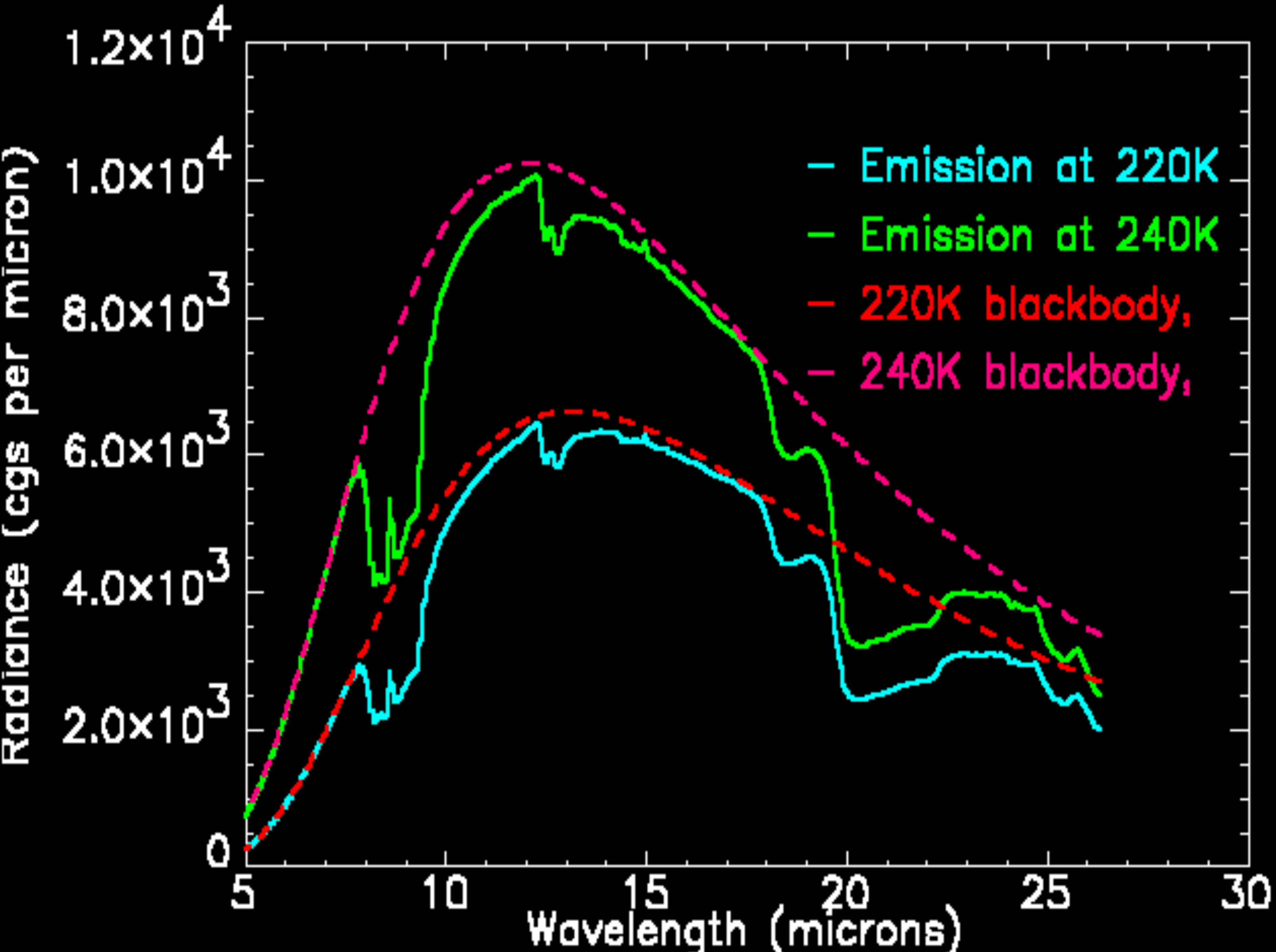
Thermal-Infrared imaging

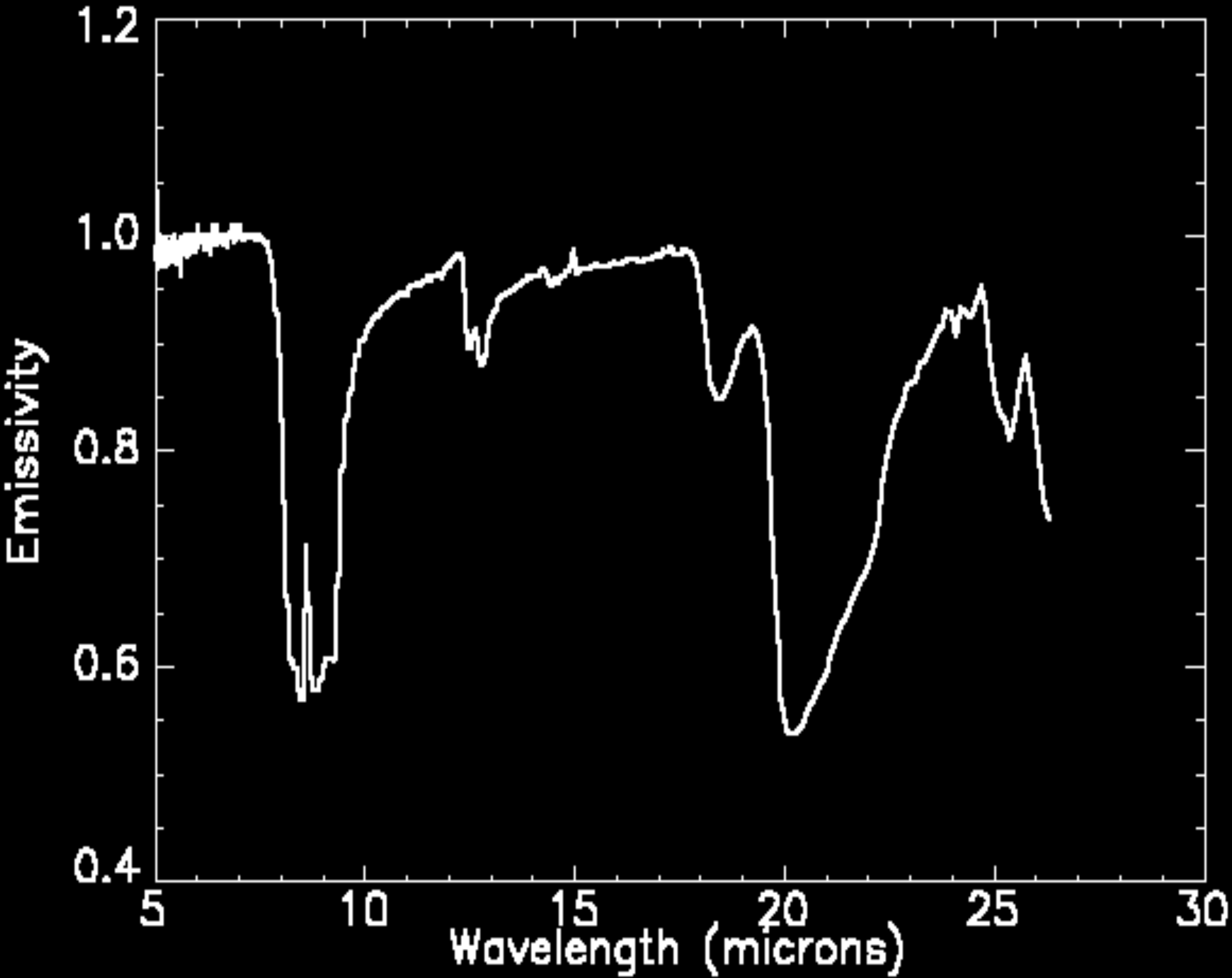
What is it?

- measurement of emitted radiation (temperature)
- at one or more times (thermal inertia)
- at one or more wavelengths (composition)

Why bother?

- see at night
- temperatures
- energy fluxes
- material properties (resistance to temperature change, i.e. thermal inertia)
- composition (emissivities)

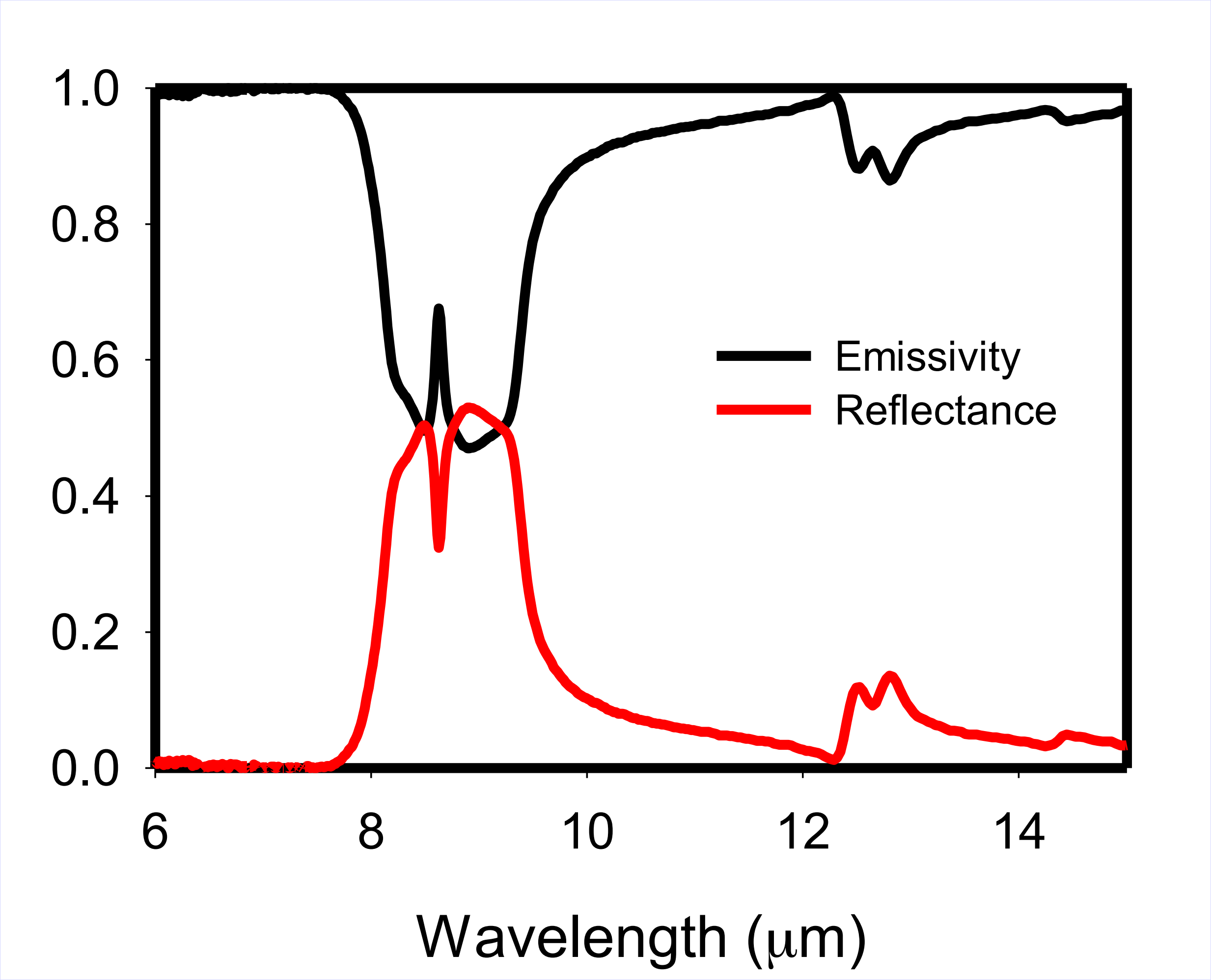

Radiance (cgs per micron)
1.2x10^4
1.0x10^4
8.0x10^3
6.0x10^3
4.0x10^3
2.0x10^3
0
5
10
15
20
25
30
Wavelength (microns)
Emission at 220K
Emission at 240K
220K blackbody,
240K blackbody,



Emissivity
1.2
1.0
0.8
0.6
0.4
5
10
15
20
25
30
Wavelength (microns)

Kirchhoff's Law

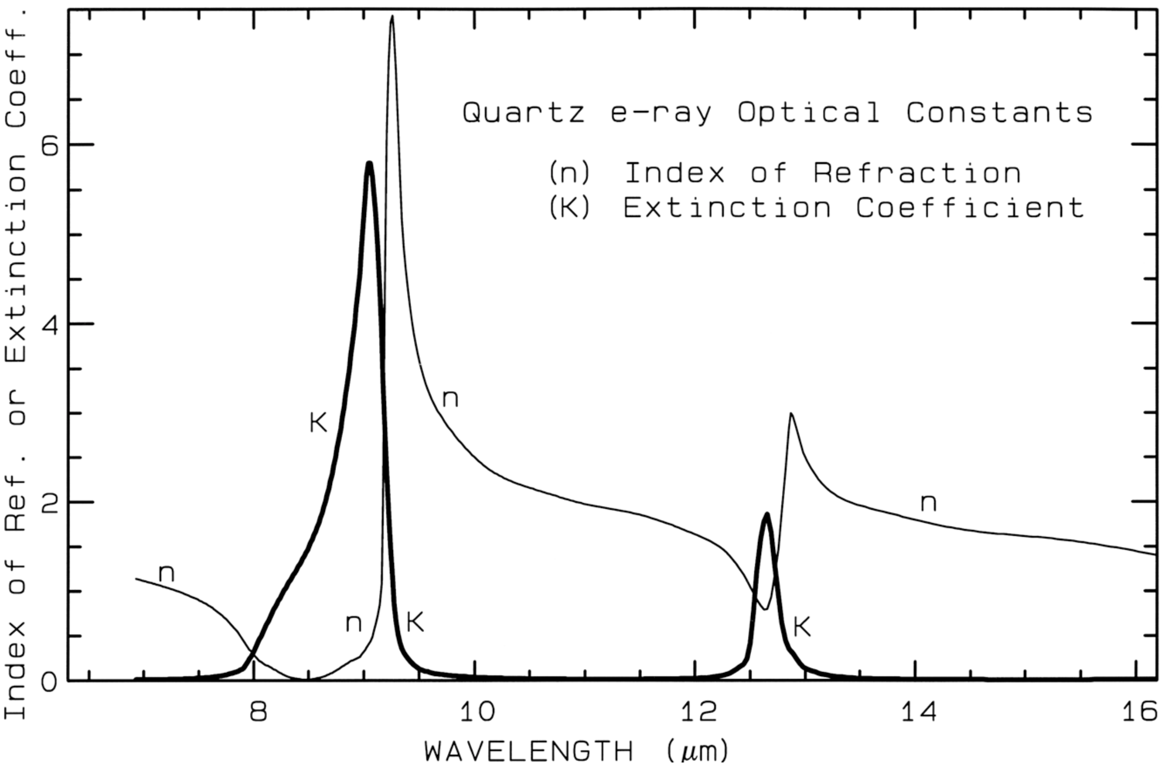
$$\varepsilon = 1 - R$$

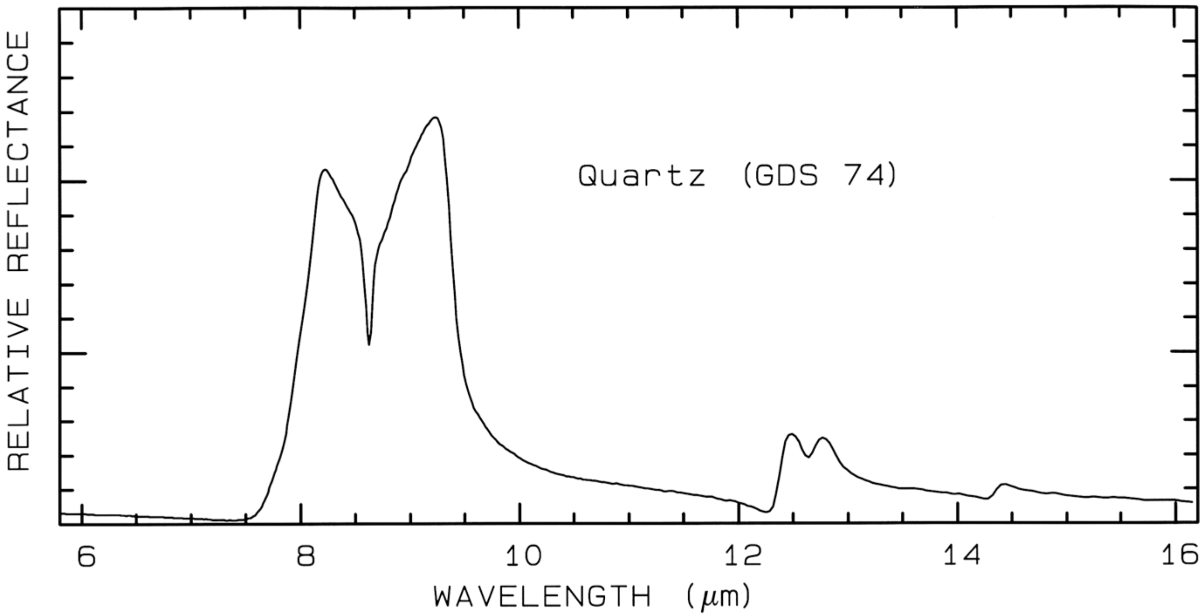


Restrahlen band: *k* maximized at fundamental vibration mode frequency

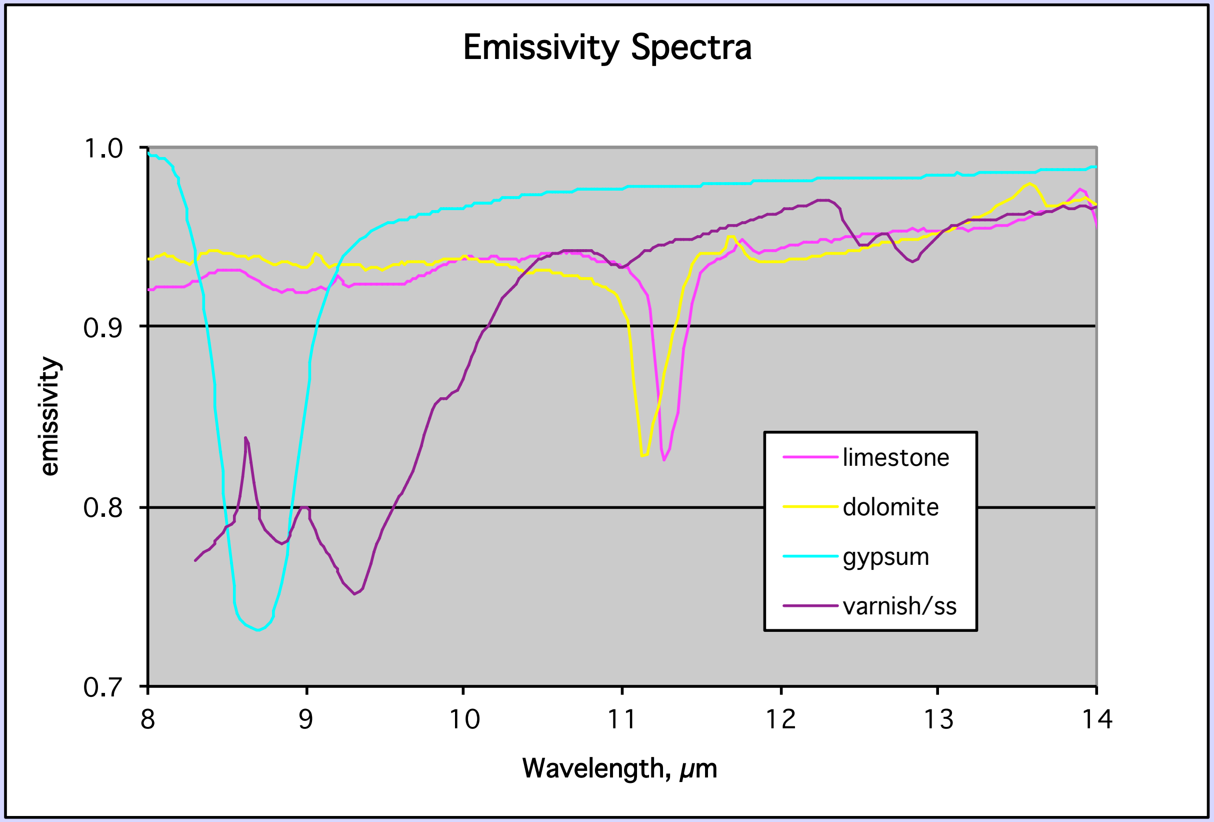
Christiansen frequency: $n = 1$, minimizing reflectance

