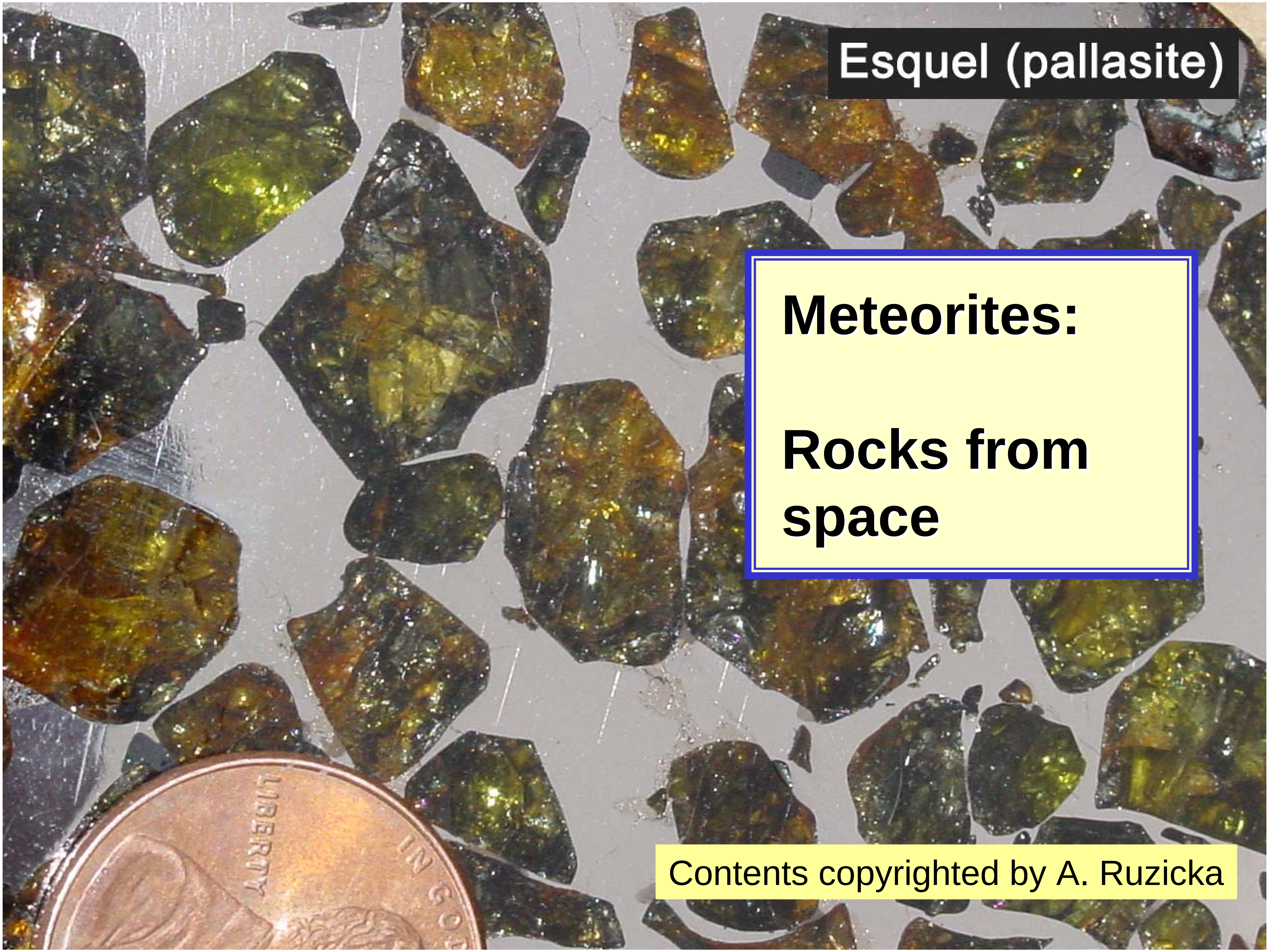
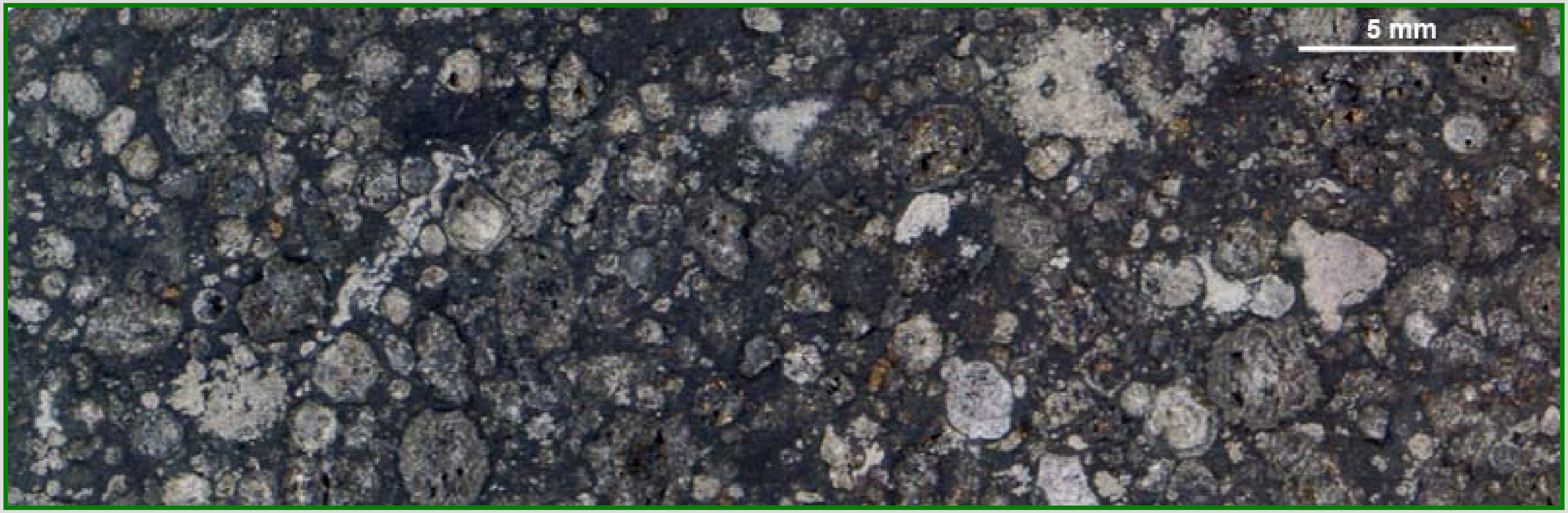

Esquel (pallasite)
Meteorites:
Rocks from space
Contents copyrighted by A. Ruzicka
LIBERTY

meteorites are mainly derived from small interplanetary bodies that escaped significant LATE endogenic activity

they provide our best rock record of early solar system processes



^^ Vigarano (CV3 carbonaceous chondrite)

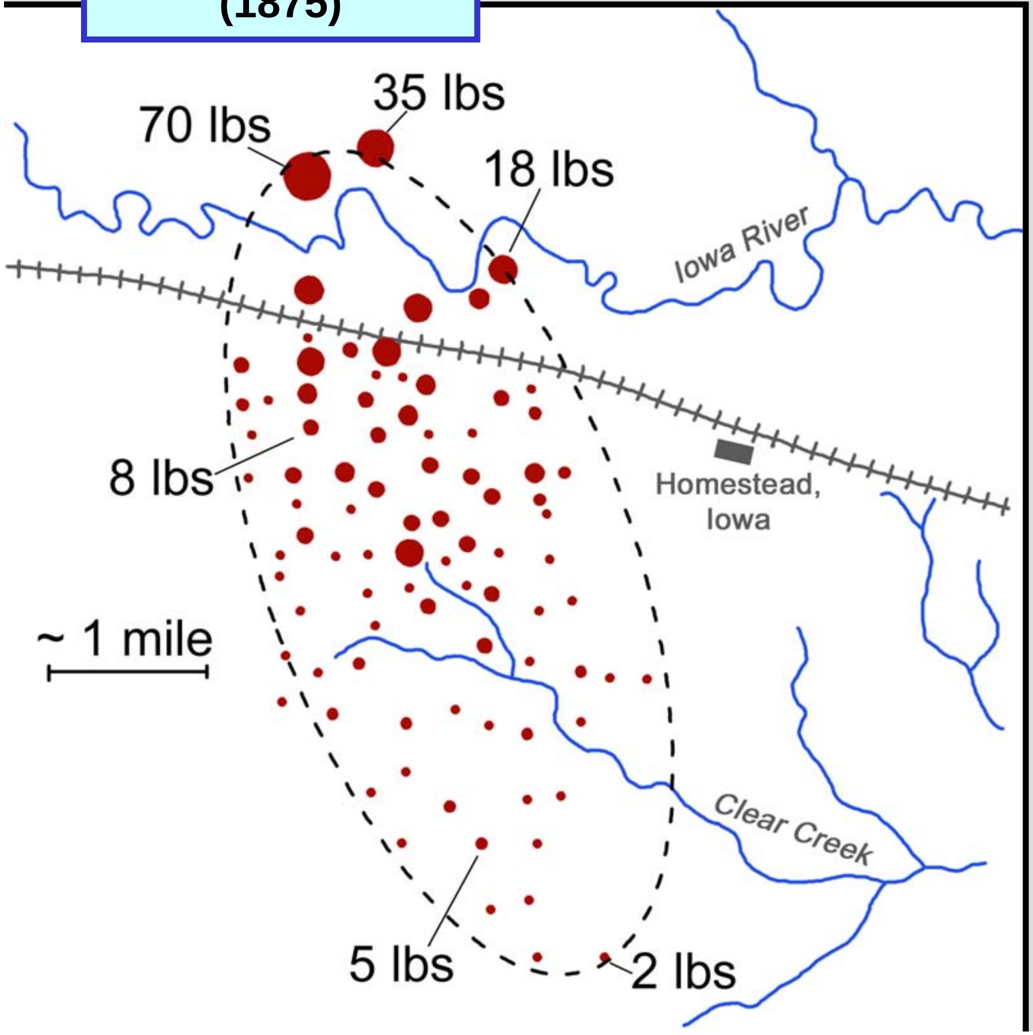
A. Meteoroids, meteors, and meteorites
B. Sources of meteorites
C. Meteorite types
D. Differentiated meteorites
E. Chondrites
F. Important results

A. Meteoroids, meteors, and meteorites

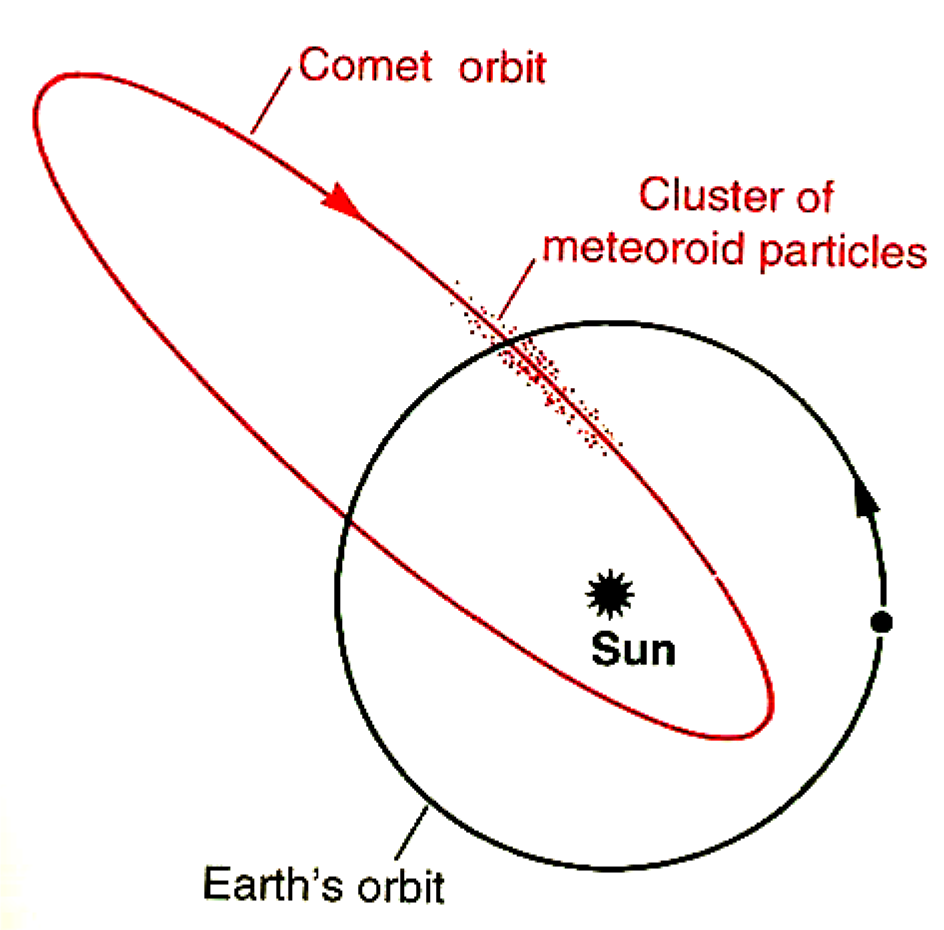
Meteoroid ↓	Object in space, smaller than asteroid
Meteor (Fireball) ↓	Object burning up (ablating) in atmosphere
Meteorite	Object found on ground, originated on different planetary body

Fireball
break-up
>

Homestead, Iowa
(1875)



<
Meteorite
strewn field



Meteoroid particles clustered along a comet's orbit can produce meteor storms if Earth encounters them.

>>

Leonid shower

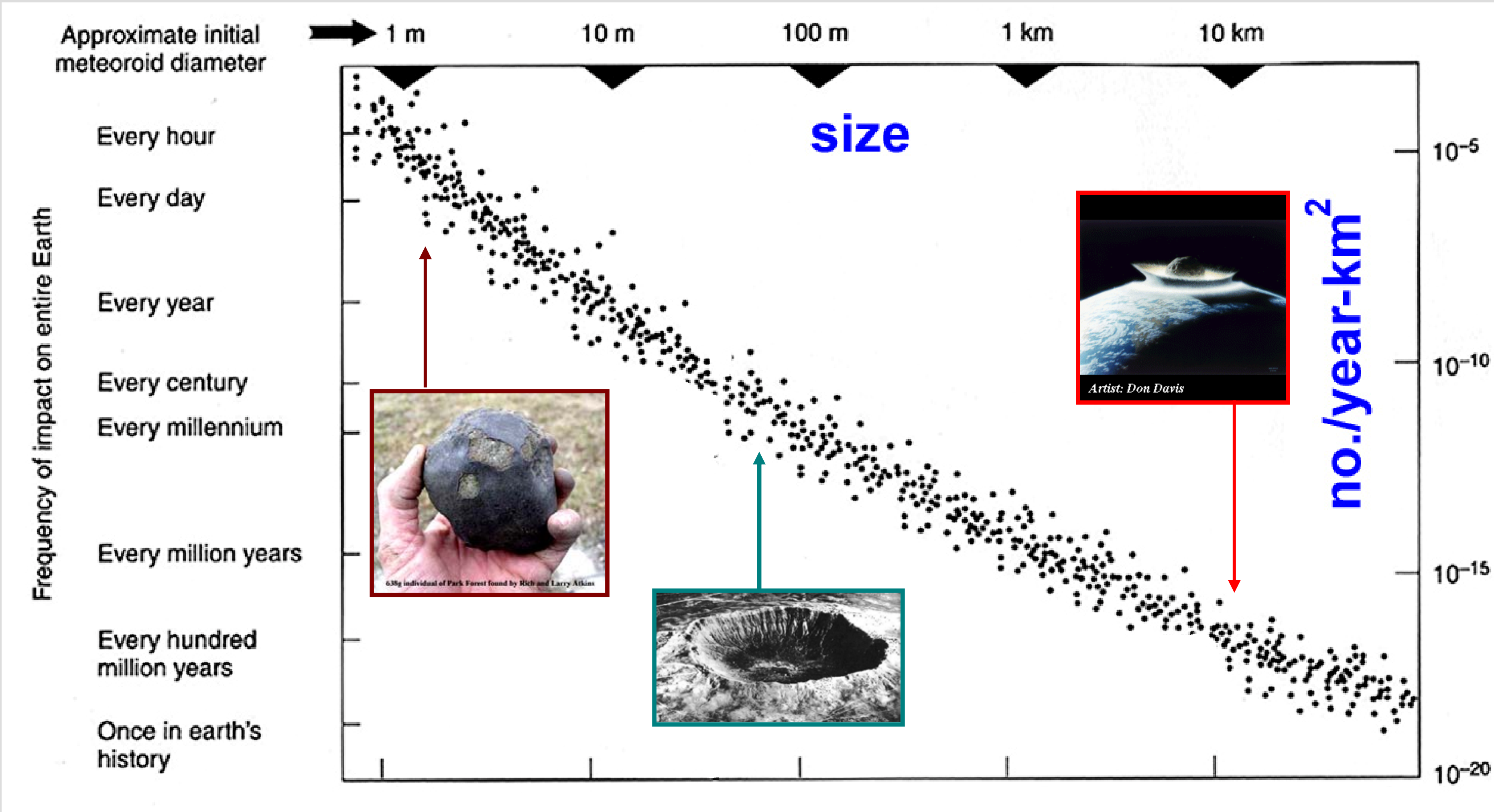
72 min composite,
8 exposures (F. Espenak)

1992 Peekskill fireball video clips

(How to turn a $300 car into one worth $10,000.)

Results of ablation: fusion crust, thumbprints, fragmentation

Size-frequency diagram for meteoroids hitting Earth



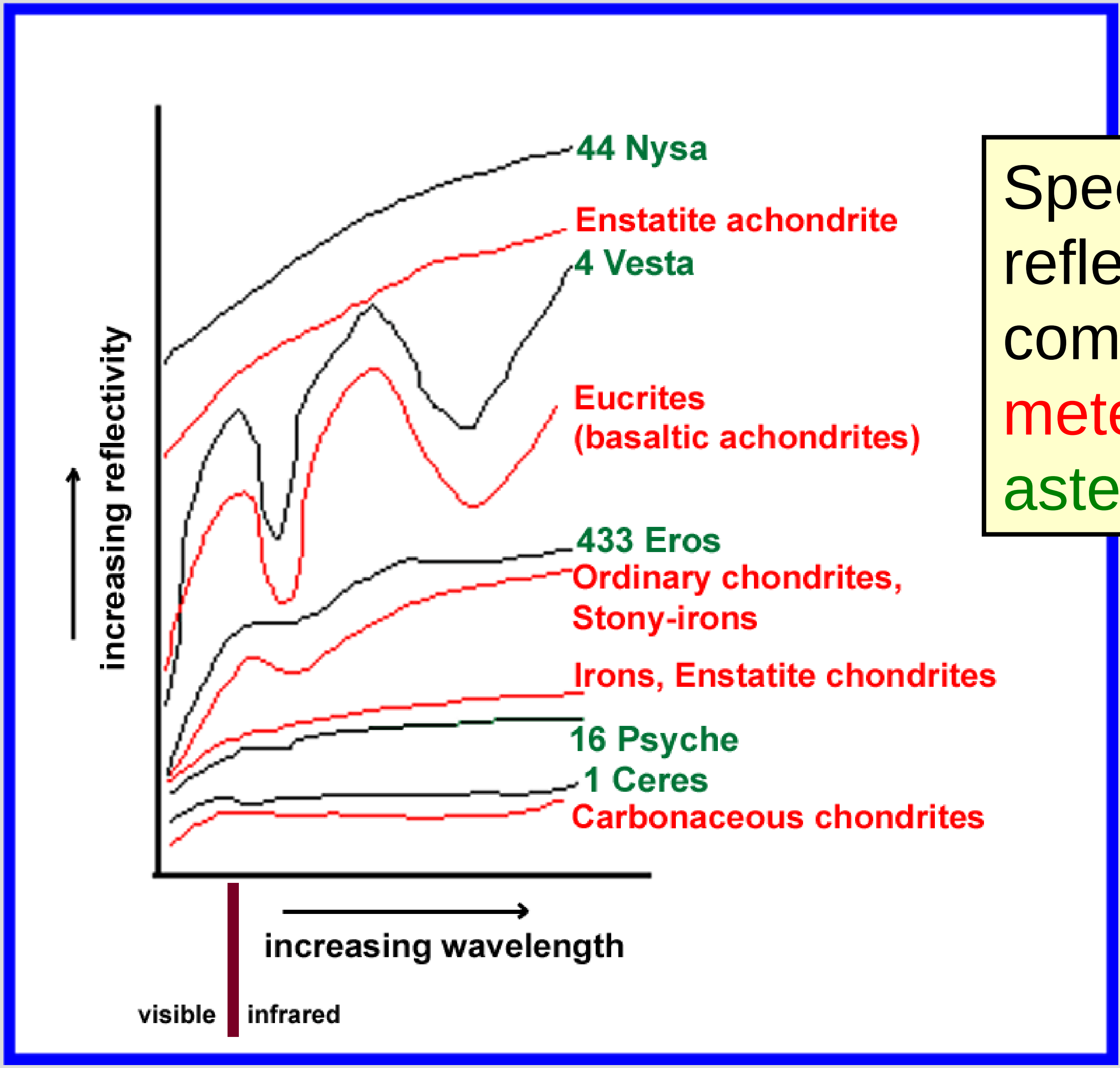
meteorites are mainly derived from meter-sized meteoroids

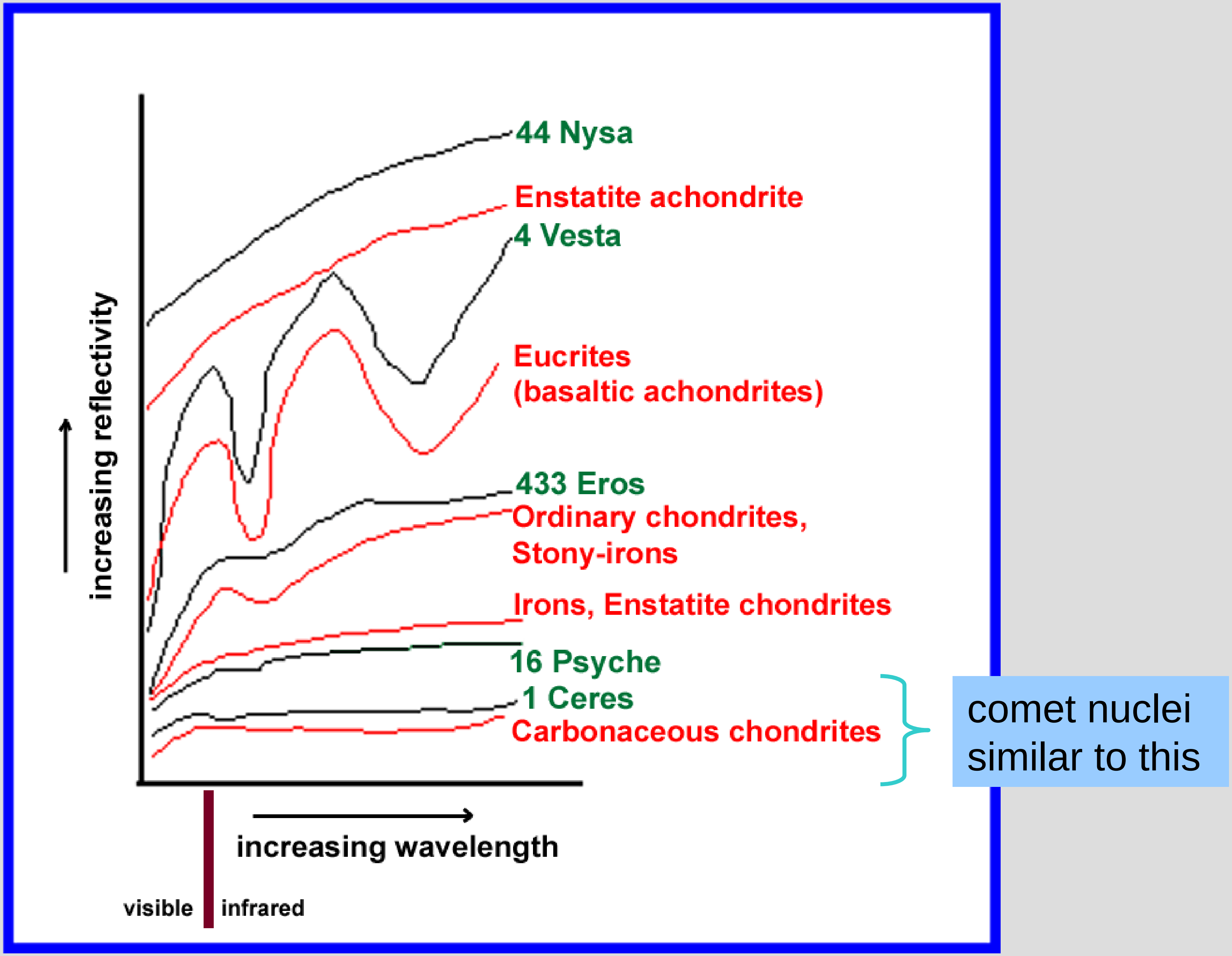
B. Sources of meteorites

sources:

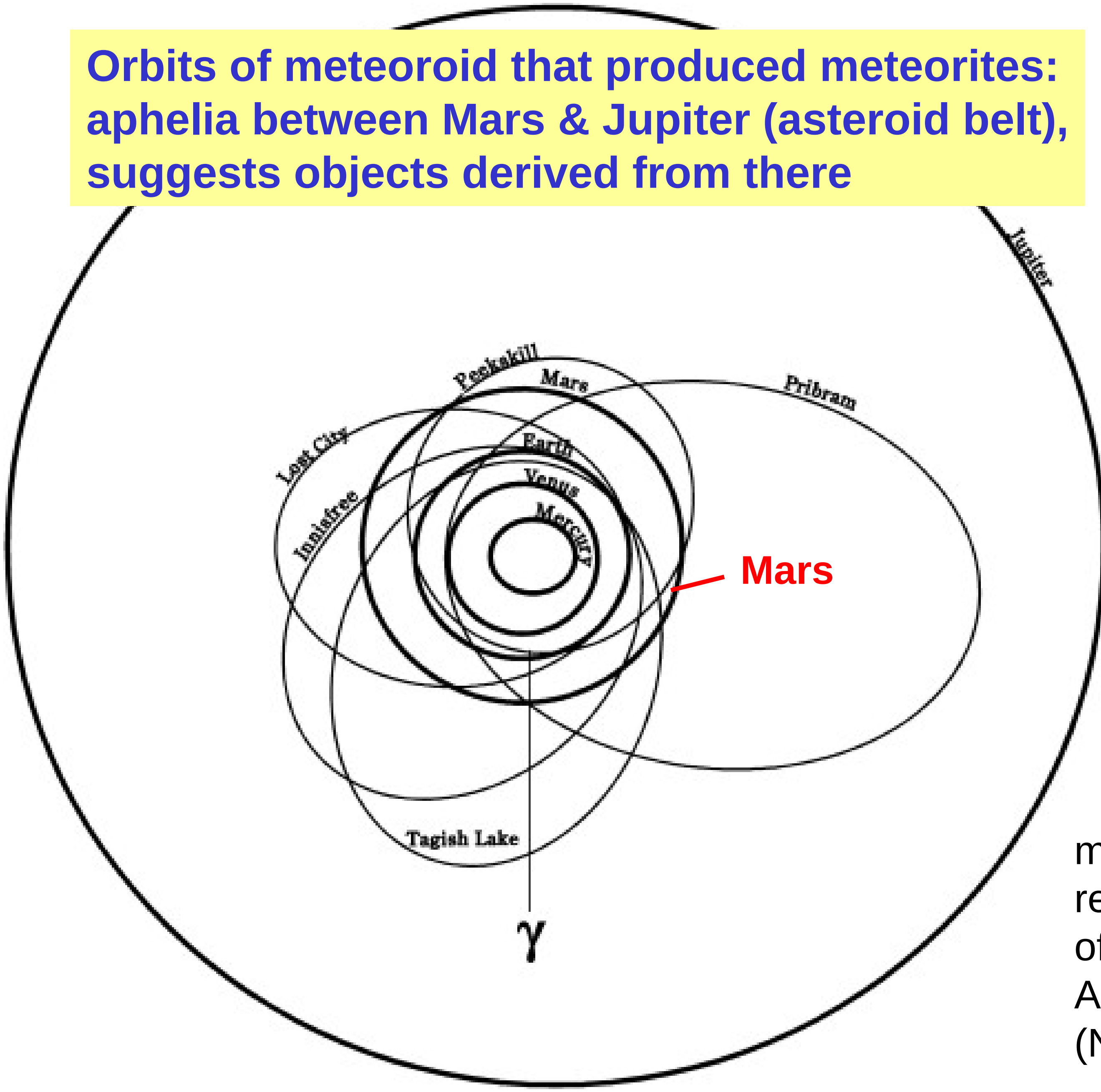
- -- interplanetary bodies (mostly asteroids, but some comet-like)
- -- Moon
- -- Mars

Spectral reflectance comparison: meteorites & asteroids




44 Nysa
Enstatite achondrite
4 Vesta
Eucrites
(basaltic achondrites)
433 Eros
Ordinary chondrites,
Stony-irons
Irons, Enstatite chondrites
16 Psyche
1 Ceres
Carbonaceous chondrites
comet nuclei
similar to this
increasing reflectivity
increasing wavelength
visible
infrared

Orbits of meteoroid that produced meteorites: aphelia between Mars & Jupiter (asteroid belt), suggests objects derived from there



meteoroid orbits resemble those of Near-Earth Asteroids (NEAs)

Example of meteorite derived from water-rich (comet-like) body, outer part of asteroid belt

Tagish Lake (C2 ungrouped carbonaceous chondrite)

5.8% C
density = 1.67 g/cm^3
spectra similar to D-type asteroids & comet nuclei
rich in phyllosilicate (saponite & serpentine), carbonate (siderite)
contains forsterite, sulfide, magnetite, spinel, low-Ca pyroxene, FeNi-metal, pre-solar grains, PAHs, chondrules, CAIs

Comparison of mineral assemblages in Tagish Lake & comets

Tagish Lake meteorite	P/Wild-2 comet dust	P/Tempel-1 comet
phyllosilicate	--	phyllosilicate
carbonate	--	carbonate
organics (PAHs)	organics	organics (PAHs)
olivine	olivine	olivine
sulfide	FeNi-sulfide	sulfide
magnetite	--	--
spinel	--	spinel
low-Ca pyroxene	low-Ca pyroxene	pyroxene
FeNi-metal	--	Fe-metal
pre-solar grains	pre-solar grains	--
chondrules	--	--
CAIs	one CAI	--
--	--	$H_2O + CO_2 + CO$ ice

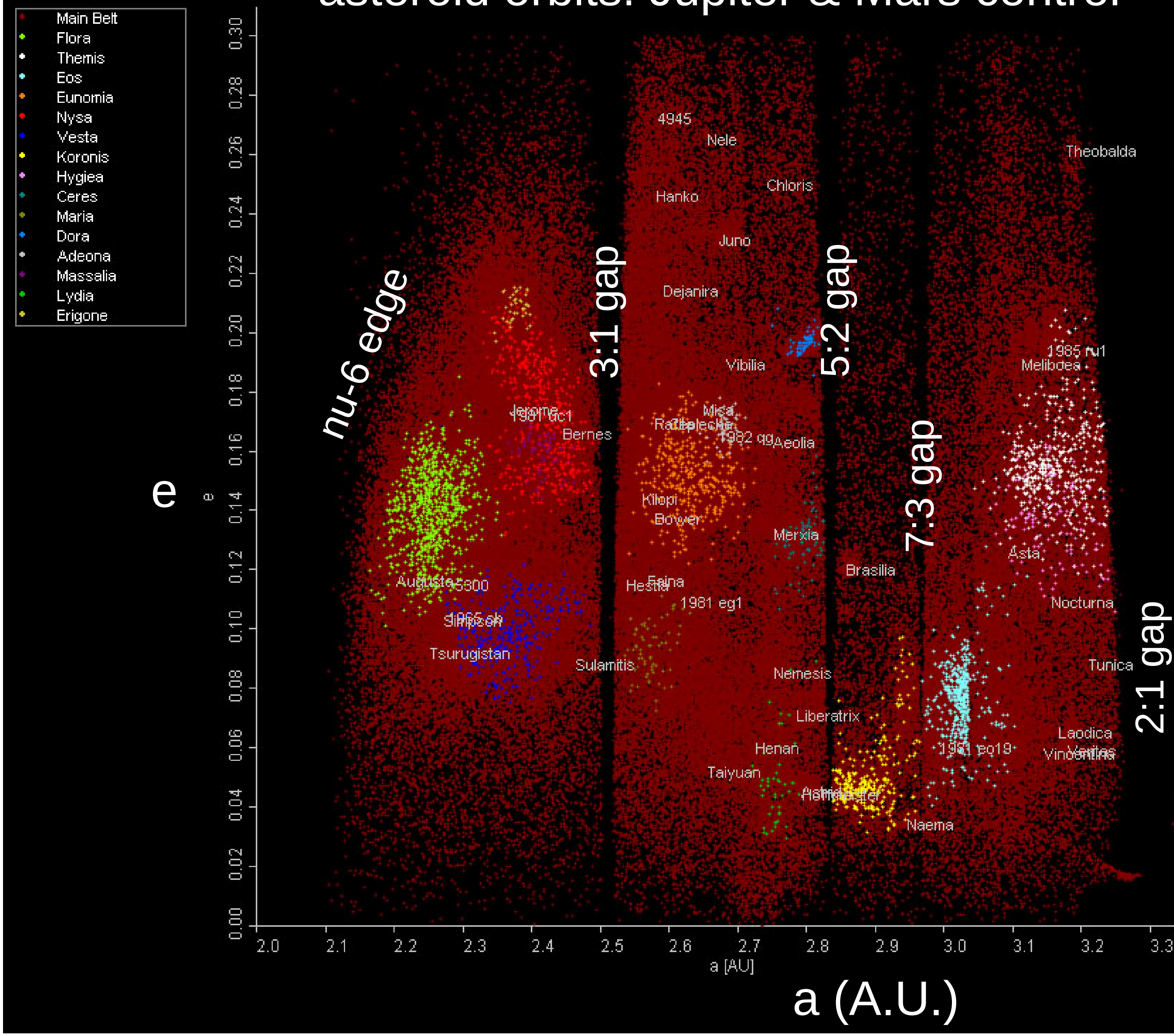
Meteorite Express: How to get from the asteroid belt to the Earth

(1) Perturbations by Jupiter…
can put asteroidal material into Earth-crossing orbits (Kirkwood gap clearing). Gravity of Mars also important.

