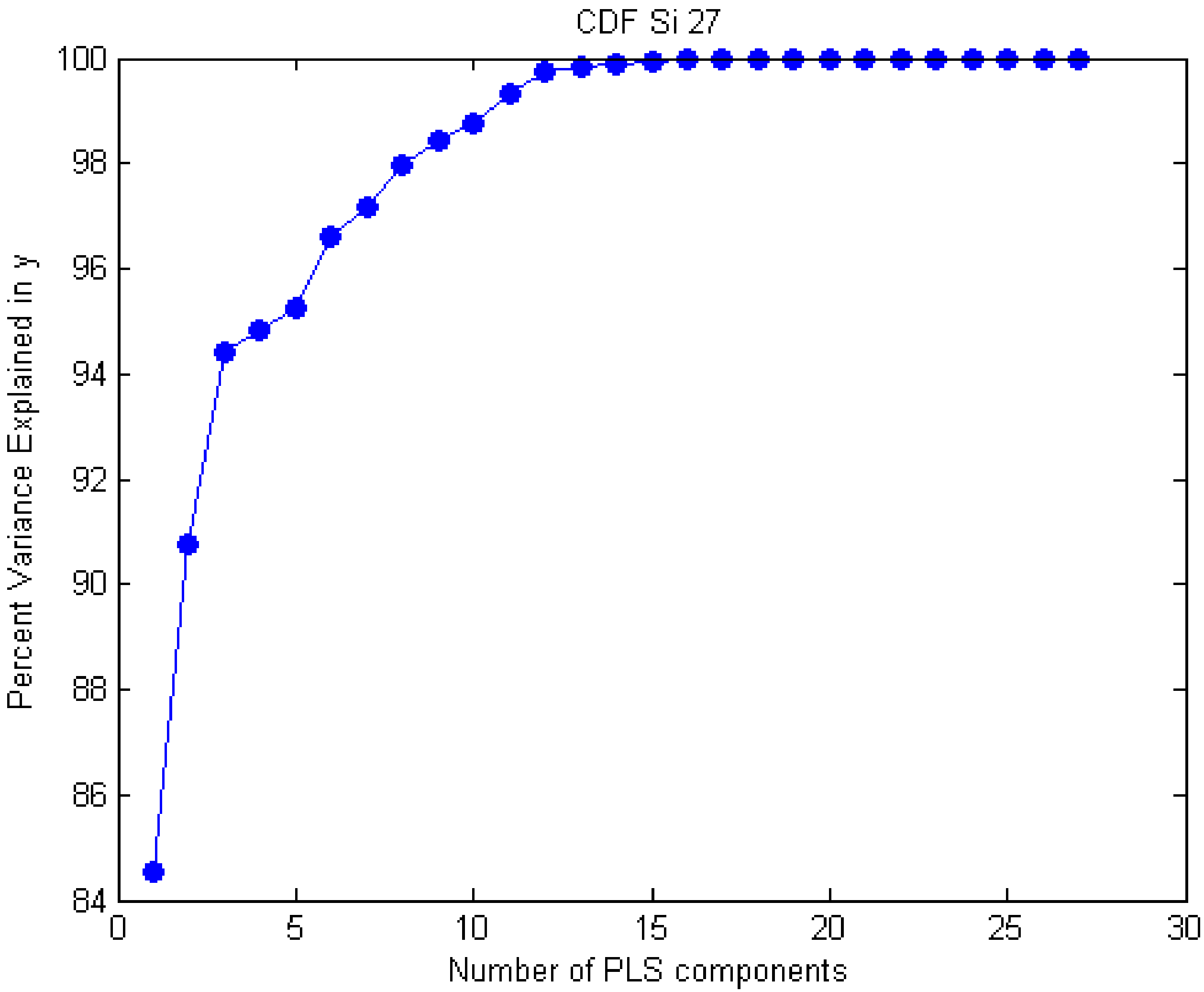
Chemical – SiO_2 PLS and % Variance Explained (27 PLS Factors)



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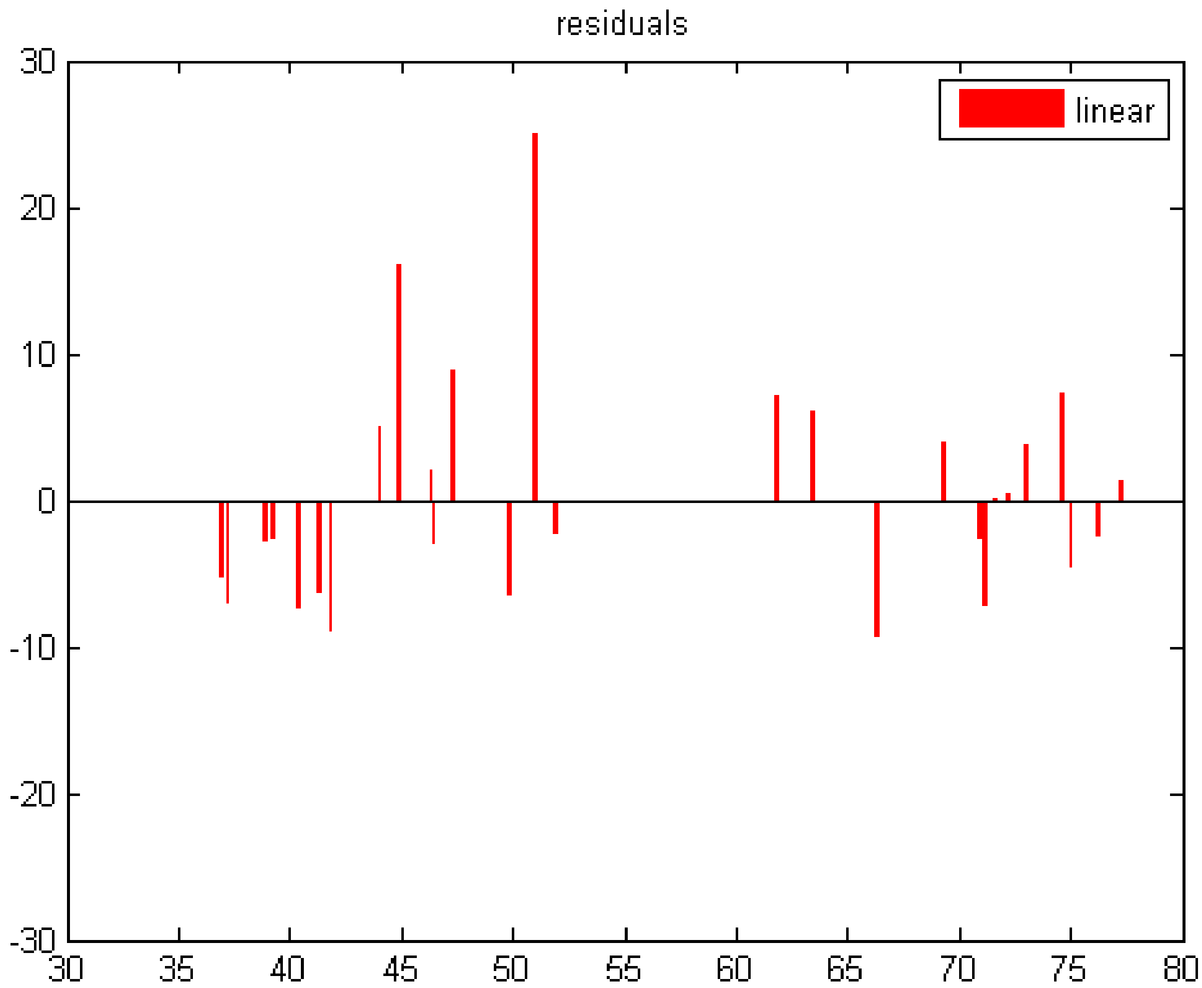
Physical, Chemical, Mechanical Modeling

Chemical – SiO_2 Prediction: Residuals (27 PLS Factors)



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Physical, Chemical, Mechanical Modeling

Correlation with Physical and Mechanical Properties of Rocks

- Purpose
  - *Determine if thermal spectroscopy can distinguish weathering grades, lithology/mineralogy, and can these spectral signatures be correlated with physical, mechanical, and chemical properties of rocks.*
  - *Determine if petrographical indices used in rock mechanics, engineering geology, and mining can be derived from thermal spectroscopy*
- Methodology
  - *Determine rock type, weathering characteristics*
  - *Determine modal composition of samples*
  - *Laboratory Spectroscopy (MWIR-LWIR)*
  - *Geochemical Analysis*
  - *Physical and Mechanical Testing*

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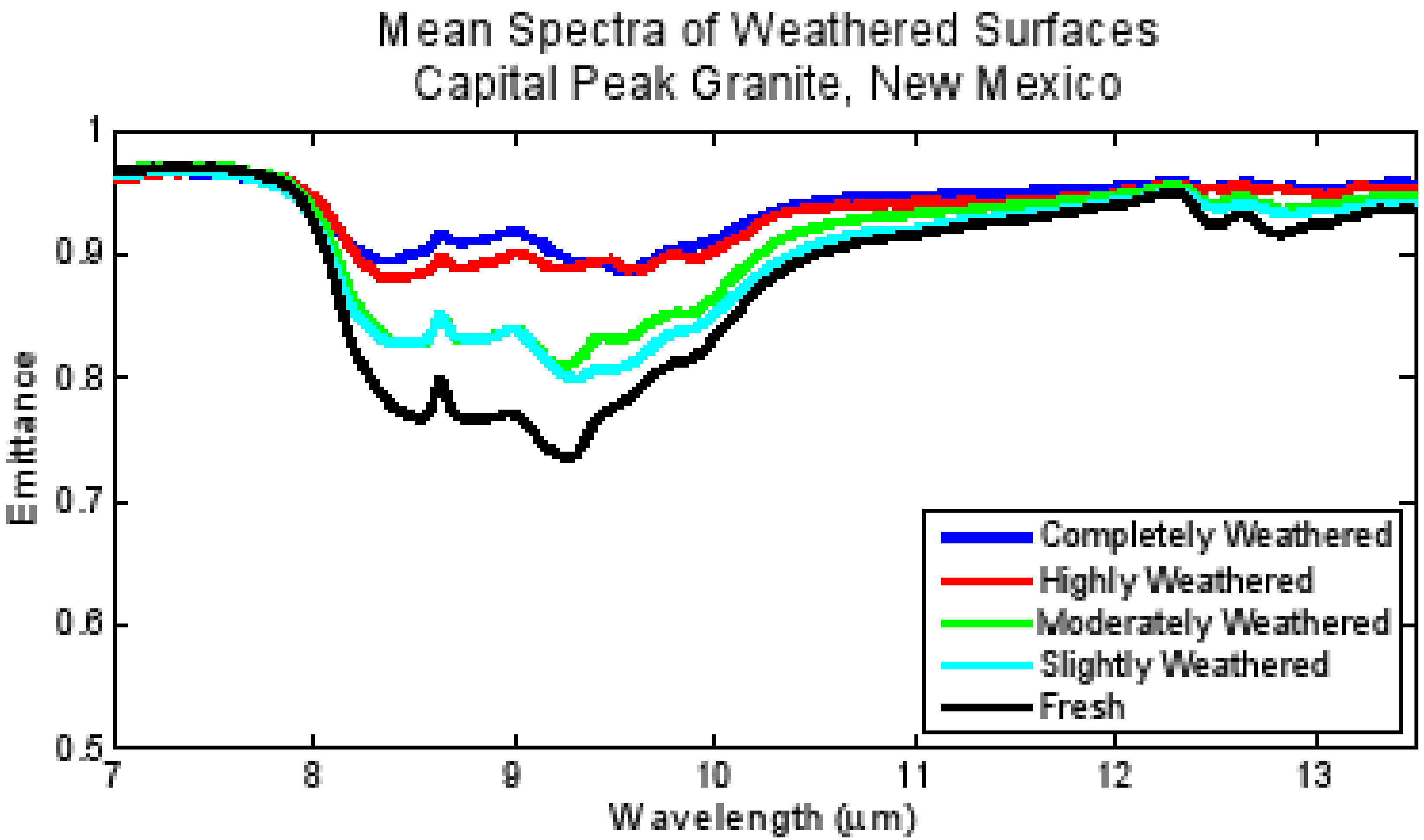
Physical, Chemical, Mechanical Modeling