Reflectance or emission spectrum results from combination of n, k variations

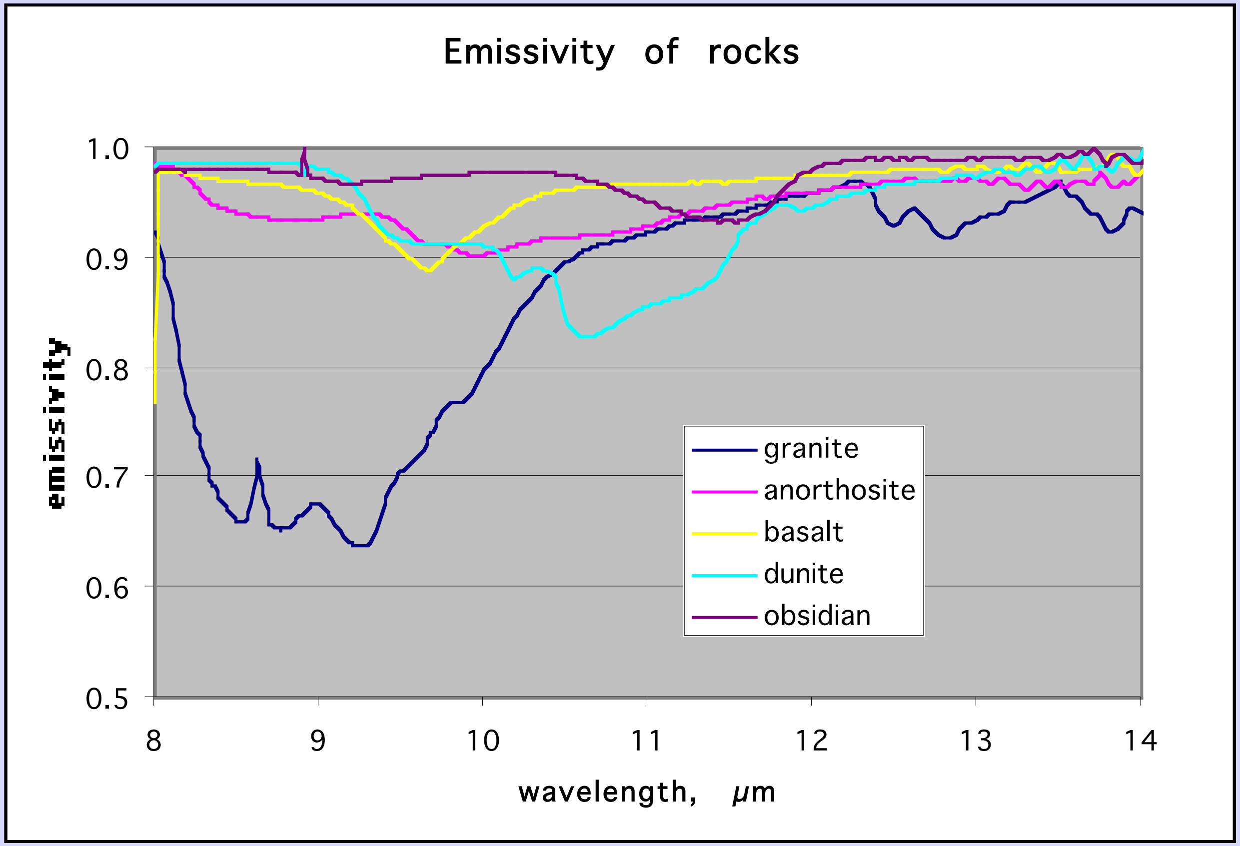




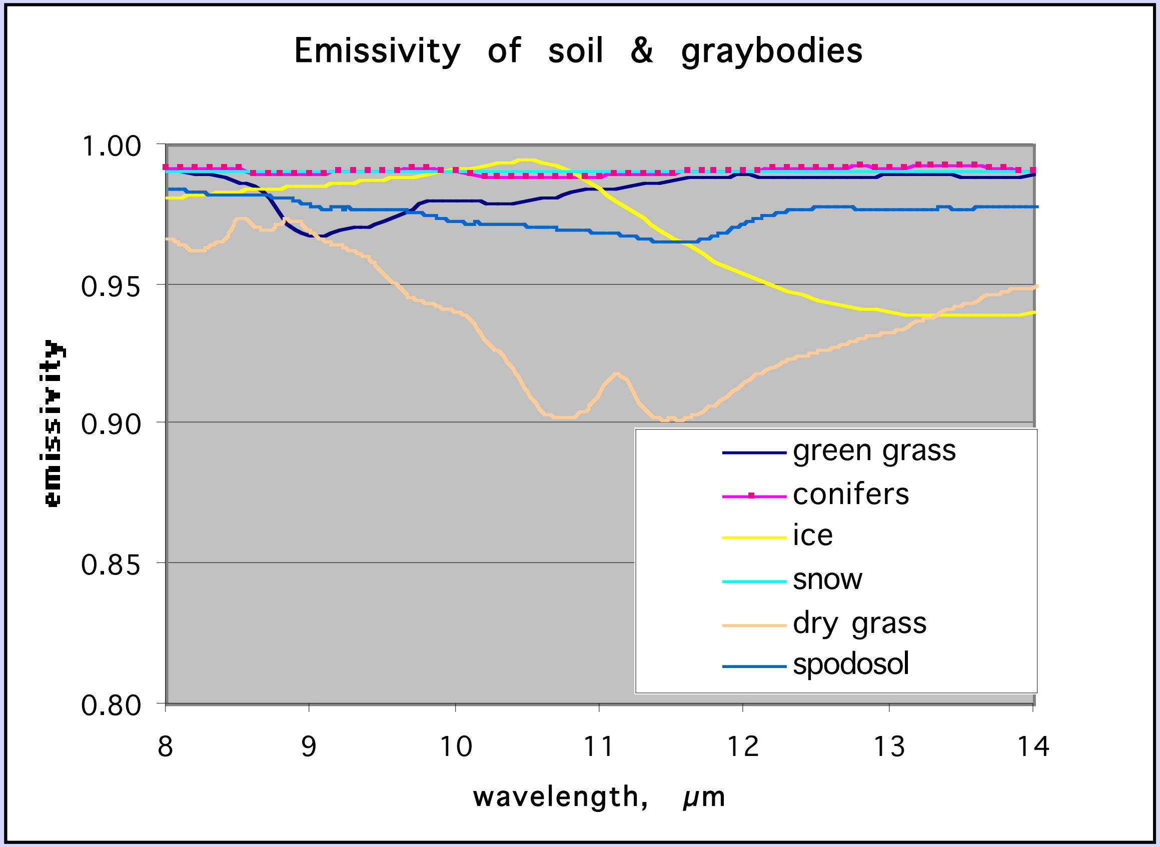
Emissivity spectra of rocks



Emissivity spectra of rocks



Emissivity spectra of approximate graybodies

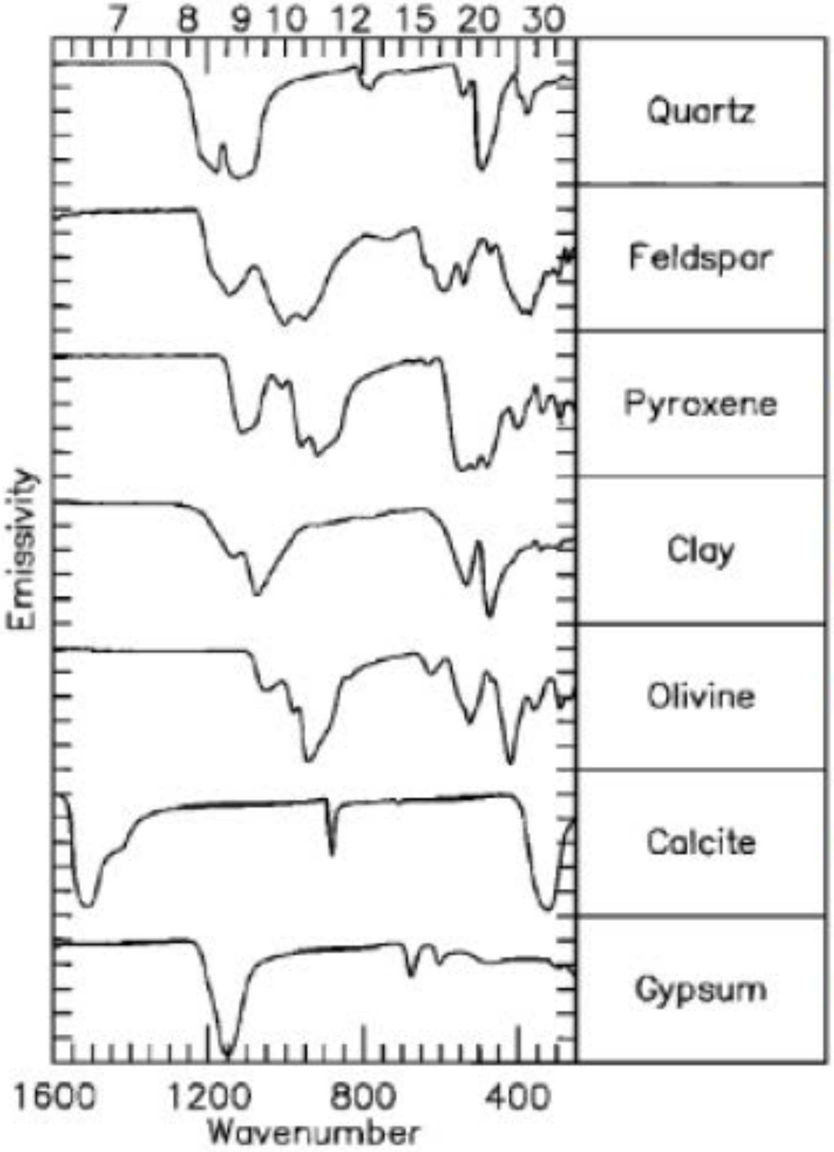


What compositions can be determined in the TIR?

Mostly vibrational resonance, not electronic processes
therefore, relatively large molecules

Silicate minerals (SiO_4^{-4}); quartz (SiO_2)
Sulfates (SO_4^{-2}); sulfur dioxide (SO_2)
Carbonates (CO_3^{-2}); carbon dioxide (CO_2)
Ozone (O_3)
Water (H_2O)
Organic molecules

MIR/TIR



SiO_2

$(Ca_x, Na, K)Al_{1+x}Si_3O_8$

$(Ca, Mg, Fe)_2Si_2O_6$

e.g. $(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \bullet n(H_2O)$

$(Mg, Fe)_2SiO_4$

$CaCO_3$

$CaSO_4 \bullet n(H_2O)$

Figure 7. Thermal infrared spectra of representative silicate, carbonate, and sulfate minerals. Laboratory data are from the Arizona State University (ASU) spectral library [*Christensen et al.*, 2000a].

MIR/TIR

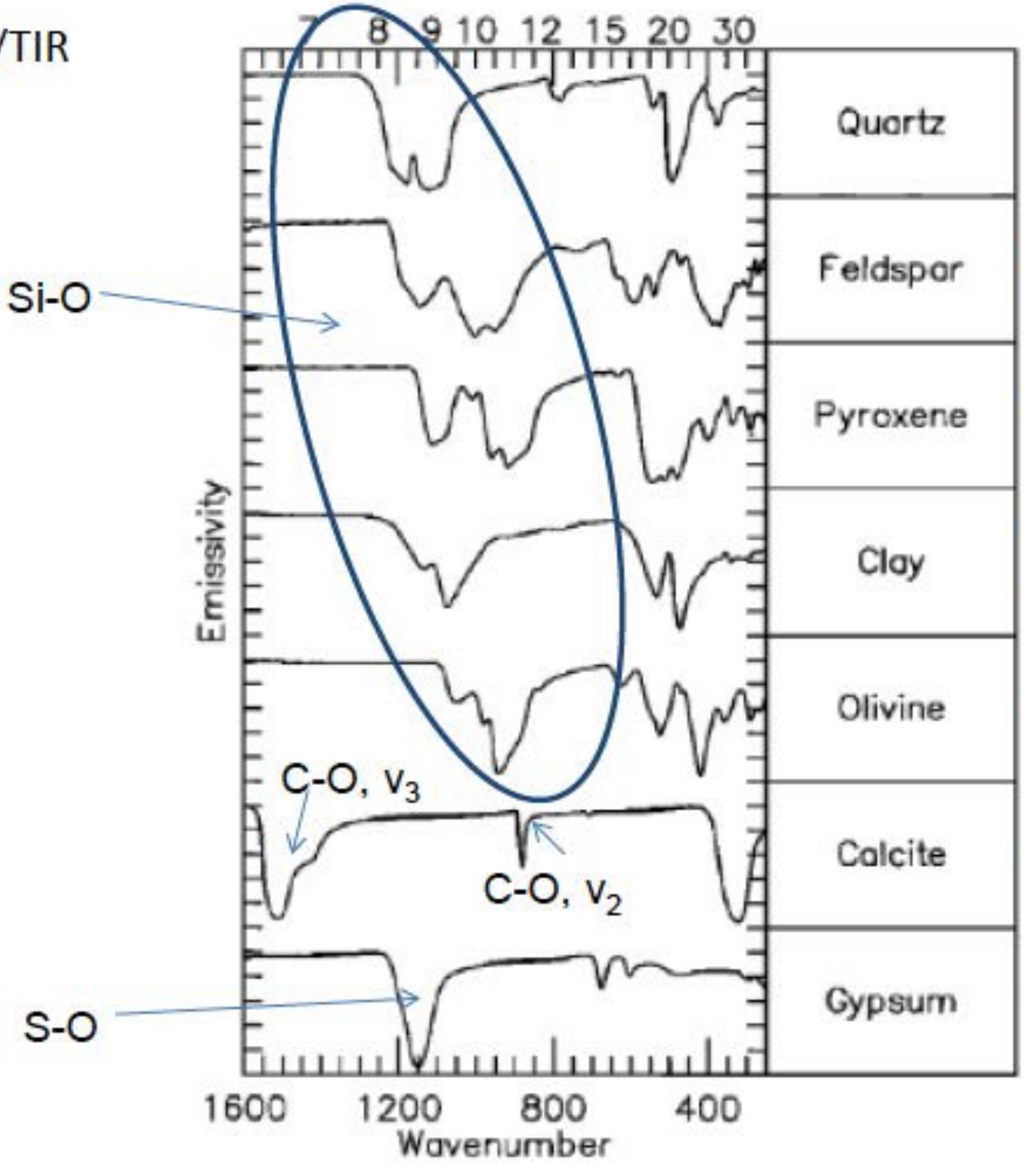


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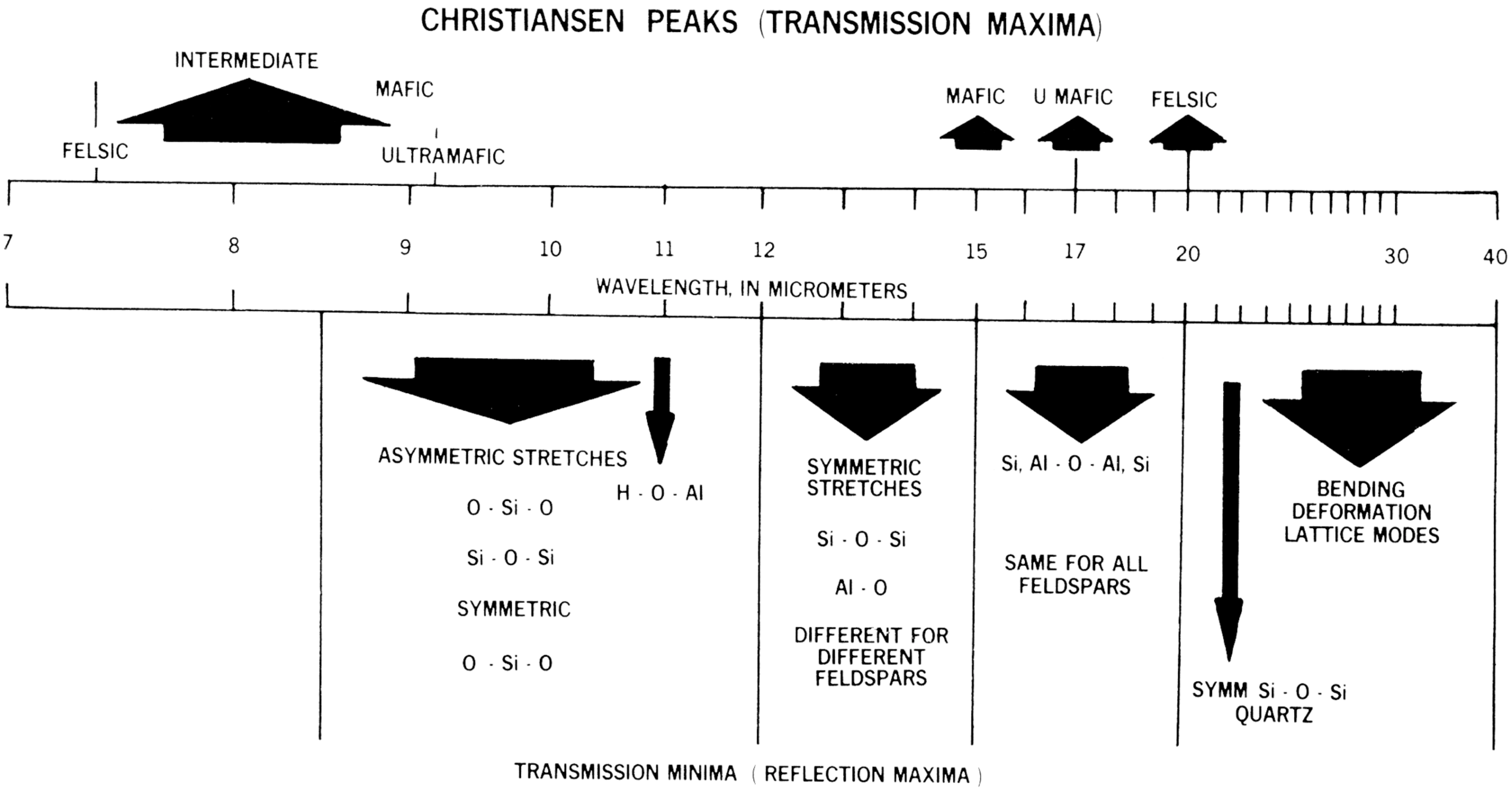
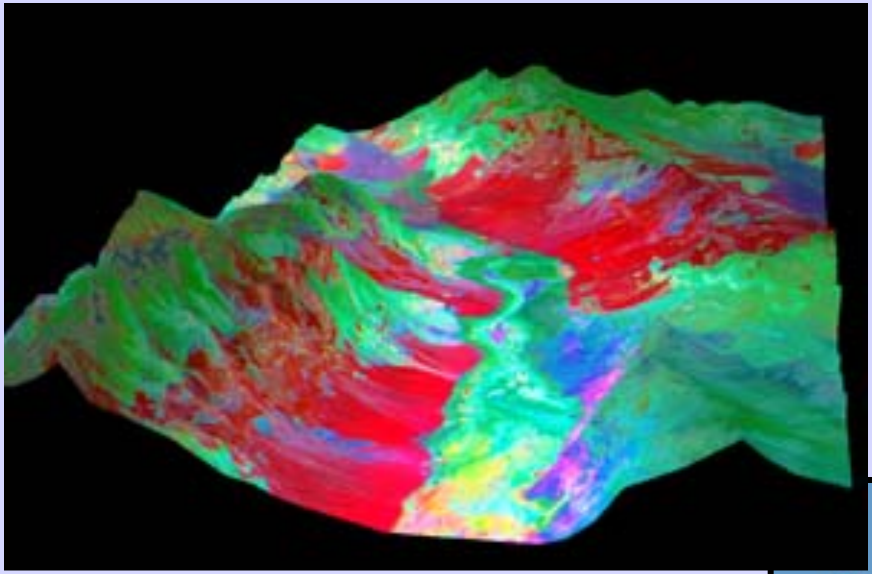
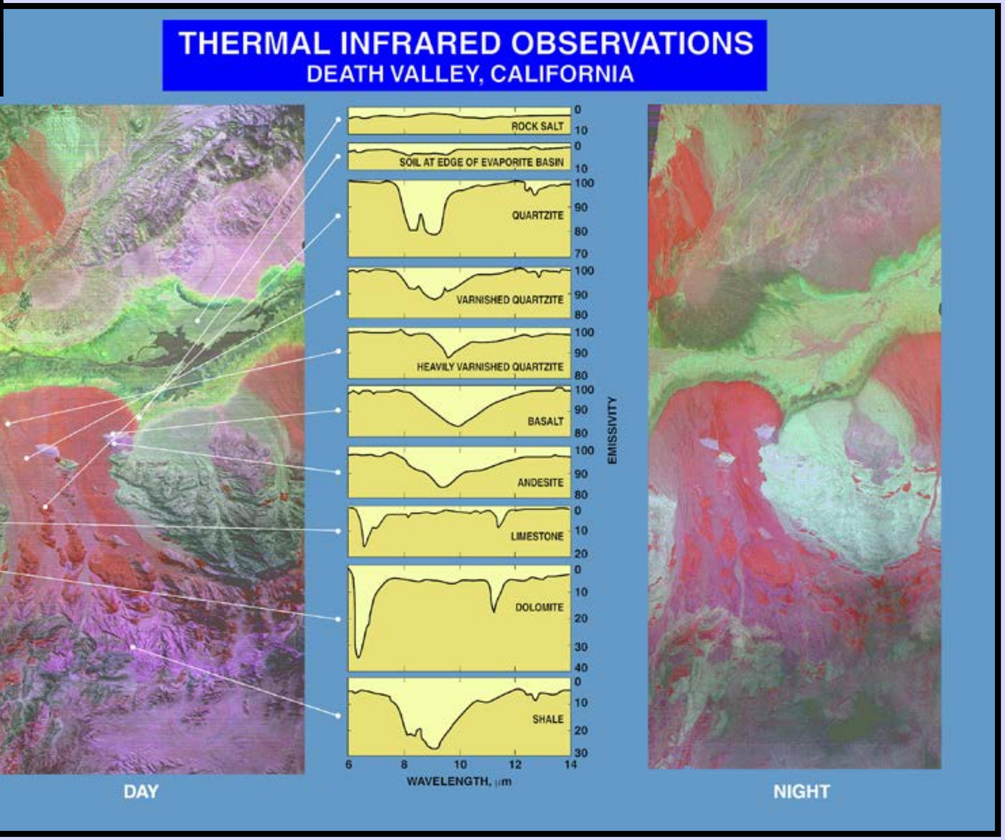
Figure 7. Thermal infrared spectra of representative silicate, carbonate, and sulfate minerals. Laboratory data are from the Arizona State University (ASU) spectral library [*Christensen et al.*, 2000a].