(2) Collisions occur…
among asteroids, producing meteoroids

(3) The Yarkovsky Effect…
can cause rotating m-sized objects to spiral inwards to (or outwards from) the sun.

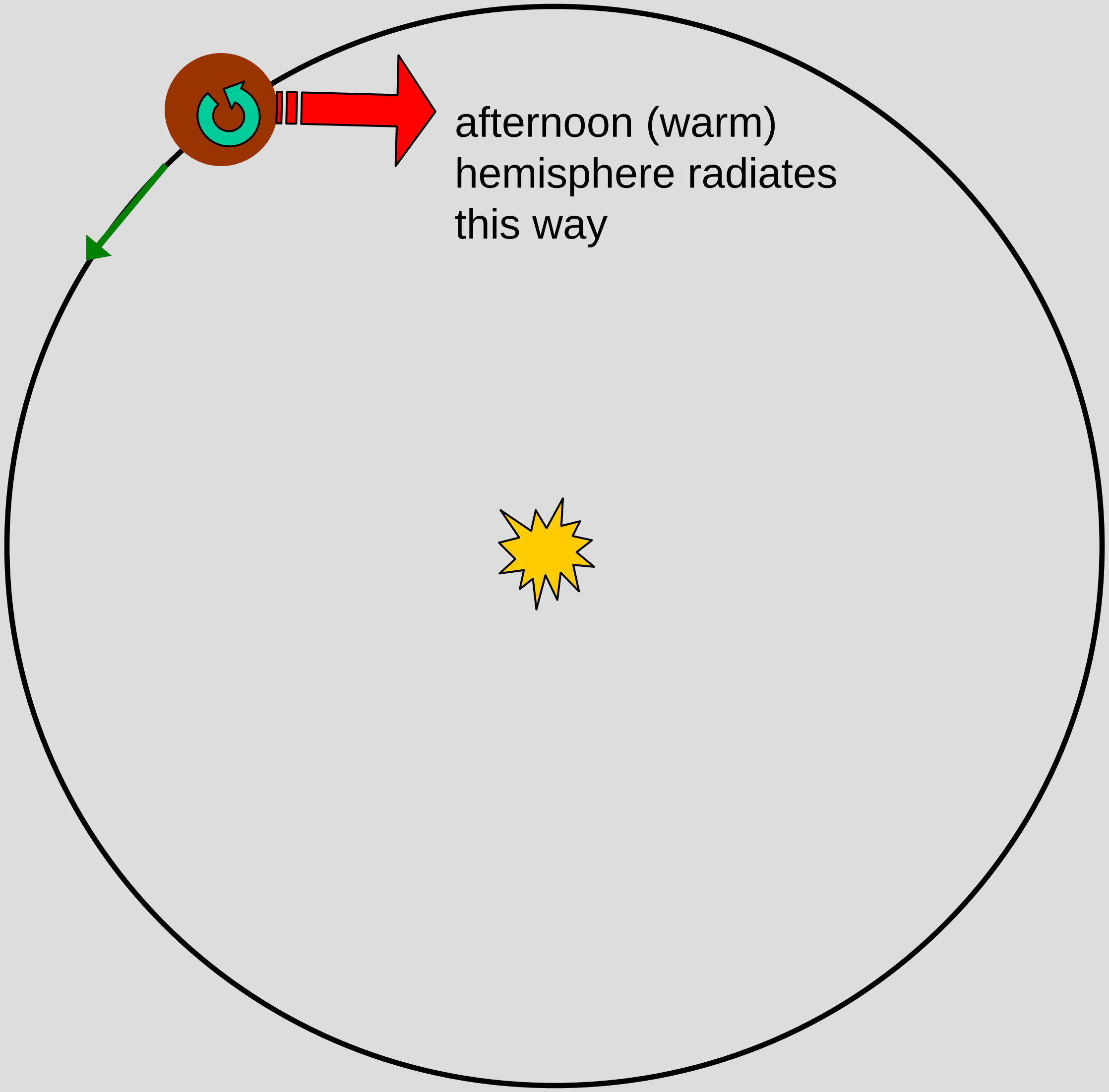
asteroid orbits: Jupiter & Mars control



Inner belt edge: Mars "Nu6" resonance

Within belt: various Jupiter resonances

The Yarkovsky Effect



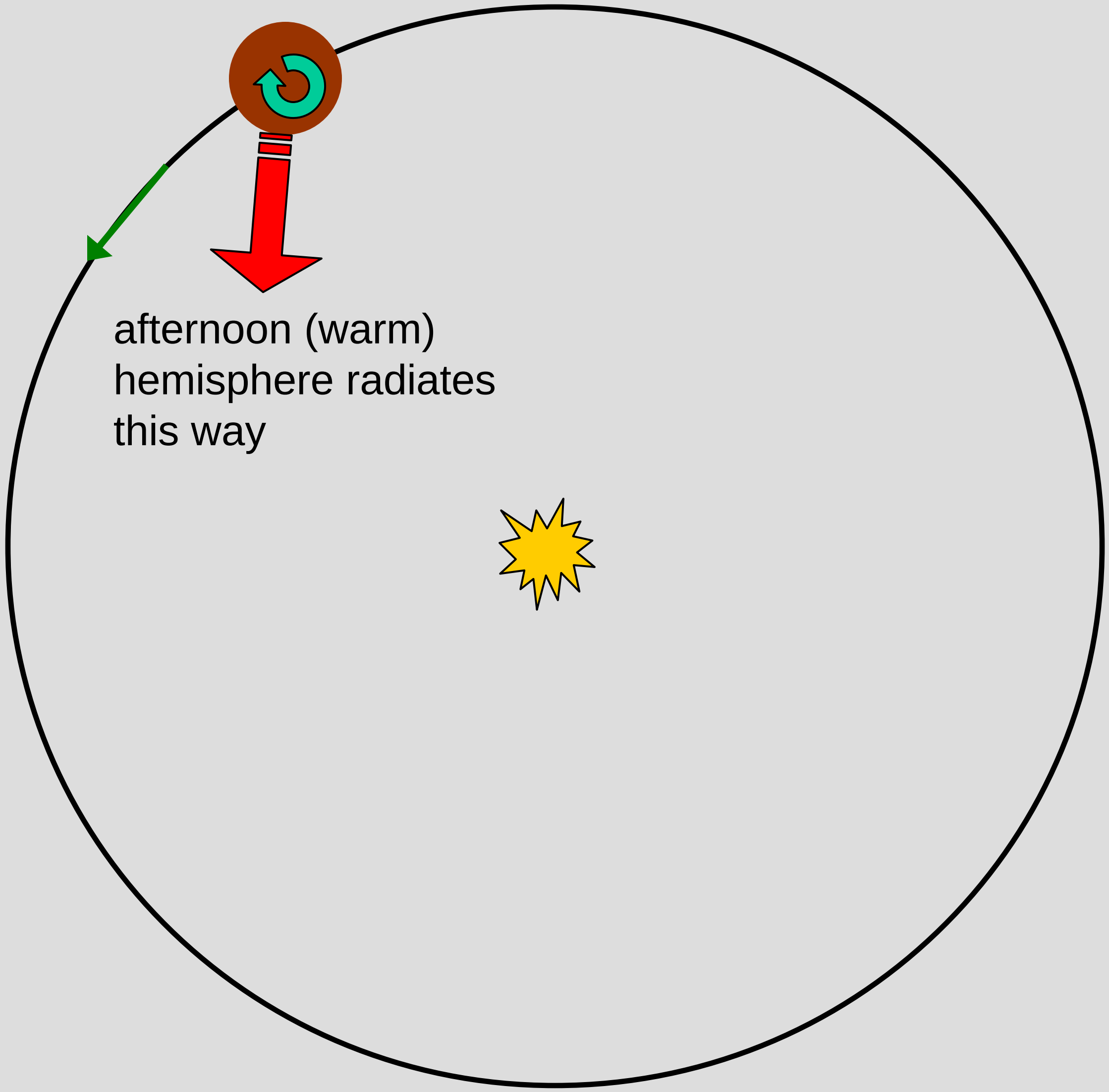
Prograde revolution + prograde rotation

---

1. IR thrust pushes object forward, like extra booster

2. Object gradually moves away from sun (orbit expands)

The Yarkovsky Effect



Prograde revolution + retrograde rotation

---

1. IR thrust acts like break

2. Object gradually falls towards sun (orbit shrinks)

The Yarkovsky Effect is most effective for m-sized bodies

Bodies << 1 m across (e.g., dust)

-- more affected by photons from sun

e.g., light pressure
causes micron-sized particles to spiral away from sun

e.g., Poynting-Robertson Effect
causes cm-sized particles to spiral in towards sun

Bodies >> 1 m across (e.g., asteroids)

-- more affected by gravity

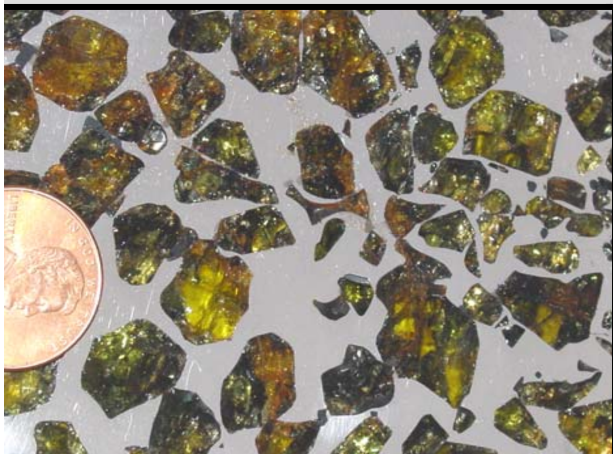
C. Meteorite types

Types of meteorites… a simple classification

Designation	Proportion of metal & silicate
Iron	*>> 50% metal alloy*
Stony-iron	*~ 50% metal, ~ 50% silicate*
Stony	*>> 50 % silicate*

Kinds of meteorites

Iron >



< Stony-iron

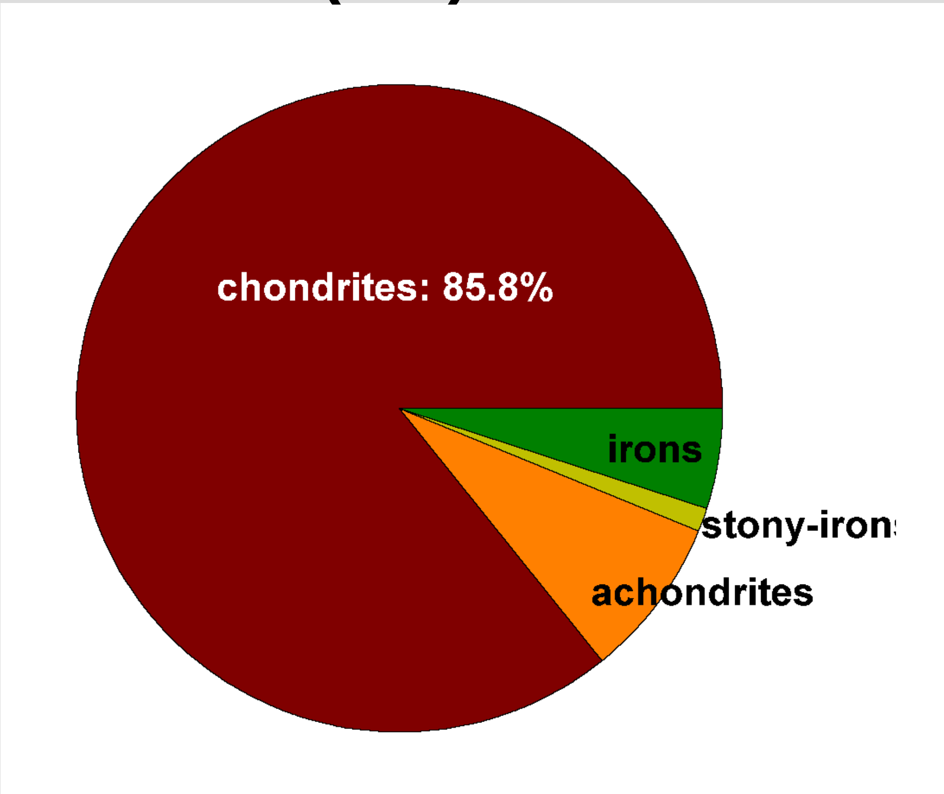
pallasite (L), mesosiderite (R)

Stony >

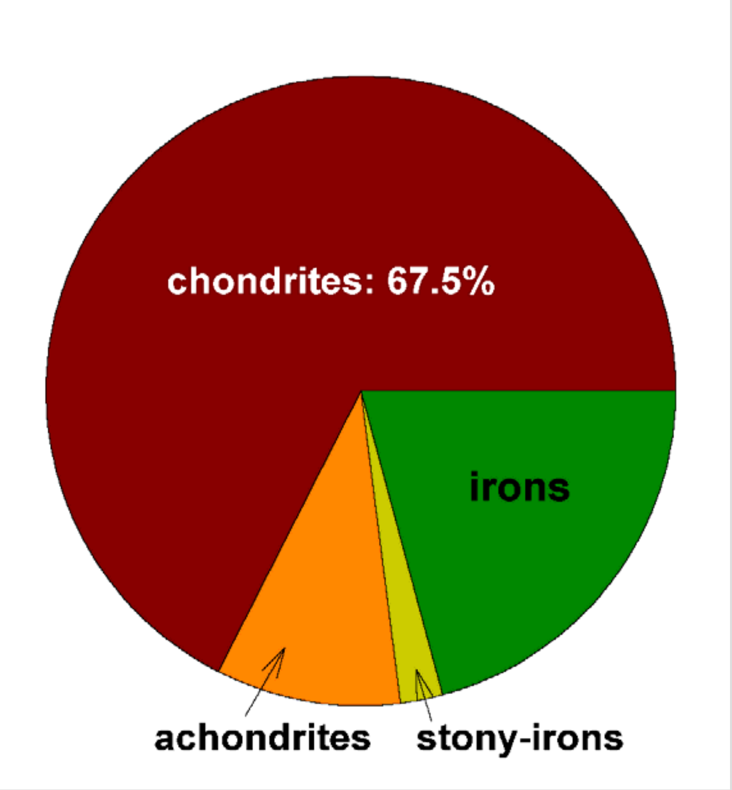
chondrite (L)
achondrite (R)

Meteorite statistics (as of year 2000)

FALLS (957)



FINDS (3854)



Probably now have >20,000 meteorites, thanks to recovery from Antarctica & the Sahara. New find statistics resemble the fall statistics.

Classes, rock types, and parent bodies

Designation	Class & rock types	# parent bodies*
Stony	chondrites: agglomerate	> 13
Stony	achondrites: igneous, often breccia	> 8
Stony-iron	pallasite: igneous	> 3
Stony-iron	mesosiderite: igneous, meta-breccia	1 (2)
Iron	many groups: igneous	50-80?

* as inferred from chemical & isotopic studies

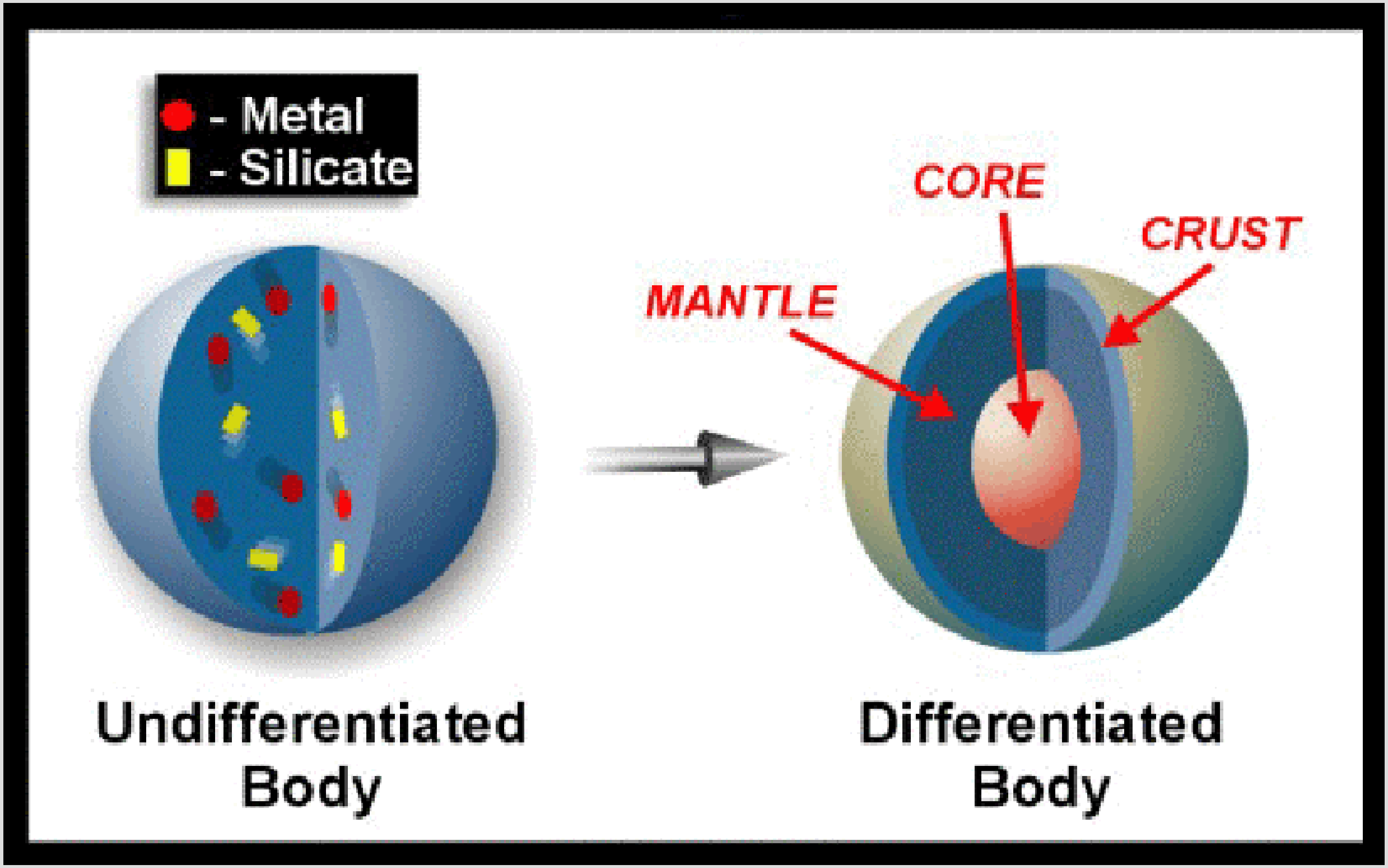
Types of meteorites… a fundamental classification

Designation	Rock type
Chondrite *(stony)*	*agglomerate-- never melted*
All else *(stony, stony-iron, iron)*	*igneous; impact breccias-- melted at least once*

Types of meteorites… a fundamental classification

Designation	Rock type
Chondrite *(stony)*	*agglomerate-- never melted*

unique (yet common) rock type in solar system; formed in early solar system only



Chondrites

All other rocks

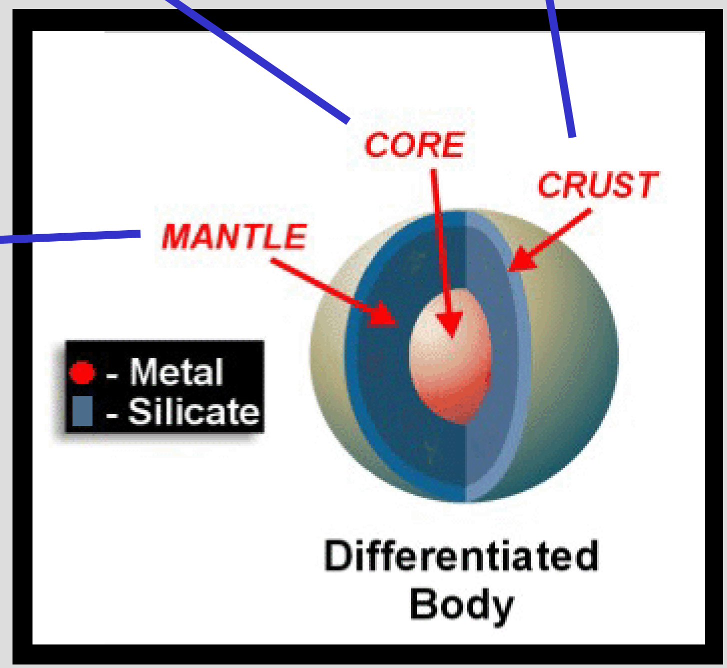
D. Differentiated meteorites

- **achondrites**
- **irons**
- **stony irons**

Gibeon (IVA iron)

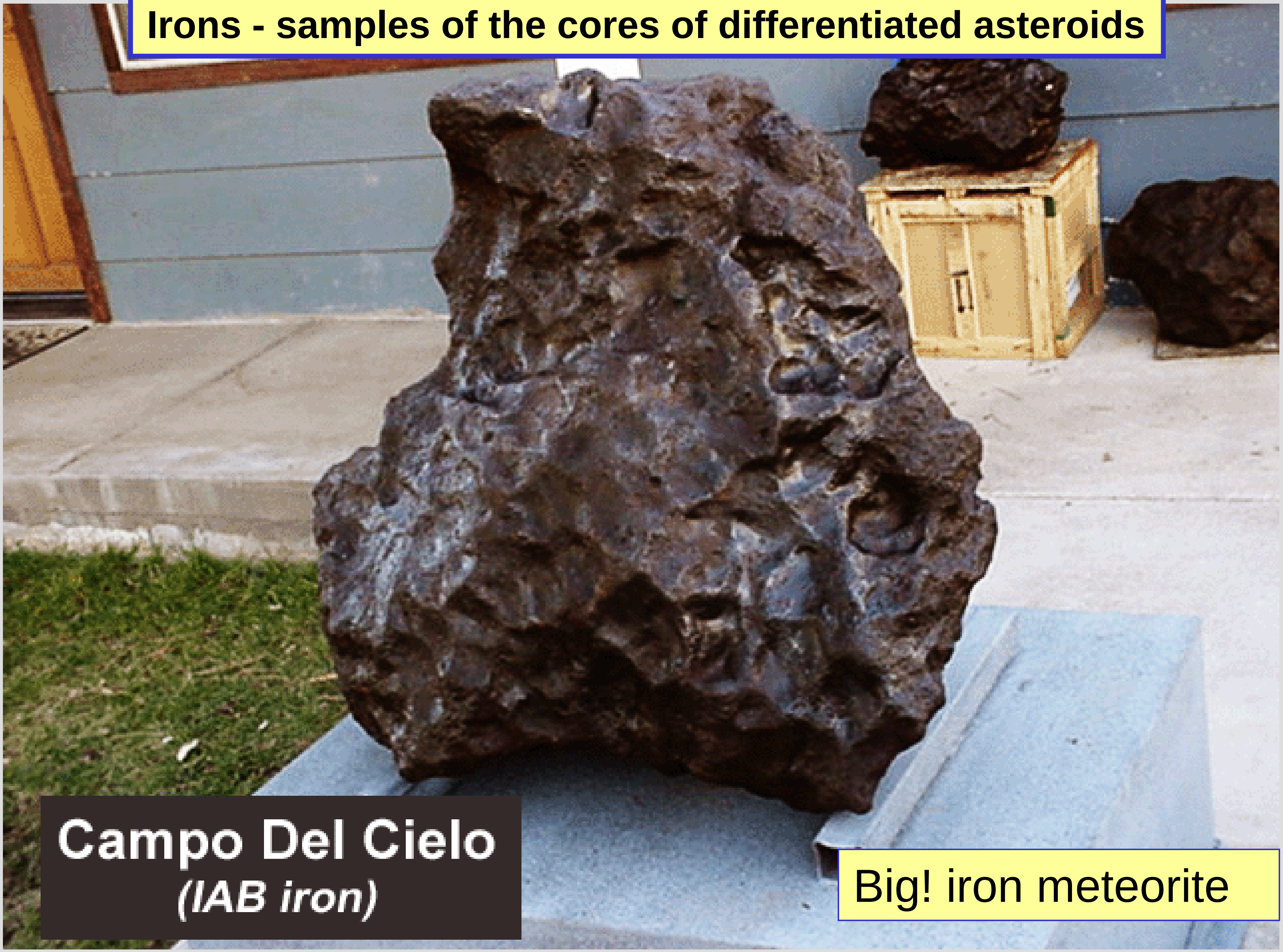
Millbillillie (eucrite)

NWA 1464 (urelilite)



Achondrite - any stony meteorite NOT a chondrite - samples of crusts and mantles of differentiated asteroids, the Moon, and Mars

Irons - samples of the cores of differentiated asteroids

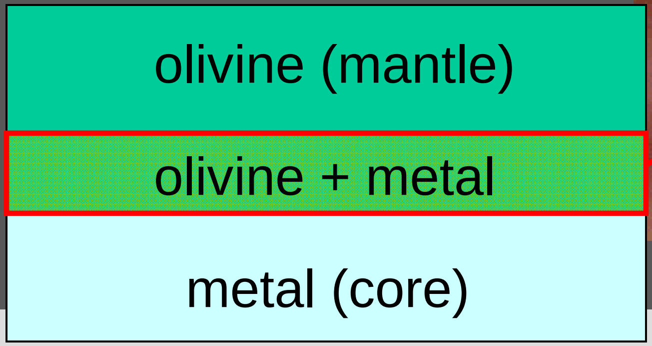


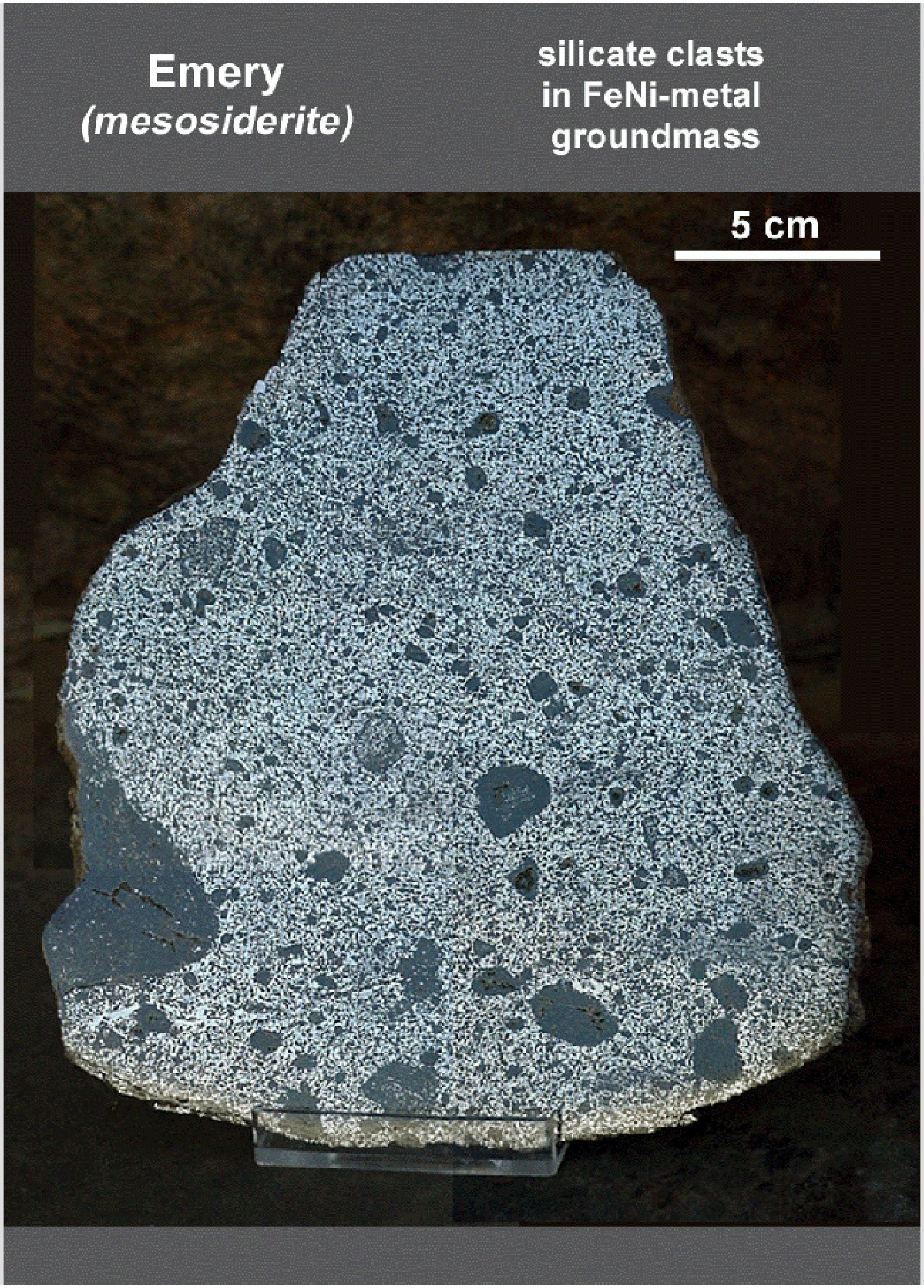
Big! iron meteorite

Iron meteorite: slow-cooling in a metallic core

Ahumada
(pallasite)

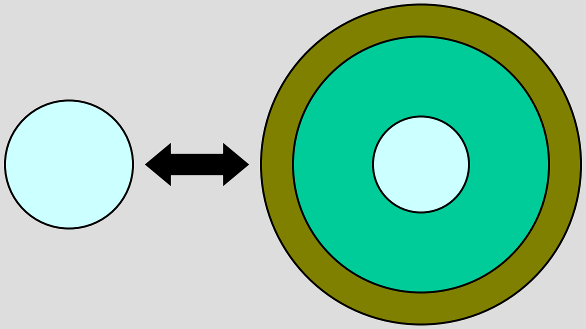
origin:
olivine crystals floating in a pool of metallic liquid (core-mantle boundary)



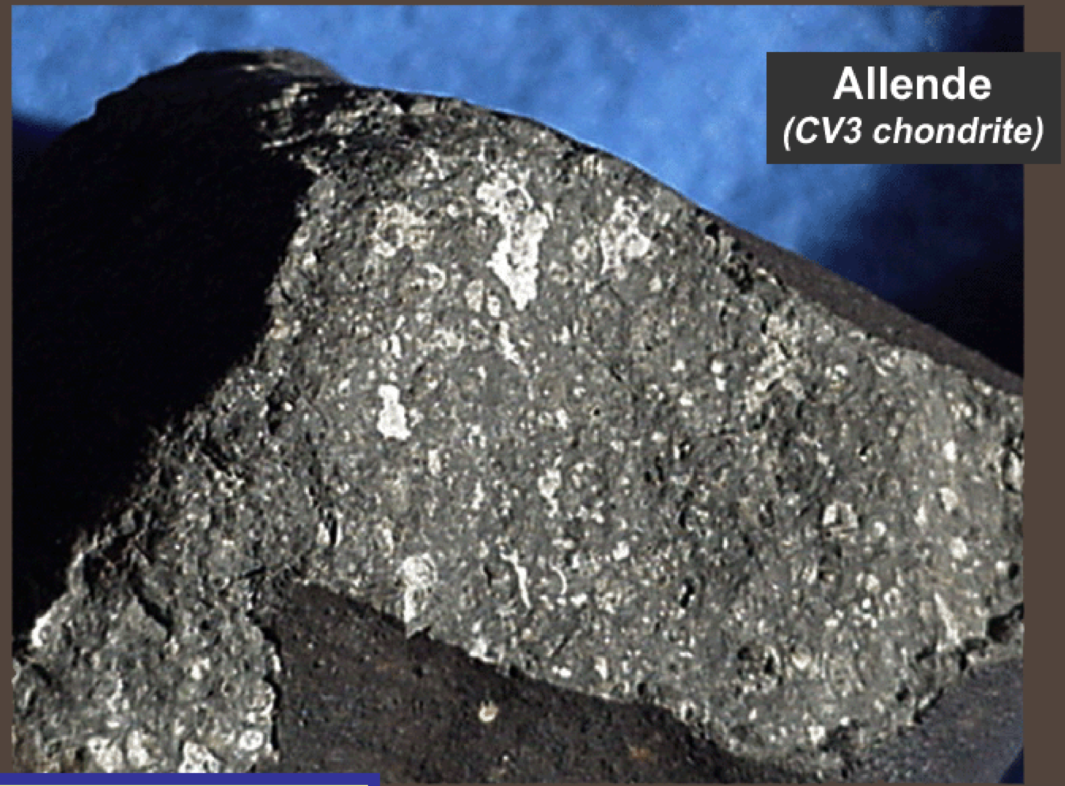


Mesosiderite

collision of two differentiated asteroids?