Spectral Signatures of different Weathering Grades



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Physical, Chemical, Mechanical Modeling

Algorithm, Library, Quantification

- Algorithm
  - *Constrained Least Squares Solution (Nonnegative, + = 1)*
  - *Constrained Library*
    - Appropriate minerals
- Library
  - *ASU TES and JHU Libraries*
  - *Major Rock Forming Minerals*
    - Qtz, Fsp (An, Ab, Or, Mc, etc), Micas (Bt, Mu), Amph, Pxs
  - *Secondary Minerals*
    - Clays, Iron Oxides, Chl
- Capital Peak Granites
  - *Modal Analysis (Condie and Budding, 1978)*

Mineral	Thermal Spectroscopy (%)	Point Counting (%)
Quartz	29	20 ± 15
Microcline	14	30 ± 15
Albite	37	15 ± 10
Anorthite	0	20 ± 10
Perthite	0	
Biotite	10	10 ± 10
Hornblende	3	5 ± 5
Clay Minerals	5	

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Physical, Chemical, Mechanical Modeling

Mineral Indices

- Degree of Decomposition (Lumb, 1962)

$$\chi_d = \frac{N_q - N_q o}{1 - N_q o} \tag{1}$$

$$N_q = \frac{Quartz}{(Quartz + Feldspar)_{soil}} \tag{2}$$

$$N_q o = \frac{Quartz}{(Quartz + Feldspar)_{rock}} \tag{3}$$

- Micropetrographic Index (Mendes, 1966)

$$\kappa = \frac{Quartz + Feldspars + Micas + Others}{AlteredMinerals + Fissures + Voids} \tag{4}$$

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Physical, Chemical, Mechanical Modeling

Mineral Indices Continued

- Petrographic Index (Irfan and Dearman, 1978)

$$I_p = \frac{\%SoundConstituents}{\%UnsoundConstituents} \tag{5}$$

- Decomposed Product (Ramana and Gogte, 1982)

$$DP = \%AlteredFeldspar + \%AlteredMafic \tag{6}$$

- Quartz Feldspar Ratio (Tugrul and Zarif, 1999)

$$TQFR = \frac{\%Quartz}{\%Feldspar} \tag{7}$$

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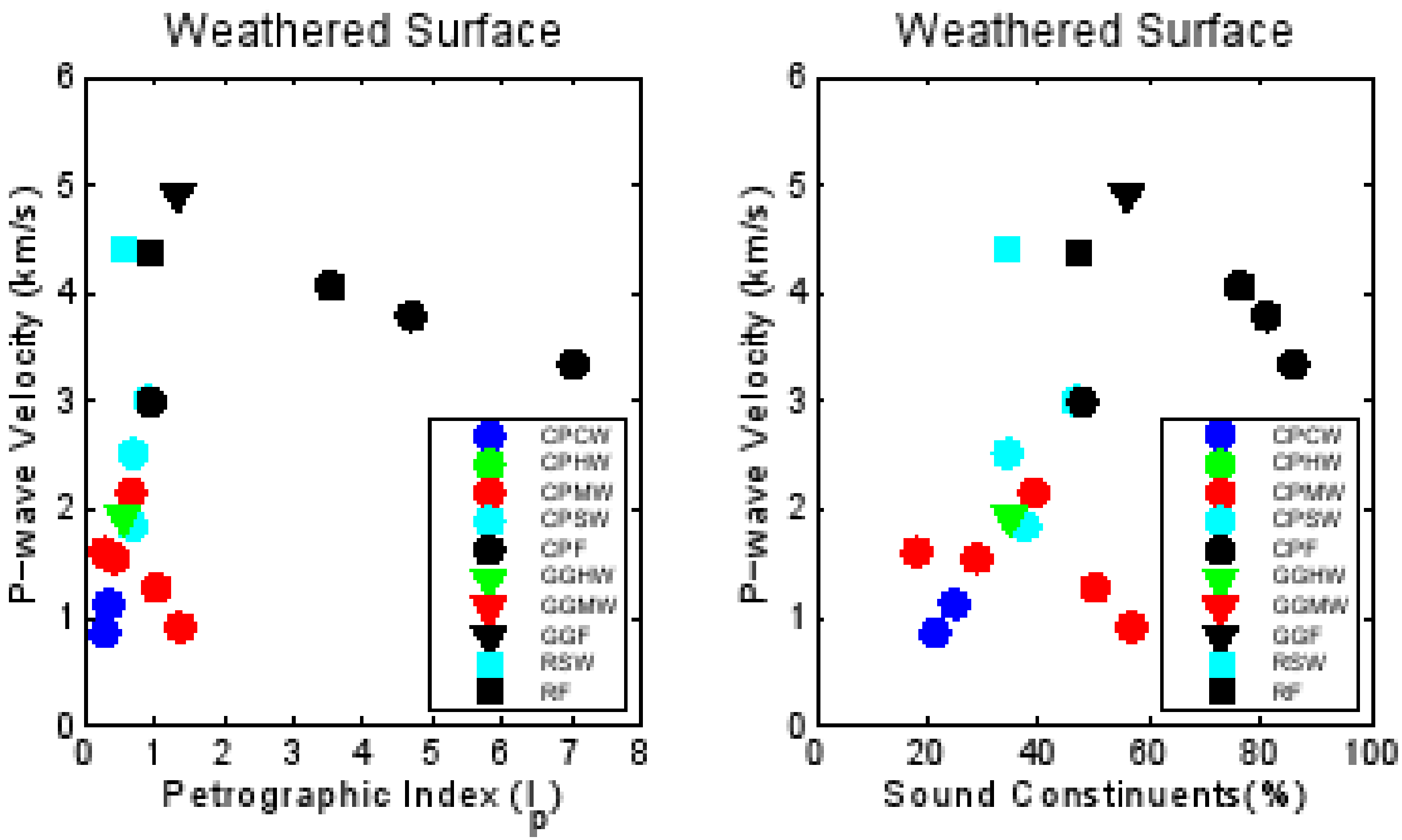
Physical, Chemical, Mechanical Modeling

Correlation between P-wave velocity and Mineral Indices



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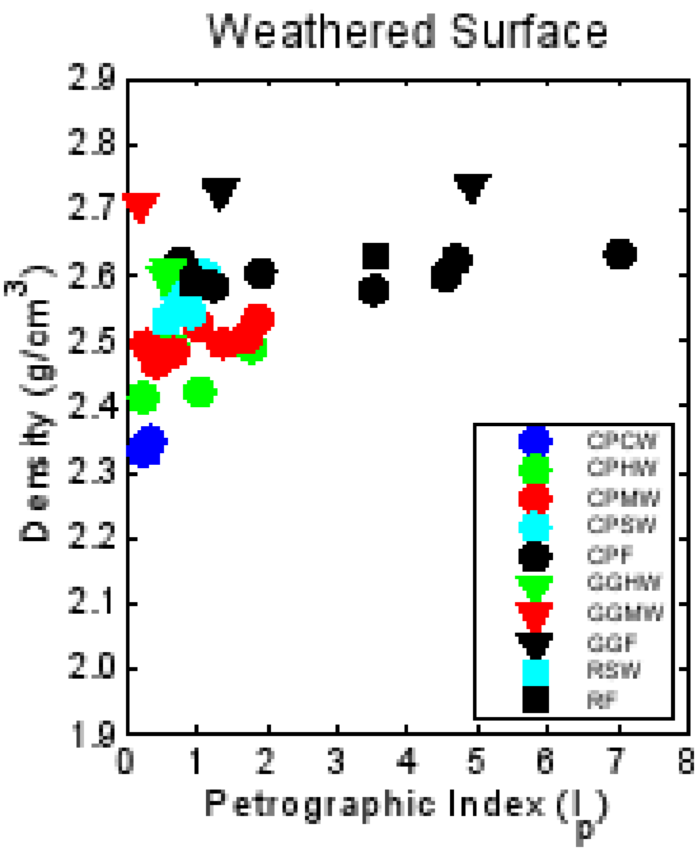
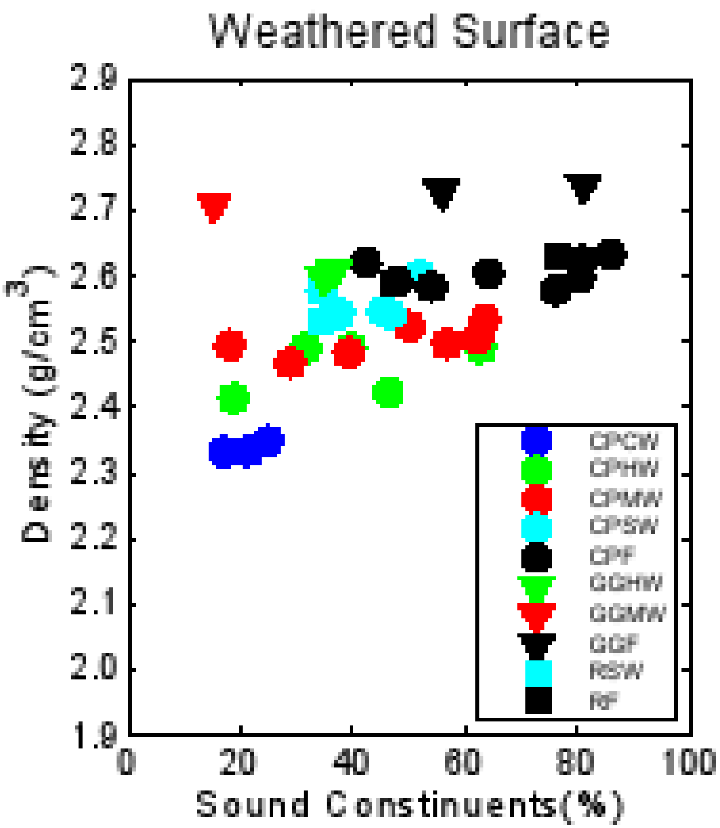
Physical, Chemical, Mechanical Modeling

Correlation between Density and Mineral Indices





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Full Spectrum Collections

History of Full Spectrum Collections

- 2005
  - *Separate Aircraft, same day*
  - *SEBASS / SpecTIR's HST*
- 2006
  - *Separate Aircraft, same day*
  - *SEBASS / SpecTIR's HST*
- 2007
  - *SEBASS / PROSPECTIR*
  - *University of Nevada Reno*
    - Beatty, NV / Leviathan, CA
  - *Different aircraft*
    - Separated by one month
- 2008
  - *SEBASS / PROSPECTIR*
  - *Same aircraft, same mount, same camera hole*
  - *May 2008 – June 2008, 5 weeks*
  - *Separate Aircraft in Northern Quebec – 6 weeks (mid July – September 1st)*
- 2009
  - *SEBASS / PROSPECTIR*
  - *Same aircraft, same mount, same camera hole*
  - *2 Collections*
- 2010
  - *SEBASS / PROSPECTIR*
  - *3 Collections*
- 2011
  - *SEBASS / PROSPECTIR*
  - *3 collections and a 4th in November*