Thermal infrared spectral features of silicates (Clark, 1999)



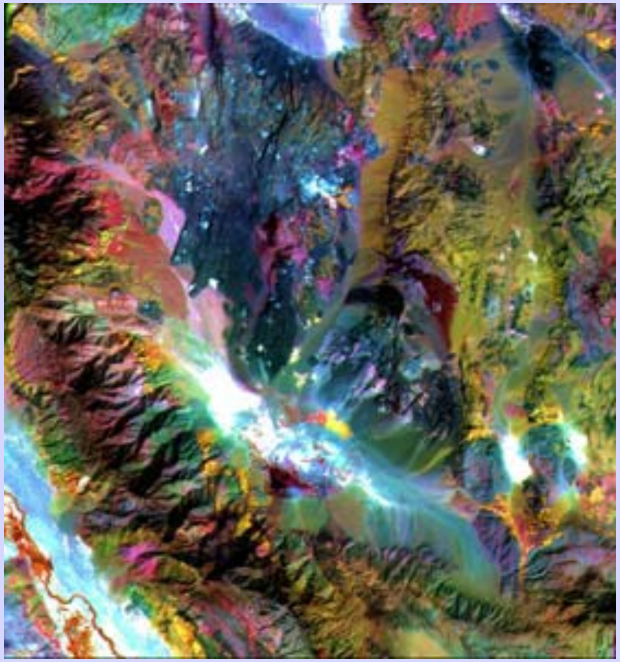


Death Valley, California

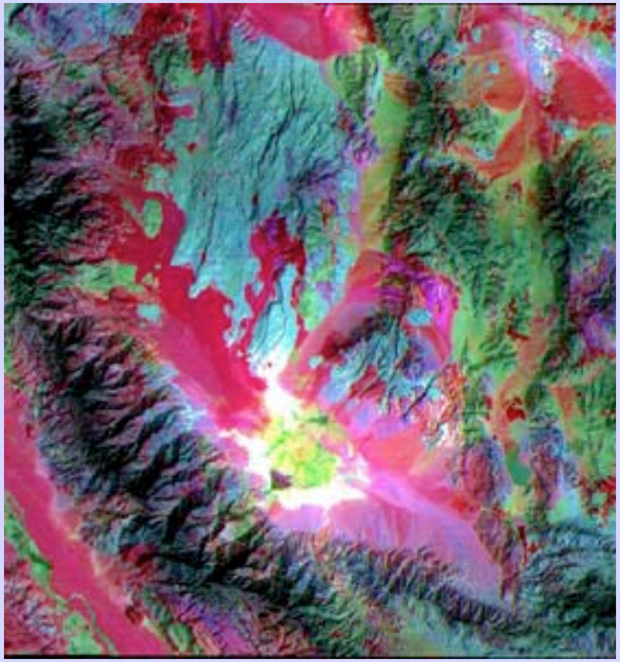


Saline Valley, California

VNIR

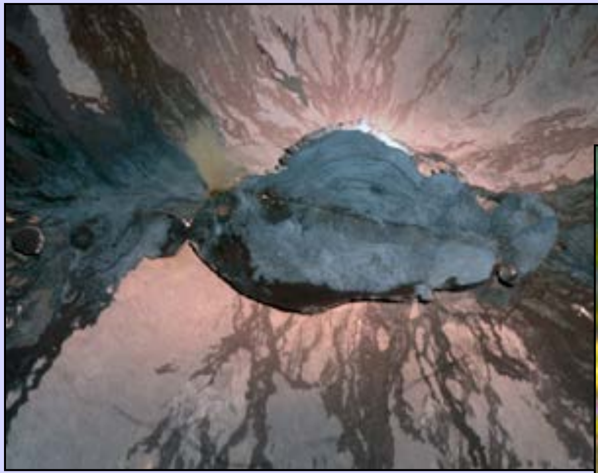


SWIR

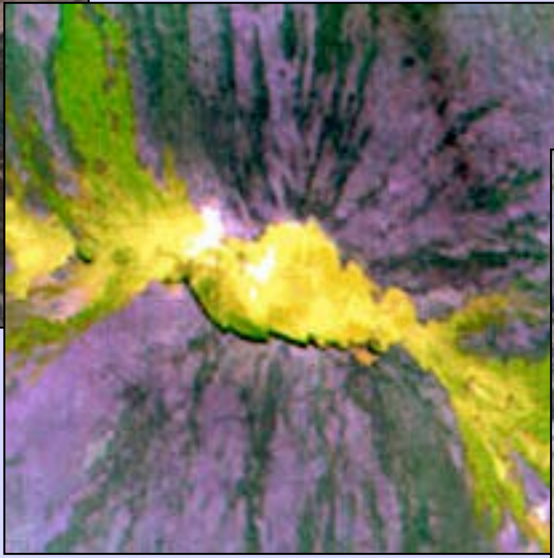


TIR

Mauna Loa, Hawaii



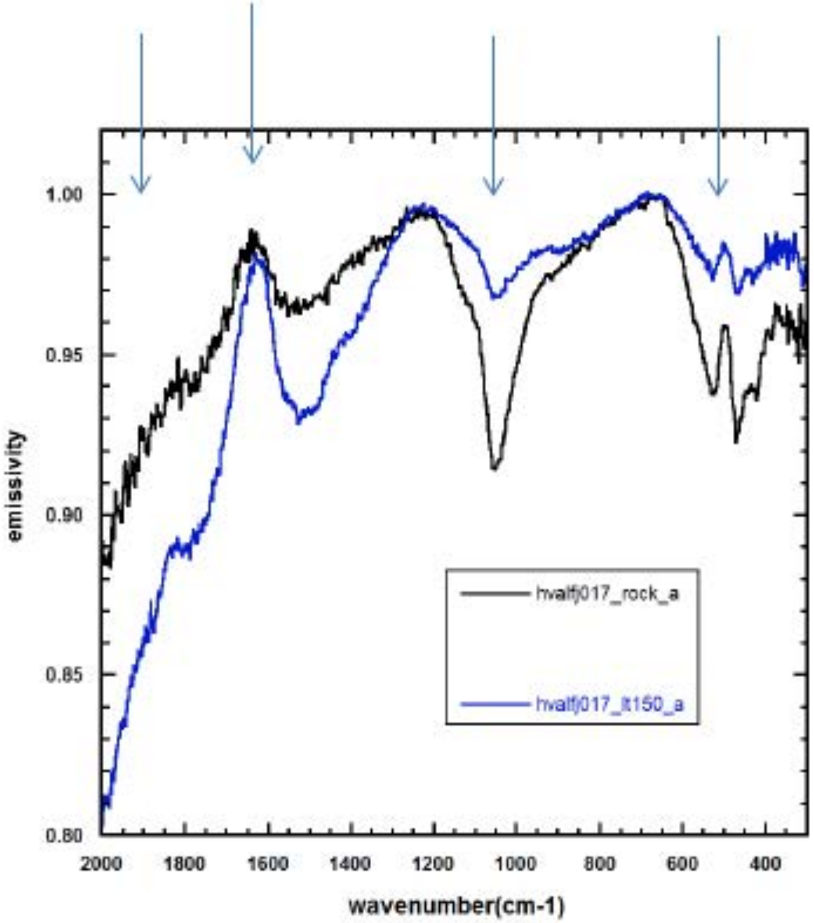
MASTER VNIR
daytime



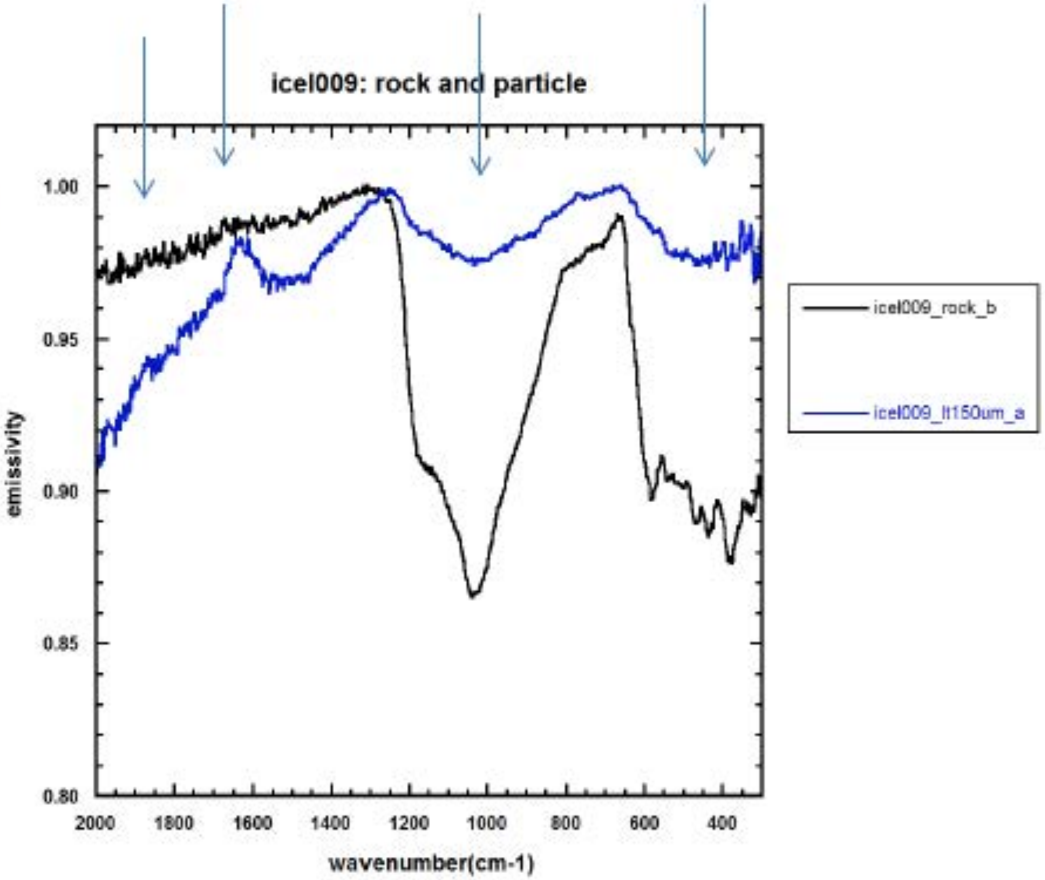
ASTER TIR,
daytime

MTI TIR,
nighttime

Effects of Particle Size, TIR



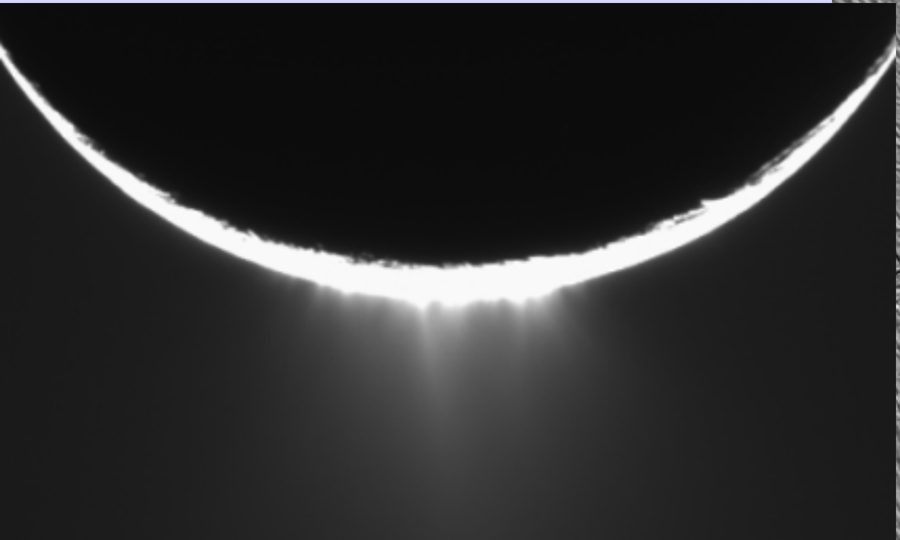
montmorillonite+hematite

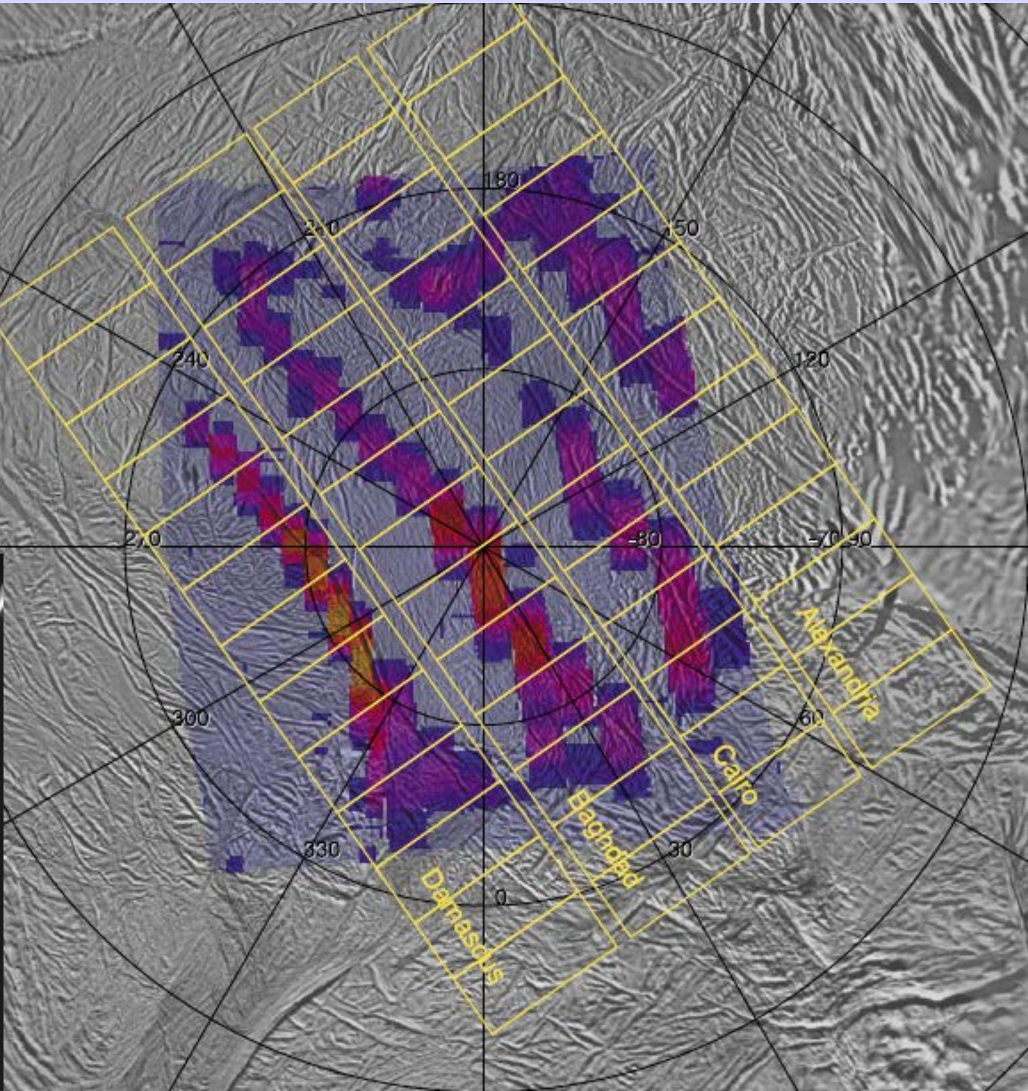


slightly altered basaltic rock

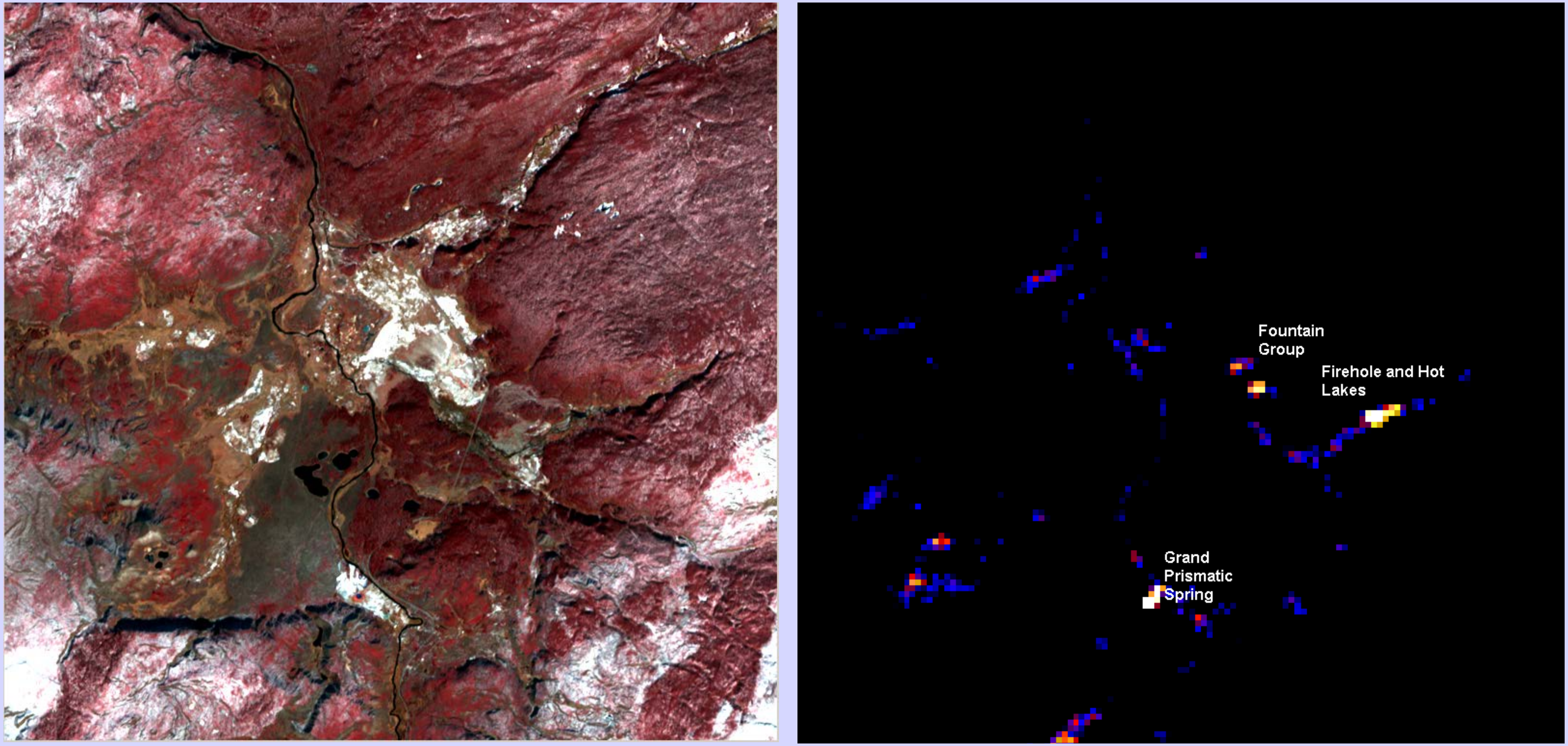
Not all thermal images are dominated by *solar* heating of the surface

Enceladus





Not all thermal images are dominated by *solar* heating of the surface



ASTER images of Yellowstone: VNIR (left) and TIR (right)

A little about solving sets of equations

If you measure R there are 2 unknowns: ε and T
If you measure R at a different λ, there is another unknown ε

If you measure a spectrum of n bands, there are n+1 unknowns

You must have the same number of measurements as unknowns to solve a set of equations

How can you do this for TIR data?

