Wed. Feb. 28, 2018

- Reminder: Midterm exam next Wednesday
  - Closed book, Closed Notes
  - Do bring a calculator
  - Review session Monday

- Today:
  - Finish Thermal Remote Sensing Pt. 1 (IR emission)
    - Use Monday's posted slides
- Today + Friday:
  - Thermal Remote Sensing Pt. 2 (Heat transfer)
    - New slides posted for today
- Tomorrow at ~3PM MST: Launch of GOES-S
  - NASA TV or <http:www.spaceflightnow.com>

GOES-S Launch Tomorrow

- 2nd of 4 in upgraded "GOES-R" series
  - First GOES-R (now GOES-16) launched Nov. 2016
  - Will be renamed GOES-17 once in operation
  - To be positioned at 137° W Long. (Pacific Coast)
    - GOES-16 is positioned off East Coast
  - 15 year expected life
- Geosynchronous (equatorial) satellites like this launch from Cape Canaveral
  - (POES launch from Vandenberg on W. Coast)
  - 2 hr launch window opens as 3:02 MST
  - Coverage on NASA TV and <http://spaceflightnow.com>

Use slides posted Monday for first part (Thermal Emission)

Heat Transfer -- Today and Friday

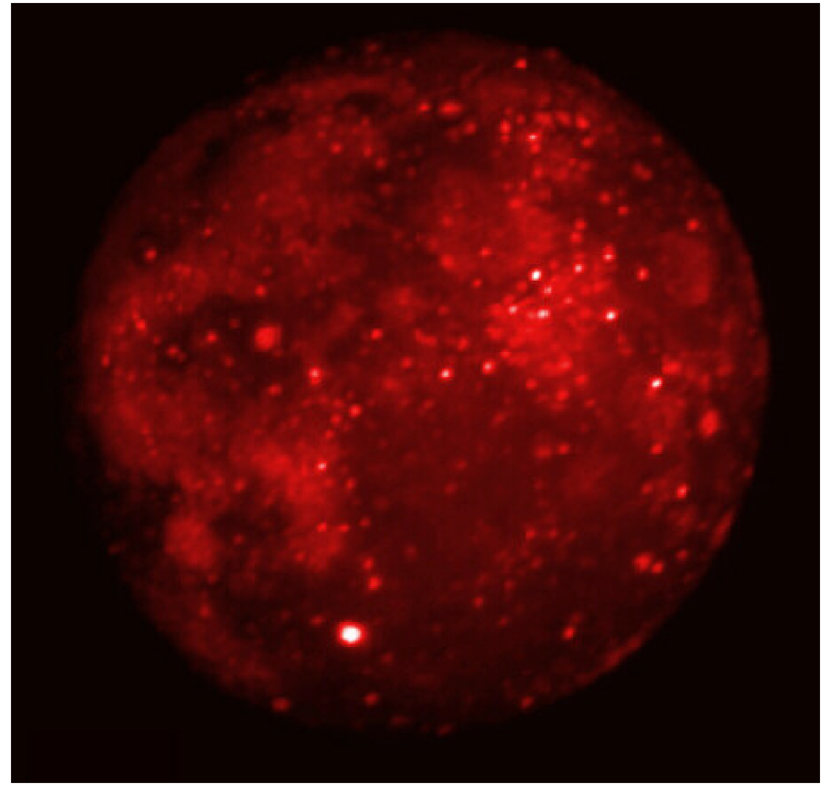
- Thermal Remote Sensing Part 2.
  - Review -- emissivity effects
  - Temperature changes:
    - conductivity, heat capacity, diffusivity
    - thermal inertia
  - Geological Examples
  - Heat loss studies

Heat Transfer

- Heat Transfer (more quantitative than Sabins)
  - Properties which control how material heats up and cools down:
    - Conductivity
    - Heat Capacity
    - Density
    - (Also albedo -- since it controls absorption of sunlight)
  - Derived terms:
    - Thermal Inertia
    - Thermal Diffusivity
    - Apparent thermal inertia

Lunar Eclipse
Measurements of Thermal Inertia

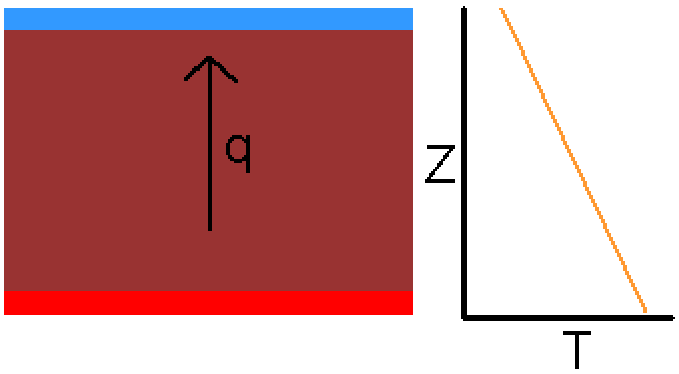
Visible image of full moon



Infrared (MSX) image in eclipse

Most of moon cools quickly: Low thermal inertia $(k\rho c)^{1/2}$ ⇒ porous regolith
Around craters is cools slowly: High thermal inertia ⇒ exposed bare rock

Thermal Constants: Conductivity



- Heat flow q: W/m^2

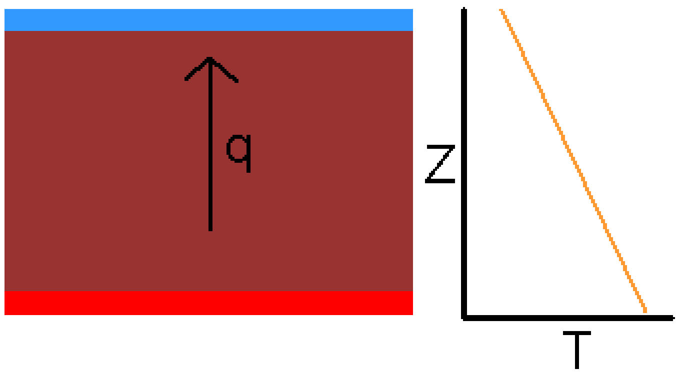
$$q = -K \frac{dT}{dz}$$

where K = Thermal Conductivity
$(W/m^2)/(K/m) = W\ m^{-1}\ K^{-1}$

book uses "older" units of

cal cm^{-1} sec^{-1} $^{o}C^{-1}$

Thermal Constants: Conductivity



Basalt:

$K = 0.0050 \text{ cal cm}^{-1} \text{ sec}^{-1} \, ^{o}C^{-1}$

$\times 4.187 \text{ J/cal} \quad \times 102 \text{ cm/m}$

$= 2.1 \text{ J s}^{-1} \text{ m}^{-1} \text{ K}^{-1}$

$= 2.1 \text{ W m}^{-1} \text{ K}^{-1}$

- Suppose diagram represents T=300K surface at top, T=1300K molten lava at base, with 0.1 m thick crust of basalt between.

$$q = -K \frac{dT}{dz} = -2.1 \; W \; m^{-1} K^{-1} \frac{1000 \text{ K}}{0.1 \; m} = \text{-21,000 W m}^{-2}$$

- A shoe sole is ~ 10 cm × 30 cm = 0.1 m × 0.3 m = 0.03 m^2 so a sole would absorb 21,000 W m^{-2} × 0.03 m^2 = 630 W.
  Will get warm – but can stand it for short time.

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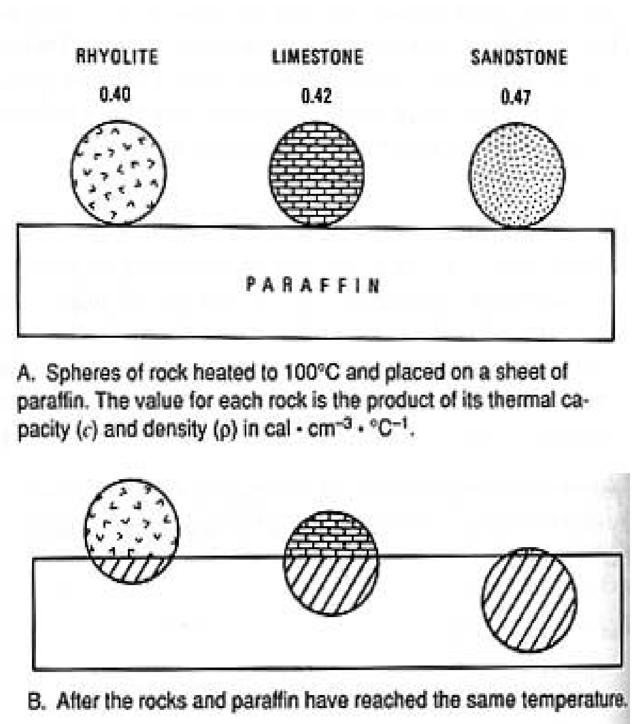
Heat Capacity



A. Spheres of rock heated to 100°C and placed on a sheet of paraffin. The value for each rock is the product of its thermal capacity (c) and density (ρ) in cal · cm^{-3} · °C^{-1}.

B. After the rocks and paraffin have reached the same temperature.

Sabins Fig. 5-4
Amount of melt is proportional to total heat capacity

C: Heat Capacity (Thermal Capacity)
J kg^{-1} ^{o}C^{-1}

Basalt:

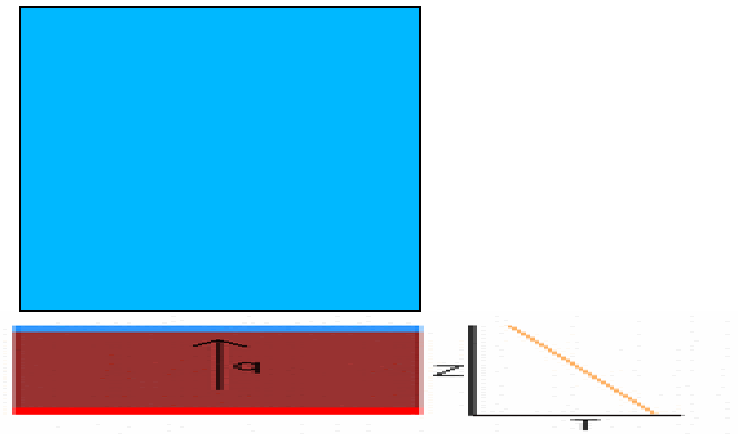
$C = 0.20$ cal g^{-1} ^{O}C^{-1}
$\times$ 4.187 J/cal $\times$ 1000 g/kg
= 840 J kg^{-1} K^{-1}

To get heat capacity of <u>unit volume</u>, find ρC where

ρ = density = 2.8 g cm^{-3}
$\times$ (10^{2} cm/m)^{3} / (10^{3} g/kg)
= 2800 kg m^{-3}

ρC = 840 J kg^{-1} K^{-1} $\times$ 2800 kg m^{-3}
= 2.3 $\times$ 10^{6} J m^{-3} K^{-1}

Heating time?



