Characterization and Monitoring of Geothermal Resources Using Simulated HyspIRI Data

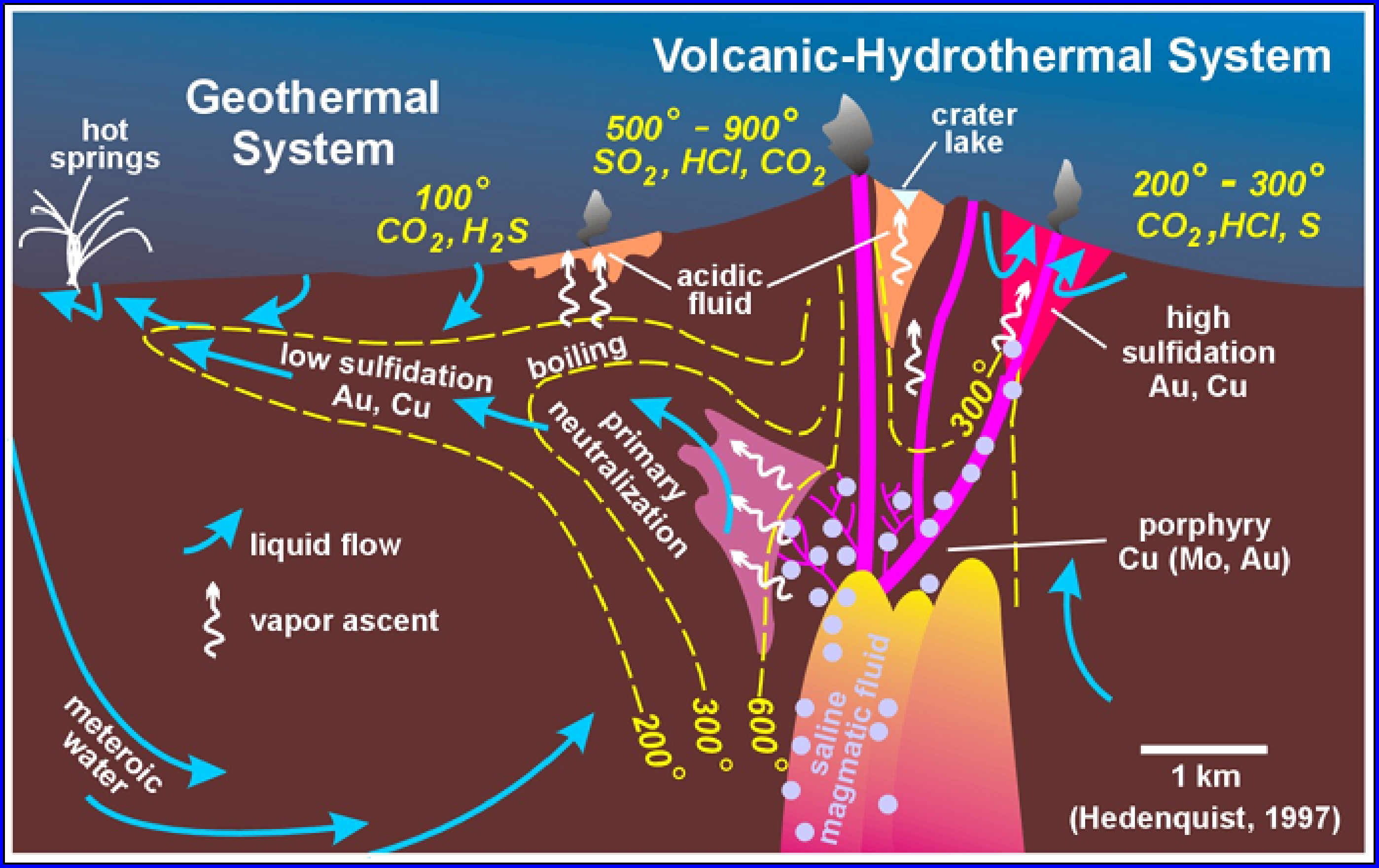
F. A. Kruse
Research Professor, Dept of Geological Sciences and Engineering
Arthur Brant Laboratory for Exploration Geophysics
University of Nevada, Reno

Overview

- Why Remote Sensing of Geothermal Systems?
- Simulation/Analysis Approach
- Selected Results
  - Cuprite, NV
  - Steamboat Springs, NV
  - Yellowstone, WY
  - Long Valley, CA
  - New Zealand Geothermal
- Prospects for HyspIRI

Why Remote Sensing of Geothermal Systems?

Surface mineral assemblages and distributions often provide key information about the origin and nature of active and fossil hydrothermal systems – these can be mapped using hyperspectral and multispectral VNIR/SWIR and LWIR approaches

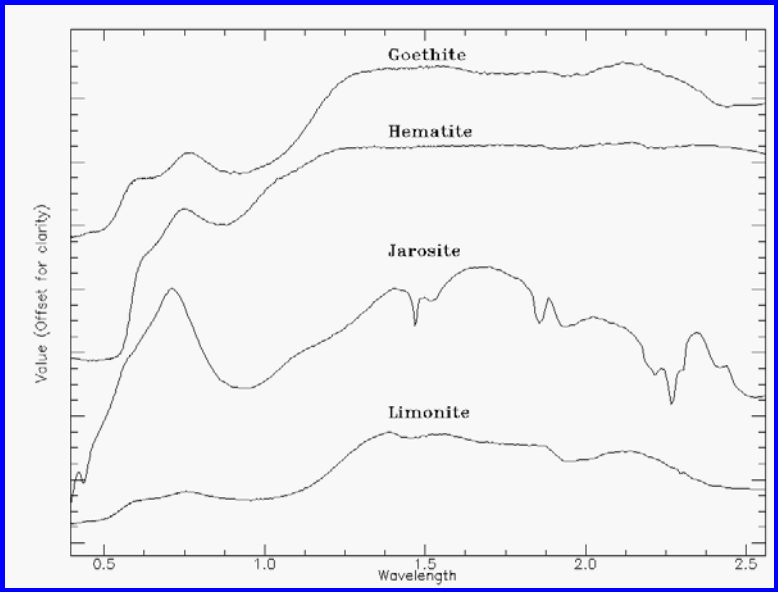


Why Remote Sensing of Geothermal Systems?

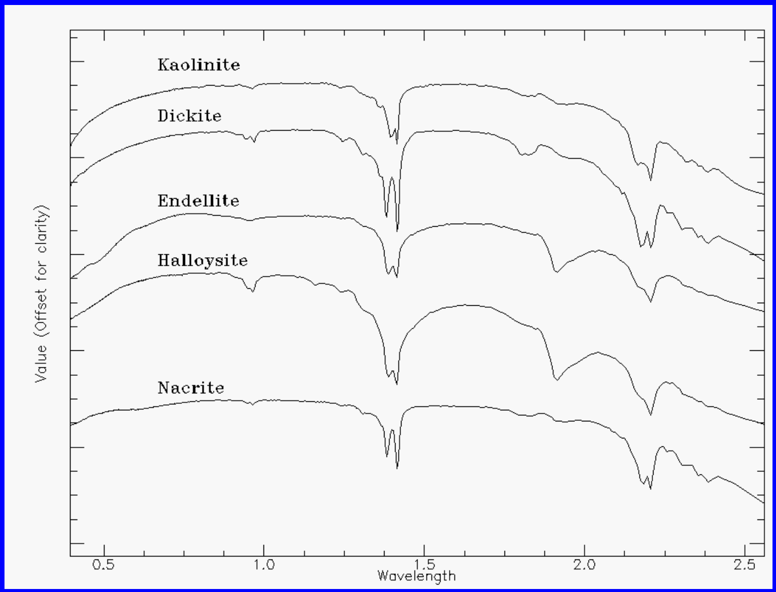
- **Mineralogy, particularly hydrothermal alteration, is however, notoriously difficult to map. Spectroscopy provides rigorous tool for mineral identification.**

Why Remote Sensing of Geothermal Systems?

– **VNIR/SWIR spectrometry has clearly demonstrated its capability to identify minerals based on molecular physics**



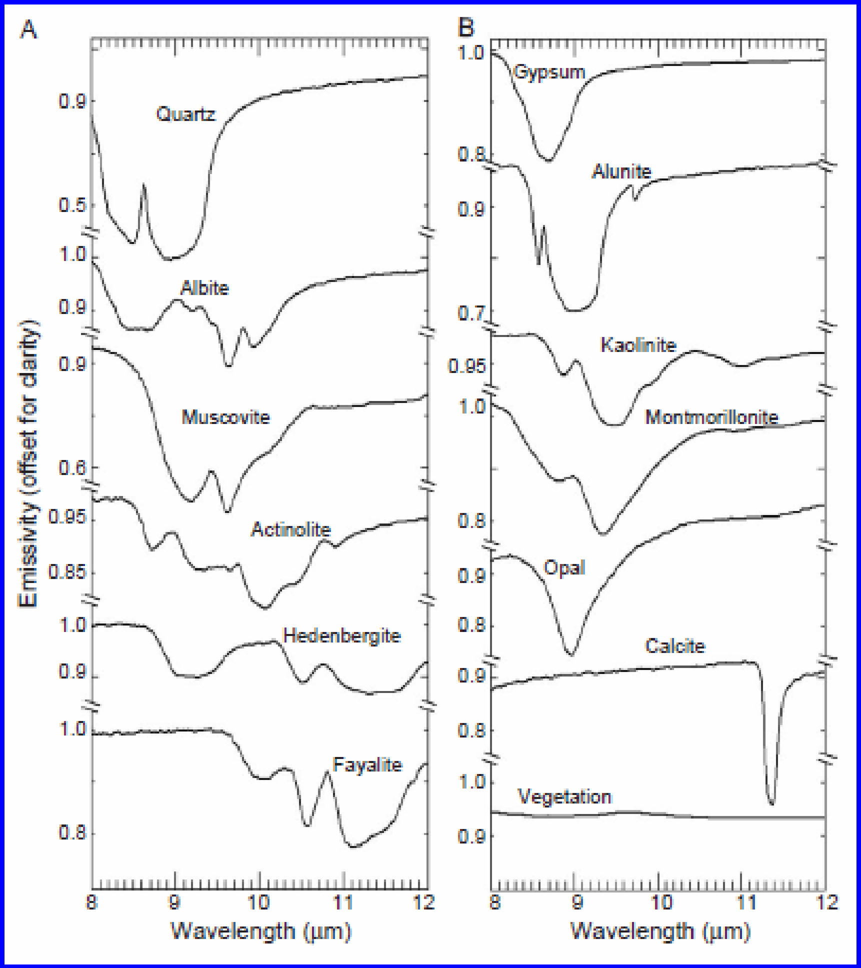
Electronic Processes (VNIR)
(Charge Transfers, Color Centers, Crystal Field Absorptions)



Vibrational Processes (SWIR)
(Overtones, Combination Tones)

Why Remote Sensing of Geothermal Systems?

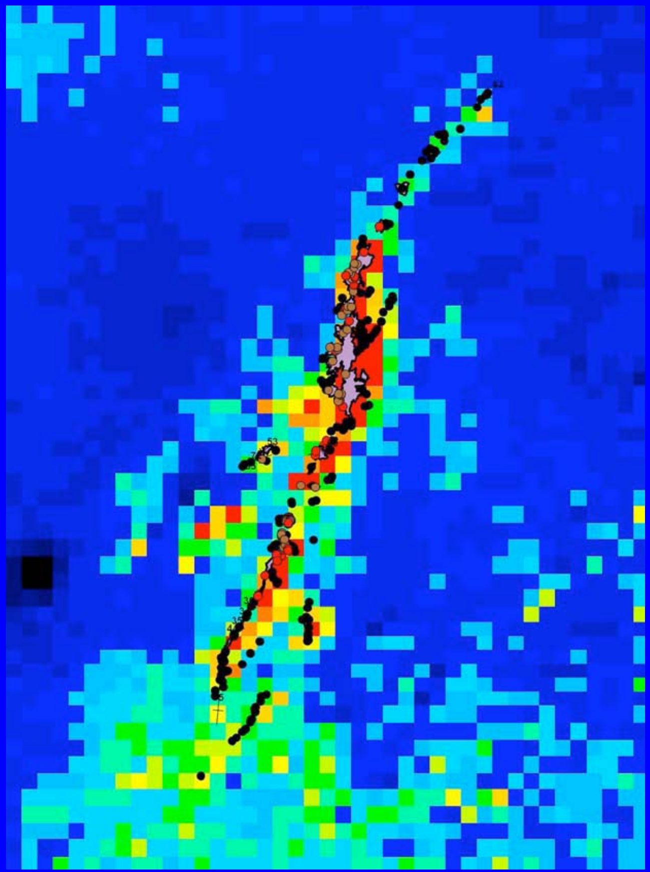
– **LWIR spectrometry has unique capabilities based on fundamental molecular vibrations**



From Vaughan et al., 2005

Surface Temperature Mapping at Geothermal Systems

- **LWIR Multispectral data provide the additional capability to estimate surface temperature**
- **Will improve understanding of known systems by detecting/mapping**
  - **Distribution of heat anomalies and links to subsurface**
  - **Structural control**
  - **Outflow areas**
- **Provide new exploration tools**
  - **Temperature anomalies and magnitudes**
  - **"Blind" Systems**
- **Develop Methods for Monitoring**
  - **System characteristics and Natural variability**
  - **Exploitation Changes**



Coolbaugh, 2007 – Temperature Anomalies at Brady Hot Springs Using ASTER. Small black and brown points indicate field located steam vents or surface hot spots.

HyspIRI Research Approach

- **Build on previous experience with epithermal mineral deposits, geothermal systems, and remote sensing data to try to improve understanding of active and fossil geothermal systems**
  - **Determination of mineral assemblages (not just the predominant mineral)**
  - **Detect and map detailed within-species variability (eg: muscovites, chalcedony vs opal, etc.)**
  - **Map additional rocks and minerals with LWIR**
  - **Use temperature mapping to quantify surface indicators of active geothermal systems**
  - **Development of comprehensive system models**

Geothermal Systems - Some Science Questions

- **How are surface mineral assemblages of hydrothermal systems tied to underlying geologic constraints (lithology, alteration, water chemistry, temperature regimes)? (VQ6, TQ5a, CQ5)**
- **What can surface mineralogy tell us about the morphology and evolution of hydrothermal systems and the link between active geothermal systems and ore deposits? (VQ6, TQ5a)**
- **What surface changes are taking place at active geothermal systems as the result of human activities such as recreation, geothermal energy exploration and drilling, and energy production? (TQ5b, CQ5)**
- **What is the magnitude of surface temperatures at active hot springs and geothermal areas? How do temperatures vary naturally? What can surface temperatures tell us about the morphology and evolution of these systems and temperature at-depth? How does surface temperature respond to geothermal production? (TQ5c)**

Geothermal Systems - Some HyspIRI Questions

- **What is the effect of the proposed HyspIRI spatial and spectral resolution, and SNR or NEΔT on detection, identification, and characterization of key rocks, minerals, vegetation, and other materials associated with active and fossil geothermal systems**
- **What is the spatial scale of temperature features that can be detected at the proposed HyspIRI 60m spatial resolution?**
- **What is the temperature contrast required for detection and characterization of geothermal systems at various scales?**
- **How does spatial mixing affect measurement of temperatures at geothermal systems. What is the magnitude and nature of these mixing effects?**

Simulation/Analysis Approach

- Use existing HSI data (AVIRIS, Hyperion, HyMap, SpecTIR) to simulate the VNIR/SWIR component of HyspIRI (214 spectral bands 0.38 – 2.52 micrometers with approximately 10nm spectral resolution and 60 m spatial resolution)
  - Atmospheric Correction
  - Spectral Resampling
  - Spatial Resampling
  - SNR Modeling
  - Spectral mapping using Reflectance Spectra

Simulation/Analysis Approach

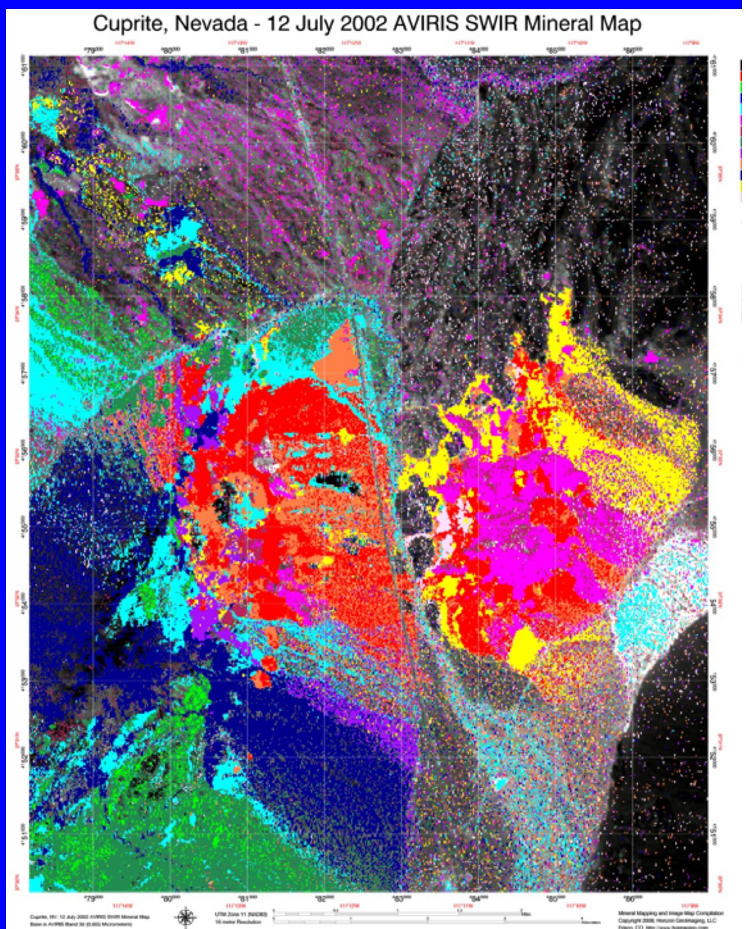
- Use existing LWIR data (TIMS, MASTER, MAS, ASTER, SEBASS) to simulate the LWIR component of HyspIRI (7 spectral bands from 7.3-12.0 micrometers.
  - Atmospheric Correction
  - Spatial and Spectral Resampling
  - Temperature-Emissivity Separation
  - Spectral Mapping using Emissivity Spectra
  - Additional temperature corrections (albedo, topo)
  - Temperature mapping and characterization
- Integrate of VNIR/SWIR/LWIR results (and ancillary information) and Combined Signature Analysis

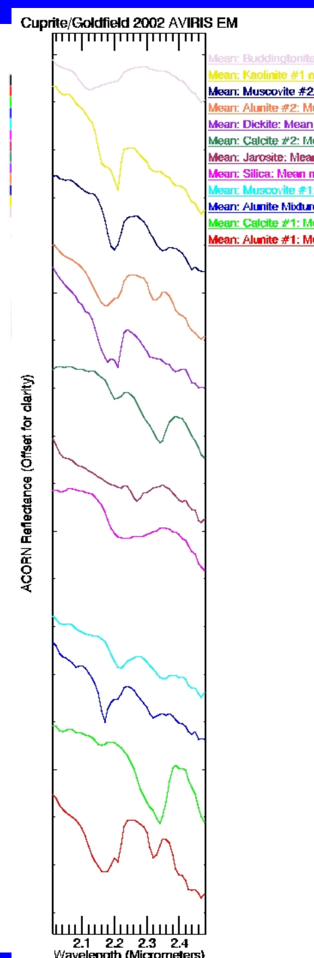
Results: Cuprite, Nevada Mining District (AVIRIS) and MASTER

- Located about 60km south of Tonopah, NV
- "Standard" South-central Nevada Geologic Test Site for Remote Sensing
- Two hydrothermal systems across US95
- 2002 AVIRIS (16m)
- 1999 MASTER (17.4m)