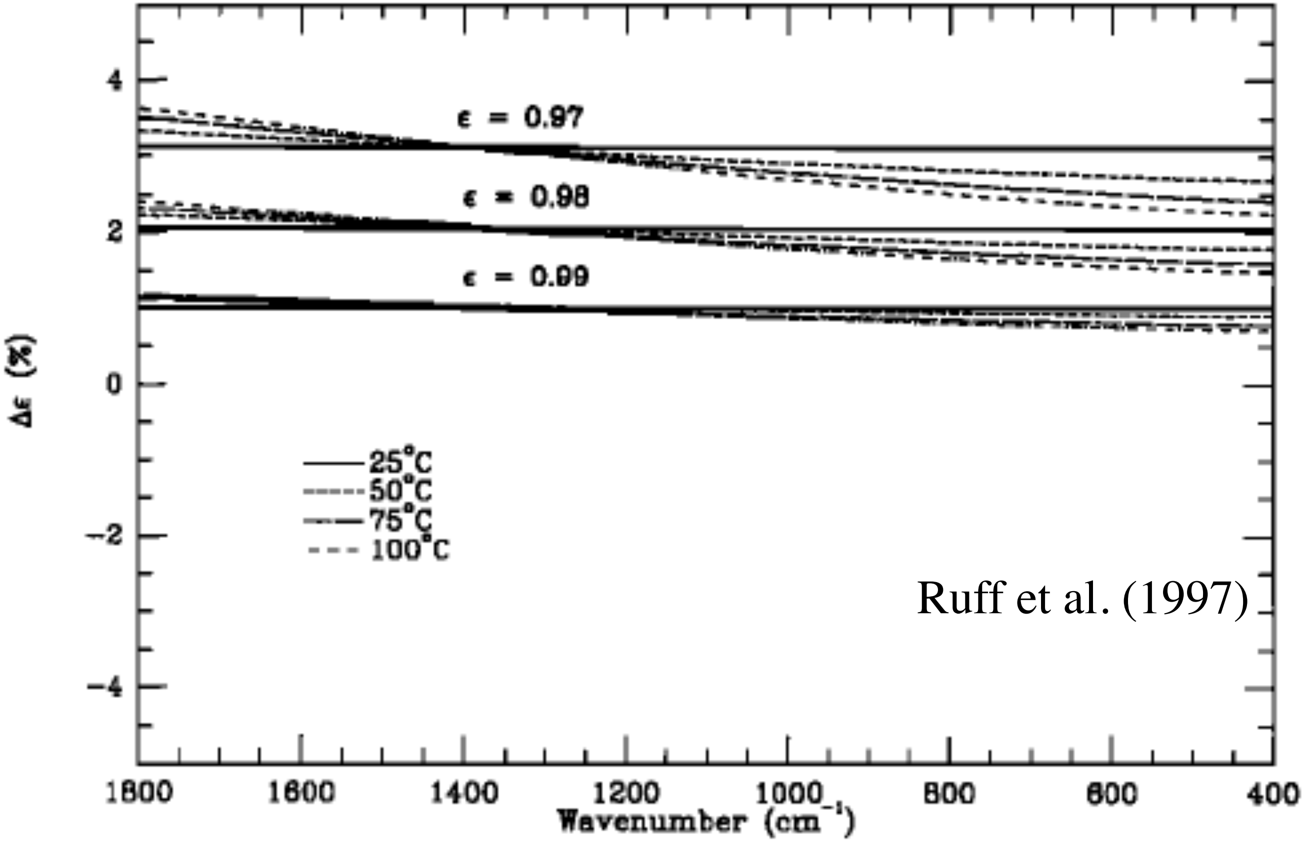
Temperature - Emissivity Separation

- Two-time two-channel method
  - *Completely determined*

- Model emissivity method
  - *Assume* $\varepsilon_{10\mu m}=0.96$

- Normalized Emissivity method
  - *Assume* $\varepsilon_{max}=1$

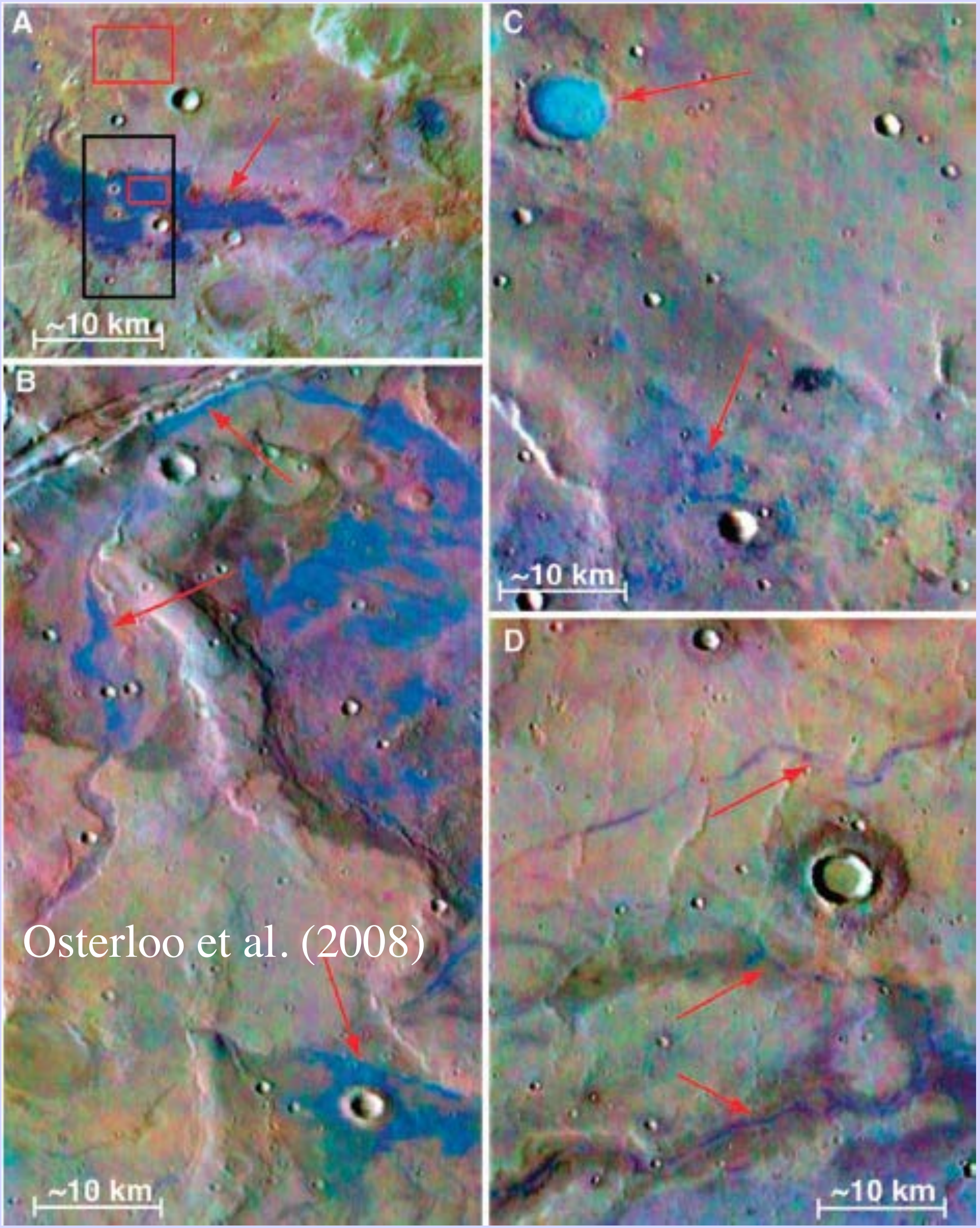
But if $\varepsilon_{max} < 1$ …



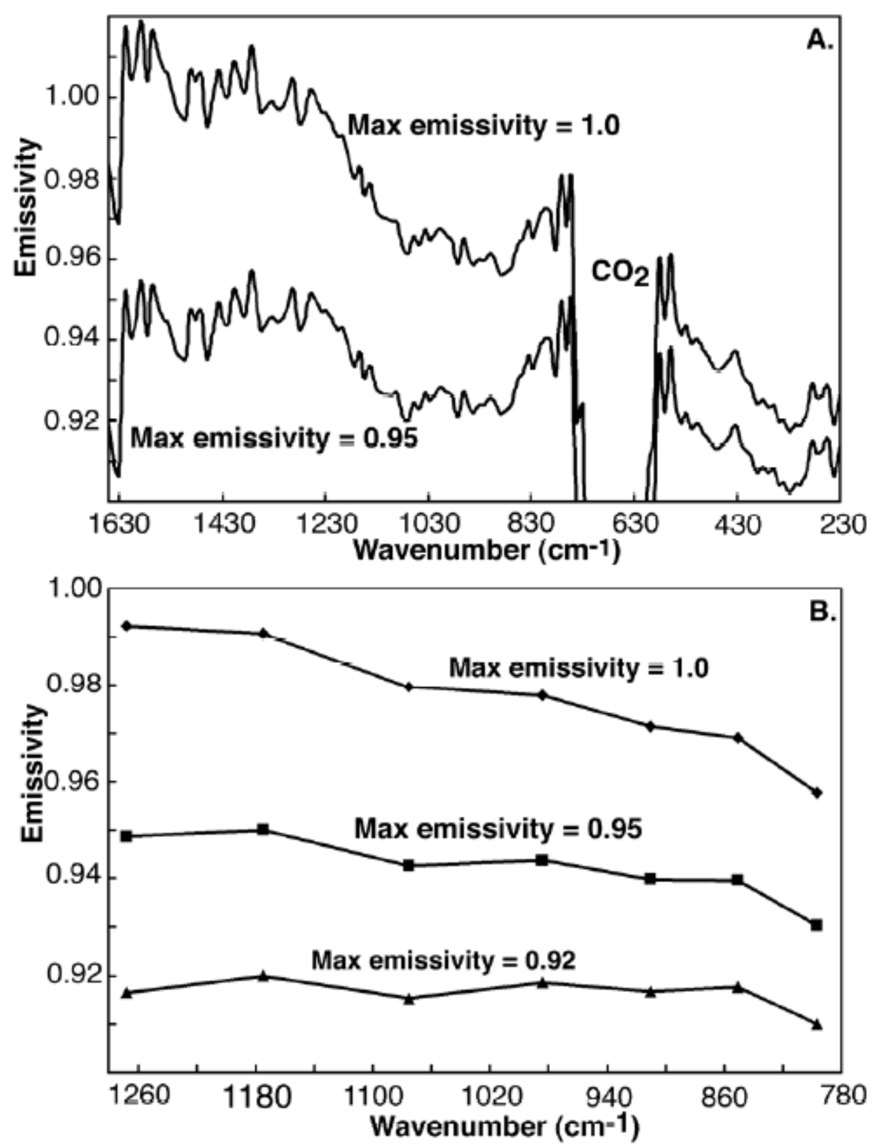
Ruff et al. (1997)

Figure 11. The emissivity error that arises from deriving sample temperature from a nonunit emissivity Christiansen feature (1359 cm^{-1} is used here). Three different ε_{CF} cases are plotted for four different sample temperatures.

Example of $\varepsilon_{max} < 1$: chlorides



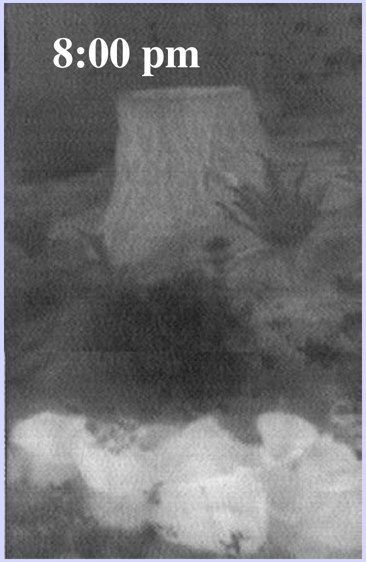
Osterloo et al. (2008)



Day/night

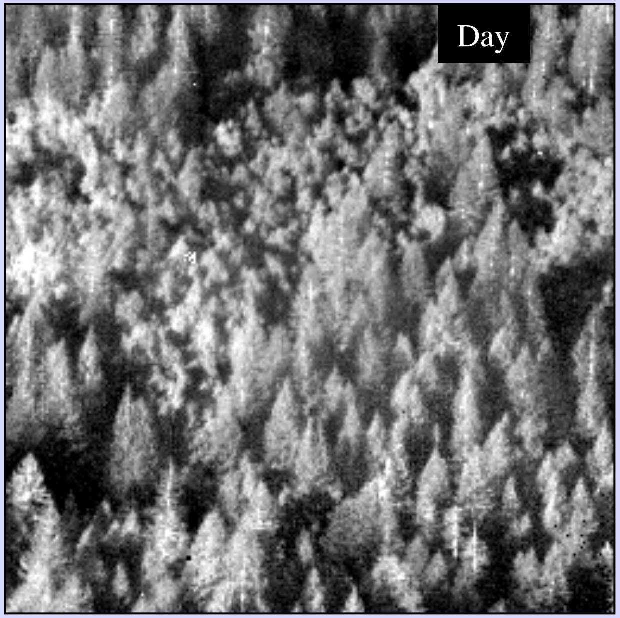
Vis

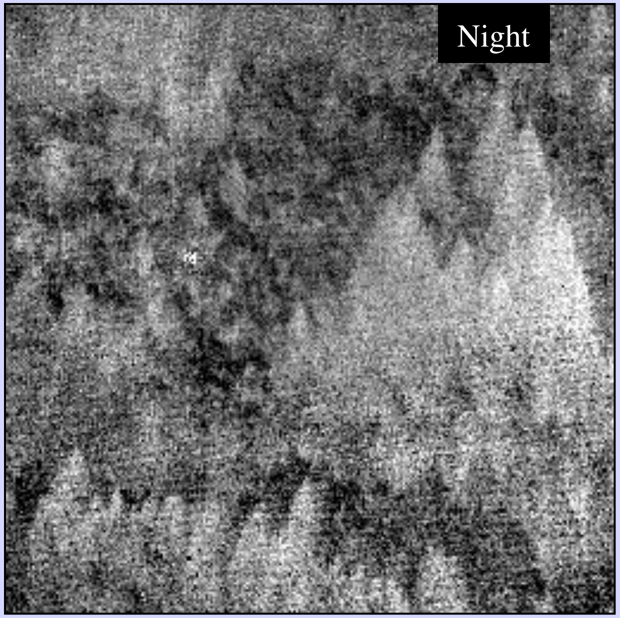
10.8 μm

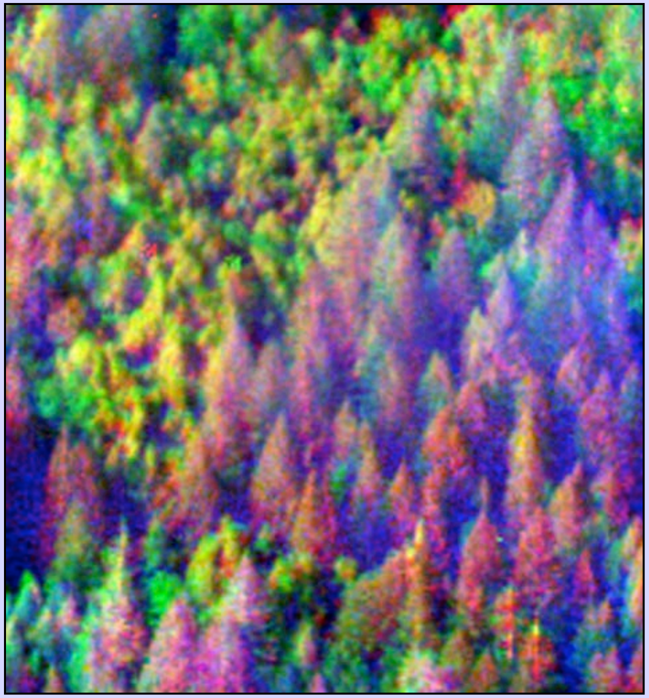


Thermal inertia:
dQ/dT
Resistance of matter
to changing temperature
as heat is applied

Veg Mapping - Thermal

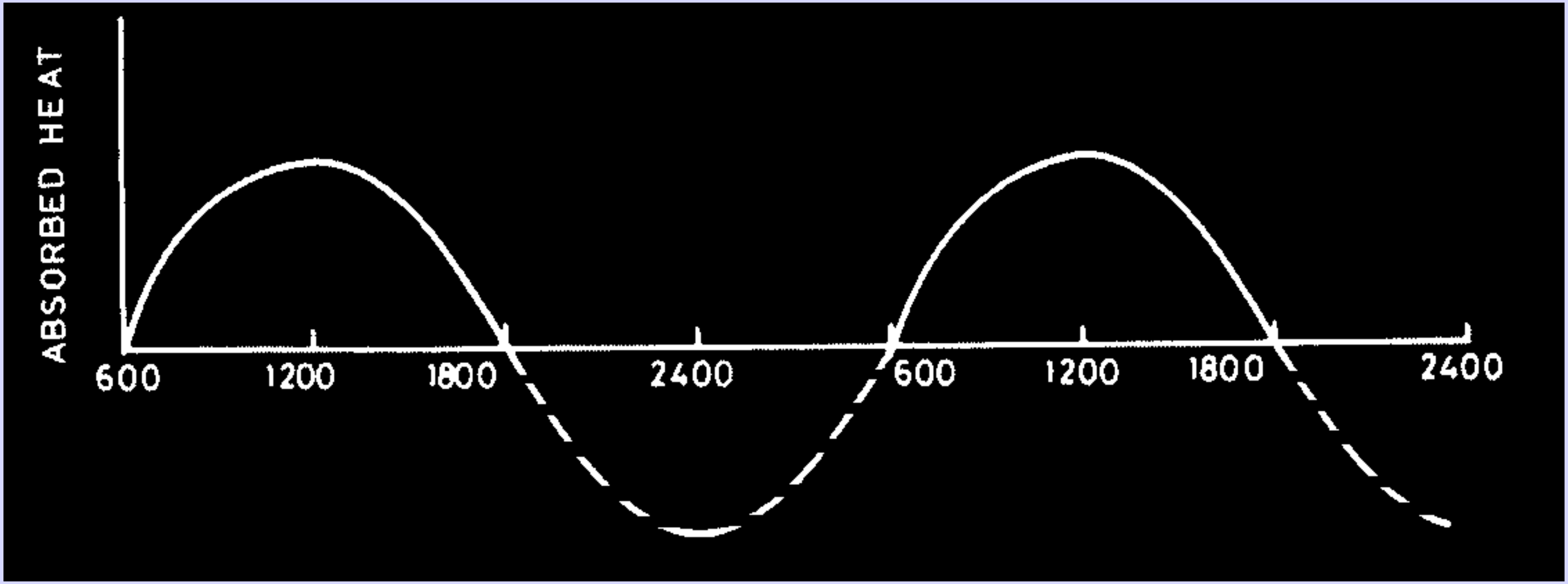






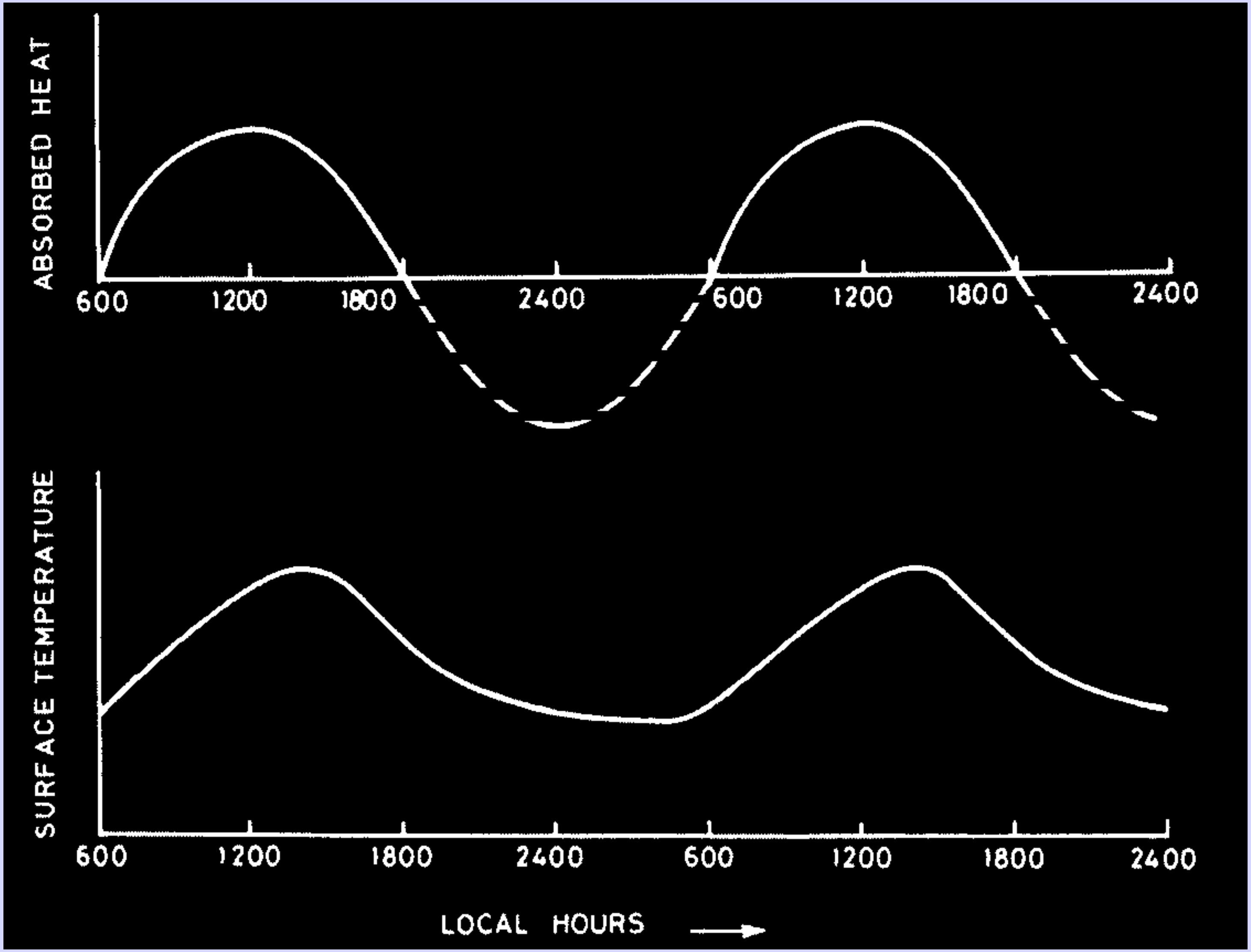
Red = 10:00 am
Green = 2:00 pm
Blue = 11:00 pm