E. Chondrites



Agglomerates of materials with diverse histories

Solar-like bulk composition (planetary building blocks)

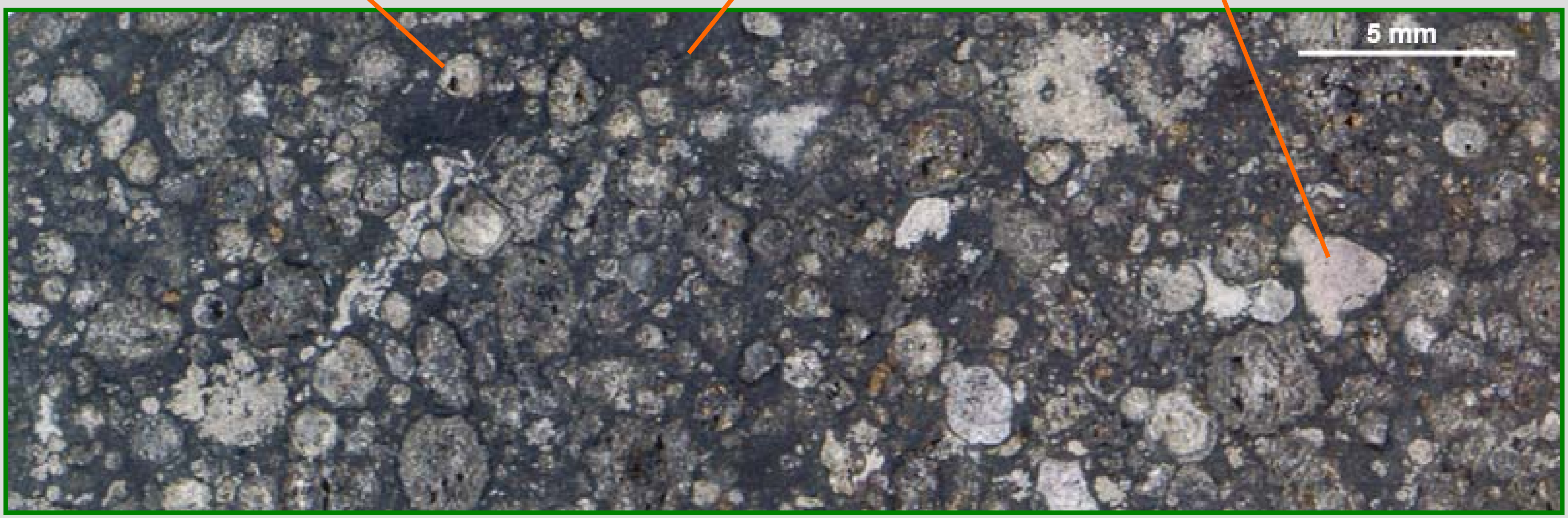
Formed in protoplanetary disk (solar nebula)

Chondrites-- agglomerates of materials with diverse histories

CAIs – high-T condensates & vaporization residues

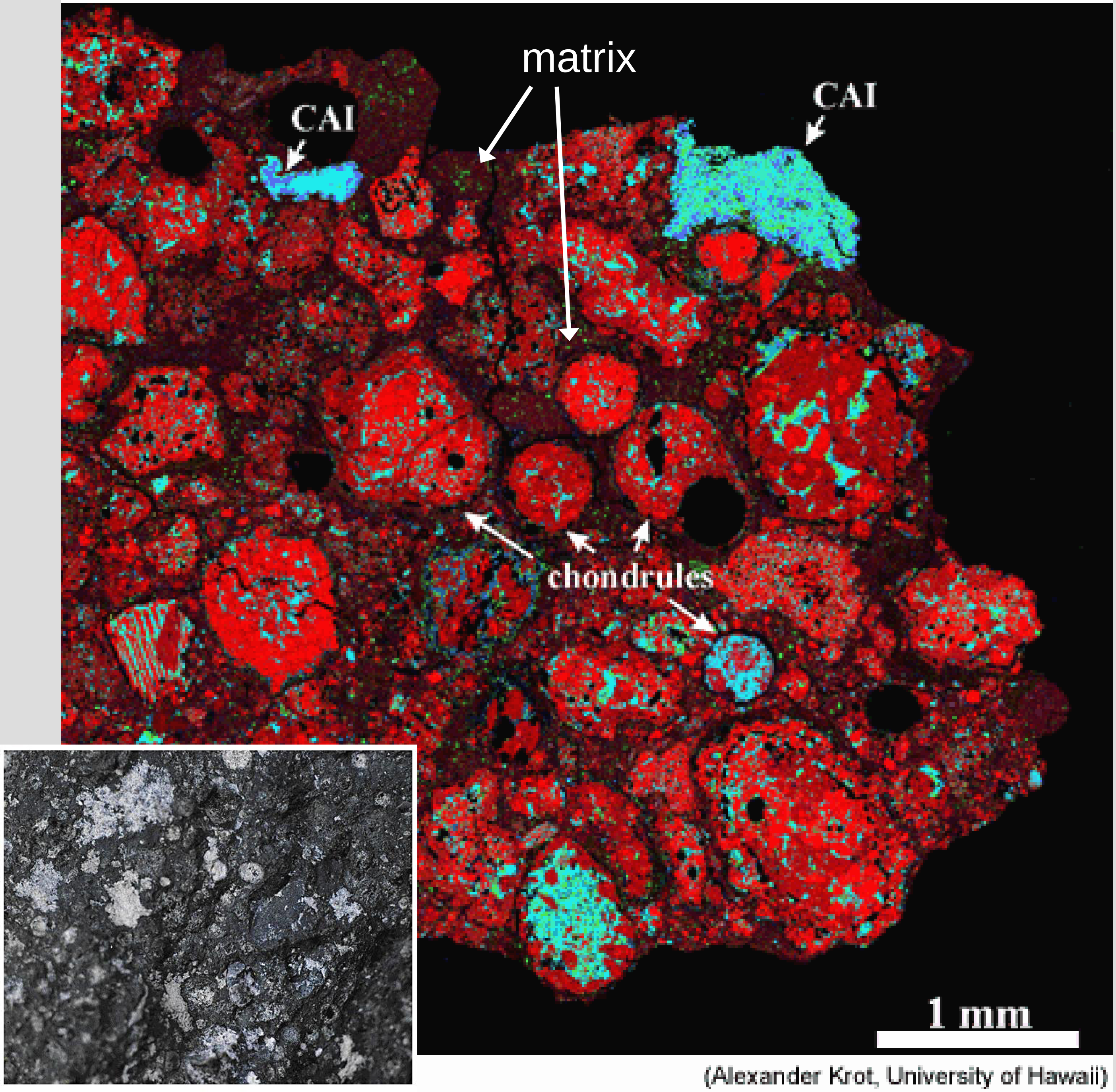
matrix, includes pre-solar grains & low-T organic matter

chondrules – remelted objects



Vigarano (CV3 chondrite)

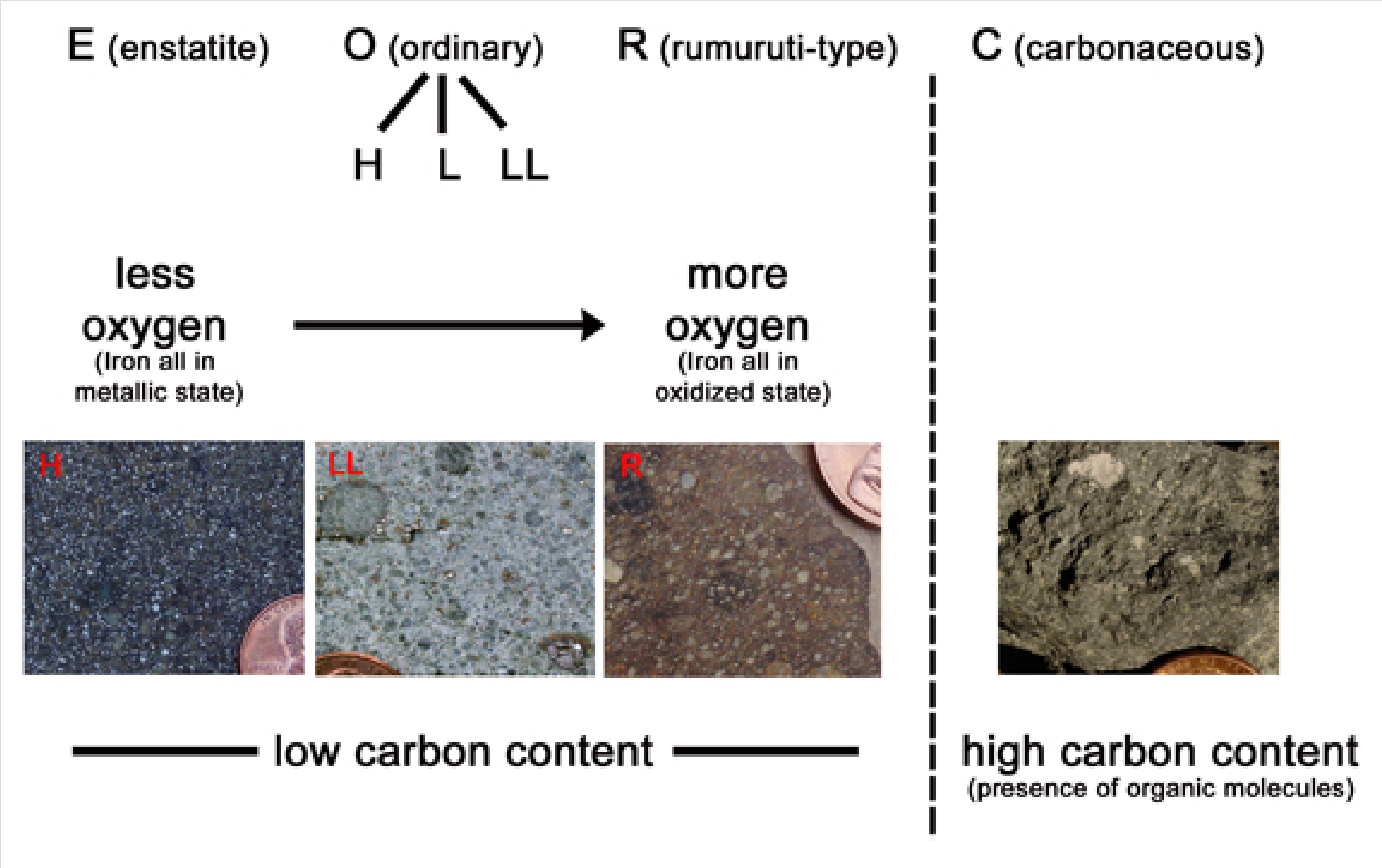
PCA 91082 CR2 chondrite

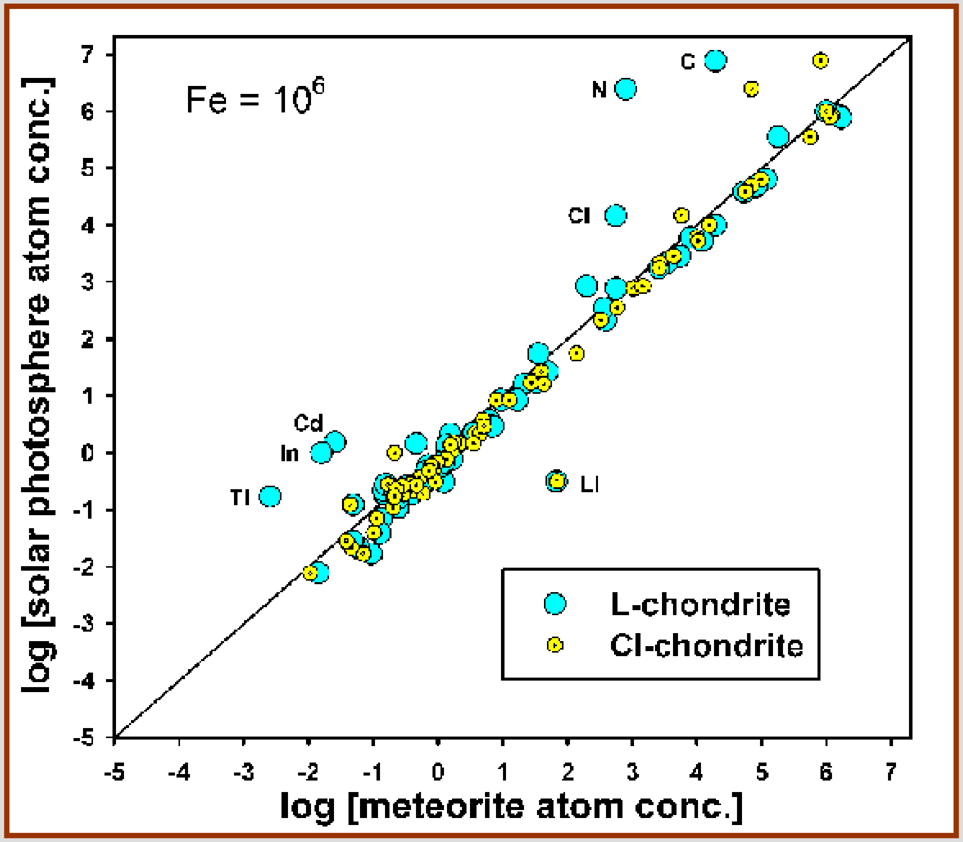


(Alexander Krot, University of Hawaii)

CAIs = Ca-Al-rich inclusions a.k.a. “refractory inclusions”

chondrules = ferromagnesian objects (rich in olivine & pyroxene) chondrites– different types, vary in proportion of carbon & oxygen

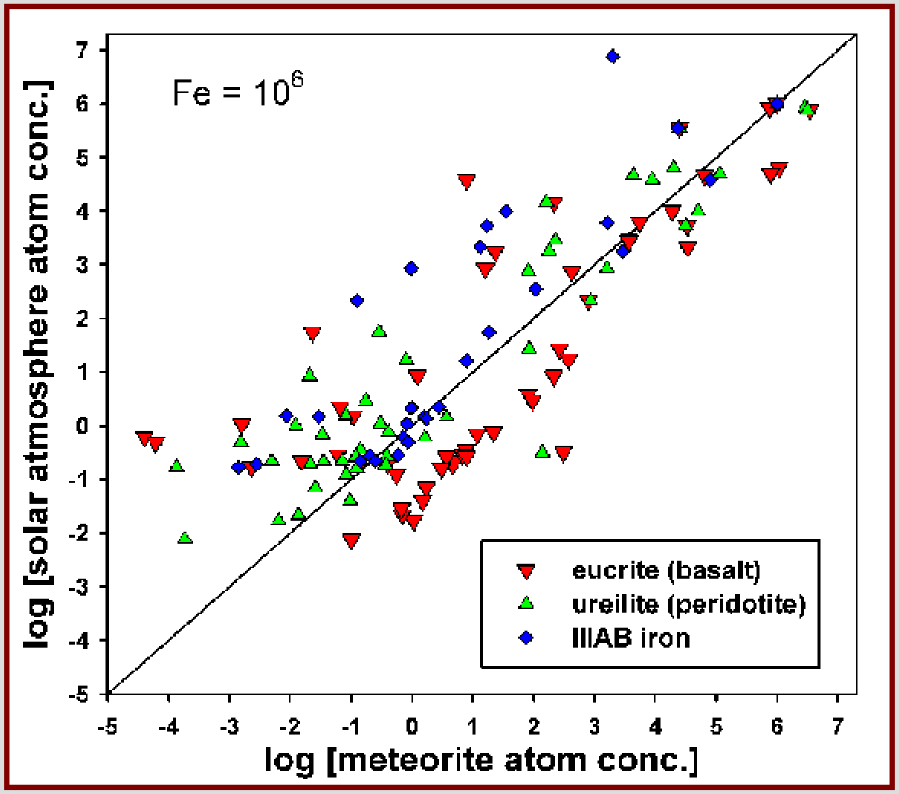




Chondrites uniquely have quasi-solar composition

^^ chondrites vs. sun

differentiated meteorites vs. sun >>



protoplanetary disks (proplyds)

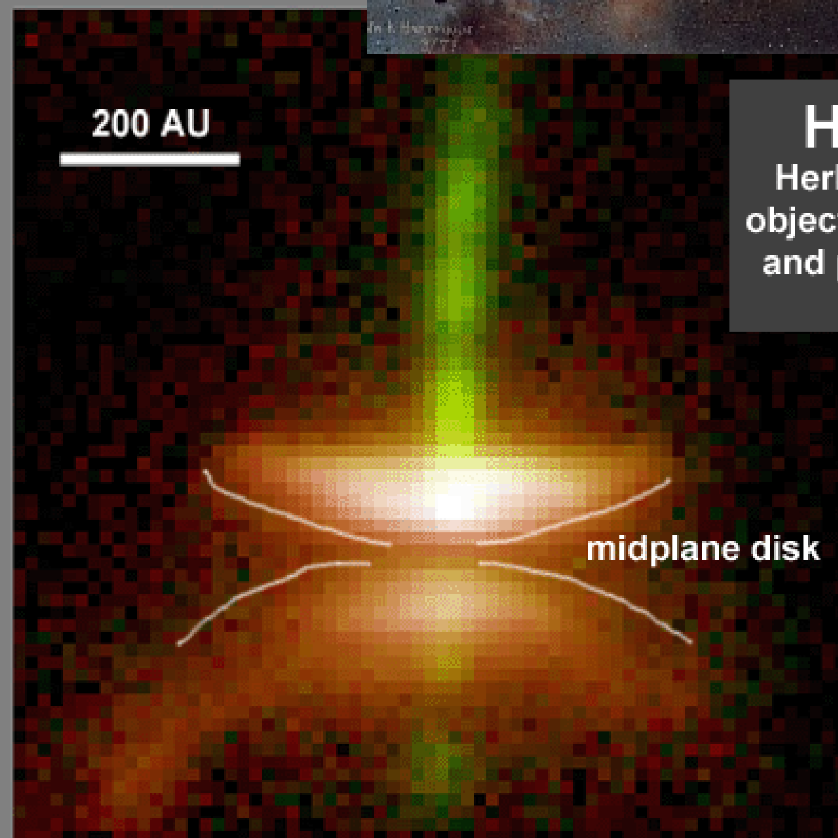


image: *Hubble Space Telescope*

F. Important results

1. Planetary rock-swapping has occurred throughout solar system history.

- ~30 martian meteorites, ~40 lunar meteorites recognized on Earth; younger than 4.56 b.y.
- Impact-blasted off surfaces; brought to Earth in last ~0.1-10 m.y. probably many more at earlier times
- Now finding meteorites on the Moon and Mars

<< Meridiani Planum iron meteorite (IAB) (MER Opportunity image, sol 339)

Important results

2. The decay of short-lived radioactive nuclides was an important heat source in the early solar system.

- Evidence for many short-lived nuclides found in various meteorites, can be used as relative chronometers

- Many meteorite parent bodies melted & differentiated. Short-lived radioactive decay most promising heat source

Important results

3. The solar system formed in a short period.

- Dating by short-lived chronometers & precise Pb-Pb system
- Time to make & melt meteorite parent bodies ~2-5 Ma

time ~ 0.1-5 Ma ↓

molecular cloud (cold gas + dust)
proplyd (warmer gas + dust)
proplyd (warmer gas + dust + planetesimals)

Important results

4. Pre-solar grains were incorporated & preserved in chondritic meteorites

<< contains microscopic pre-solar grains, found by acid dissolution, gas extraction, or isotope mapping

Pre-solar grains:

- SiC
- nanodiamond
- graphite
- corundum
- Si_3N_4
- organic matter

Formed around multiple types of stars (red giants, supervovae)

Important results

5. Pre-biotic organic synthesis occurred in solar system building blocks

- Organic compounds found in interstellar medium (ISM)--molecular clouds
- Solar system formed by collapse of molecular cloud; chondrites formed in the early solar system and contain similar organic compounds

Rich in pre-biotic
organic material
(incl. amino acids)

Many organic compounds in carbonaceous chondrites

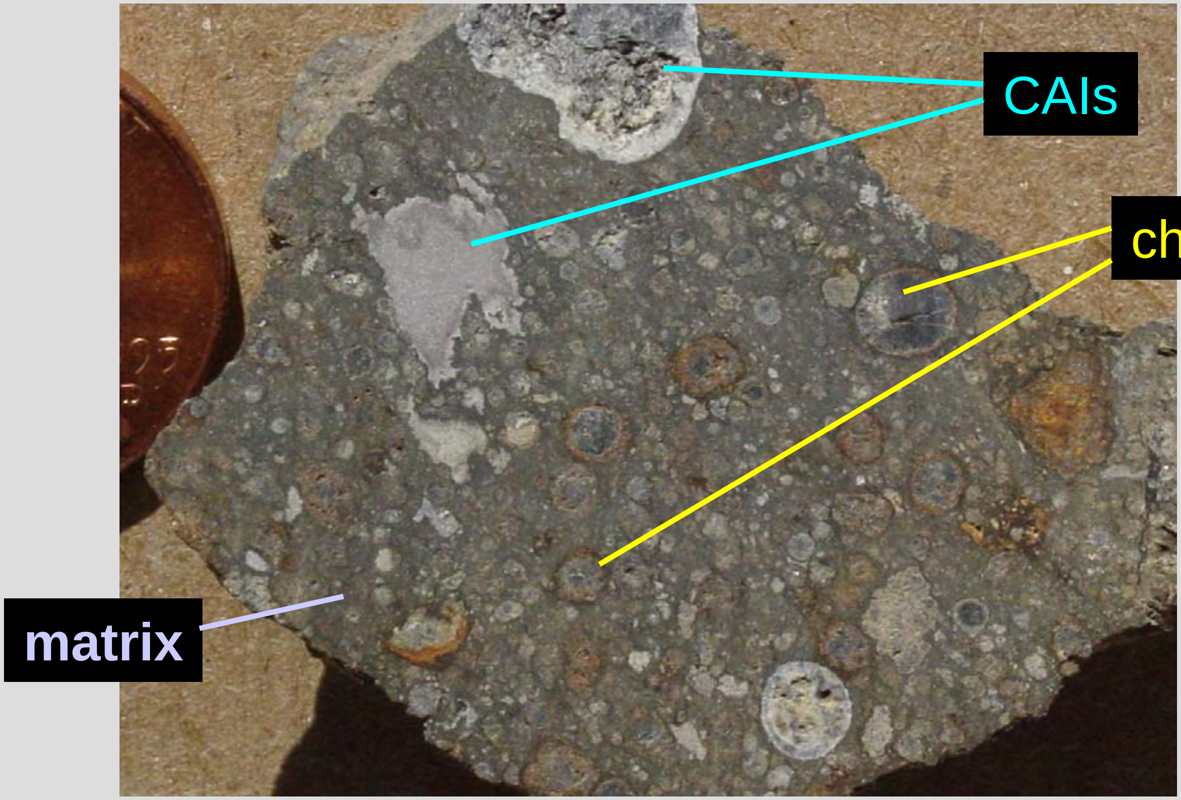
Include: macromolecular (kerogen-like) carbon, carboxylic acids, dicarboxylic acids, amino acids, lower alkanes, higher alkanes, aromatic hydrocarbons, N-compounds

Pre-terrestrial origin:

- no terrestrial source for some compounds
- compounds destroyed by terrestrial exposure & weathering
- racemic mixtures
- often isotopically anomalous (e.g., high D/H ~ 10x seawater)

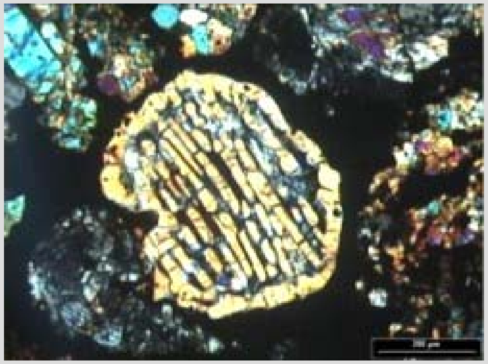
Important results

6. A substantial amount of dust in the early solar system was processed by intense heating events to make chondrules & CAIs (Ca-Al-rich inclusions).



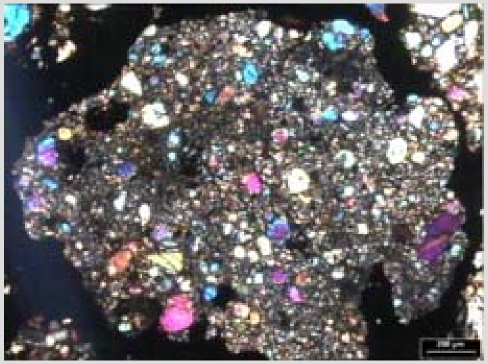
<<
NWA 2697
(CV3 chondrite)

Chondrule textures in thin-section



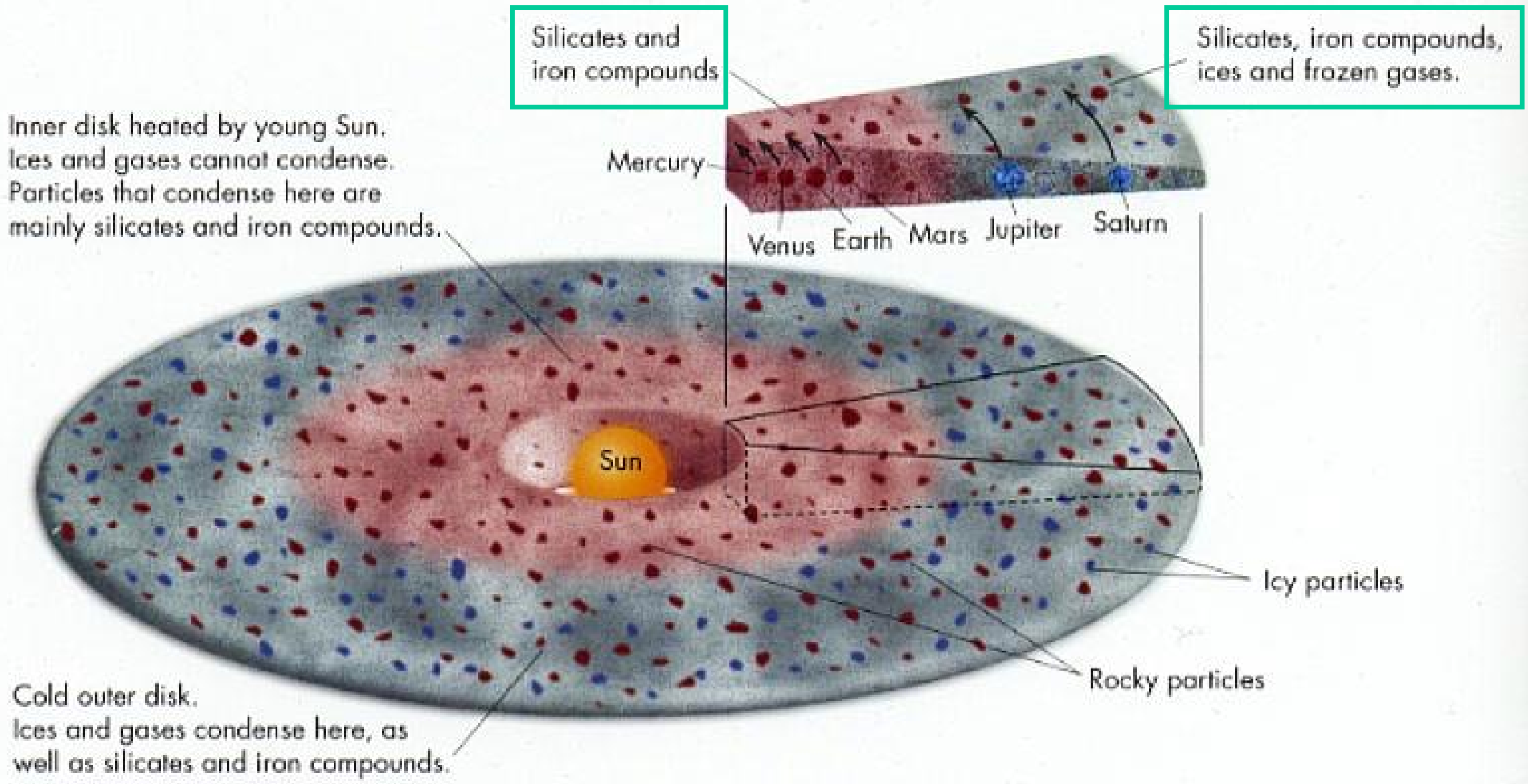
<< barred olivine, almost completely remelted

<< microporphyritic olivine >>
mostly remelted

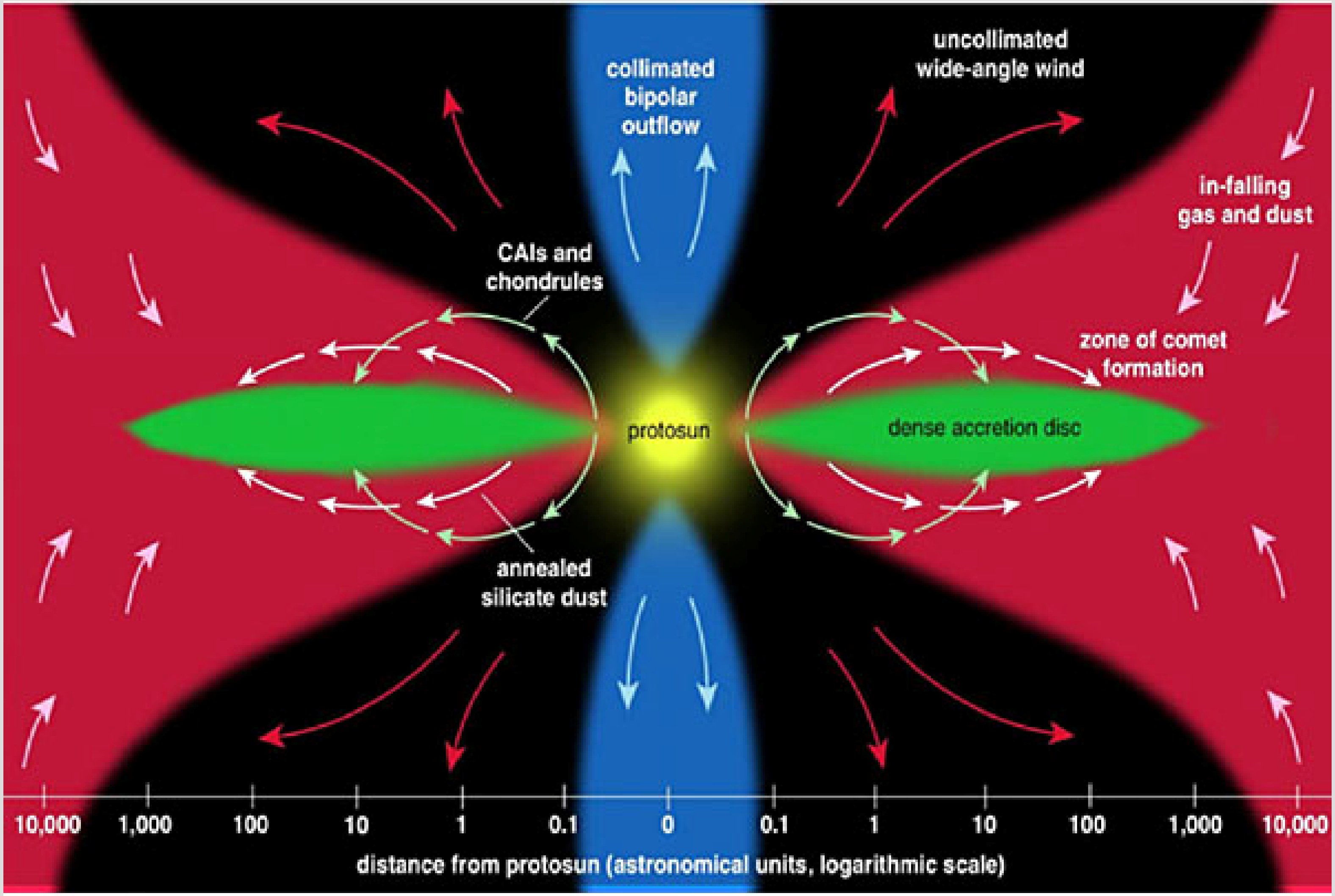


radial pyroxene & microporphyritic
pyroxene , completely or partly remelted >>

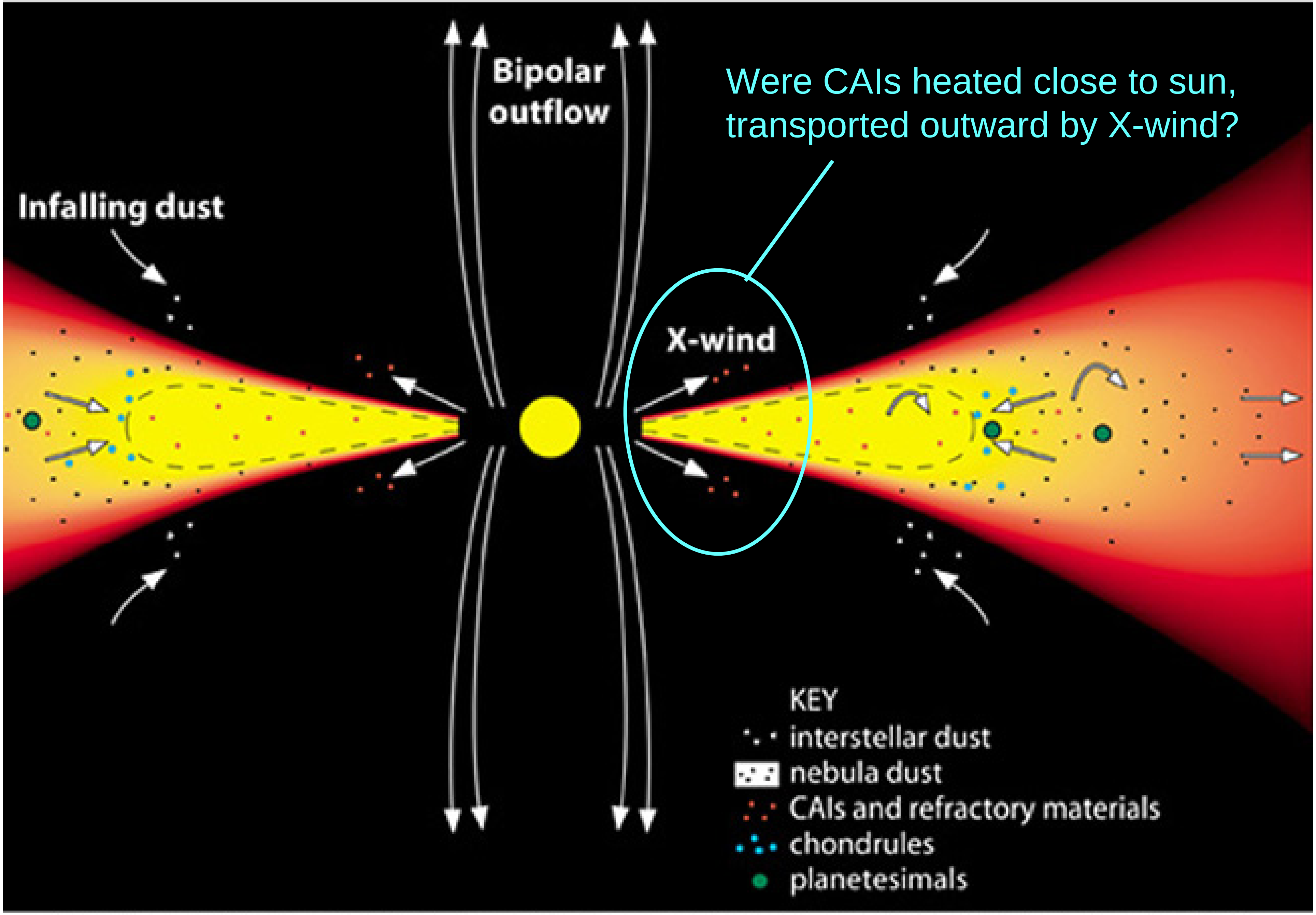
General picture of solar nebula: hotter closer to sun…
so dust composition must vary with distance from sun