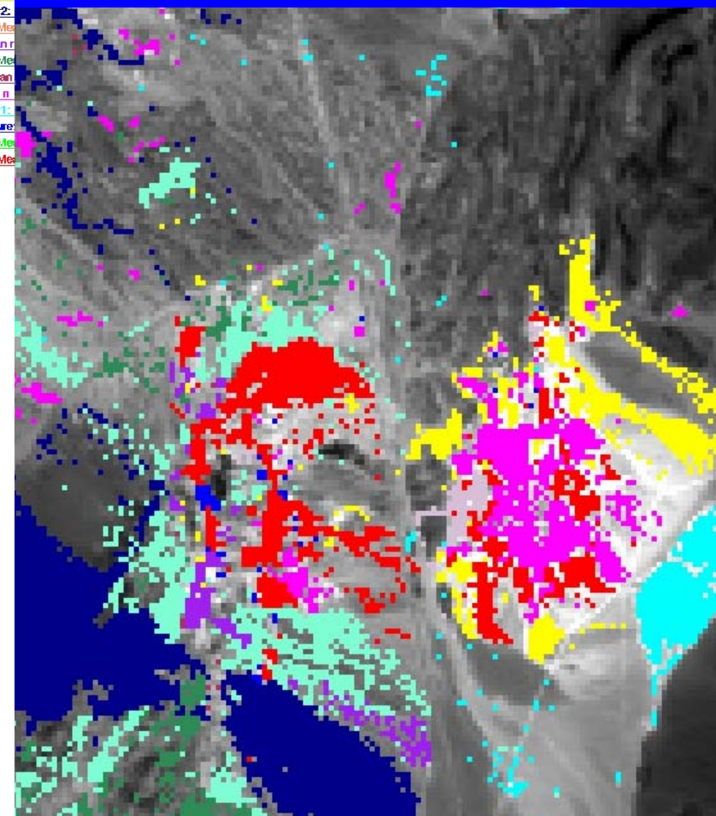
Cuprite, NV 2002 AVIRIS versus HyspIRI-Simulated 60m SWIR MTMF Mineral Map (Kruse, Unpublished)

AVIRIS (16m)





Simulated HyspIRI



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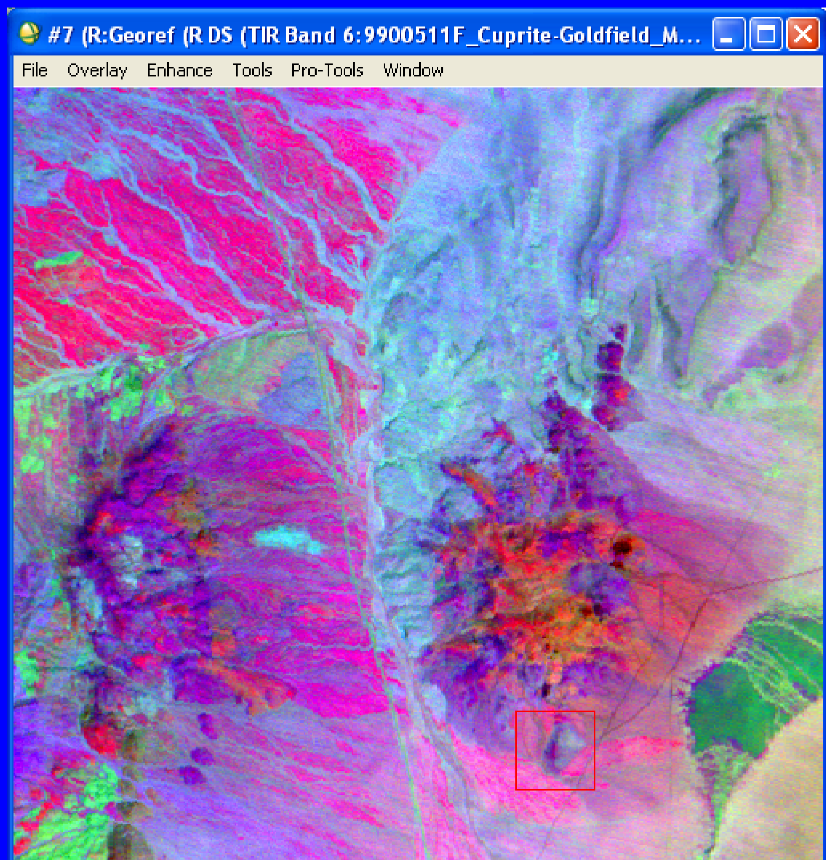
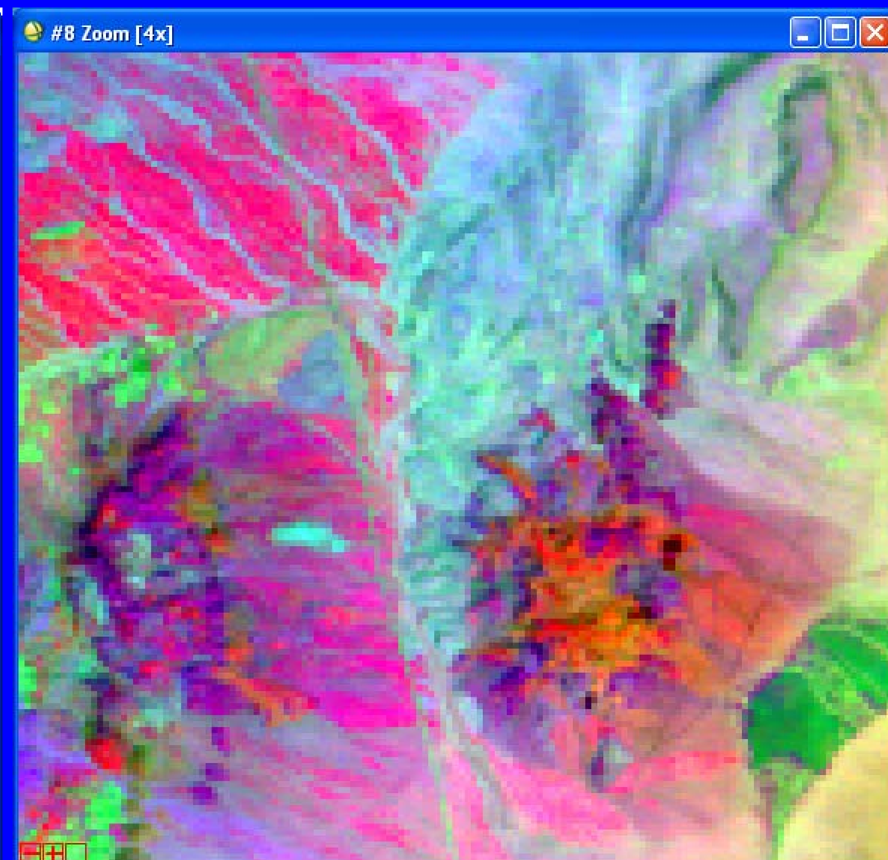
Cuprite, NV 1999 MASTER 6, 5, 3 (RGB)
Decorellation Stretch versus HyspIRI-Simulated 60m





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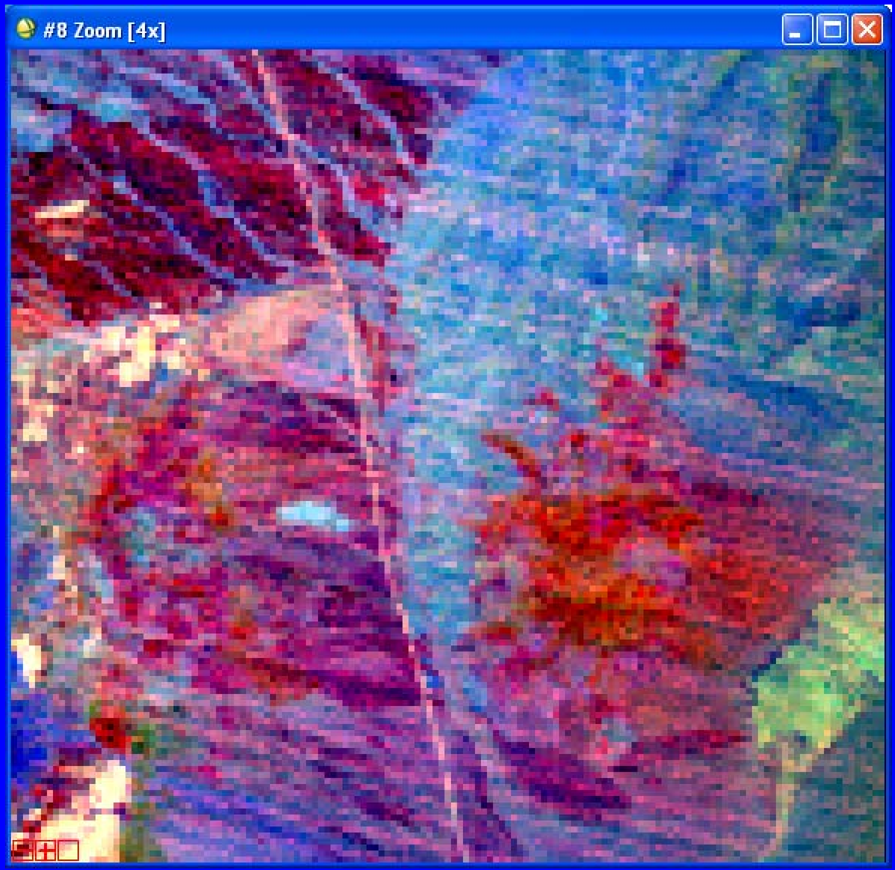
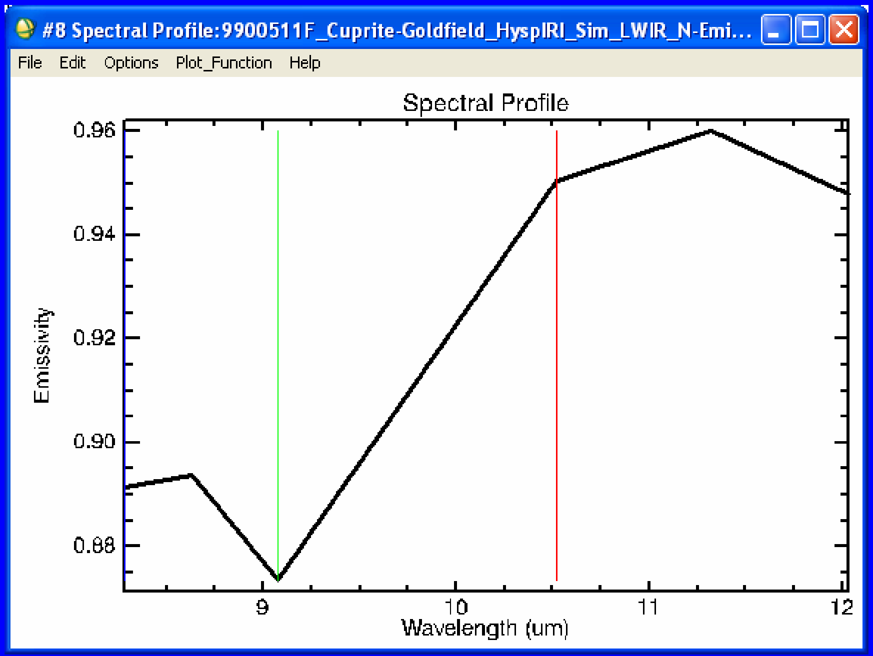
Cuprite, NV HyspIRI-Simulated 60m emissivity from 1999 MASTER





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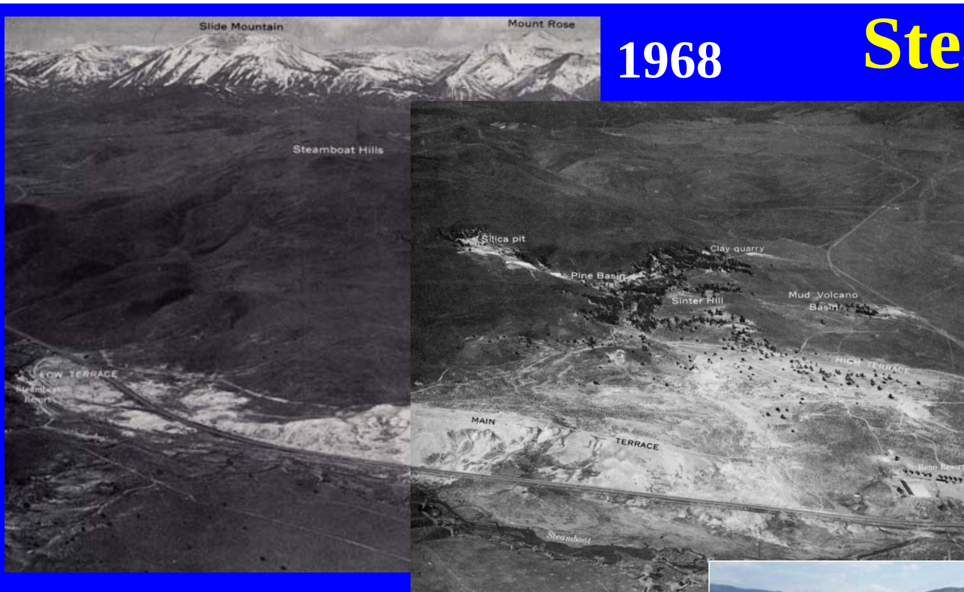
Steamboat Springs, NV



1968

- The principal surface mineralogy at Steamboat consists of porous opaline sinter deposits on young terraces and chalcedonic sinter on older terraces

Main Terrace - 1987

Main Terrace - 1999

Steamboat Springs, NV – Summary

- **VNIR/SWIR and LWIR high-spatial resolution systems well established for mapping key materials associated with geothermal system**
- **Some mapping of temperature anomalies using multi-band LWIR demonstrated**
- **Datasets Include**
  - **AVIRIS – 1995 (16m), 1998 (1.5m)**
  - **Hyperion – 2002 (30m)**
  - **HyMap – 1998 (2.2m), 1999 (3m)**
  - **TIMS – 1996 (10m), Day-Night**
  - **MASTER – 1999 (4.1m), 2006 (3.5m, night)**
  - **SEBASS – 1999 (2m)**
  - **ASTER – 2007 (15, 30, 90m)**

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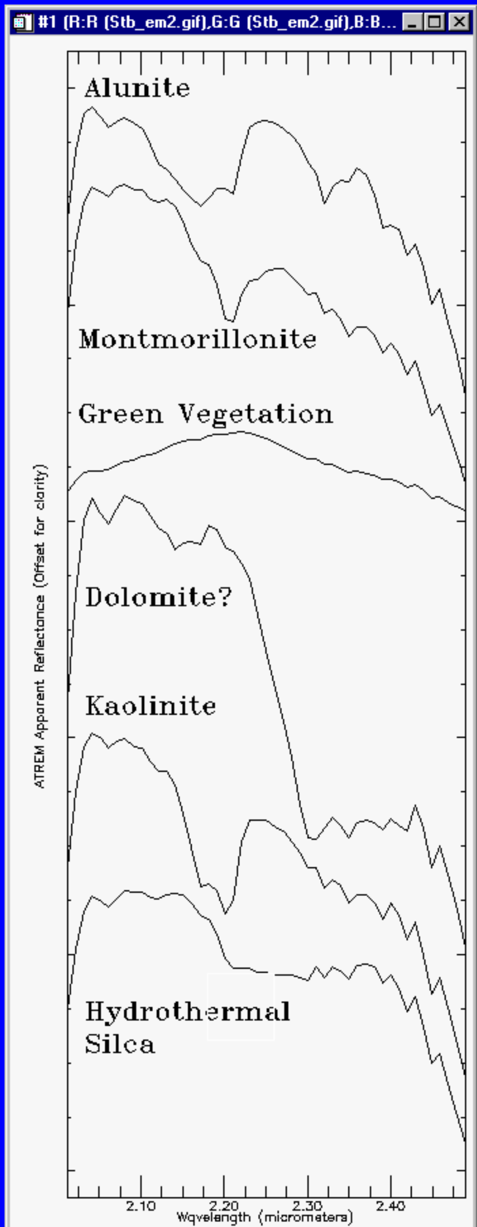
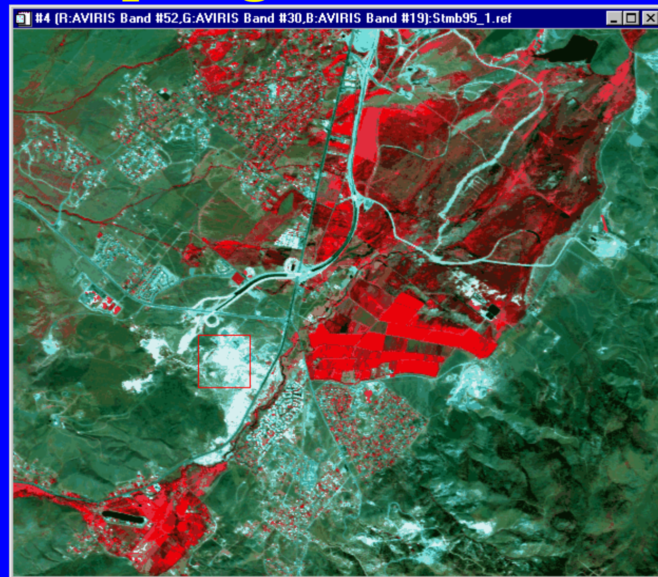
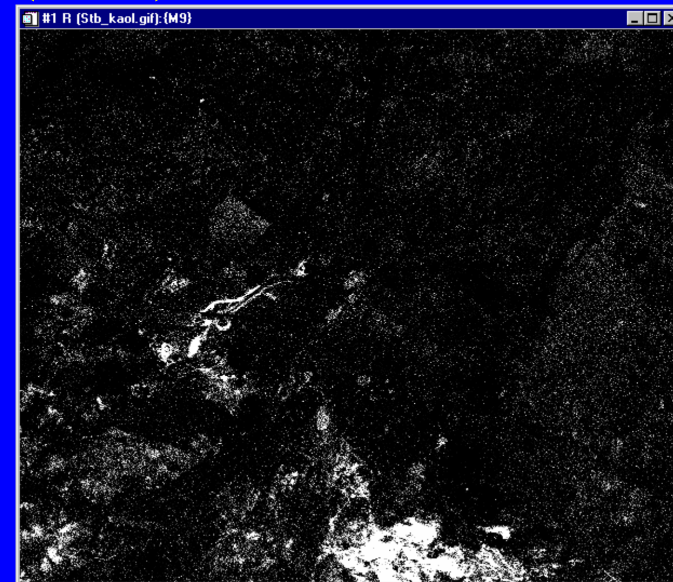
Steamboat Springs 1995 AVIRIS (16m) Results