Conifers cooler during day
& warmer at night



Sunlight heats planetary surfaces

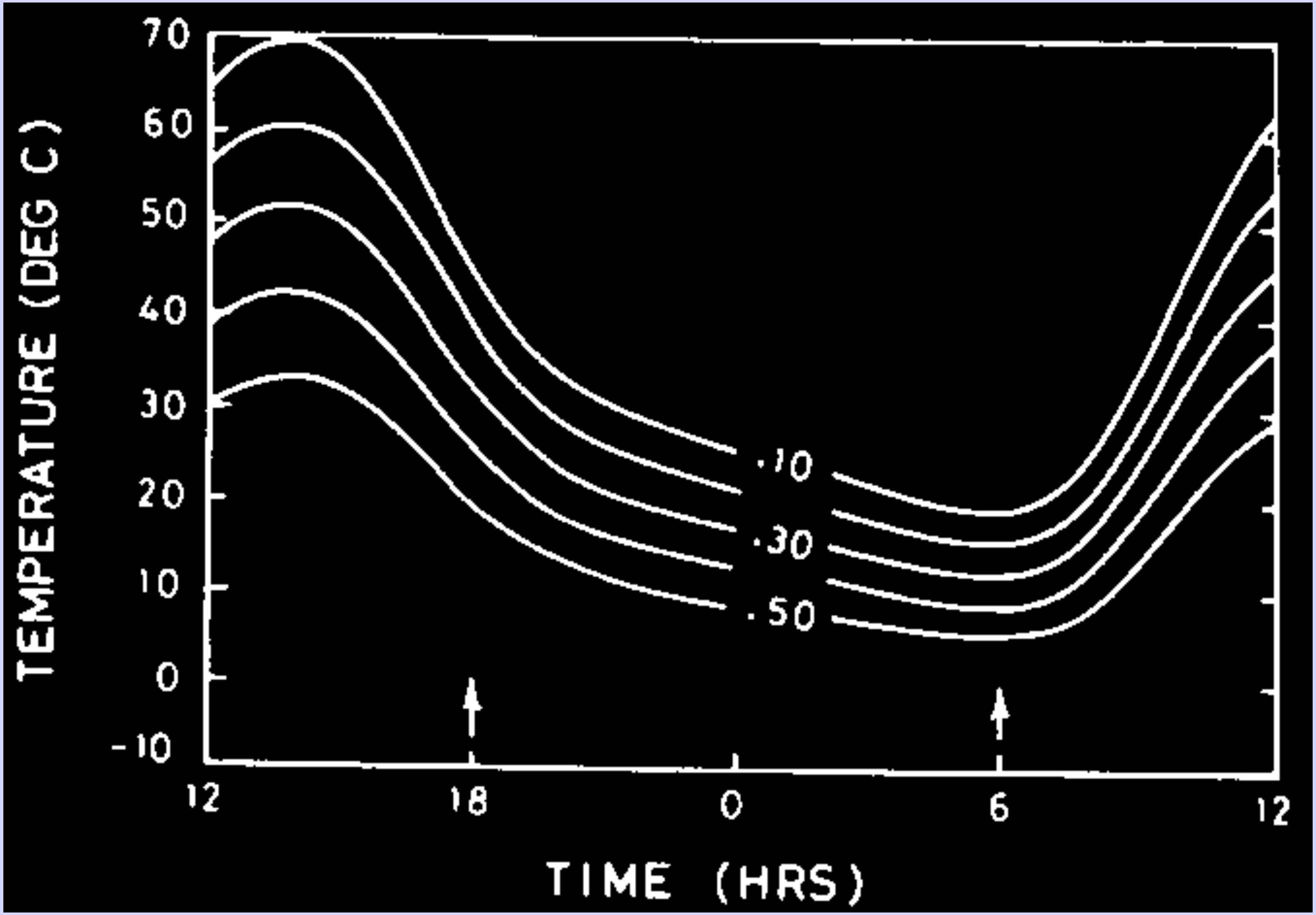
in a sinusoidal pattern



Surface temperature responds to heating
(and lack of heating), but with a lag.

Albedo

- The *albedo* of a planetary surface (A) is the percent of sunlight that it reflects.
- Albedo can range from $A=1$ (pure white) to A=0 (pure black). For Earth, average A is 0.39. For the Moon, average A is 0.12.
- The amount of sunlight absorbed by a surface is $1-A$



The effect of varying albedo on diurnal temperature curves

Other physical quantities that affect temperature

- Thermal Conductivity (*k*) is a measure of the rate at which heat is conducted by a medium.

$$k_{\text{rock}} < k_{\text{water}} < k_{\text{steel}}$$

- Specific heat capacity (*C*) is a measure of the amount of heat required to raise the temperature of a given amount of material by a certain number of degrees.

$$C_{\text{water}} > C_{\text{rocks}} > C_{\text{steel}}$$

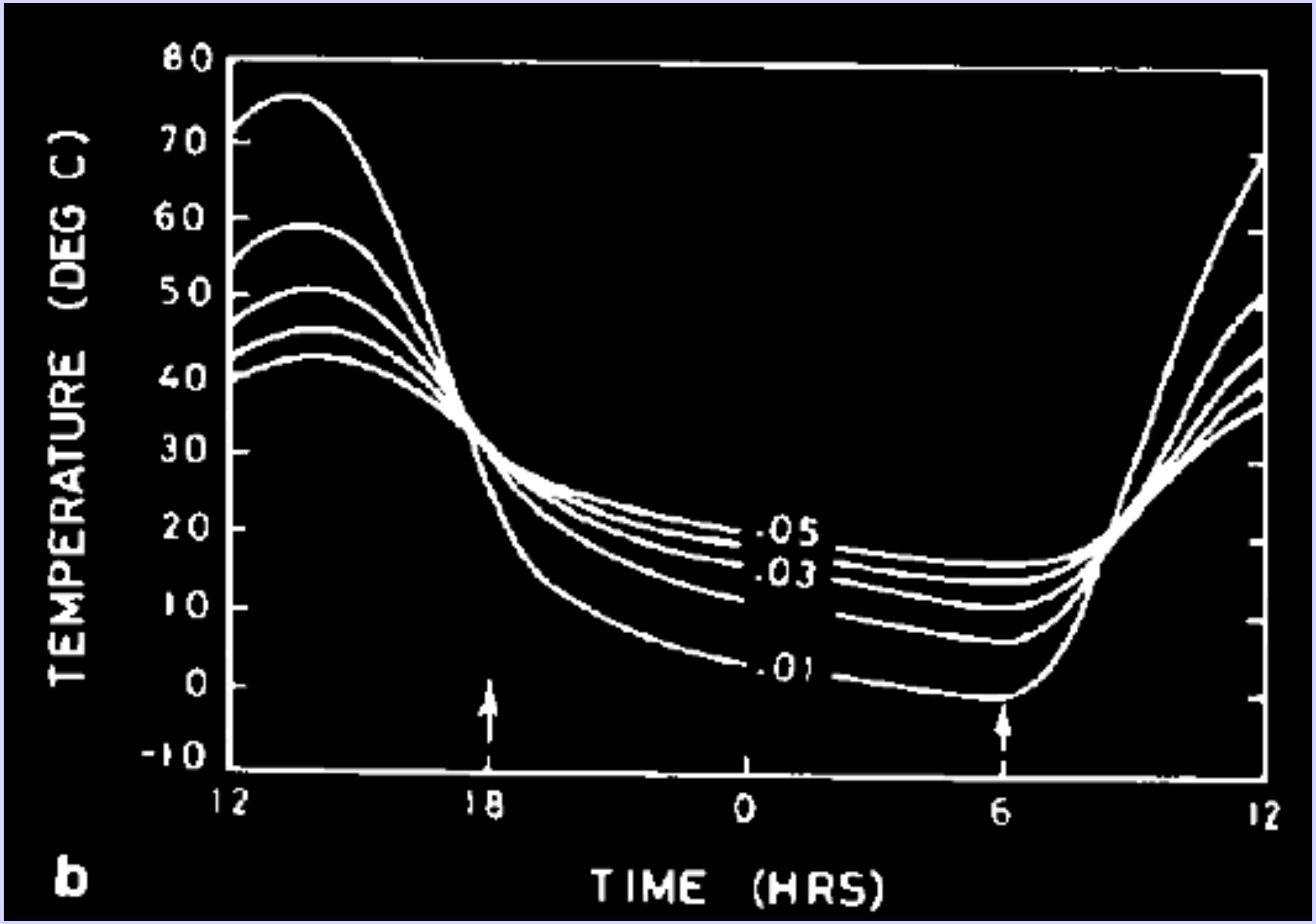
- Density (ρ) also important

Thermal Inertia

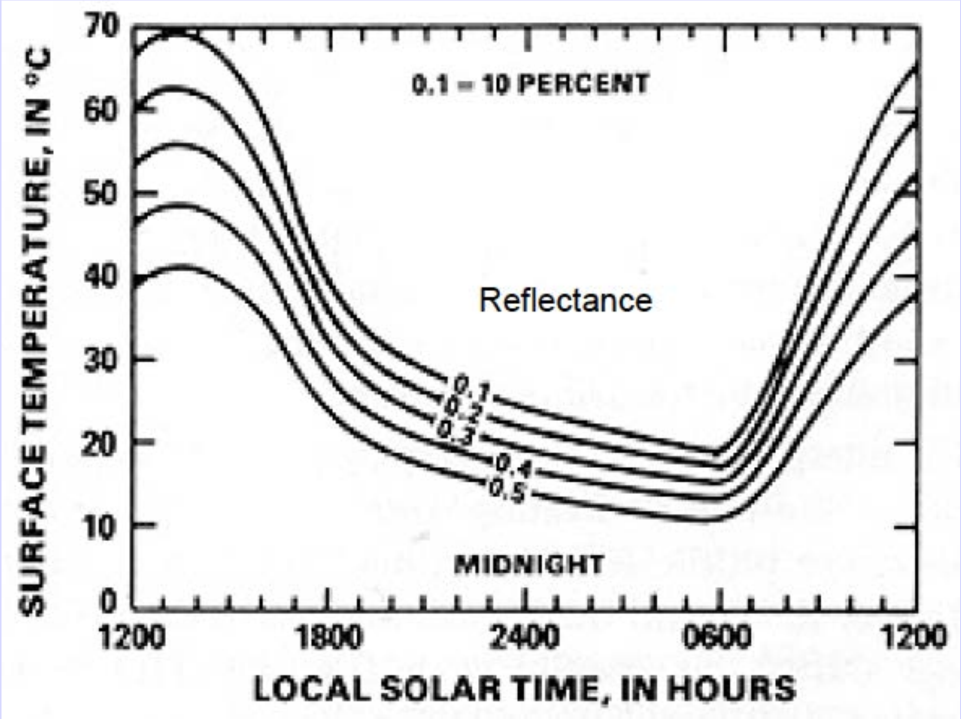
- Thermal inertia is a measure of the resistance offered by a substance undergoing temperature changes. It is given by:

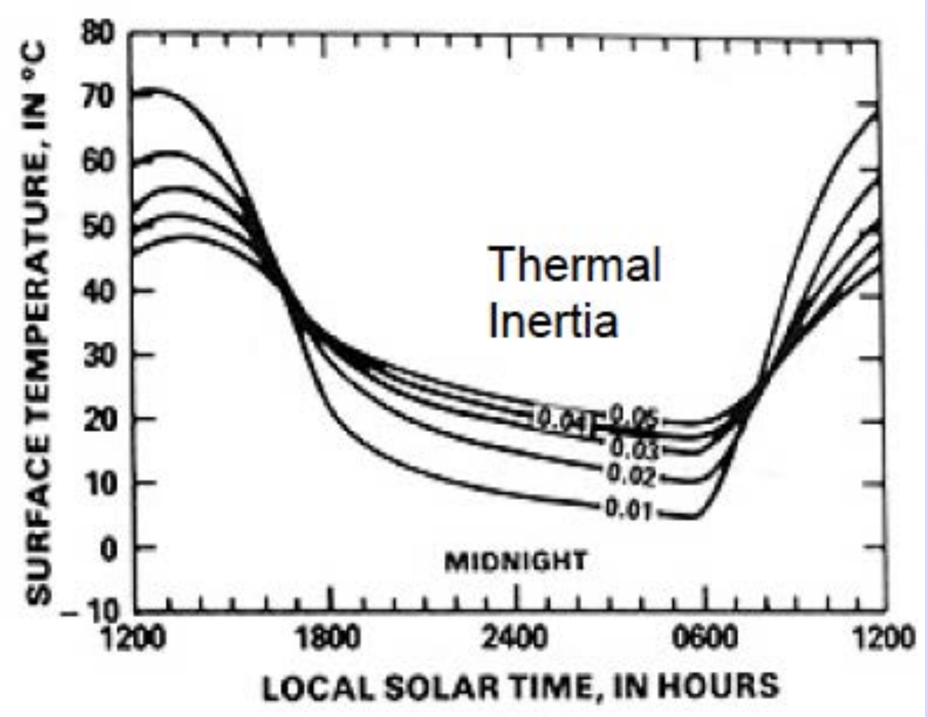
$$\text{T.I.} = (k\,\rho\,C)^{1/2}$$

Units are J m^{-2} $s^{-1/2}$ K^{-1} (tiu)



The effect of thermal inertia on diurnal temperature curves





Thermal inertia and albedo are the two parameters that fundamentally control the shape of the diurnal temperature curve.

Thermal Inertia of Geologic Materials

$$\text{T.I.} = (k\,\rho\,C)^{1/2}$$

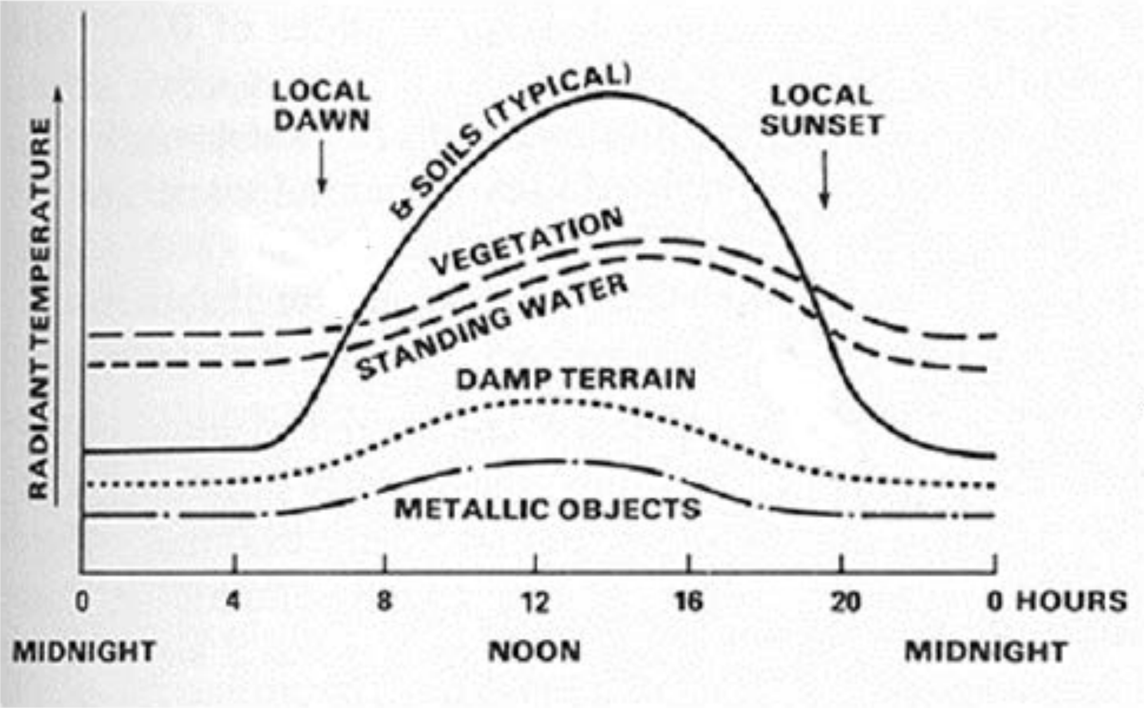
- For most geologic materials, ρC only varies by a factor of two, whereas k varies by many orders of magnitude.

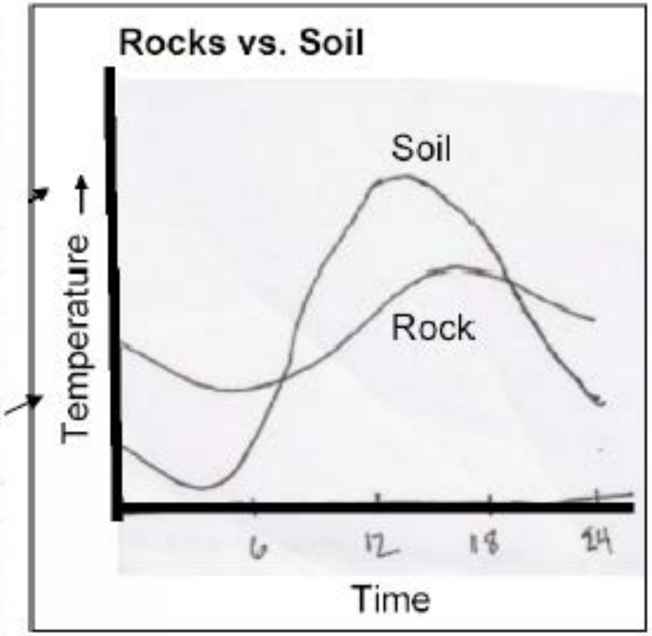
- k is mostly determined by particle size, degree of induration.

⇒ A concrete sidewalk has a much higher thermal inertia than a sandy beach!

Note that on Earth, the high C of water means moisture content also plays a big role in determining T.I.