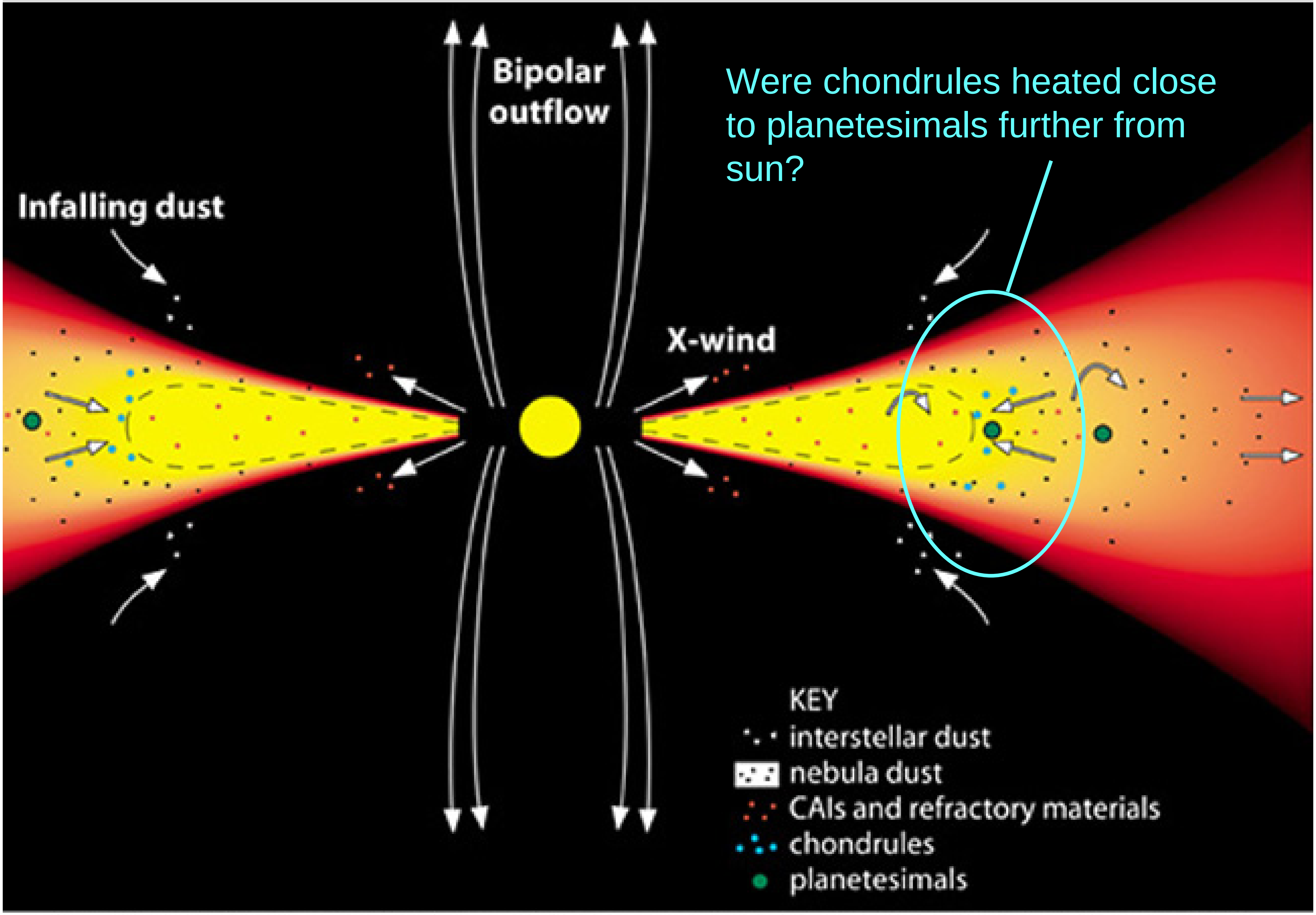
But chondrules & CAIs indicate we have also localized intense heating. Heated particles must become mixed with cooler dust to form chondritic material (unmelted asteroids & comets).



(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)



(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)



(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

Our Moon in a New Light

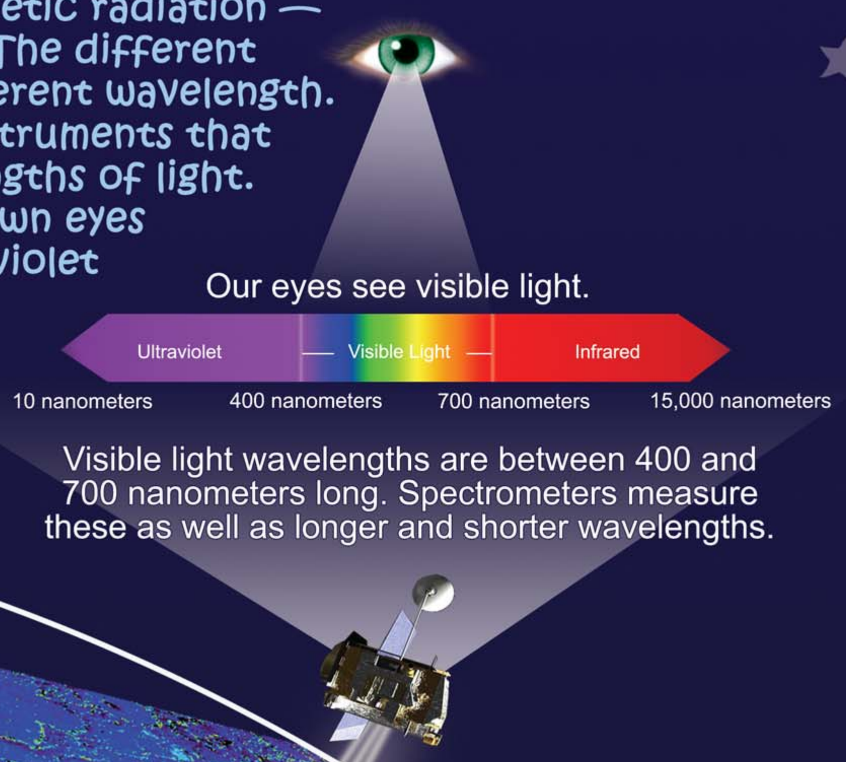
Mapping Our Moon!

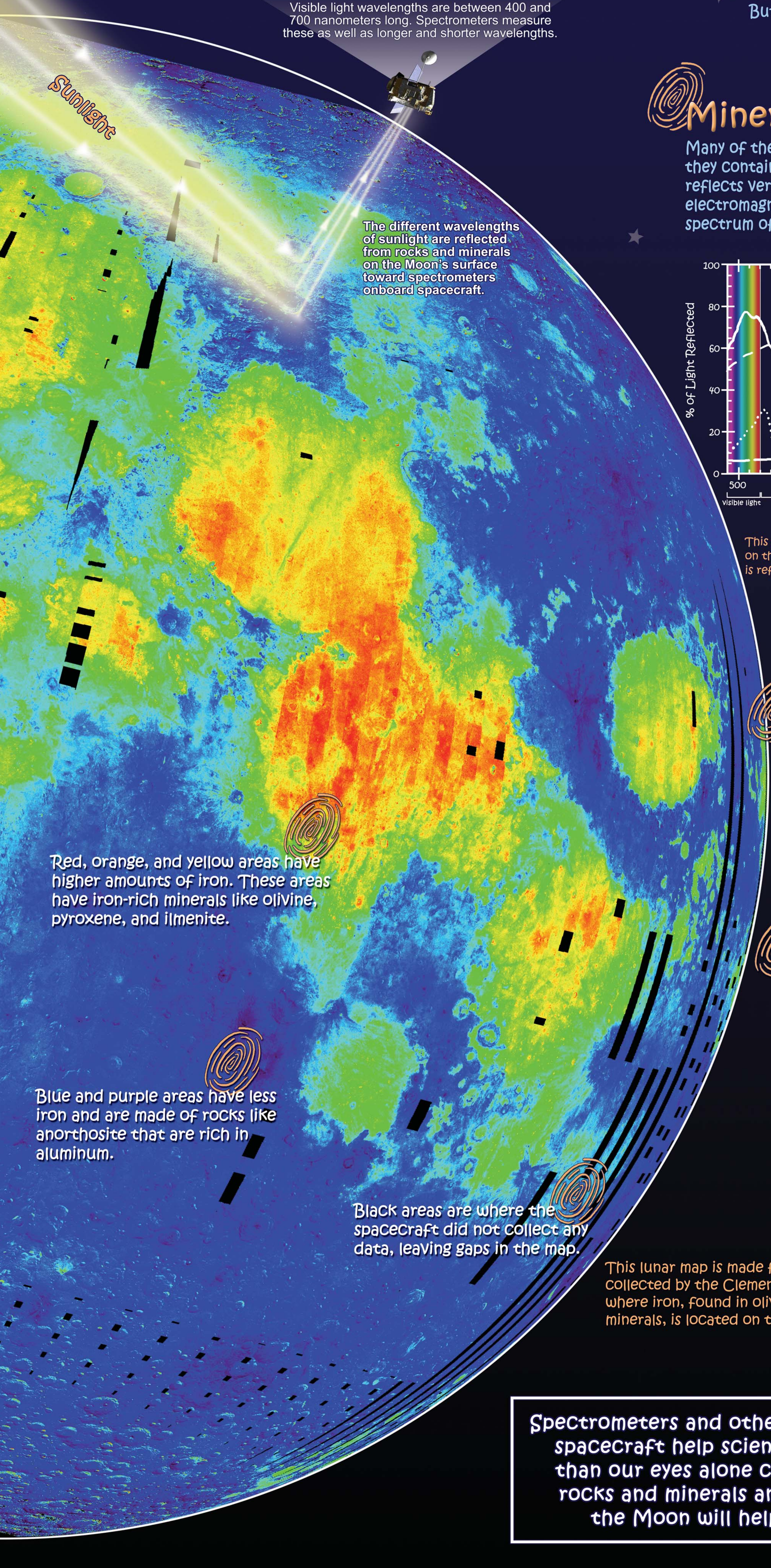
As we plan our journey back to the Moon, it is important that we know where different types of rocks and minerals are located. Apollo astronauts visited only six places — much of our Moon still needs to be explored . . .

Seeing More

To characterize materials on the Moon, scientists use reflectance spectroscopy, a measure of the amounts of electromagnetic radiation at different wavelengths that reflect from the Moon's surface.

We can see some electromagnetic radiation — our eyes detect visible light. The different colors we see are each a different wavelength. Spectrometers are special instruments that also detect different wavelengths of light. They can measure what our own eyes see and more, including ultraviolet light, infrared radiation, and beyond!





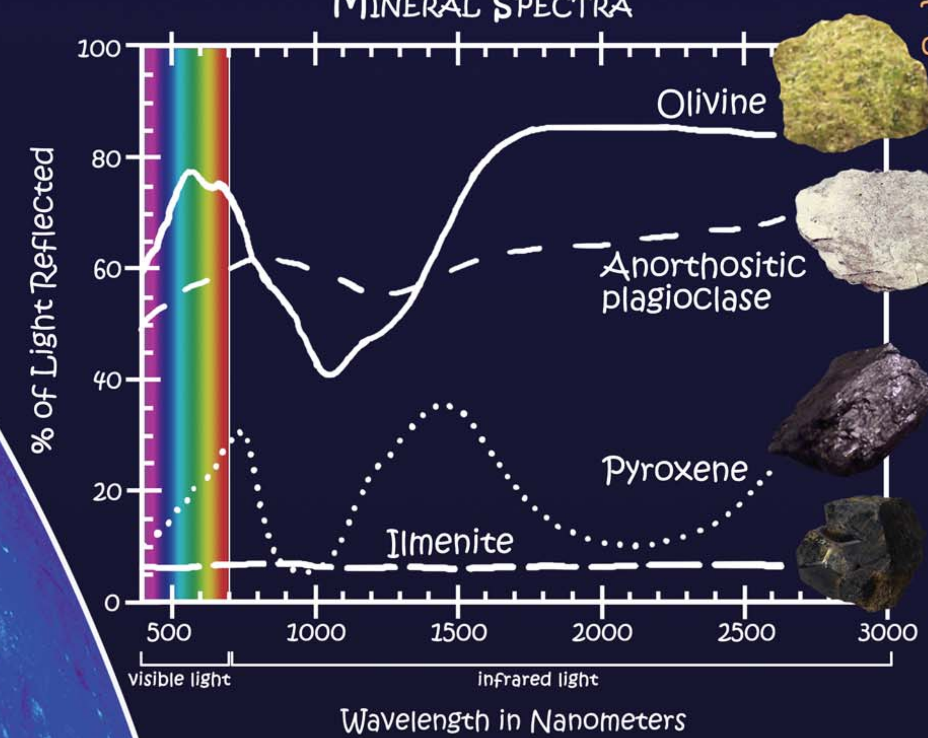
This lunar map is made from spectral measurements collected by the Clementine spacecraft. It shows where iron, found in olivine, pyroxene, and other minerals, is located on the Moon's surface.

What Can You See?

When you look at the Moon, you see the big dark patches of lunar maria that are made of basalt rock. You also see the bright lunar highlands that are made of anorthosite. But spectrometers help us see even more.

Mineral Fingerprints

Many of the rocks on the surface of the Moon may *look* similar, but they contain different minerals or amounts of minerals. Each mineral reflects very specific amounts of the different wavelengths of electromagnetic radiation, so each mineral has a characteristic spectrum of reflected light — a spectral fingerprint.



This graph shows spectral fingerprints of different minerals that make up the rocks on the Moon. The shape of each curve — or spectrum — represents how much light is reflected for different wavelengths. Each mineral has a unique spectrum.

Exploring the Whole Moon

Spectrometers onboard spacecraft in orbit around the Moon collect reflectance measurements as they pass over different areas, allowing scientists to gather spectral data from the entire Moon.

Matching Fingerprints

Scientists examine the spectral data collected from the Moon's surface and compare these measurements to spectral curves gathered from known Earth and Apollo rock and mineral samples. This comparison allows scientists to determine how much of each mineral is present at a location on the Moon's surface. Using spectral measurements, scientists can make a very detailed map of the mineral and chemical composition of the entire Moon — without collecting more rocks from the surface!

Spectrometers and other special instruments onboard orbiting spacecraft help scientists discover more about our Moon than our eyes alone can detect. Knowing where different rocks and minerals and chemical elements are located on the Moon will help us plan our future exploration.

NASA
Lunar and Planetary Institute

Introduction to the Moon

Paul D. Spudis
Lunar and Planetary Institute

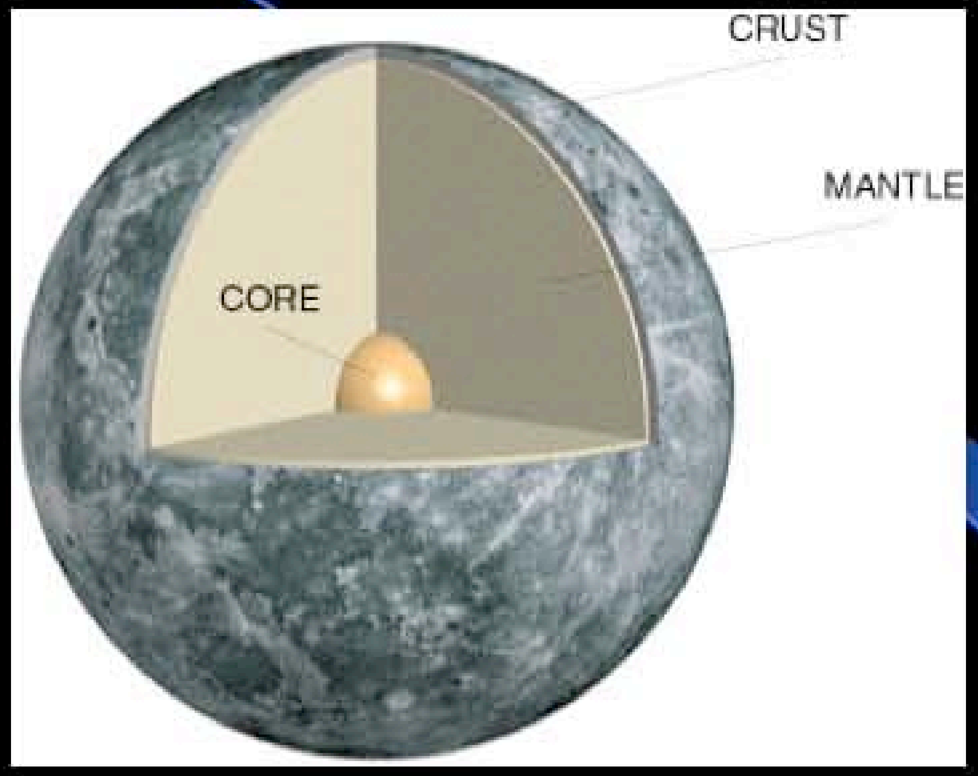
spudis@lpi.usra.edu

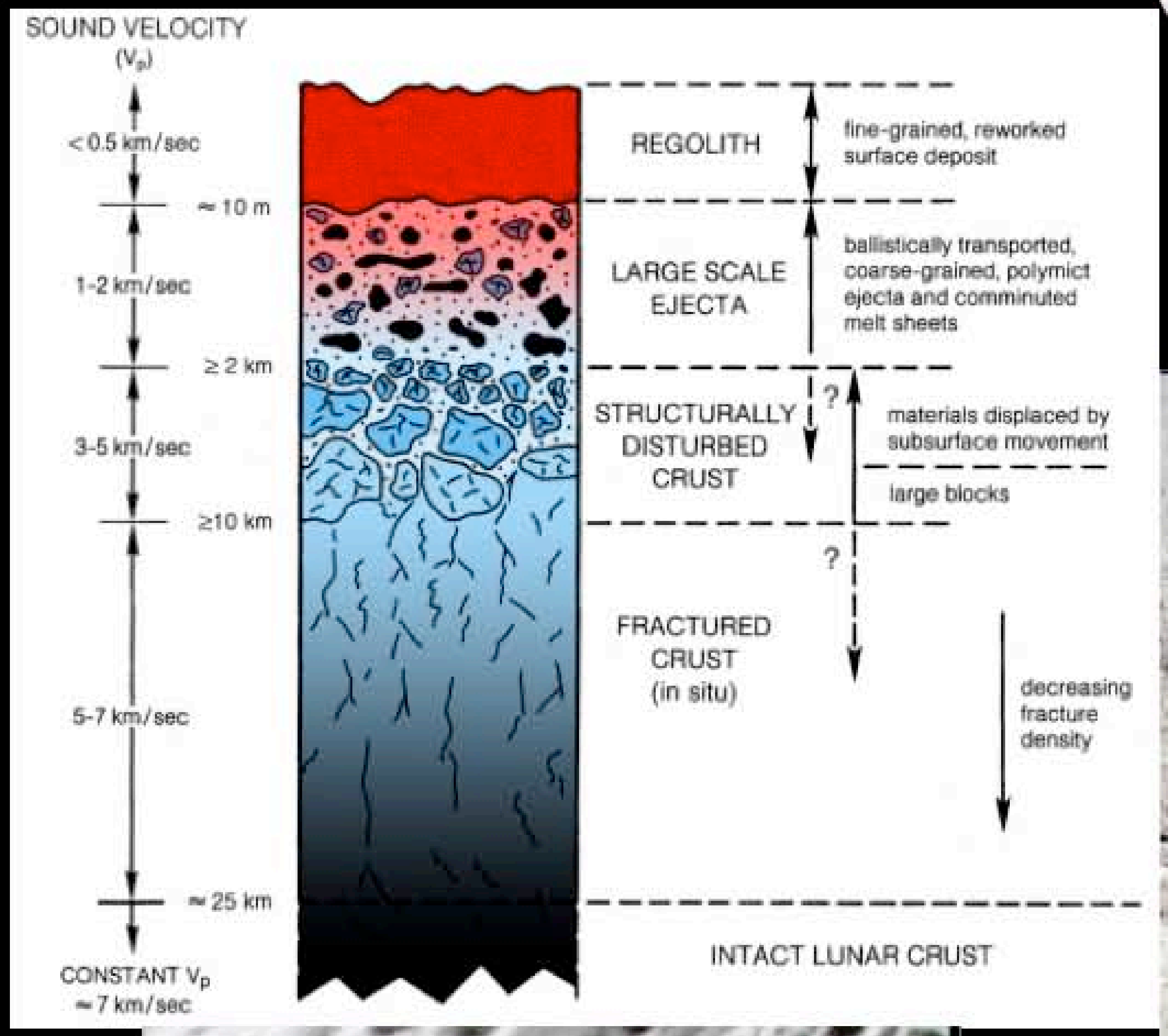
http://www.spudislunarresources.com

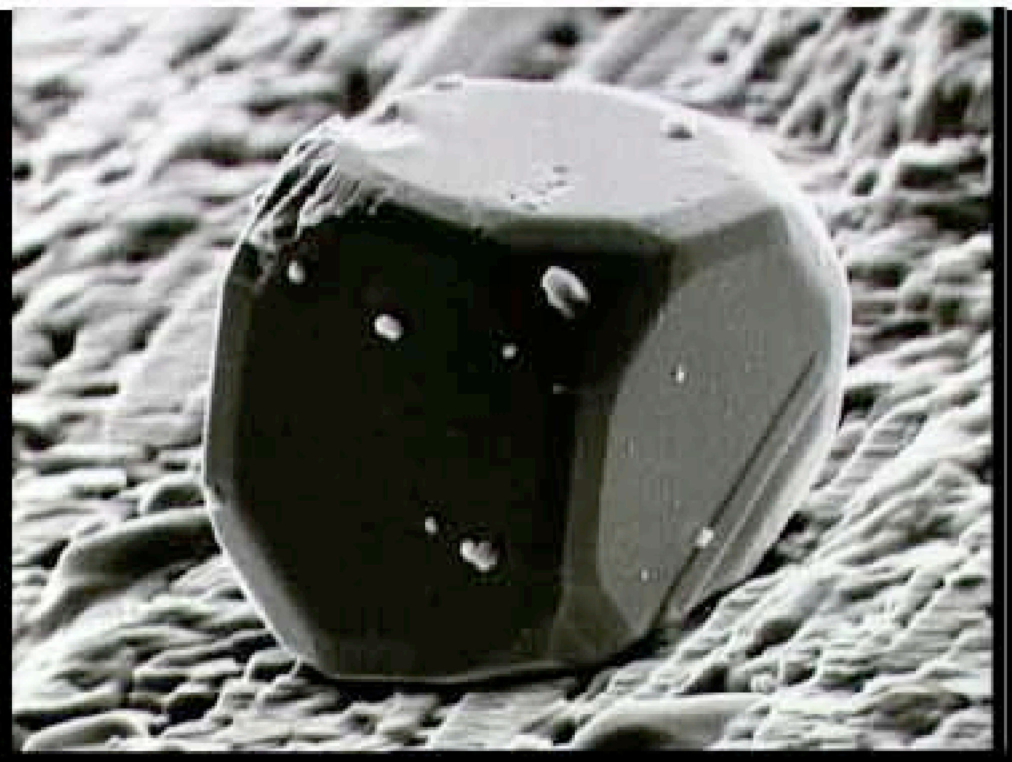
Moon 101
NASA Johnson Space Center
4 June, 2008

The Nature of the Moon

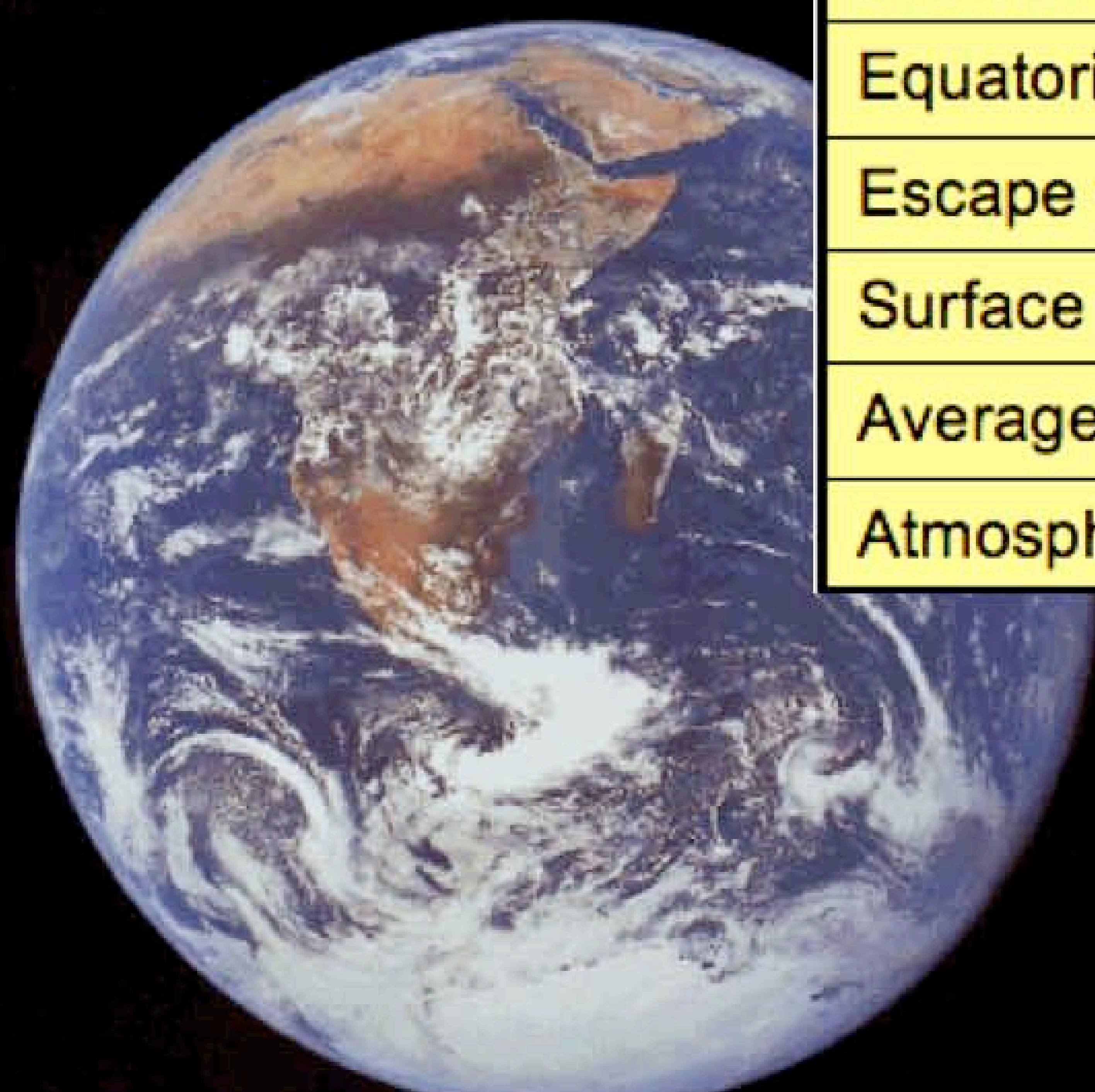
- A rocky planetary object, differentiated into crust, mantle, and core
- Heavily cratered surface; partly flooded by lava flows over 3 Ga ago
- Since then, only impacts by comets and asteroids, grinding up surface into chaotic upper layer of debris (regolith)
- Regolith is easily accessed and processed; likely feedstock for resource extraction