Have 1 meter on a size block,
with heat flowing into it as given in previous example: $q = 21{,}000$ W m^{-2}

Heat capacity per unit volume is
$\rho C = 2.3 \times 10^{6}$ J m^{-3} K^{-1}
Volume is 1 m^3 so total heat capacity is 2.3×10^{6} J K^{-1}

Total heat flow is 21,000 W = 21,000 J s^{-1}
since area A = 1m^2.

Heating rate will be
2.1×10^{4} J s^{-1} / 2.3×10^{6} J K^{-1} =
0.91×10^{-2} K s^{-1} ~ 10^{-2} K s^{-1}

Note – in above we didn't allow heat to flow out of top of block. Within material, heating rate will be proportional (heat flow in) – (heat flow out) .

Heating rate was proportional to
$q/ \rho C \propto K/(\rho C)$

Define $k = K/(\rho C)$
as "Thermal Diffusivity"

$k = 2.1$ W m^{-1} K^{-1} /
2.3×10^{6} J m^{-3} K^{-1}
$= 9.1 \times 10^{-7}$ m^2 s^{-1} for basalt

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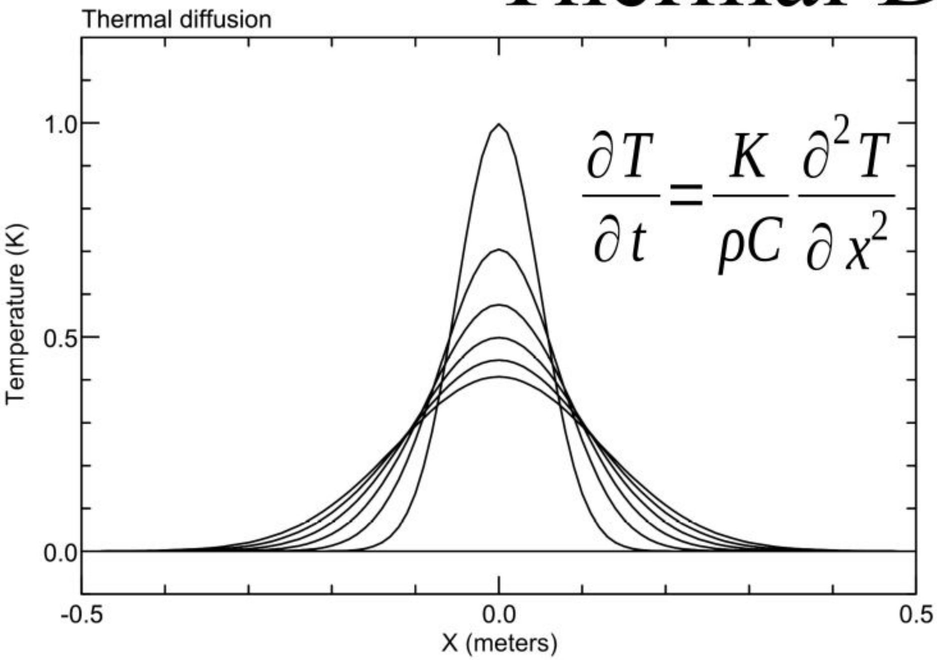
Thermal Diffusivity



$$\frac{\partial T}{\partial t} = \frac{K}{\rho C} \frac{\partial^2 T}{\partial x^2}$$

How far does thermal wave propagate in given Δt ?

Assume given ΔT, solve for Δx:

$$\frac{\Delta T}{\Delta t} = \frac{K}{\rho C} \frac{\Delta(\Delta T)}{(\Delta x)^2}$$

$$\Delta x = \sqrt{\frac{K}{\rho C} \Delta t}$$

For basalt k = 9×10^{-7} m^2 s^{-1}

If you wait 1 year = 3.15×10^7 s, how far does thermal wave propagate?

Δx = (9×10^{-7} m^2 s^{-1} $\times$ 3.15×10^7 s)^{½} = (28 m^2)$^{1/2}$ = 5.3 m

With sandy soil k = 3×10^{-7} m^2 s^{-1} so

Δx = (3×10^{-7} m^2 s^{-1} $\times$ 3.15×10^7 s)^{½} = (9.4 m^2)$^{1/2}$ = 3.1 m

If you wait 1 day = 8.6×10^4 s, how far does thermal wave propagate in sandy soil?

Δx = (3×10^{-7} m^2 s^{-1} $\times$ 8.6×10^4 s)^{½} = (2.6×10^{-2} m^2)$^{1/2}$ = 0.16 m

Periodic Heating of Surface

If you solve heat conduction equation for the case where

$F = F_0 \cos(\omega t)$ is net heat flux through surface

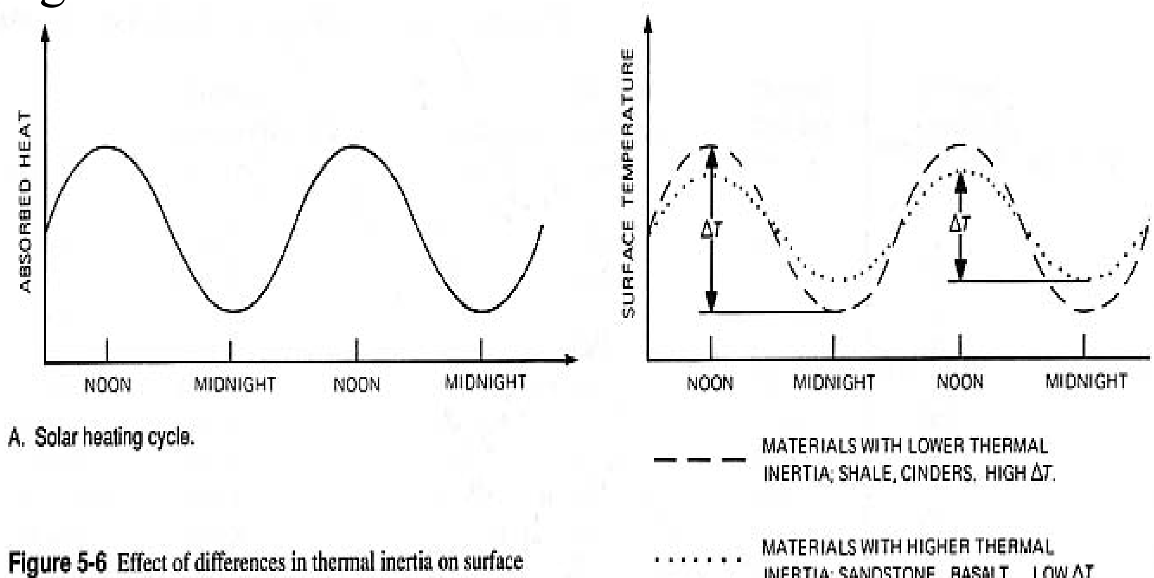
$$T = \frac{F_0}{P\sqrt{\omega}} \cos\left(\omega t - \frac{\pi}{4}\right) + T_0$$ will be <u>surface</u> temperature.

where $\omega = \frac{2\pi}{\text{Period}}$ = Angular frequency

where $P = \sqrt{K\rho C}$ = Thermal Inertia (most people use symbol γ, not P)

So amplitude of T variation is $\propto F_o/(P\omega^{1/2})$

Large thermal inertia ⇒ small T variation



A. Solar heating cycle.

B. Variations in surface temperature.

Figure 5-6 Effect of differences in thermal inertia on surface temperatures during diurnal solar cycles. Note differences in ΔT for materials with high and low thermal inertia.

Sabins Fig. 5-6

Note – figure is badly oversimplified.

T should really be delayed in phase

Also, <u>NET</u> flux is not sinusoidal.

Basalt Thermal Inertia

For Basalt

$$P = \sqrt{K\rho C} = \sqrt{2.1 \text{ W m}^{-1} K^{-1} \; 2800 \text{ kg m}^{-3} \; 840 \text{ J kg}^{-1} K^{-1}}$$

$$= 2.2 \times 10^{3} \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$$

If the net flux varied by 500 W m^{-2} (about 1/3 F_{sun})

and the frequency $\omega = \frac{2\pi}{1 \text{ day}} = \frac{2\pi}{8.64 \times 10^{4} \text{ s}} = 7.27 \times 10^{-5} \text{ s}^{-1}$

then we would expect a temperature variation of

$$\frac{F_0}{P\sqrt{\omega}} = \frac{500 \text{ W m}^{-2}}{2.2 \times 10^{3} \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2} \; \sqrt{7.27 \times 10^{-5} \text{ s}^{-1}}} = 26 \; K$$

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Remote Determination of Thermal Inertia

- Despite what book says, you really can determine P remotely if you have $(1\text{-}A)\times F_{sun}(t)$ and $T(t)$.

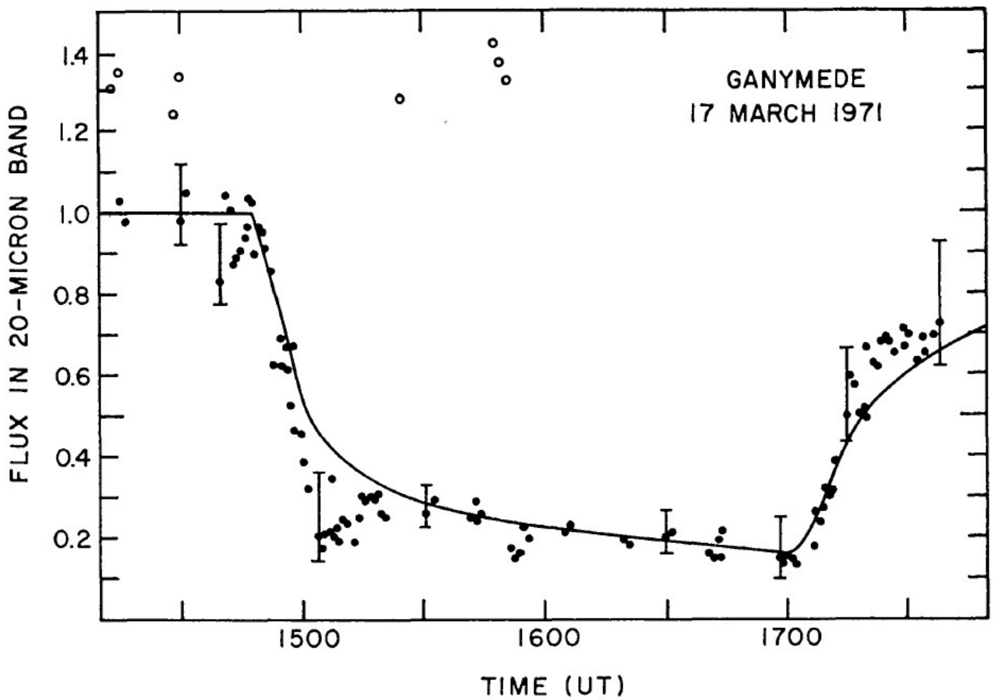

FIG. 2.—Radiometry of Ganymede compared with predicted 20-μ fluxes. *Filled circles*, measurements of Ganymede with sample estimated error bars indicated. *Open circles*, observations of Callisto (J IV). *Solid curve*, the prediction of the best-fitting homogeneous model, for which the thermal inertia is 3×10^4 ergs cm^{-2} $s^{-1/2}$ $°K^{-1}$.

$P = 3\times10^4$ erg cm^{-2} $s^{-1/2}$ K^{-1}

$= 3\times10^{-3}$ J cm^{-2} $s^{-1/2}$ K^{-1}

$= 7.2\times10^{-4}$ cal cm^{-2} $s^{-1/2}$ K^{-1}

Text quotes sandy soil as 0.050 ($=5\times10^{-2}$) cal cm^{-2} $s^{-1/2}$ K^{-1}

so Ganymede resists T changes 100 × worse.

$P = (K\,\rho\,C)^{1/2}$
If change is due to K,
it is 10000 × smaller, due to pulverized regolith

Summary: Material Terms

K	Thermal conductivity How well material conducts heat
C	Heat capacity How much energy is stored
ρ	Mass per unit volume
A	Albedo Fraction of sunlight reflected
$\kappa = k = \frac{K}{\rho C}$	Thermal diffusivity How fast thermal wave travels
$\gamma = P = \sqrt{K\rho C}$	Thermal Inertial How well surface resists T changes
$\text{ATI} = \frac{1\text{-A}}{\Delta T}$	Apparent Thermal Inertia Simple observational measure of thermal inertia

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Typical Thermal Properties

Thermal diffusivity : Distance of propoagation of thermal wave in time Δt ?

$$\Delta x = \sqrt{\frac{K}{\rho C}\Delta t}$$

For sandy soil and t = 1 day = 8.6×10^4 s
$\Delta x = (3\times10^{-7}\ m^2\ s^{-1} \times 8.6\times10^4\ s)^{1/2} = (2.6\times10^{-2}\ m^2)^{1/2} = 0.16$ m

Thermal inertia : Degree of resistance to temperature change

For Basalt

$$P = \sqrt{K\rho C} = \sqrt{2.1\ \mathrm{W\ m^{-1} K^{-1}}\ \ 2800\ \mathrm{kg\ m^{-3}}\ 840\ \mathrm{J\ kg^{-1}\ K^{-1}}} = 2.2 \times 10^3\ \mathrm{J\ m^{-2}\ K^{-1}\ s^{-1/2}}$$

Amplitude of T diurnal variation $\approx \dfrac{F_0}{P\sqrt{\omega}} = 26$ K

(so ΔT =52K, probably an overestimate if we include atmospheric cooling, etc.)

Thermal Inertia and diurnal cycle

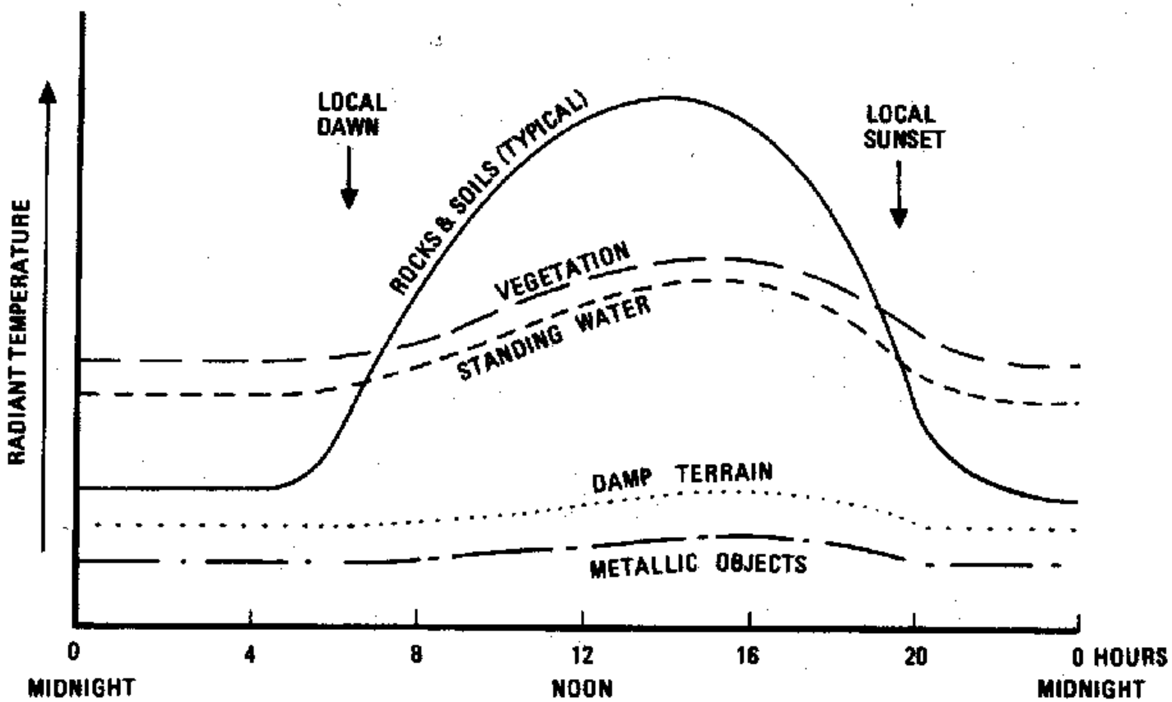

Figure 5-7 Diurnal radiant temperature curves (diagrammatic) for typical materials.

Sabins Fig. 5-7

$F_{net} = (1\text{-}A)\ F_{sun} - \sigma\ T^4$

where A = Albedo

Wet soil has higher thermal conductivity so higher thermal inertia,

but it and vegetation are also affected by evaporation, which limits temperature rise.

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Crossover times for two materials

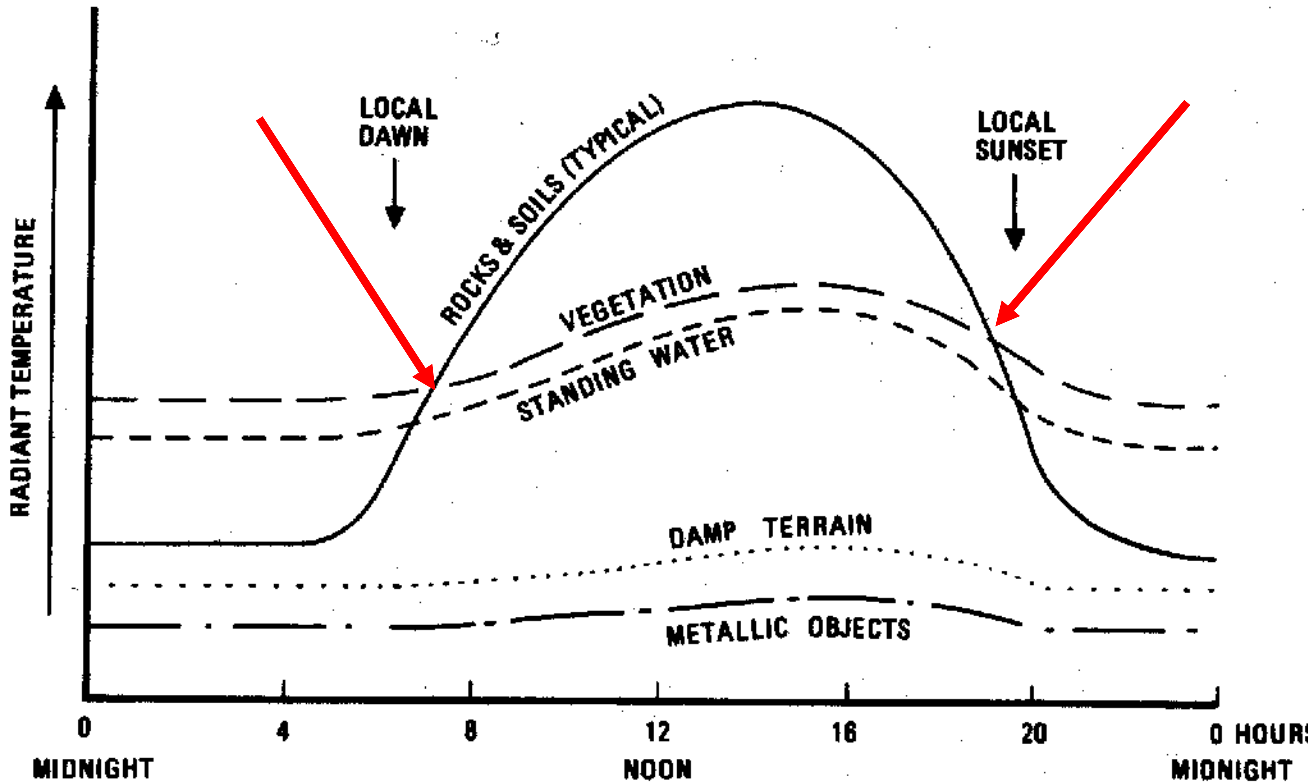
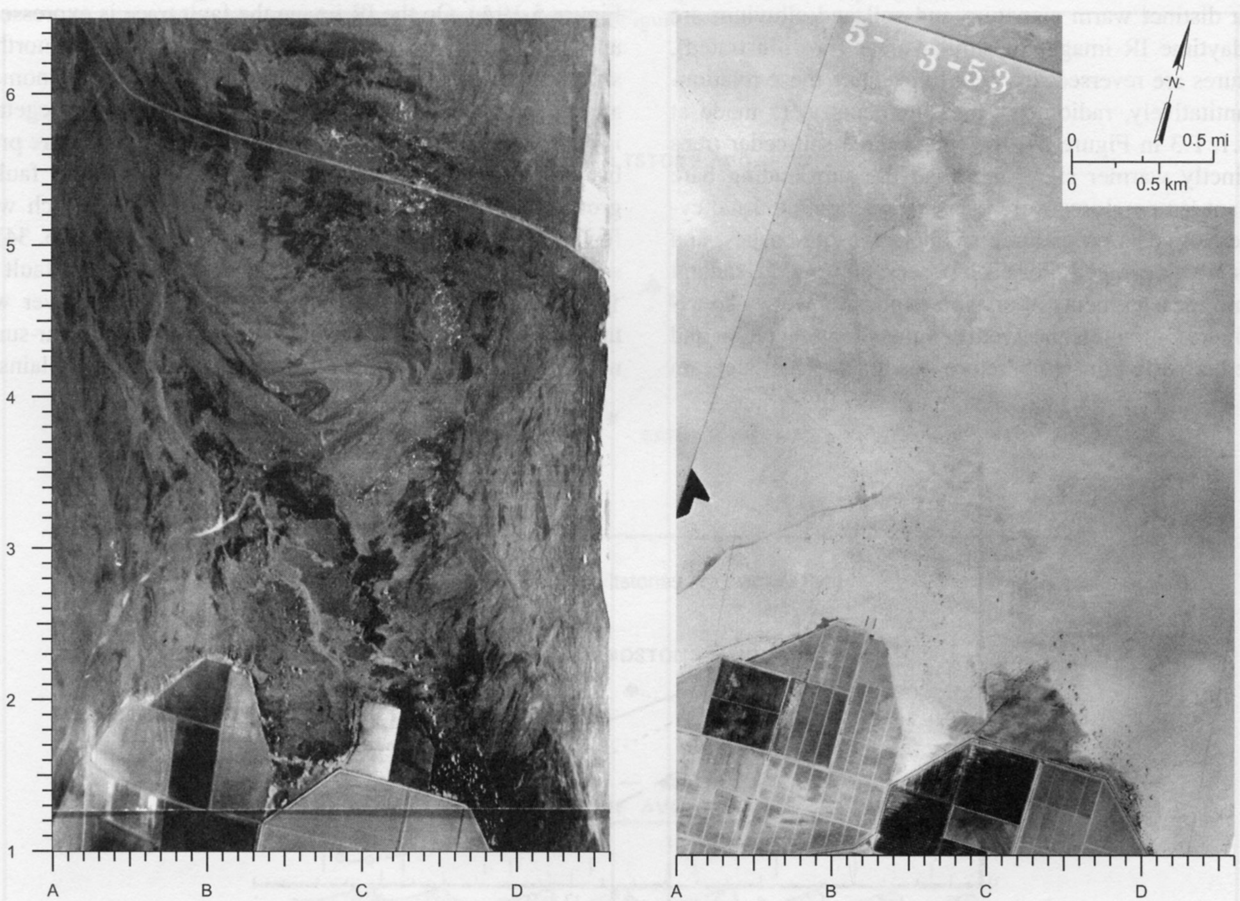


Figure 5-7 Diurnal radiant temperature curves (diagrammatic) for typical materials.

Thermal Images: Imler Rd., CA



A. Nighttime thermal IR image (8 to 14 μm) acquired August 1961.

B. Aerial photograph acquired May 5, 1953.

Figure 5-23 Images of the Imler Road area, Imperial County, California. From Sabins (1969, Plate 1).

How far does thermal wave propagate in given Δt?

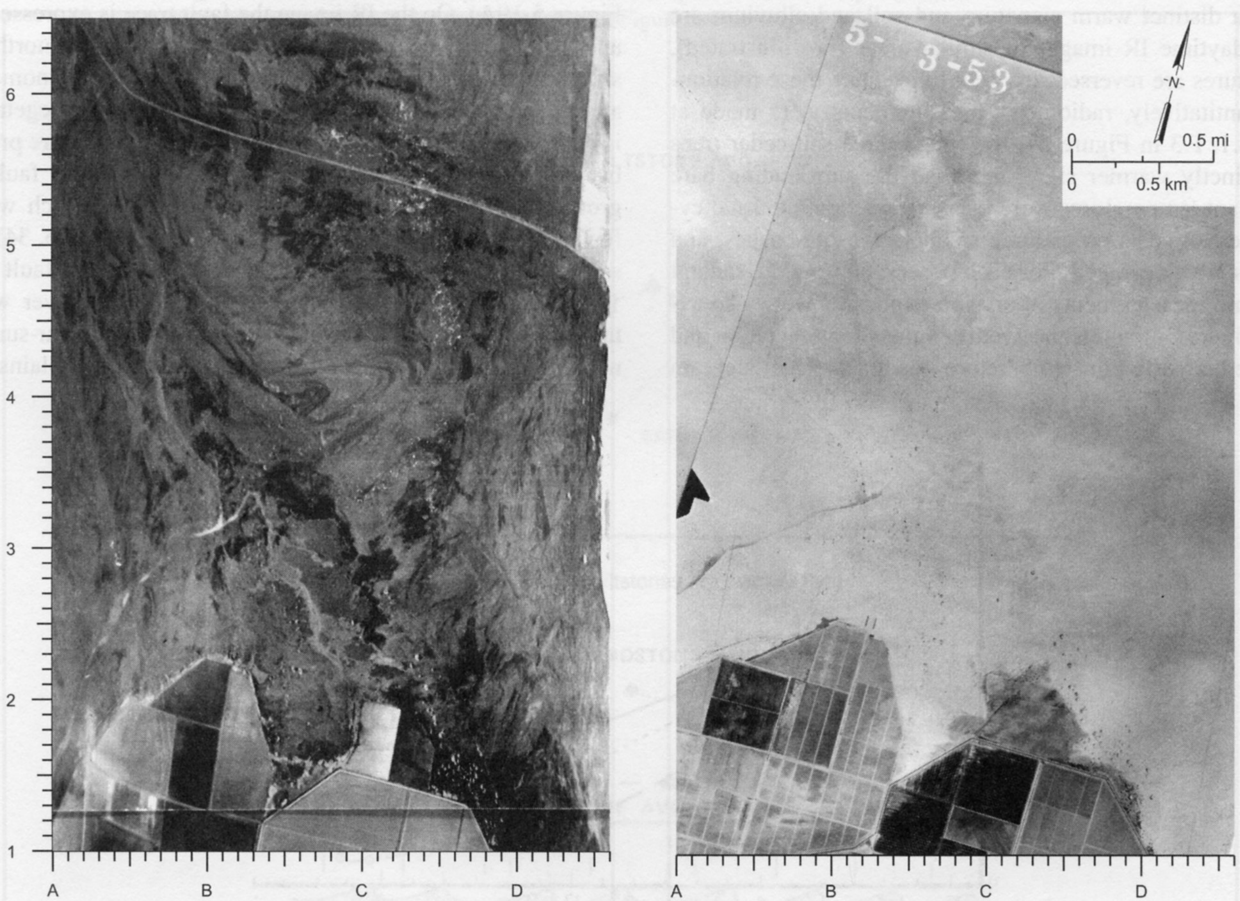
Assume given ΔT, solve for Δx:

$$\Delta x = \sqrt{\frac{K}{\rho C}\Delta t}$$

$= 0.16\ \text{m}$ in sandy soil in 24 hr.

Sabins Fig. 5-23 & 5-25 pg. 158-159 Aerial Photo, Nighttime IR, Imler Rd. CA
Gravel and windblown sand conceal bedrock. Cover thinner than diurnal skin depth.

Thermal Images: Imler Rd., CA



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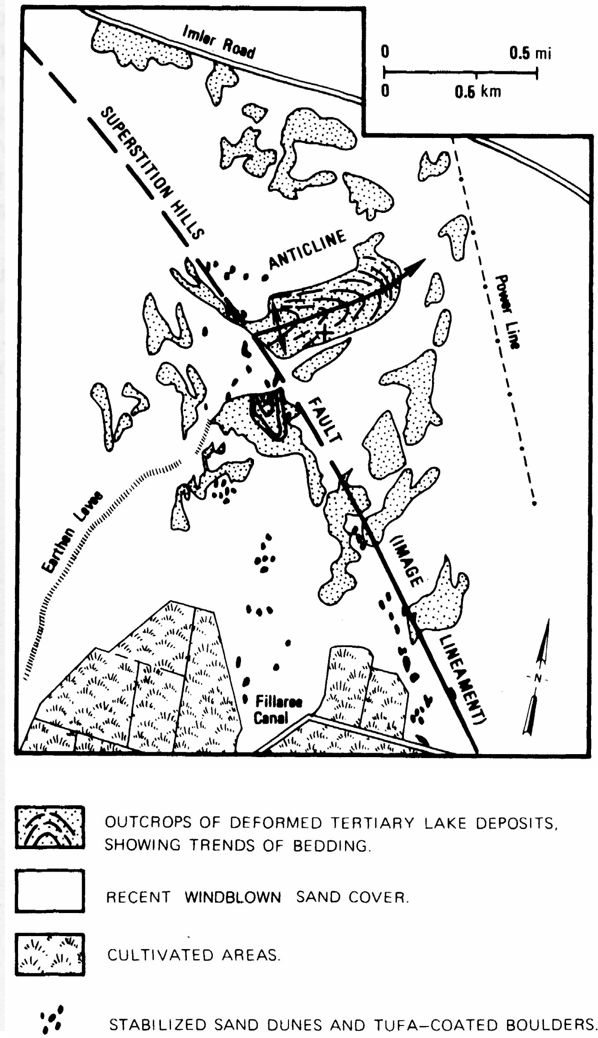
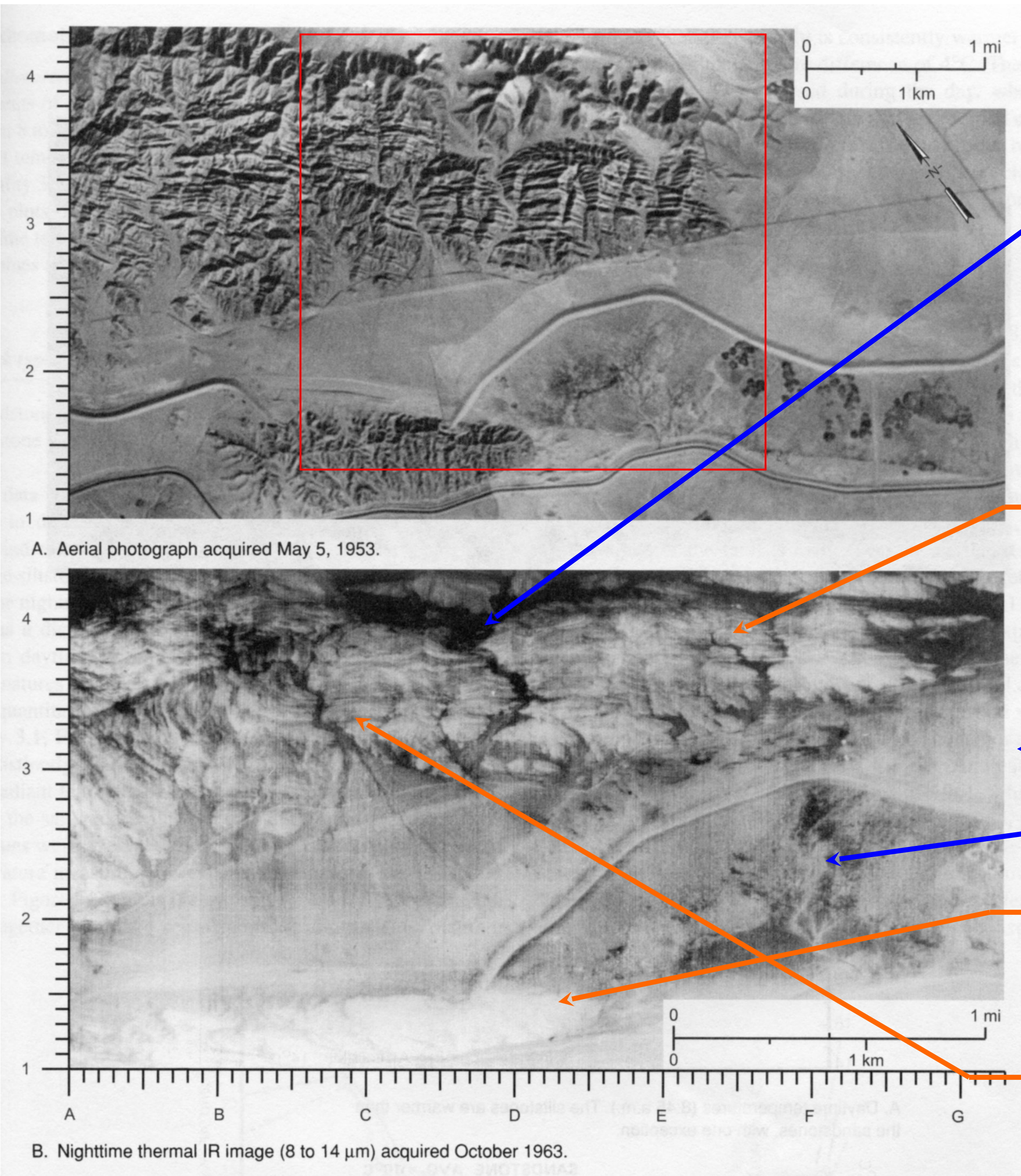


Sabins Fig. 5-23 & 5-25   pg. 158-159   Aerial Photo, Nighttime IR,   Imler Rd. CA
Gravel and windblown sand conceal bedrock. Cover thinner than diurnal skin depth.

Aerial Photo and Night Thermal Imagery, Indio Hills

Sabins Fig. 5-19 pg 155



Cool:

Alluvium?

Damp?

Shadows?

Palm Springs Formation: alternating beds of resistant conglomerate sandstone and nonresistant siltstone

Alluvium

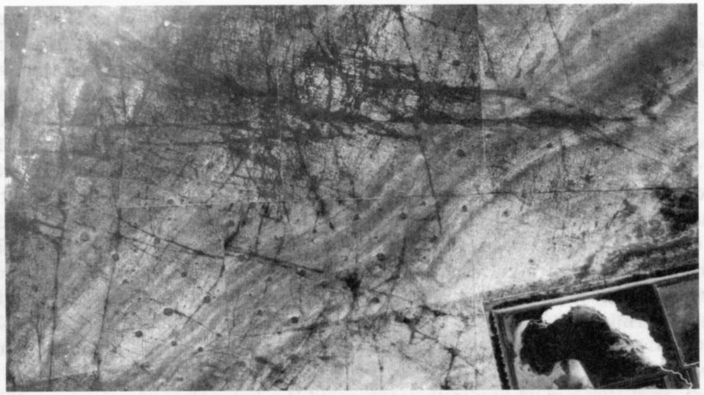
Vegetation

Ocotillo Conglomerate:

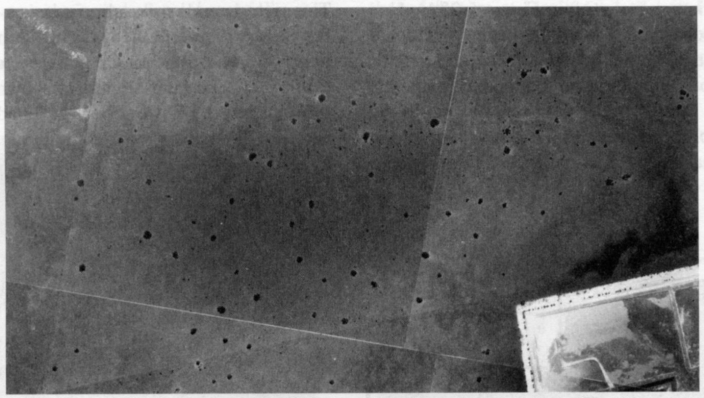
Poorly stratified

Syncline and Anticline

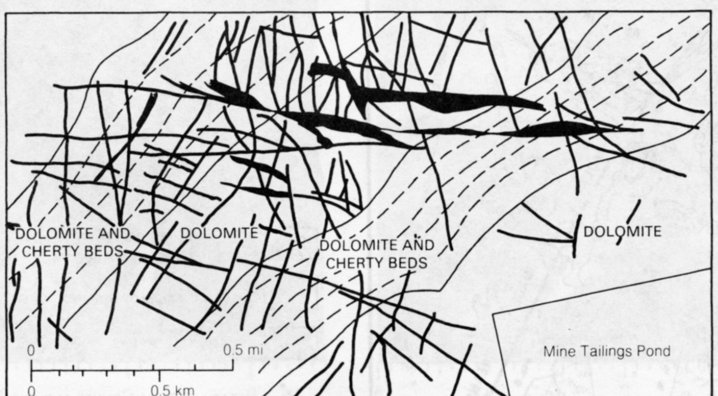
Thermal Images: Stilfontein



A. Nighttime thermal IR image (8 to 14 μm).



B. Aerial photograph.



C. Interpretation map of thermal IR image.

Figure 5-25 Stilfontein area, western Transvaal, South Africa. From Warwick, Hartopp, and Viljoen (1979, Figures 8 and 9).

Sabins Fig. 5-25 pg. 160
Aerial Photo, Nighttime IR, Interpretation
Stilfontein, South Africa

Dark linear features: Faults and joints filled with moist soil

Dolomite: Warm (bright) High ρ and Thermal Inertia

Chert-Rich beds: Cool (dark) Low ρ and Thermal Inertia

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Apparent Thermal Inertia

- Simplified version is often used in terrestrial remote sensing:
- Apparent Thermal Inertia $\mathrm{ATI} = \dfrac{1 - A}{\Delta T}$

where $\Delta T = T_{\max} - T_{\min}$

- Works because F_{sun} is roughly similar "everywhere" on Earth
- Can make an "ATI" image from a visible image (to get A) and a day and a night thermal image (to get T_{max} and T_{min}).

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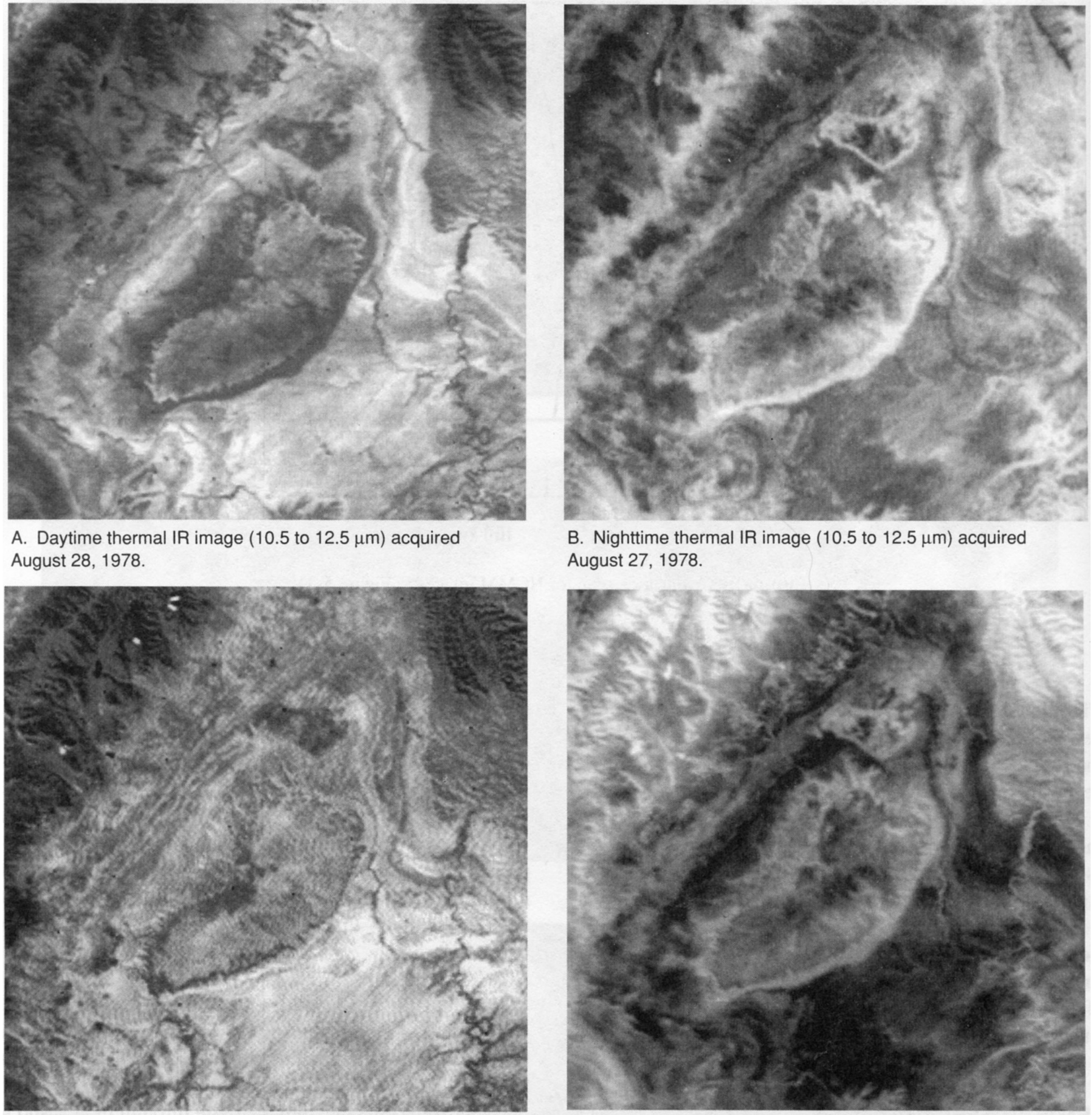
ATI Derivation for San Rafael Swell, Utah

$$ATI = \frac{1 - A}{\Delta T}$$



A. Daytime thermal IR image (10.5 to 12.5 µm) acquired August 28, 1978.

B. Nighttime thermal IR image (10.5 to 12.5 µm) acquired August 27, 1978.

C. Visible (albedo) image acquired August 28, 1978.

D. Apparent thermal inertia image.

Figure 5-33 Enlarged HCMM images of the San Rafael Swell, Utah. From Kahle and others (1981). Courtesy A. B. Kahle, Jet Propulsion Laboratory.

Sabins Fig. 5-33

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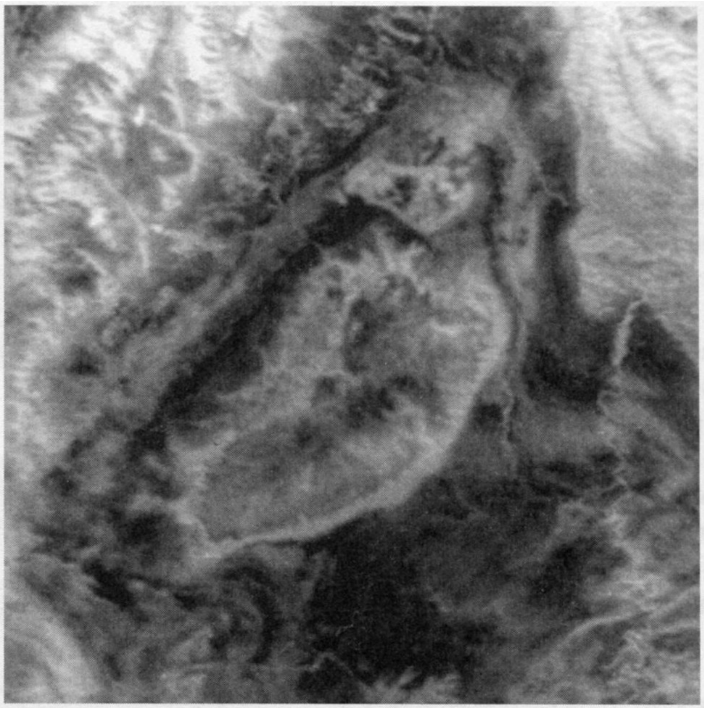
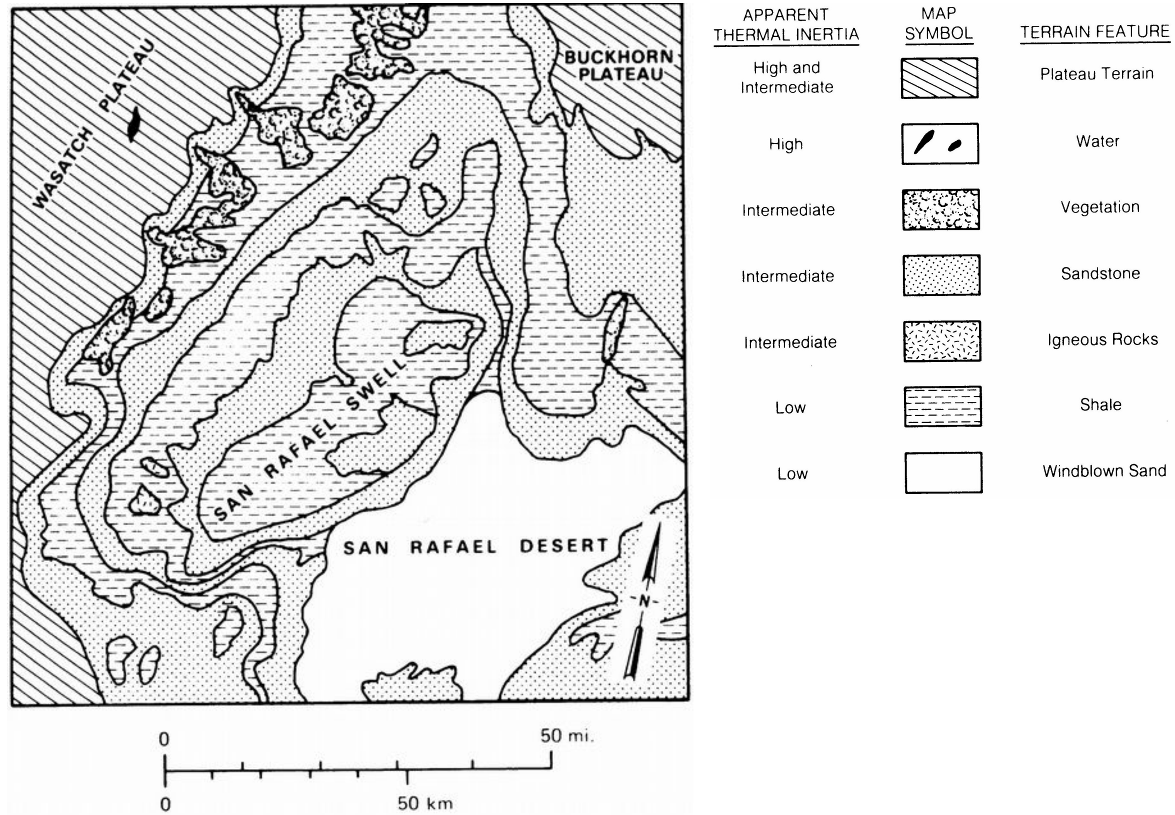
ATI Interpretation, San Rafael Swell, Utah



D. Apparent thermal inertia image.



Sabins Fig. 5-33d and 5-34

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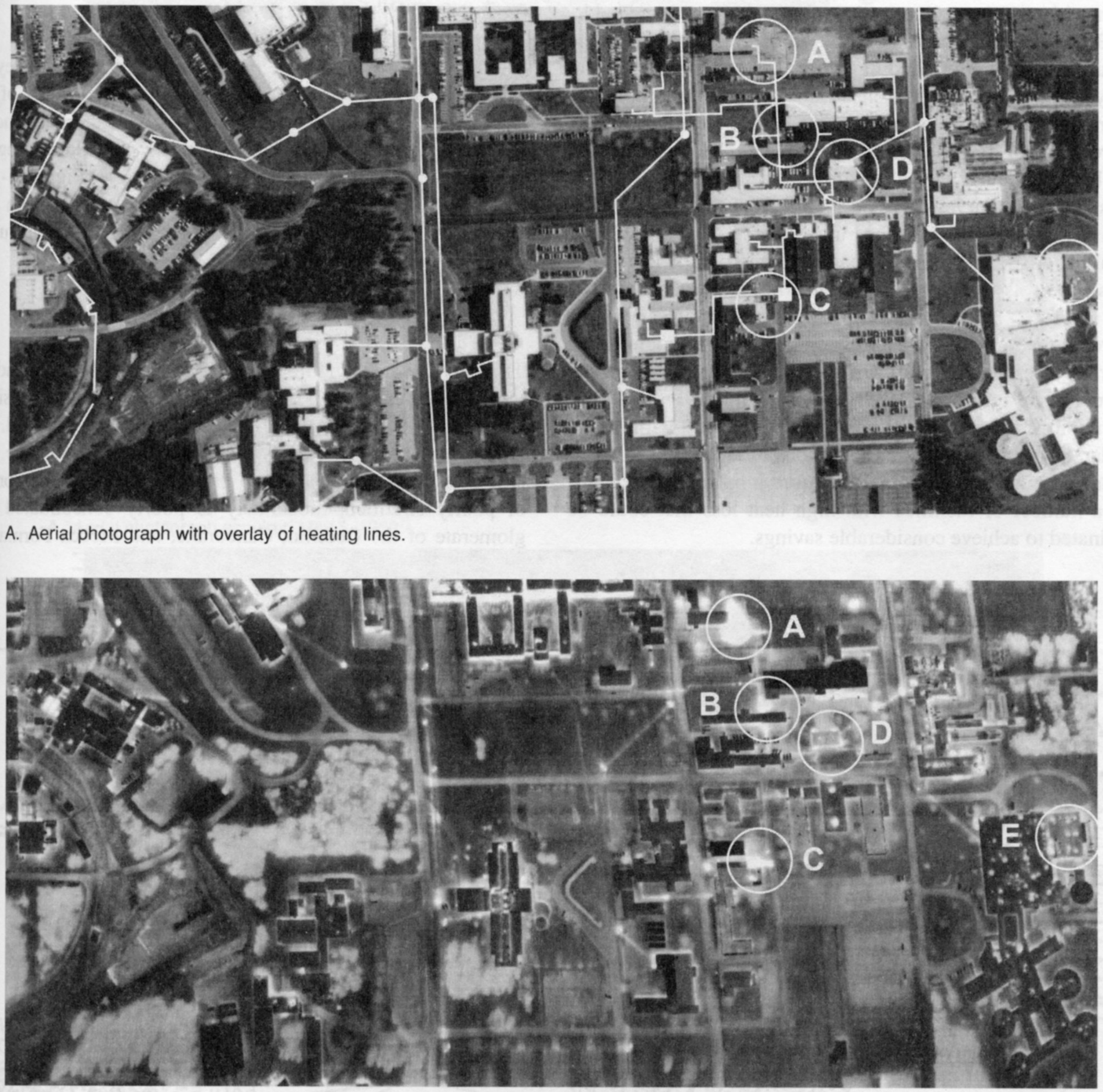
Urban Heat Loss



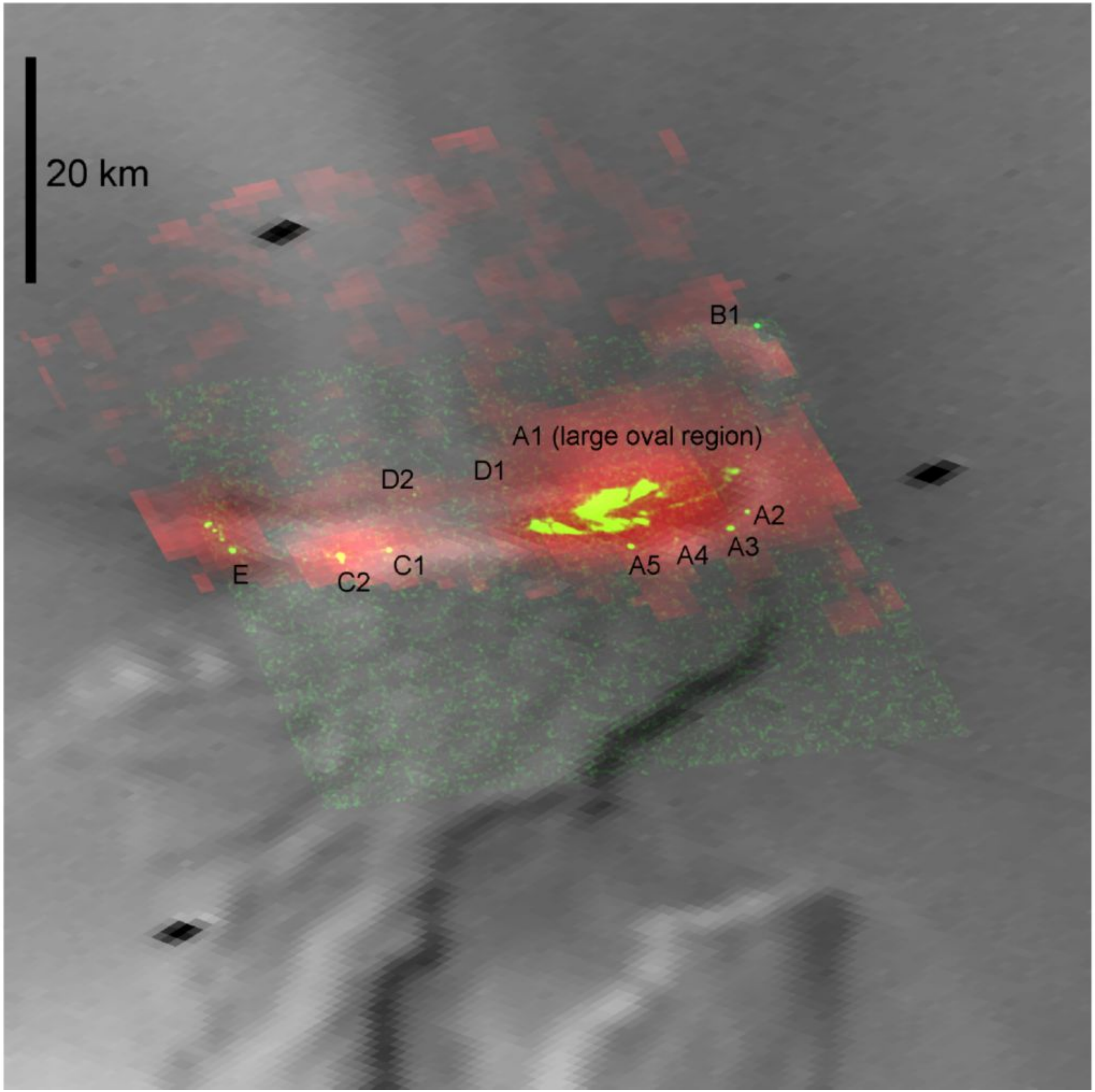
A. Aerial photograph with overlay of heating lines.

B. Night thermal IR image (8 to 14 µm).

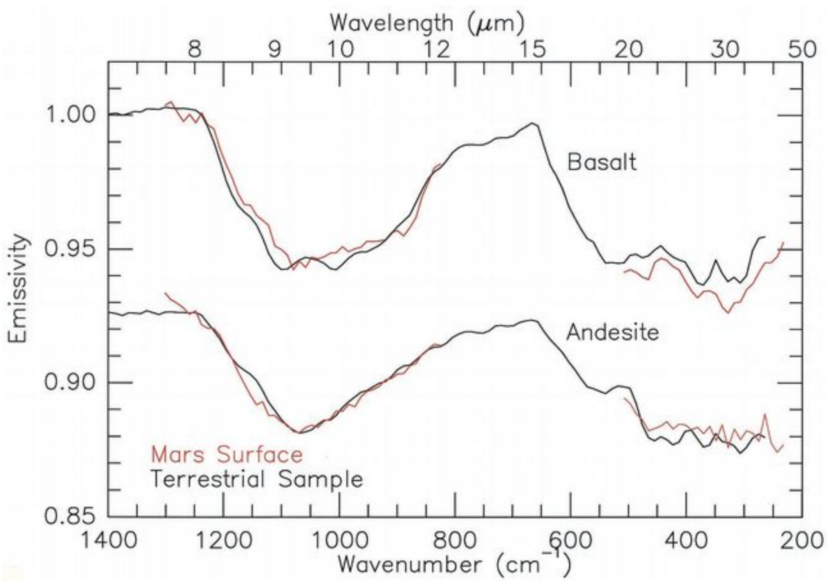
Figure 5-17 Heat-loss survey of Brookhaven National Laboratories, Long Island, New York. Localities are explained in the text. Courtesy Daedalus Enterprises, Inc.

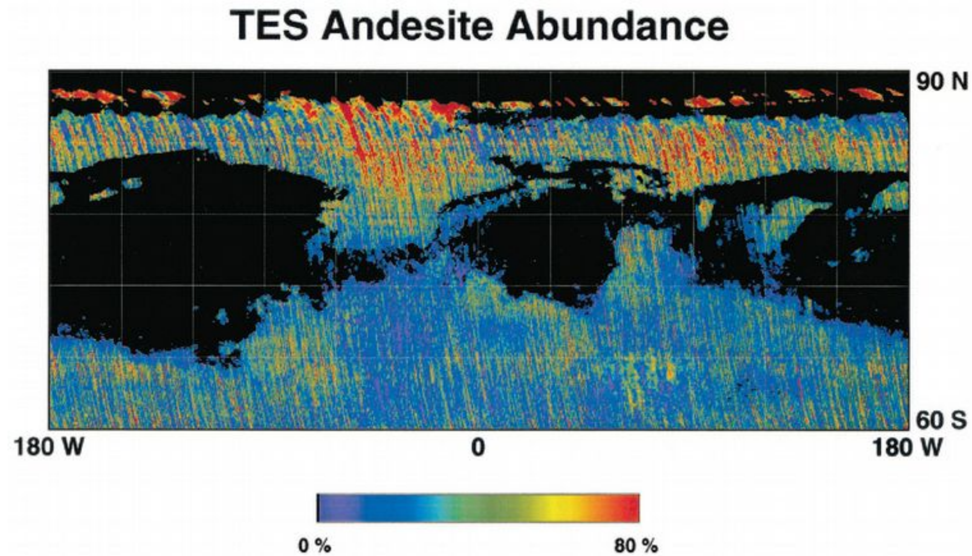
Sabins Fig. 5-17

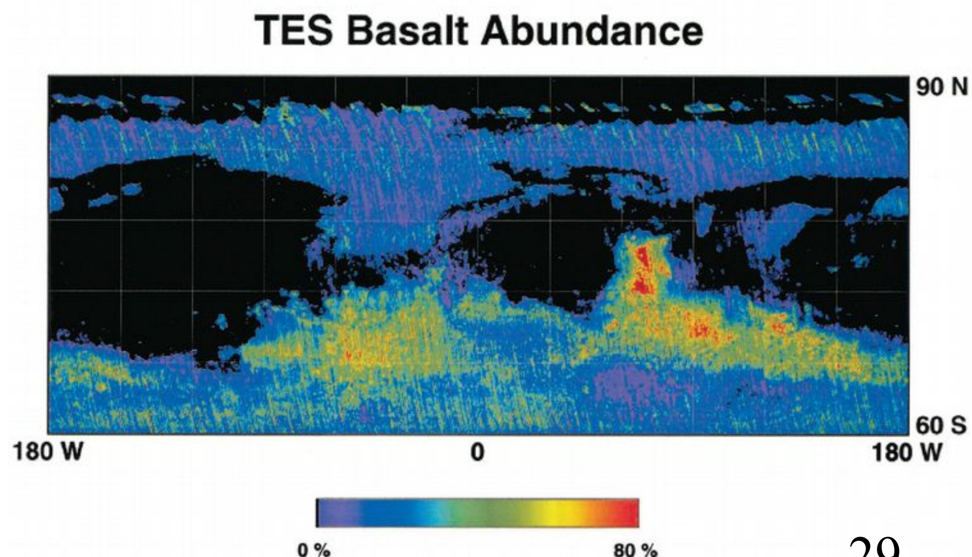
Io Volcanism: Pele



Mars "TES" Results







TIMS: Cuprite Hills, NV

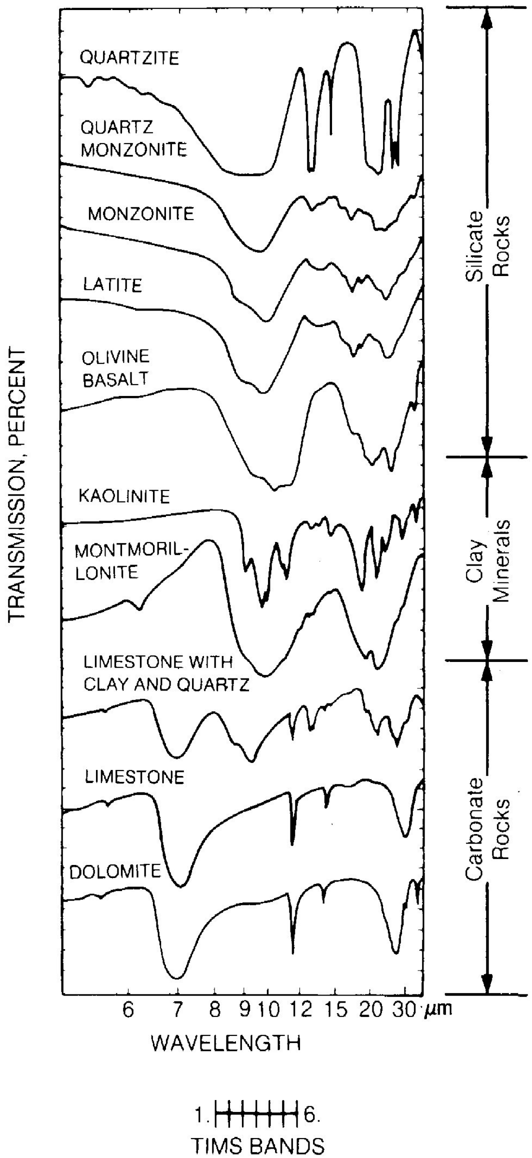
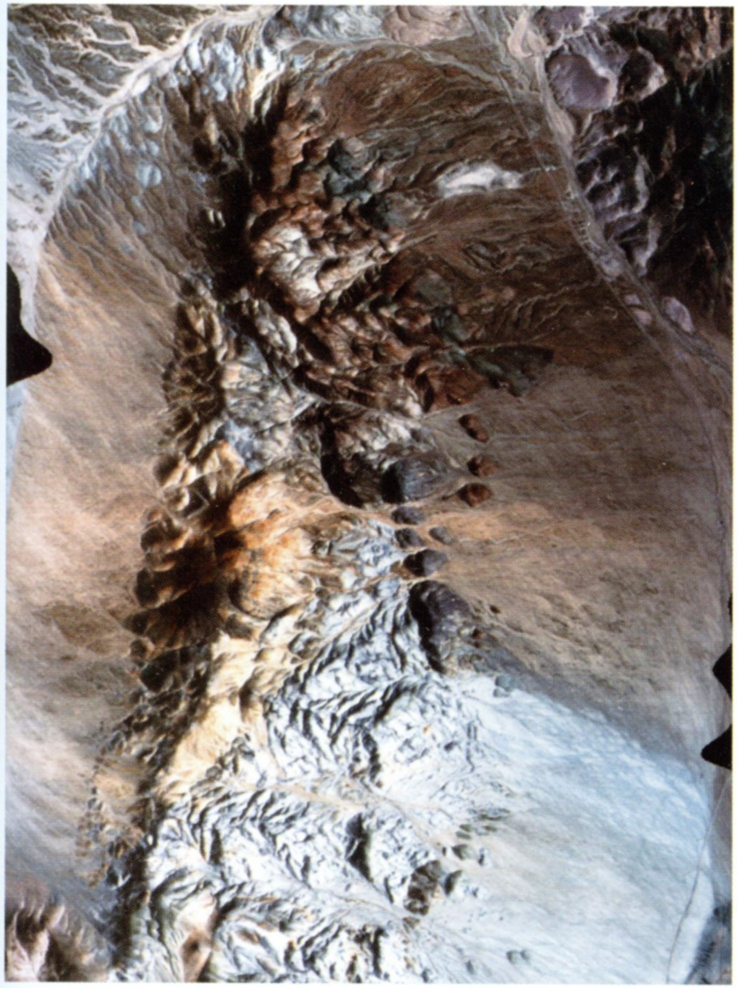


Figure 5-37 Thermal IR spectra of rocks and minerals. Spectra are offset vertically. From Kahle (1984, Figure 4).

B. TIMS image showing kinetic temperature and emissivity, Cuprite Hills, Nevada.

Sabins: TIMS image showing bands 3,2,1 as RGB

TIMS: Cuprite Hills, NV



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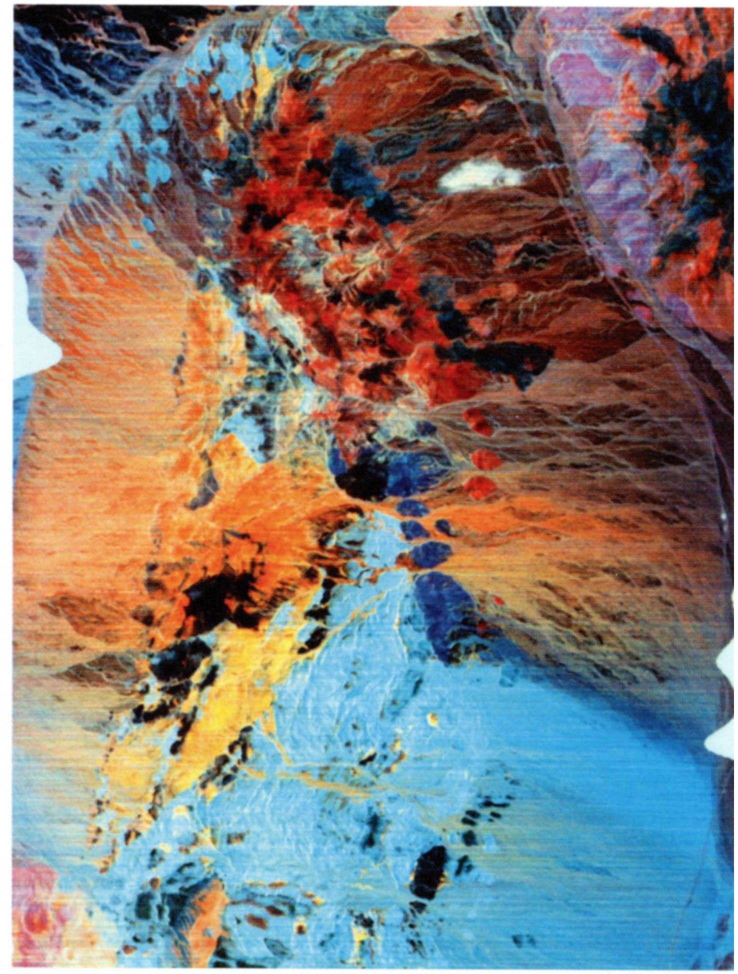

C. TIMS image showing emissivity information, Cuprite Hills, Nevada.

Sabins: TIMS image showing bands 3,2,1 as RGB, then image showing emissivity variations

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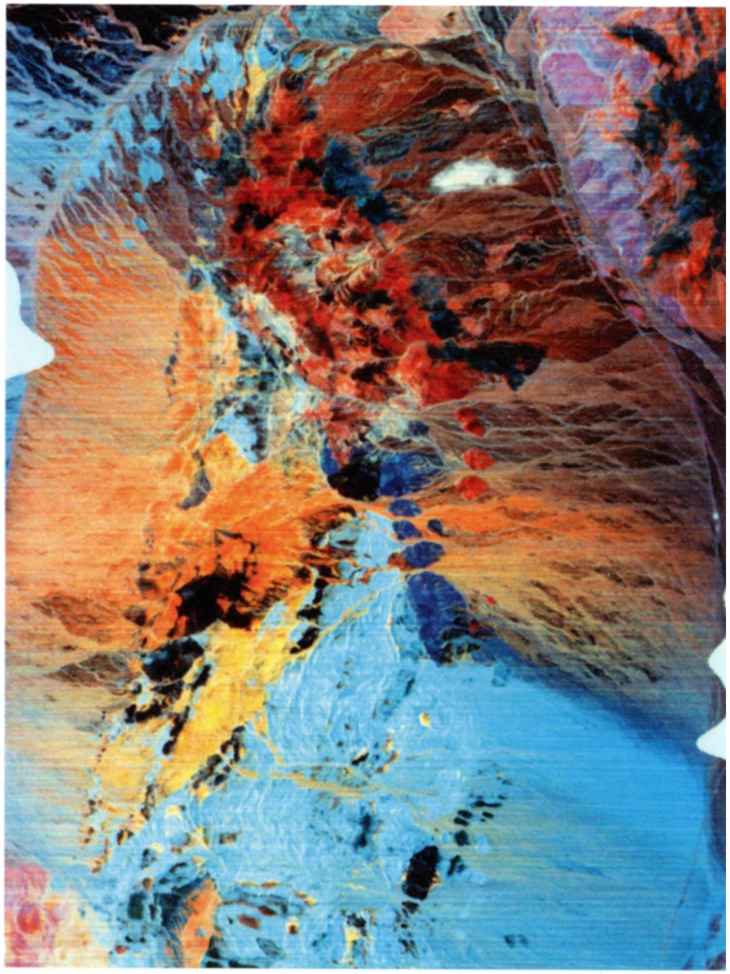
TIMS: Cuprite Hills, NV



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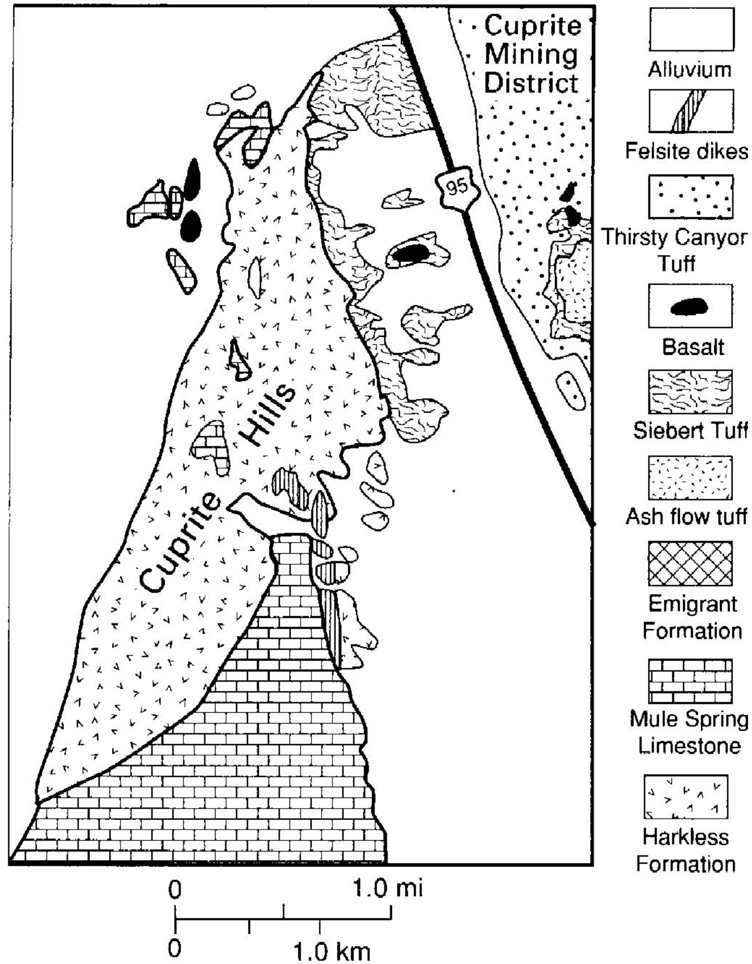

Figure 5-38 Interpretation map of TIMS images of the Cuprite Hills, Nevada. From Hook and others (1992, Figure 5).

Sabins: TIMS emissivity image and map

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