Diurnal Temperature Curves





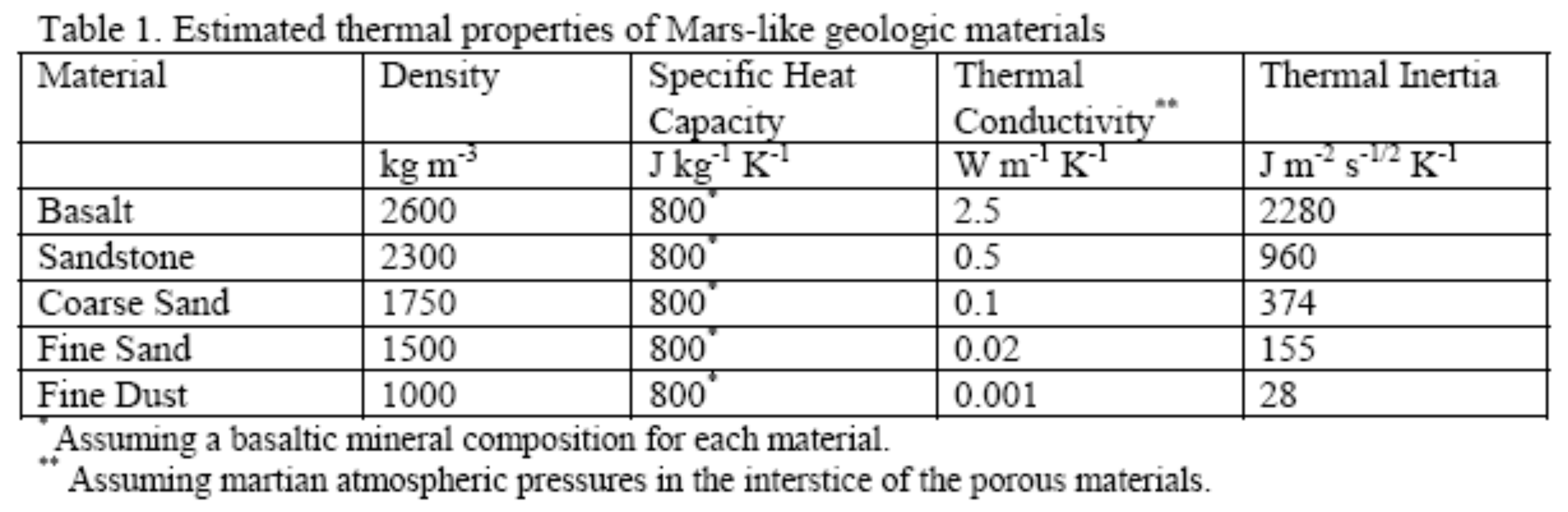


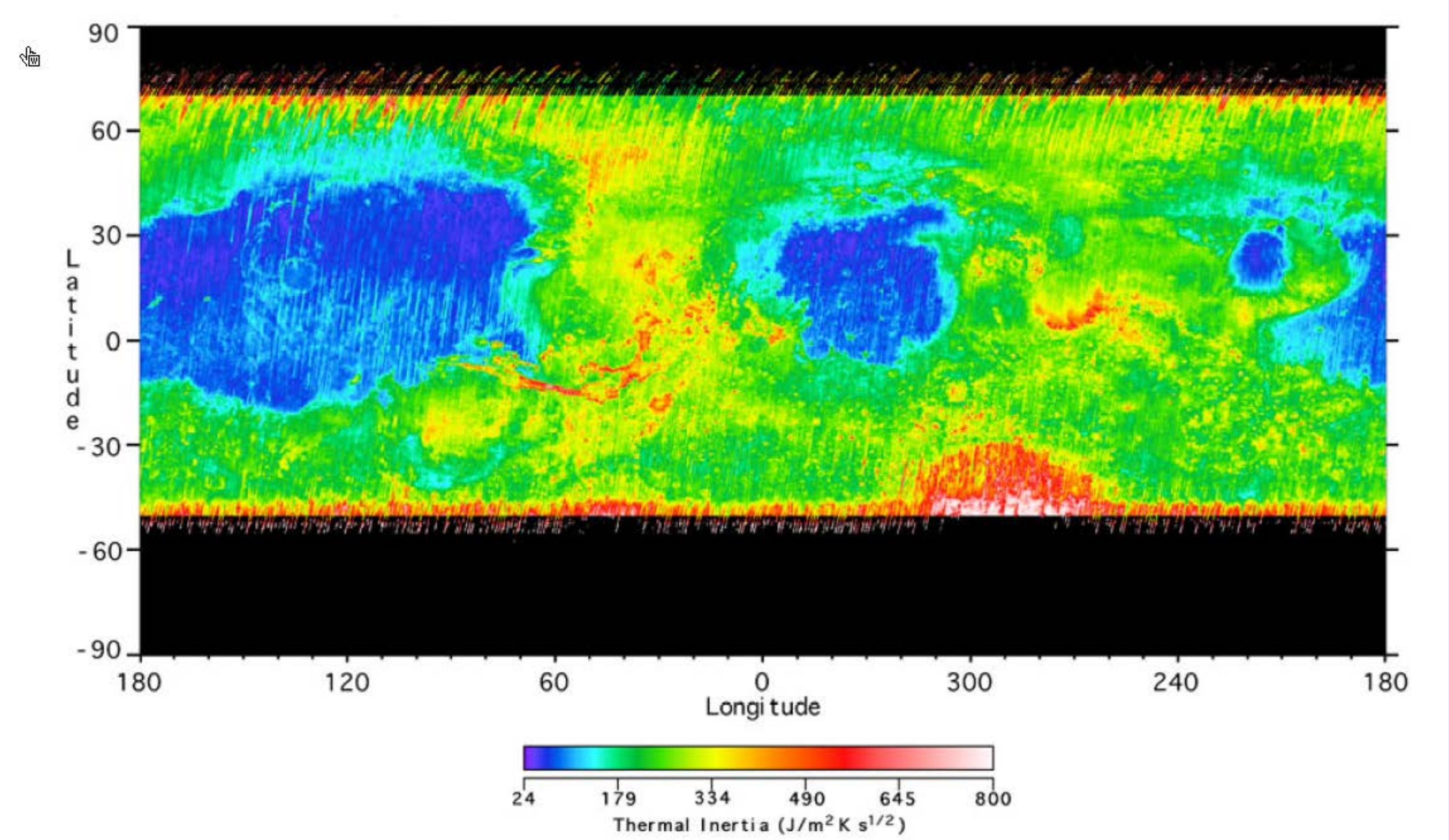
Table 1. Estimated thermal properties of Mars-like geologic materials

Material	Density	Specific Heat Capacity	Thermal Conductivity**	Thermal Inertia
	kg m^{-3}	J kg^{-1} K^{-1}	W m^{-1} K^{-1}	J m^{-2} $s^{-1/2}$ K^{-1}
Basalt	2600	800*	2.5	2280
Sandstone	2300	800*	0.5	960
Coarse Sand	1750	800*	0.1	374
Fine Sand	1500	800*	0.02	155
Fine Dust	1000	800*	0.001	28

* Assuming a basaltic mineral composition for each material.

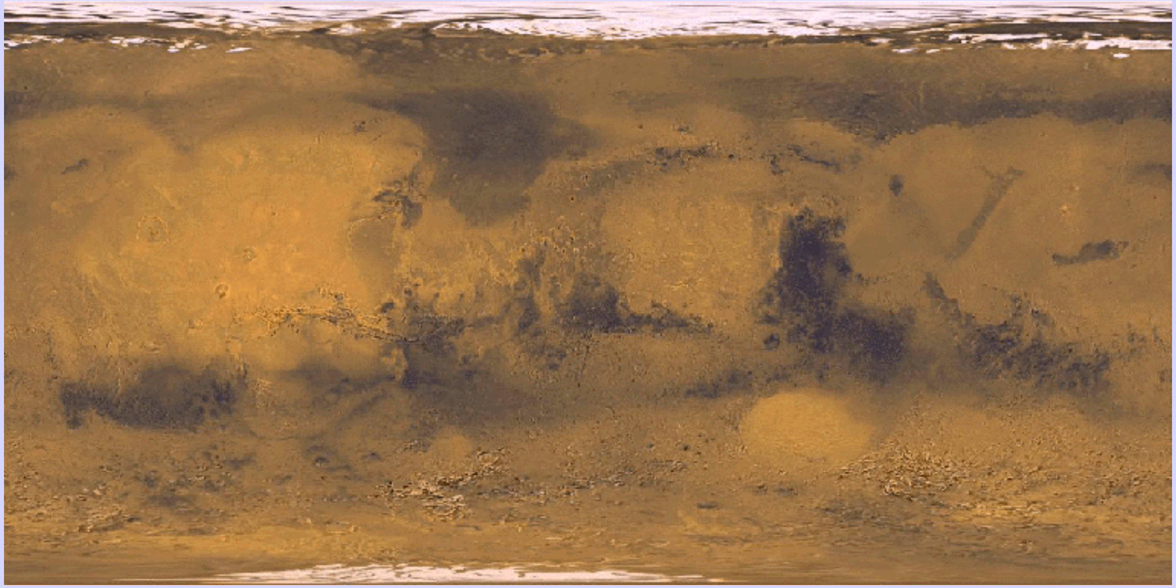
** Assuming martian atmospheric pressures in the interstice of the porous materials.

Martian Global Thermal Inertia Map



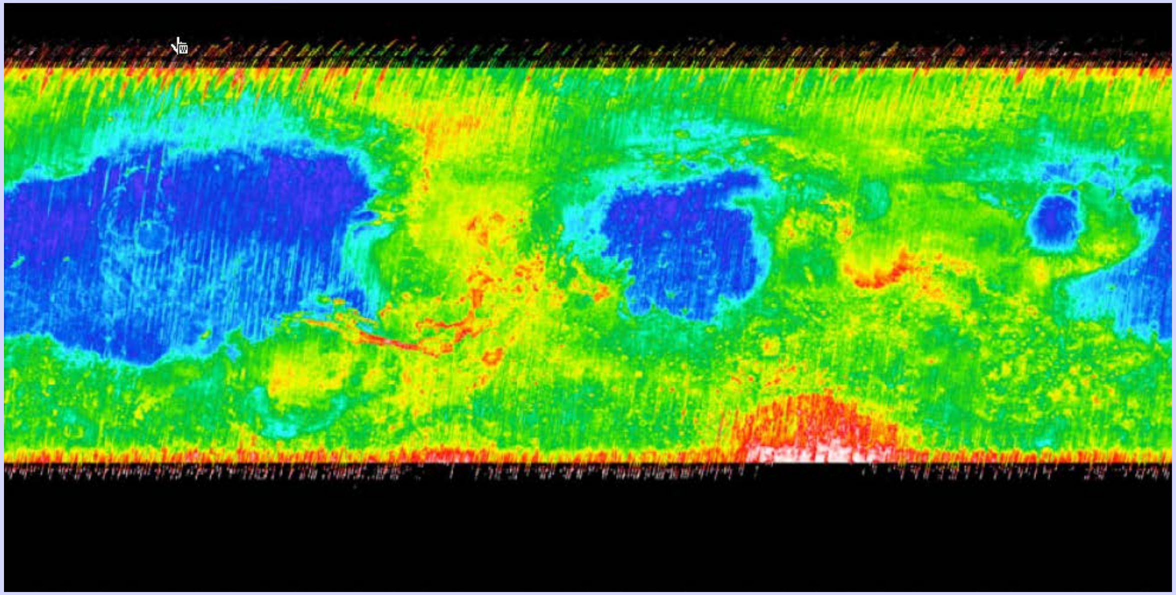
Blues indicate low TI ⇒ Fine-grained dust

Reds indicate high TI ⇒ Lots of rocks and outcrop



Martian

albedo

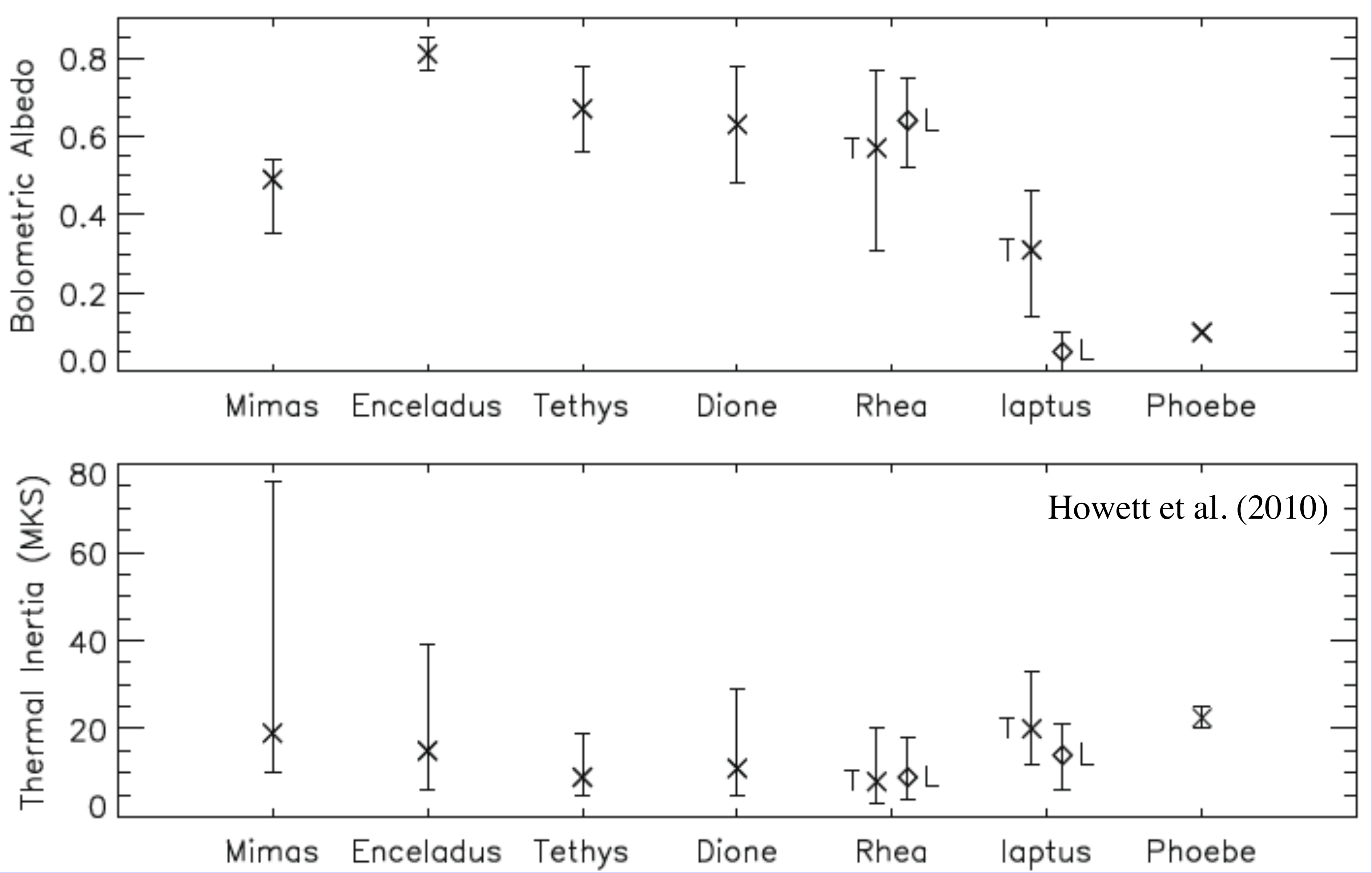


Martian

thermal

inertia

Very low T.I. on Saturn moons → high porosity?



Howett et al. (2010)

Computation of Thermal Inertia

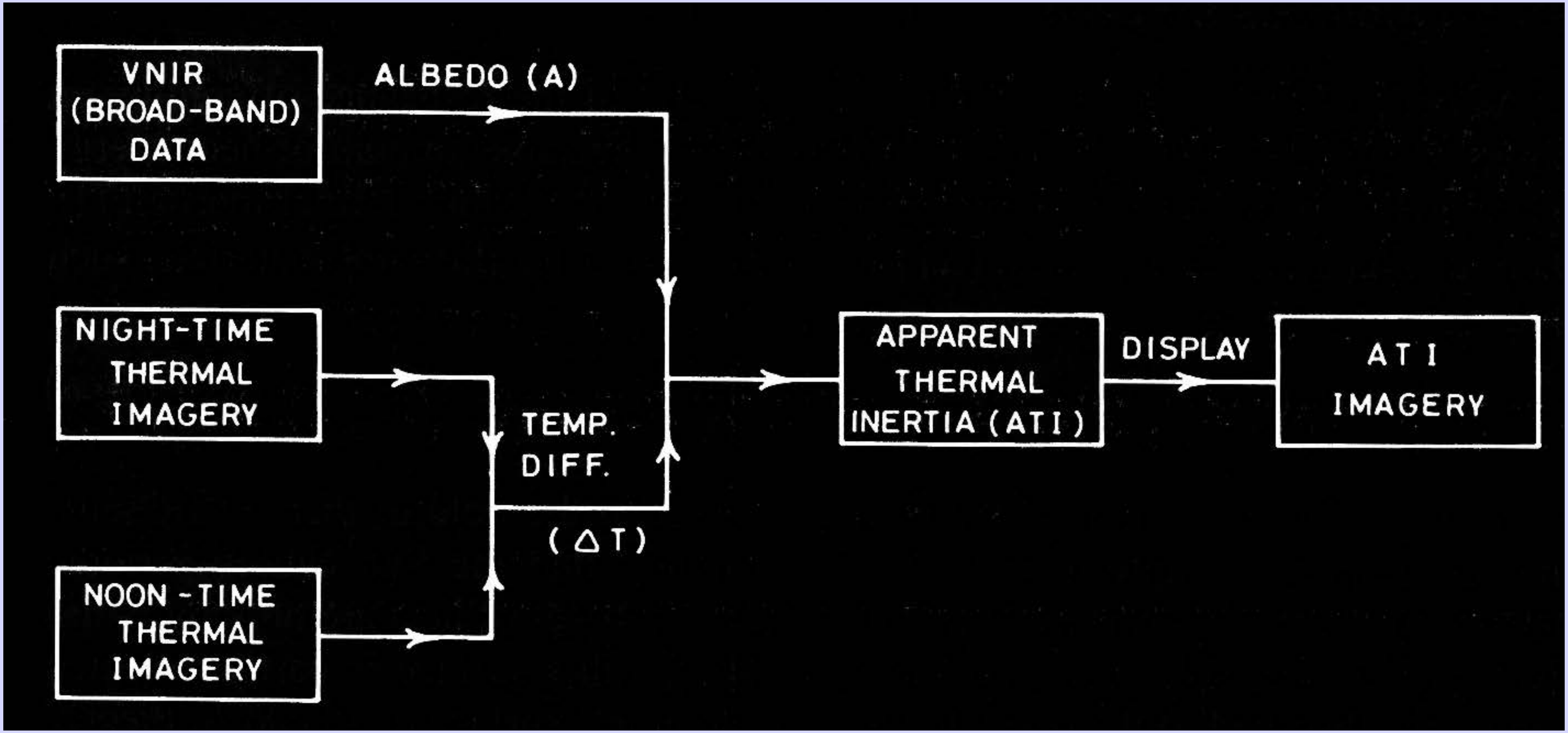
For terrestrial applications, commonly use “Apparent Thermal Inertia” (ATI).

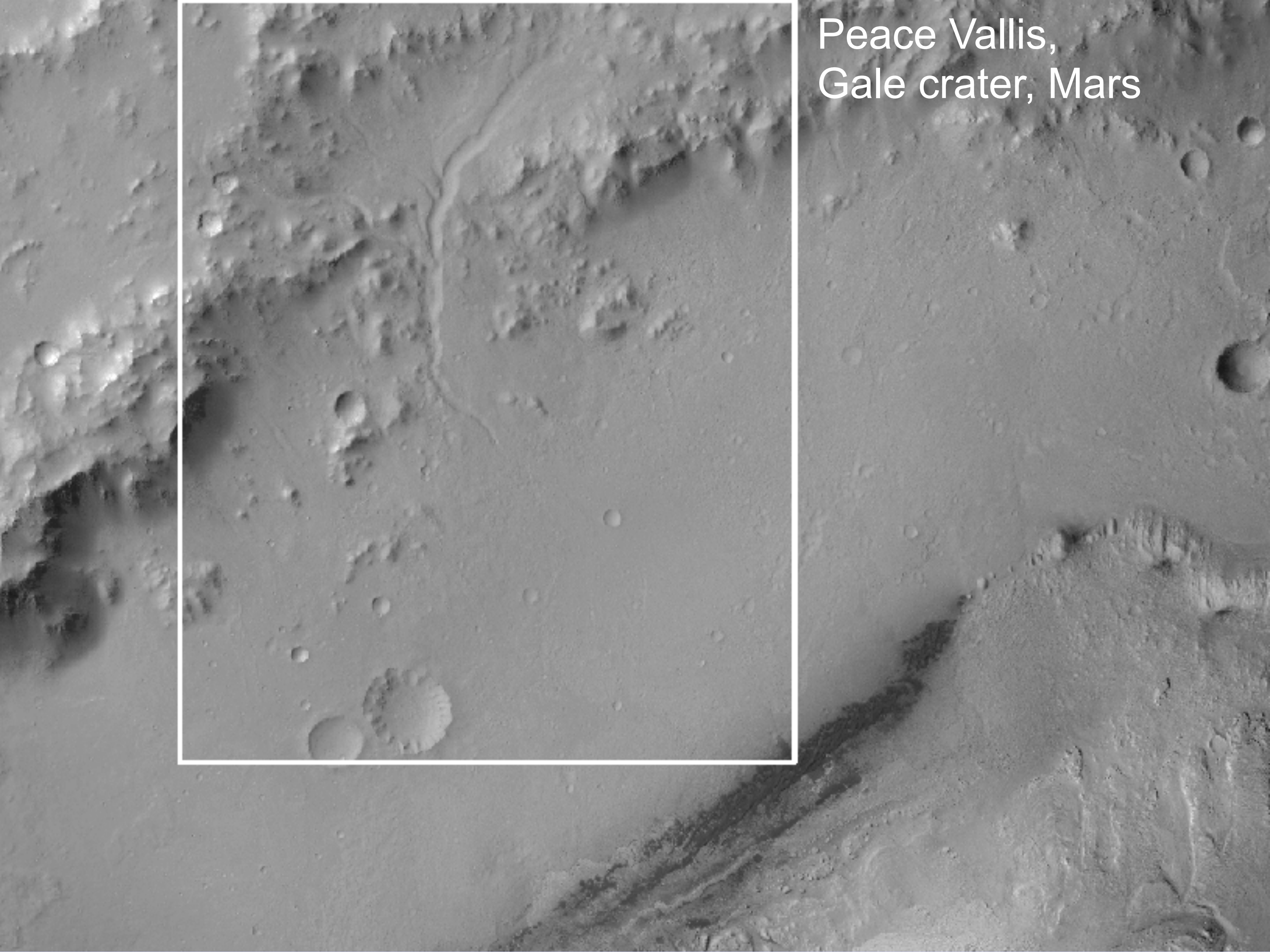
$$ATI = N * (1-A)/\Delta T$$

The denominator just indicates that thermal inertia is inversely proportional to the diurnal temperature range. The numerator normalizes for amount of insolation absorbed by the surface.