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Full Spectrum Collections

Observable & Detectable Phenomena

- Visible – Short Wave Infrared
  - *Iron Oxides (Fe^{2+}, Fe^{3+})*
  - *Carbonates (CO_3, i.e. Calcite, Magnesite, Dolomite)*
  - *Phyllosilicates*
  - *Sulfates (i.e. Alunite, Jarosite)*
  - *Al - OH (i.e. Clay, Muscovite)*
  - *Mg - OH (i.e. Biotite, Phlogopite, Amphiboles)*
  - *Rare Earth Element Oxides (REE)*
  - *Vegetation*
- Long Wave Infrared
  - *Silicates (i.e. Qtz, Fsp, Gt, Px, Ol, Am, Clays, Micas)*
  - *Sulfates (i.e. Alunite, Jarosite, Gypsum, Anhydrite)*
  - *Carbonates (CO_3 ; i.e. Calcite, Magnesite, Dolomite)*
  - *Phosphates (i.e. Apatite)*
  - *Vegetation*

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Full Spectrum Collections

Sensors

	ProspecTIR (Hawk and Eagle)		SEBASS
SENSOR	VNIR (Hawk)	SWIR (Eagle)	MWIR / LWIR
Acquisition Altitude (m)	3000 (1.0 VIS – 5.0 LWIR; depending requirements)		
# Bands	356 (118 VNIR / 238 SWIR)		128 / 128
Spatial Swath (m; @ 3000 m)	1598	1238	422
IFOV (mrad)	1.31		1.1
Average Spectral Resolution (µm)	0.005 (0.00485 VNIR / 0.00629 SWIR)		0.025 / 0.050
Spectral Range (µm)	0.400 – 0.990	0.970 – 2.450	2.5 – 5.3 / 7.6 – 13.5
GSD @ 3000 m (Pixel Size)	1.56	3.93	3.3
# of Flight Lines / day	20 (depending on requirements for collection, distance from airport)		
Flight Lines length (km)	20 (dependent on GSD, and flight conditions)		

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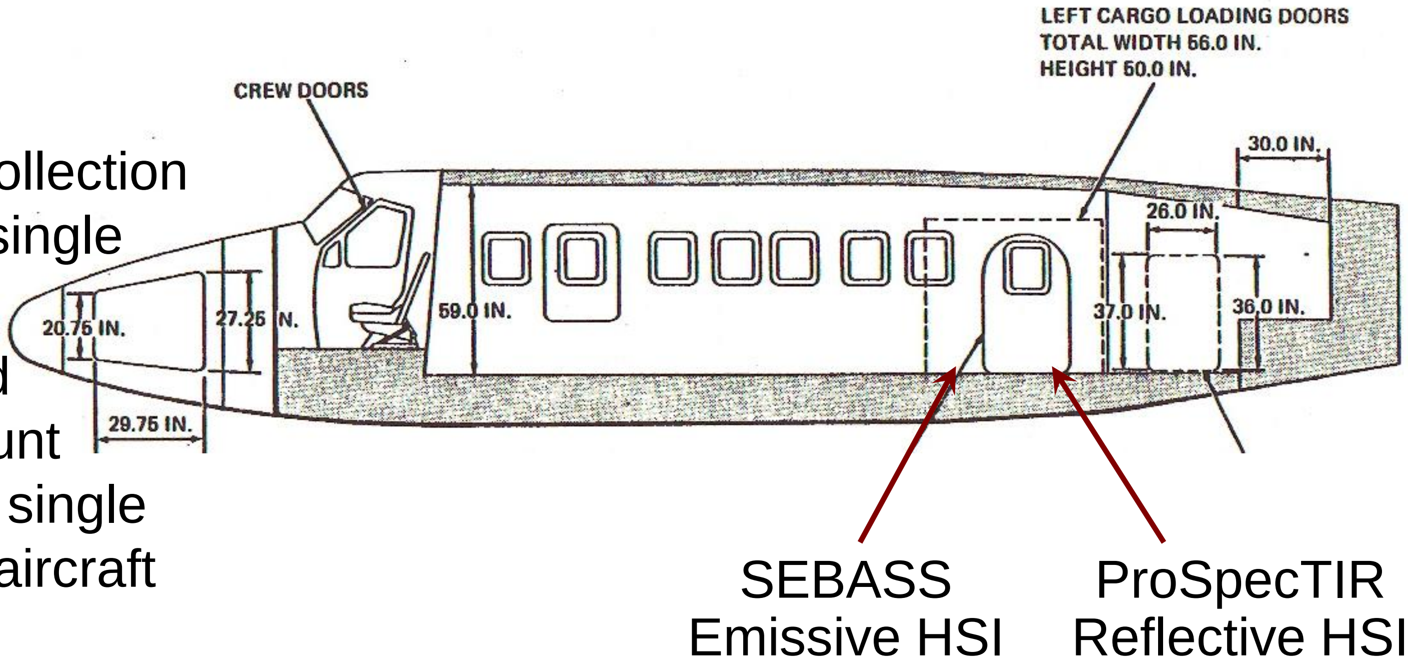
Full Spectrum Collections

Full Spectrum Collection Capability

- Technology Demonstration between Aerospace and SpecTIR
- Full-spectrum collection capability on a single aircraft
- Sensors located together on mount looking through single camera hole in aircraft



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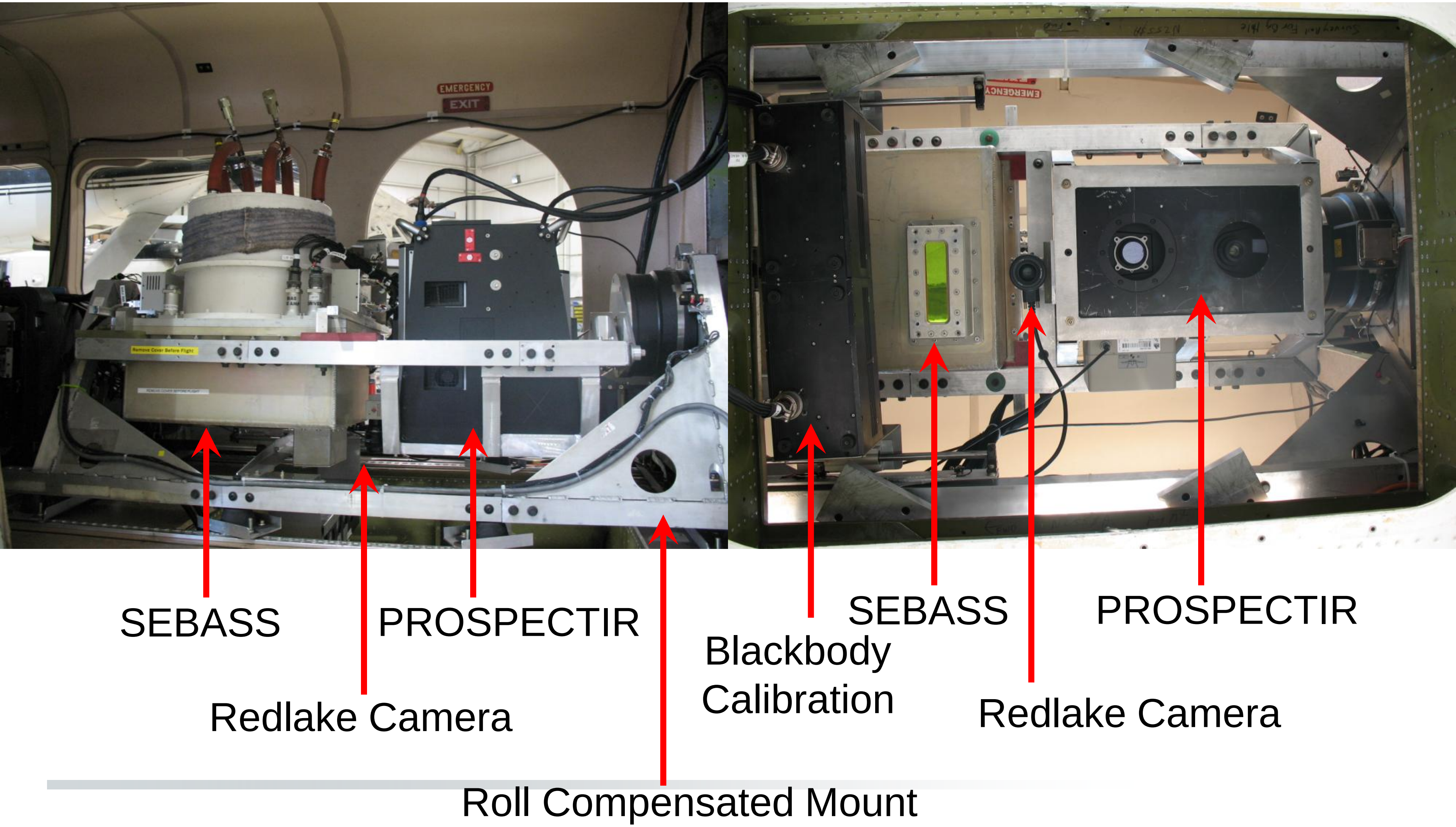
Full Spectrum Collections

Sensor Setup in Twin Otter



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Sensor Setup Continued

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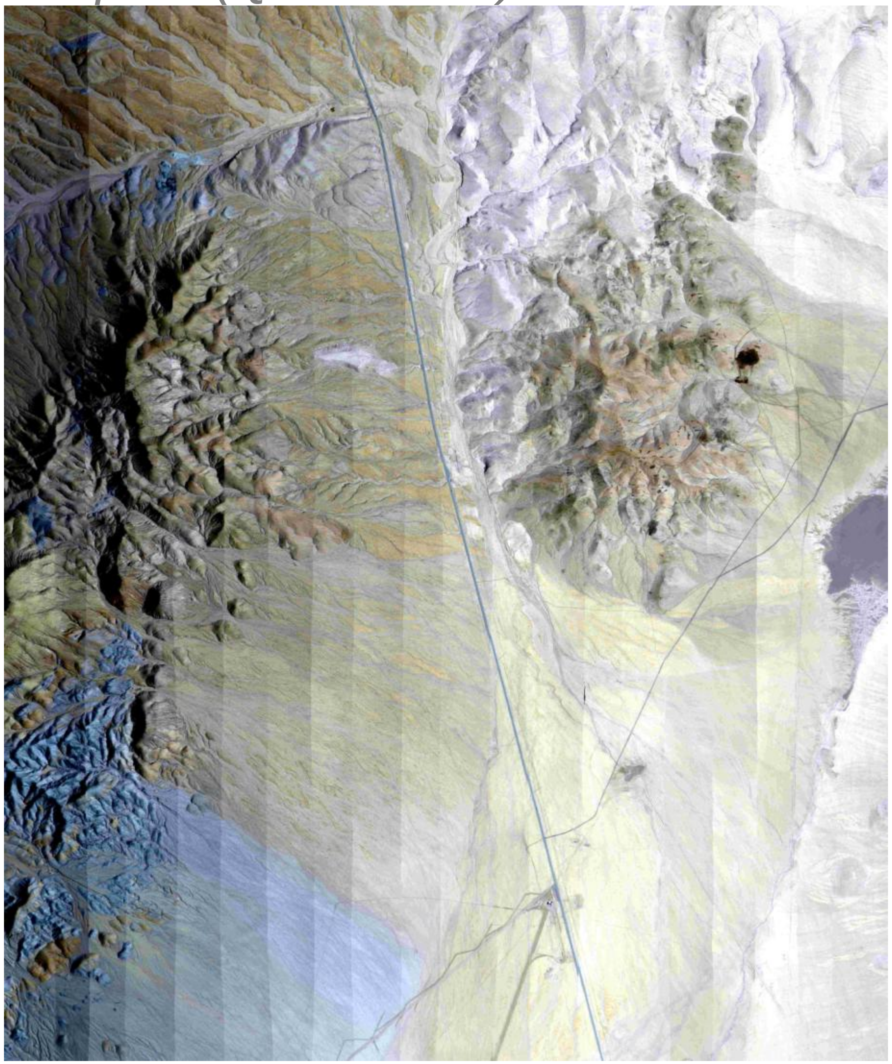
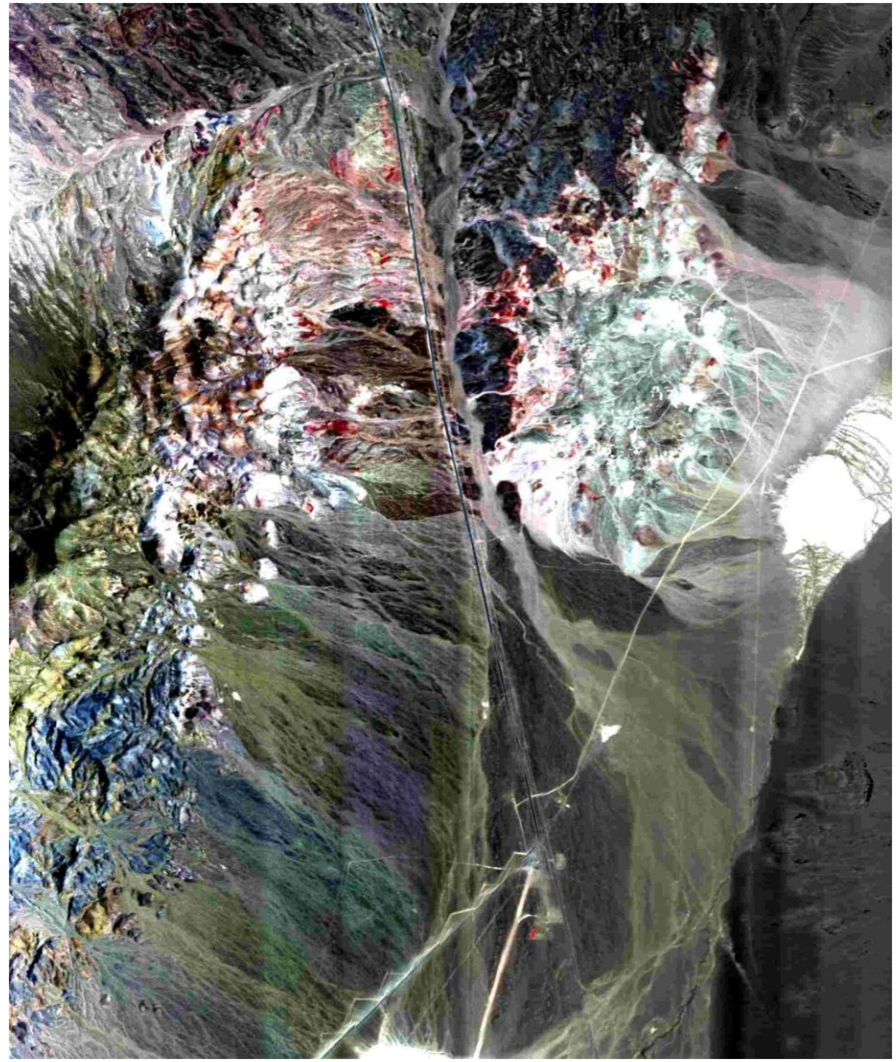
Cuprite (Quick Look)