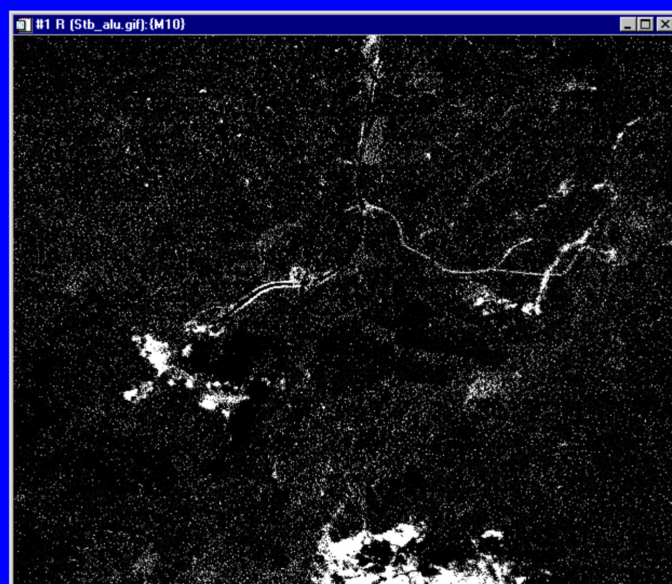




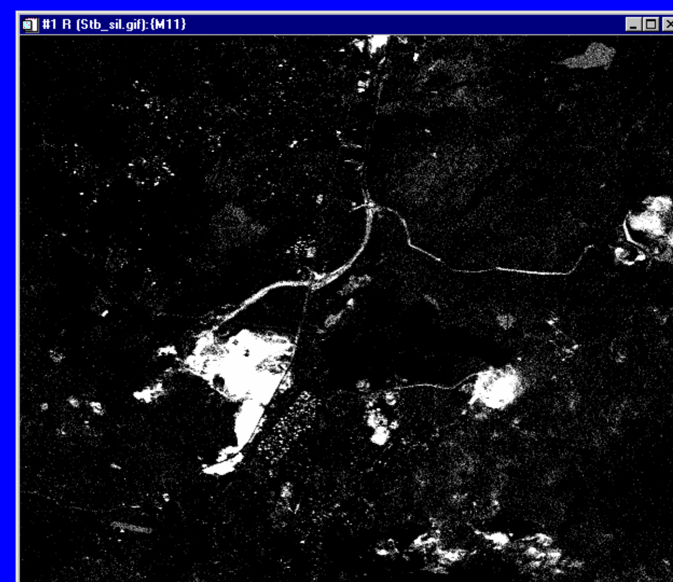
Kaolinite



Alunite



Silica



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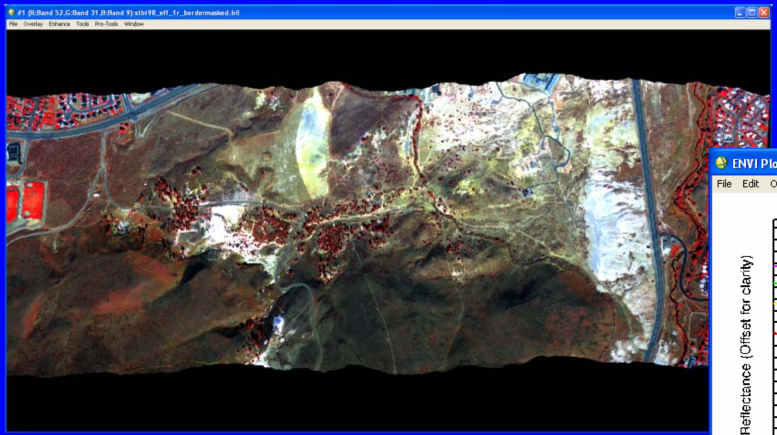
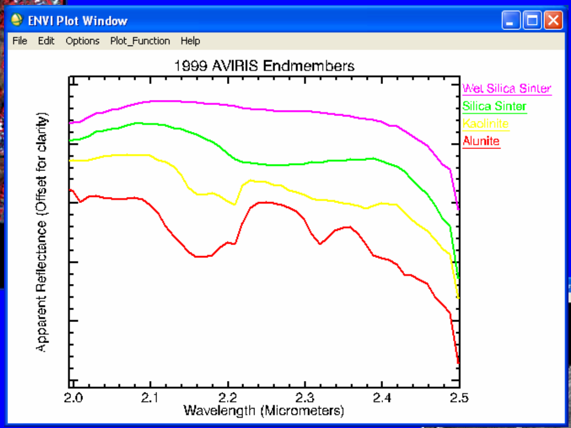
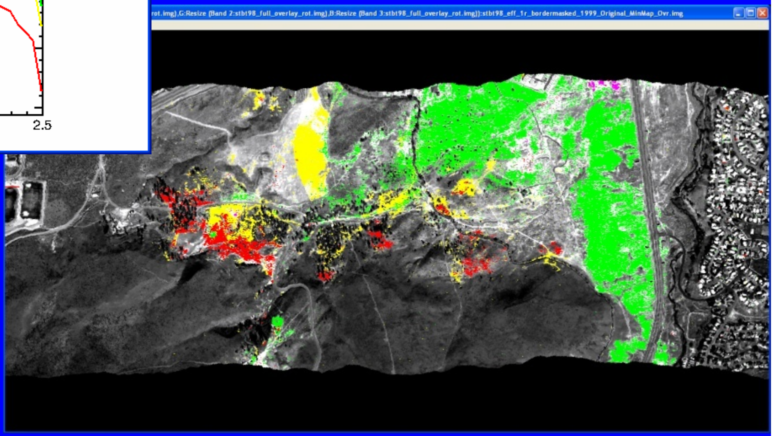
Steamboat, NV, 1998 (1.5m) AVIRIS

- **Generalized Mineral Mapping using AVIRIS**







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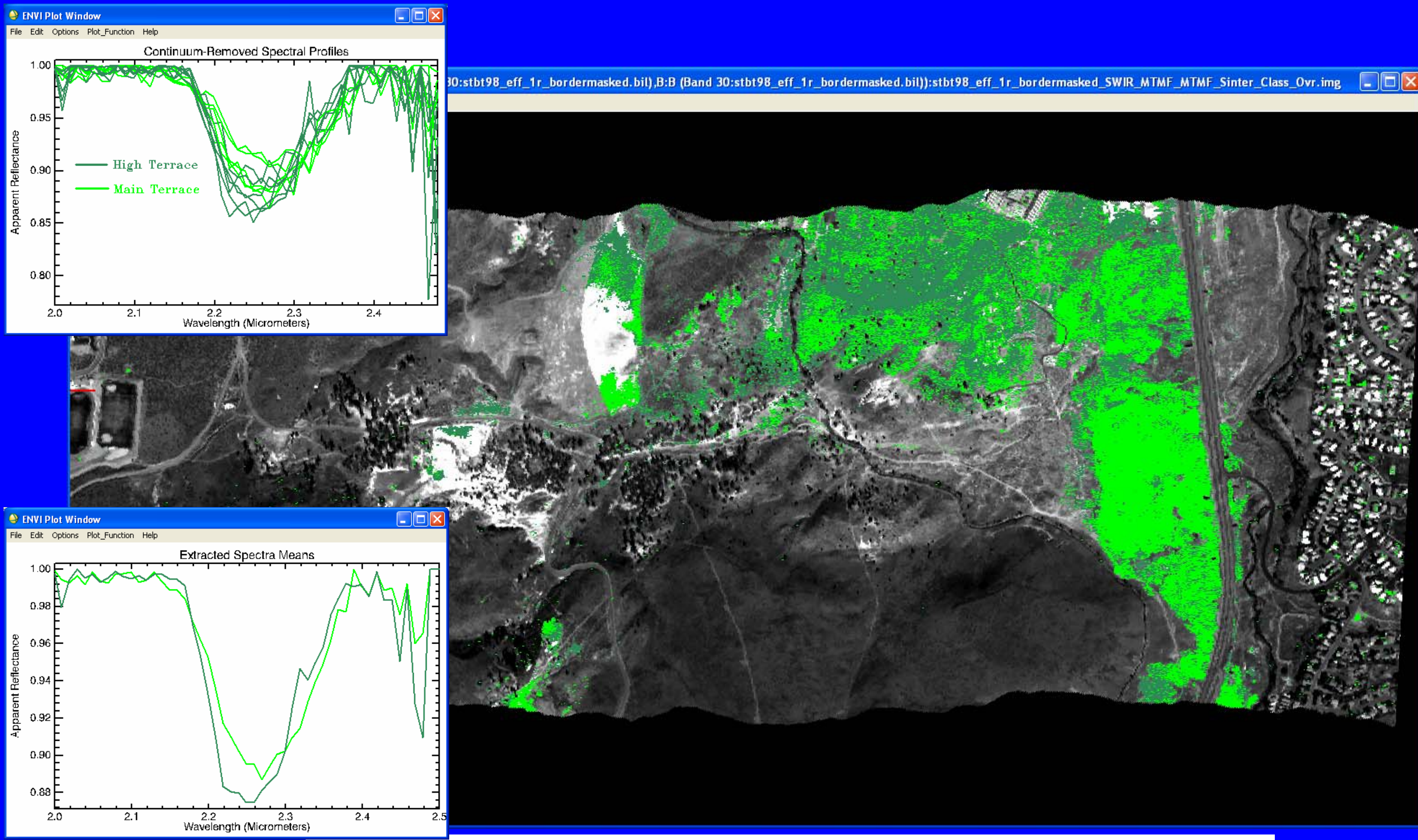
Steamboat, NV – Sinter Variability



Source	Feature	Position	Depth	FWHM	Asym
Main	1-1	2.26860	0.11250	0.13860	0.01415
High	1-1	2.25870	0.12487	0.11728	0.00710

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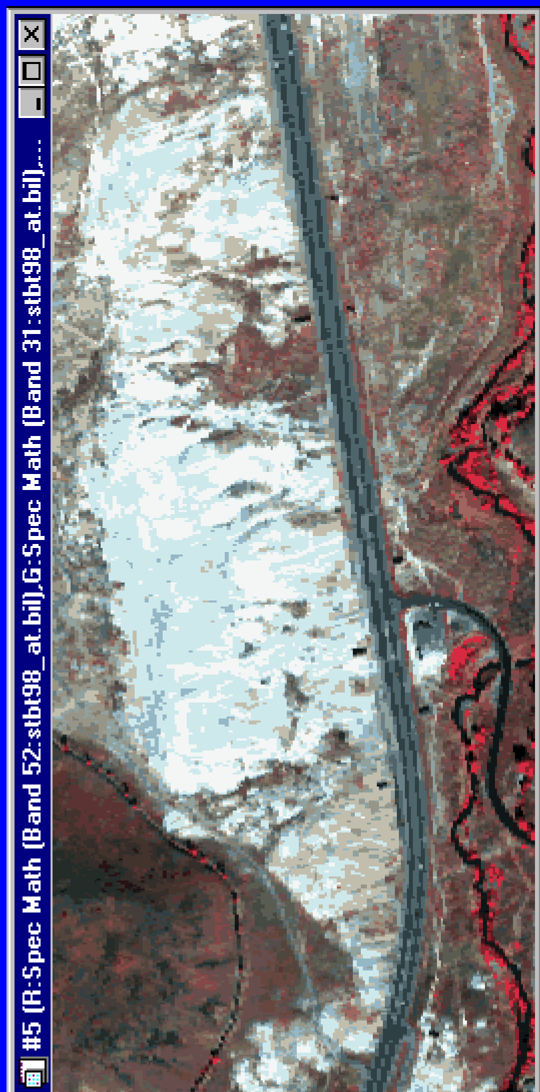
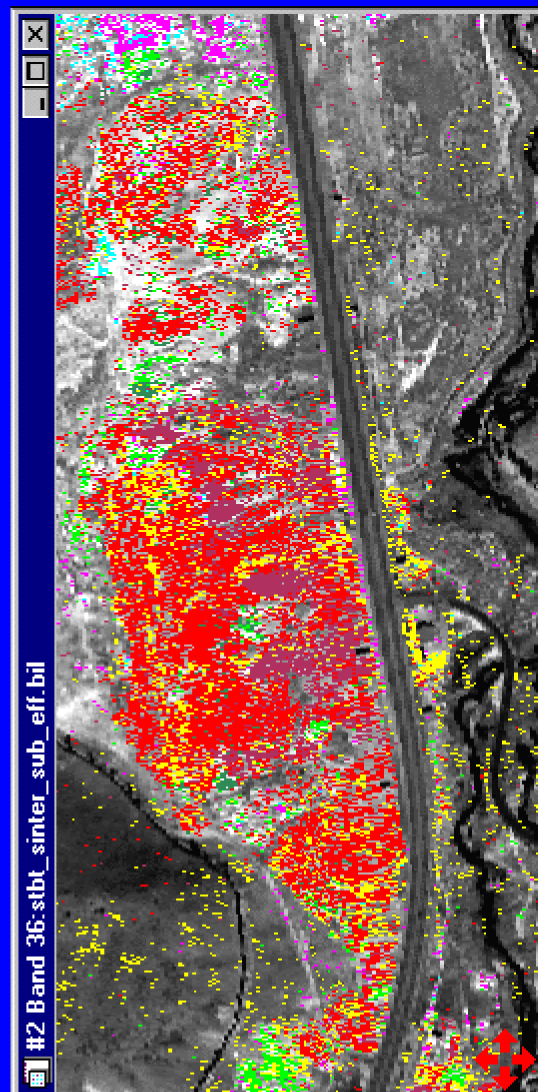
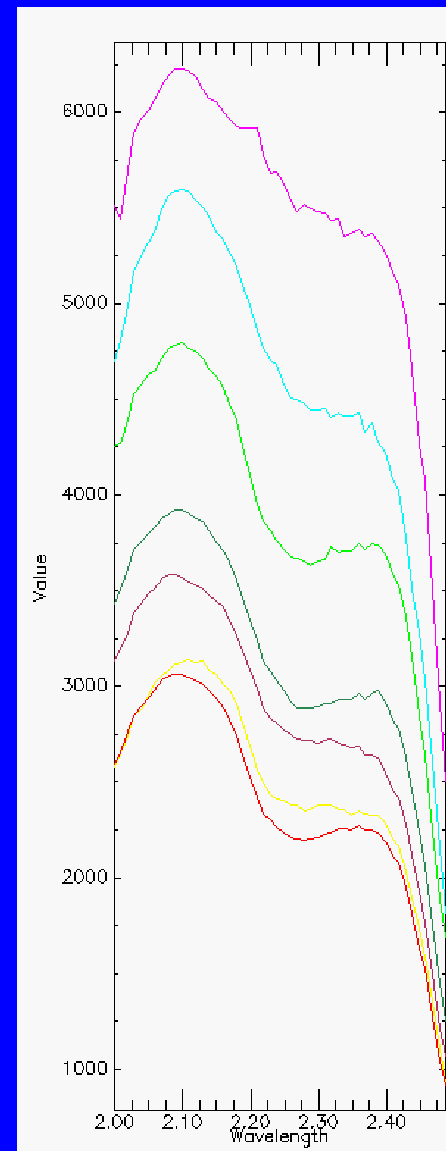
Steamboat Sinter 1998 AVIRIS MTMF Results







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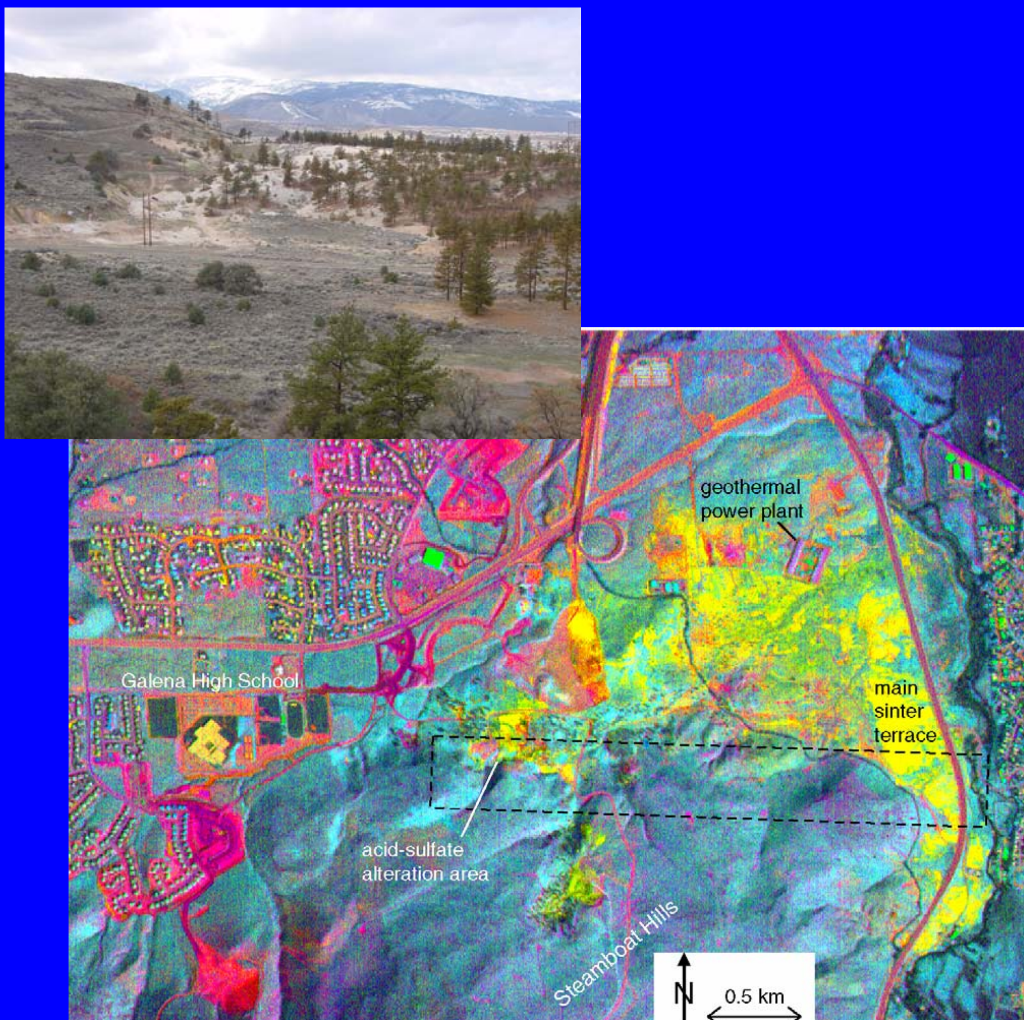
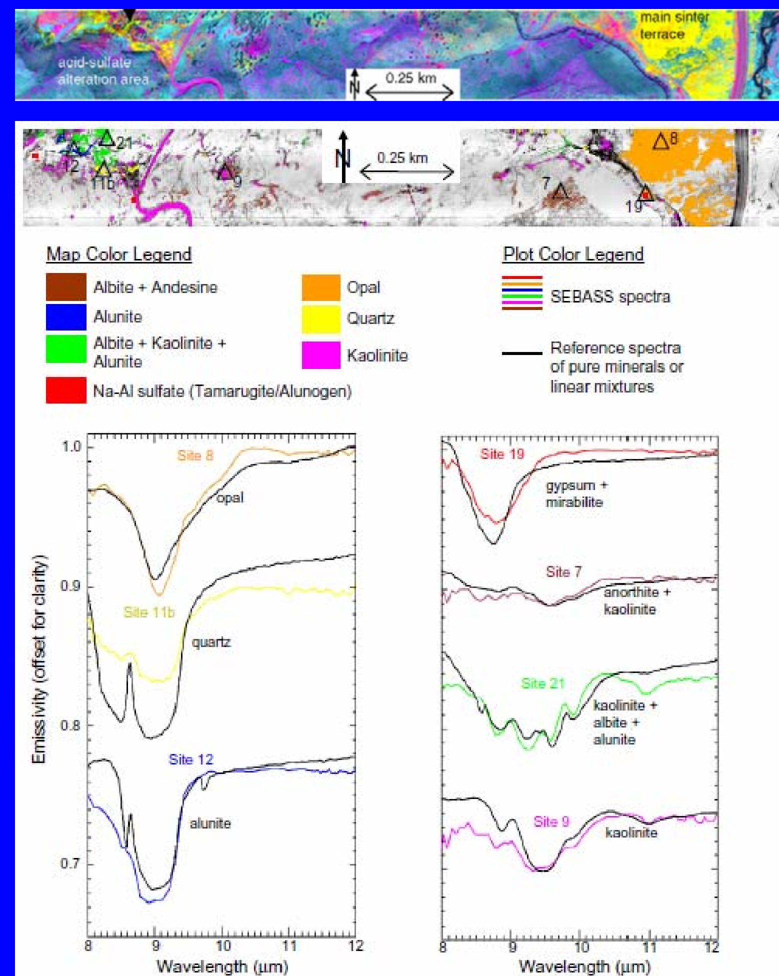
MASTER/SEBASS LWIR Classification, Steamboat Springs



MASTER Decorrelation

SEBASS Decorrelation



Vaughan et al., 2003, 2005

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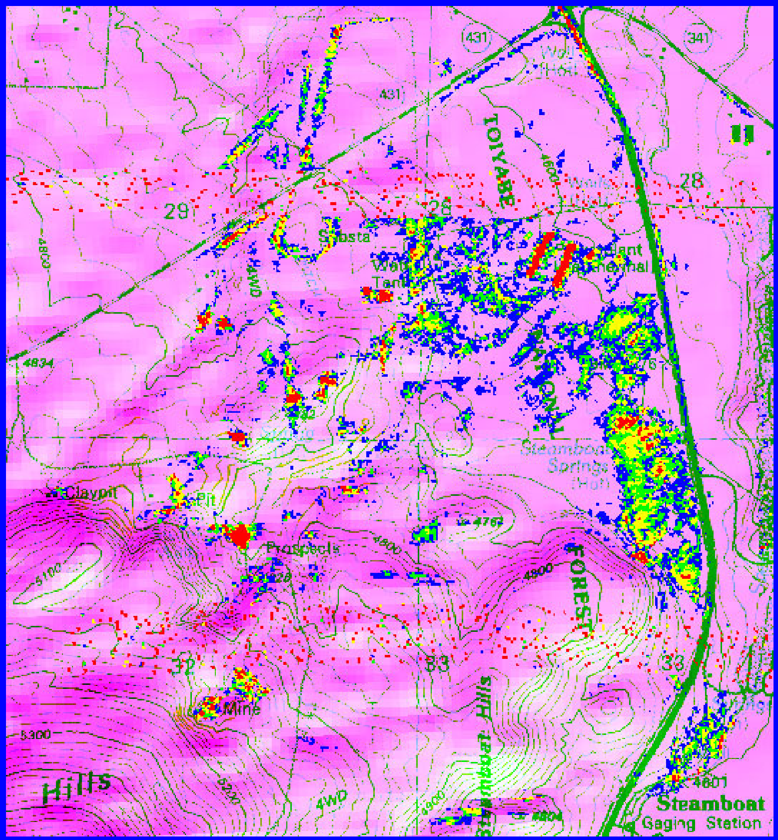
Temperature Mapping Example