Terrestrial work mostly uses Apparent Thermal Inertia (ATI)

$$\mathrm{ATI} = \mathrm{N} * (1 - A) \; / \; \Delta T$$

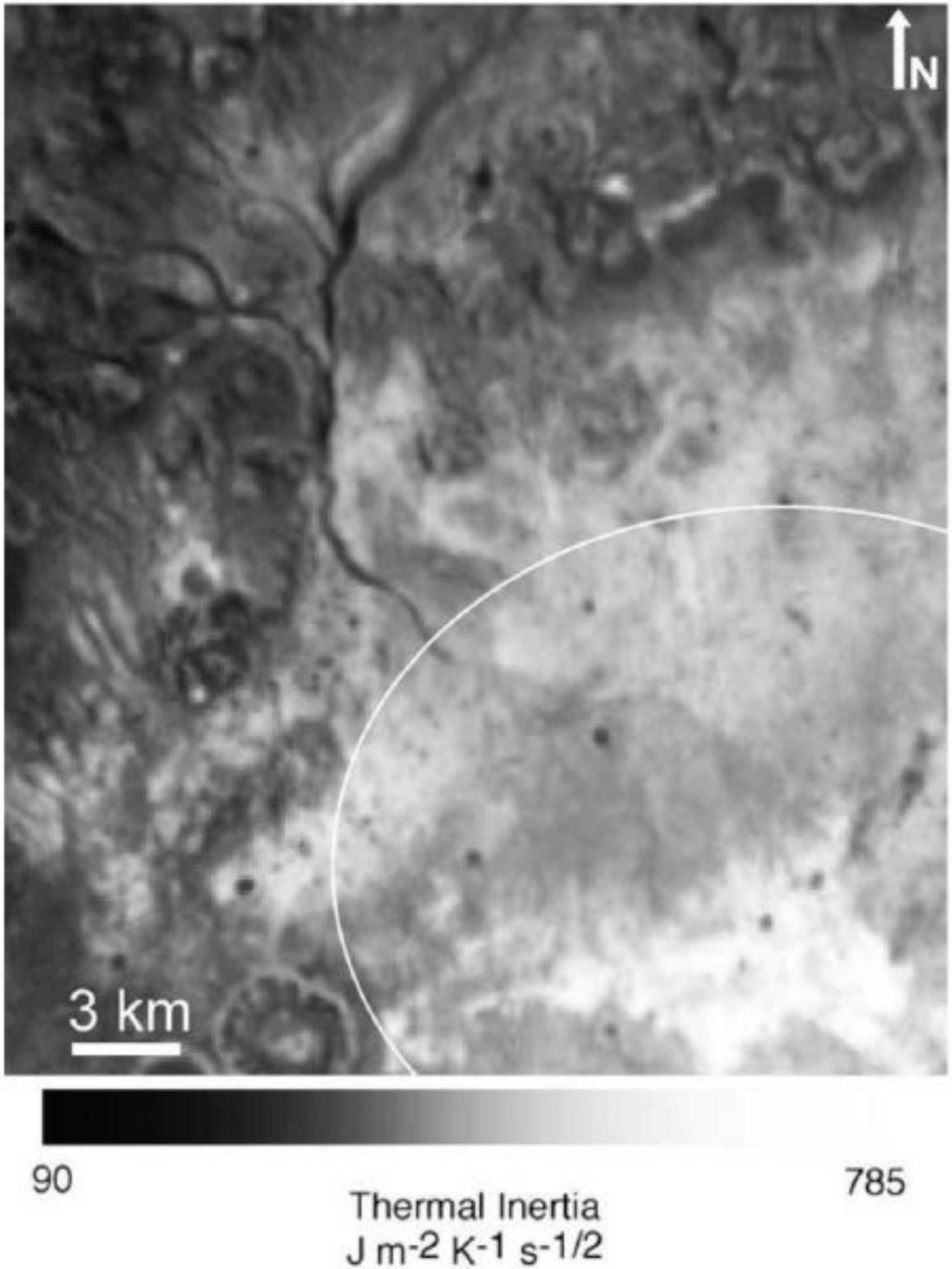


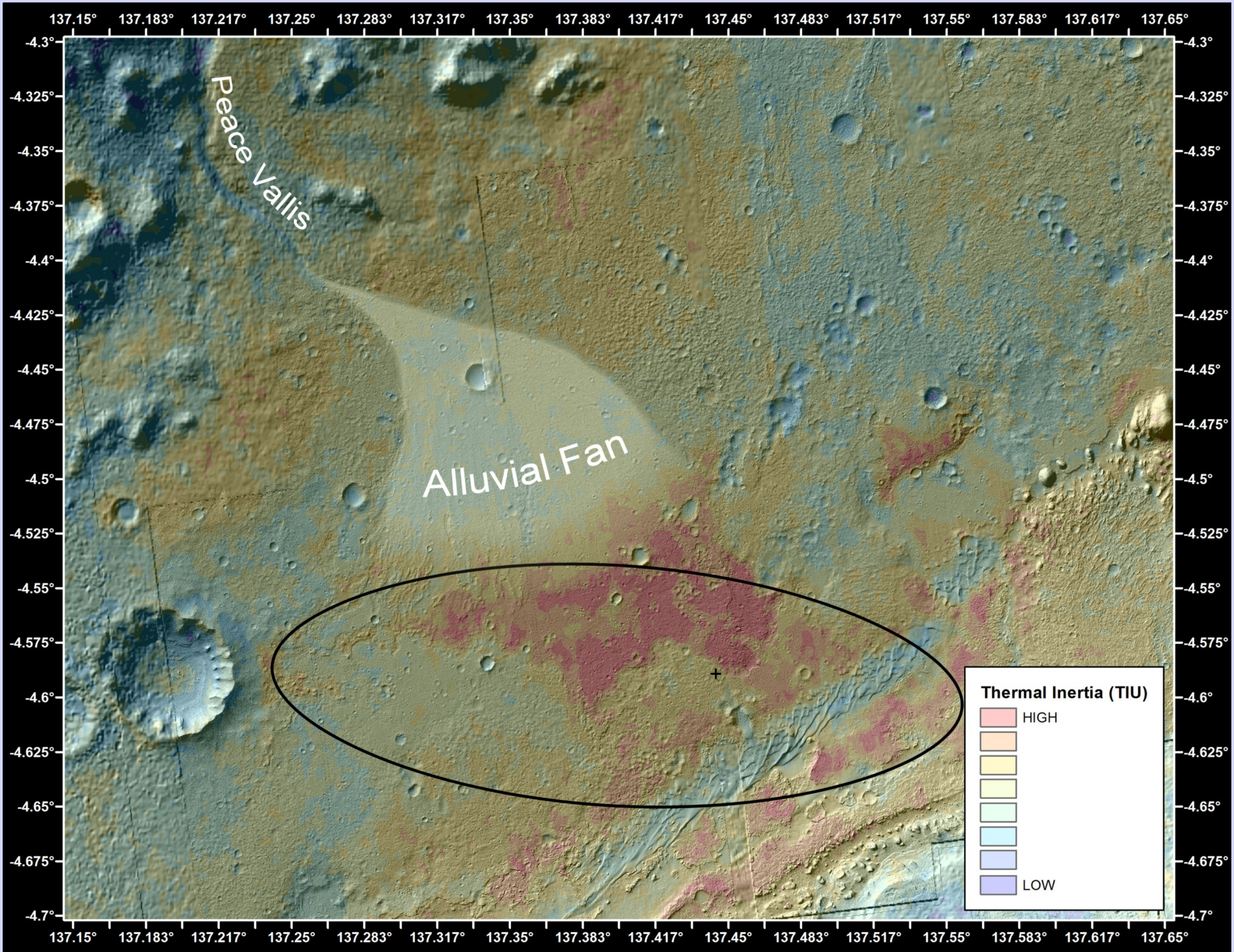


Peace Vallis,
Gale crater, Mars

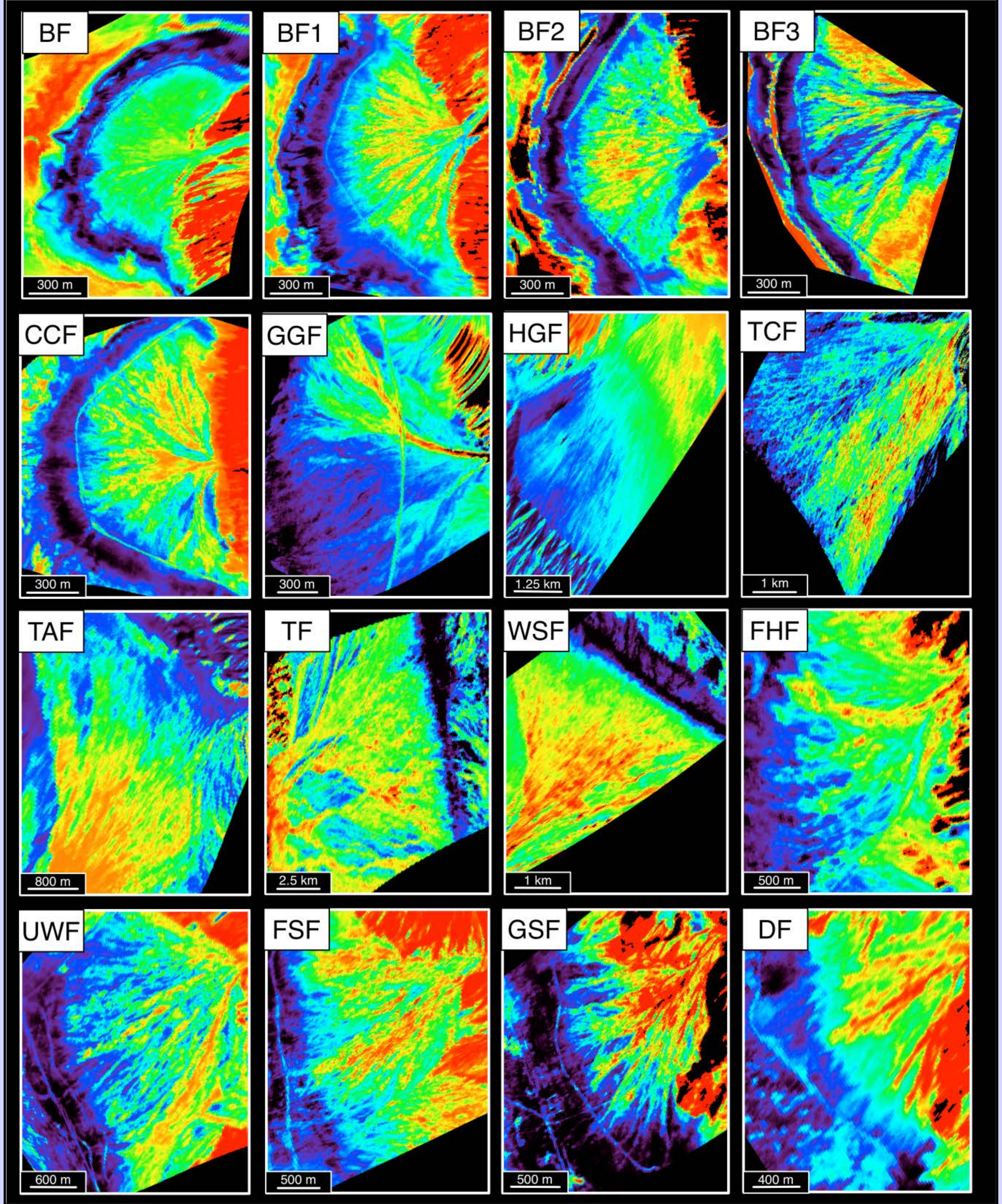
Calculated from day-night image pairs from the THEMIS instrument around Mars

Fergason et al., 2006; Anderson & Bell, 2010




137.15°
137.183°
137.217°
137.25°
137.283°
137.317°
137.35°
137.383°
137.417°
137.45°
137.483°
137.517°
137.55°
137.583°
137.617°
137.65°
-4.3°
-4.325°
-4.35°
-4.375°
-4.4°
-4.425°
-4.45°
-4.475°
-4.5°
-4.525°
-4.55°
-4.575°
-4.6°
-4.625°
-4.65°
-4.675°
-4.7°
Peace Vallis
Alluvial Fan
Thermal Inertia (TIU)
HIGH
LOW

ΔT images of alluvial fans, Death Valley & Owens Valley, CA



Hardgrove et al. (2010)

Temperature and Land Cover

Remote Sensing of Atlanta, Georgia in Thermal Infrared

Georgia Dome

Project ATLANTA, Marshall Space Flight Center, Huntsville, Alabama. Accessed 2 Feb 2005. http://www.ghcc.msfc.nasa.gov/atlanta/

Question

Below are daytime and nighttime thermal infrared images (9.60-10.2µm) of Atlanta at 10m/pixel resolution. Describe the changes in appearance of roads, buildings, forest, and water over the course of the day.

In light of this information, what should urban planners do to minimize the “urban heat island” effect?

ATLAS-TIR, 10m resolution, Band 13 (9.60-10.2µm)

Day (~12pm), air temp 25ºC

Night (~3am), air temp 10ºC

Columbus crater *(Night IR over Day IR)*

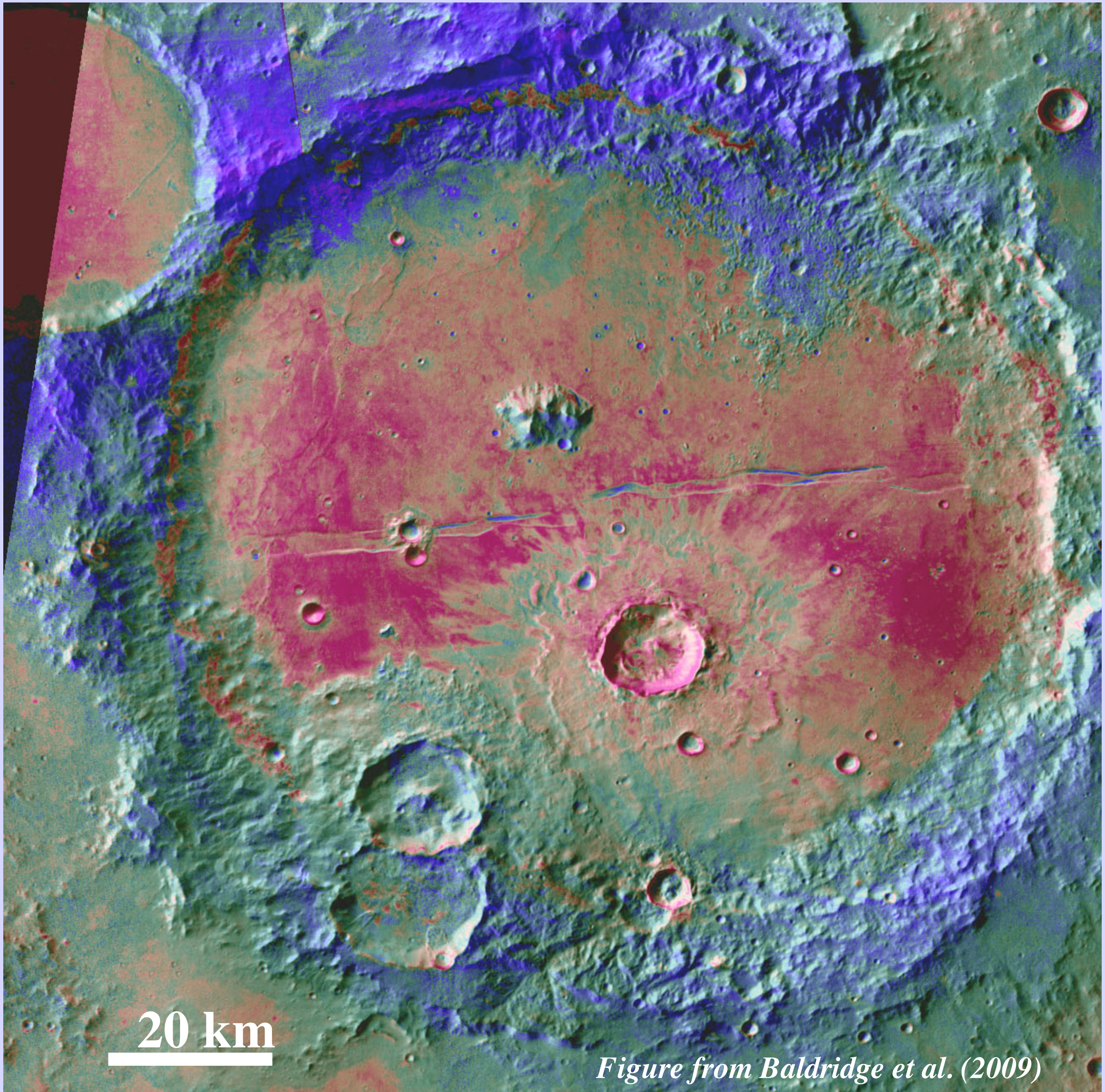
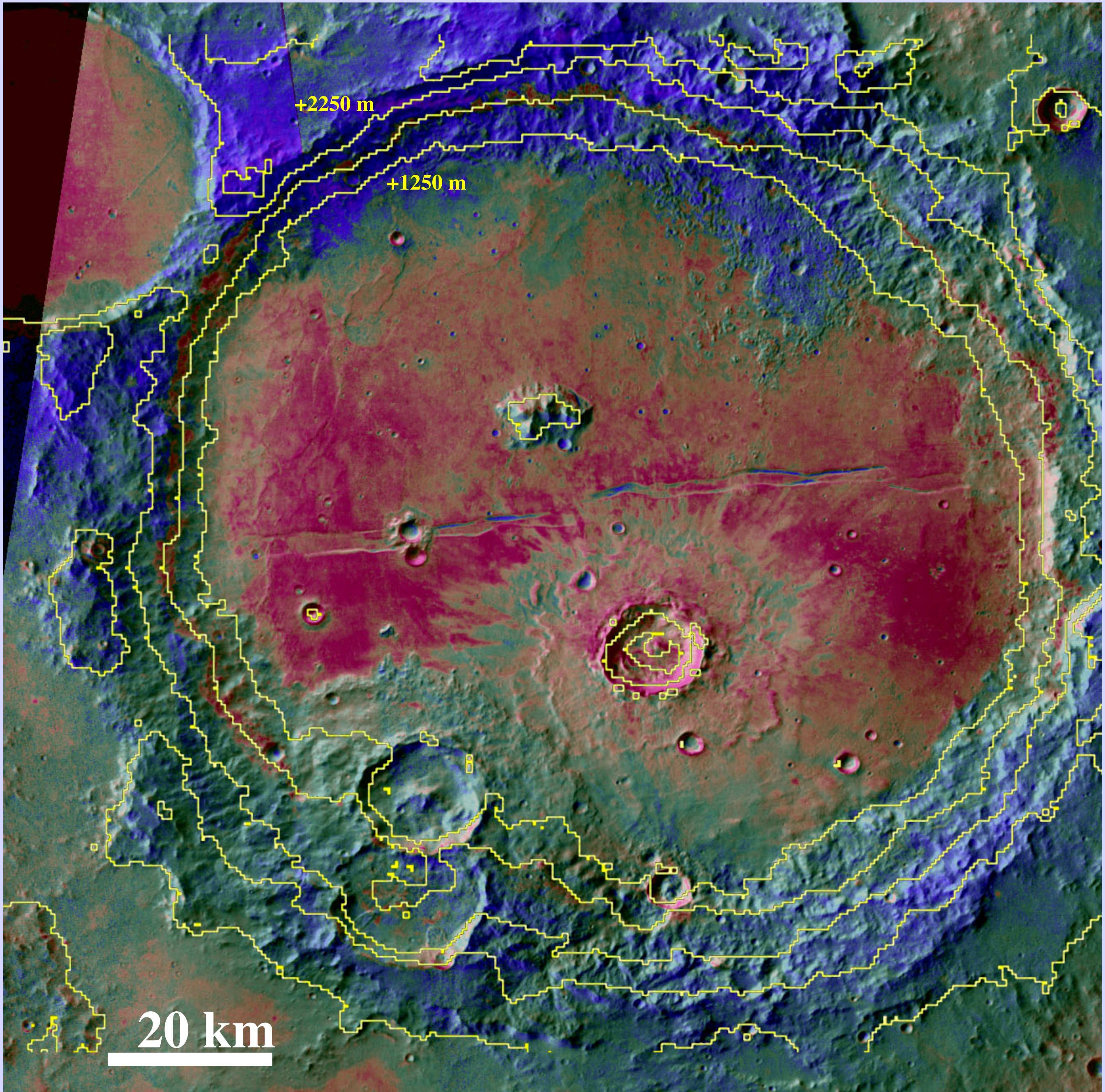
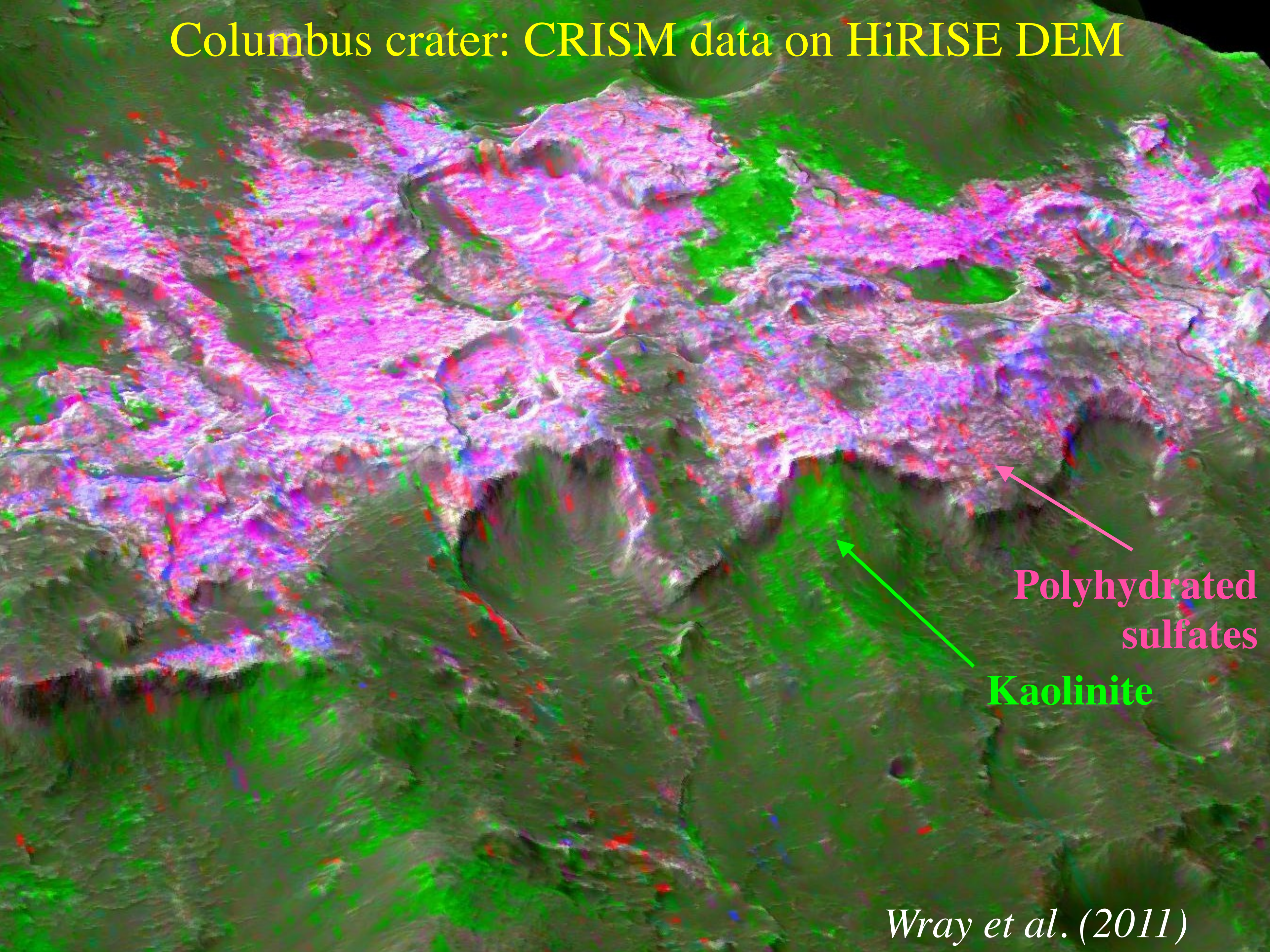