SEBASS RGB: 11.33 μm, 12.95 μm, and 9.22 μm)



PROSPECTIR RGB: 0.638 μm, 0.534 μm, 0.460 μm)

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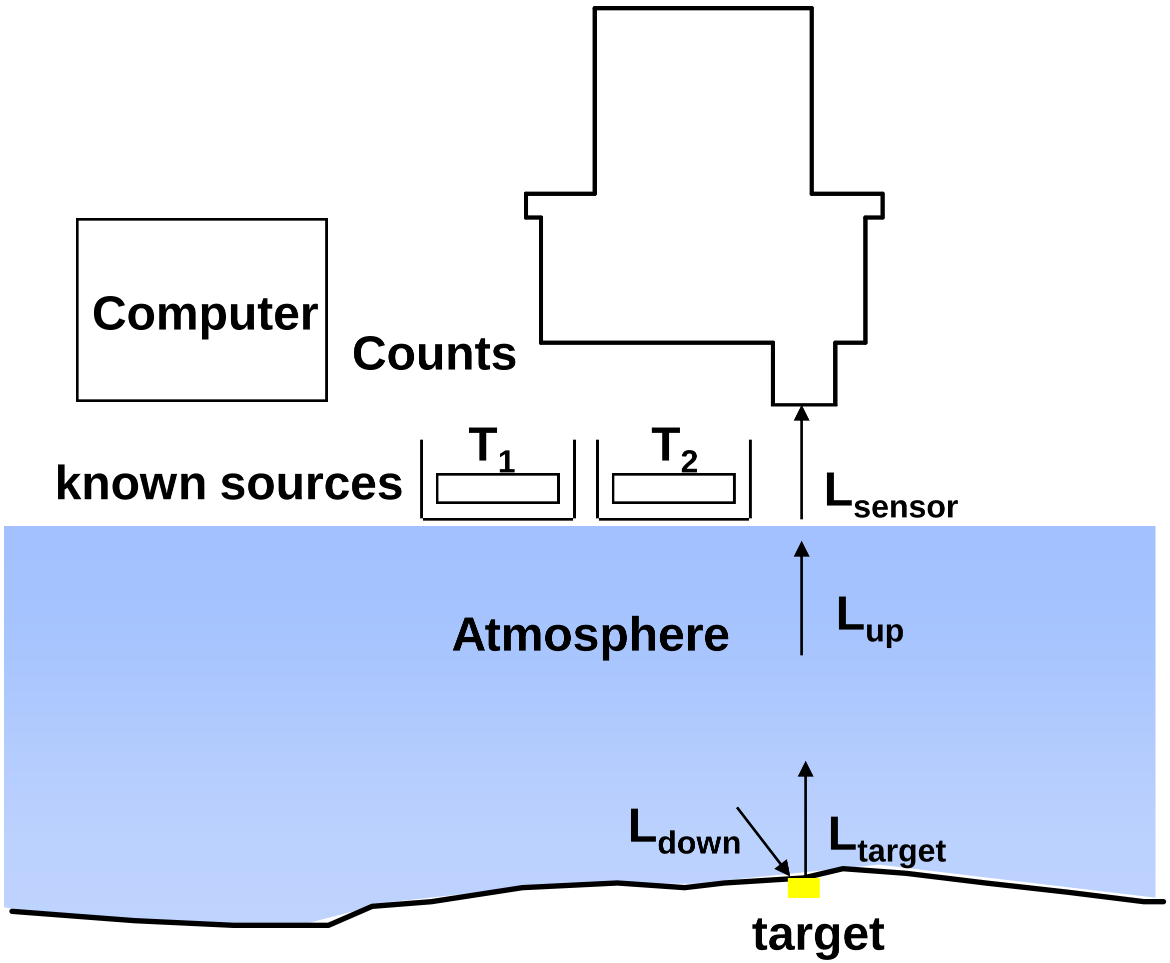
Thank you - Questions

Back Up Slides

Full Spectrum Collection – SEBASS Operation

SEBASS Sensor Calibration



- Introduce sources T_1 and T_2 with known radiances
- Fit between counts and radiance gives slope and offset values that link Counts to L_{sensor}
- Current system uses blackbody sources that flood SEBASS aperture

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Mineral and Rock Emissivities

- Arizona State University Thermal Emission Spectroscopy Mineral Library
- NASA JPL ASTER Mineral Library
- Johns Hopkins University Mineral Library
- Hapke's equations (Remote Sensing)
  - *Reflectance/Emittance (Areal Mixture)*
    - $E_H = \Sigma f_i E_i$
    - $R_H = \Sigma f_i R_i$
- Kirchoff's Law
  - *1 – Reflectance = Emissivity*

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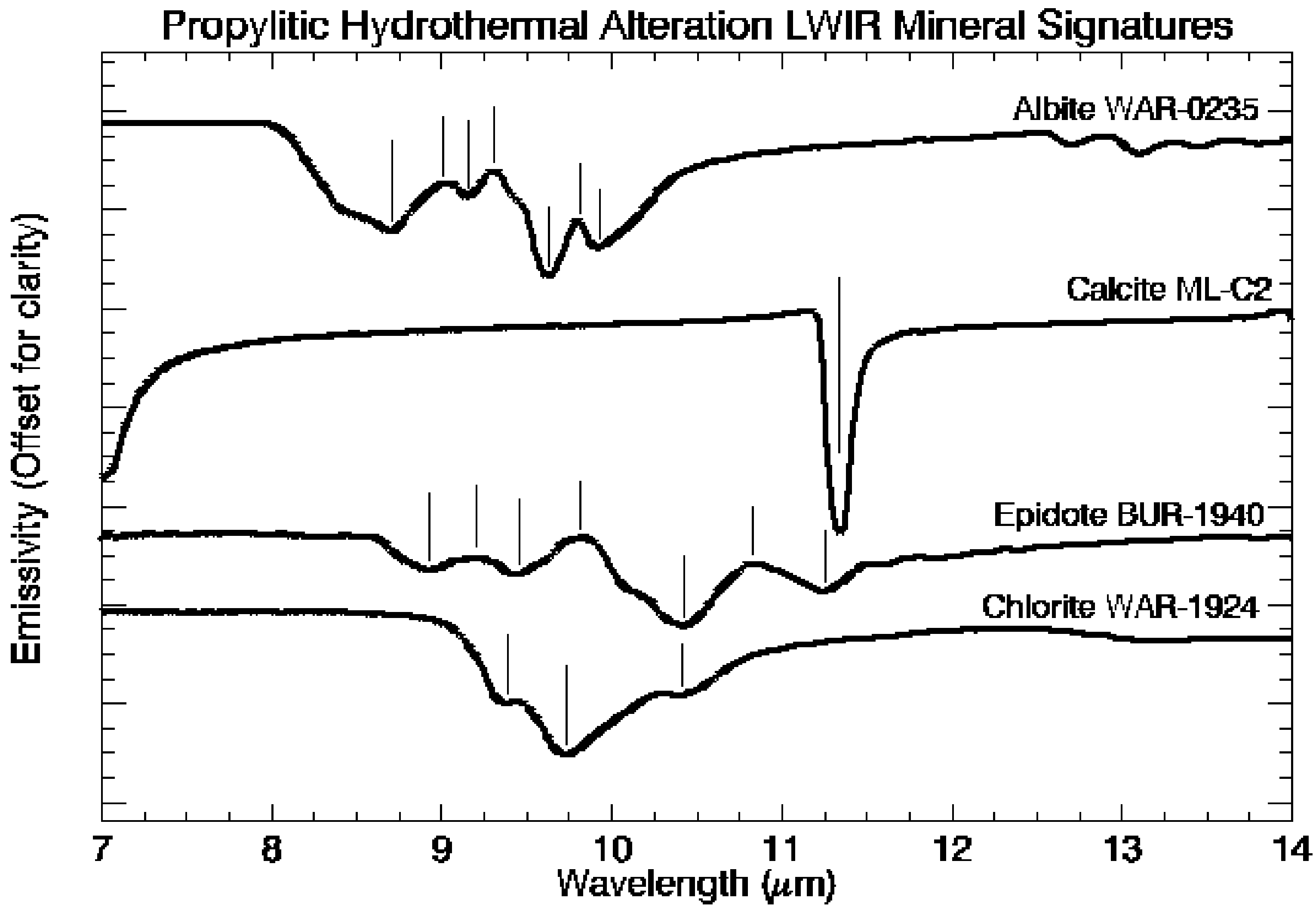
Porphyry Copper LWIR Mineral Signatures