- **TIMS Temperature mapping**
  - **Pre-dawn acquisition**
  - **Processed to compensate for the cooling effects of high albedo and low thermal inertia,**



Coolbaugh et al., 2000 – Temperature Anomalies at Steamboat Springs

Active Geothermal Systems: Yellowstone, Wyoming

- Yellowstone National Park covers nearly 3500 square miles in the northwest corner of Wyoming and contains the largest concentration of geothermal features in the world
- Yellowstone has been the site of extensive volcanism throughout the Cenozoic , with the geyser basins underlain entirely by Quaternary-age (young) rhyolitic rocks
- Regional fault systems and the Yellowstone Caldera control the distribution of thermal features
- The park contains around 100 hot springs groups, totaling over 10,000 individual thermal features
- Numerous examples of a variety of hot springs types, all as part of one large geothermal system
  - Alkaline-type: Upper, Midway, and Lower Geyser Basins
  - Travertine-type: Mammoth Hot Springs
  - Acidic type: Mud Volcano area (Hayden Valley)
  - Mixed types: Norris Geyser Basin

Yellowstone Datasets for HyspIRI Simulation

- **AVIRIS, 1996 (16m)**
- **AVIRIS, 1998, 1999 (1.5m)**
- **MODIS Airborne Simulator (MAS), 50 bands (0.46 – 14.2 micrometers), 7 Aug 96, (33.4m)**
- **TIMS, 1997 (7m)**
- **ASTER, 2001 (15, 30, 90m)**
- **MASTER, 2006 (50m) (some clouds)**

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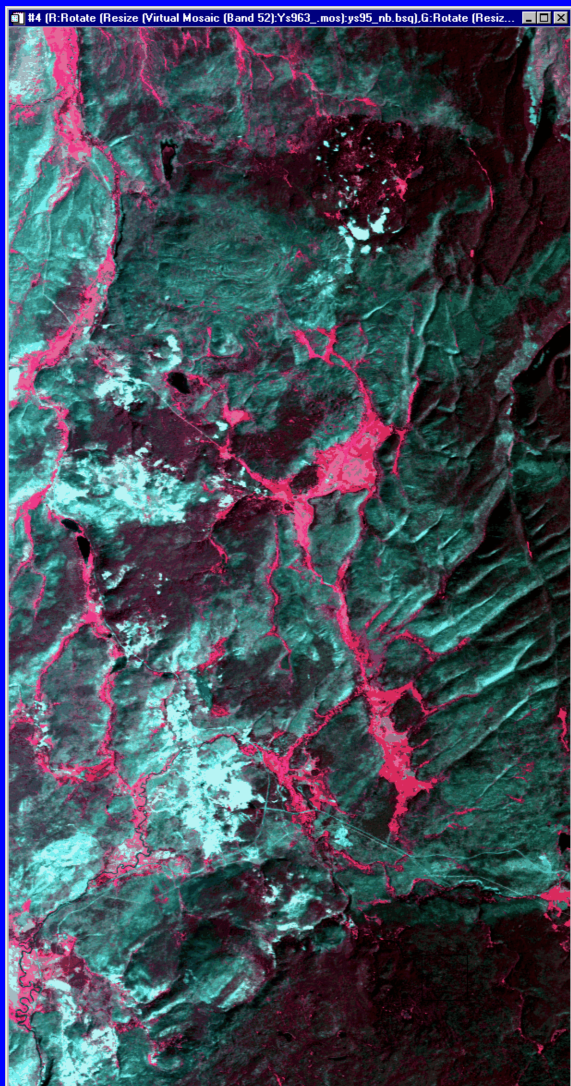
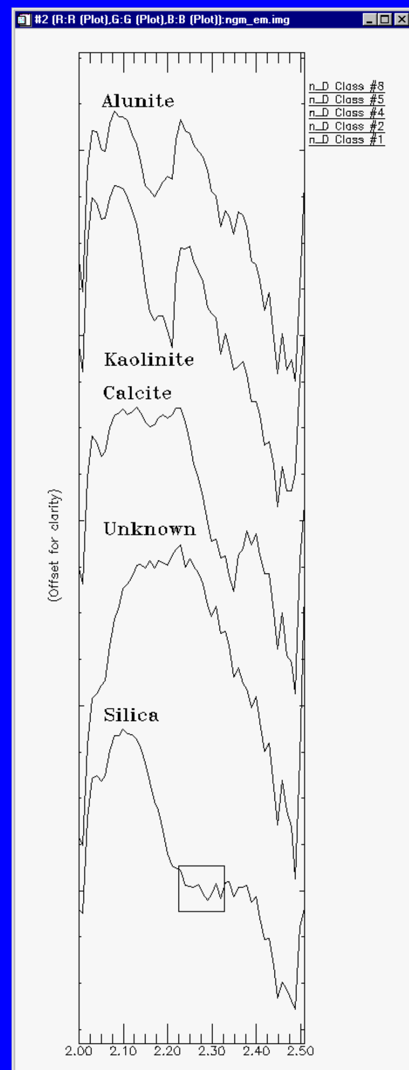
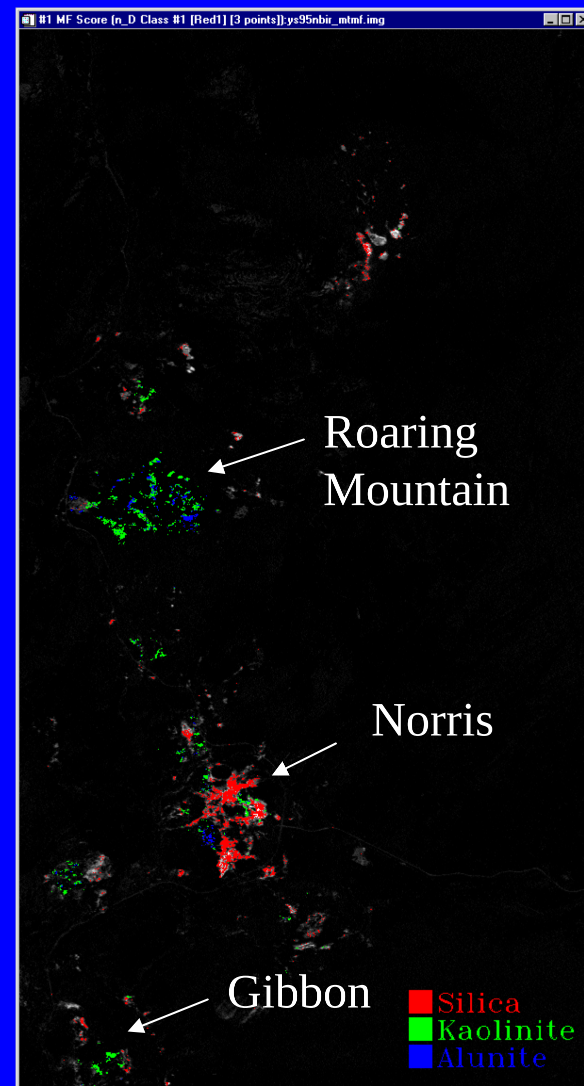
AVIRIS Results (16m) Norris/Gibbon Geyser Basins
Mixed Acid Sulfate/Alkaline



Color Infrared Composite



Endmembers



Spectral Feature Fitting Results

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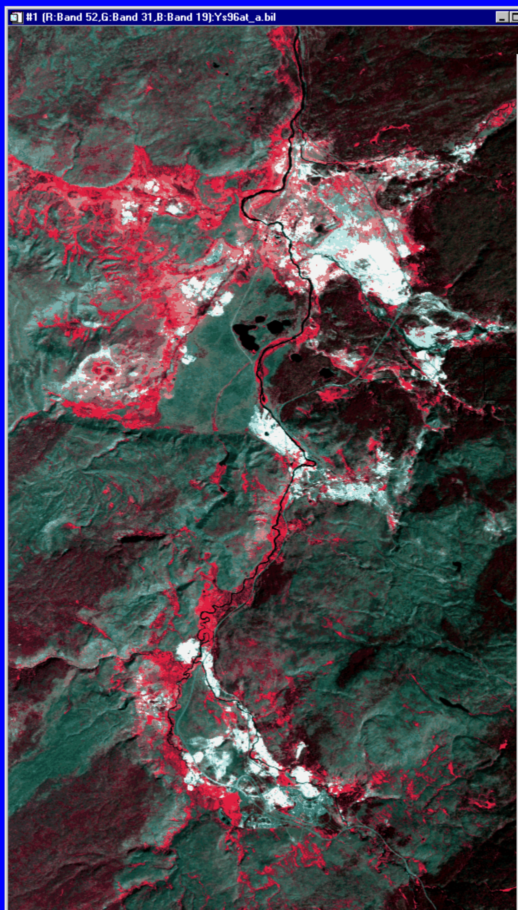
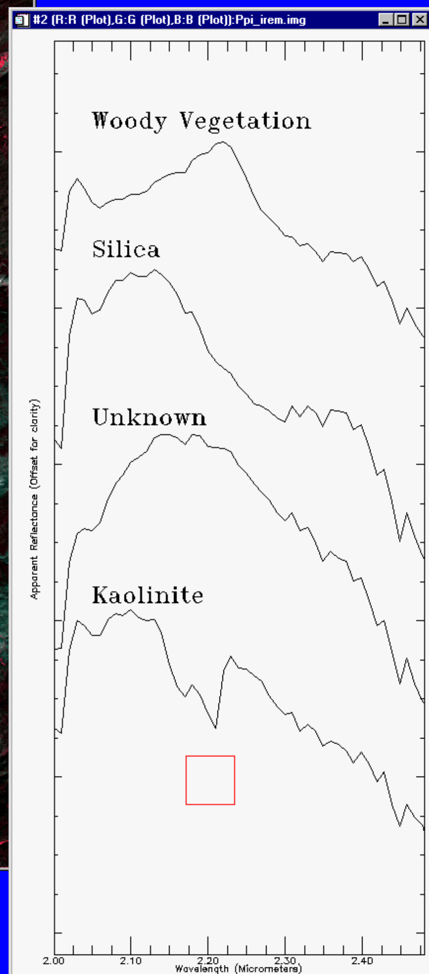
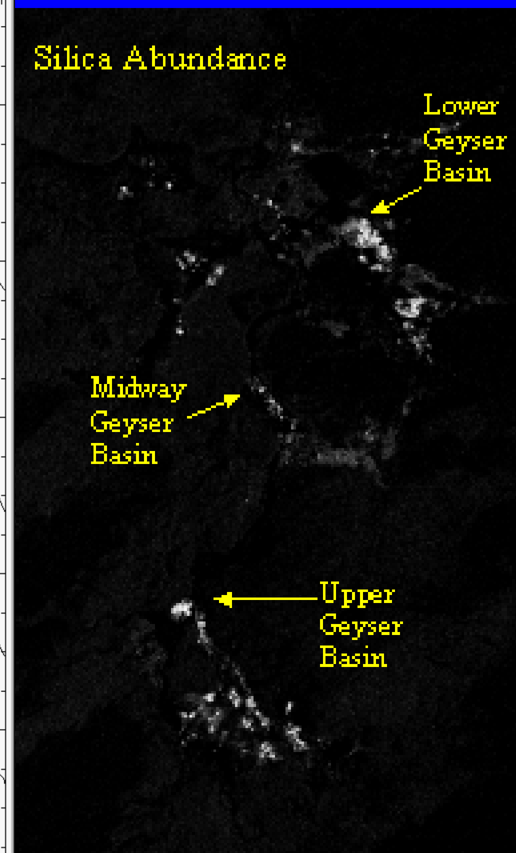
AVIRIS Results (16m) Firehole River Alkaline, with Acid Sulfate on margins



Color Infrared Composite



Endmember Spectra



Silica

Kaolinite

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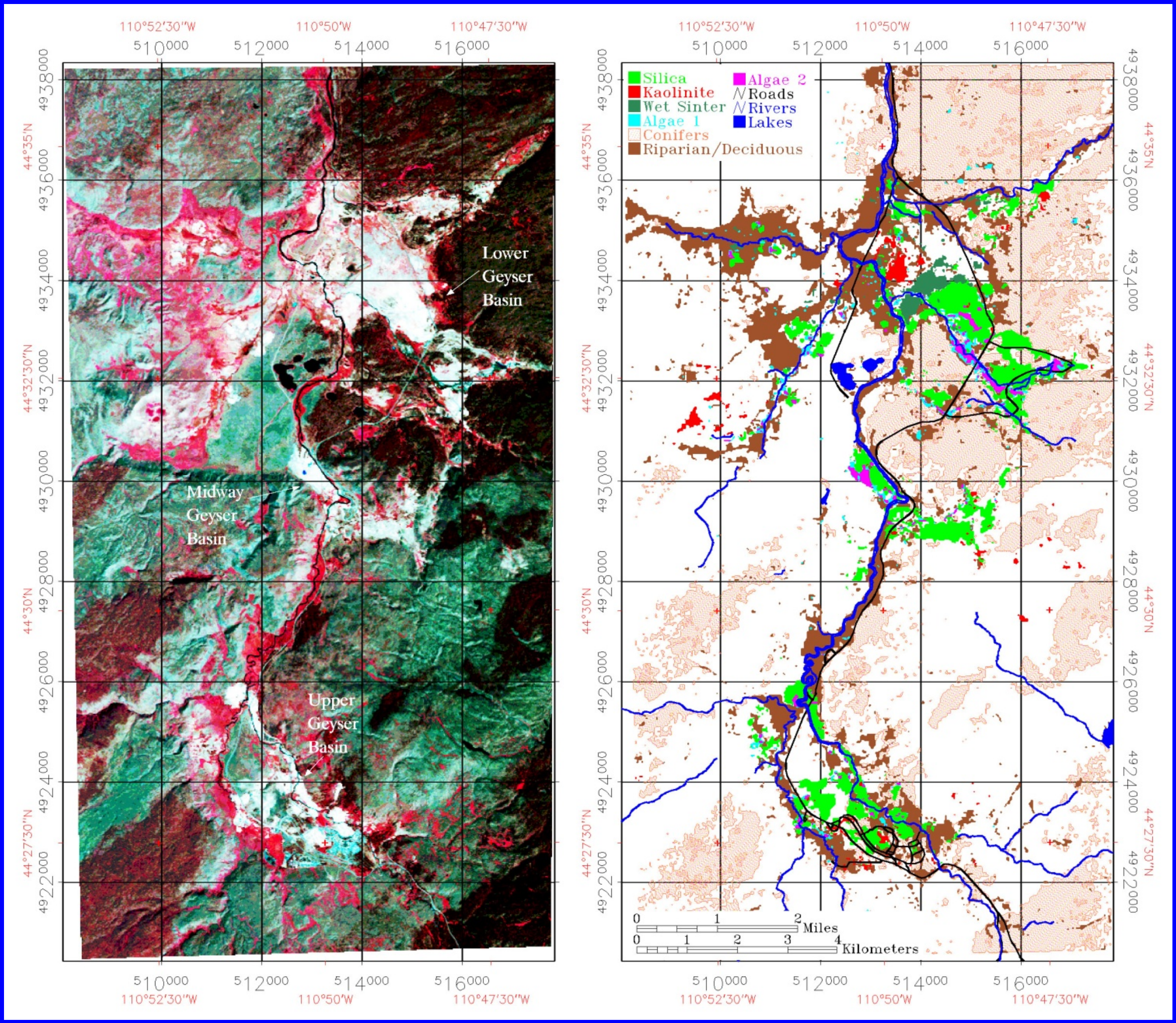
AVIRIS (16m) Firehole River Combined Results



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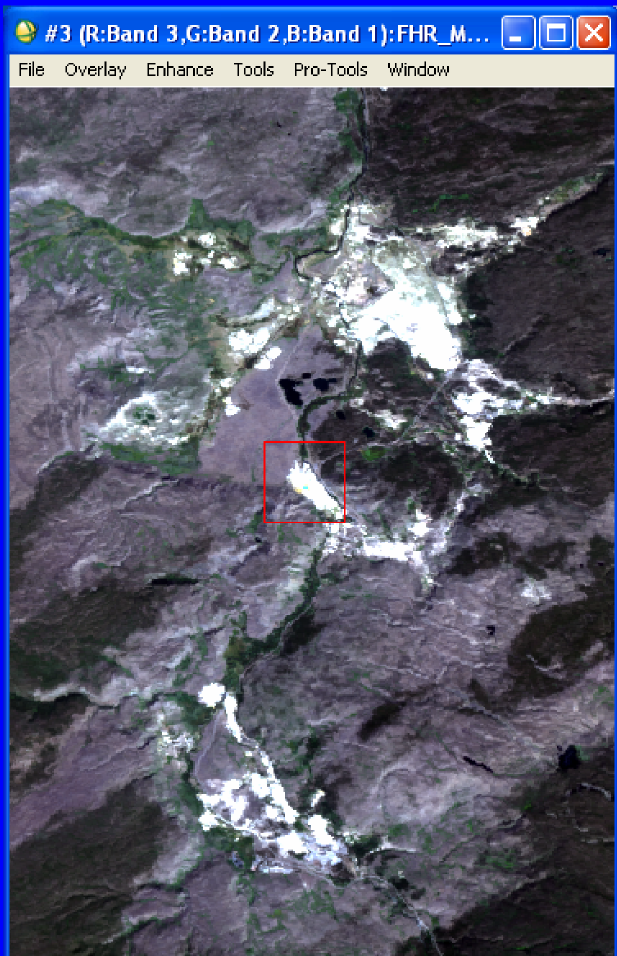
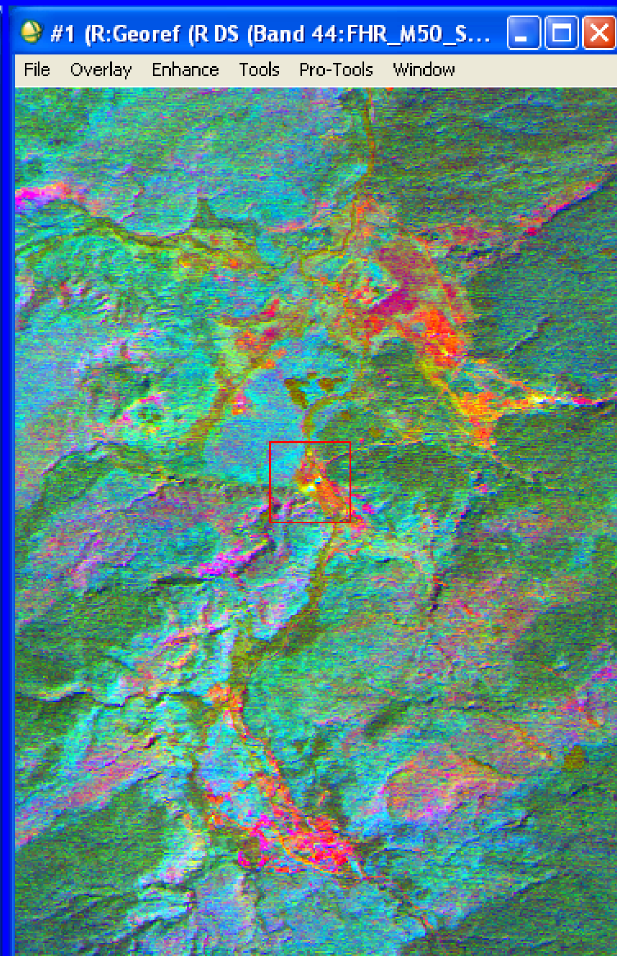
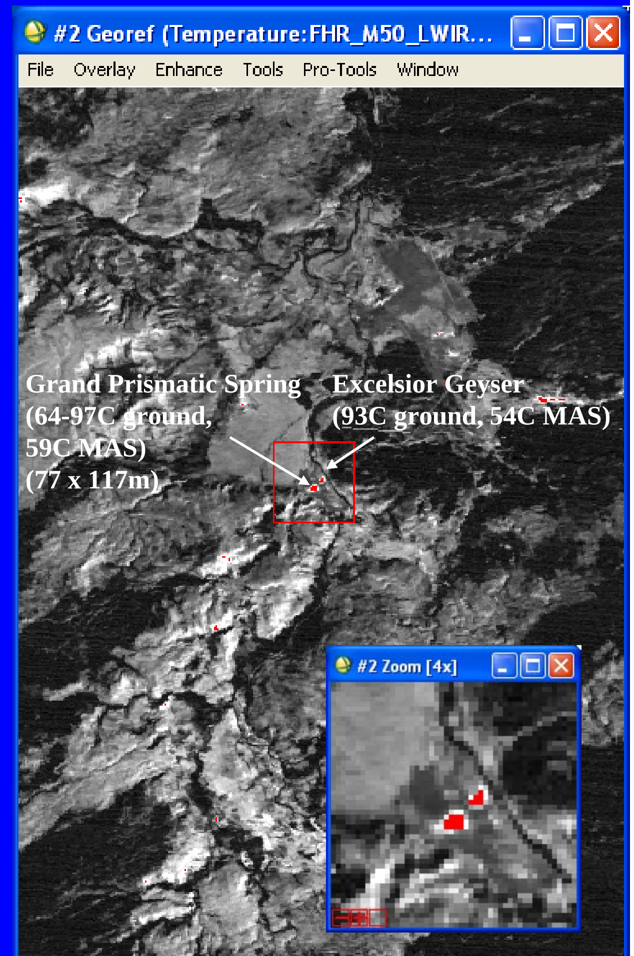
MAS data (33m) were acquired of portions of the park in 1996 (Midway Geyser Basin at center)



True Color



Decor 5, 3, 1



Temperature

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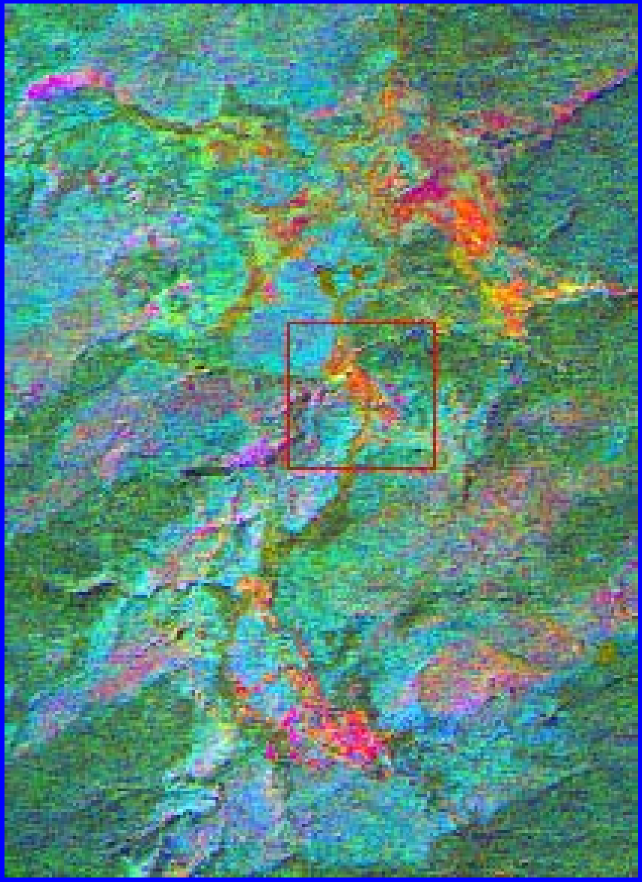
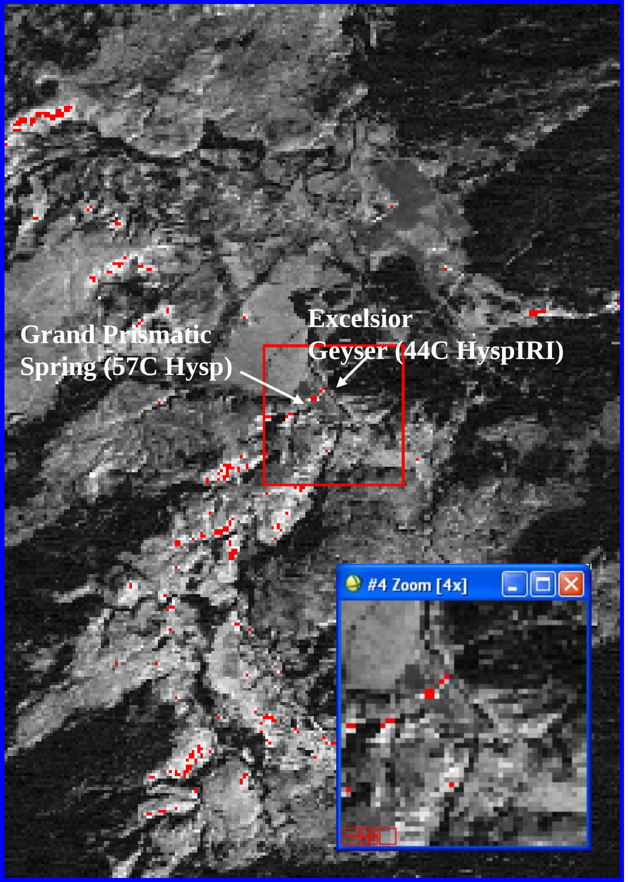
HyspIRI Simulation using MAS data @60m)

True Color



Decor 5, 3, 1



Temperature

Hot Creek Gorge – Photo M. Sneed, USGS

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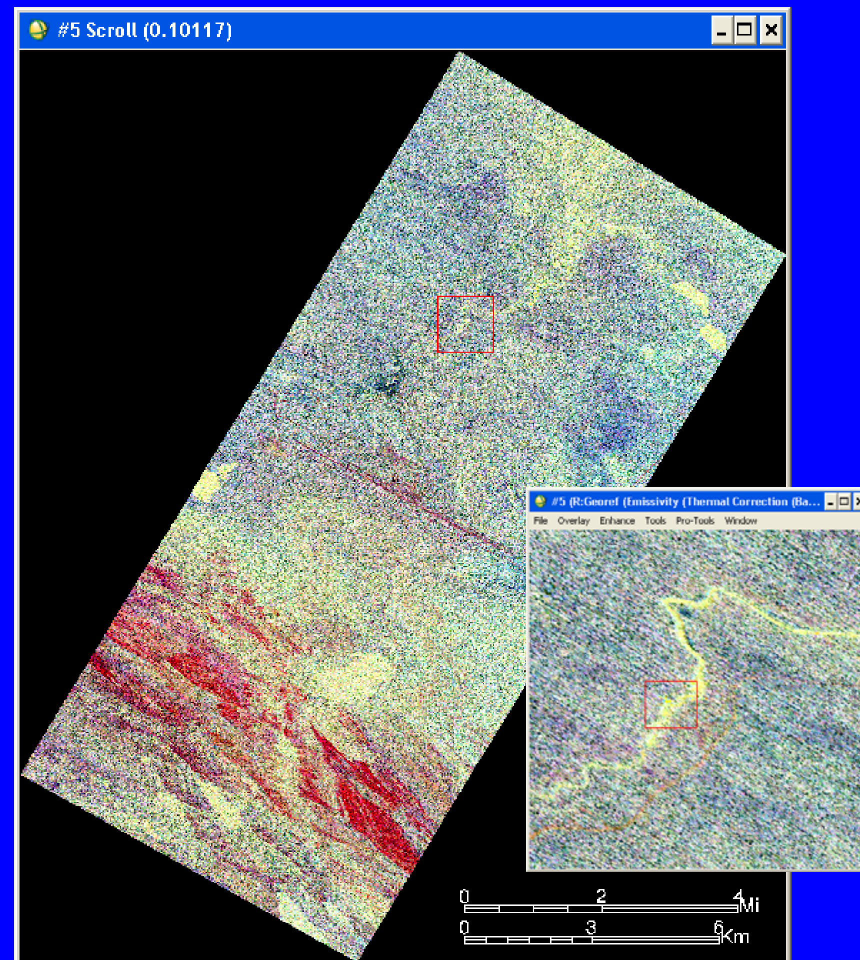
- **Active, producing geothermal system**
- **Hot Creek Area (known discharge area)**
- **1999 HyMap, ~5m, ~3m MASTER, June 2002, Night acquisition)**
- **Spectral Resampling, Spatial resampling to 60m pixels (~17 x ~17 = ~300 pix)**
- **ISAC atmospheric correction**
- **Normalized Emissivity calculation with temperature extraction**

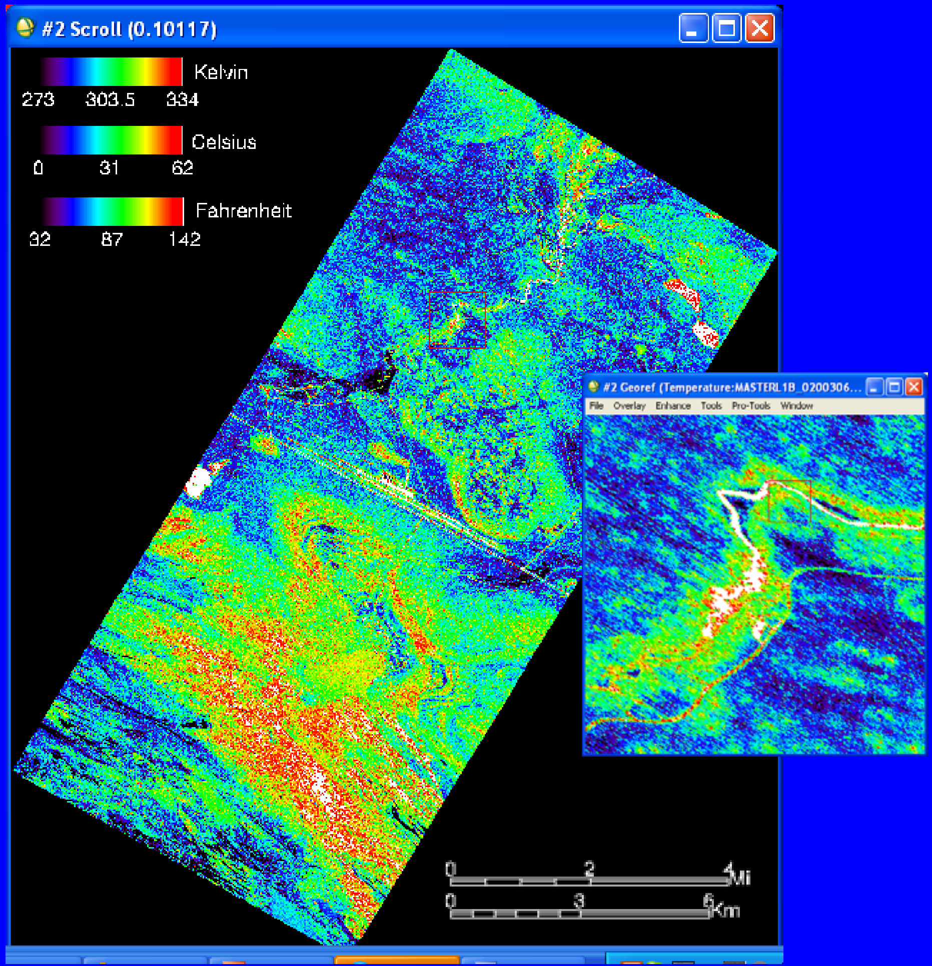
Long Valley, CA MASTER Emissivity (night), 16 June 2002



Emissivity (46, 44, 42), Night-Time MASTER, (Hot Creek), Long Valley, CA

Long Valley MASTER Temperature (night), 16 June 2002

- **Density sliced temperature from MASTER**
- **Scene Temperature Variability**
- **"Hot" Spots**
  - **Water**
  - **Residual Solar (Topographic) Effects**
  - **Albedo effects**
  - **Geothermal outflows**



TES-Extracted Temperature, Night-Time MASTER, (Hot Creek), Long Valley, CA

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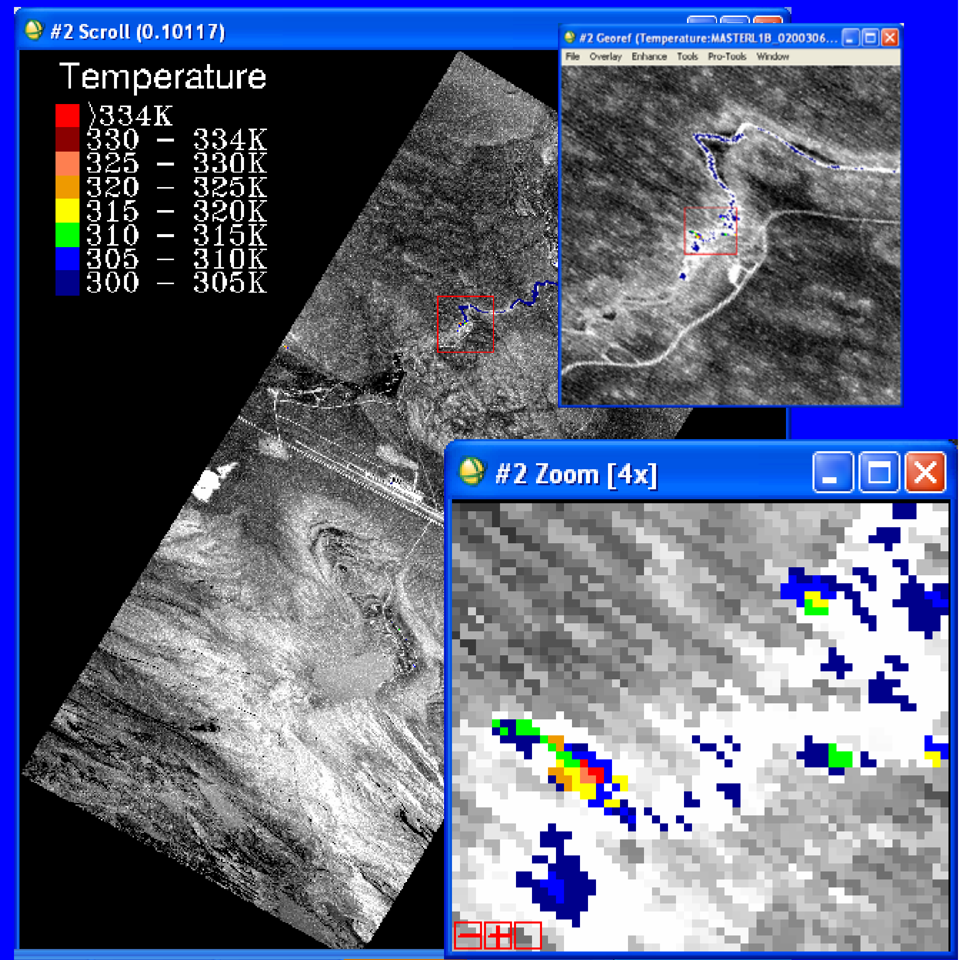
Long Valley MASTER Temperature (night), 16 June 2002

- **3.4m MASTER**
- **Scene Temperature Variability**
- **300 – 305K: 3943 Pixels**
- **305 – 310K: 192 Pixels**
- **310 – 315K: 94 Pixels**
- **315 – 320K: 67 Pixels**
- **320 – 325K: 39 Pixels**
- **325 – 330K: 14 Pixels**
- **330 – 334K: 0 Pixels**
- **>334K: 4 Pixels**

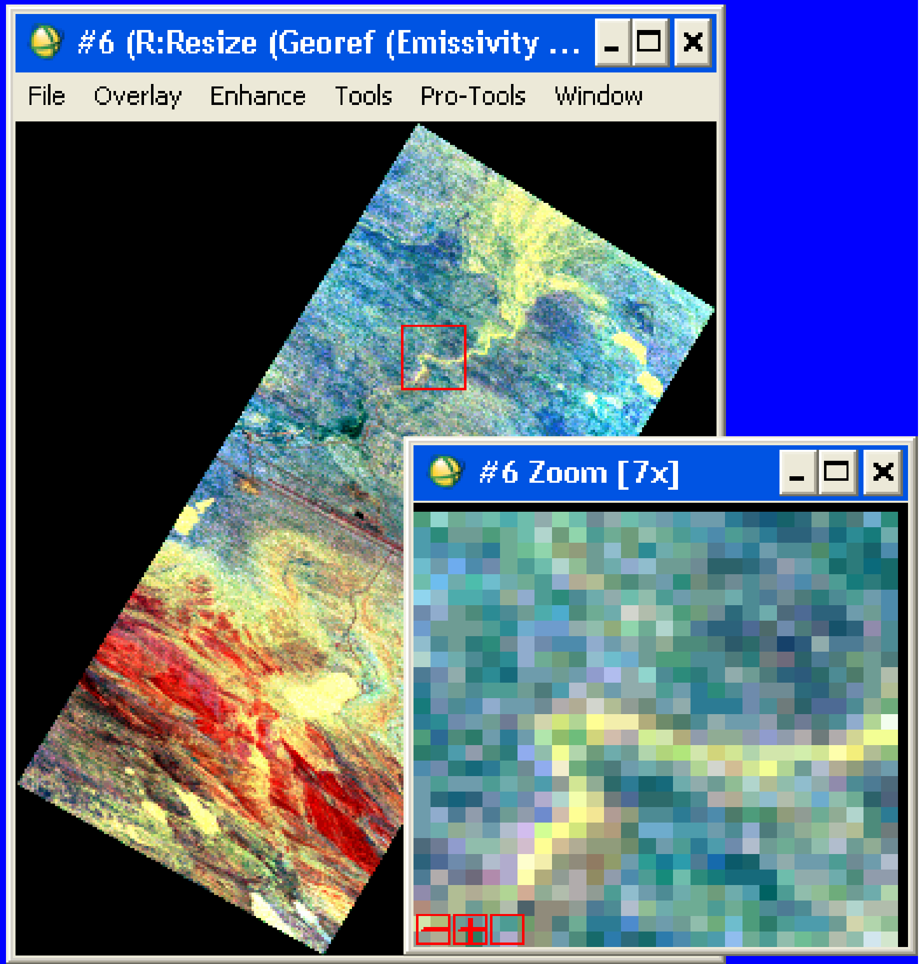


- **Geothermal Outflows**

TES-Extracted Temperature, Night-Time MASTER, (Hot Creek), Long Valley, CA

Long Valley 60m HyspIRI TIR Simulation (night), 16 June 2002
Emissivity Bands 6, 5, 3 (10.52, 9.08, 8.28 Micrometers) (RGB)

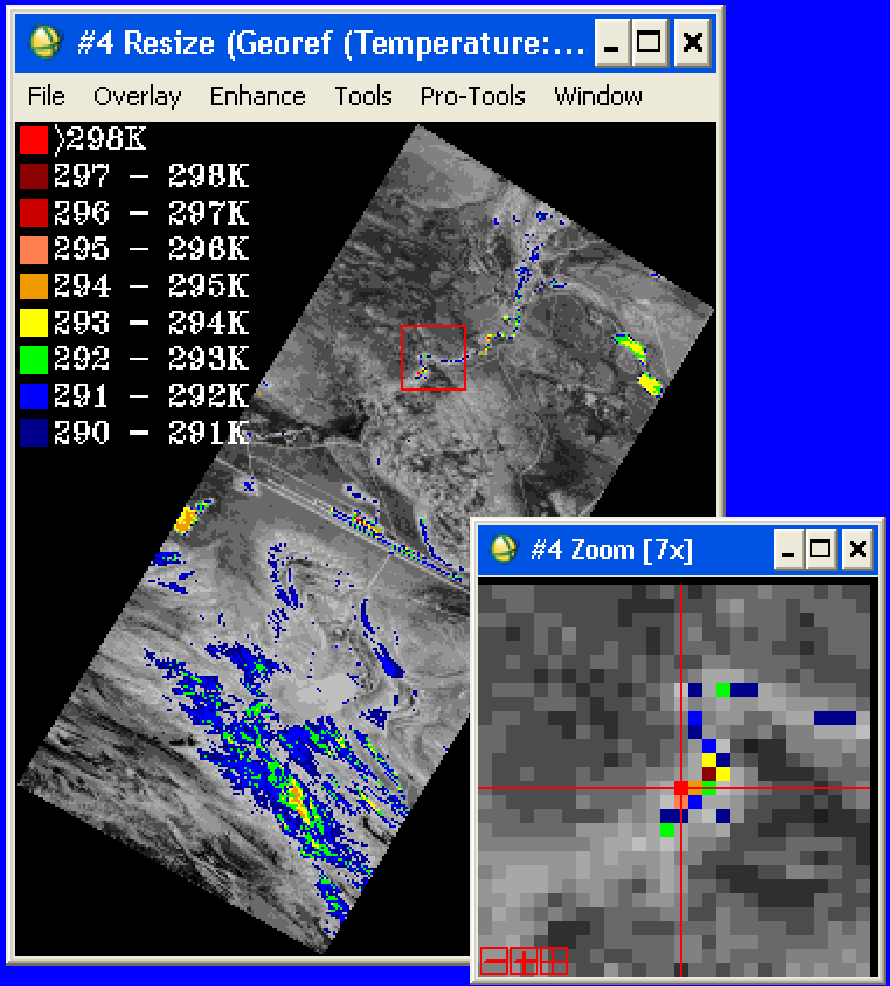
- **60 meter spatial resolution**
- **Resampled to HyspIRI band responses (no band 1 or 2)**
- **ISAC Atmospheric compensation**
- **Normalized Emissivity**



HyspIRI 60m Emissivity Bands 6, 5, 3 (RGB), Night-Time MASTER, Long Valley, CA

Long Valley 60m HyspIRI TIR Simulation (night), 16 June 2002

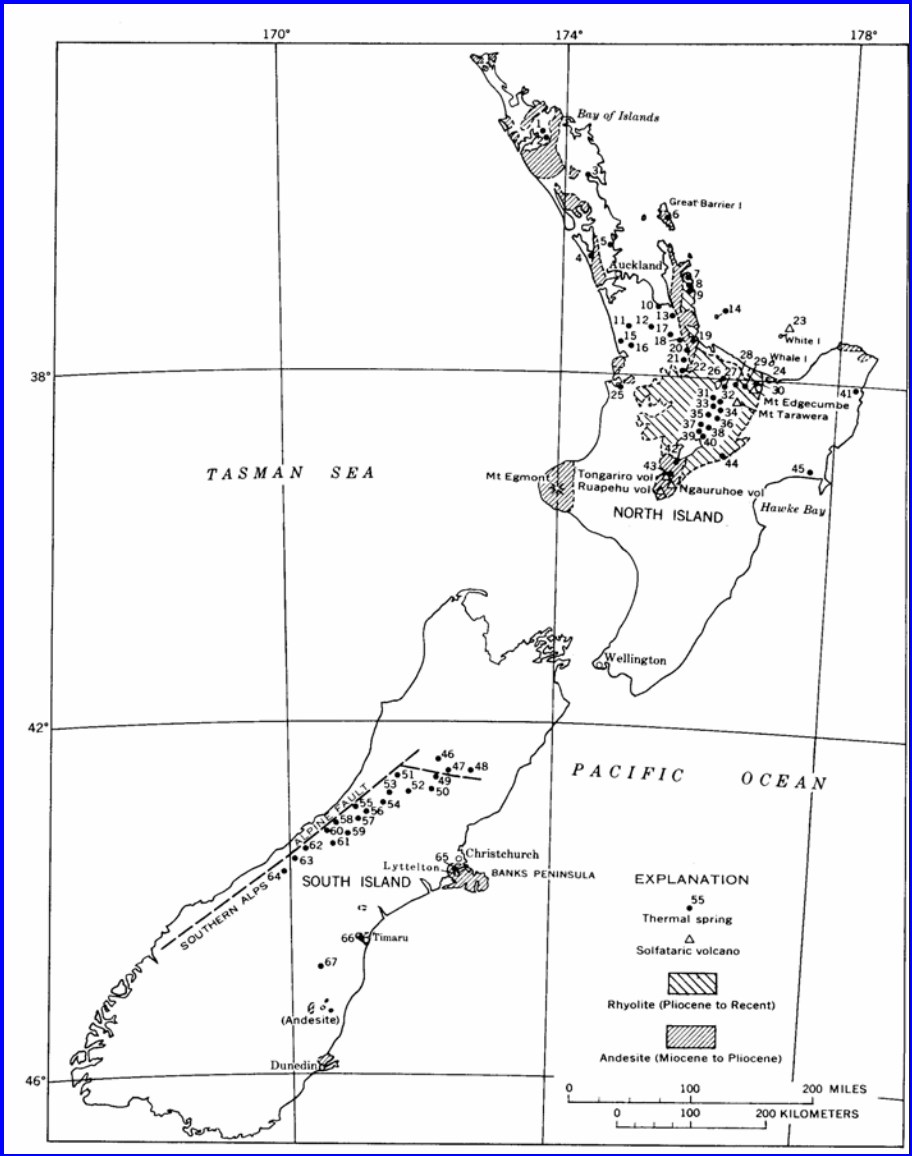
- **60m HyspIRI Simulation using MASTER, Temperatures >290K**
- **Scene Temperature Variability**
  - **290 – 291K: 4486 Pixels**
  - **291 – 292K: 2438 Pixels**
  - **292 – 293K: 950 Pixels**
  - **293 – 294K: 323 Pixels**
  - **294 – 295K: 87 Pixels**
  - **296 – 297K: 12 Pixels**
  - **297 – 298K: 8 Pixels**
  - **>298K: 1 Pixel**
- **"Hot" Spots**
  - **Water**
  - **Residual Solar (Topographic) Effects**
  - **Albedo effects**
  - **Geothermal Effects**



HyspIRI TES-Extracted Temperature, Night-Time MASTER, (Hot Creek), Long Valley, CA

F. A. Kruse ♦ 303-499-9471 ♦ fkruse@unr.edu ♦ http://www/unr.edu/mines/able

New Zealand Hyperion/MASTER Data HyspIRI Simulations



- **Numerous NZ geothermal systems and hot springs have been well known since pre-European times**
- **Over 500 thermal pools and at least 65 geyser vents**

Aerial view of Whakarewarewa, Rotorua, NZ, Jan 2002. Pohutu Geyser is erupting in the center (Wikipedia.org)

F. A. Kruse ♦ 303-499-9471 ♦ fkruse@unr.edu ♦ http://www/unr.edu/mines/able

Taupo Volcanic Zone, North Island, NZ

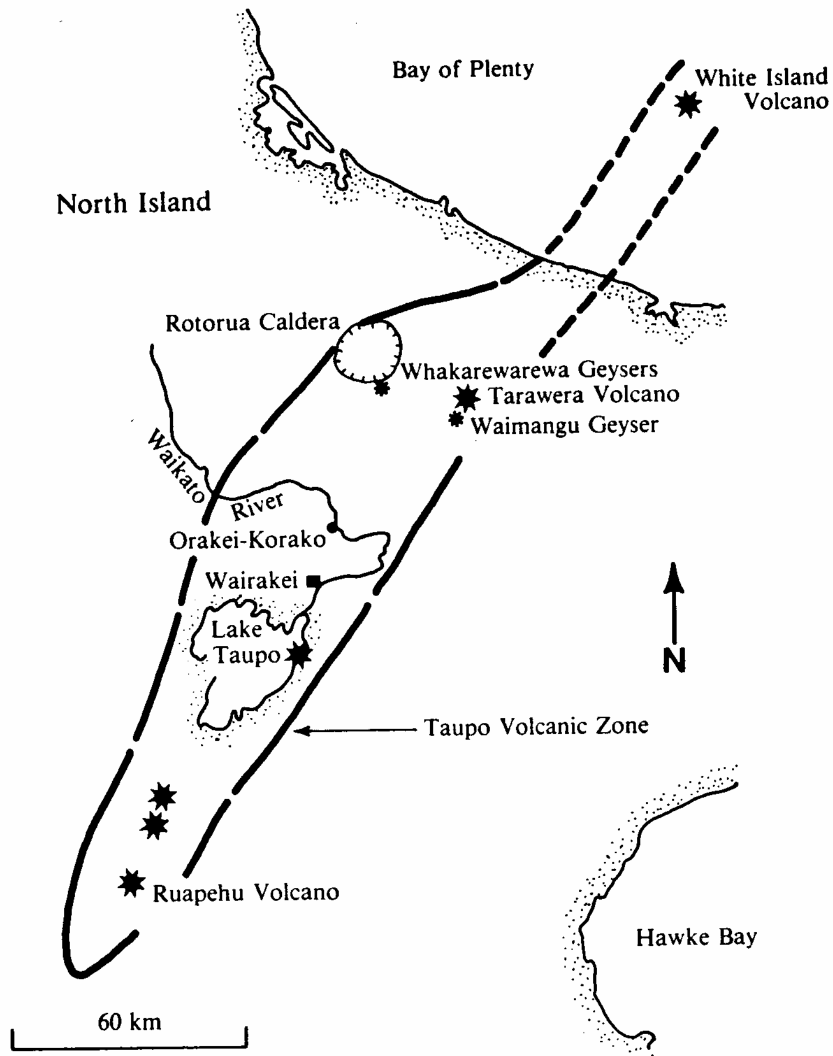
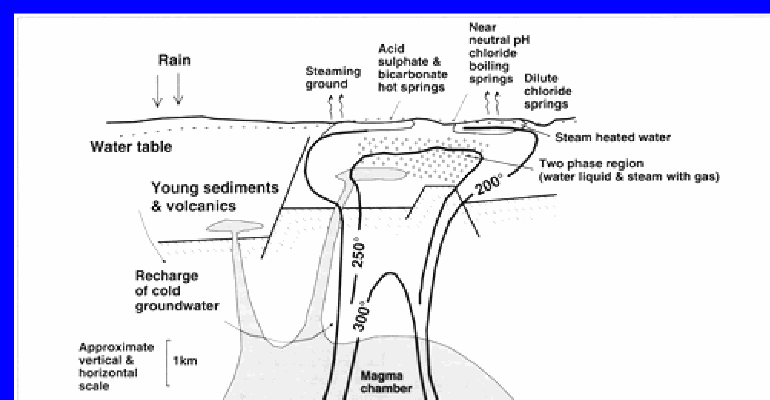


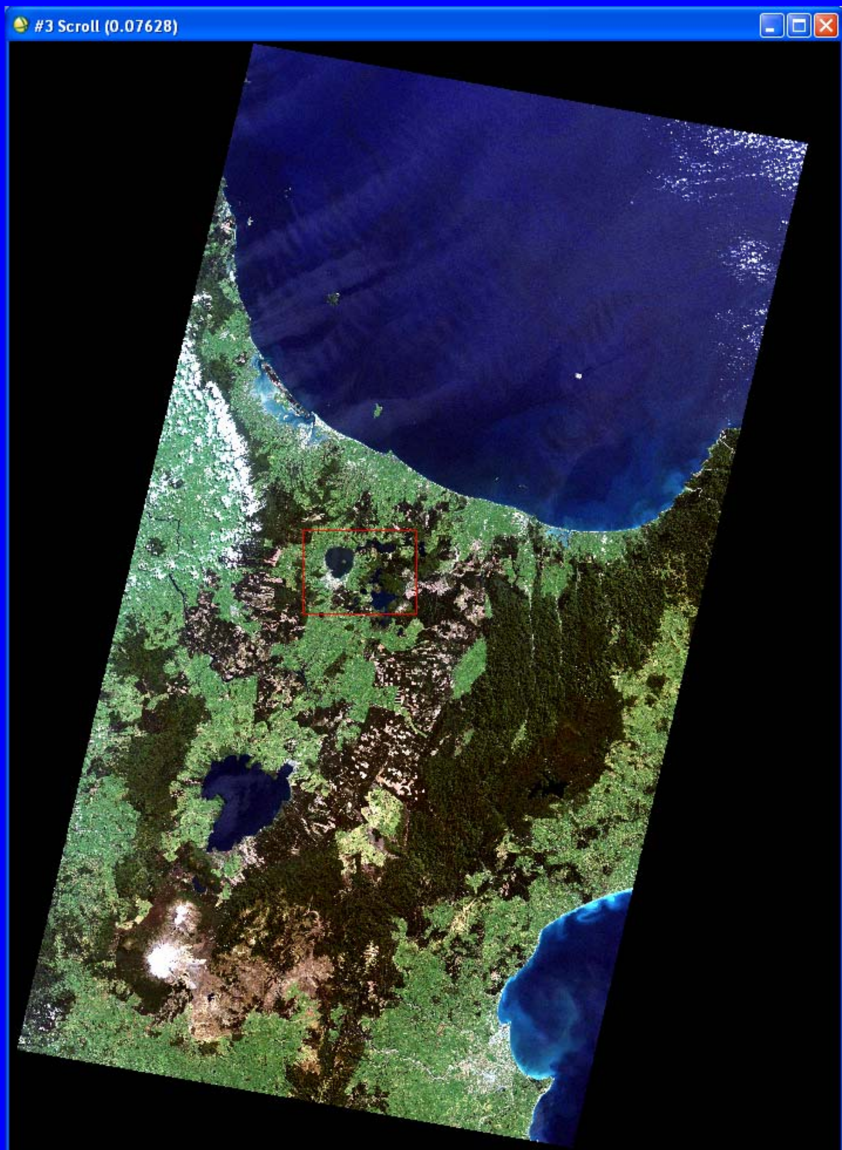
Figure 1-10. Taupo Volcanic Zone, North Island, New Zealand, showing major geologic and geothermal features. (Adapted from Healy, 1964.)

- **Southern portion of the active Lau-Havre-Taupo back-arc basin, which lies behind the Kermadec-Tonga subduction zone**
- **Numerous volcanic vents and geothermal fields exist in the zone, with Mount Ruapehu, Mount Ngauruhoe and White Island erupting most frequently**
- **Associated with young and active rhyolitic volcanism**
- **Mount Tarawera eruption in 1886 killed over 100 people**
- **Rotorua Caldera (now occupied by Lake Rotorua) is the remnants of a collapsed volcano 22km in diameter**

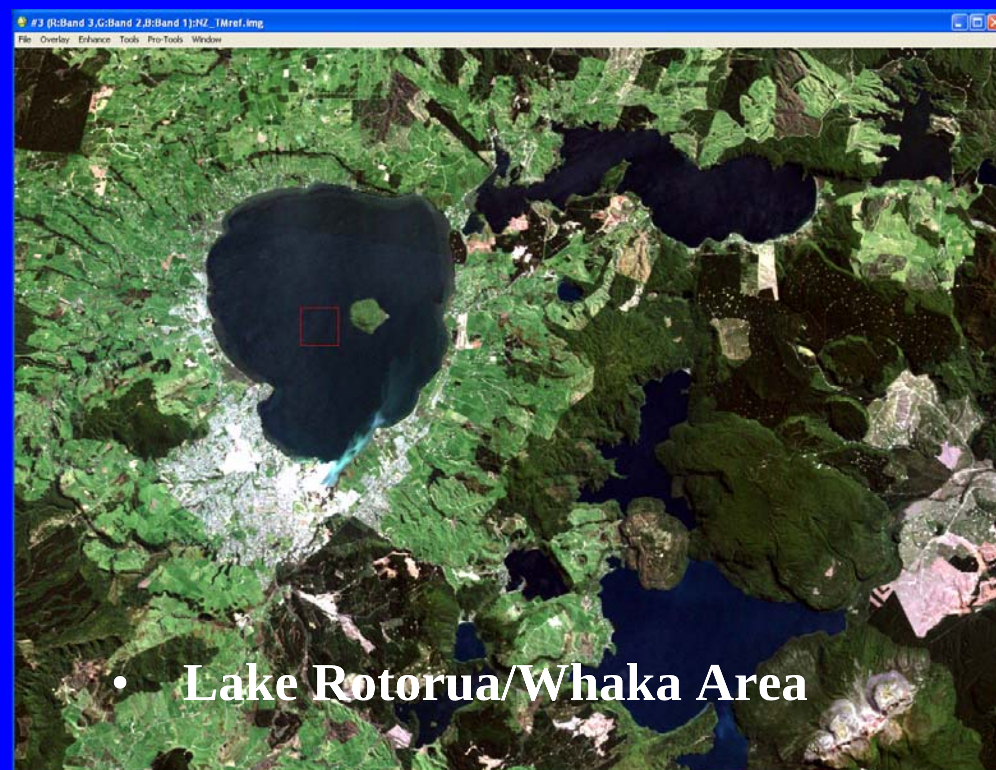


Generalized Geothermal System of the Taupo Volcanic Zone (After Henley & Others, 1986)

Landsat TM – True Color



- **Hyperion – 2001, 2002 (30m)**
- **MASTER – 2000 (18m)**
- **Landsat – 1999 (15, 30m)**
- **ASTER - ? (15, 30, 90m)**



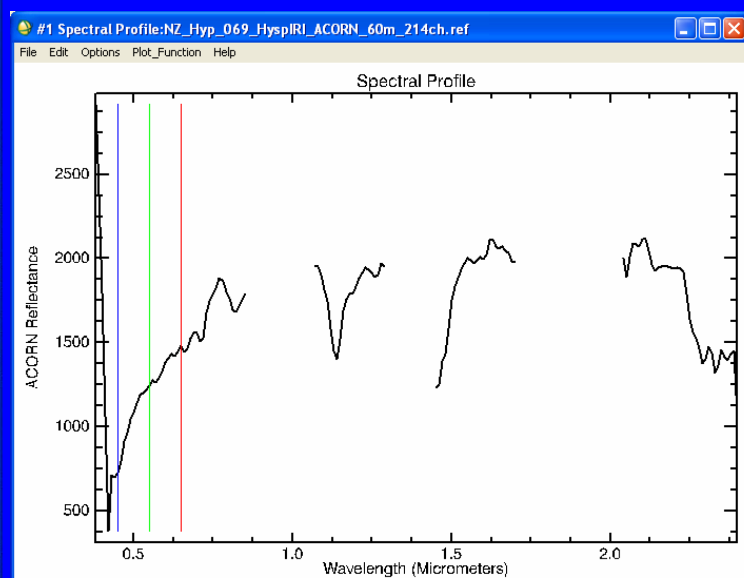
- **Lake Rotorua/Whaka Area**

F. A. Kruse ♦ 303-499-9471 ♦ fkruse@unr.edu ♦ http://www/unr.edu/mines/able

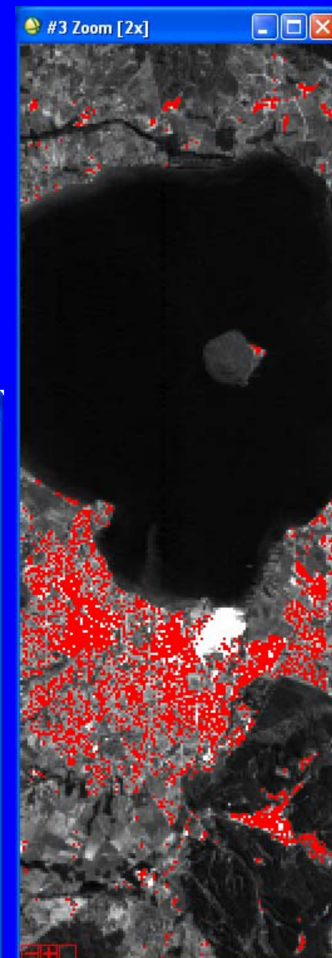
HyspIRI VNIR/SWIR Simulation using Hyperion

True Color

- **Hyperion 3/10/2001**
- **Resampled to HyspIRI Bands**
- **Resampled to 60m**
- **Poor SNR !**
- **SWIR Mapping**

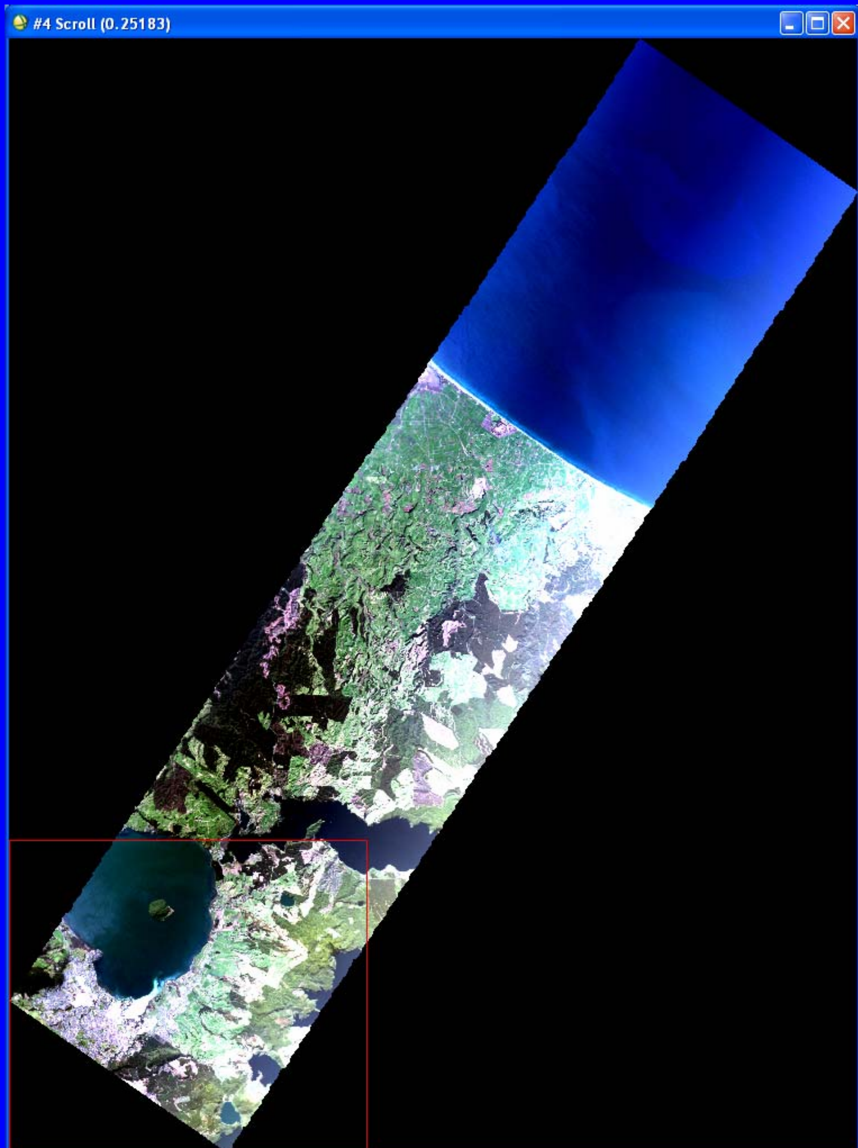


2.2 Micrometer Feature

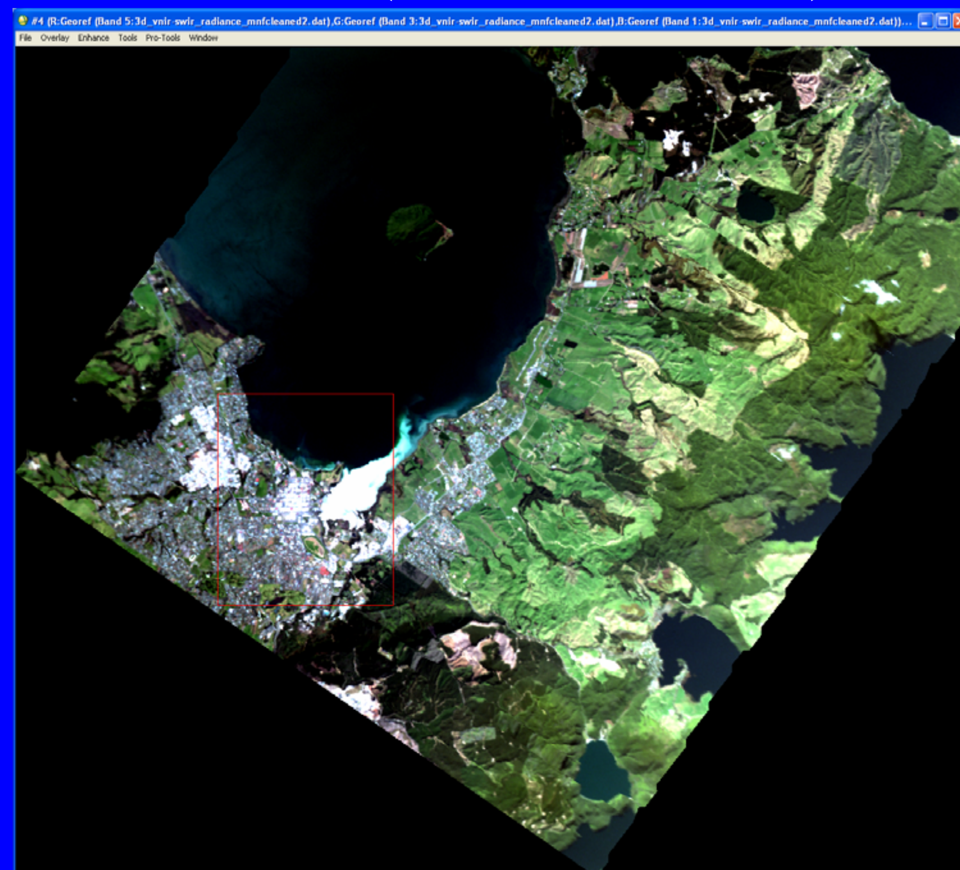


F. A. Kruse ♦ 303-499-9471 ♦ fkruse@unr.edu ♦ http://www/unr.edu/mines/able

MASTER (ER-2, 18m)



- 14 August 2000, daytime data
- ER-2, 18m Spatial Resolution
- 25 VNIR/SWIR bands (0.46 – 2.39 Micrometers)
- 15 MWIR Bands (3.2 – 5.2 Micrometers)
- 10 LWIR Bands (7.8 – 12.9 Micrometers)



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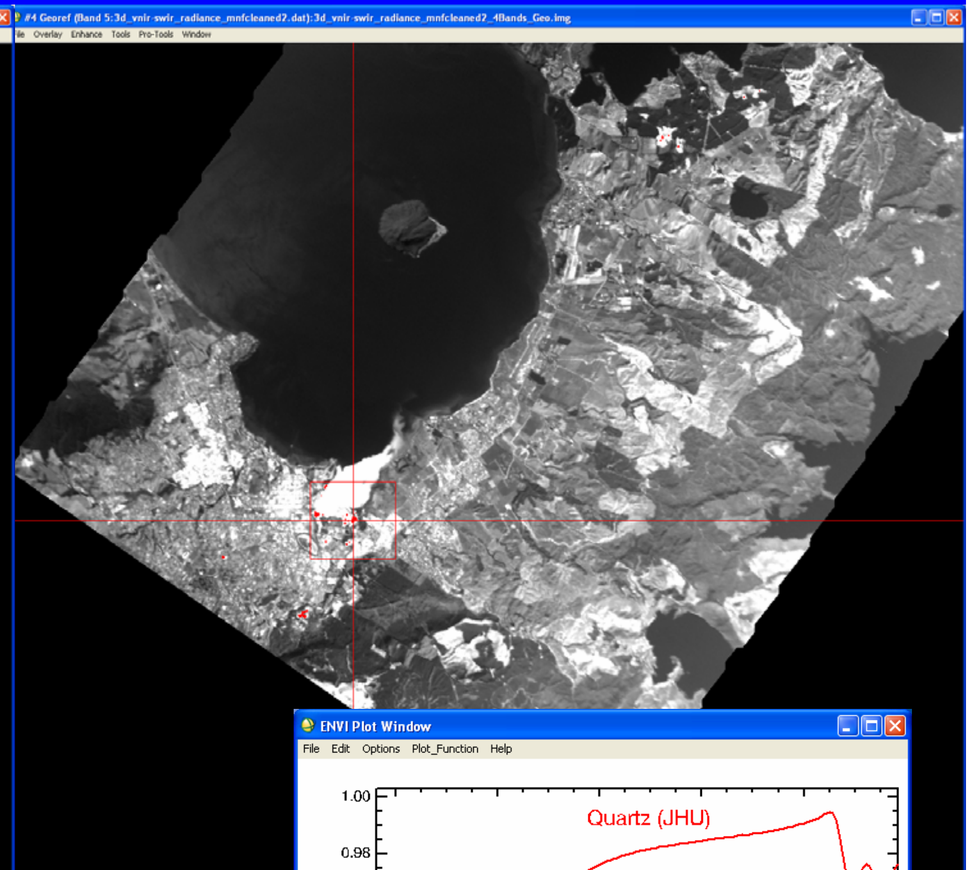
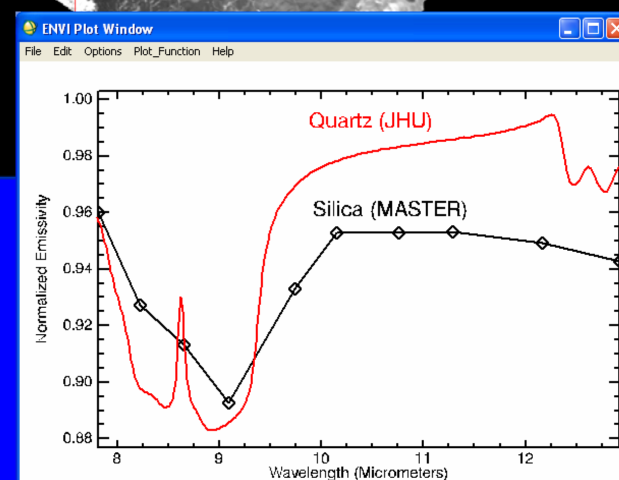
MASTER Silica Mapping

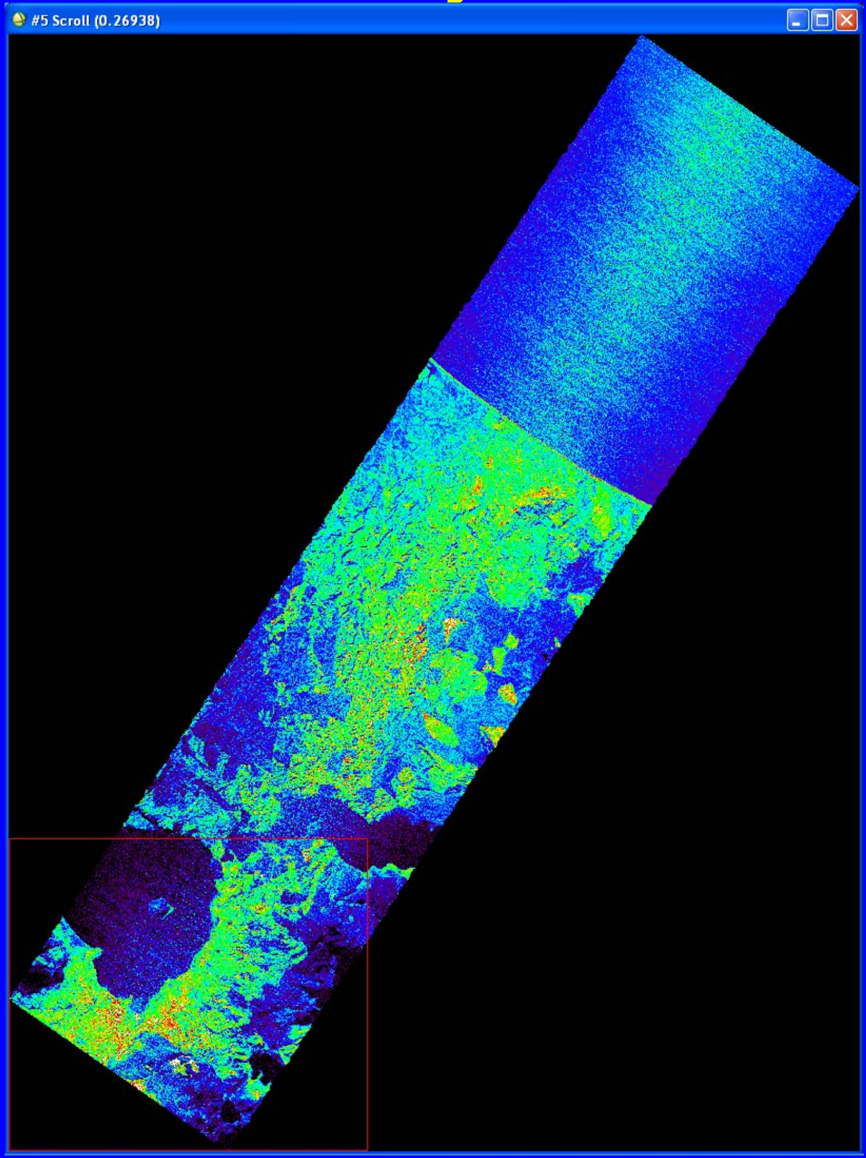


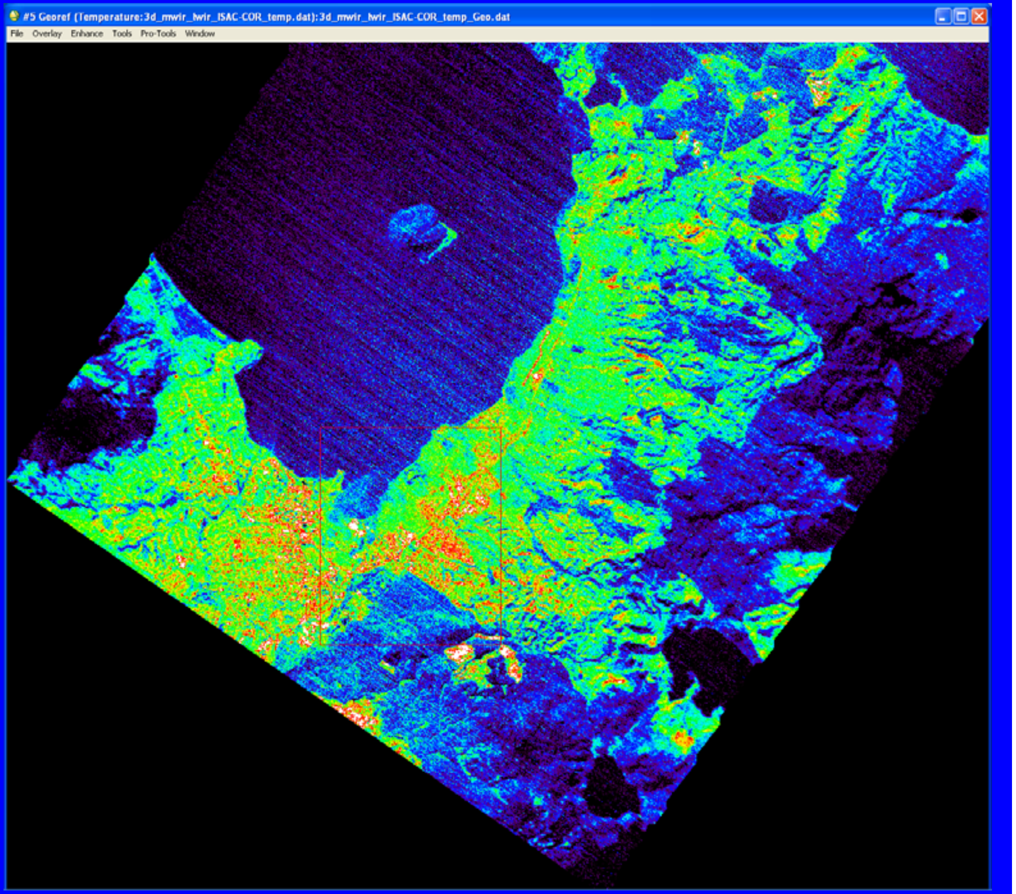


- **Emissivity Spectrum Extraction**
- **Spectral Mapping (MTMF) shows best Silica matches (high certainty)**

F. A. Kruse ♦ 303-499-9471 ♦ fkruse@unr.edu ♦ http://www/unr.edu/mines/able

Density Sliced MASTER Temperature





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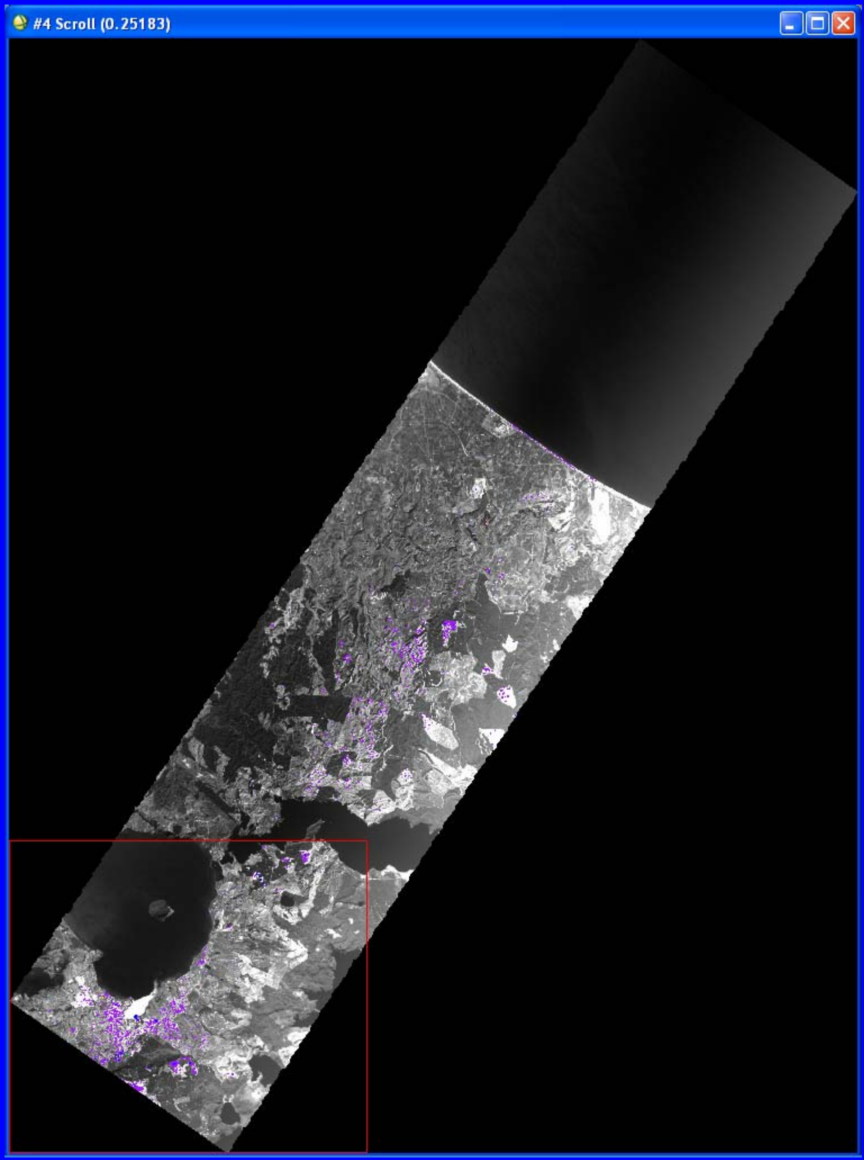
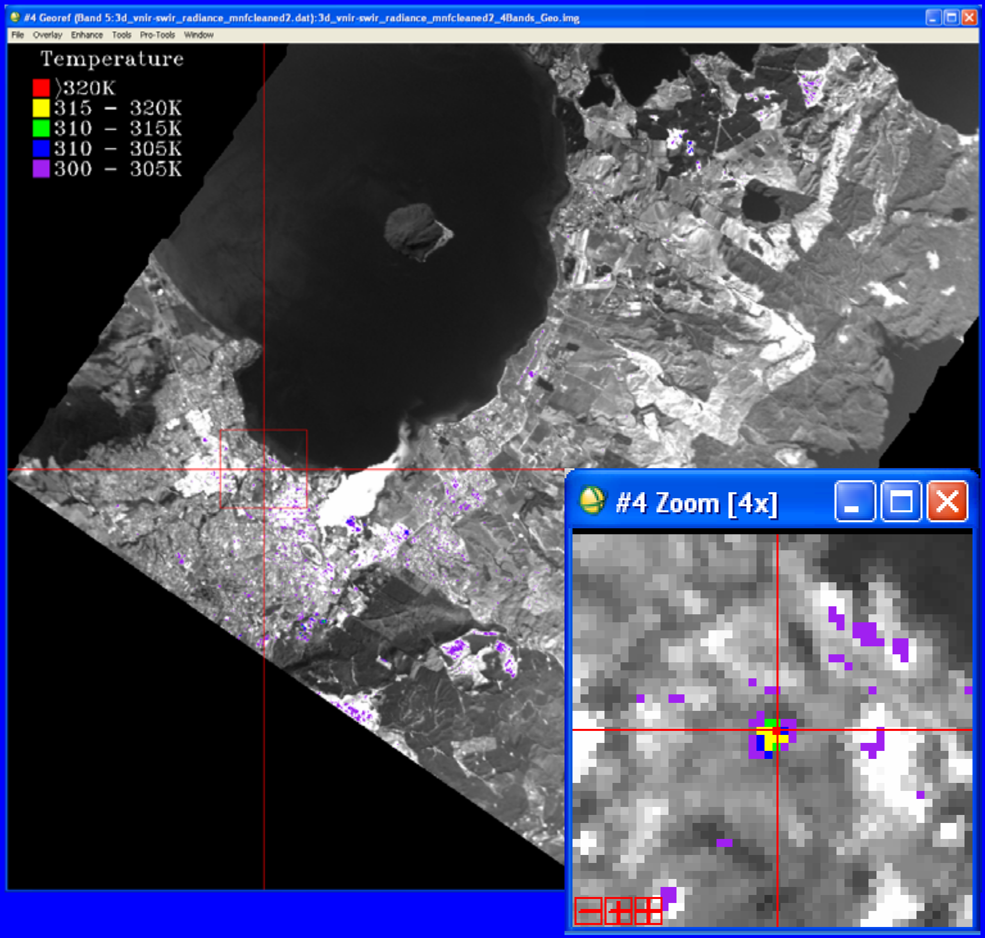
New Zealand MASTER High Temps 1



on 0.65 micrometer band



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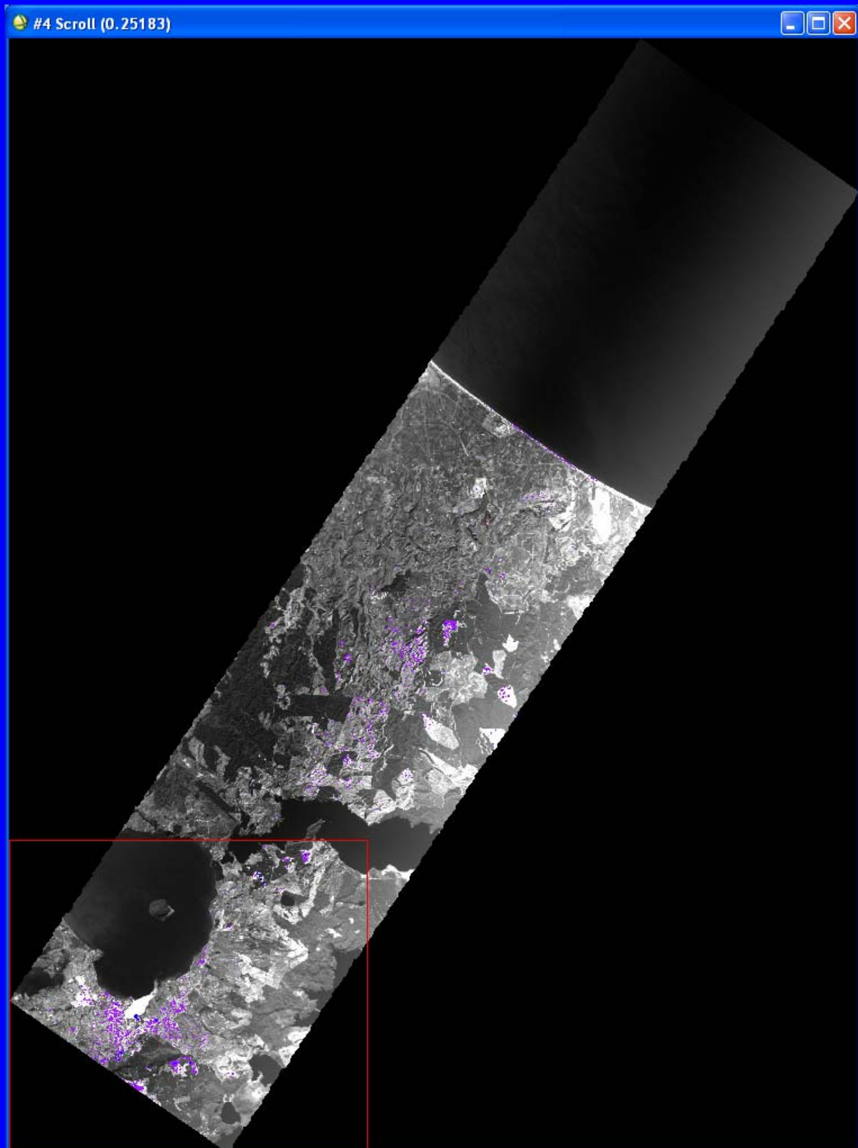
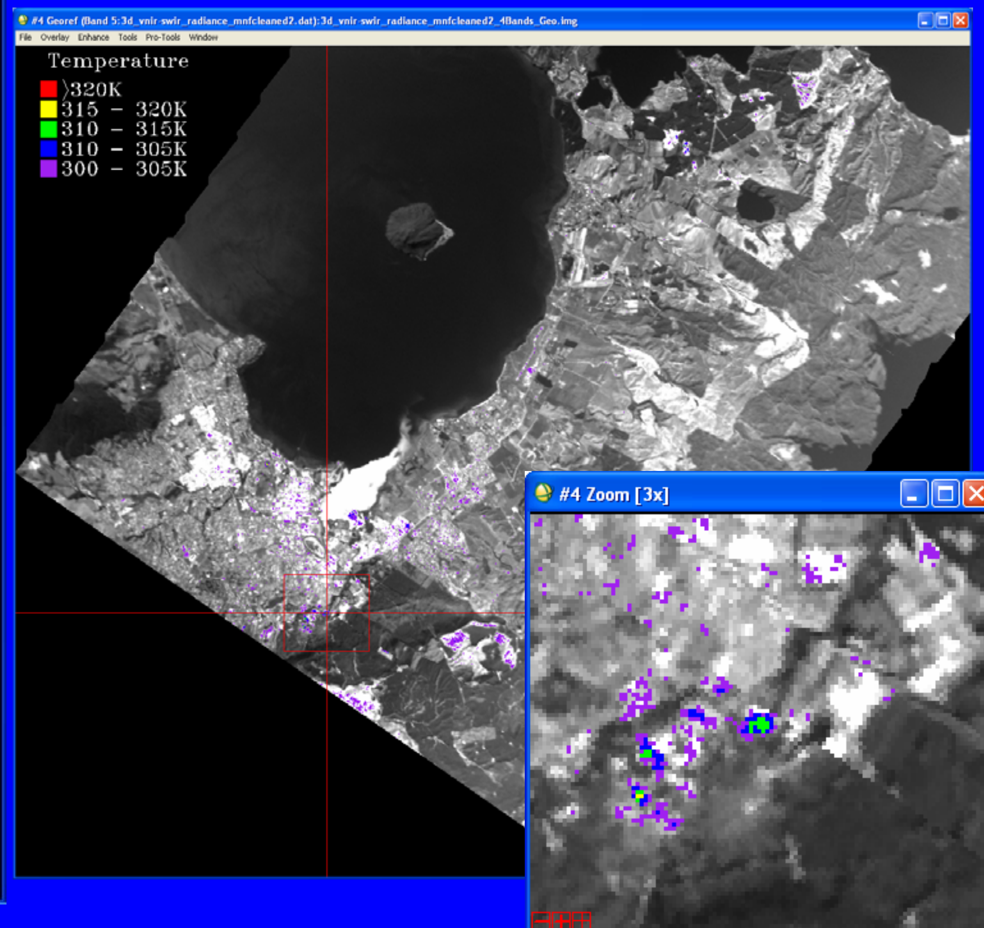
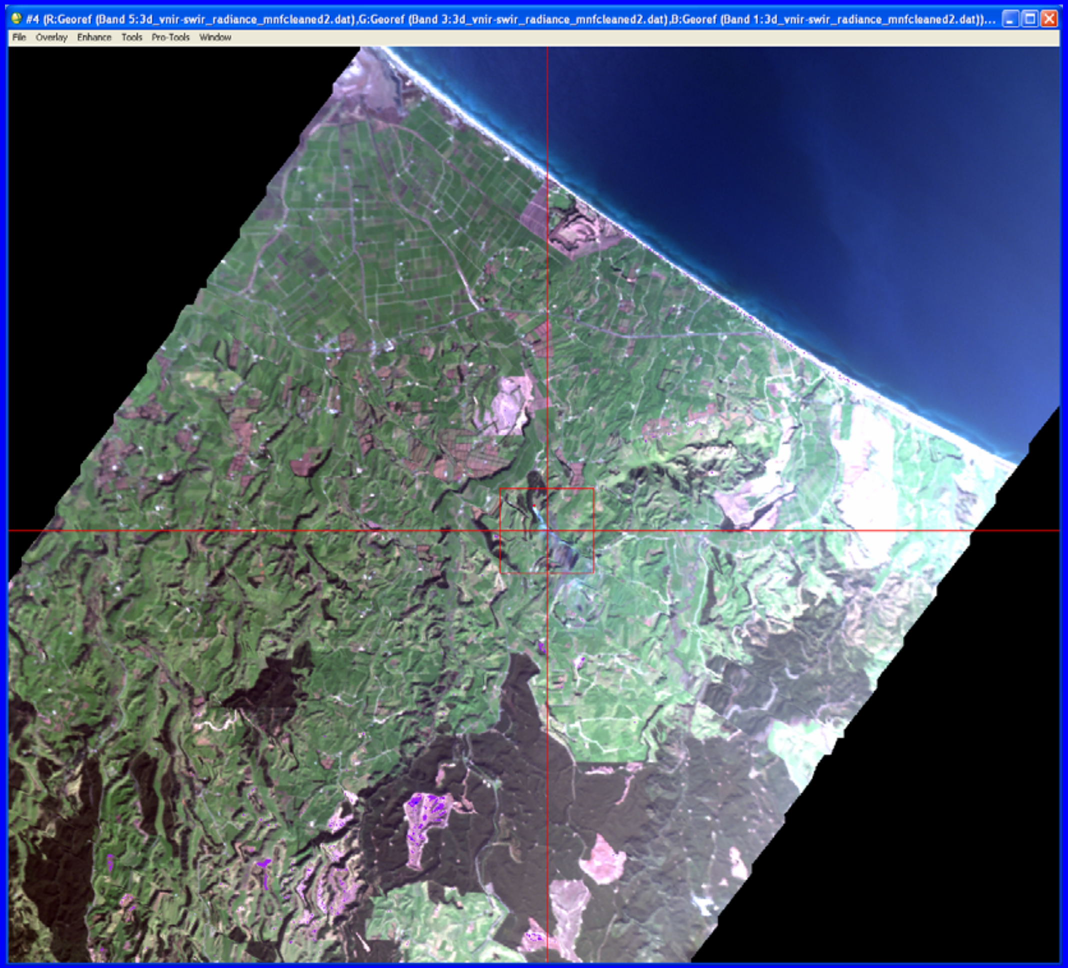
New Zealand MASTER High Temps 2

on 0.65 micrometer band





New Zealand Master – Fire/Plume

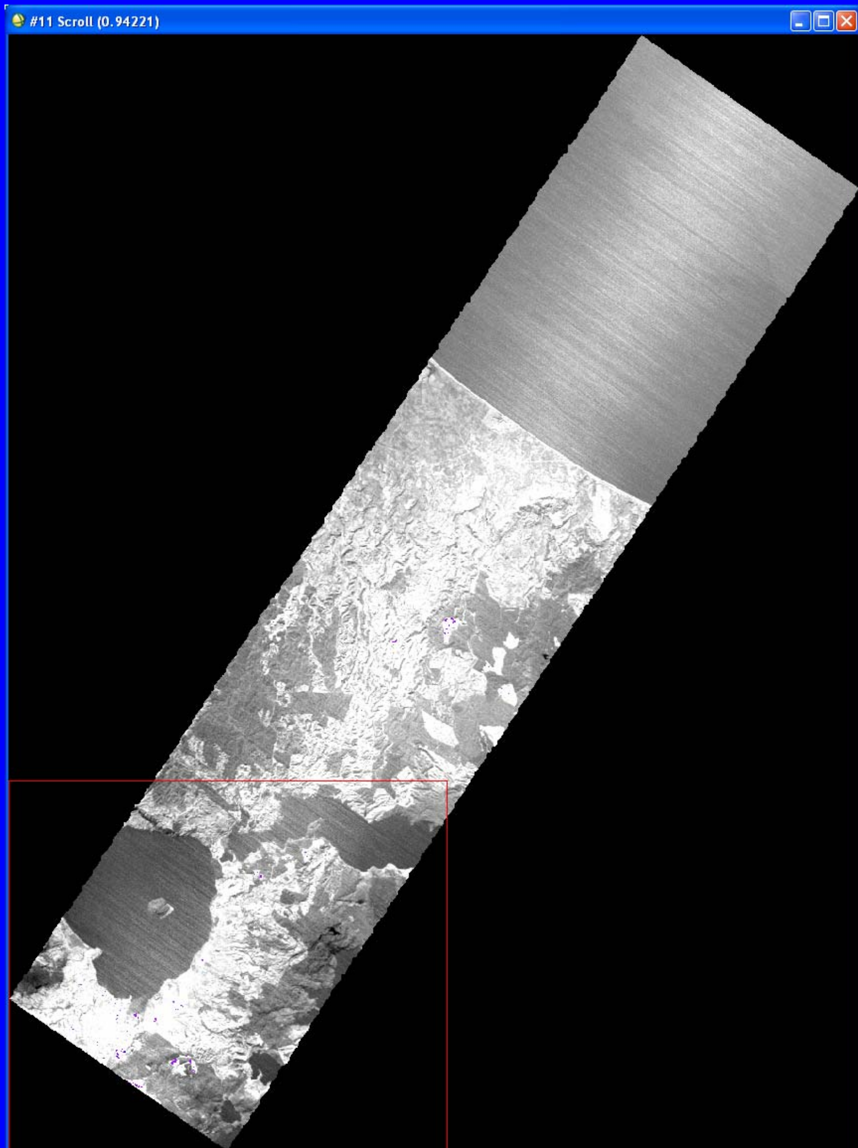


New Zealand MASTER Temperature Results

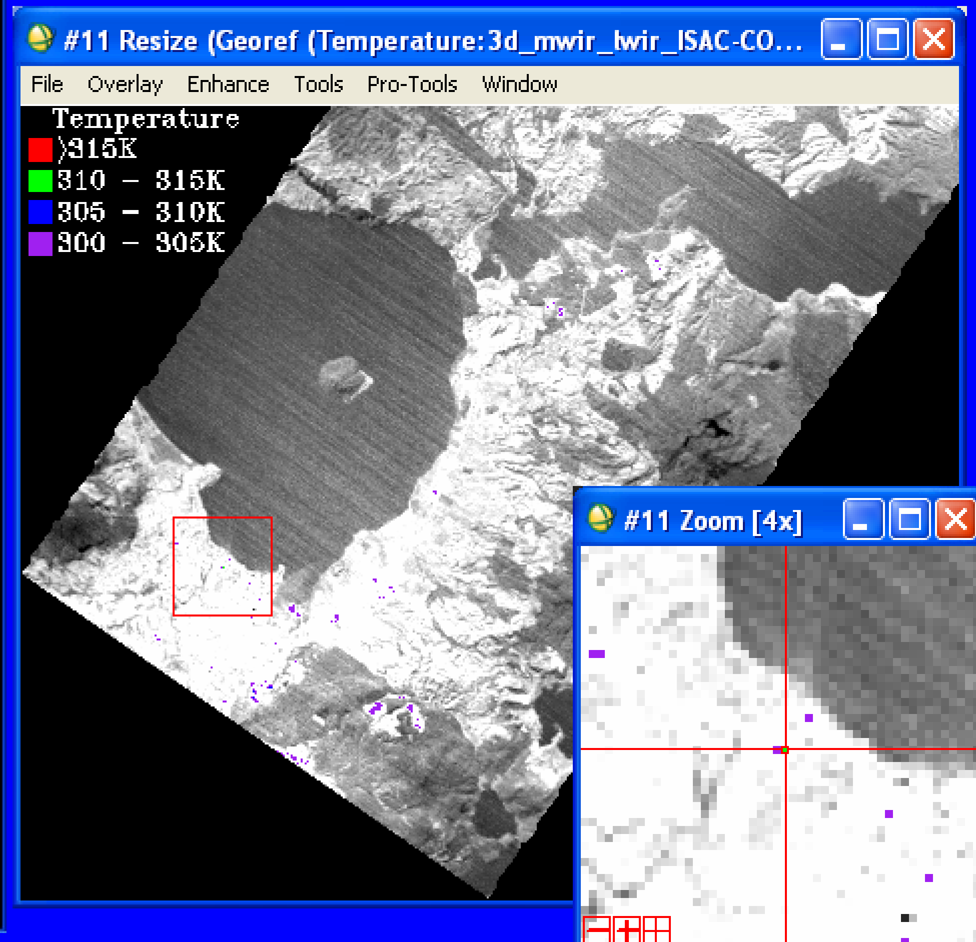
- **Background, ~293K, 20C, 68F**
- **Solar Heated Slopes, 300K, 27C, 81F**
- **Geothermal Features, >305K, 32C, 90F**
- **Hottest Geothermal, 322K, 49C, 120F**
- **Fire/Smoke Plume = Hottest Pixels 370K, 97C, 207F**

F. A. Kruse ♦ 303-499-9471 ♦ fkruse@unr.edu ♦ http://www/unr.edu/mines/able

New Zealand HyspIRI Simulated 60m Temperature



- **Background ~295K, 22C, 72F**
- **Max Geothermal Temp=312K, 39C, 112F**
- **Fire/Plume = 323K, 50C, 122F**



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HyspIRI Simulation Mineral Mapping Observations

- Proposed HyspIRI sensor is well suited to detection, characterization and mapping of key materials for geothermal systems
  - VNIR/SWIR successfully maps key minerals such as hydrothermal silica, kaolinite, alunite, montmorillonite, calcite, and other materials such as dry vegetation, green vegetation, algae associated with active and fossil geothermal systems
  - LWIR Emissivity/Decor data allow mapping of silica
  - Mineral maps provide information about present and past geothermal water compositions and spatial patterns associated with known hydrothermal activity
- Additional scaling studies and new SNR modeling required

HyspIRI Simulation Temperature Observations

- Temperature extraction from the LWIR data is more problematic and requires further work and assessment
  - Temperature data for active geothermal systems are highly influenced by topography and differential solar heating – only the hottest areas are easily and unambiguously extracted from the LWIR data
- Preliminary Results are:
  - Measured temperatures drop, contrast decreases, and anomalous temperatures approach average background temperature as pixel size increases (mixing/averaging), resulting in loss of detail in anomalously hot areas
  - Numerous false alarms occur that will be difficult to separate from genuine temperature anomalies occur with increasing pixel size
- Additional temperature contrast required for detection, thus corrections affecting temperature become more important
- Albedo and topographic corrections needed for quantitative temperature extraction – expecially for day-time data

Prospects for HsypIRI - Enabling New Research

- **HyspIRI sensor will deliver the tools needed for further hydrothermal/geothermal system remote sensing research – combined VNIR/SWIR/LWIR aspects are important**
- **HyspIRI will provide the capability to access new sites, world-wide**
- **Repeat temporal coverage will make monitoring of active geothermal systems possible (~ 5 days TIR day/night, ~19 days VNIR/SWIR Repeat)**
- **Nesting with higher spatial resolution datasets, additional LWIR corrections and improved understanding of scaling issues will be required to extract the most information**

Where To Next?

- Additional modeling of HyspIRI spatial/spectral resolution and scaling effects using VNIR/SWIR/LWIR for active/fossil geothermal systems
  - VNIR/SWIR mineral mapping using existing methods and evaluate capabilities
  - Improved LWIR mapping using emissivity and applying lessons learned with analysis of MSI/HSI VNIR/SWIR data
  - Quantitative temperature mapping using LWIR data
  - SNR and NEΔTmodeling and assessment of effects
- Explore use of extended (combined VNIR/SWIR/LWIR) signatures
- Synthesis of combined HyspIRI data results and application to geothermal research problems
  - Evaluate surface-subsurface links: between surface mineralogy and underlying geologic constraints (lithology, alteration, water chemistry, temperature regimes) (VQ6, TQ5a, CQ5)
  - Explore the links between active and fossil geothermal systems (VQ6, TQ5a)
  - Evaluate surface changes at active geothermal systems (TQ5b, CQ5)
  - Assess temperature distributions and magnitudes and links to the morphology and evolution of geothermal systems at depth (TQ5c)