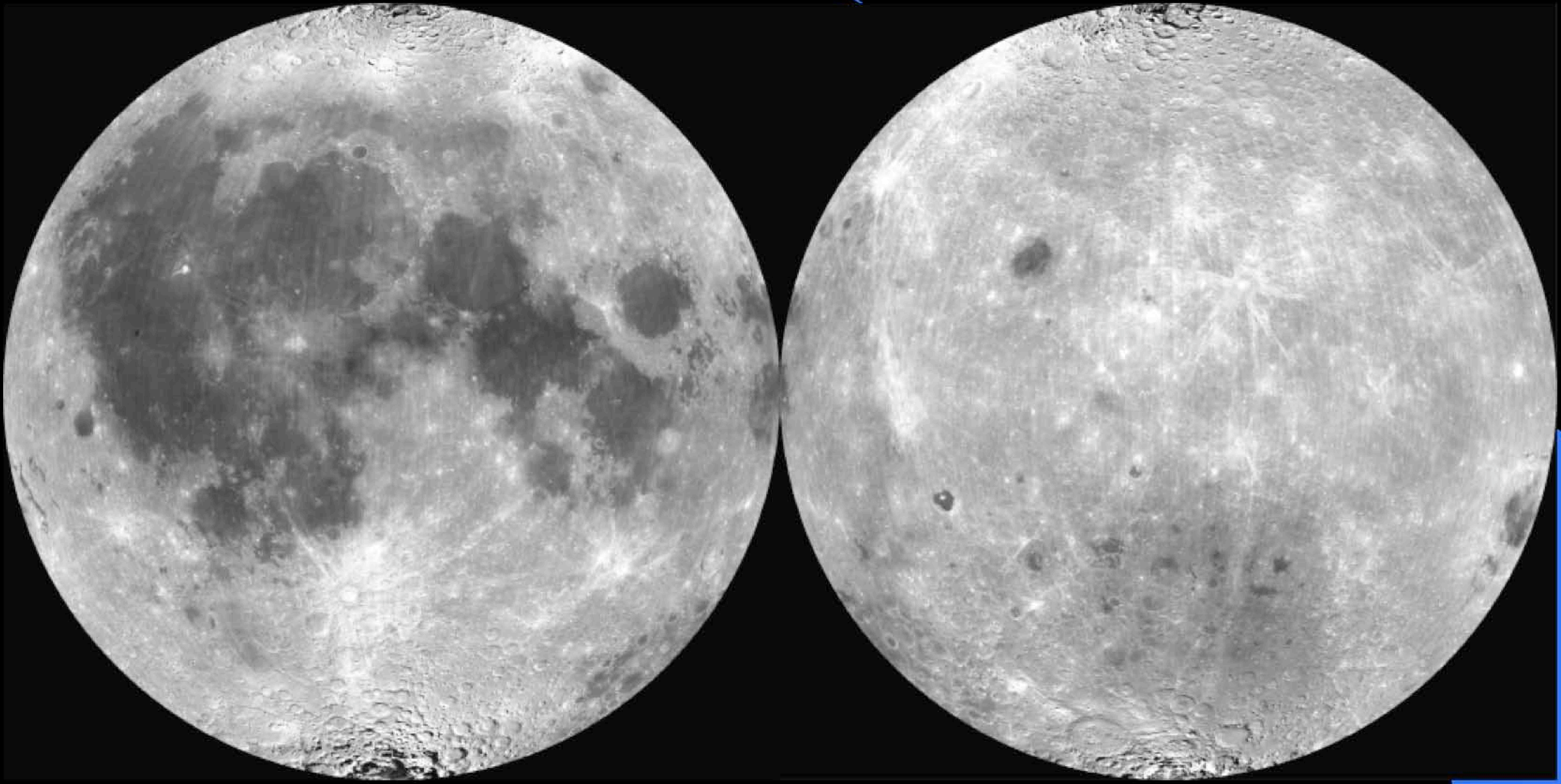


Some General Properties



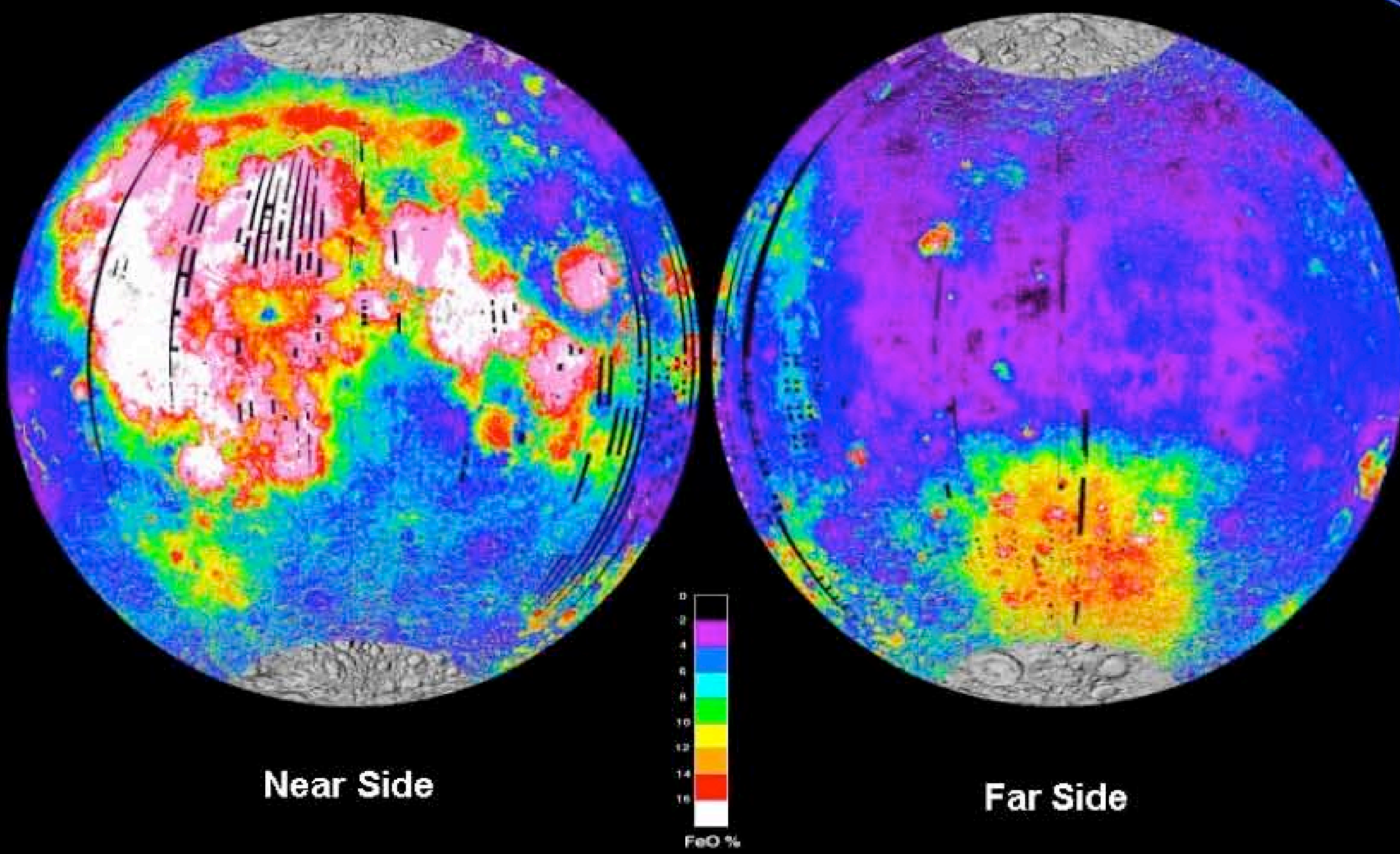
	Unit	Moon	Mars	Earth
Mass	10^{22} kg	7.34	64.2	598
GM	$kg^3\ m^2$	4896.8	42828.2	398930.3
Density	$kg\ m^{-3}$	3340	3920	5520
Equatorial radius	km	1738	3393	6378
Volume	$10^{10}\ km^3$	2.2	16.3	108.2
Surface Area	$10^6\ km^2$	37.9	144	511
Moment of Inertia		0.395	0.345-0.365	0.332
Equatorial gravity	$m\ s^{-2}$	1.62	3.71	9.83
Escape velocity	$km\ s^{-1}$	2.37	5.03	11.19
Surface magnetic field	G	$< 2 \times 10^{-3}$	$< 5 \times 10^{-4}$	0.31
Average temperature	K	253	210	275
Atmospheric pressure	Pa	$< 10^{-7}$	560	10,000

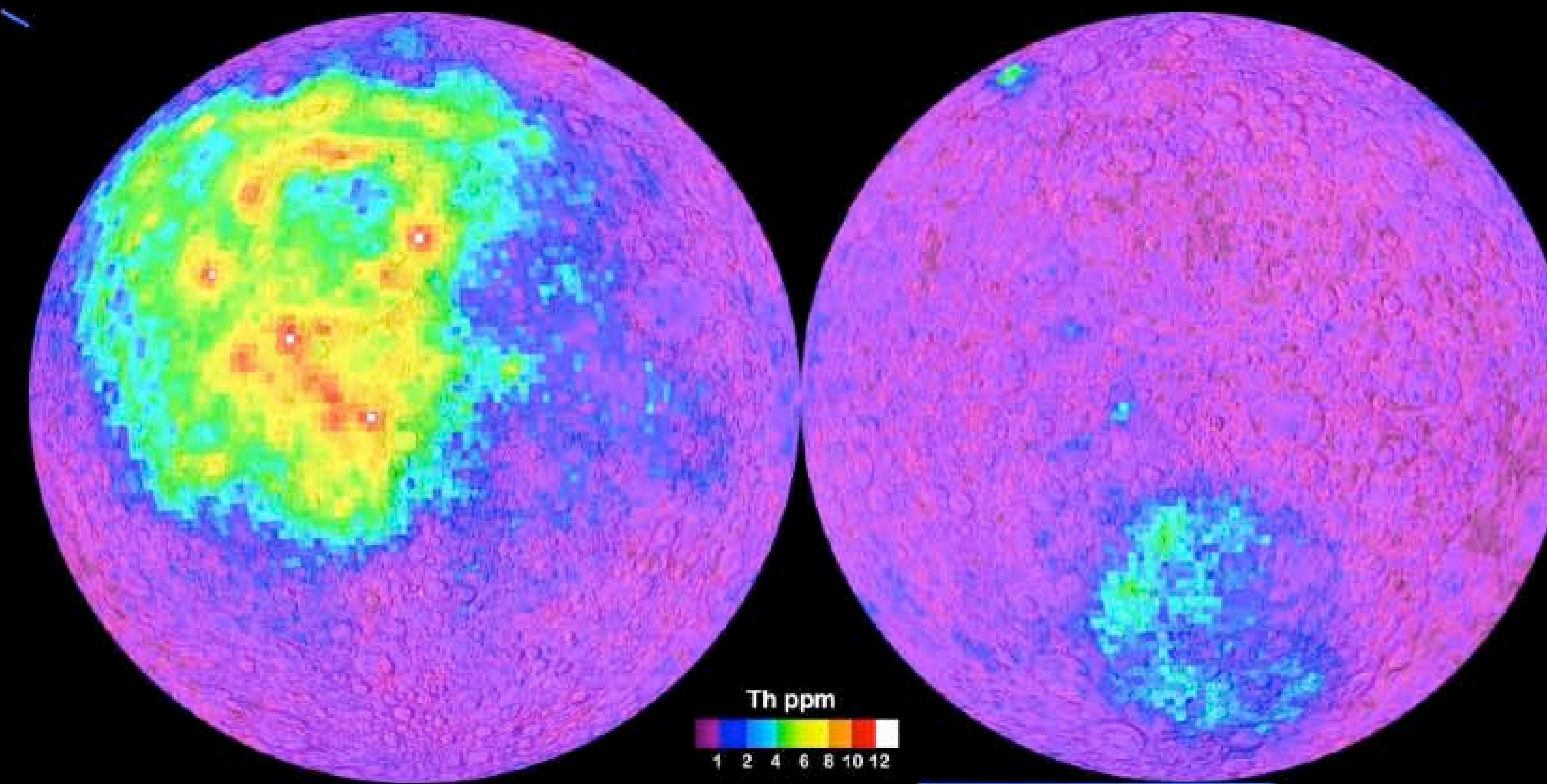
Moon – Near and Far Sides

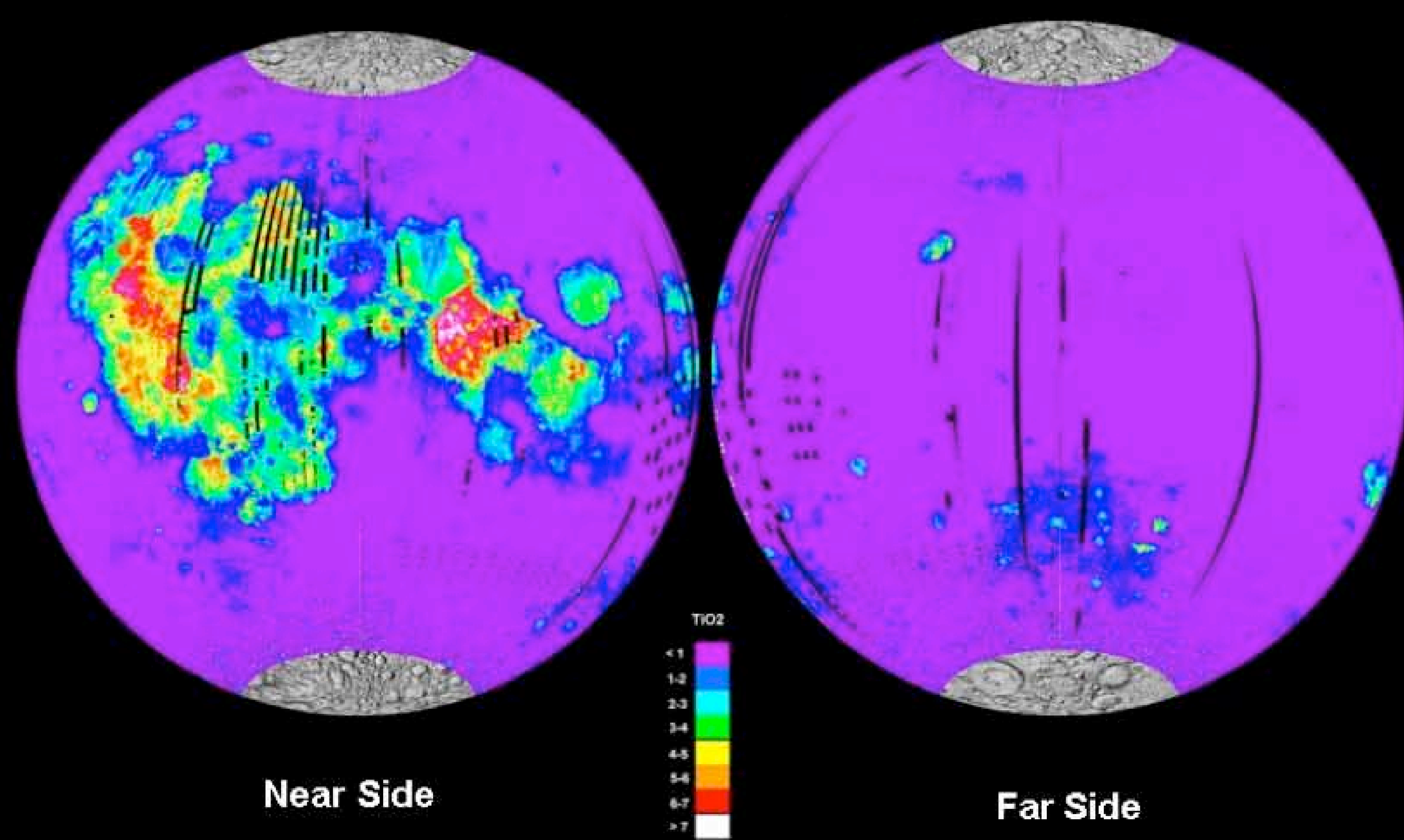


Near side **Far side**

Moon – Elemental Composition







Iron (Fe) - maps mare basalts, mafic highlands (e.g., SPA basin floor)

Titanium (Ti) - all mostly in maria; high Ti ~ high H_2

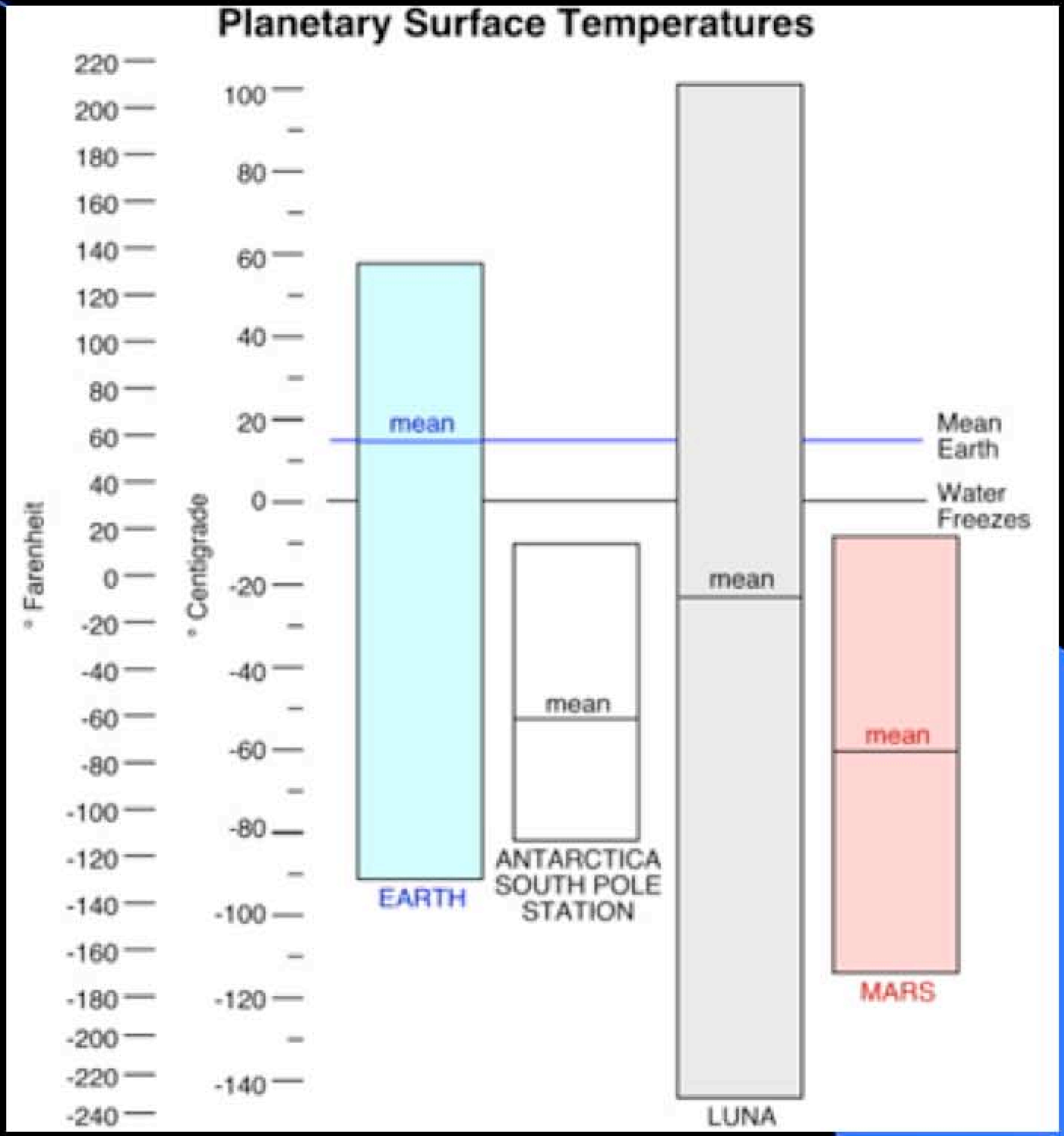
Thorium (Th) - asymmetrically distributed in western near side; maps KREEP

Environment

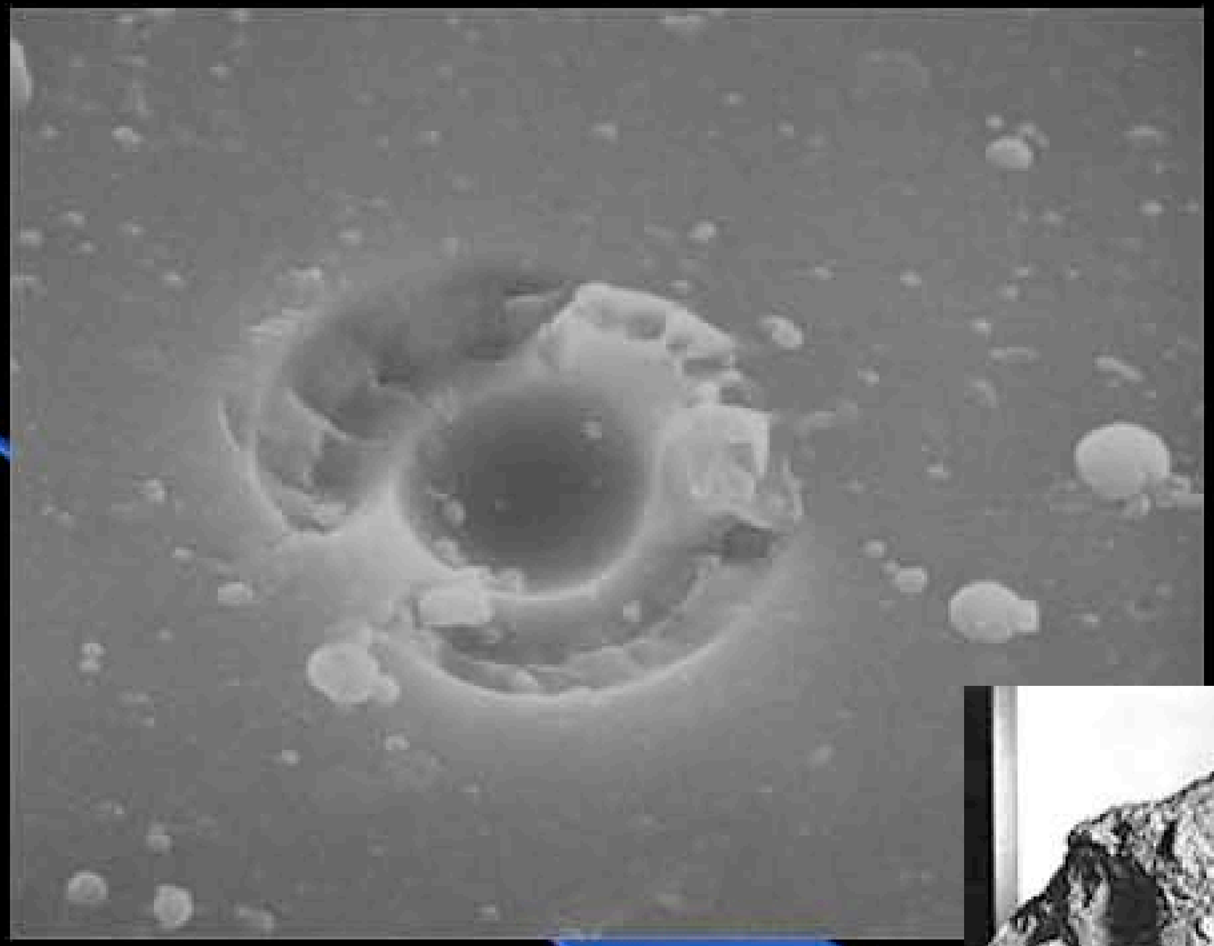
	Non-polar	polar
Temperature	-150º C to + 100º C	-50º C (lit) to -200º C (dark)
Sunlight	~354 hrs ± 90º incidence angle	~530 to 708 hrs ± 1.7º incidence angle
Darkness	~354 hrs	0 to 148 hrs (discontinuous)
H content	10-90 ppm	> 150 ppm
Resource Potential	Solar wind gases Bound oxygen	Solar wind gases Bound oxygen Volatiles in shadows
Direct Earth Communications	Continuous on near side, Relay satellite needed for far side	Discontinuous but predictable (~1/2 time in Earth view)

Thermal Conditions

- Surface temperature dependant on solar incidence
  - Noontime surfaces ~ 100° C
  - Coldest night temperatures ~ -150° C
- Temperature variations minimal below surface ≥ 30 cm (constant -23°± 5° C)
- Polar areas are always either dark or at grazing solar incidence
- Lit areas have sunlight ~ 1 incidence
  - Average temperatures ~ -50° ± 10° C
- Dark areas are very cold
  - Uncertainty in lunar heat flow values suggest cold traps between 50 and 70 K (-220° to –200° C)



Micrometeorites



Nothing to impede impact of all-sized debris; r.m.s. impact velocity ~ 20 km s^{-1}

Estimated lunar impact hazard roughly factor of 4 **lower** than in LEO

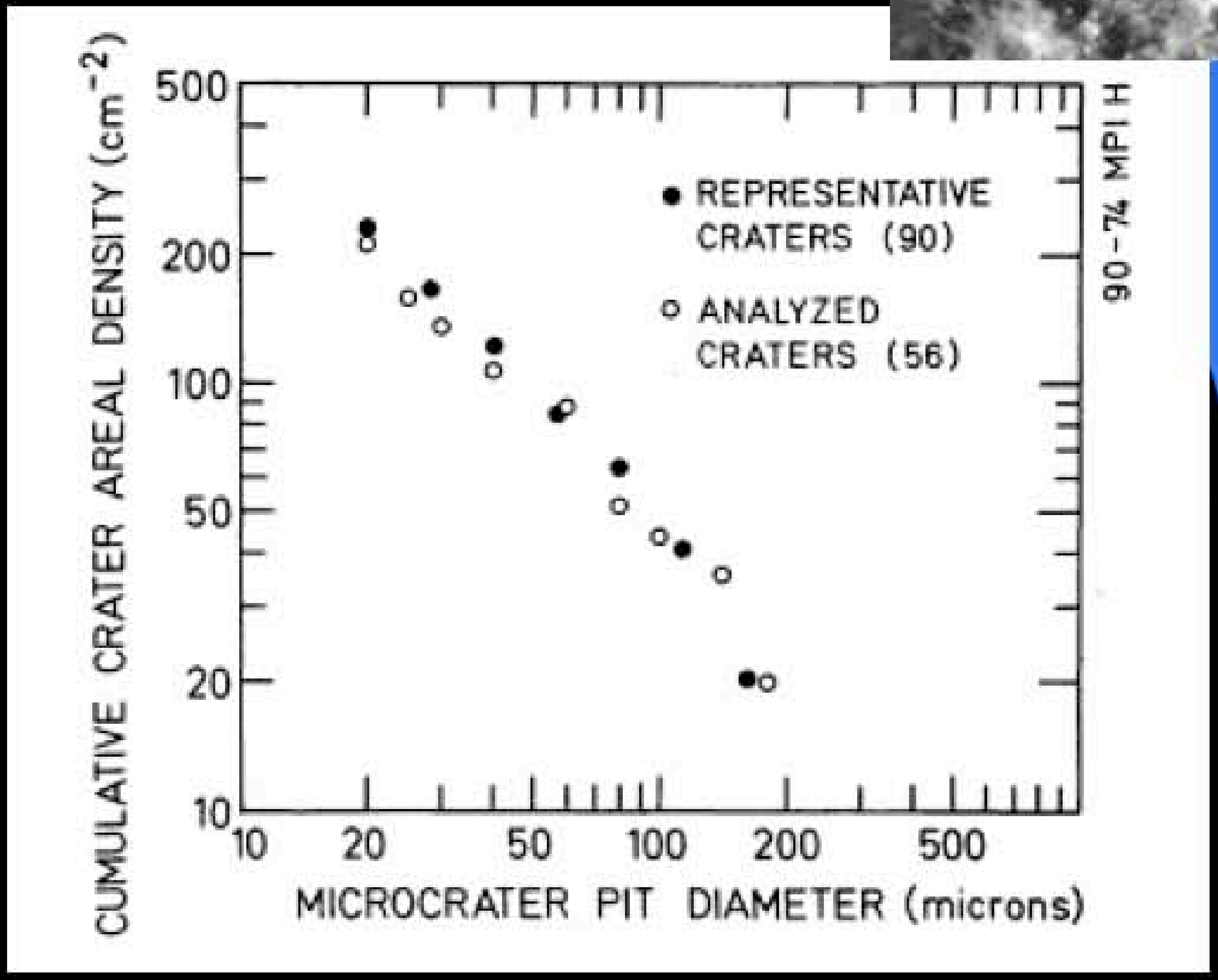
Estimated flux:

Crater Diameter (μm)	# craters / m^2 / yr
0.1	3×10^5
> 1	1.2×10^4
>10	3×10^3
>100	6×10^{-1}
>1000	1×10^{-3}

Microcraters from 1-10 μm will be common on exposed lunar surfaces

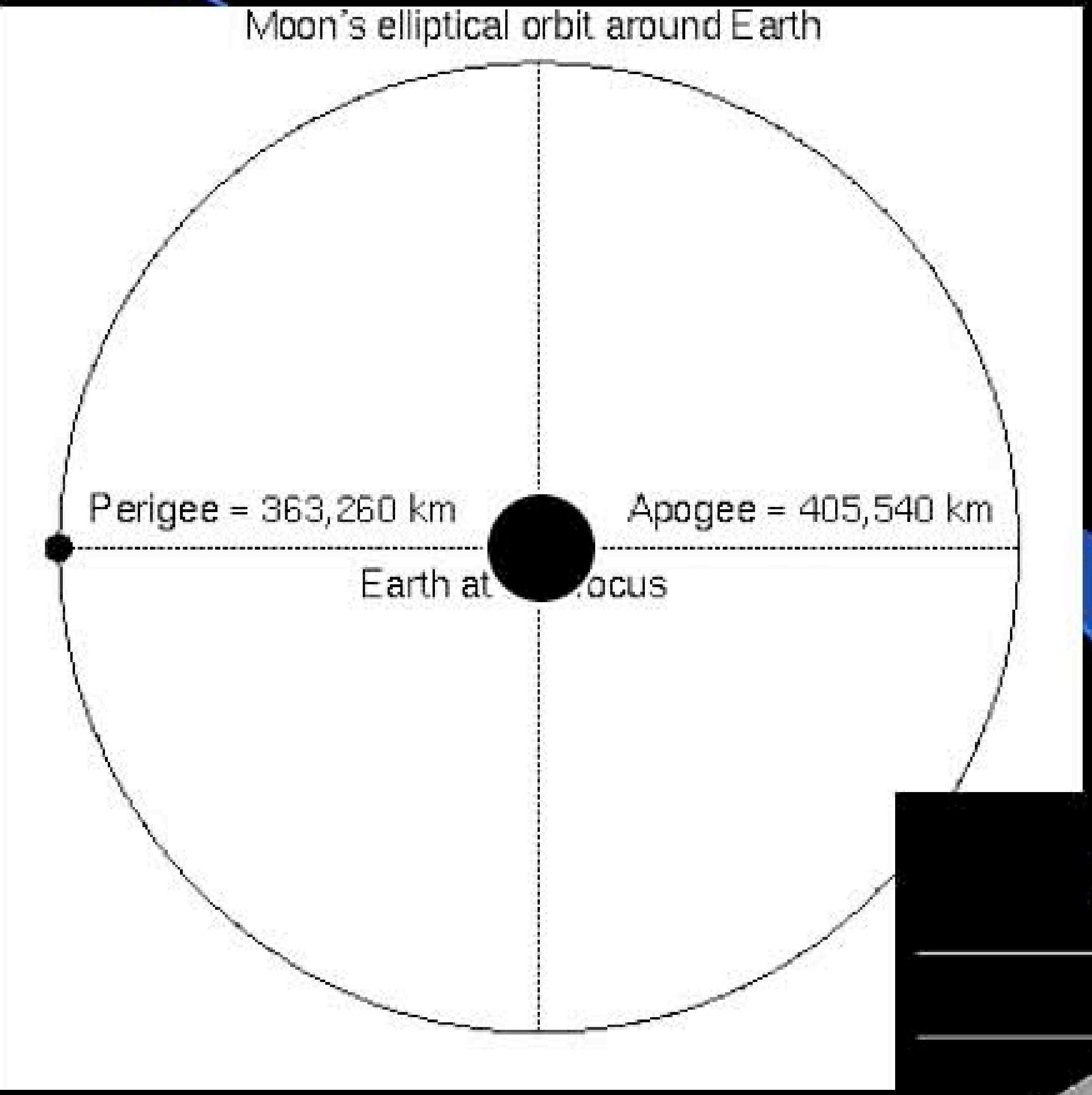
Craters ~100 μm dia. ~ 1 / m^2 / yr

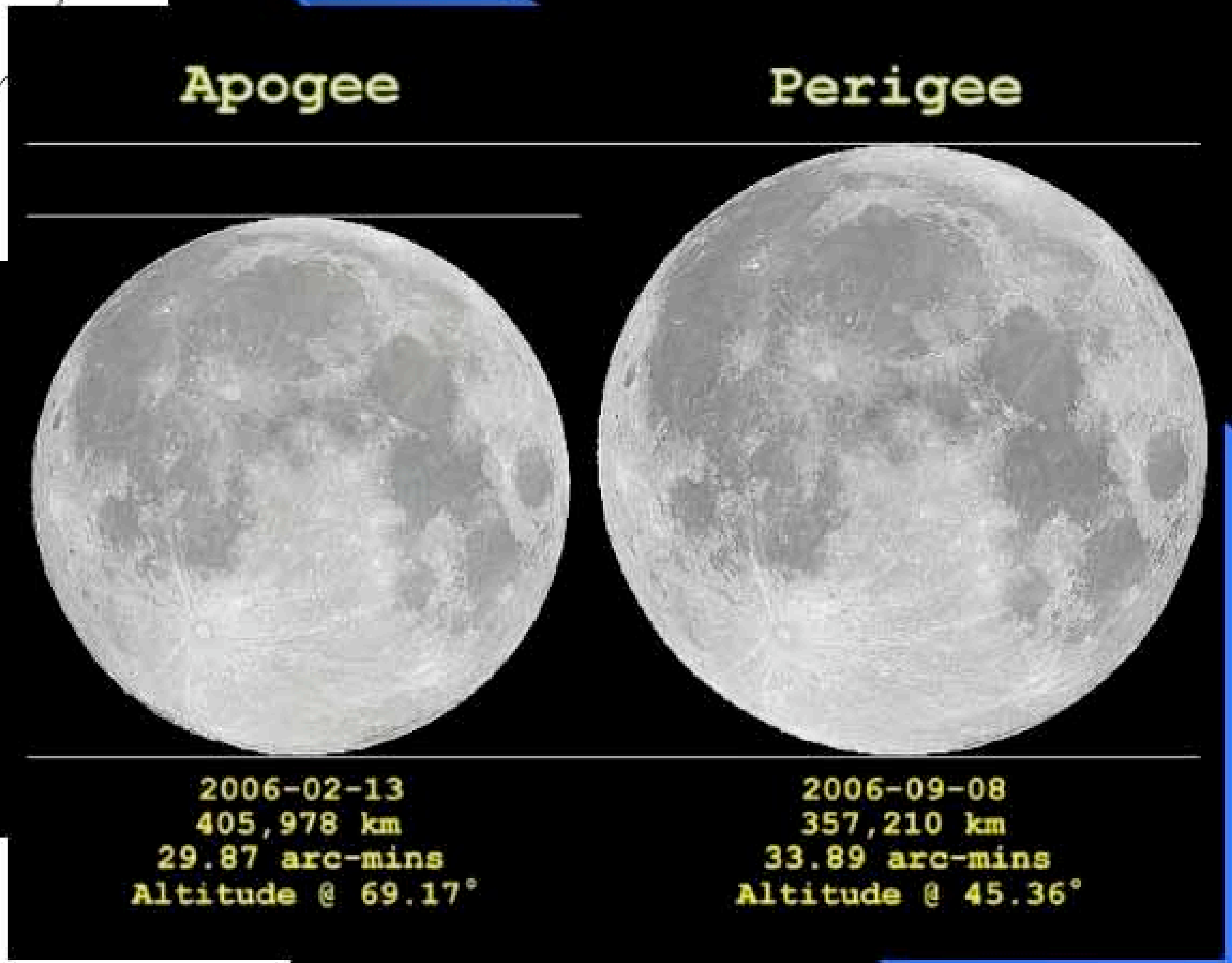
Effects of secondary impact ejecta not well quantified