Figure from Baldridge et al. (2009)

Columbus crater *(Night IR over Day IR)*

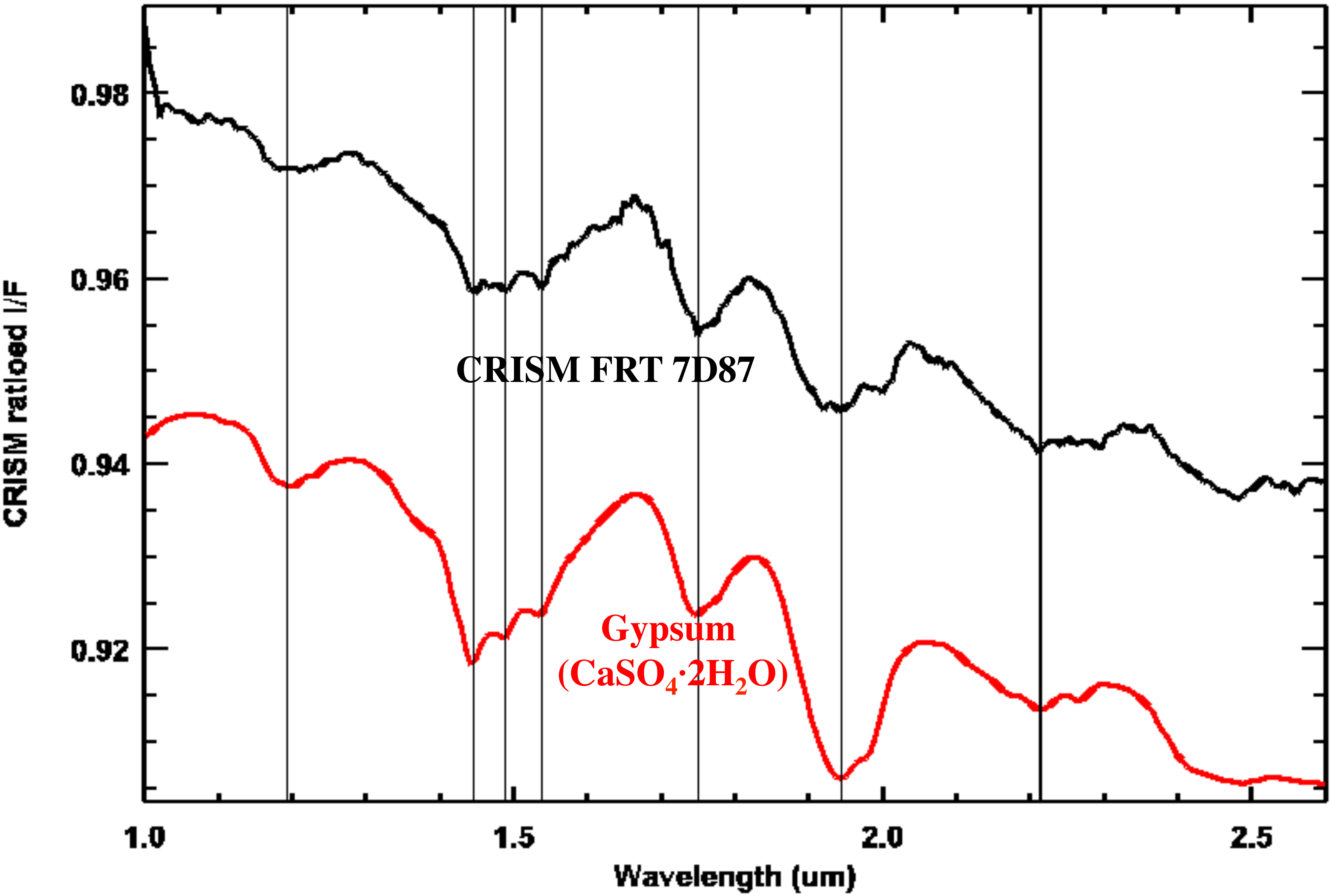


Columbus crater: CRISM data on HiRISE DEM

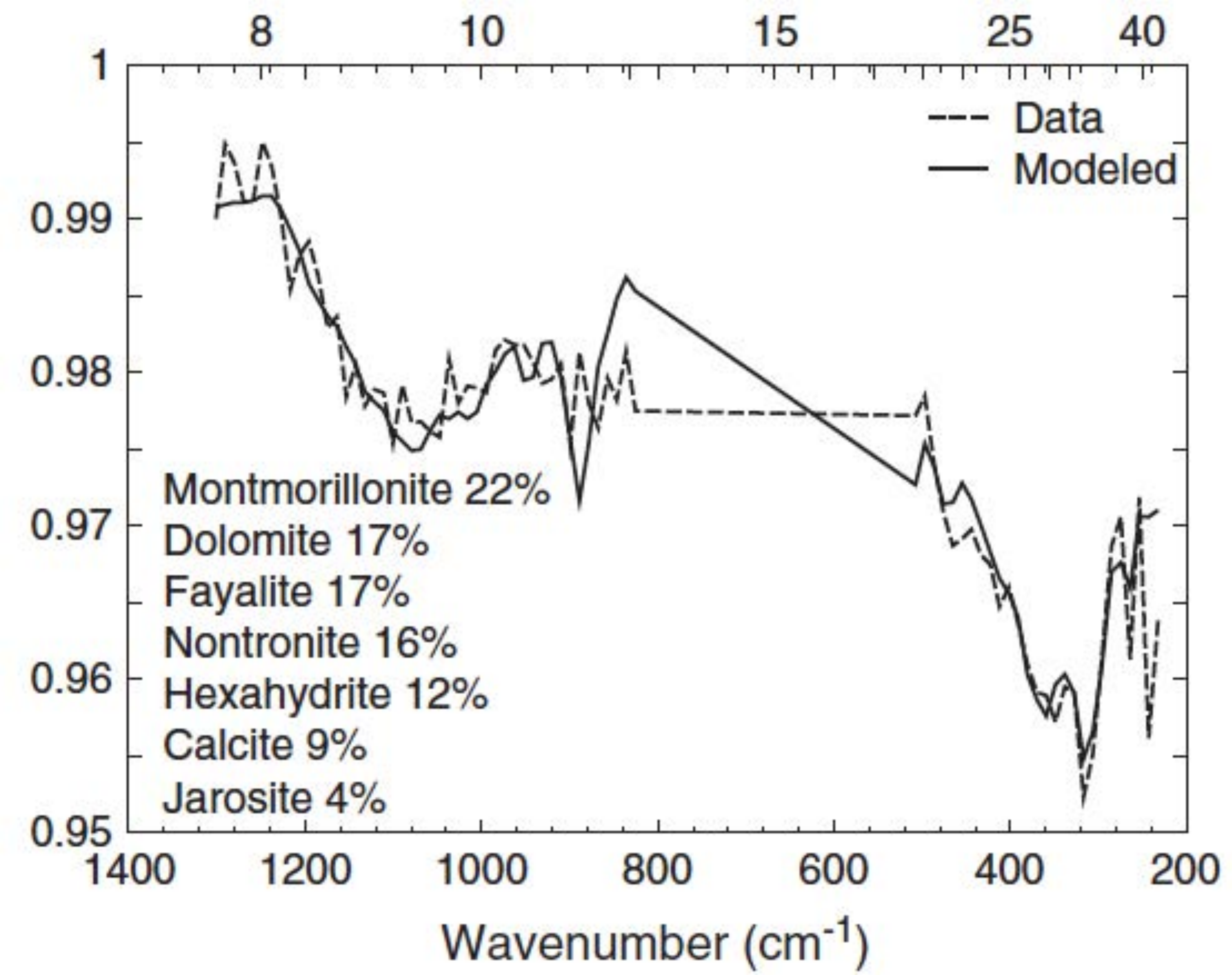


Wray et al. (2011)

Near-IR spectra allowed precise mineral identification



Thermal IR spectral data allowed estimating ***abundances***



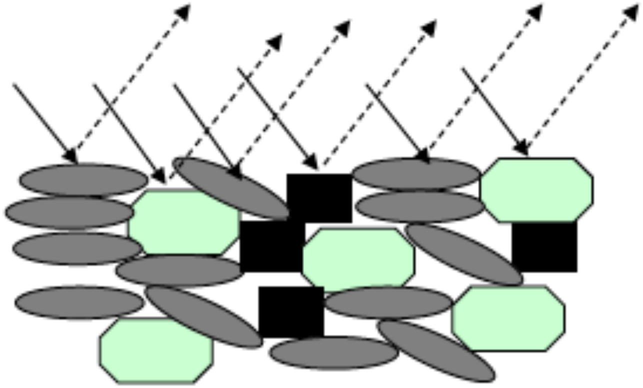
Baldridge et al. (2013)

Why is “How Much?” a difficult question?

Thermal Infrared

Dominated by single-scattering for coarse granules or rocks

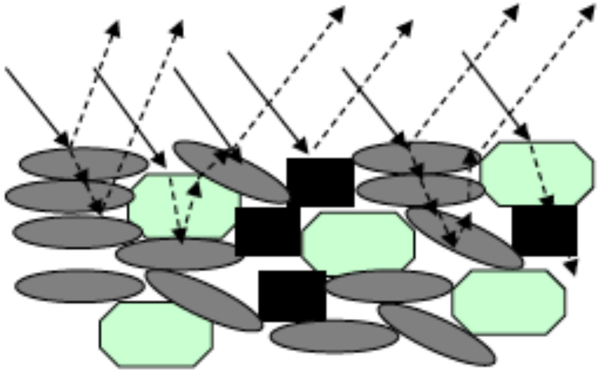
~ Linear



Visible/Near-Infrared

Dominated by multiple-scattering, grain size and composition effect scattering

~ Non-linear



But rough surfaces can complicate thermal IR unmixing… (because single scattering no longer dominates)

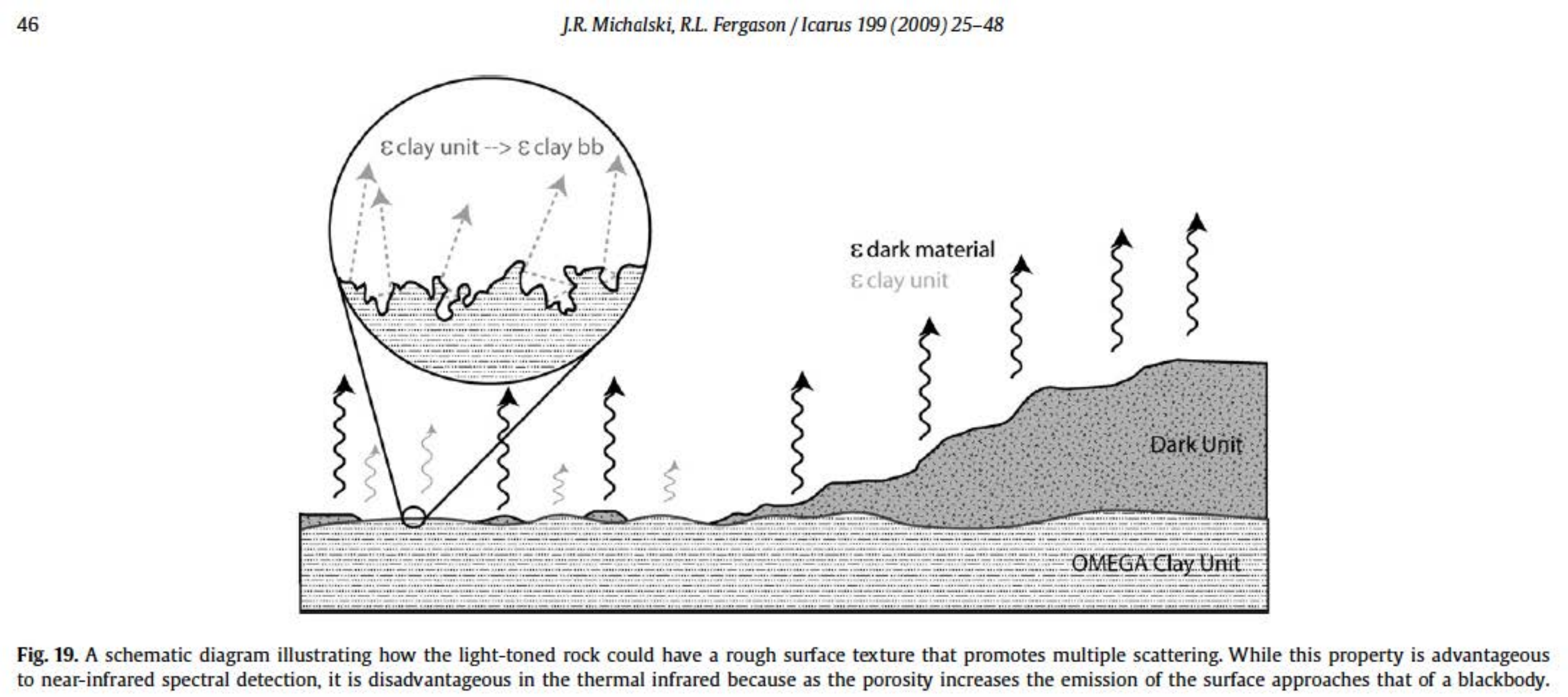


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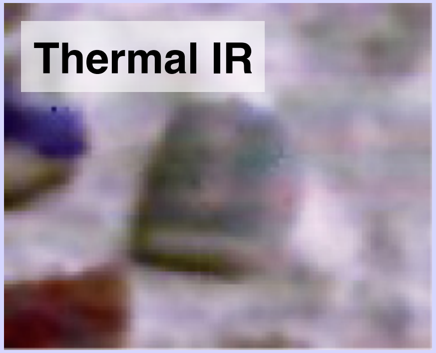
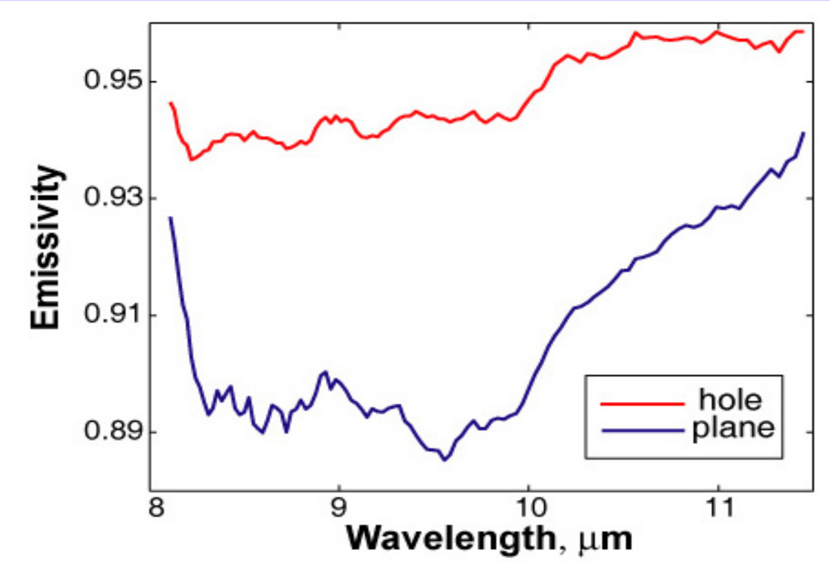
Fig. 19. A schematic diagram illustrating how the light-toned rock could have a rough surface texture that promotes multiple scattering. While this property is advantageous to near-infrared spectral detection, it is disadvantageous in the thermal infrared because as the porosity increases the emission of the surface approaches that of a blackbody.

Cavity Effect

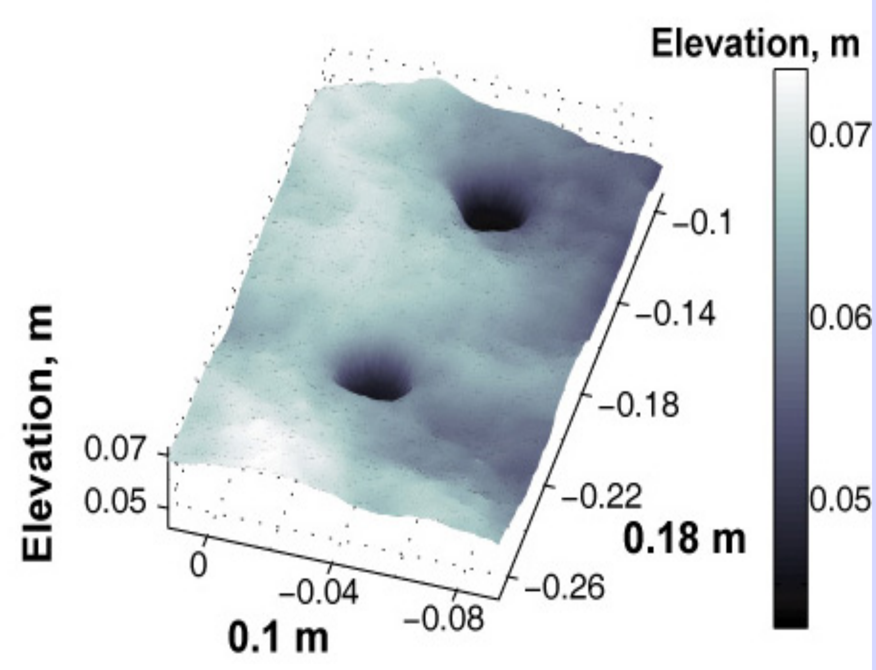
Norite rock with two drilled holes:



Thermal IR spectra:



3D view (DTM resolution 0.002 m):



Modeled apparent emissivity: