Ground-Based Thermal Monitoring: Use of Infrared Data for Active Volcanic Systems

FLIR observation of Bezymianny Volcano
photograph by J. Dehn (U. Alaska Fairbanks)

Michael Ramsey
Dept. of Geology and Planetary Science
University of Pittsburgh, Pittsburgh, PA, USA

Presentation Overview

- **Thermal Infrared (TIR) Data**
  - theory
    - spectra, emissivity, surface temperature
    - deriving composition/texture: rocks, glass, gas/ash
  - use of TIR radiometers and FLIR cameras
  - complicating factors
- **Review of Results**
  - Bezymianny (2000 – 2008)
  - Mt. St. Helens (2004)
  - Kilauea (2005 – 2011)
  - *new application: Multispectral FLIR (2009 – 2011)*

What Can We Measure?

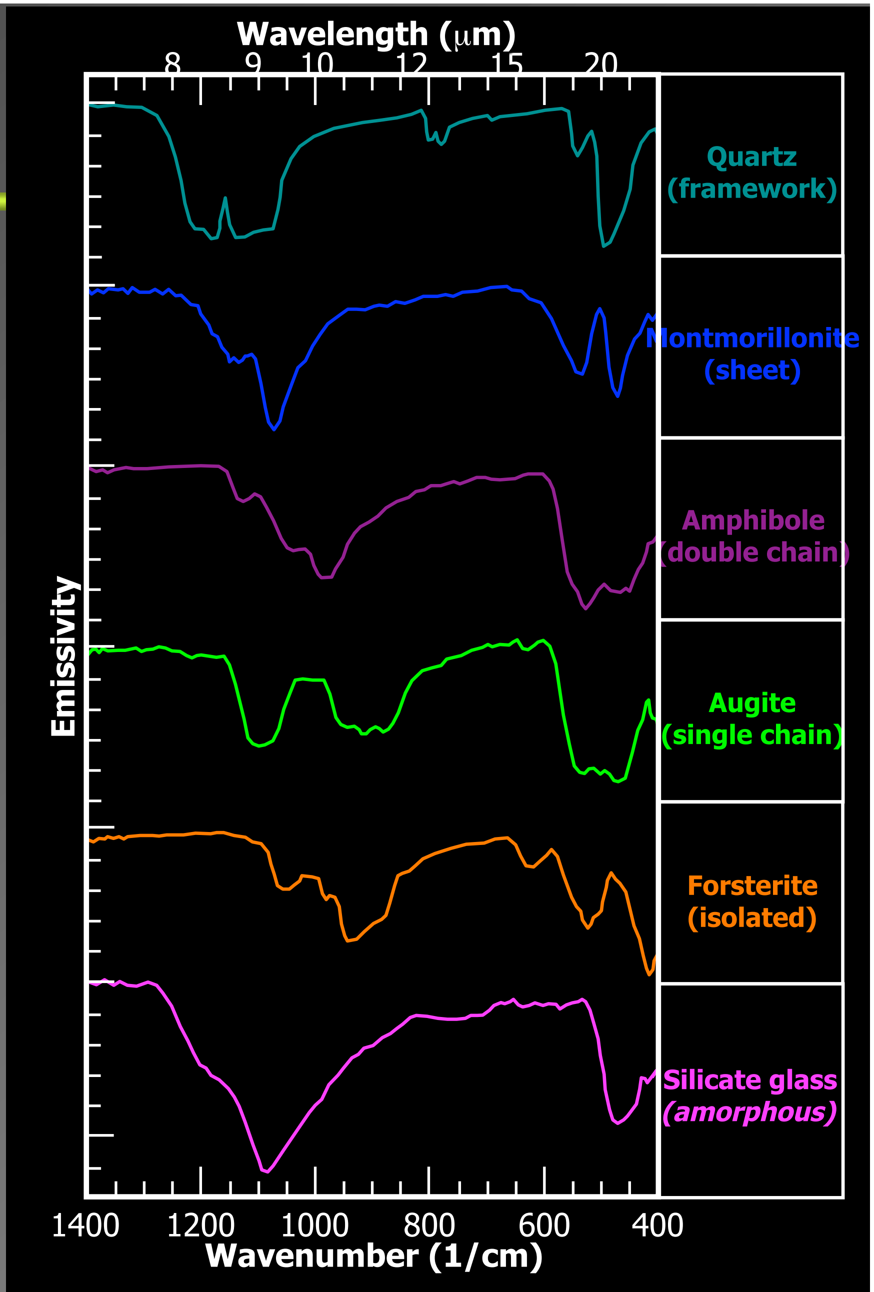
- **Emitted Energy**
  - combination of temperature *[T]* and emissivity *[ε(λ)]* integrated over the pixel area

$$L(\lambda,T) = \varepsilon_\lambda \left\{ \frac{(c_1\lambda^{-5})}{\exp(c_2 / \lambda T) - 1} \right\}$$

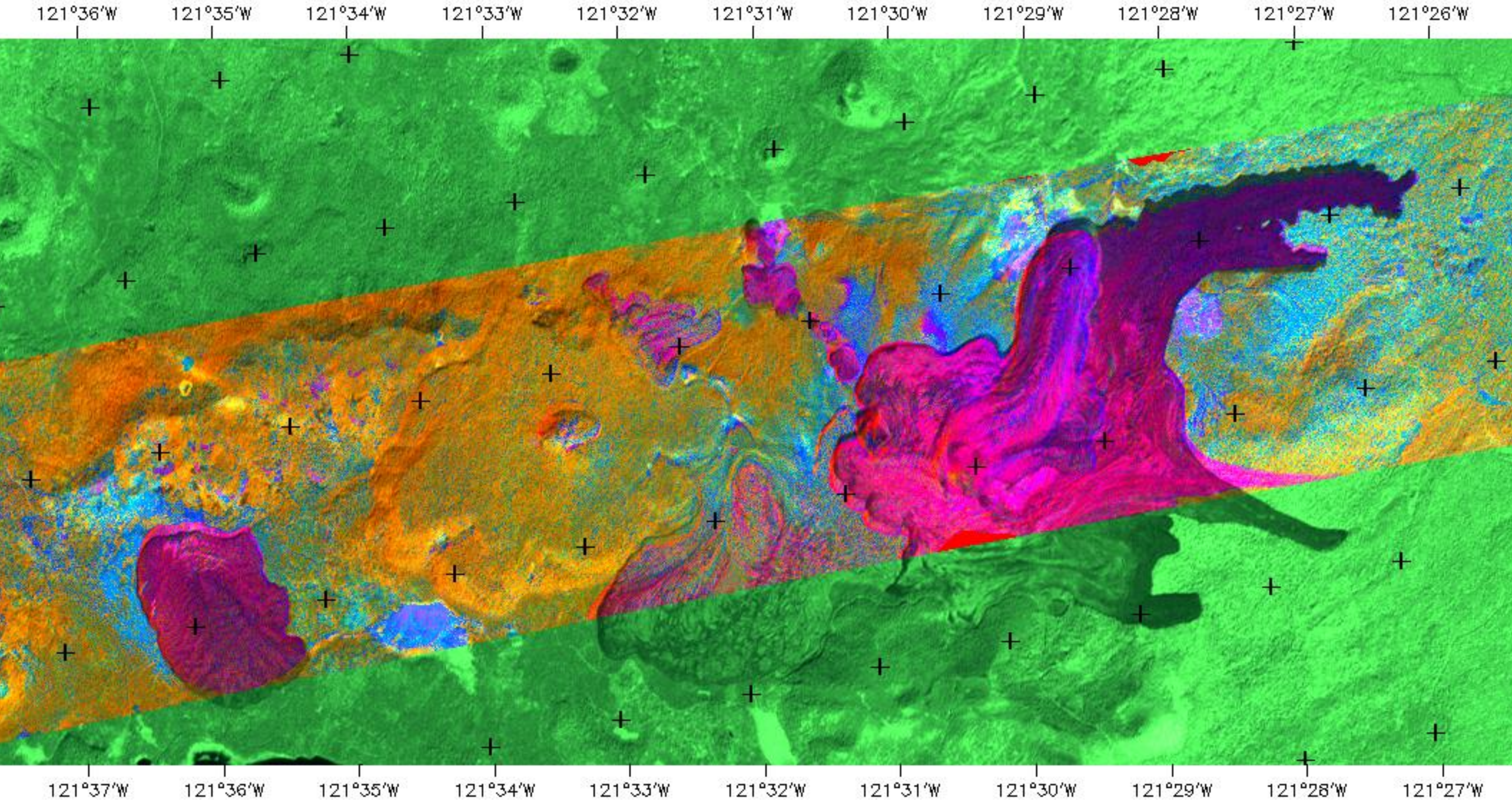
    - where,
      - $\mathbf{c_1}$ = 3.74x10^{-16} Wm^2 and $\mathbf{c_2}$ = 0.0144 m K
  - emissivity and temperature are linked and yet underdetermined
  - emissivity → fundamental absorption band
    - 8 – 12 μm region *(clear portion of the Earth's atmosphere)*
    - most silicates, carbonates, sulfates, (as well as gases)

TIR Radiance

- **Emissivity**
  - wavelength-dependent, mineral-specific property
  - higher spectral resolution → more accurate analysis
  - must be separated from the temperature with an assumption
    - error can be introduced:
      - based on the assumption
      - spectral resolution
      - atmospheric window
      - mixing of emissivity
      - mixing of temperatures



Airborne TIR Data *(DCS)*

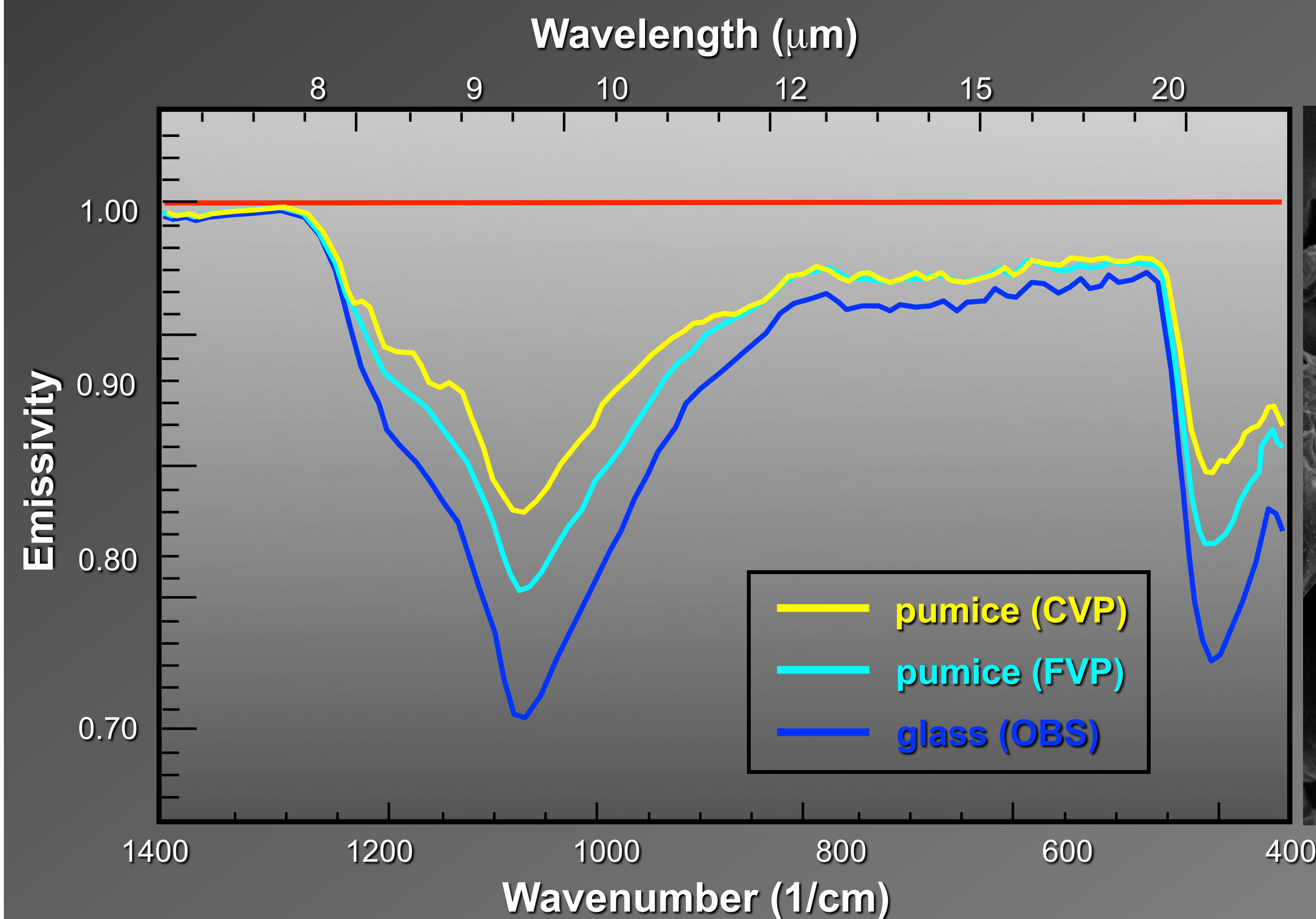


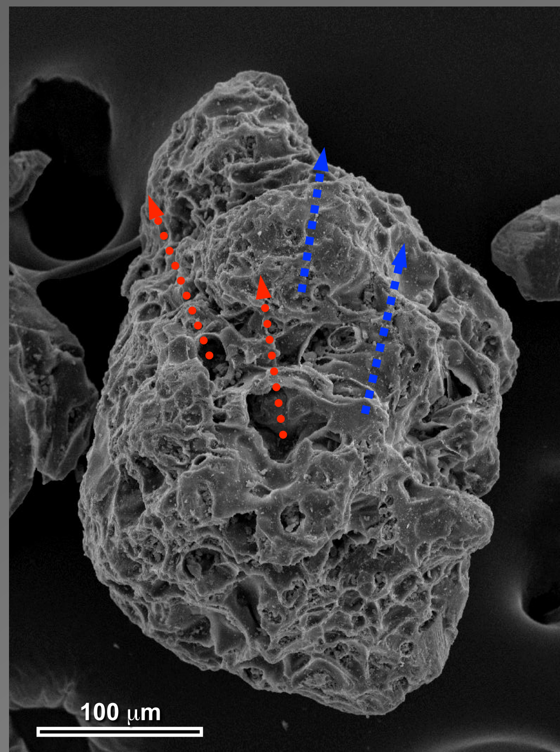
Medicine Lake Caldera, CA

TIR Radiance

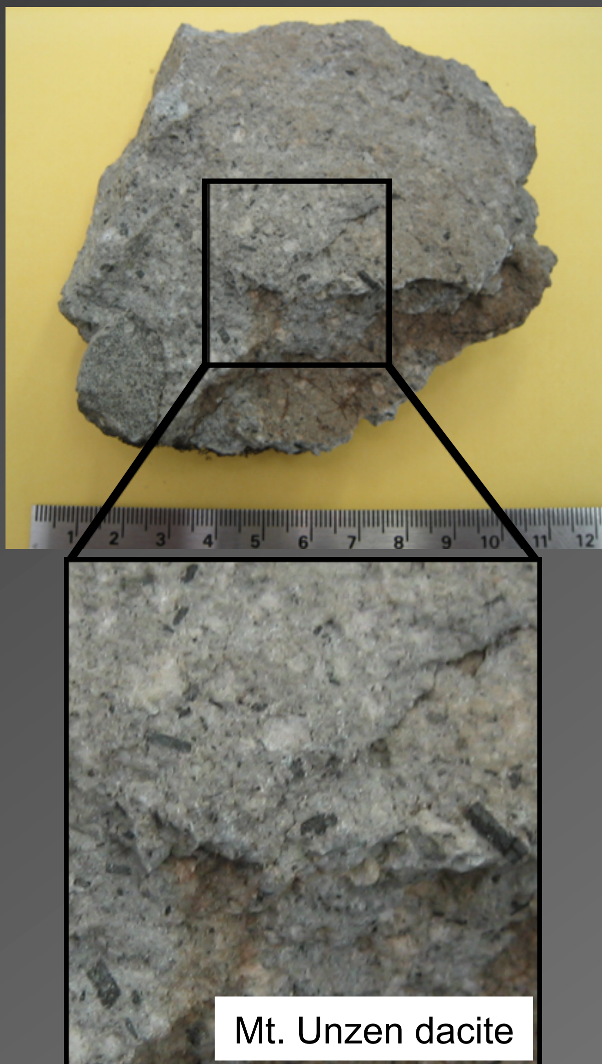
- **Spectral Deconvolution** *Ramsey & Christensen [1998]*
  - – series of techniques designed to extract information
    - below the scale of the pixel
    - and/or within a mixed spectrum
      - need some other *a priori* information *(i.e., spectral library)*
      - assumption of linear mixing is valid in the mid-IR region
        - characterized by particles being >> than the wavelength
        - most minerals have high absorption coefficients
      - invalid in certain cases
        - non-isothermal surfaces
        - very fine-grained (<60 μm) particles

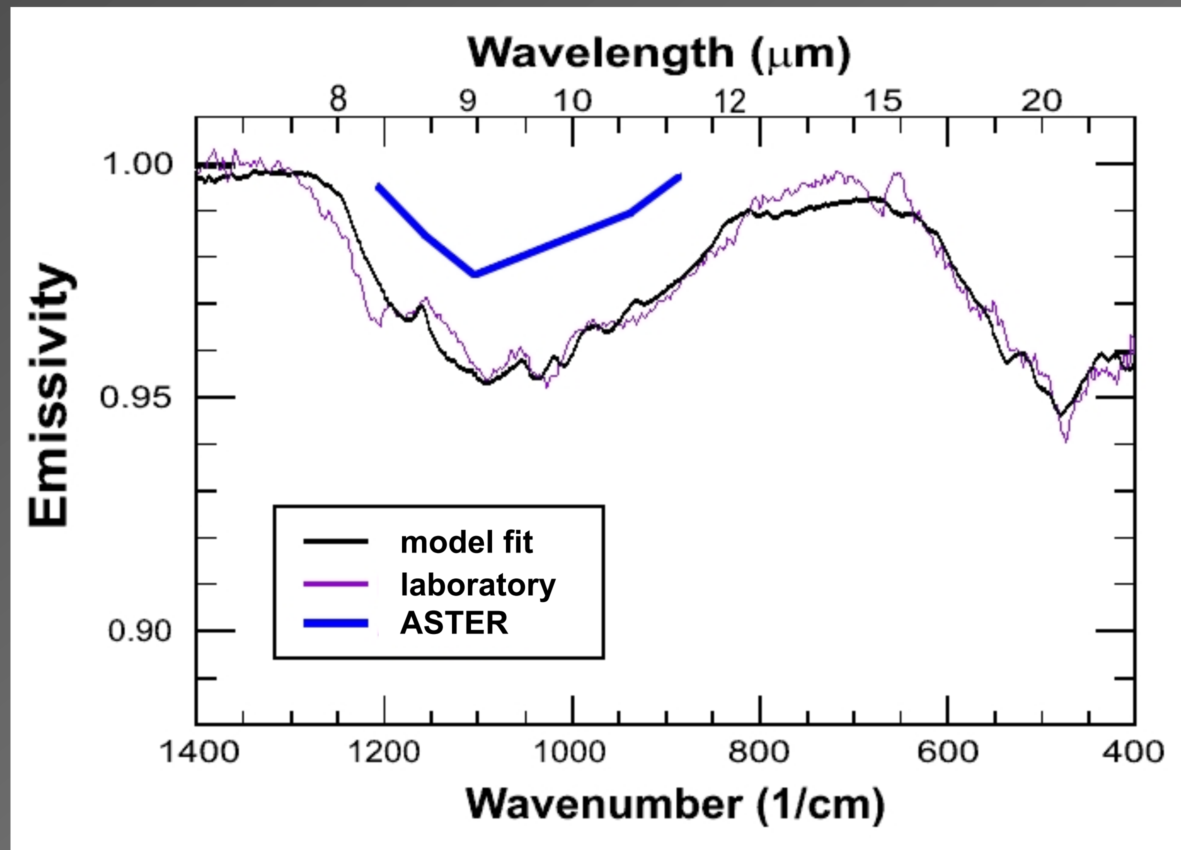
Deconvolution *(texture)*





Deconvolution *(composition)*



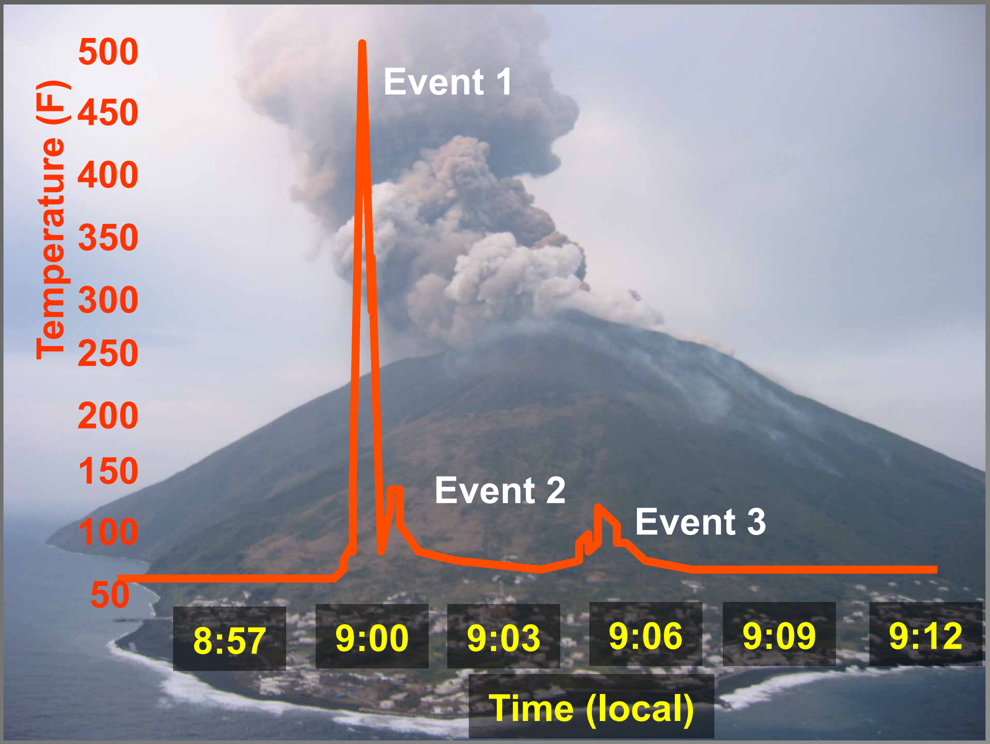


- **Plag: 37.9%**
- **Amp: 25.3%**
- **Clay: 17.5%**
- **Cpx: 13.5%**
- **Qtz: 5.9%**

TIR Radiance

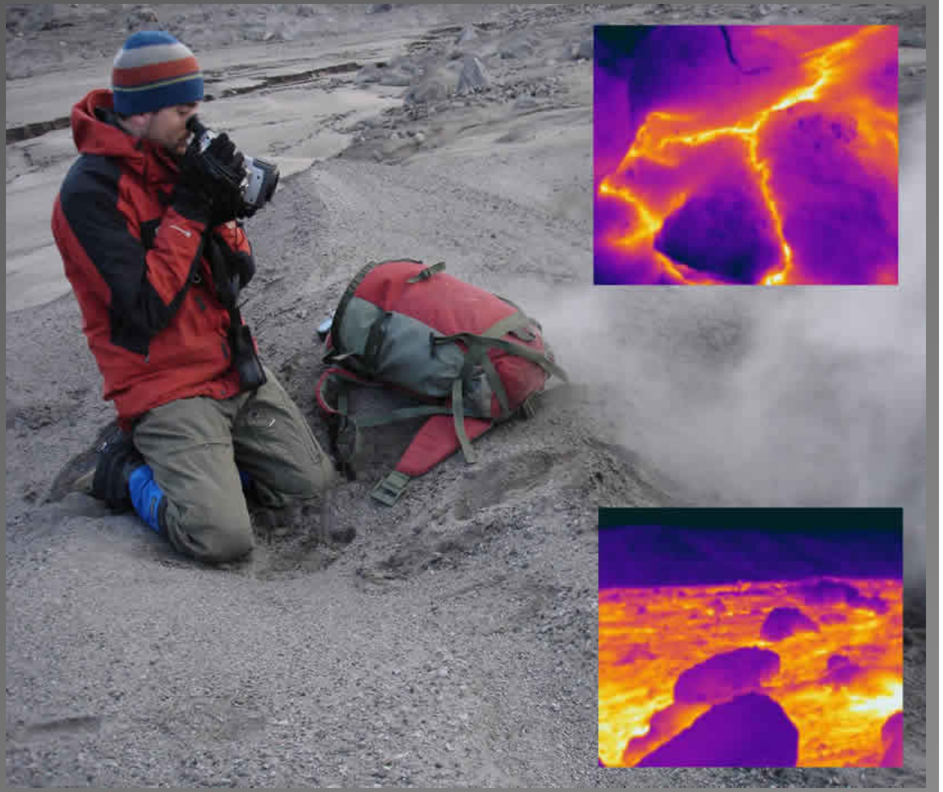
- **Temperature: Radiometers**
  - transmitting images at rates of 4Hz
  - ground-based thermal trace
  - 5 April 2003: Stromboli explosive paroxysm
    - collected at a rate of 54 Hz in real-time
    - allows event onset and development to be tracked with the same temporal precision

Rosi et al. [2006]

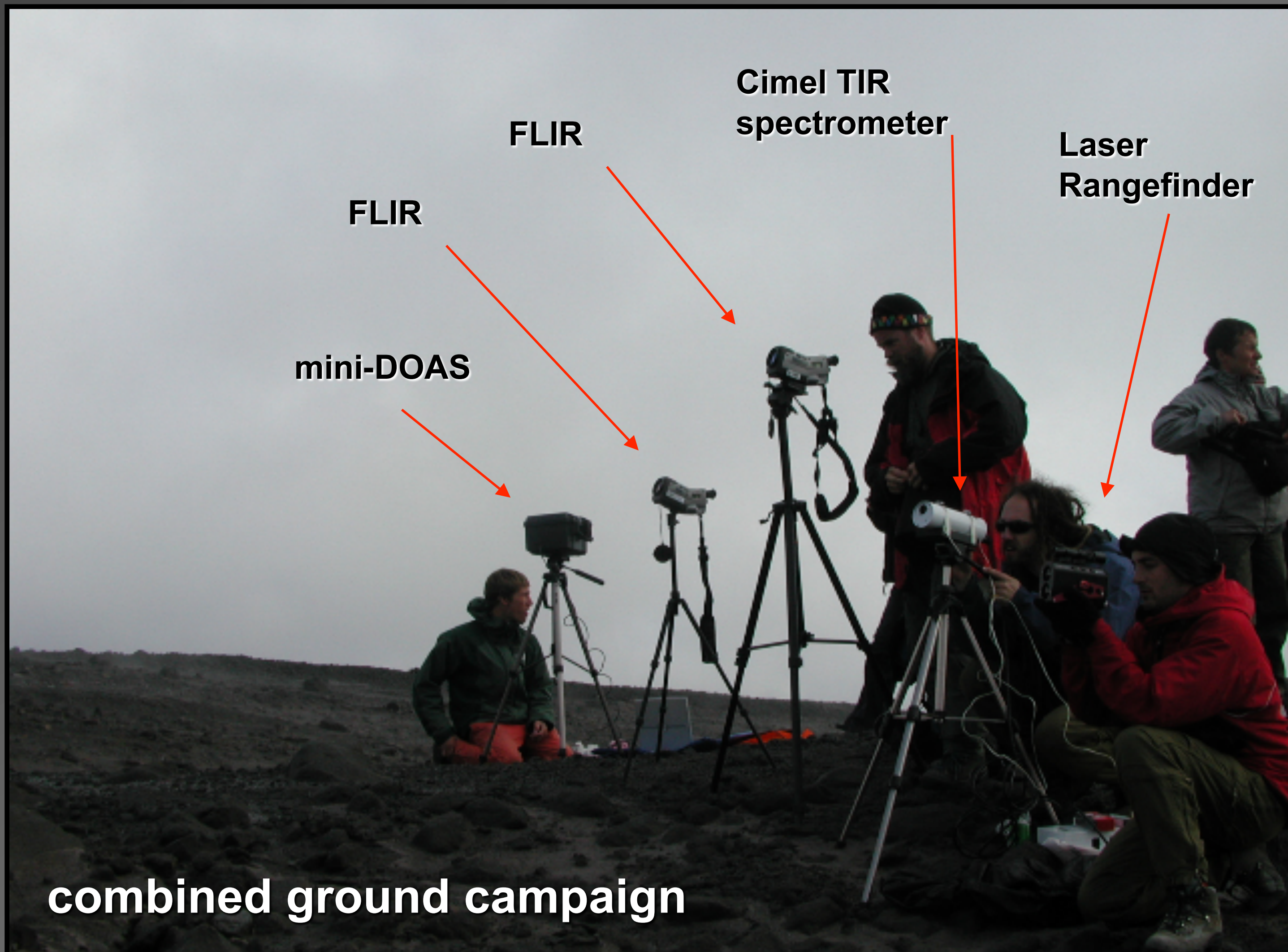


TIR Radiance

- **Temperature: FLIR Camera**
  - Forward Looking Infrared Radiometer S40 camera
  - broadband radiometer 7.5-13 μm (TIR window)
  - 320 x 240 pixels (76,000)
  - thermal sensitivity of < 0.1 °C at 30 °C
  - accuracy of +/- 2 °C
  - light weight (1.4 kg)
  - still (1 image/sec) or video (60 Hz) function available
  - three gain settings: -40°C to 120°C, 0°C to 500°C, and 350°C to 1500°C

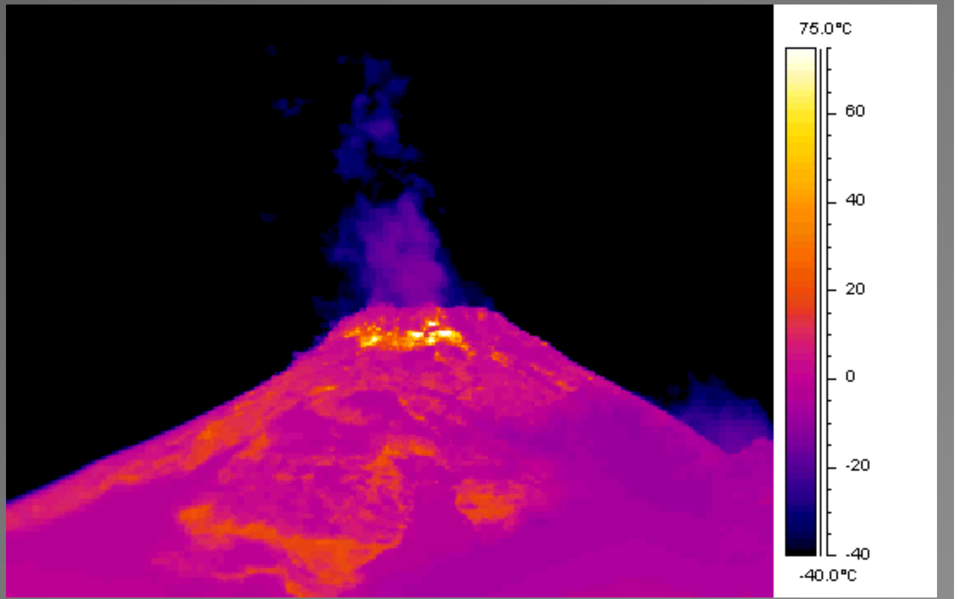


Complicating Factors



Complicating Factors

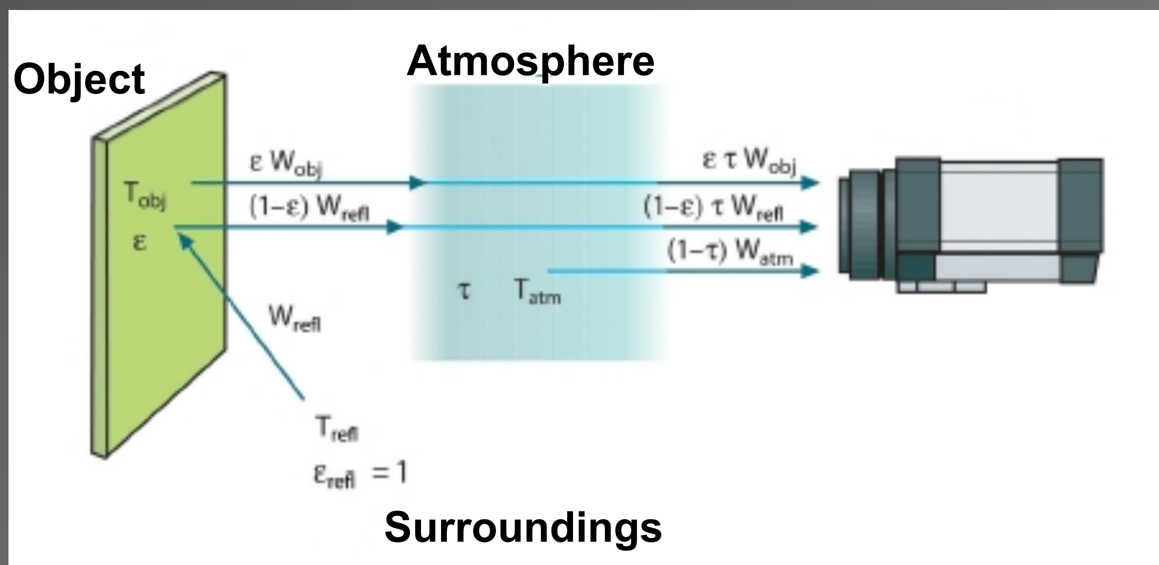
- **Operator Input Values:**
  - object emissivity (ε)
  - relative humidity (RH%)
  - object distance (D_{obj})
  - average atmospheric temperature (T_{atm})
  - reflected ambient temperature (T_{refl})



degassing of the Bezymianny lava dome

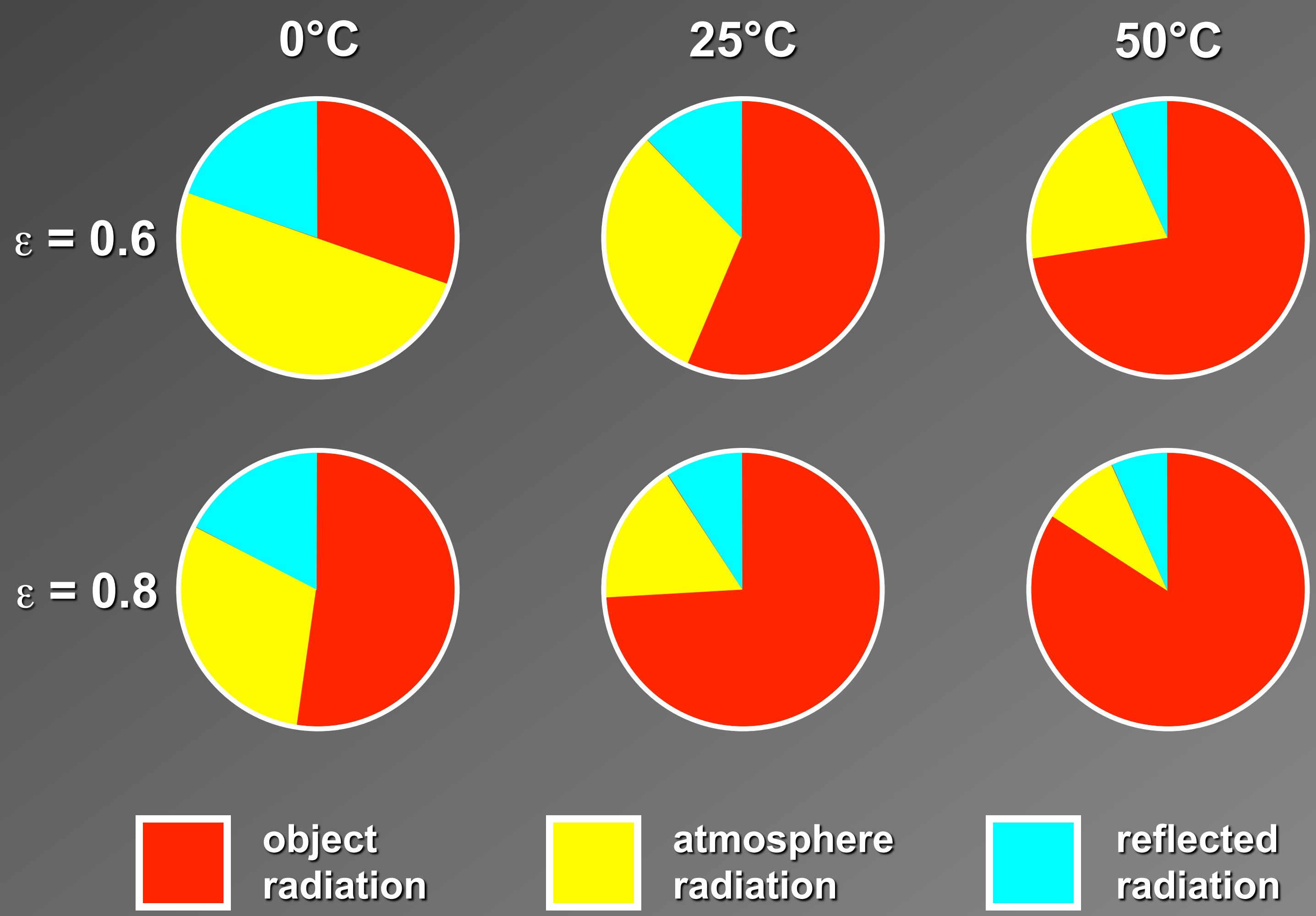
Complicating Factors

- **Measurement Conditions:**
  - need to account for other thermal energy sources
    - surrounding emitting objects
    - atmosphere
      - camera has built-in atmospheric look-up parameters



$$W_{tot} = \varepsilon\tau W_{obj} + (1-\varepsilon)\,\tau W_{refl} + (1-\tau)\,W_{atm}$$

Complicating Factors

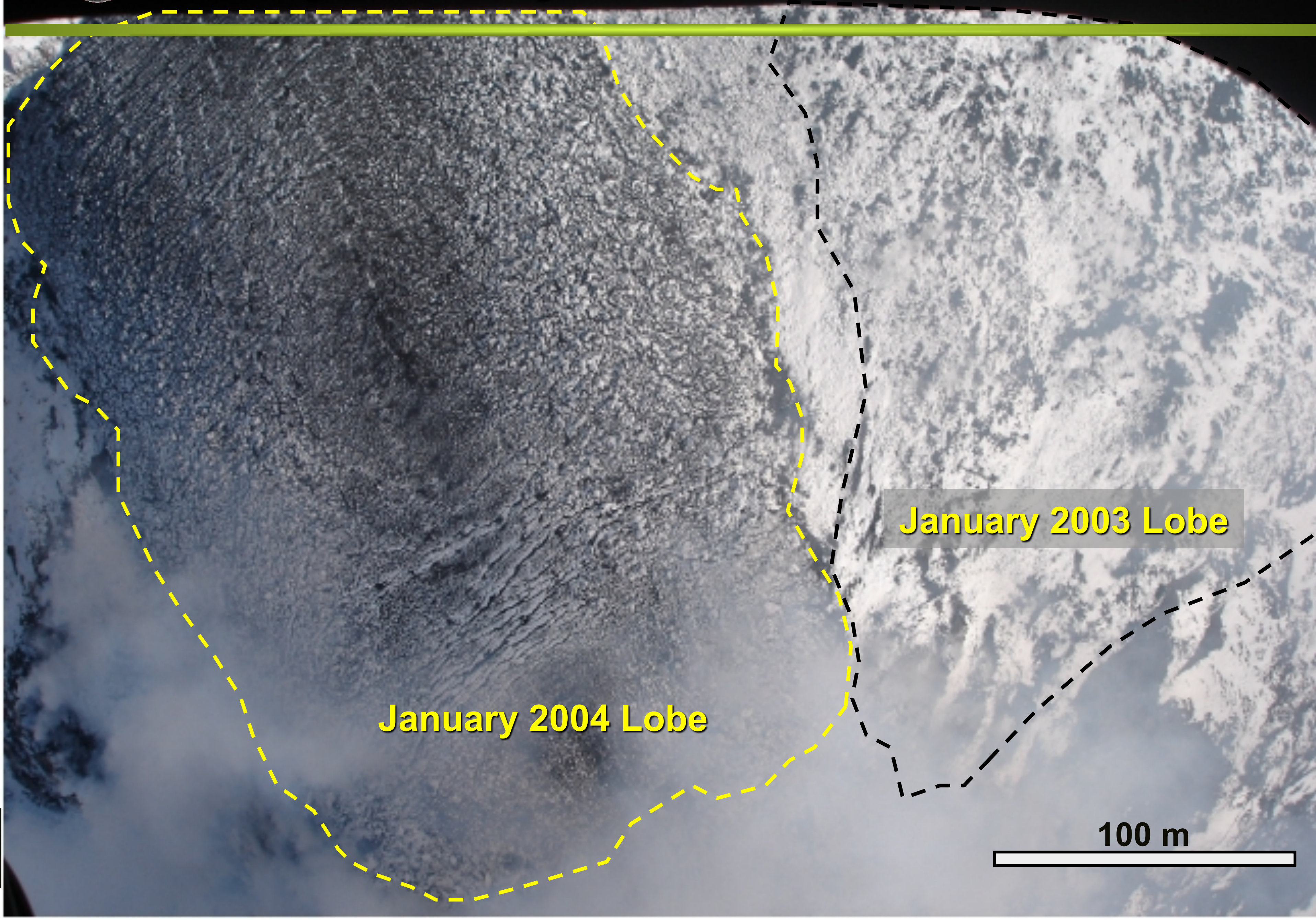


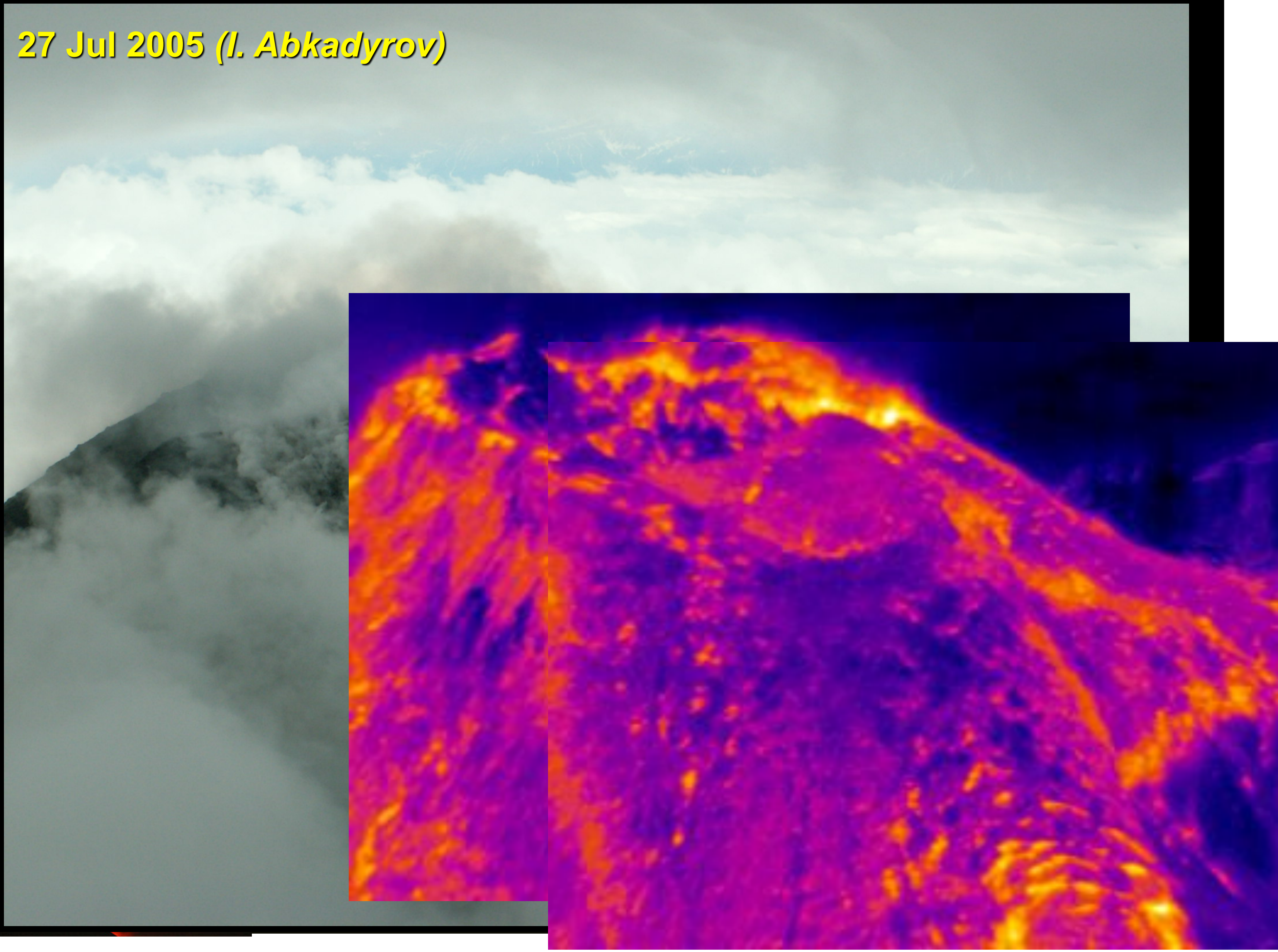
Example: Bezymianny V.

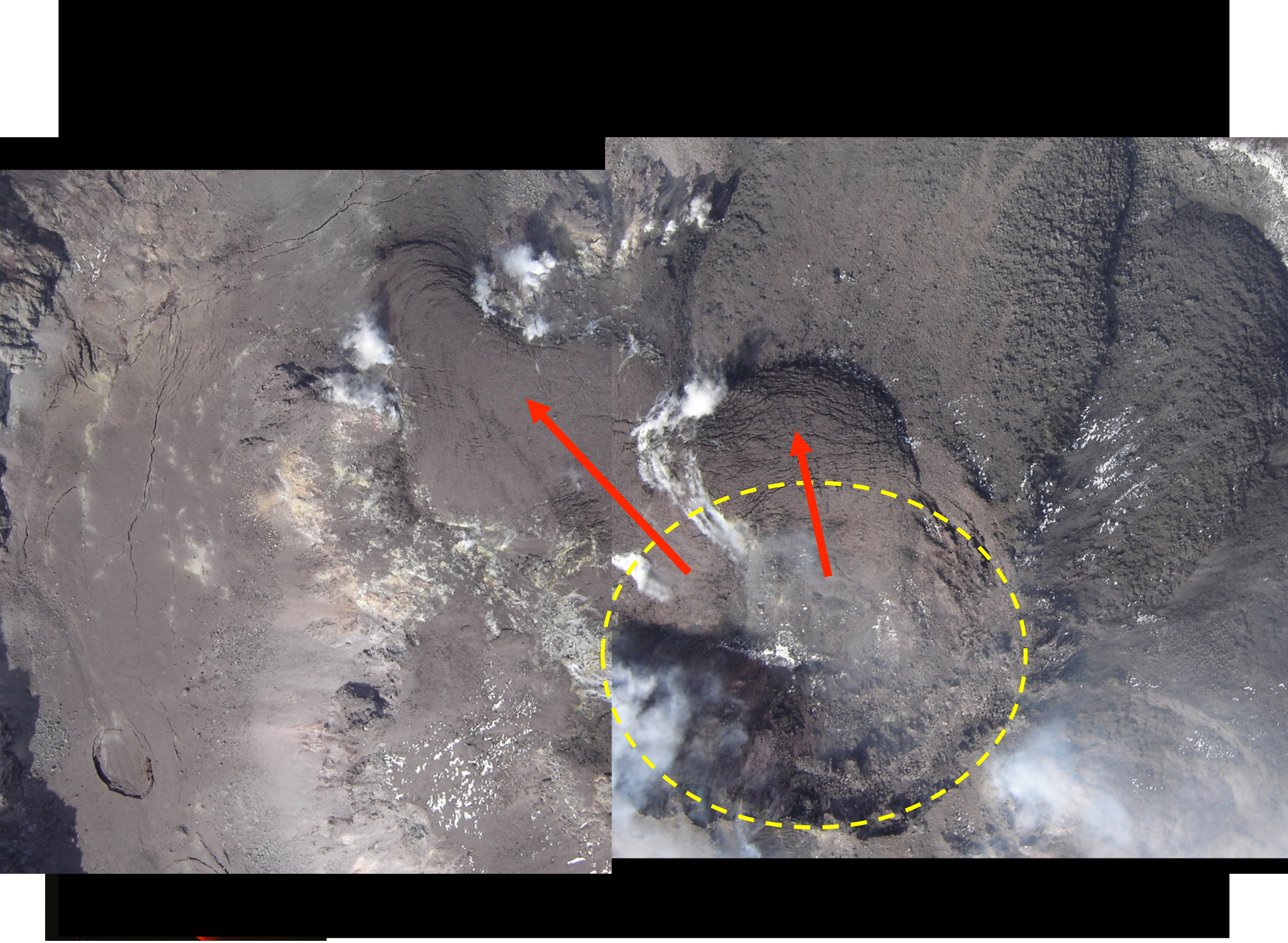
FLIR Data Collection

- **Airborne**
  - multiple field campaigns to examine thermal flux of the dome regions
    - 2004, 2005, 2007, 2011
  - coincident handheld thermal camera(s) (FLIR) and/or visible video data over the summit/dome
    - 500 – 800 m above dome
- **Ground Based**
  - long-distance acquisitions

Bezymianny V.

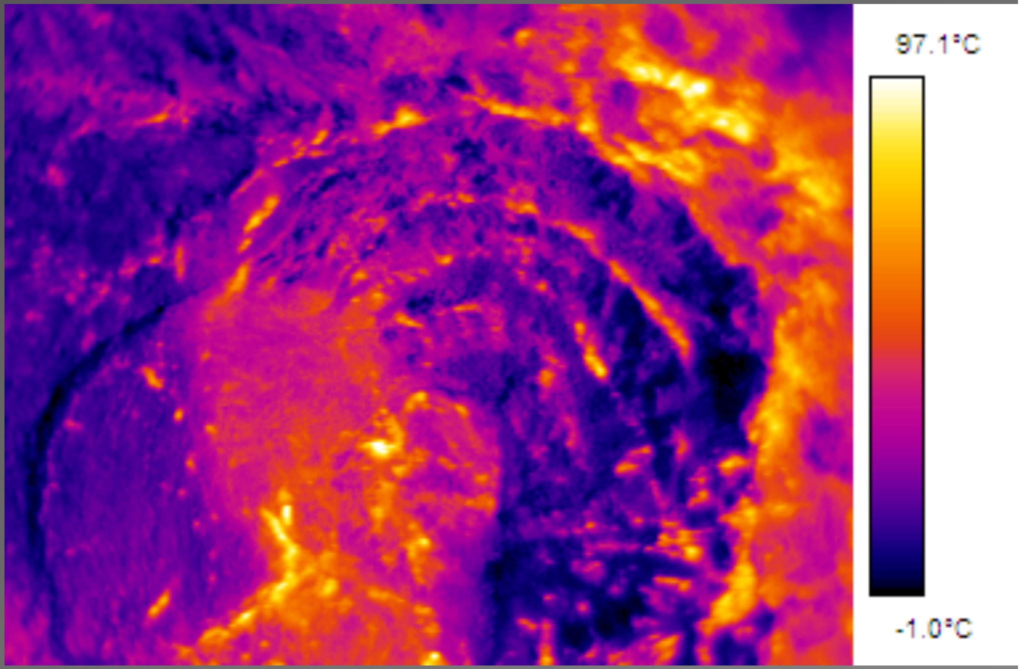



27 Jul 2005 (I. Abkadyrov)



Bezymianny: Results

- **How Was TIR Used?**
  - detection of a crater:
    - recent exogenous lobes draping crater rim
    - concentric scarps
    - collapse rather than explosive origin
      - new behavior at Bezymianny's dome



  - revealed a complex eruption sequence of explosion(s), viscous lava extrusion, and the formation of the crater
    - based on this sequence, the conduit could have become blocked/pressurized

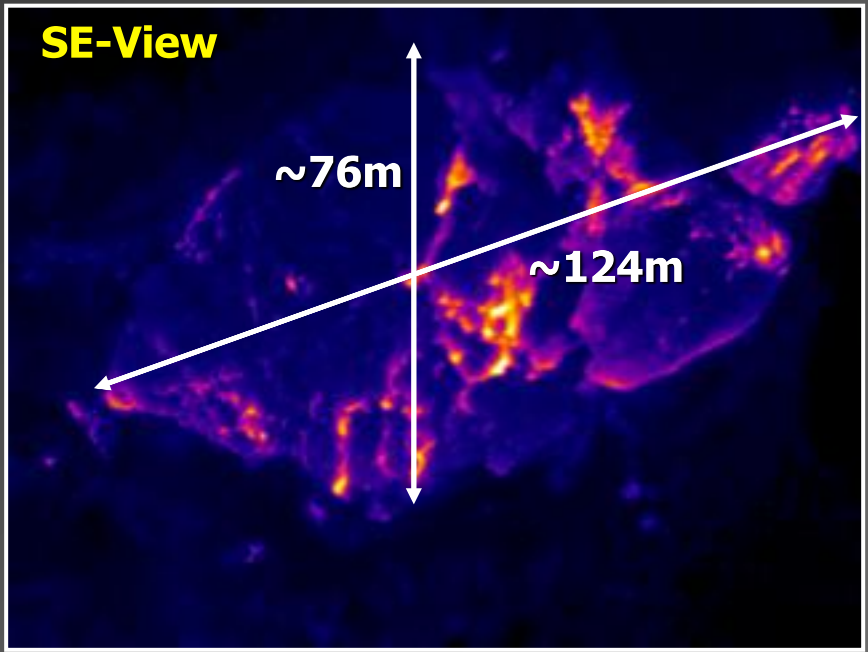
Carter et al. [2007]

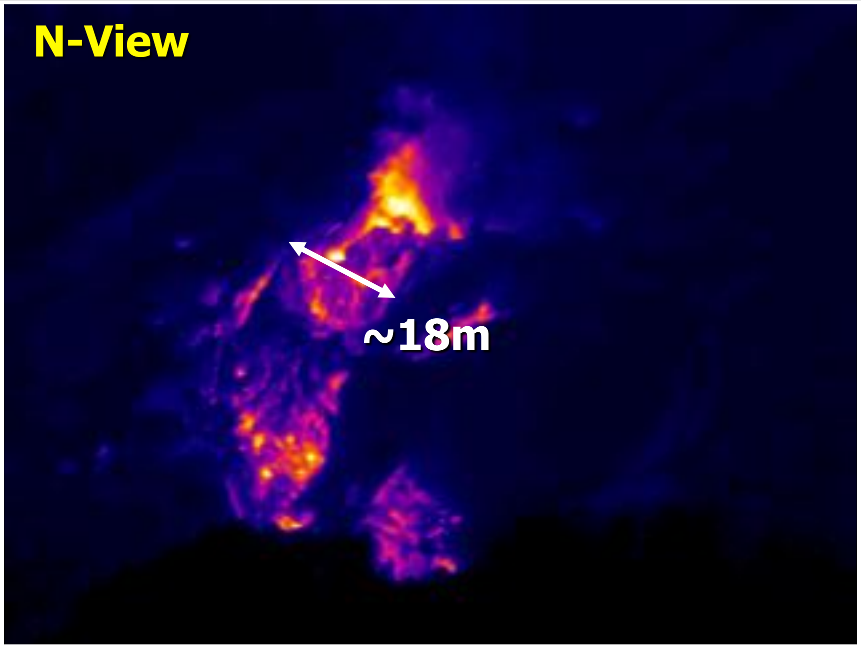
Example: Mt. St. Helens V.

FLIR Data Collection

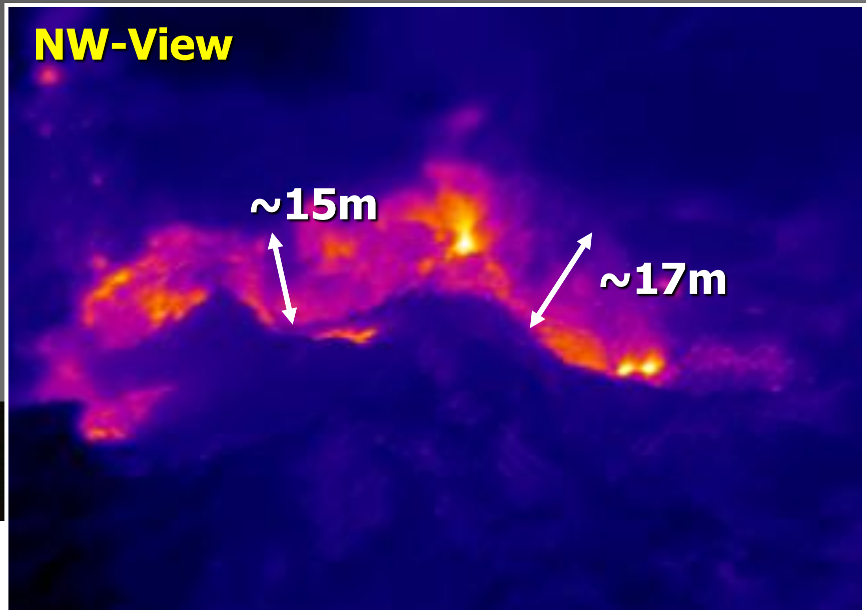
- **Helicopter Based**
  - both nadir and side viewing geometries
  - early phases of the 2004 eruption
  - commonly was the only verification of the new dome's morphology/size during the first two weeks
  - how was TIR used?
    - volume and extrusion rates calculated
    - thermal model created to forward-predict the timing of the dome's initial extrusion using pre-eruptive data

Volume Estimate: *Post Eruption*





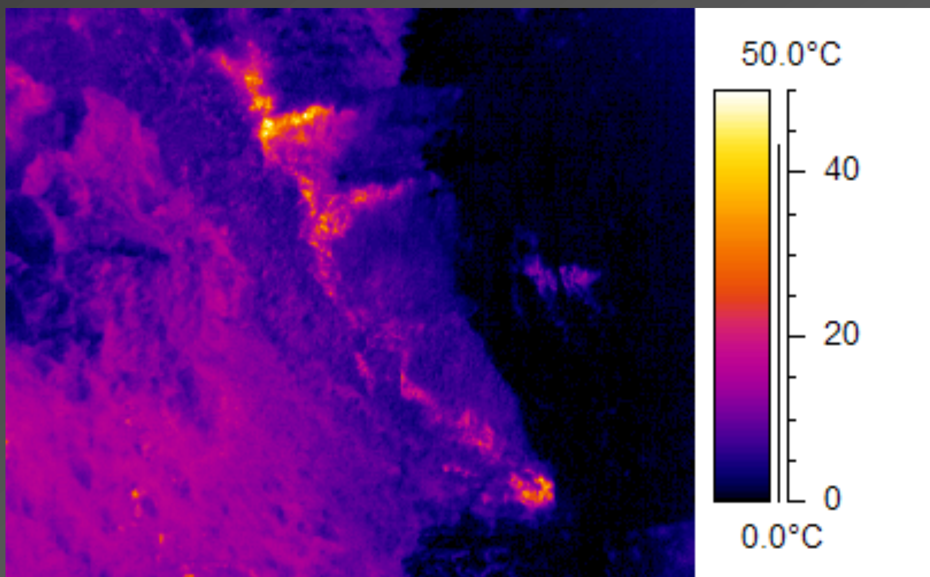
14 OCT 2004



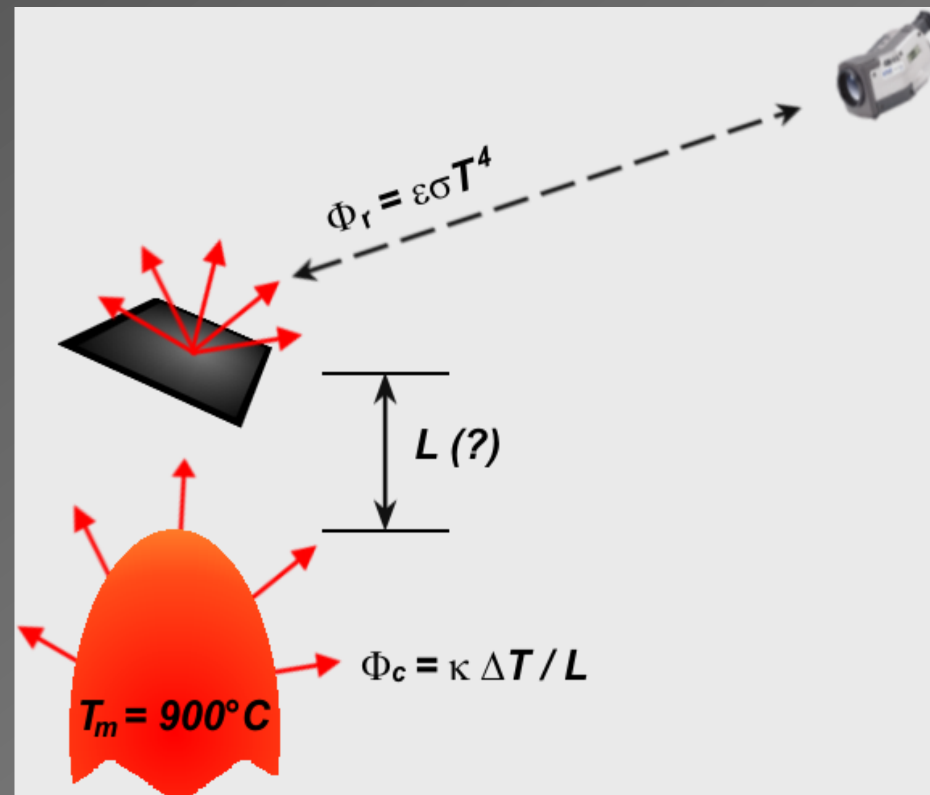
Extruded Volume:
~ 84,816 m^3

Post-Eruption Estimates

Modeling Approach: *Pre Eruption*

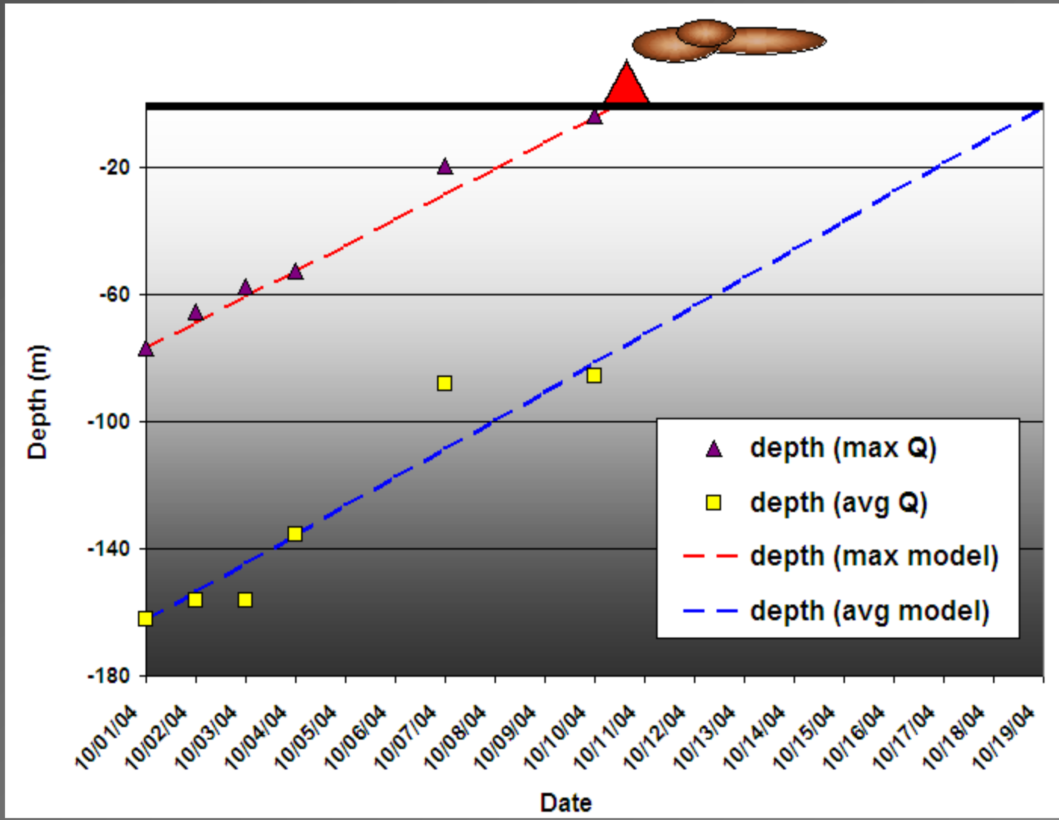


3 OCT 2004



Modeling Approach: *Pre Eruption*

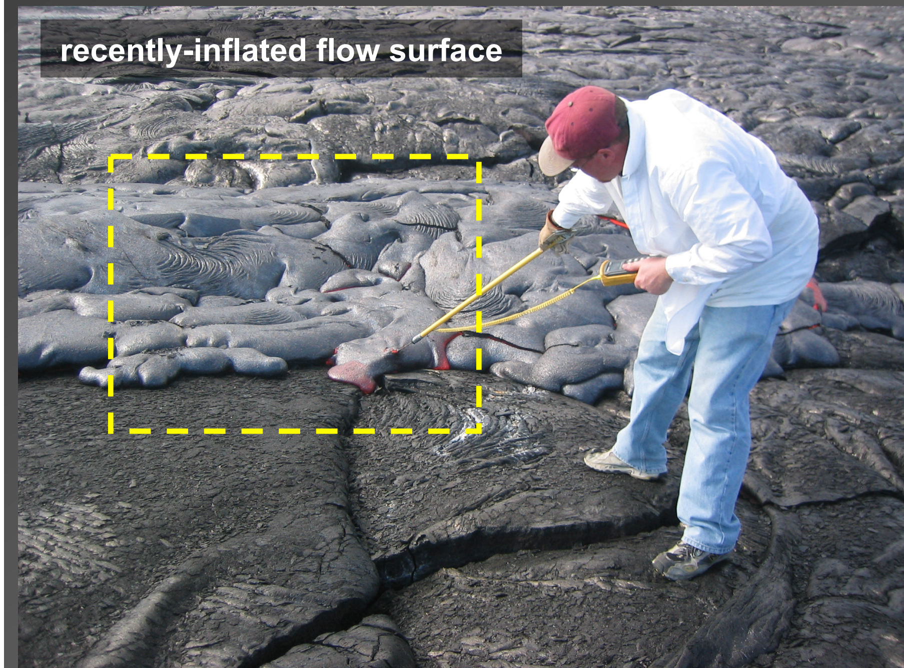
- **Radiative Heat Loss**
  - increased every observation day
    - linear trend inversely related to depth
    - average heat loss over the larger area
      - forecast dome extrusion 8 days late



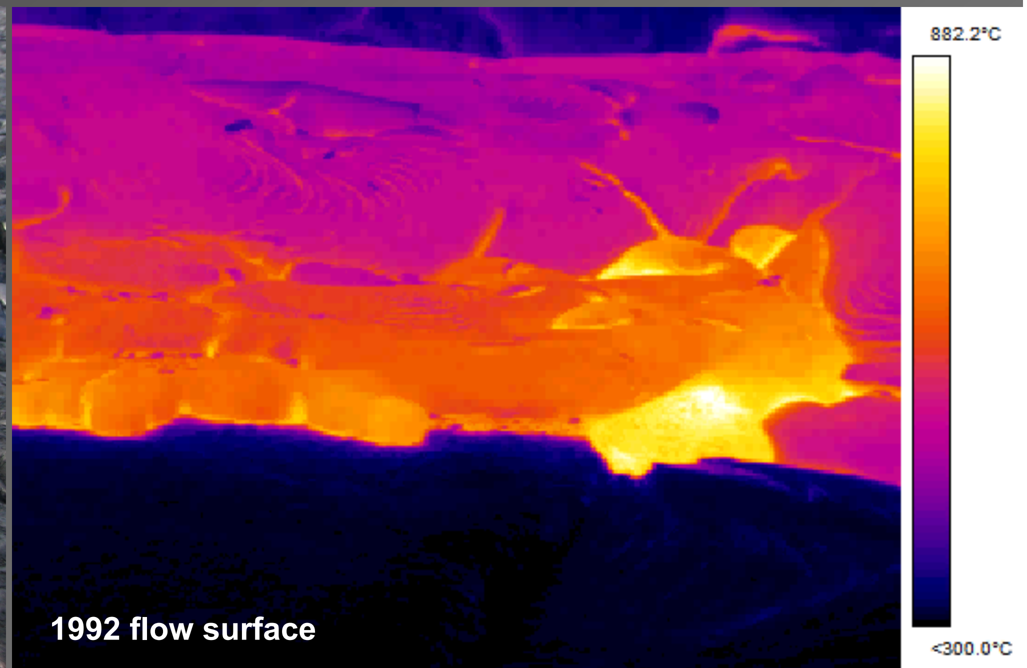
    - average heat loss over the hottest zone
      - forecast dome extrusion with 24 hours actual event

Ramsey et al. [2005]

Example: Kilauea V.



digital video image capture showing thermocouple measurement



FLIR radiant temperature video image
(data captured at ~ 15 images/sec)

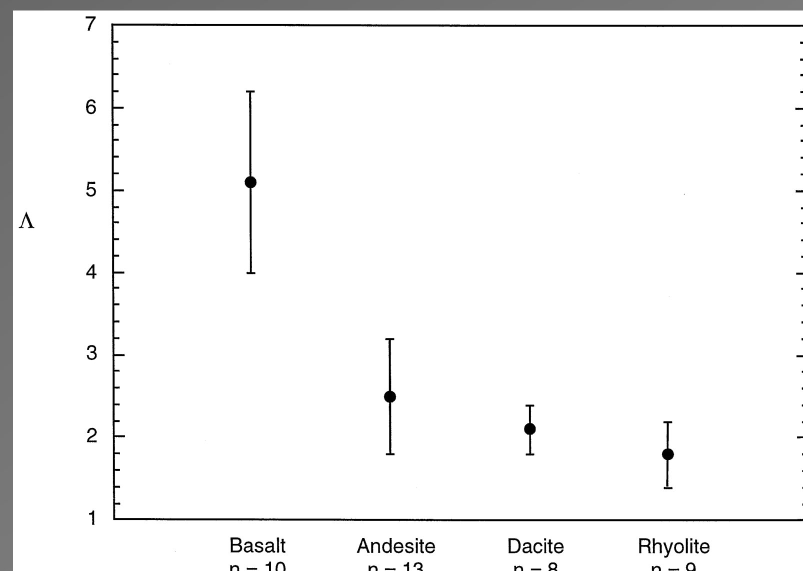
Flow Fold Formation

- **Relationships**

after Gregg et al. [1998]

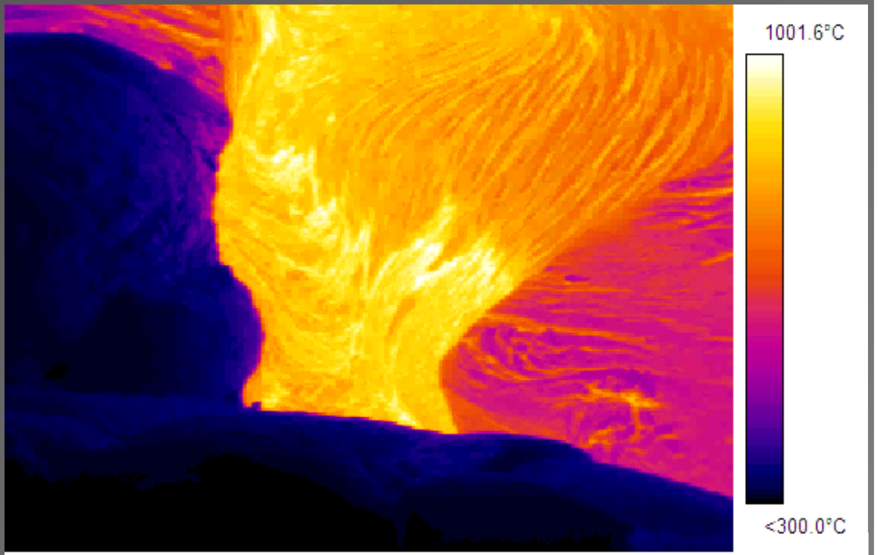
  - **$h = (1/\gamma)$ ln R**, where:
    - h = crust thickness
    - $\gamma = 1/L_d$
    - $R = (\eta_o / \eta_i)$
  - $\Lambda = L_2 / L_1$
    - Λ is a function of crust cooling + flow shortening
    - results:
      - $\Lambda_{basalt} = 5.1 \pm 1.1$

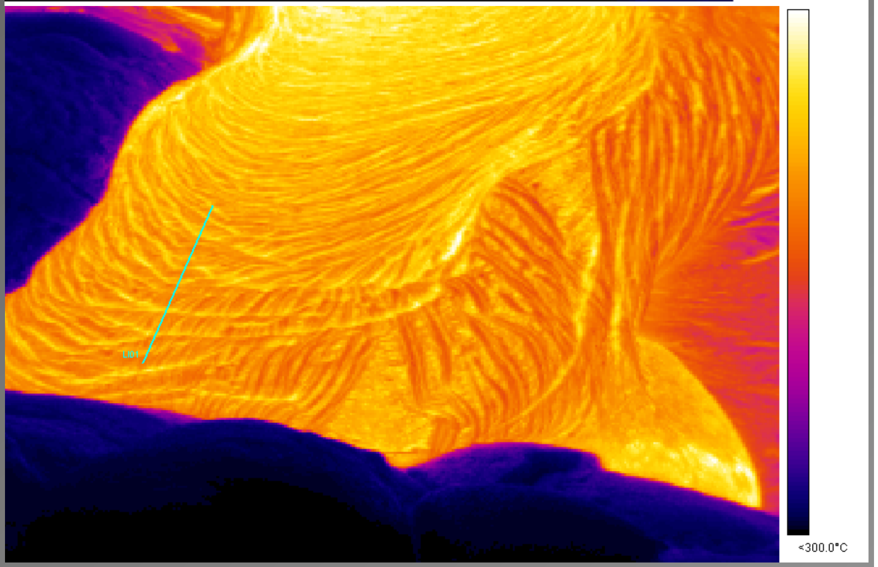
L_2 *(second generation fold)* is ~ 6 times larger than L_1 *(first generation fold)*



Flow Fold Formation

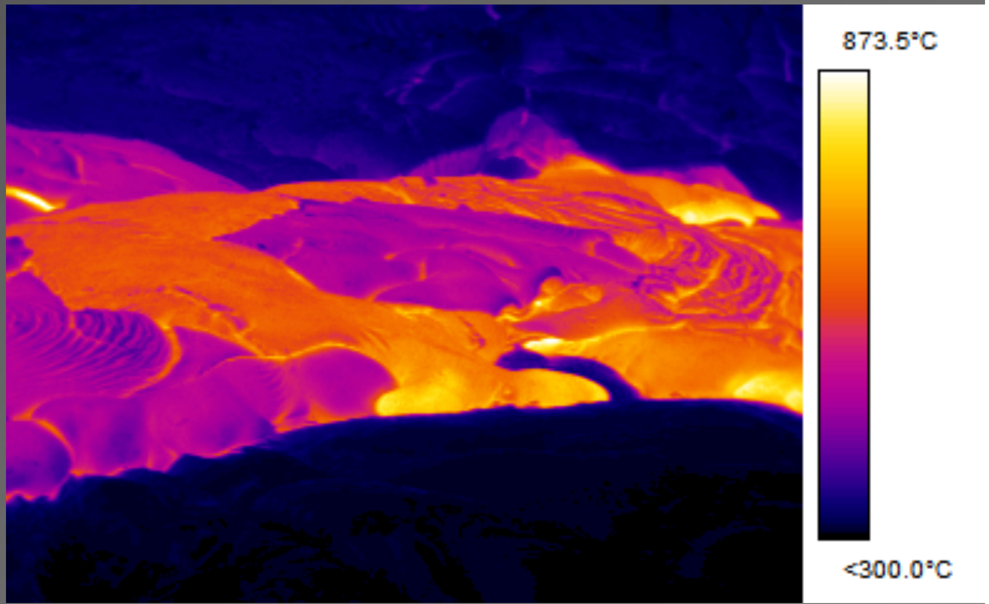
- **Results**
  - L_1 wavelengths:
    - 10.6 mm and 15.9 mm
    - $T_{formation}$ = 802°C
    - crust thickness (h):
      - 0.69 – 1.04 cm
  - L_2 wavelengths:
    - 31.8 mm and 37.1 mm
    - $T_{formation}$ = 768°C
    - crust thickness (h):
      - 2.08 – 2.42 cm
  - $\Lambda = 2.6 \pm 0.3$
    - differs from Gregg by ~ 2x





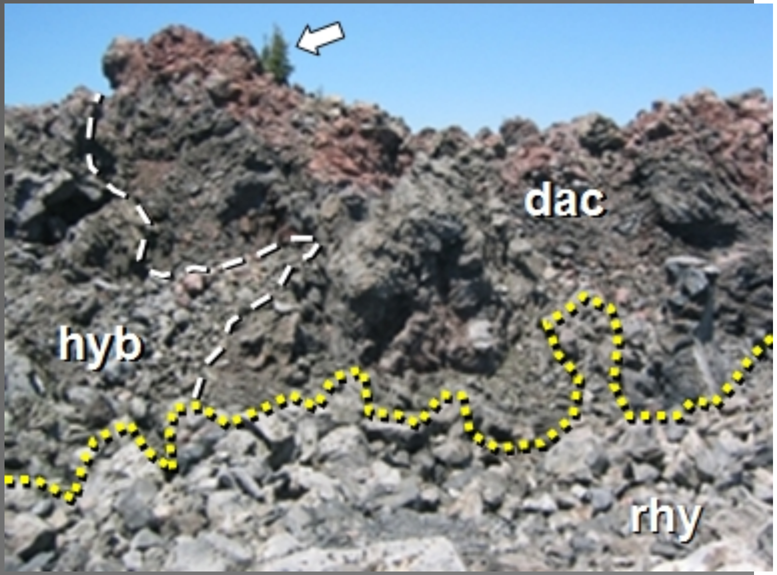
Kilauea Results

- **How Was TIR Used?**
  - interest in the emissivity response to change of state
    - structural composition of the melt / radiative efficiency of the flow
    - initial crust formation (micron-scale) derived from emissivity
    - cooling and continued crust formation derived from flow folding
      - initial folding at scales different from *Gregg et al. [1998]*
      - suggests cooling (not compression/thickening) is more important initially for basalt flows



Example: Multispectral FLIR

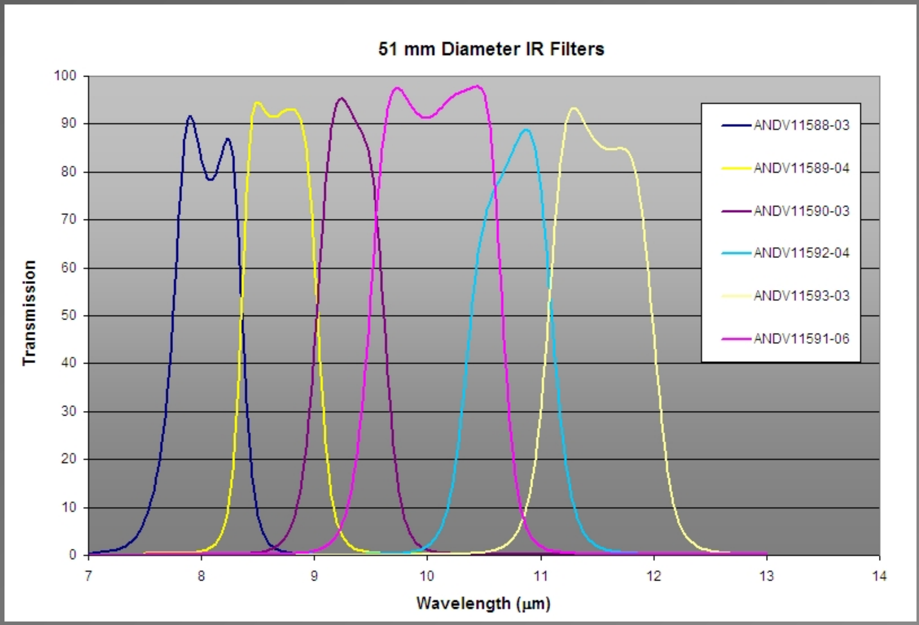
- **Medicine Lake Volcano, CA**
  - located 50 km N-NE of Mt. Shasta Volcano, USA
  - bimodal volcanism *(extensional regime)*
    - older, peripheral calc-alkalic basalt flows
    - younger, summit rhyolite / dacite domes



  - Big Glass Mountain (BGM)
    - variable composition (63 - 74 wt. % SiO_2) *[Donnelly-Nolan, 1990]*
    - complex mixing / emplacement dynamics *[Eisinger et al., 2000]*
    - overprinting of composition and texture causes complications in the TIR emissivity data

Filter Specifications

- **Fabricated: Andover Corporation, Salem, NH**
  - wavelengths: 8.3, 8.6, 9.0, 9.8, 10.6 & 11.3 μm ±0.15
  - bandwidths: 0.5 μm *(8-9 μm)*, 1.0 μm *(9-12μm)*
  - transmission: 70% (min)
  - blocking: 7.5 - 13.0 micron
  - size: 51.0 ±0.2
  - thickness: 2 - 3 mm
  - substrate: Germanium
  - construction: SWP/LWP, ring-mounted
  - polarization: Random



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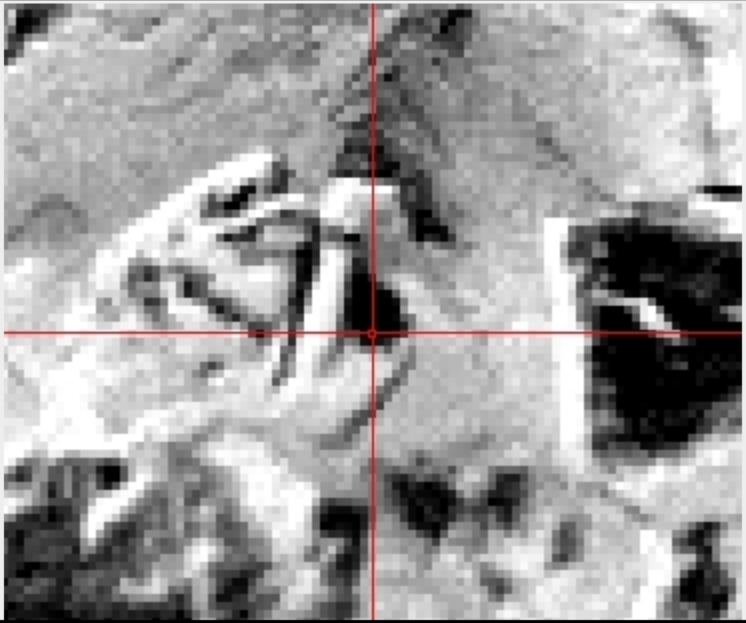
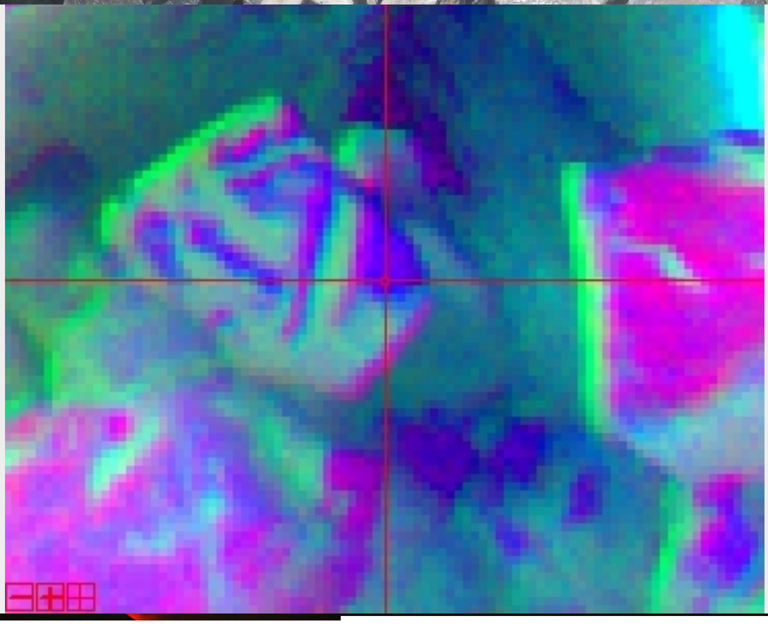
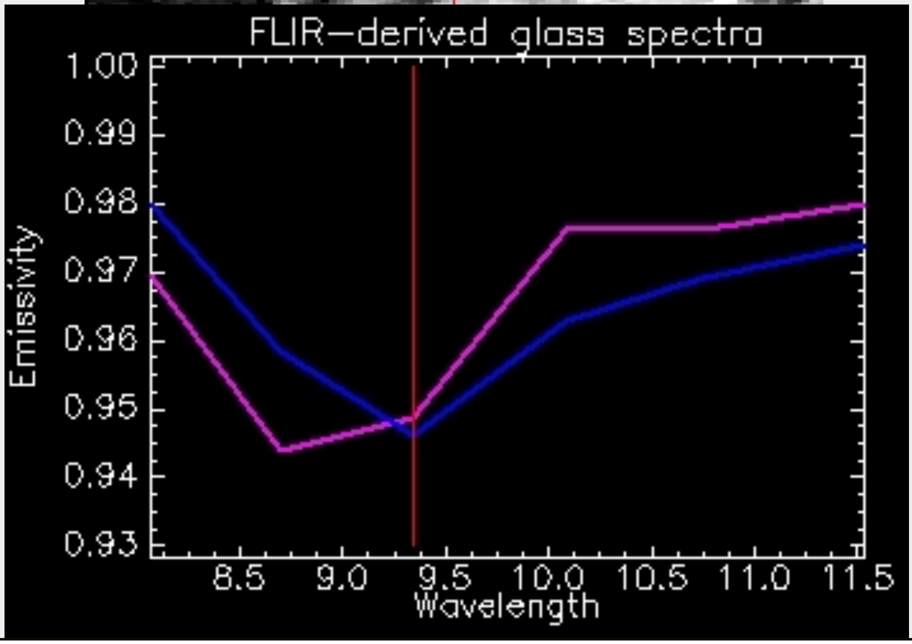
Compositional Mapping





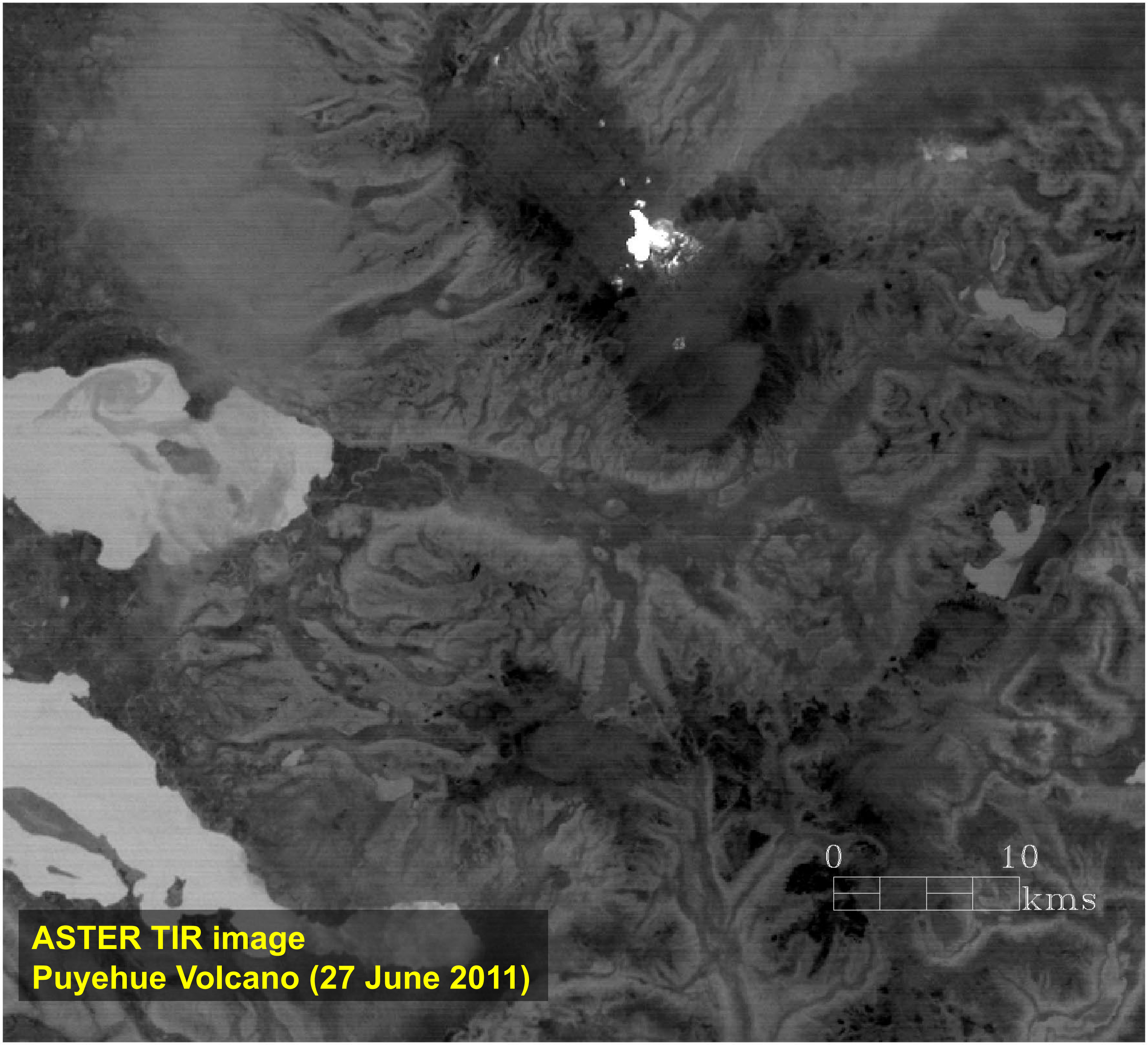


Conclusions I

- **Ground-Based TIR Measurements of Volcanic Surfaces**
  - ideal for indirect (“brightness”) temperature measurements
    - both near and far field
    - detection of new flows/deposits/dome processes
    - instantaneous heat flow/thermal flux over time
      - can be used as inputs into models of heat loss, crust formation, flow development, and magma rise time
    - caution where scaling through a long atmospheric path length and/or “warm” targets
  - integration with other monitoring tools/models
    - especially critical for magma rise, gas emission, petrology,
    - remote sensing

Conclusions II

- **Can Be Expanded To Extract Emissivity**
  - *one approach:* multispectral filters mated with a thermal camera
    - derive compositional and textural variations on flow surfaces
    - more accurate estimates of sub-pixel temperatures
    - preliminary results appear promising
      - compositional variability on glassy lava domes
      - initial testing for SO_2 absorption at Poas Volcano
  - future work here
    - analysis of filter anomalies
    - scripting for faster post-processing
    - filter automation & new mounting hardware
      - application to more dynamic processes
      - automated tool for monitoring


0
10
kms
ASTER TIR image
Puyehue Volcano (27 June 2011)