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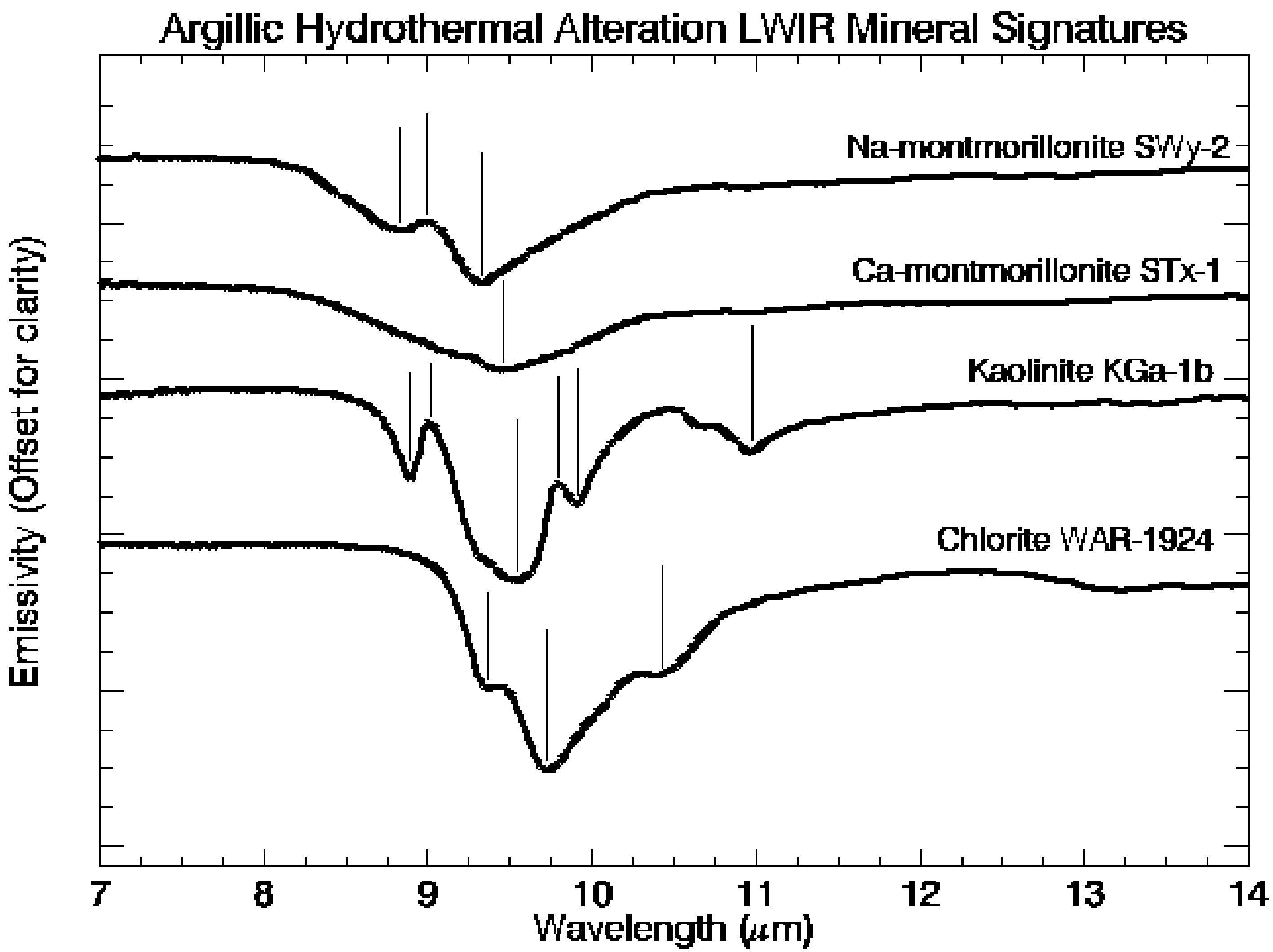
Porphyry Copper LWIR Mineral Signatures



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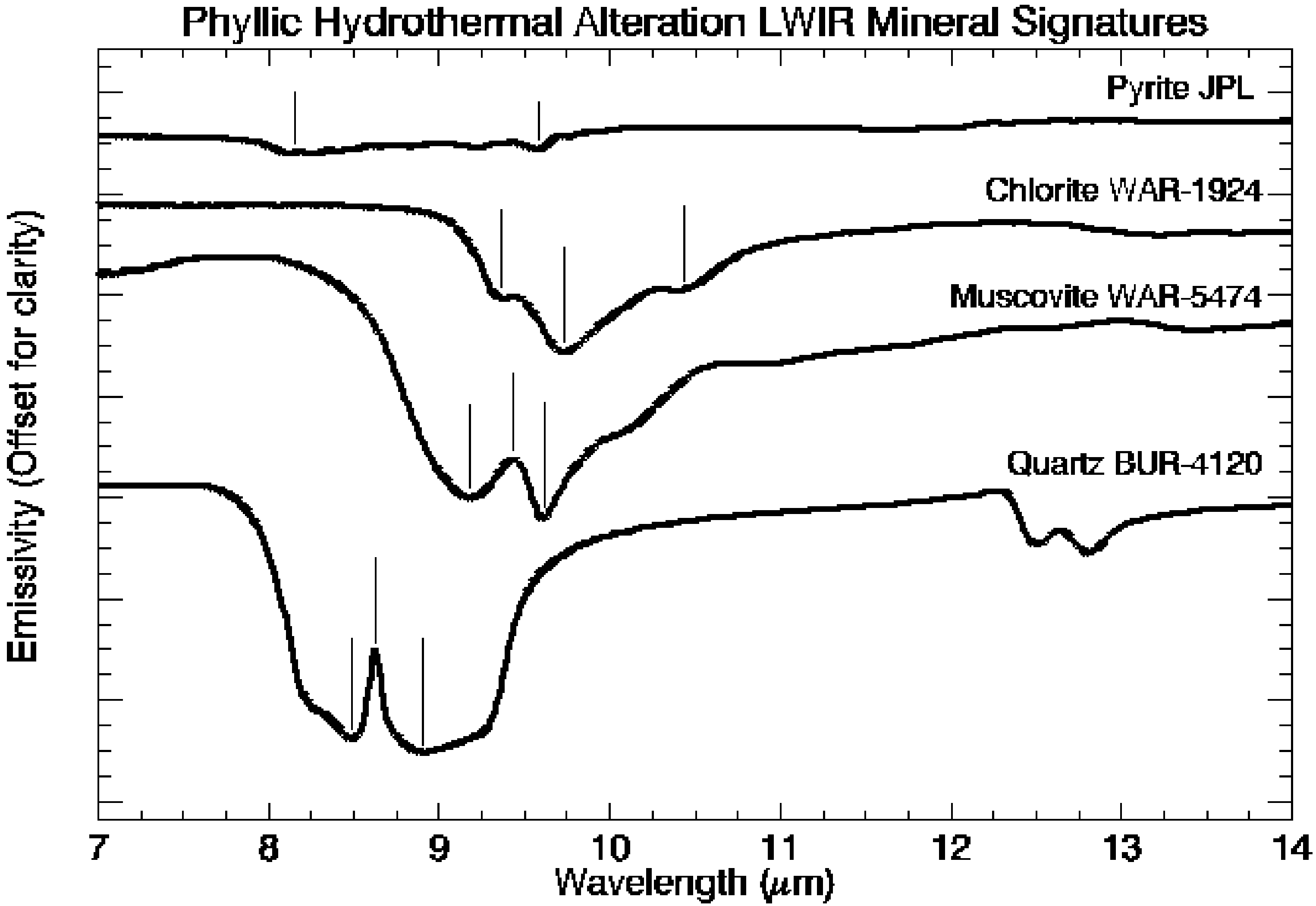
Geological Applications

Porphyry Copper LWIR Mineral Signatures



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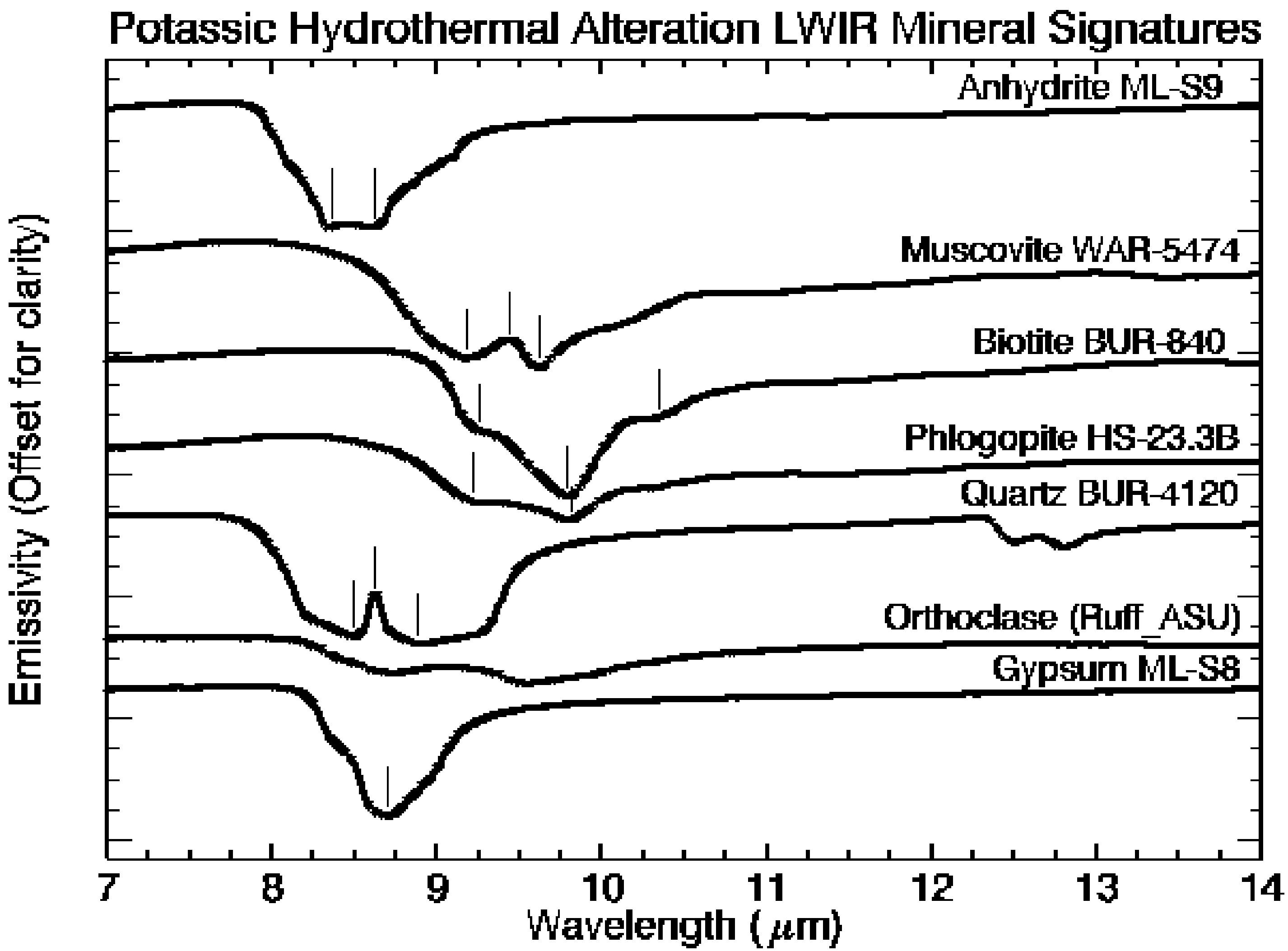
Porphyry Copper LWIR Mineral Signatures



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Copper Skarn Model

- Calcic Skarn
  - *Andradite + Diopside + Chalcopyrite*
- Mg – Skarn
  - *Forsterite + Serpentine + Talc ± Tremolite ± Magnetite*
- Hornfels – Skarnoid
  - *Wollastonite Rock*
    - Wollastonite ± Quartz ± Calcite
  - *Diopside Hornfels*
    - Diopside + Quartz
  - *Calc-Silicate Hornfels*
    - Quartz + Tremolite + Plagioclase + Epidote + Diopside
      - *Epidote + Albite = Actinolite + Oligioclase*
  - *Skarnoid*
    - Garnet (Al-Si rich; grossular, almandine, pyrope)
- Other Minerals
  - *Gypsum*

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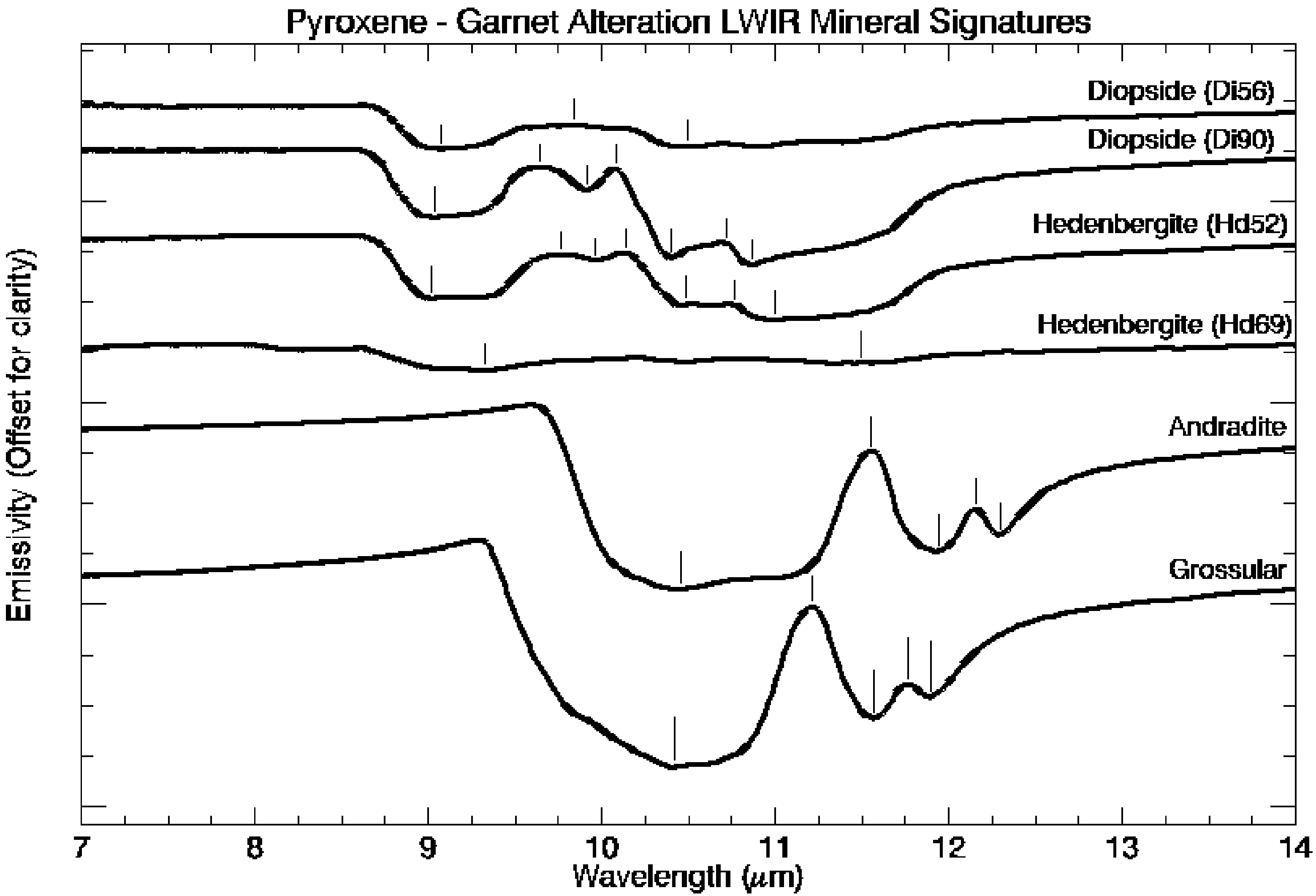
Copper Skarn Mineral Signatures



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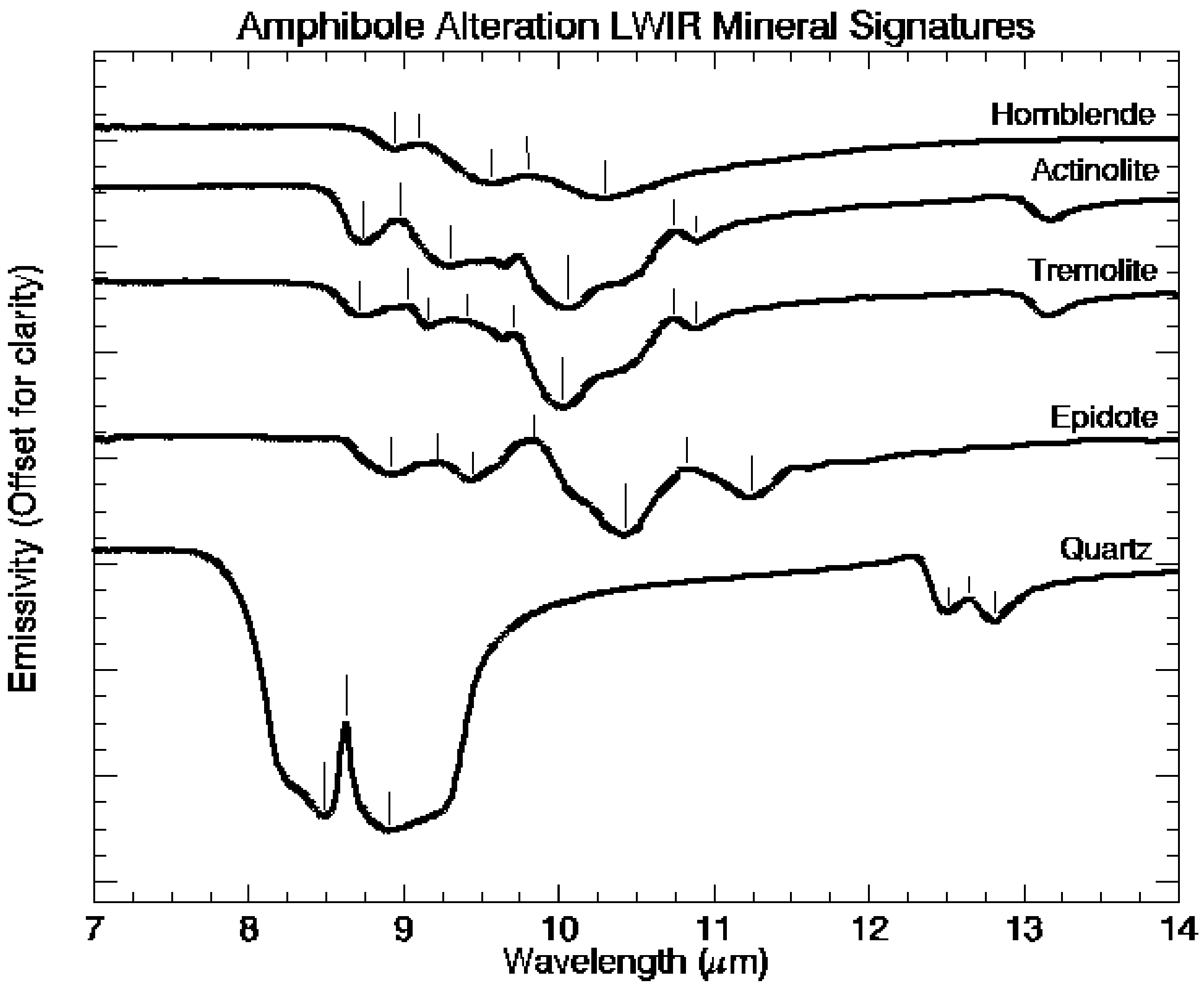
Amphibole Signatures



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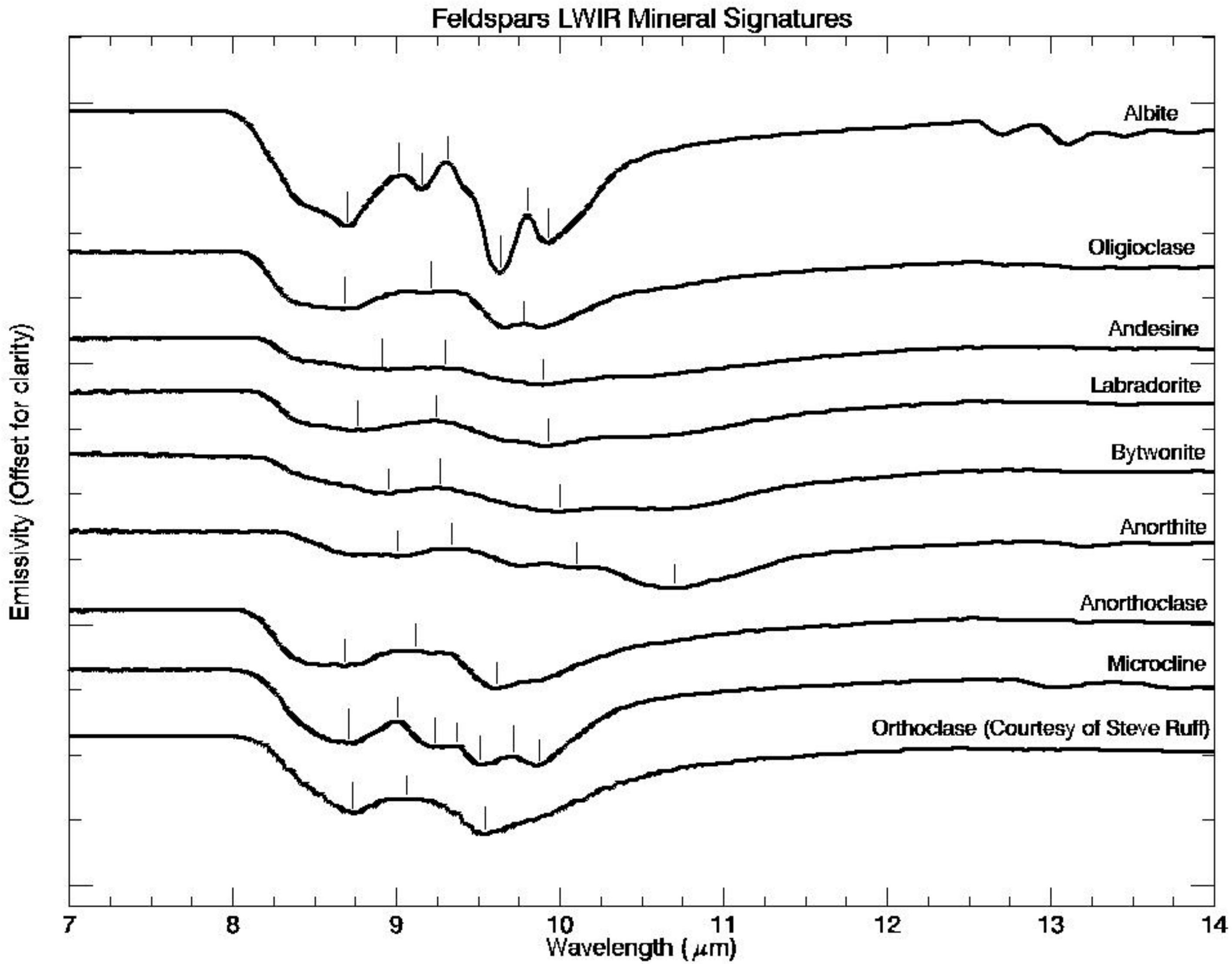
Plagioclase and Quartz Mineral Signatures



SEBASS Image Analysis

- Image Calibration
  - *In-Scene Atmospheric Correction (ISAC)*
- Temperature Emissivity Normalization
- Band Ratio Images
  - *Garnet (11.4/11.0 µm), Feldspar (9.9/9.6 µm), and Carbonate (11.3/11.1 µm) Chemistry*
- Spectral Feature Fitting
  - *Least squares fit*
  - *Continuum Normalization*
  - *Minerals from Deposit Model*
- Band Ratio
  - *Scale Image / RMS Image = "Fit Image"*
- Threshold using Rule Classifier
  - *≥ 2 standard deviation*

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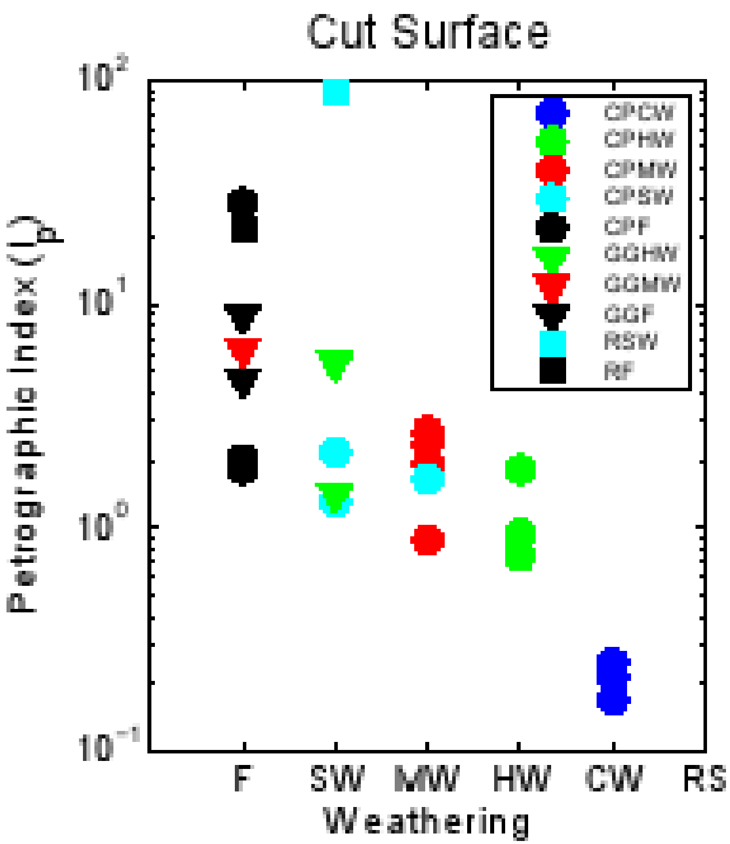
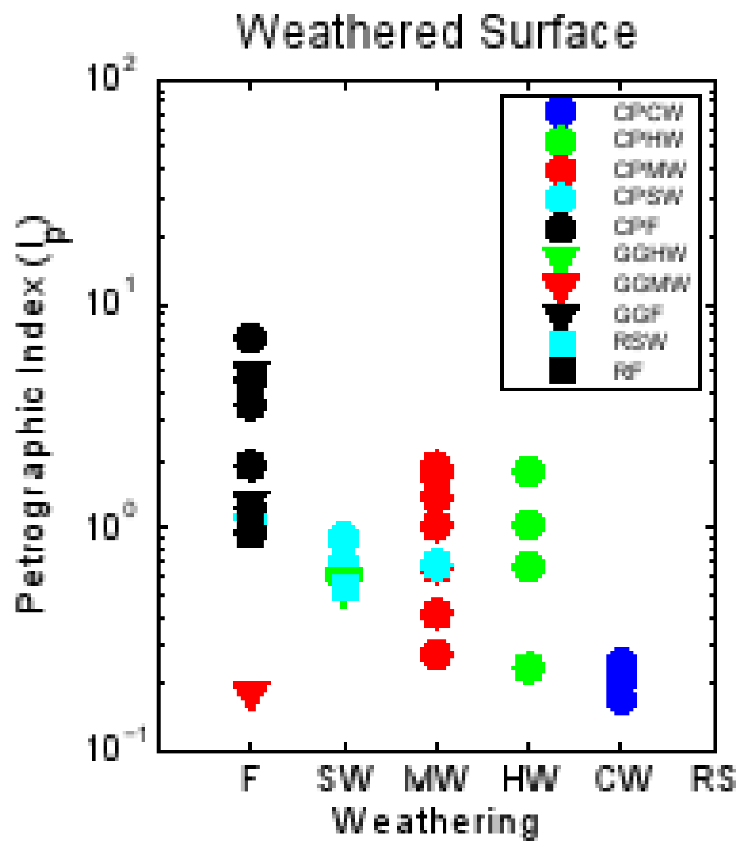
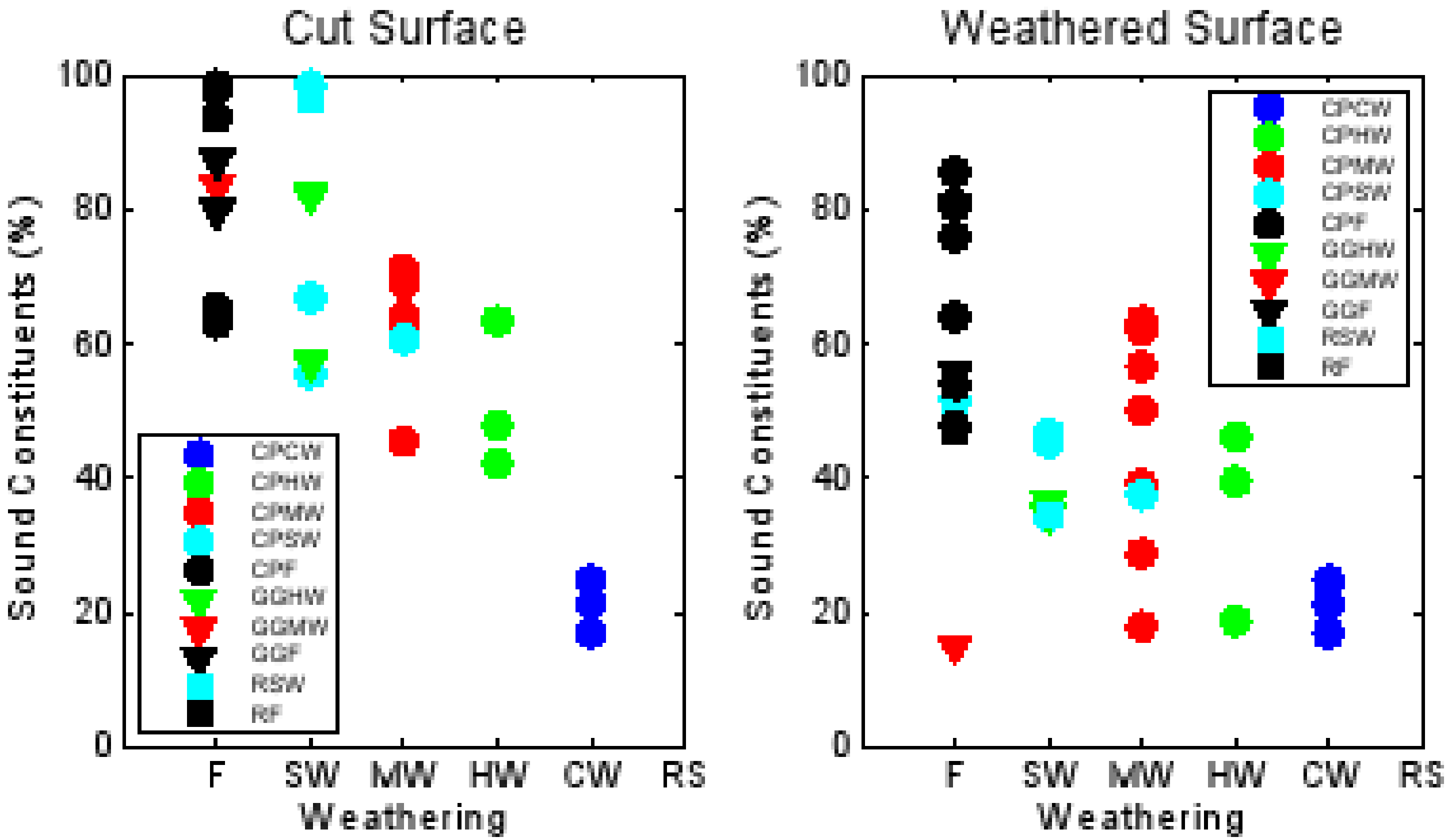
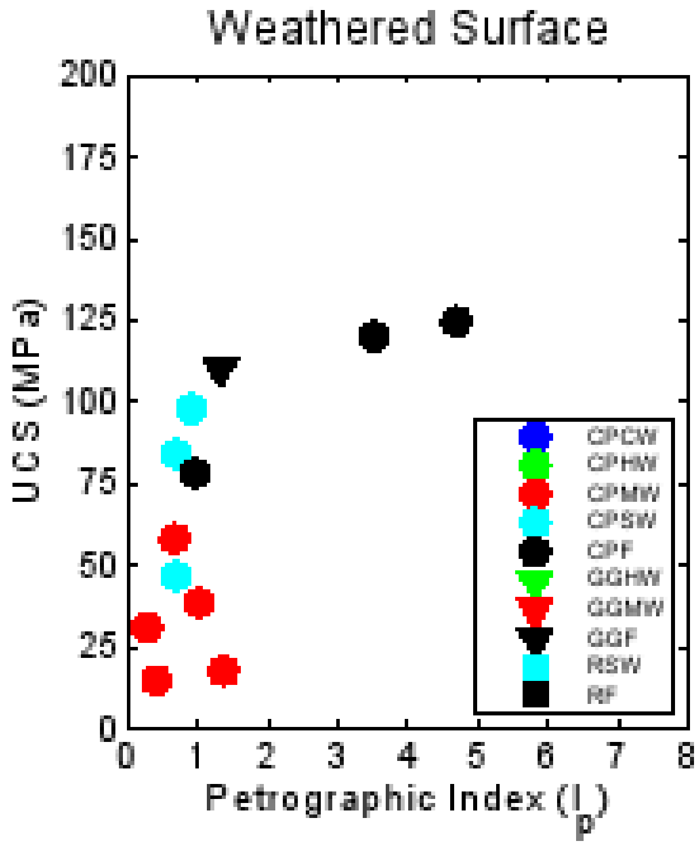
Weathering Grade and Mineral Indices

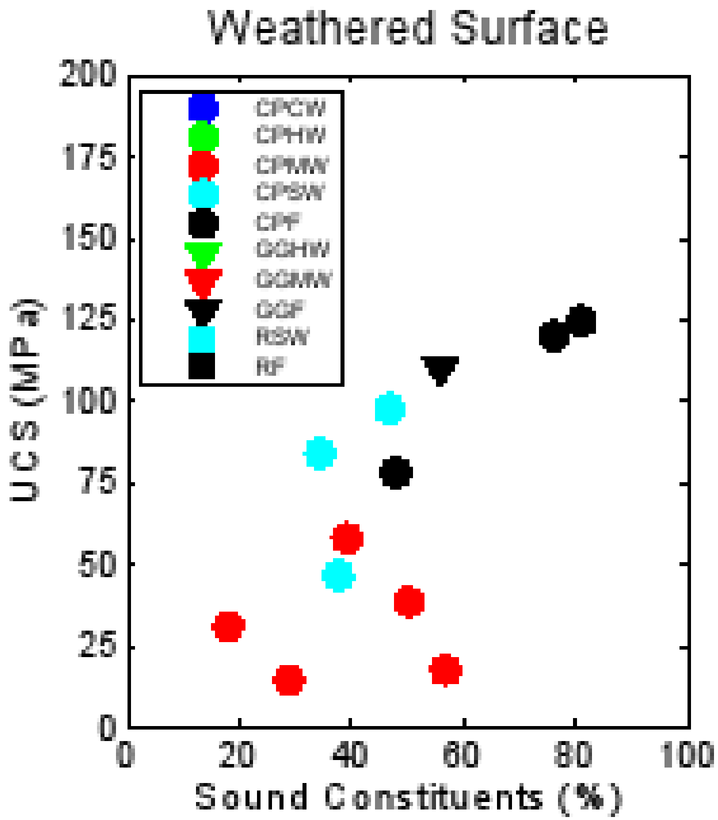


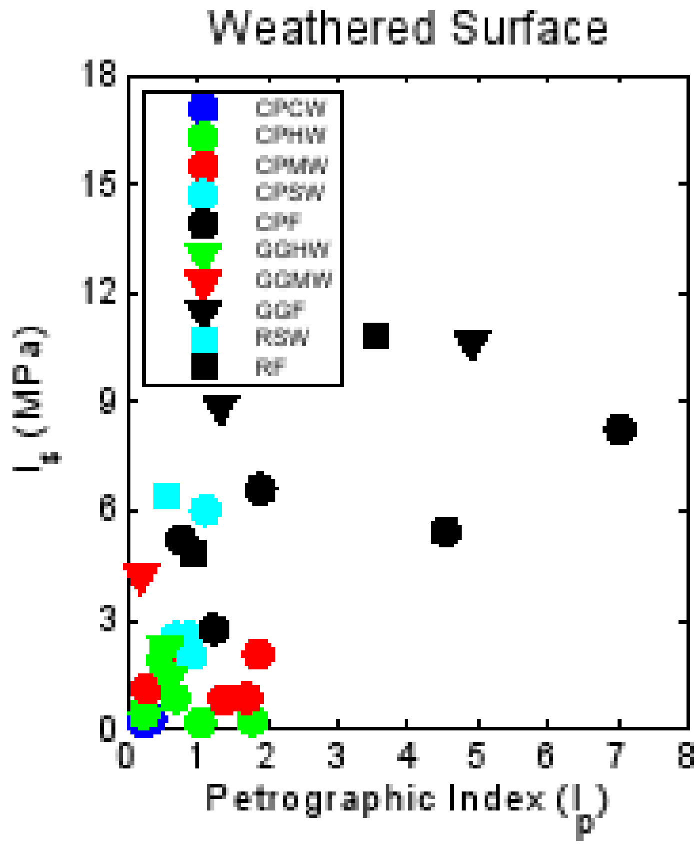


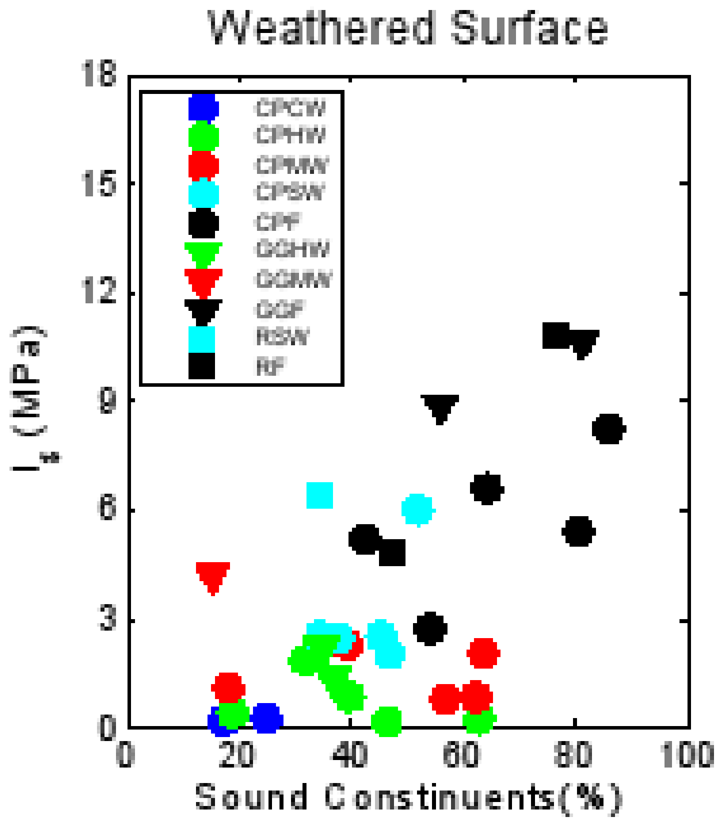
Weathering Grade and Mineral Indices



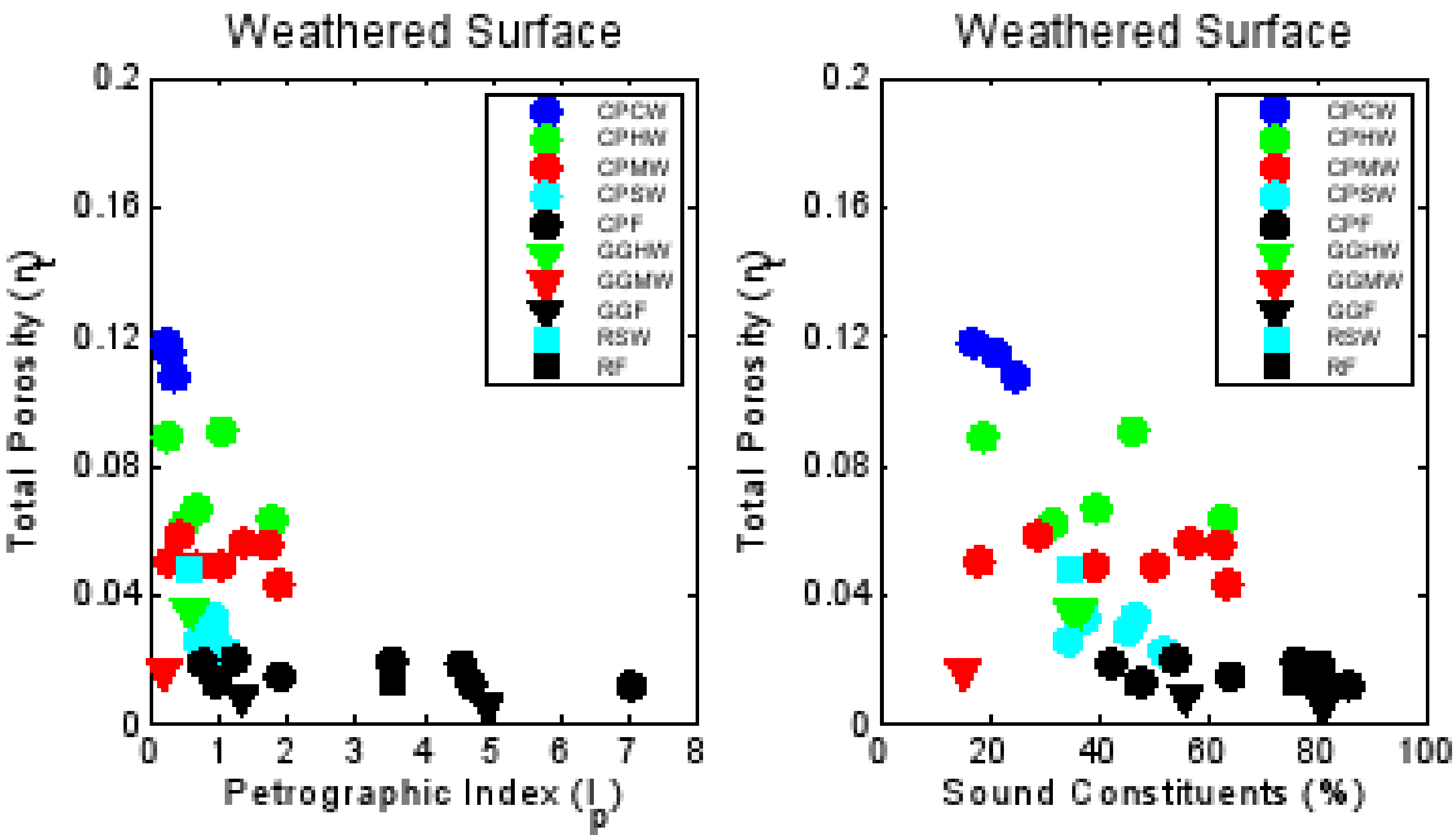

Weathered Surface
UCS (MPa)
Petrographic Index (I_p)
CPCW
CPHW
CPMW
CPSW
CPF
GGHW
GGMW
GGF
RSW
RF


Weathered Surface
UCS (MPa)
Sound Constituents (%)
CPCW
CPHW
CPMW
CPSW
CPF
GGHW
GGMW
GGF
RSW
RF


Weathered Surface
CPCW
CPHW
CPMW
CPSW
CPF
GGHW
GGMW
GGF
RSW
RF
Is (MPa)
Petrographic Index (Ip)

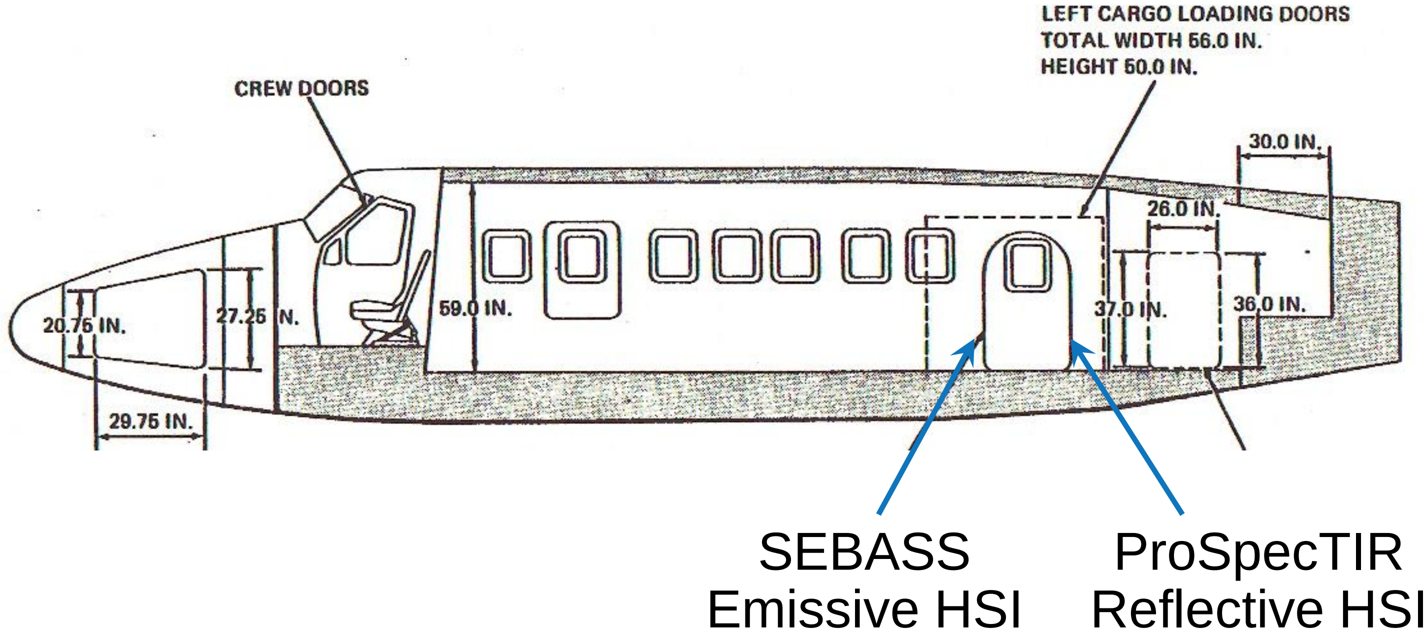

Weathered Surface
CPCW
CPHW
CPMW
CPSW
CPF
GGHW
GGMW
GGF
RSW
RF
Is (MPa)
Sound Constinuents(%)

Physical Properties



Full Spectrum Collection Capability

PECORA 18: Hyperspectral Thermal Infrared Remote Sensing



- Technology Demonstration between Aerospace and SpecTIR
- Full-spectrum collection capability on a single aircraft
- Sensors located together on mount looking through single camera hole in aircraft

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AEROSPACE