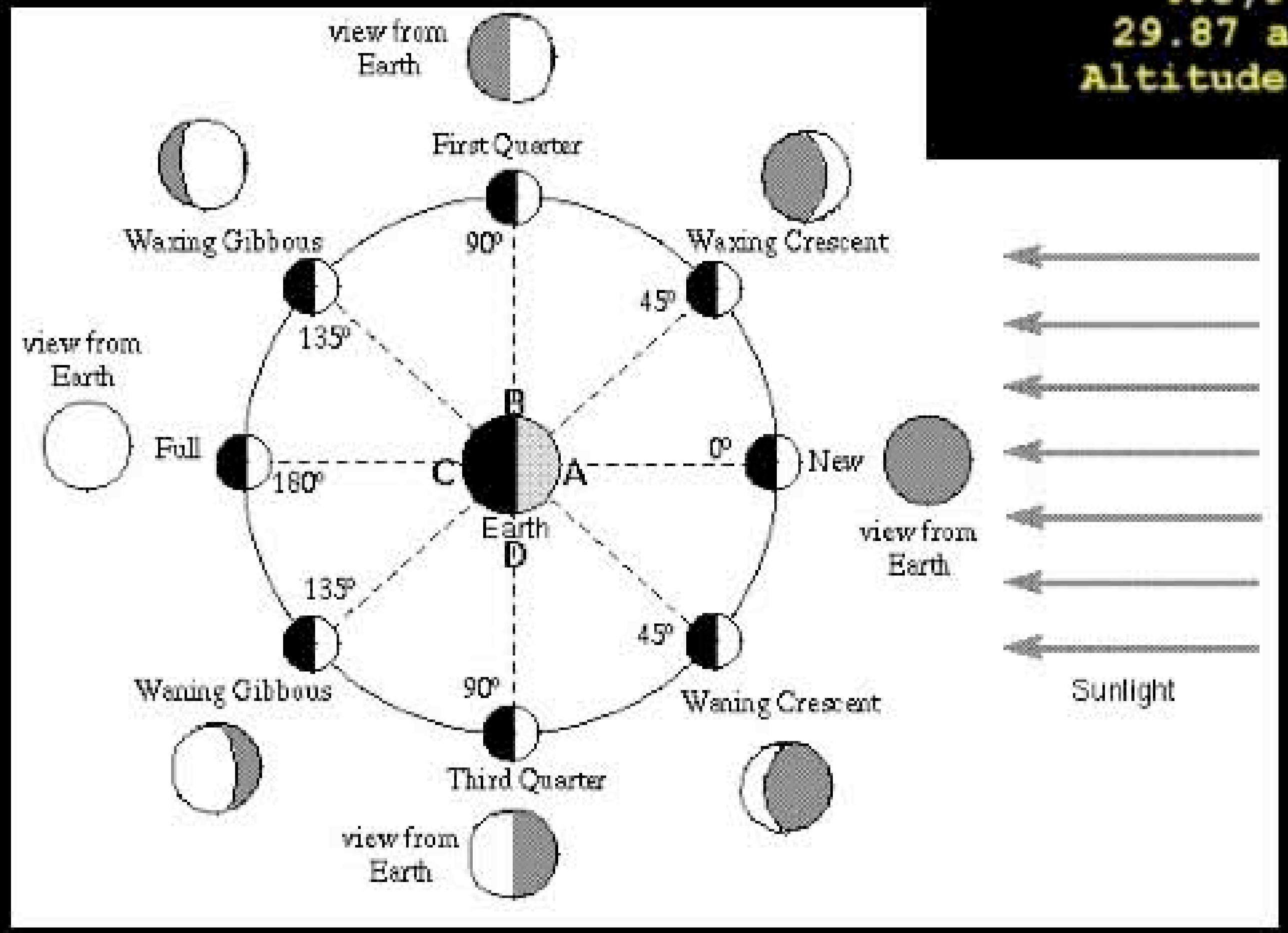


The Moon's Orbit

- Elliptical orbit
  - apogee 405,540 km
  - perigee 363,260 km
- Earth-Moon barycenter ~1700 km beneath Earth surface
- Orbital period 27.3 days
- Moon rotation 29.5 days (708 hours), sunrise to sunrise
- Moon orbital plane inclined 5.5º to ecliptic
- Moon spin axis 1.5º inclination from normal to ecliptic

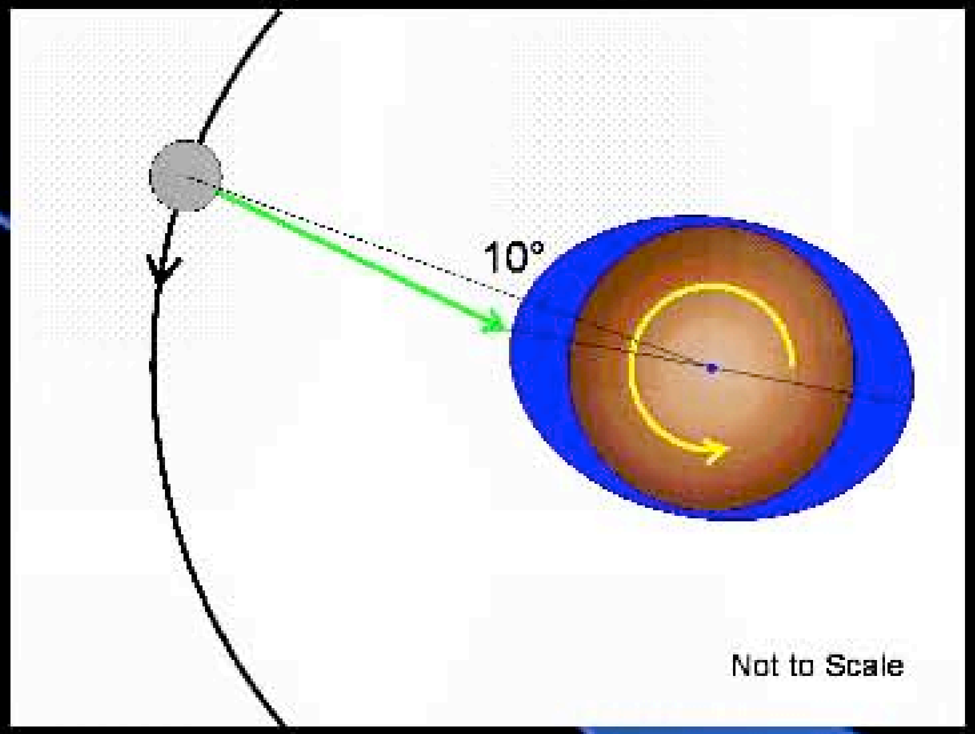


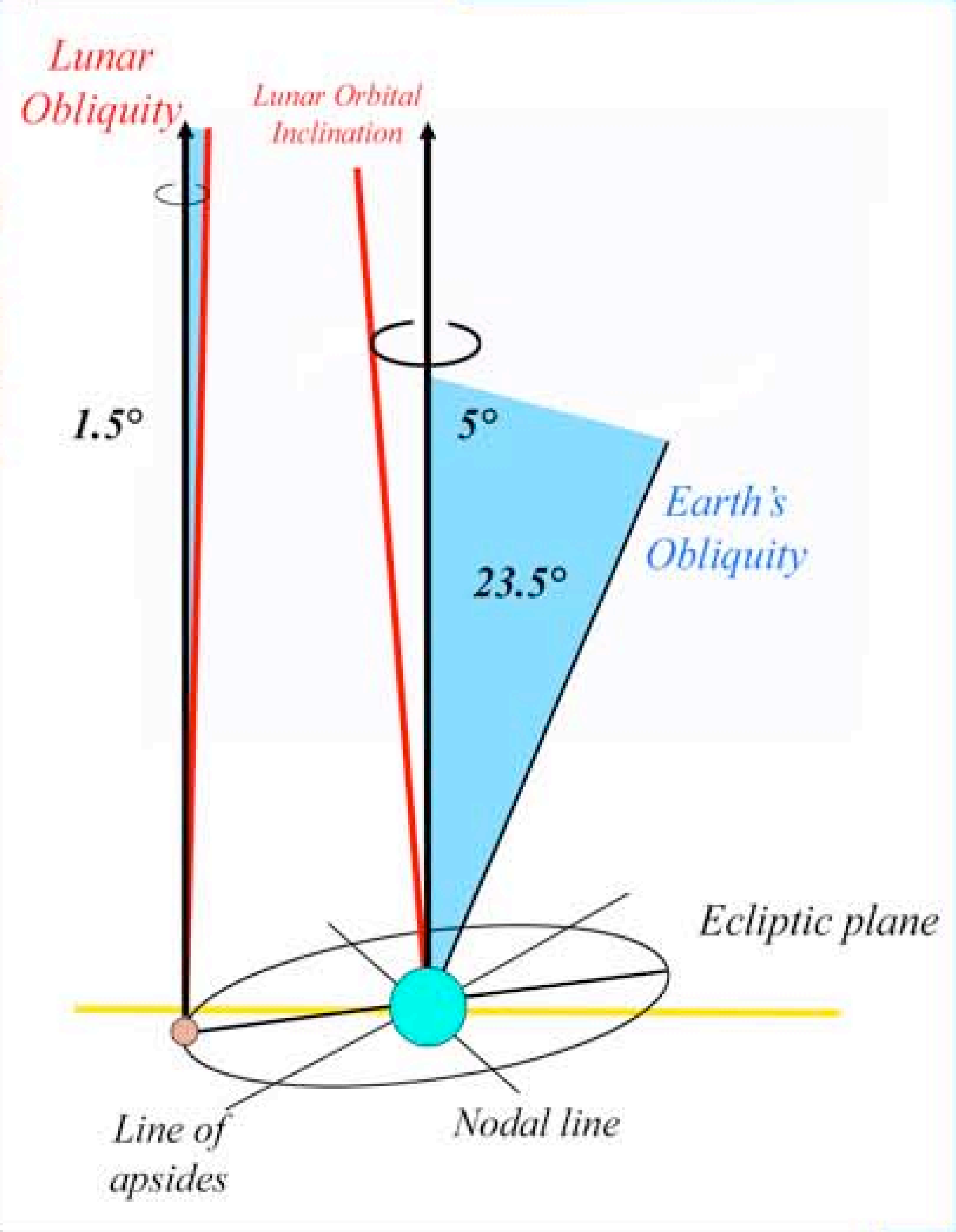




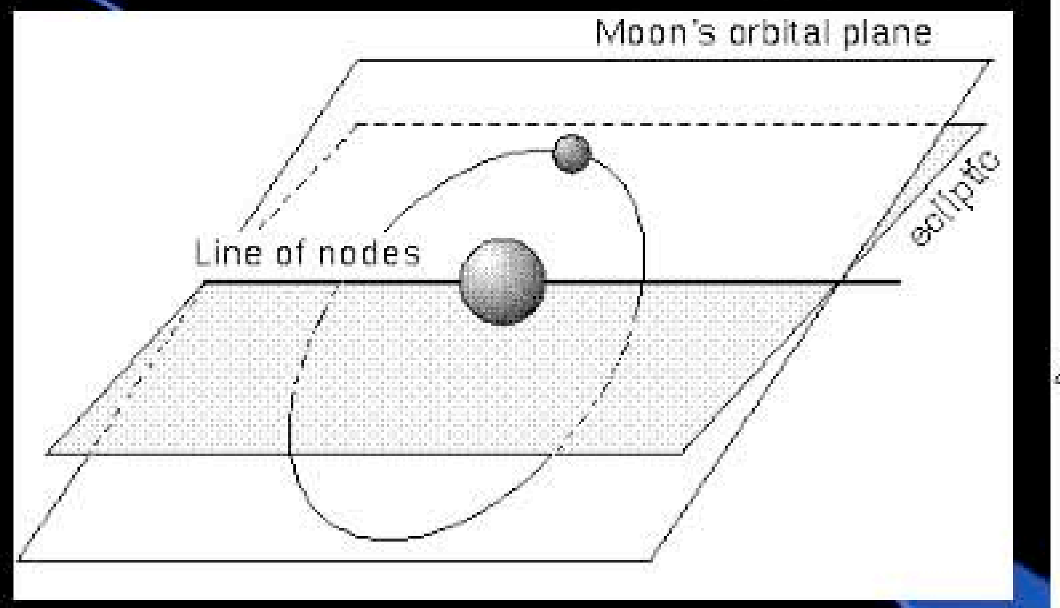
History of the Moon's Orbit

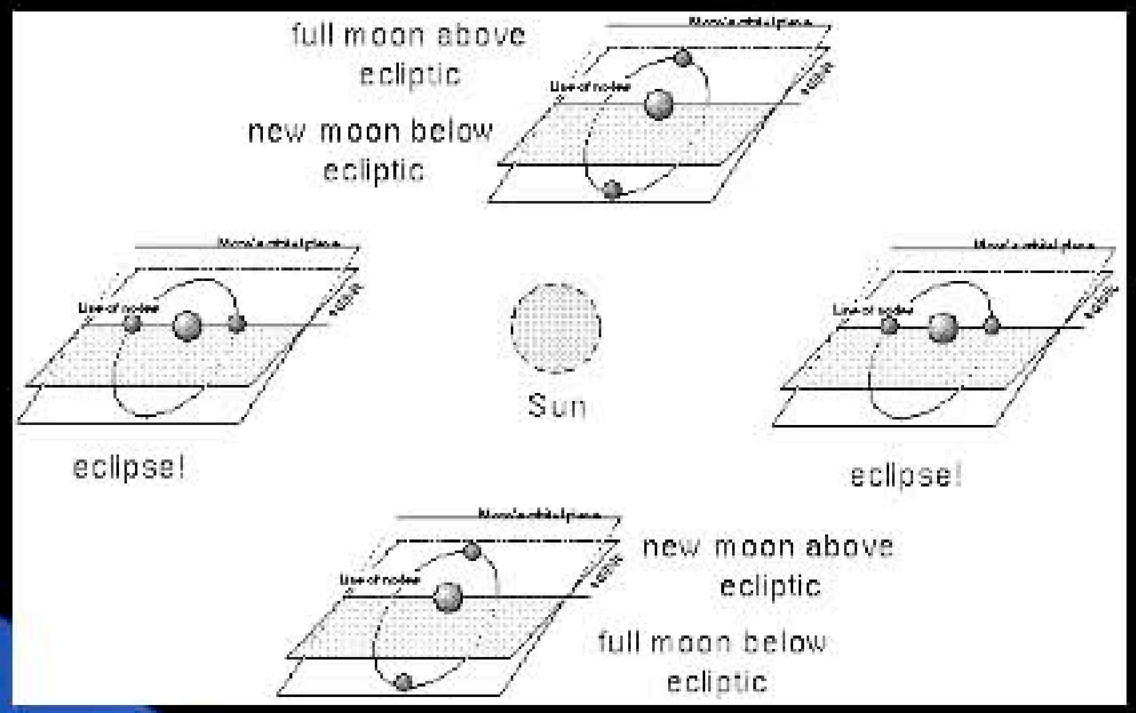
- Moon is receding from Earth at a rate of ~3.8 cm/year due to tidal braking
- Implication is that Moon was once much closer to Earth
  - Confirmed by growth rings of fossil corals
- History of orientation of orbital plane, spin axis uncertain; spin axis in current position for at least last 2 Ga



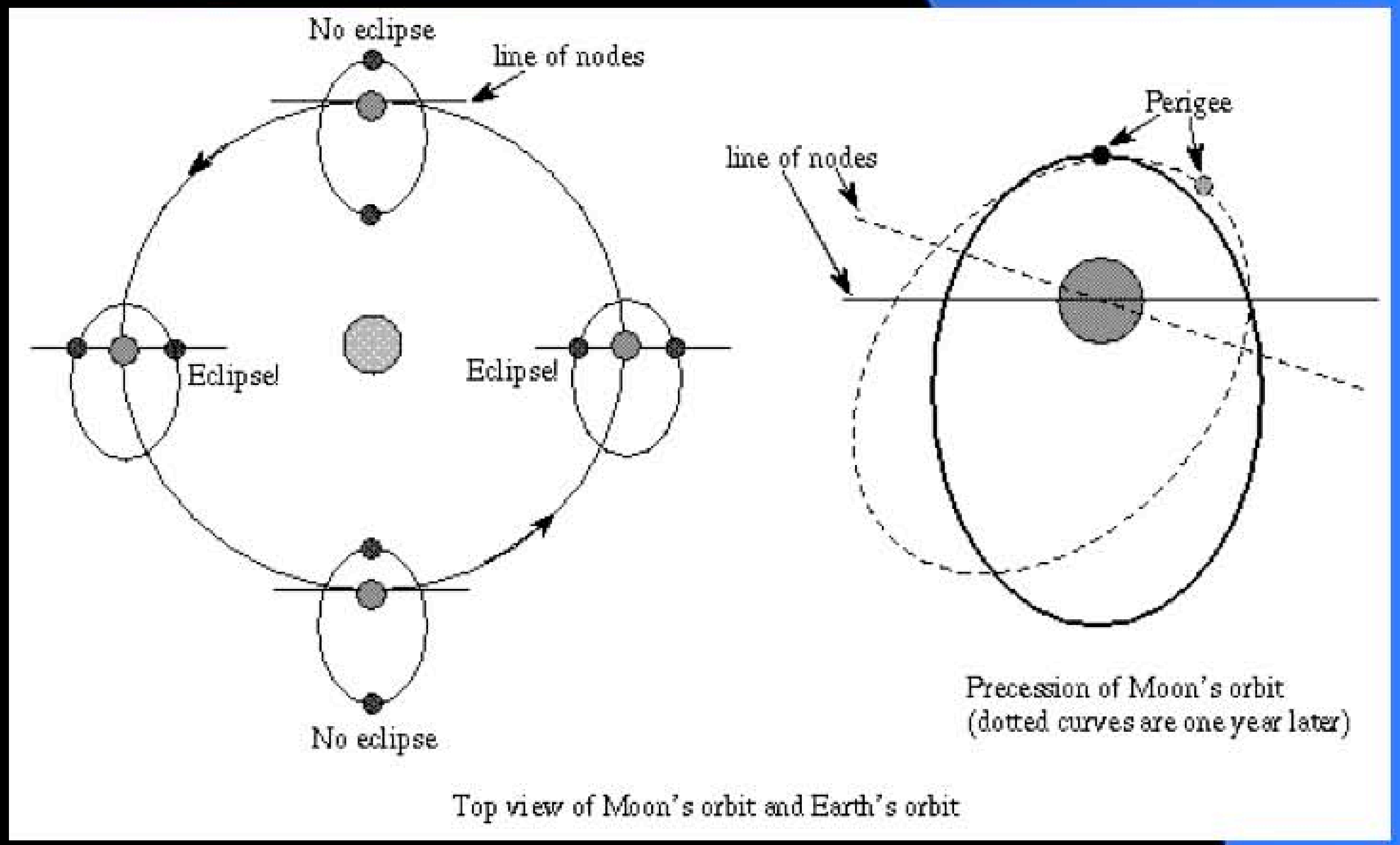


Moon's Orbit and Eclipses





- Orbital plane of Moon inclined 5.5º to ecliptic
- Earth spin axis inclined 23.5º to ecliptic
- Line of nodes shifts 19.3º /year while perigee shifts 40.7º /year
- Line of nodes completes one full precession in 18.61 years
- Eclipses can only occur when line of nodes crosses orbital plane



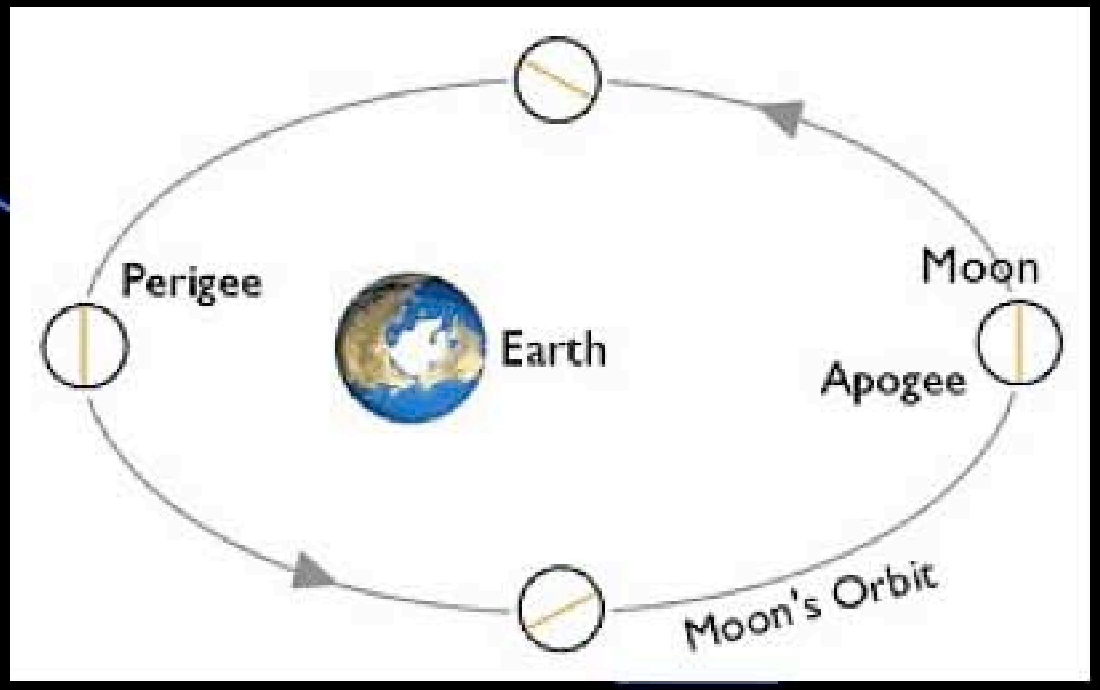
Libration

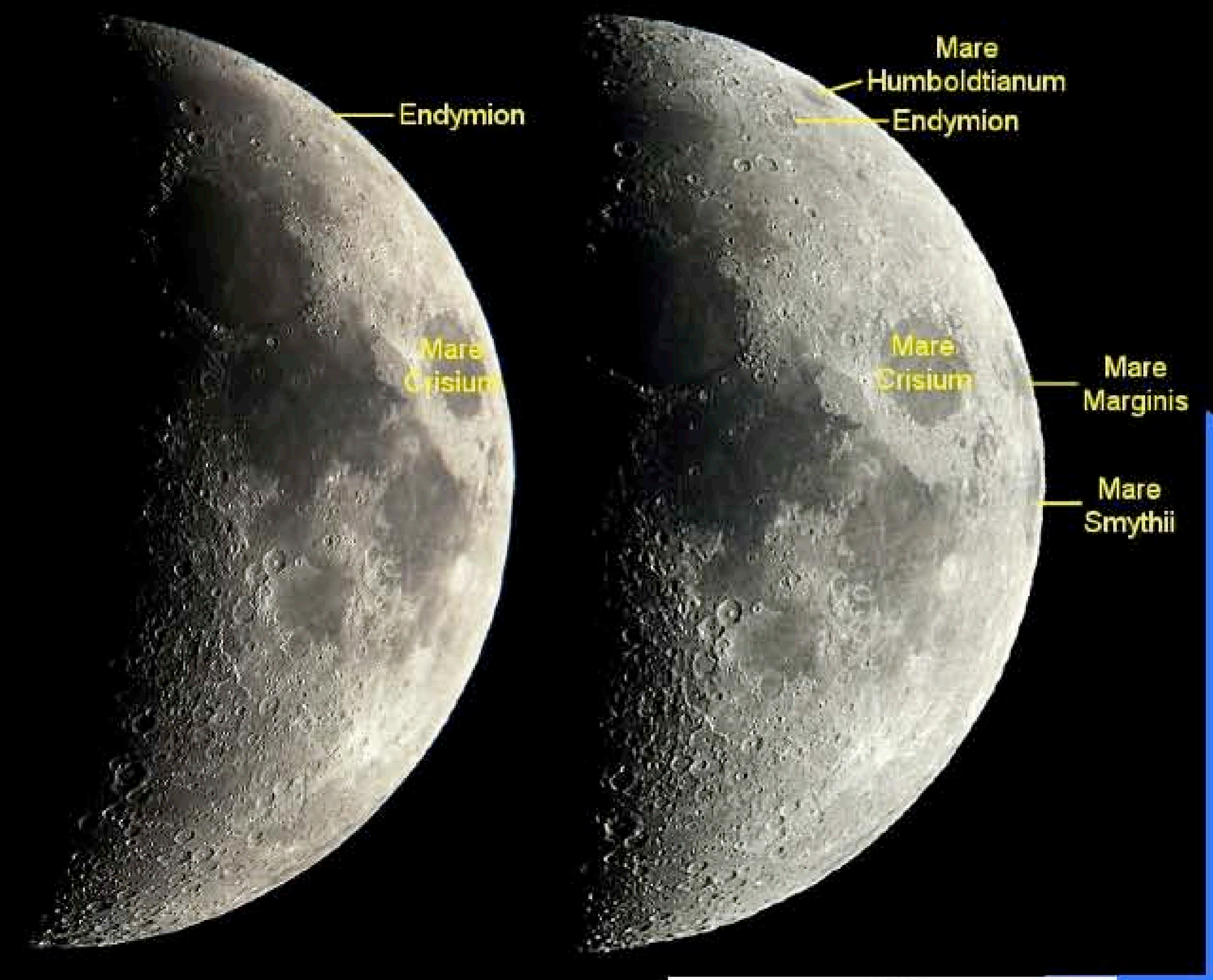
Longitudinal

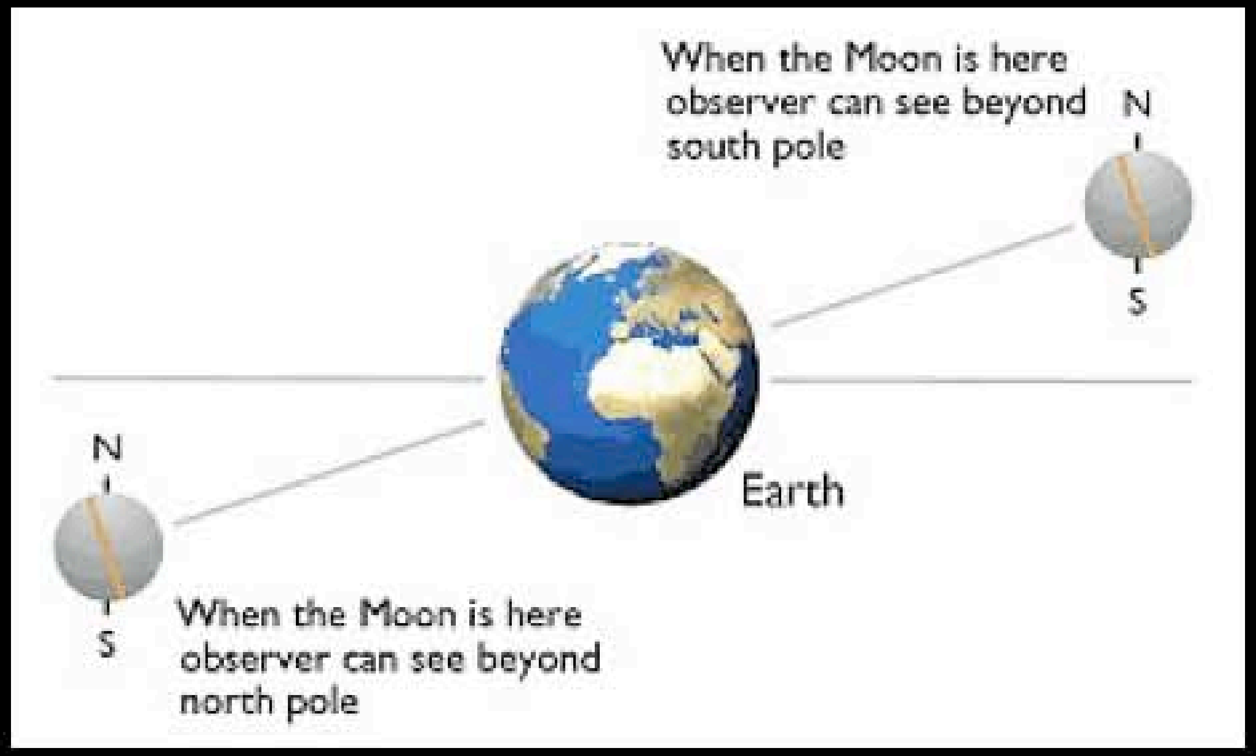
- Caused by Moon's elliptical orbit
- Can see approx. 8° beyond 90° W and 90° E limbs
- Diurnal parallax of observer ~1° due to diameter of Earth

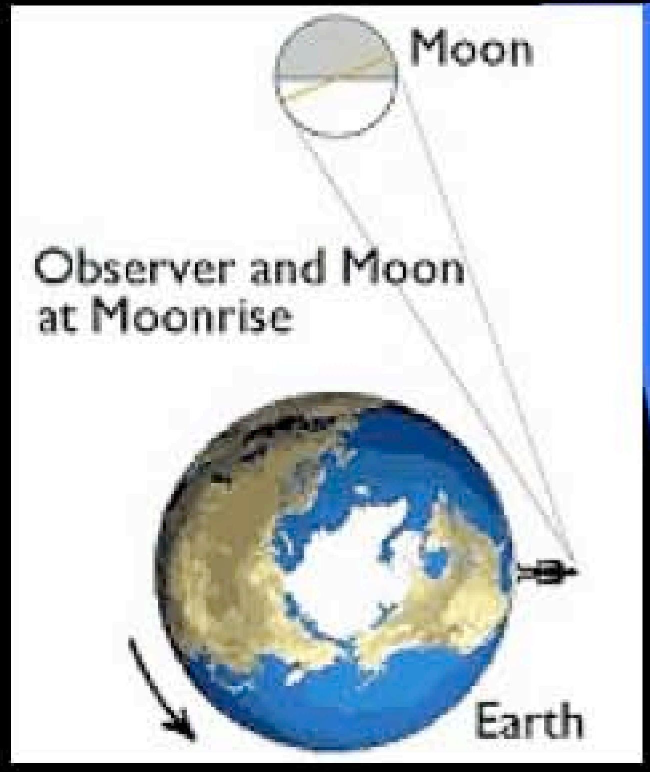
Latitudinal

- Caused by inclination of lunar orbital plane
- Can see approx. 6.5° beyond polar limbs
- Diurnal parallax of observer ~1° due to diameter of Earth



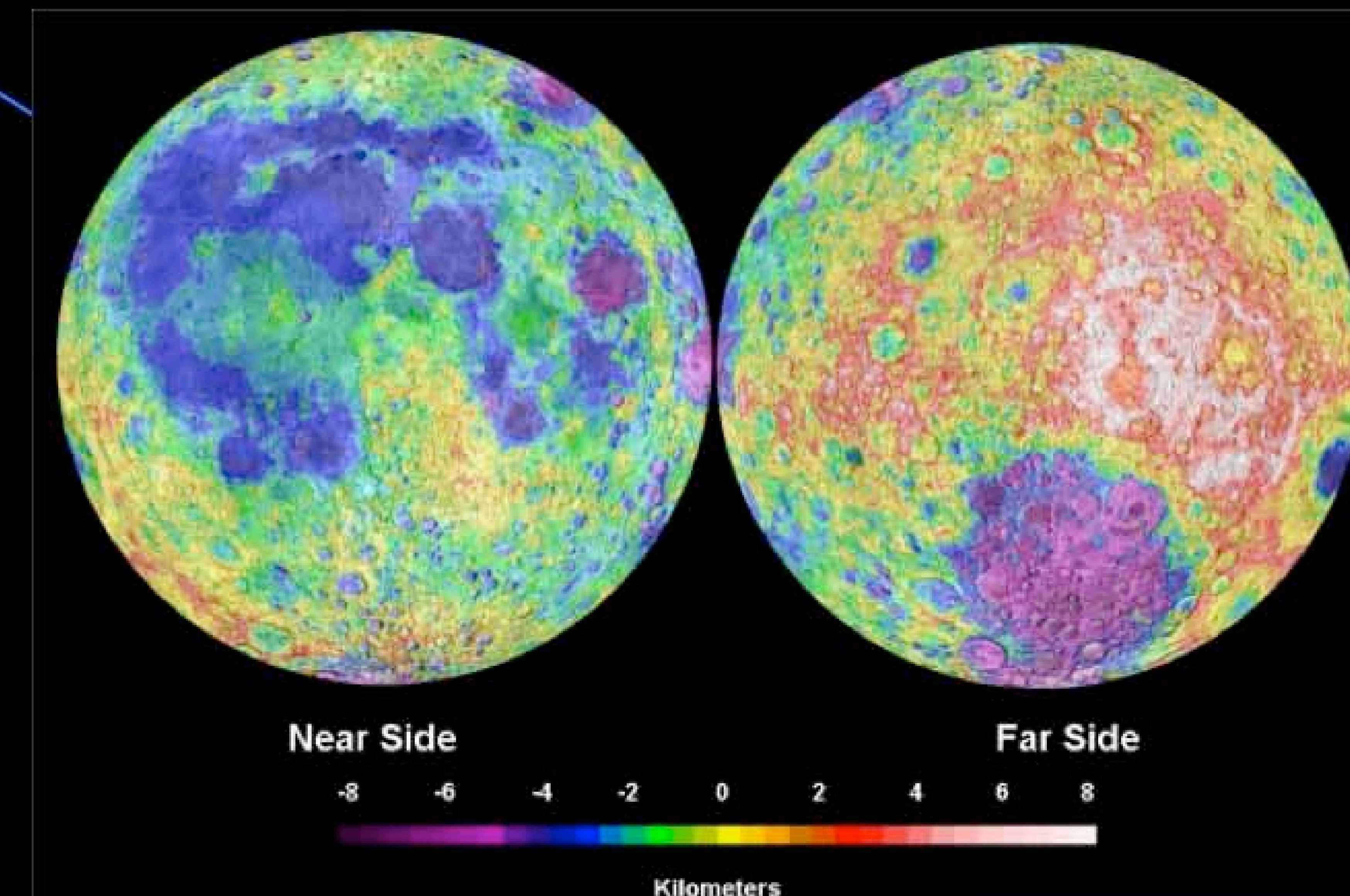


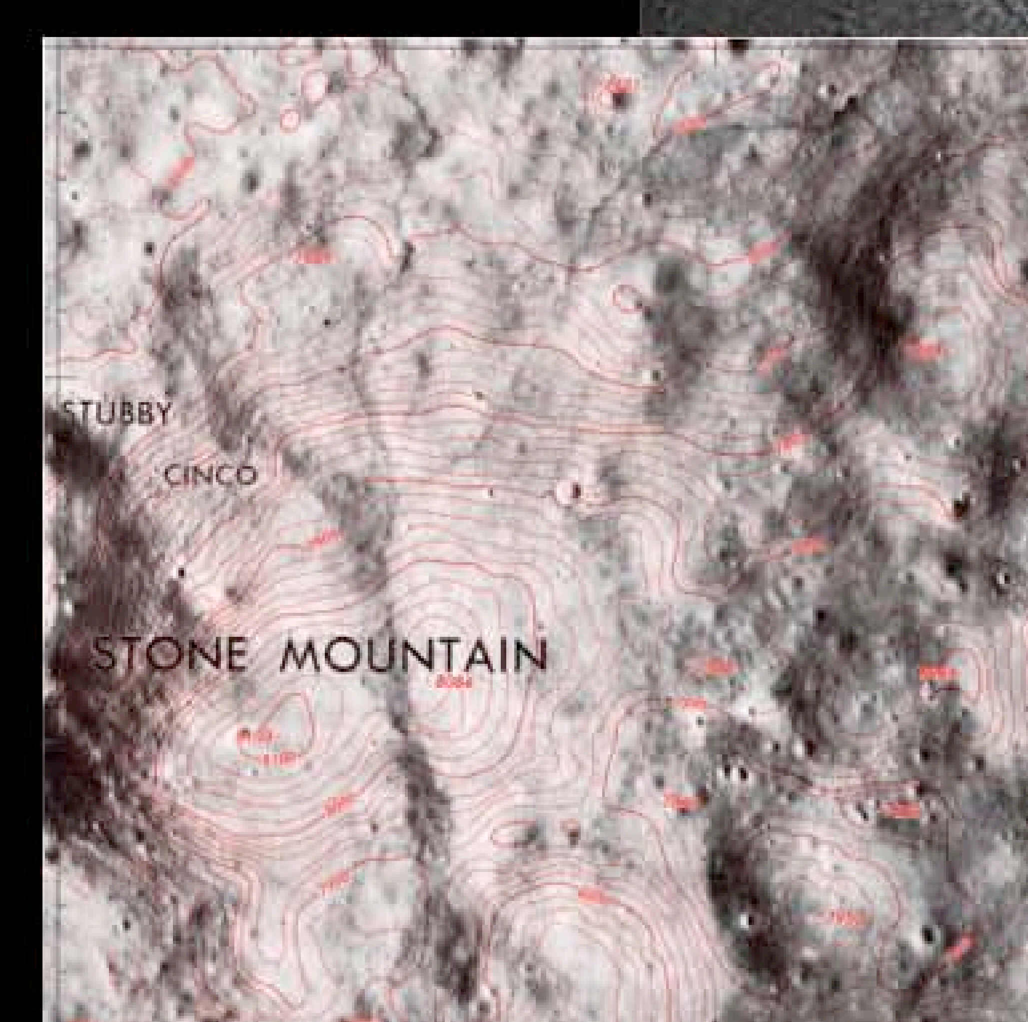




Topography

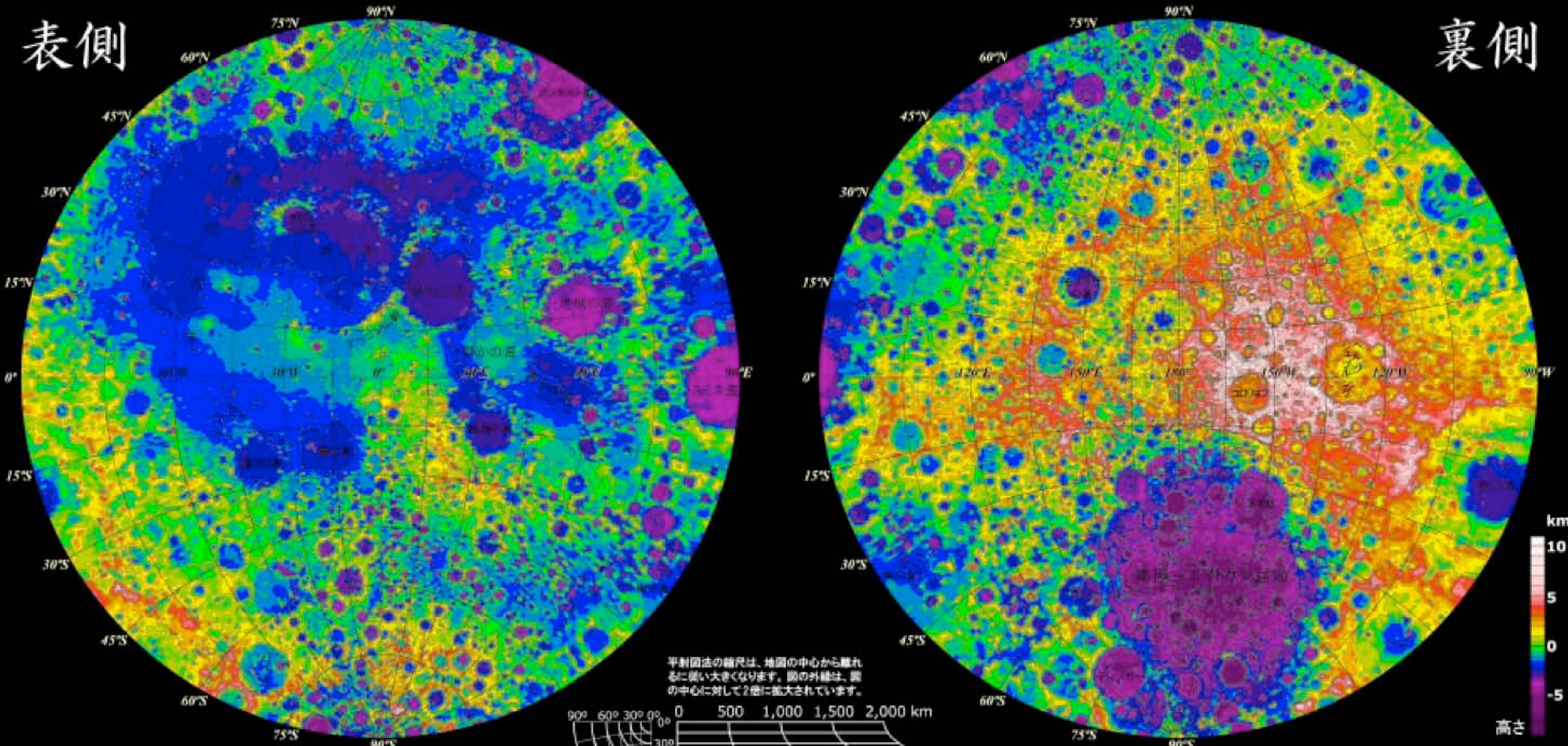
- Global figure is roughly spherical, but with major departures
  - South Pole-Aitken basin on far side is major feature
- Moon is very "bumpy"; extremes of elevation + 8 km to –9 km (same dynamic range as Earth, sea floor to mountains)
- Physiography divided into rough, complex bright highlands (terra) and relatively flat, smooth dark lowlands (maria)
- Landforms dominated by craters, ranging in size from micrometers to thousands of km across
- Smooth flat areas are rare, but occur in maria (modulated by sub-km class cratering)
- Average slopes: 4-5° in maria, 7-10° in highlands





New Kaguya Topographic Map

「かぐや」が見た月の地形



平射図法の縮尺は、地図の中心から離れるに従い大きくなります。図の外縁は、図の中心に対して2倍に拡大されています。

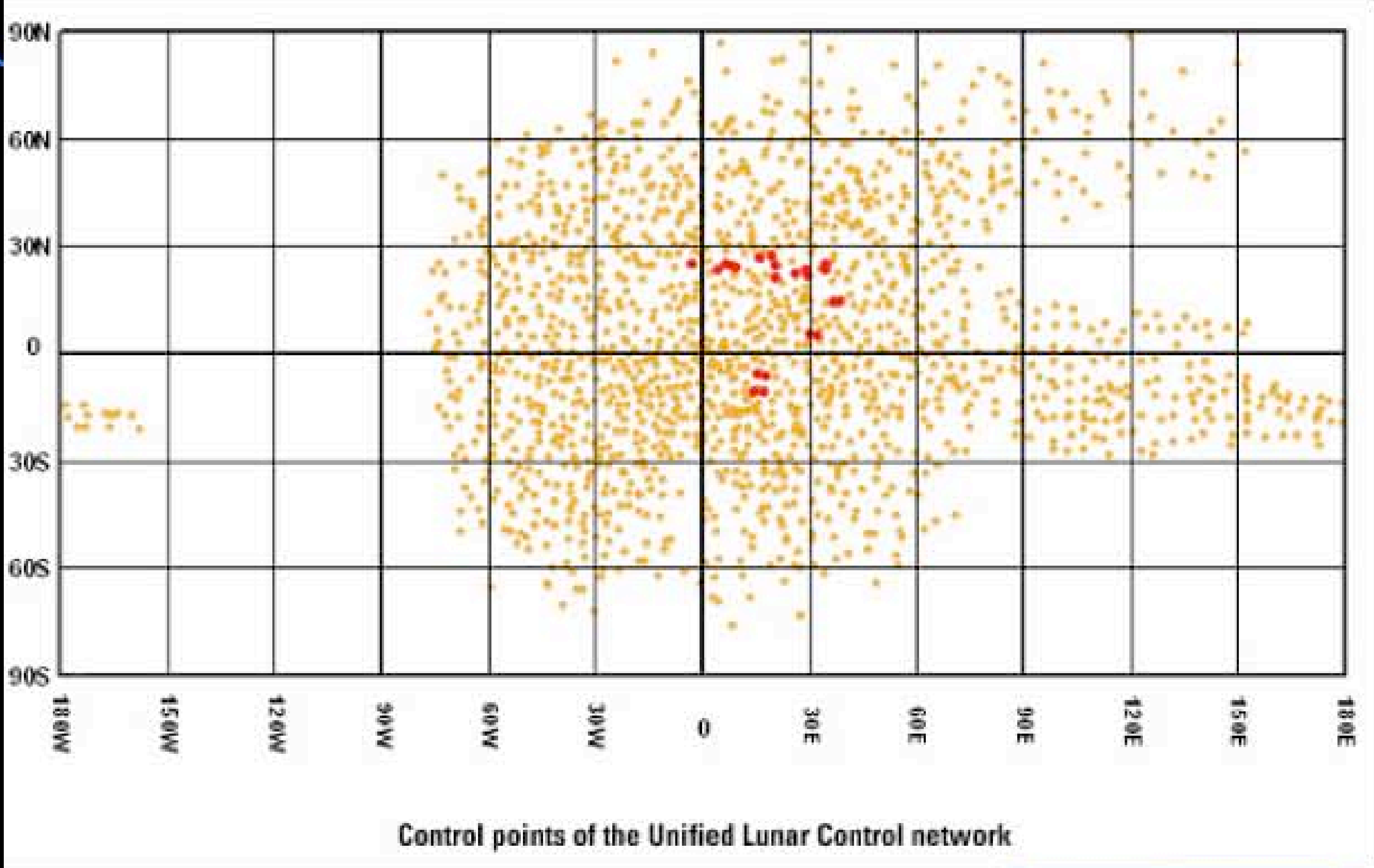
この地図は、JAXAの月周回衛星「かぐや(SELENE)」に搭載したレーザ高度計(LALT)の観測精度5mの観測データをもとに作成しました。等高線間隔は1km、高さの基準は重心を中心とする半径1,737.4kmの球です。投影法は平射図法、経度0°は地球から見える月中心を通る子午線です。観測期間は平成20年1月7日〜1月20日です。
月の表側は玄武岩で覆われた平坦で薄暗い海が比較的多いのに対し、裏側は大小さまざまなクレータで覆い尽くされており海はほとんどありません。

また裏側の南半球には、南極ーエイトケン盆地と呼ばれる直径約2,500km もある巨大な衝突盆地があり月面で最も低い地域です。海は円形もしくは楕円形をしているものが多く、衝突盆地の窪みに溶岩が噴出して溜まったものと考えられています。しかし南極ーエイトケン盆地は海にはなっていません。これは地殻の厚さや岩石の組成が表側と違うためではないかと考えられています。

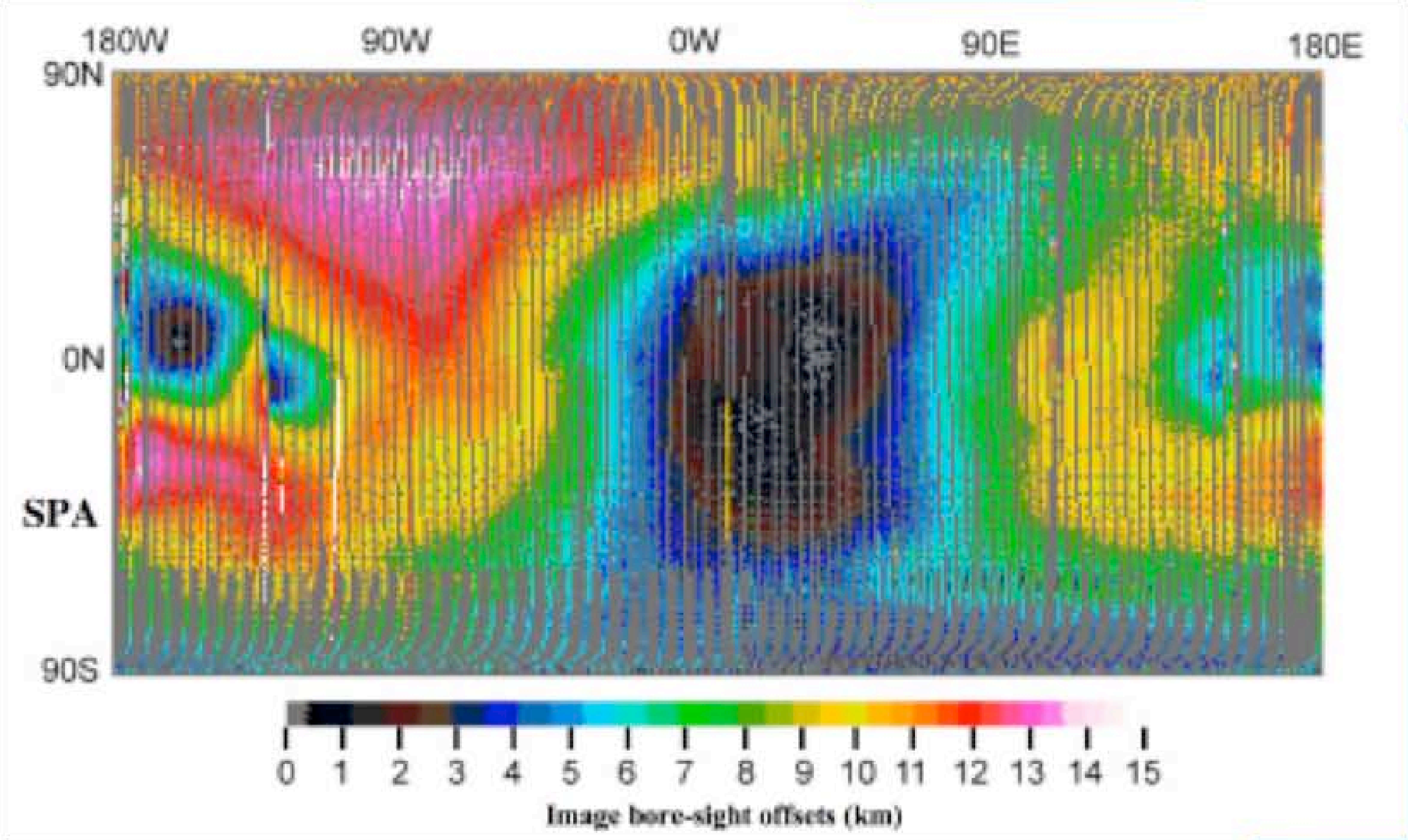
LALTのデータ処理・解析　自然科学研究機構 国立天文台
地 形 図 の 作 成　国土交通省 国土地理院

Geodetic Control

- Defining the coordinates of known features in inertial space
- All coordinates referenced to lunar center-of-mass (CM)
- Best telescopic geodetic network (1980) had positional accuracy of ~ 4 km
- Control network based on Apollo photography (1989) and sphere of 1738 km radius had positional accuracy of meters in equatorial near side; several km for parts of far side
- New Unified Control Net 2005 uses Apollo, VLBI, Clementine, referenced to USGS radii model developed from Clementine global laser altimetry. Still multi-km offsets, especially on far side

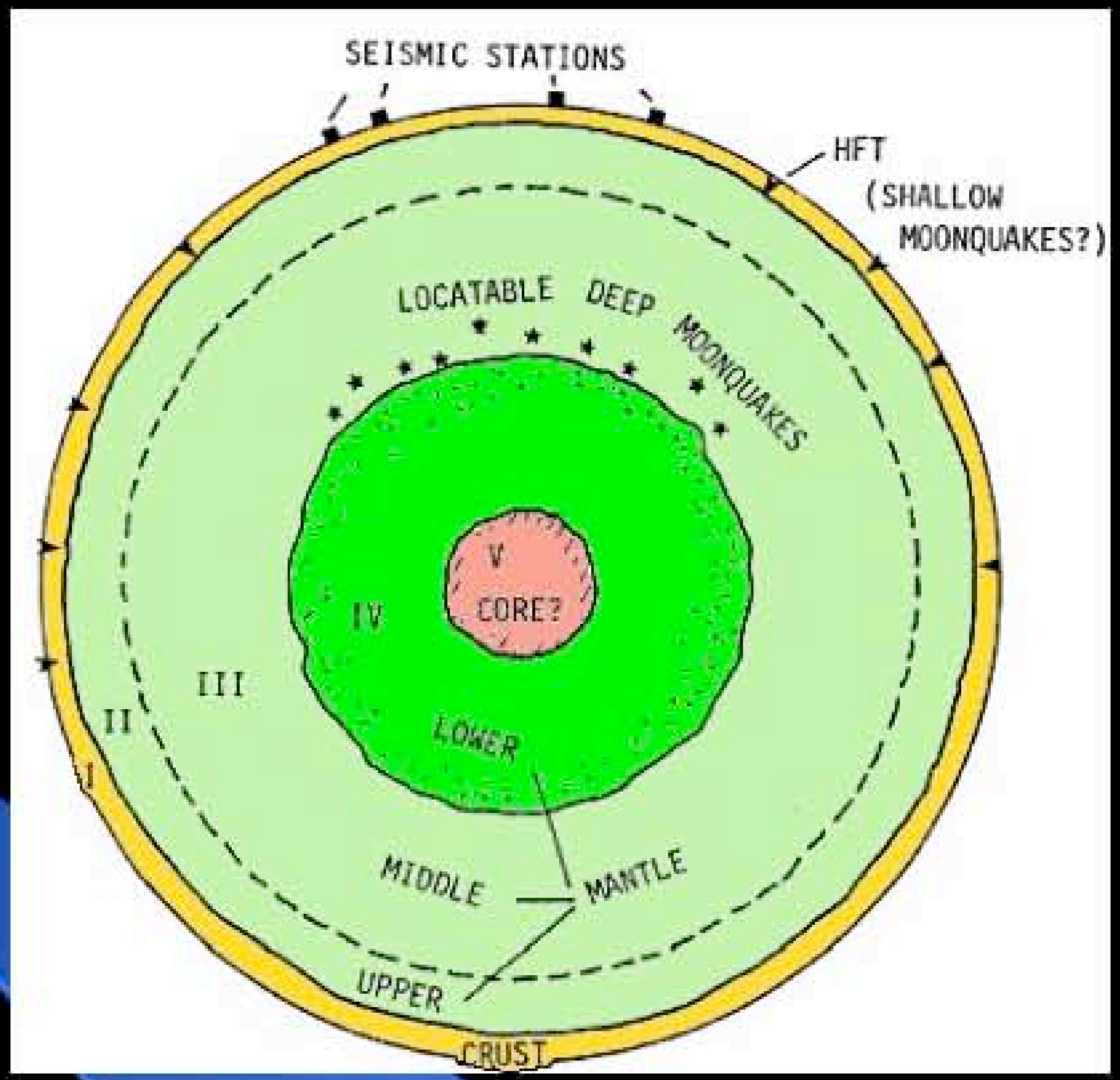


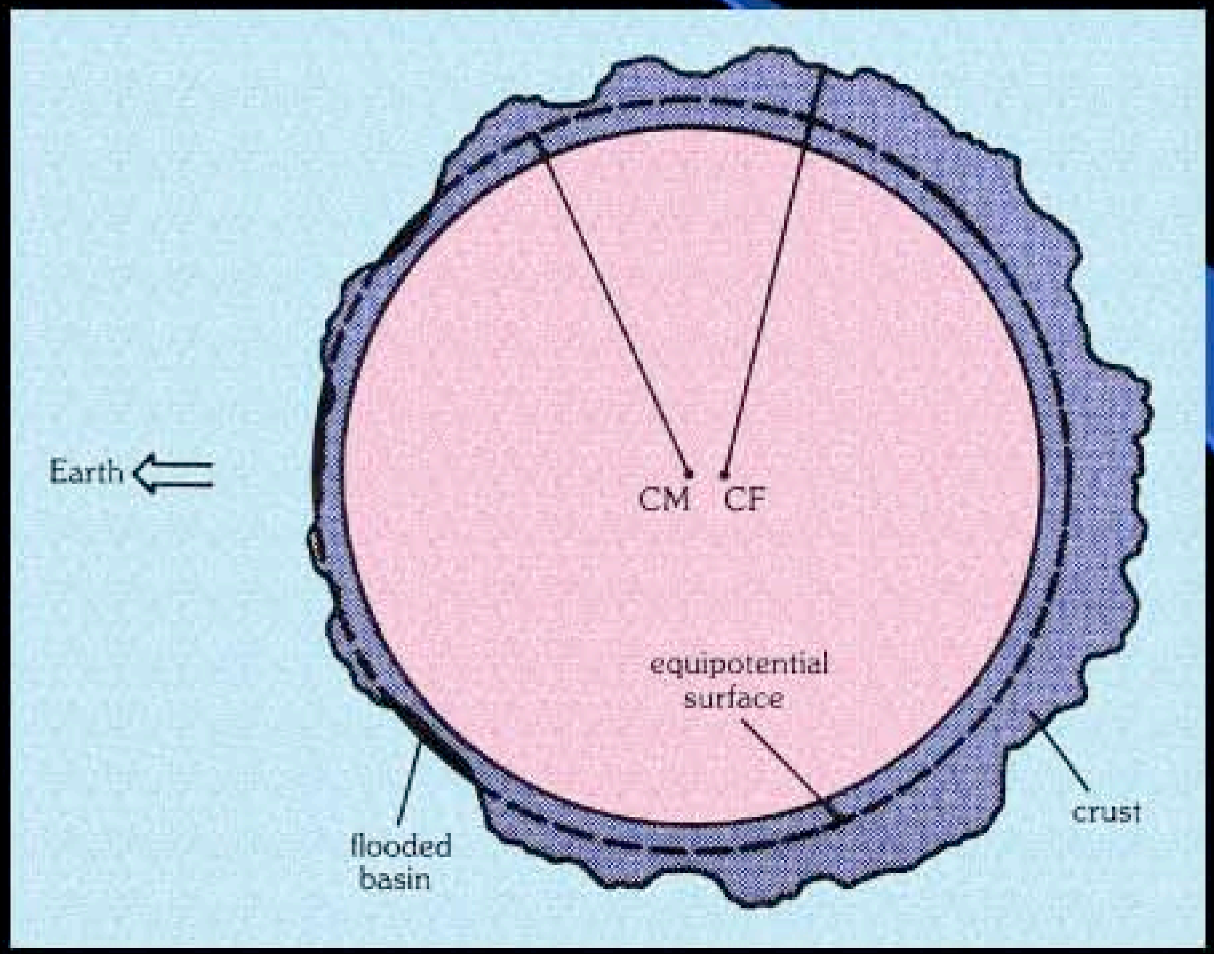
Control points of the Unified Lunar Control network



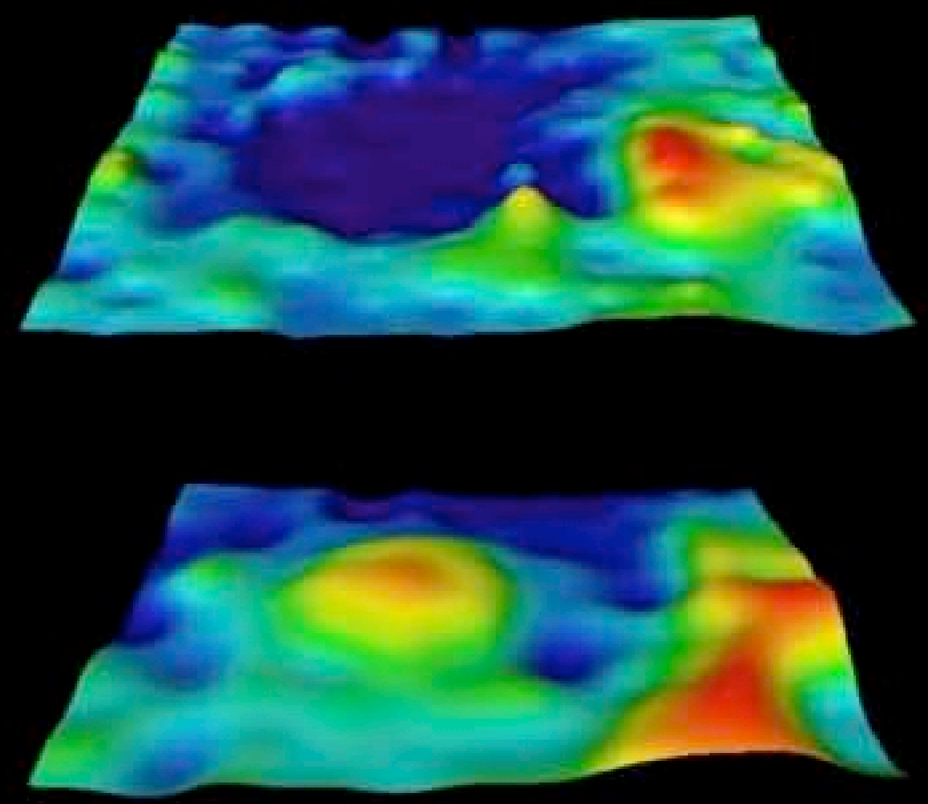
Moment of Inertia and CM-CF

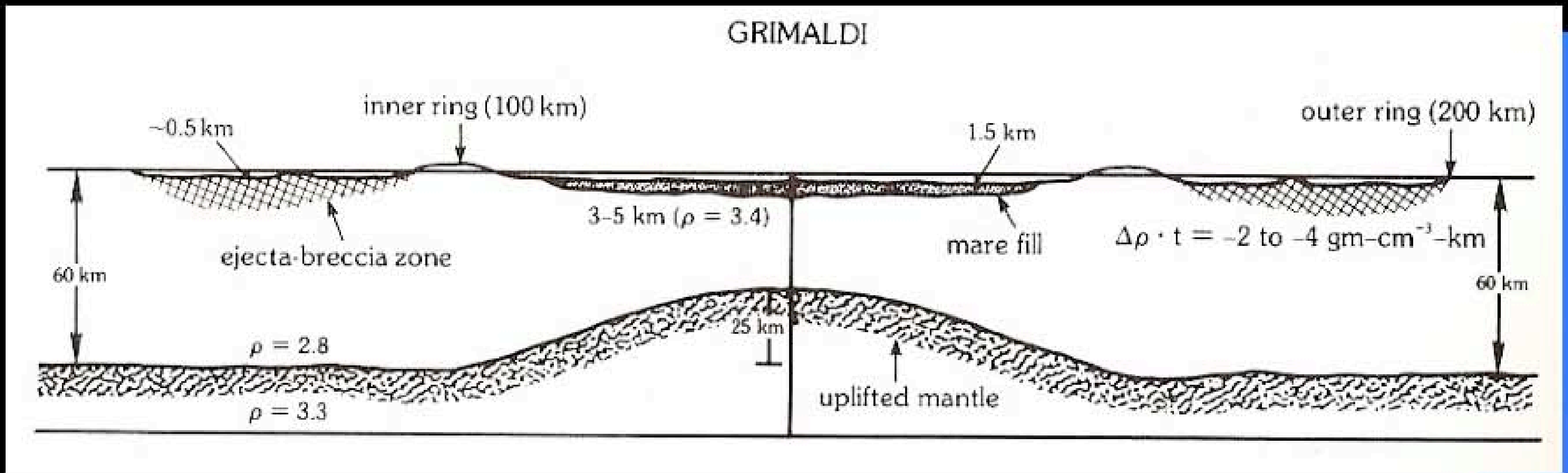
- Lunar Moment of Inertia 0.395 ± 0.0023 (core < 400 km radius)
- Center of Mass is offset ~2 km towards Earth from Center of Figure
  - Result of thicker far side crust (?)
  - Responsible for more maria on near side?
- Mass distribution asymmetric in outer few tens km (mascons)
  - Mass concentrations are superisostatic crustal loads
  - Responsible for decay of lunar orbits
  - Associated with impact basins
  - Fill by dense lava or uplifted mantle?





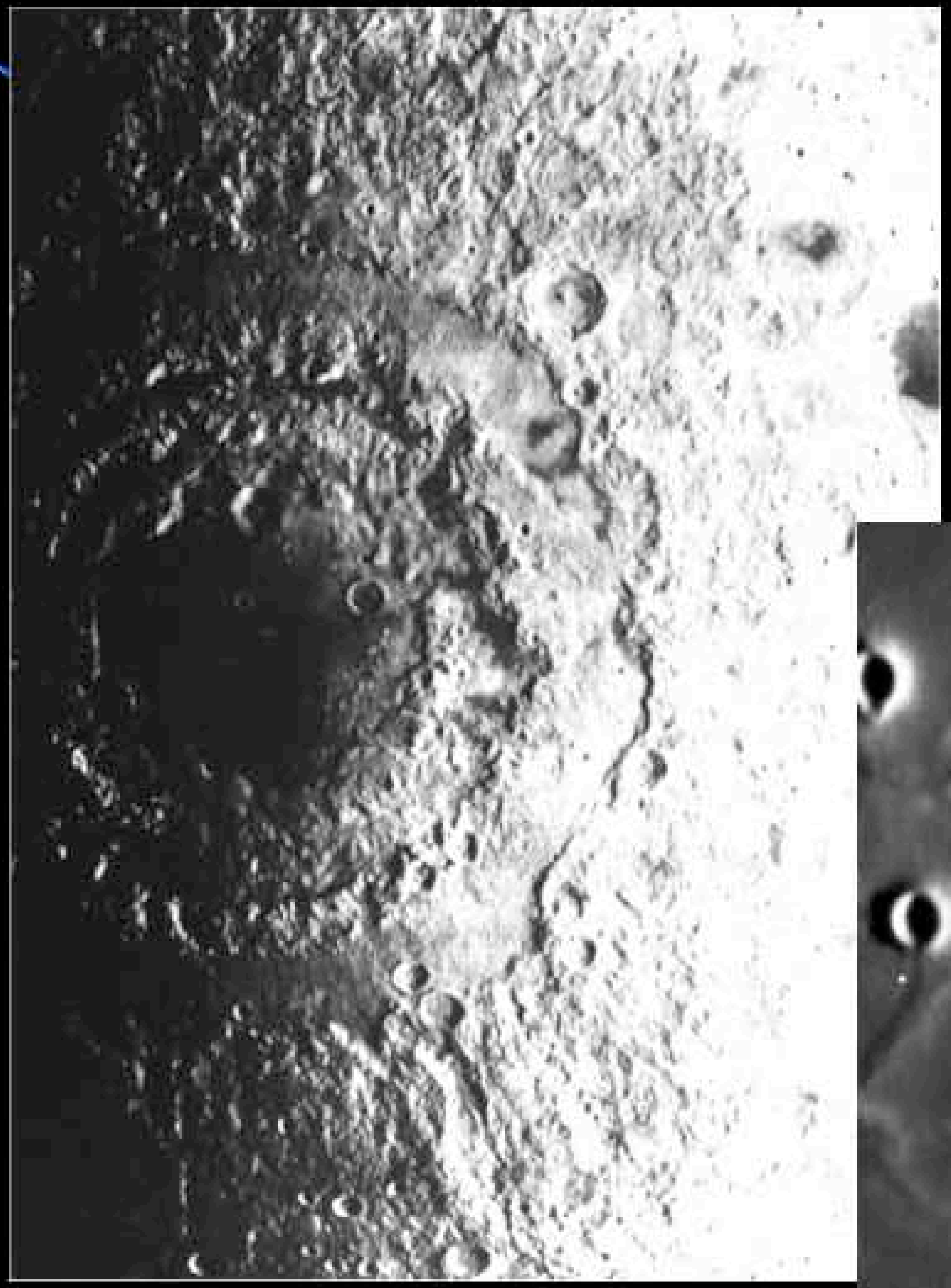
MARE SMYTHII

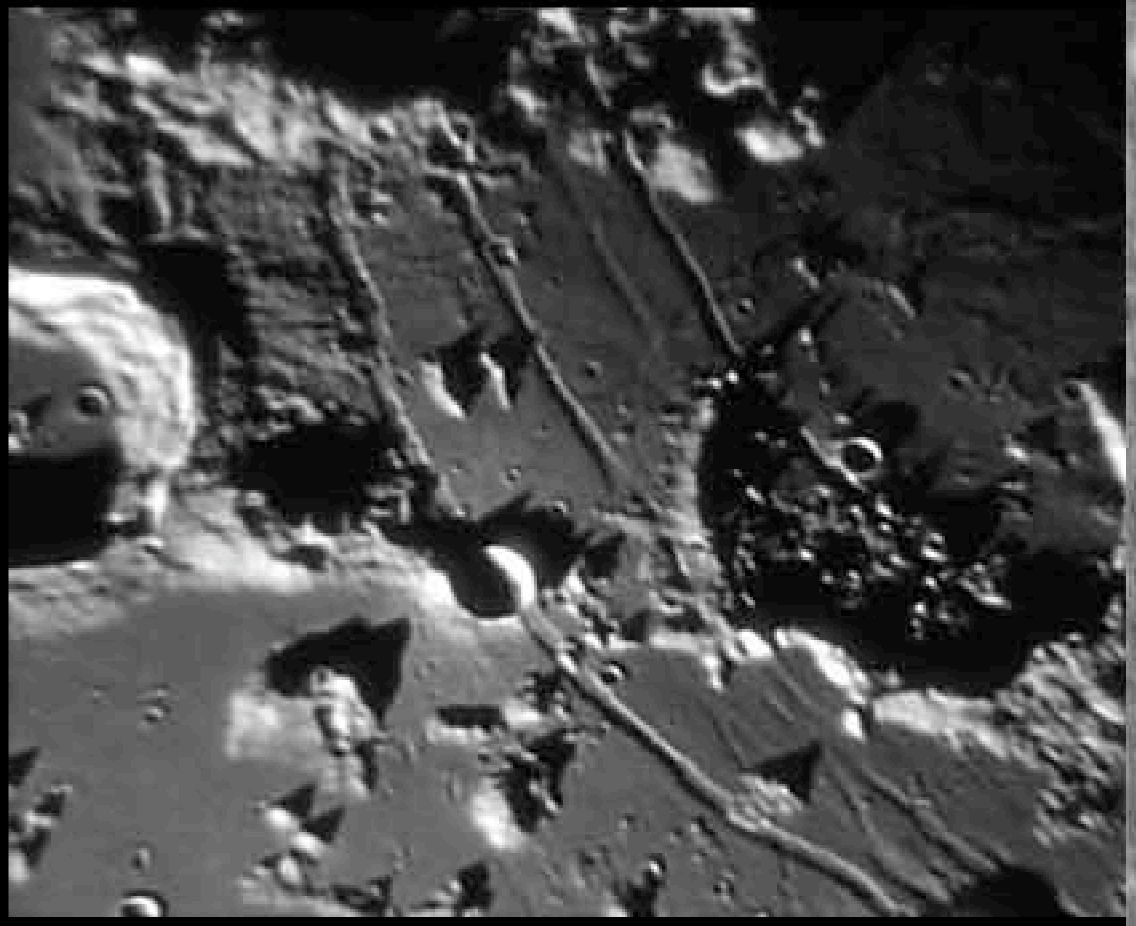
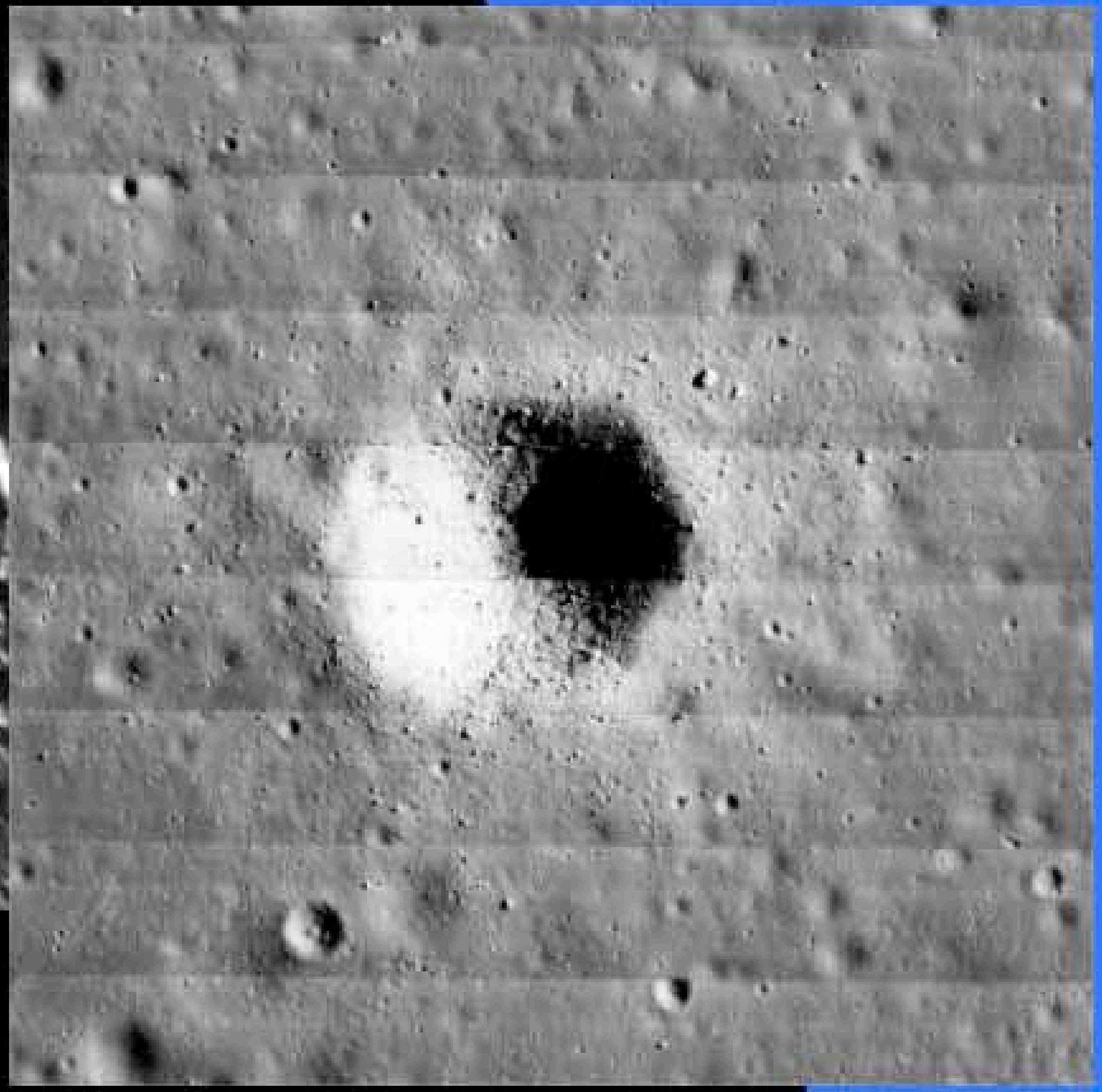




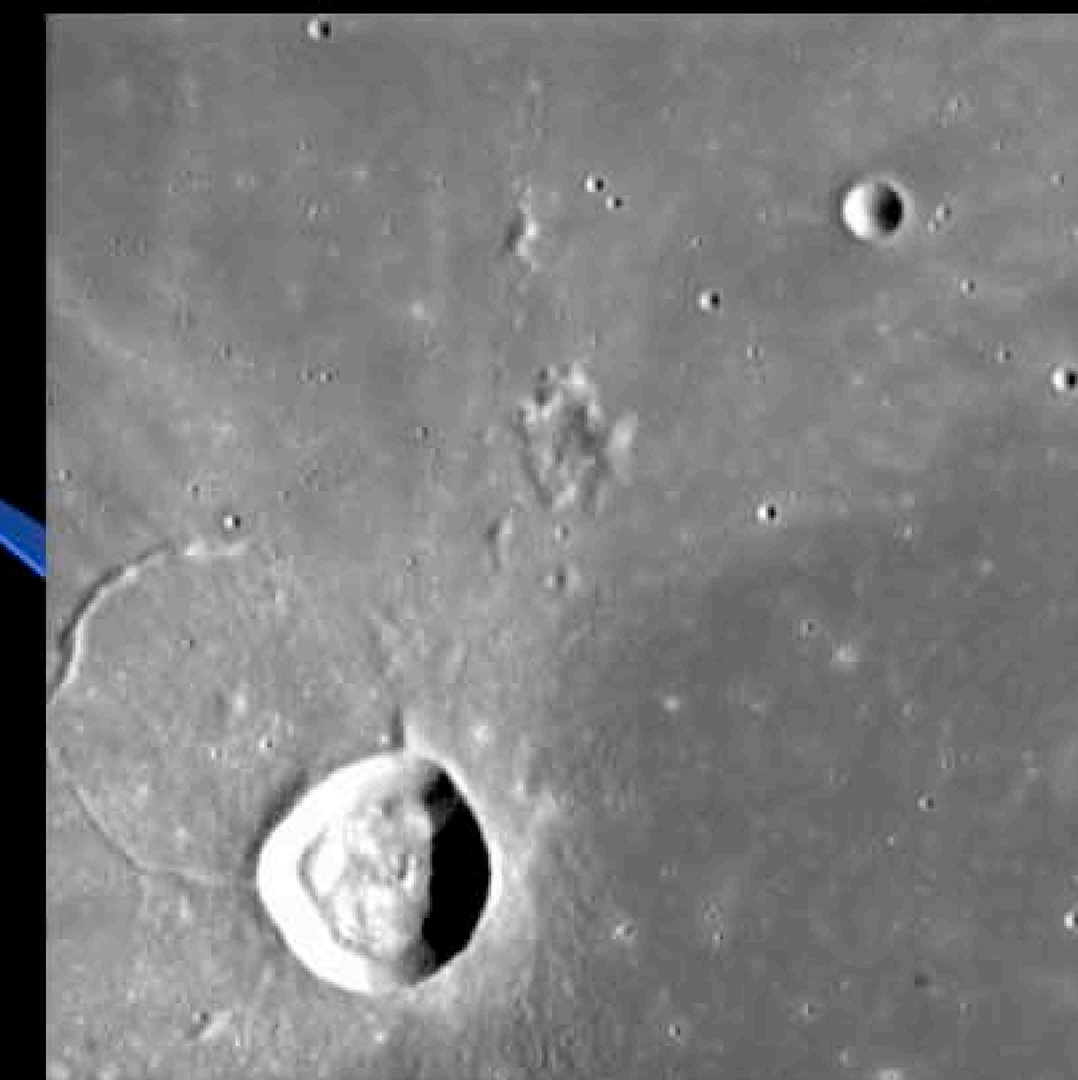
Surface Morphology and Physiography

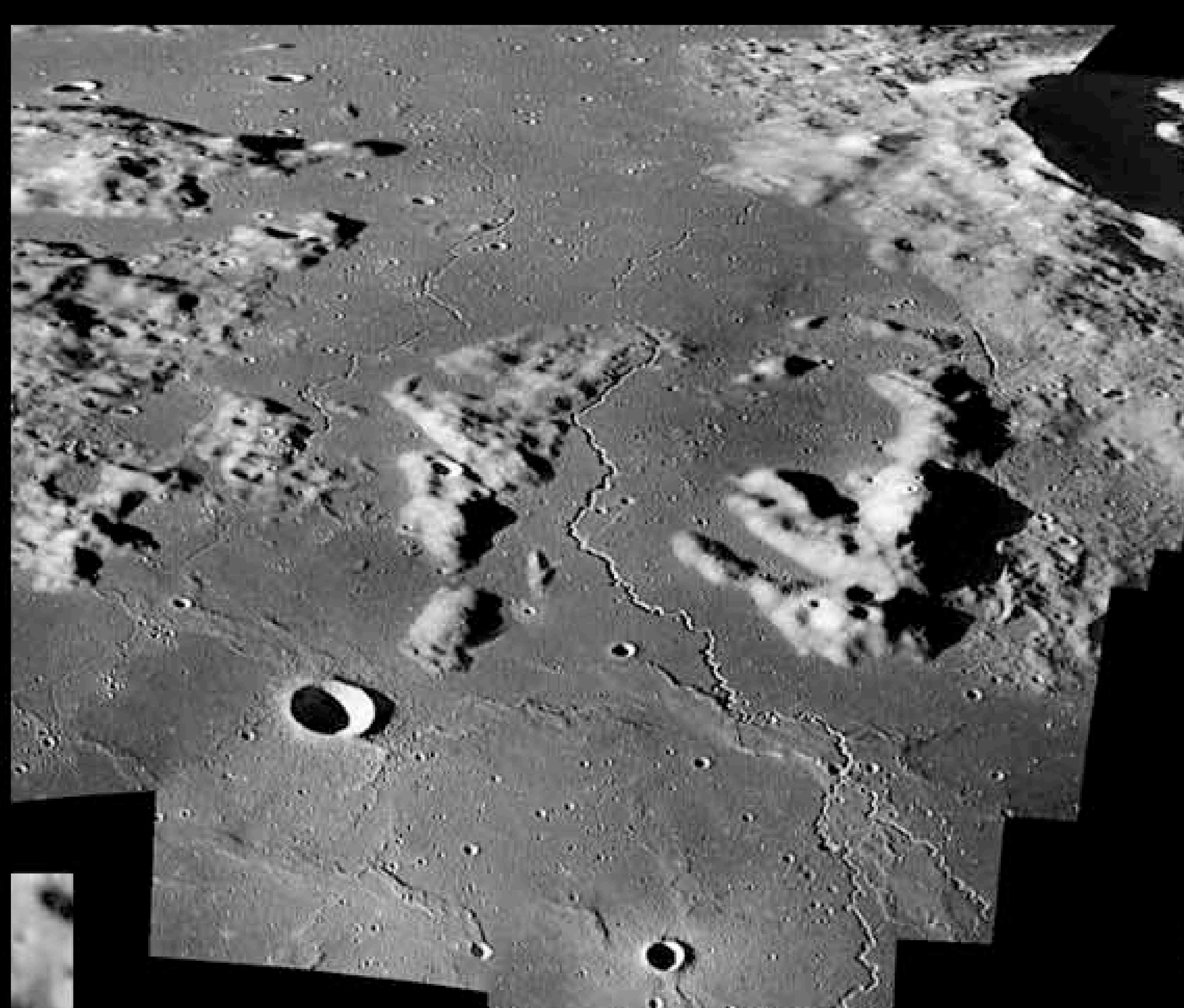
- Craters dominate all other landforms
  - Range in size from micro- to mega-meters
  - Shape and form change with increasing size (bowl shaped to central peaks to multiple rings)
- Maria are flat-lying to rolling plains, with crenulated ridges
  - Low relief, all mostly caused by post-mare craters
- Few minor landforms
  - Domes and cones
  - Faults and graben
  - Other miscellaneous features

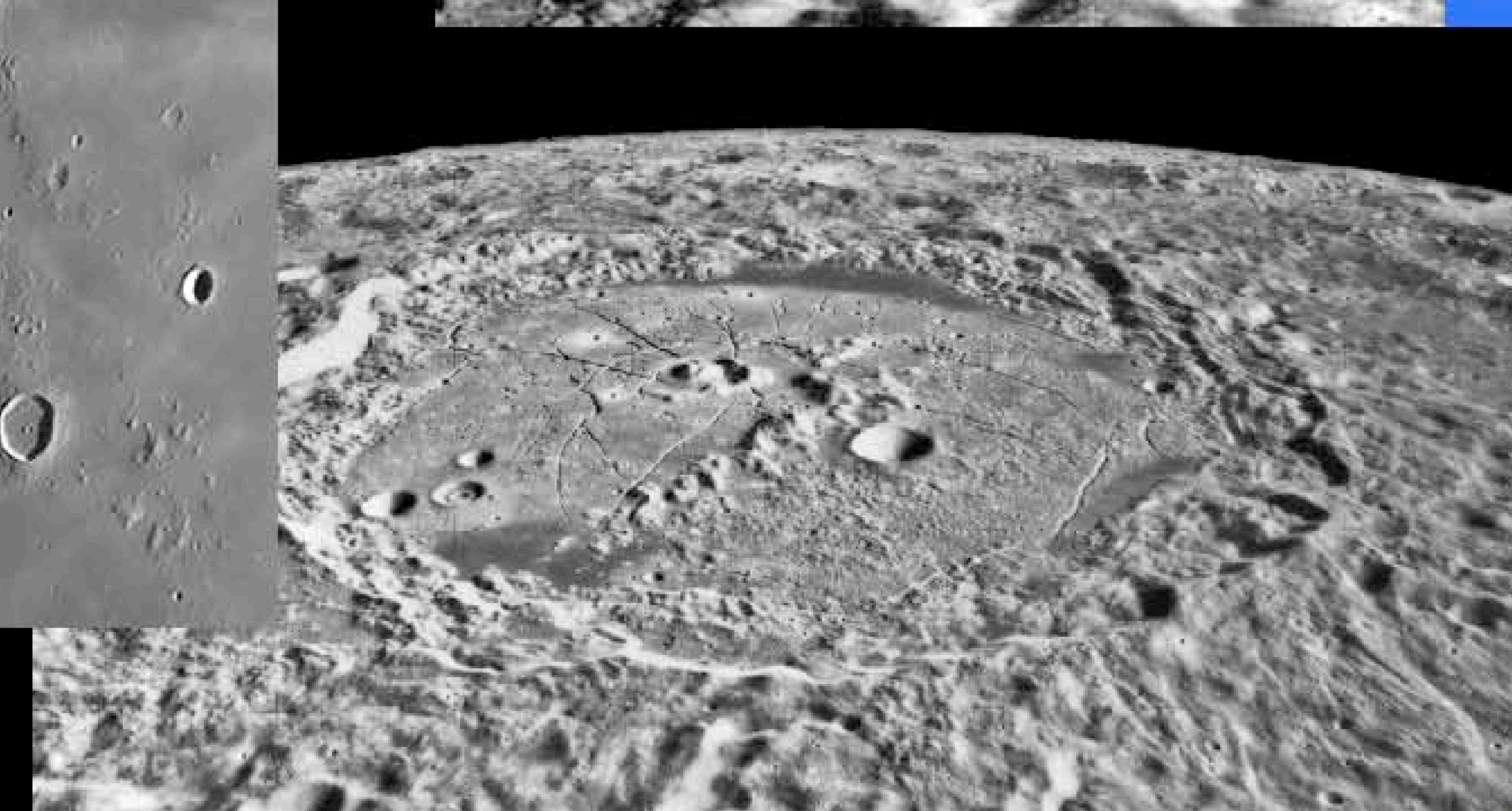


Some Lunar Landscapes







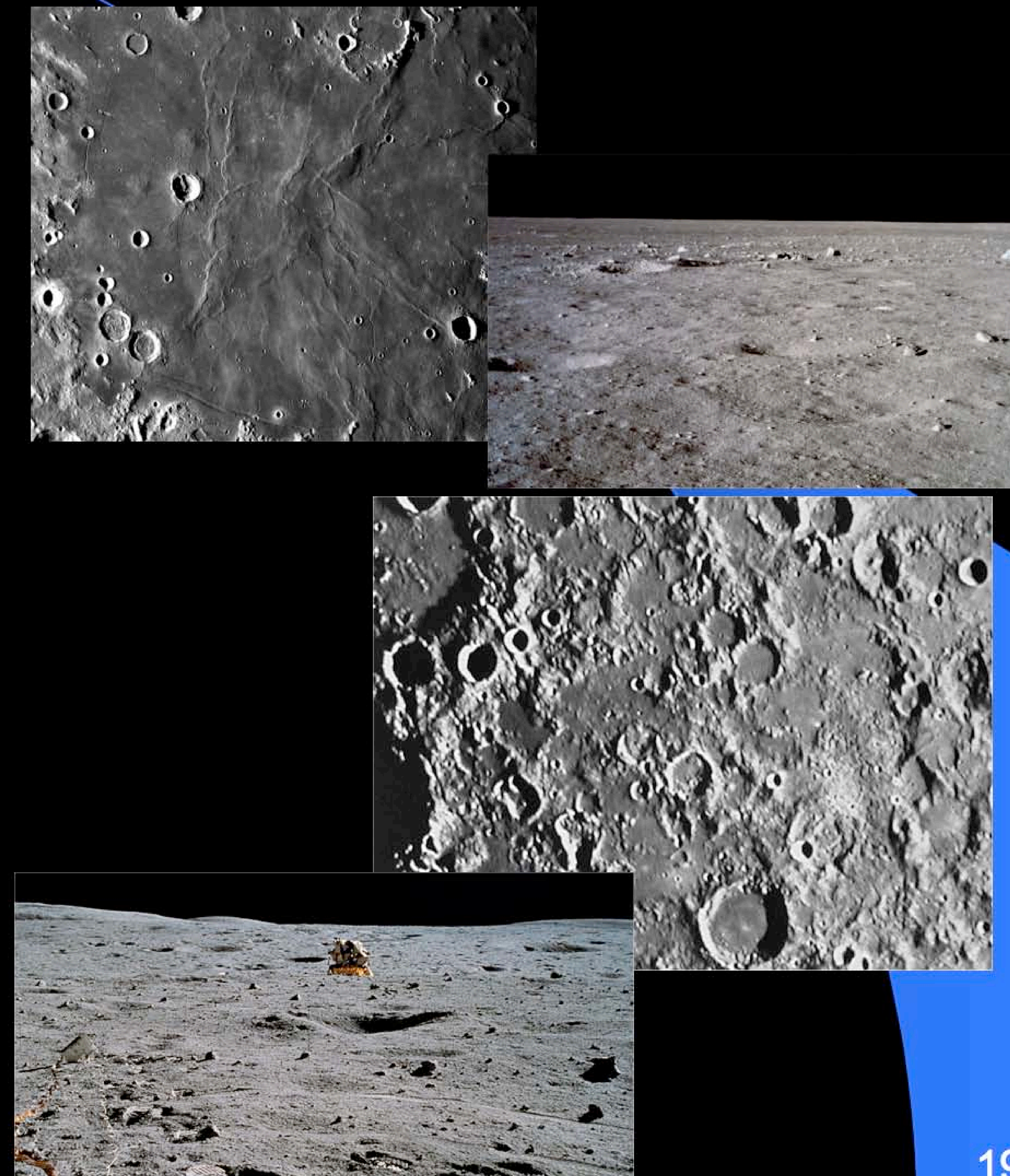
Lunar Terrains

Maria

- Flat to gently rolling plains
- Numerous craters D < 20 km; larger craters rare
- Blockier (on average) than highlands (bedrock is closer to surface)
- Mean (r.m.s.) slopes 4°- 5°

Highlands

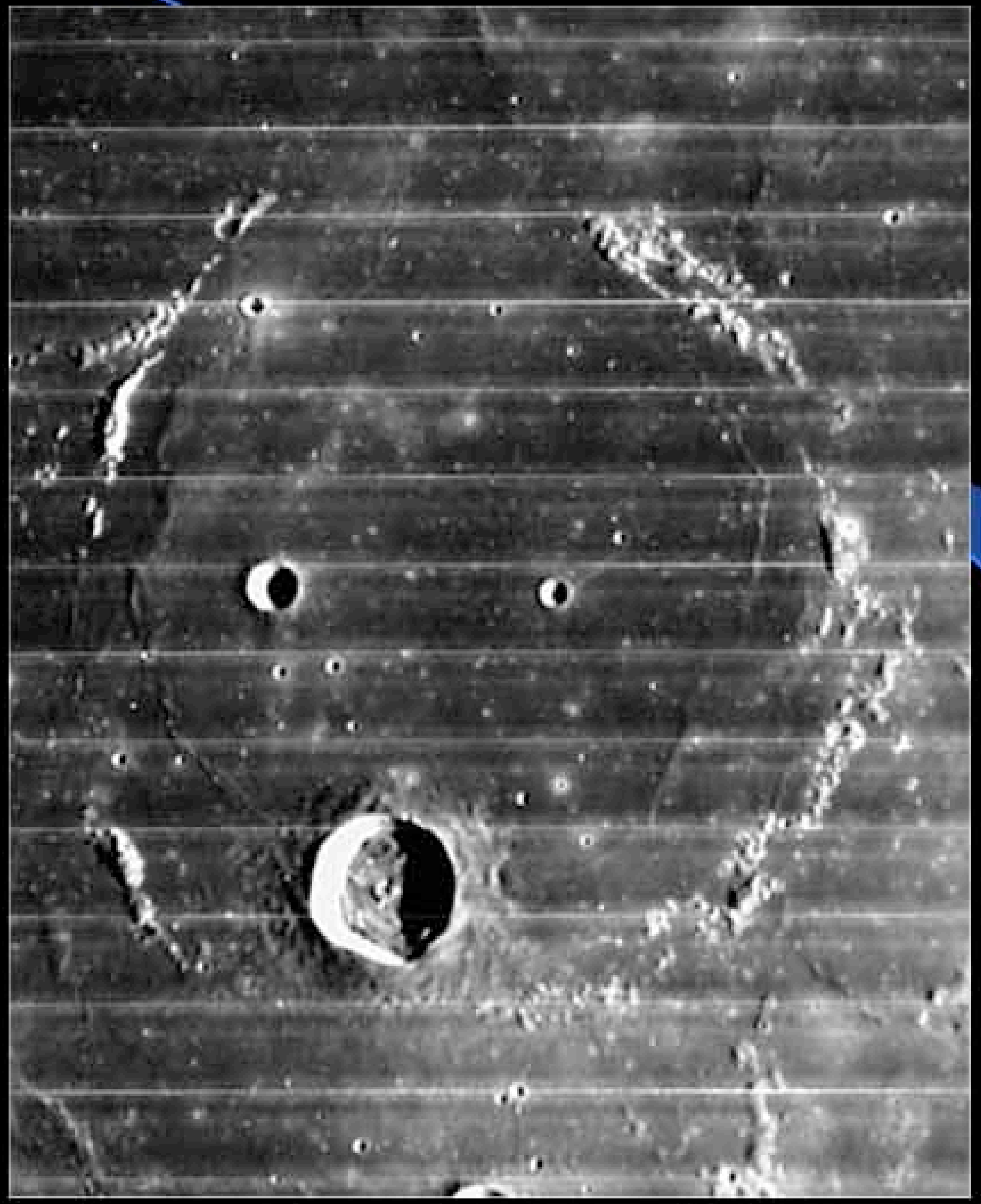
- Rugged, cratered terrain
- Smoother intercrater areas
- Numerous craters D > 20 km
- Large blocks present, but rare; “sandblasted” Moon
- Mean (r.m.s.) slopes 7°- 10°

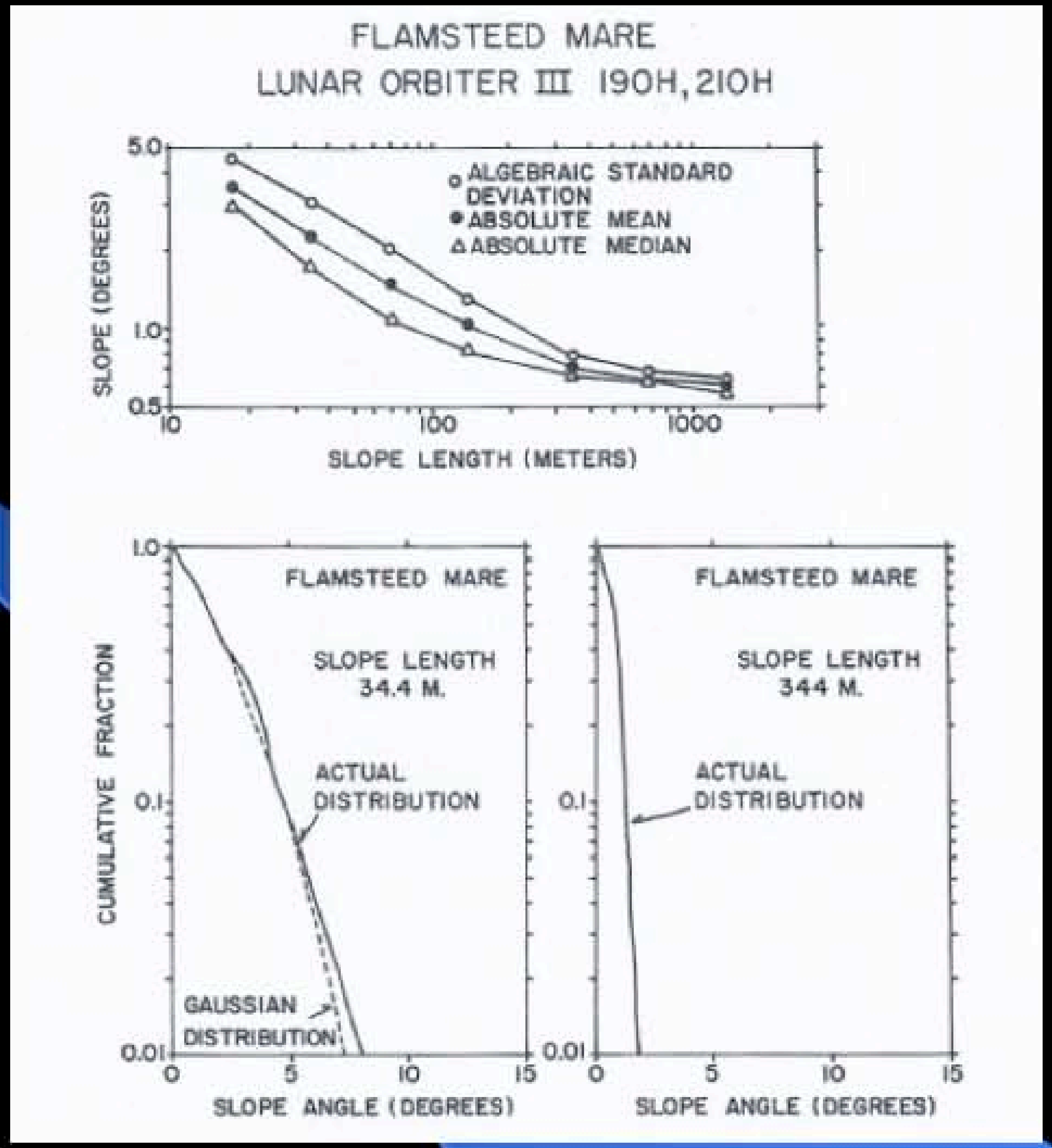


Terrain Slopes

Mare – Flamsteed ring mare

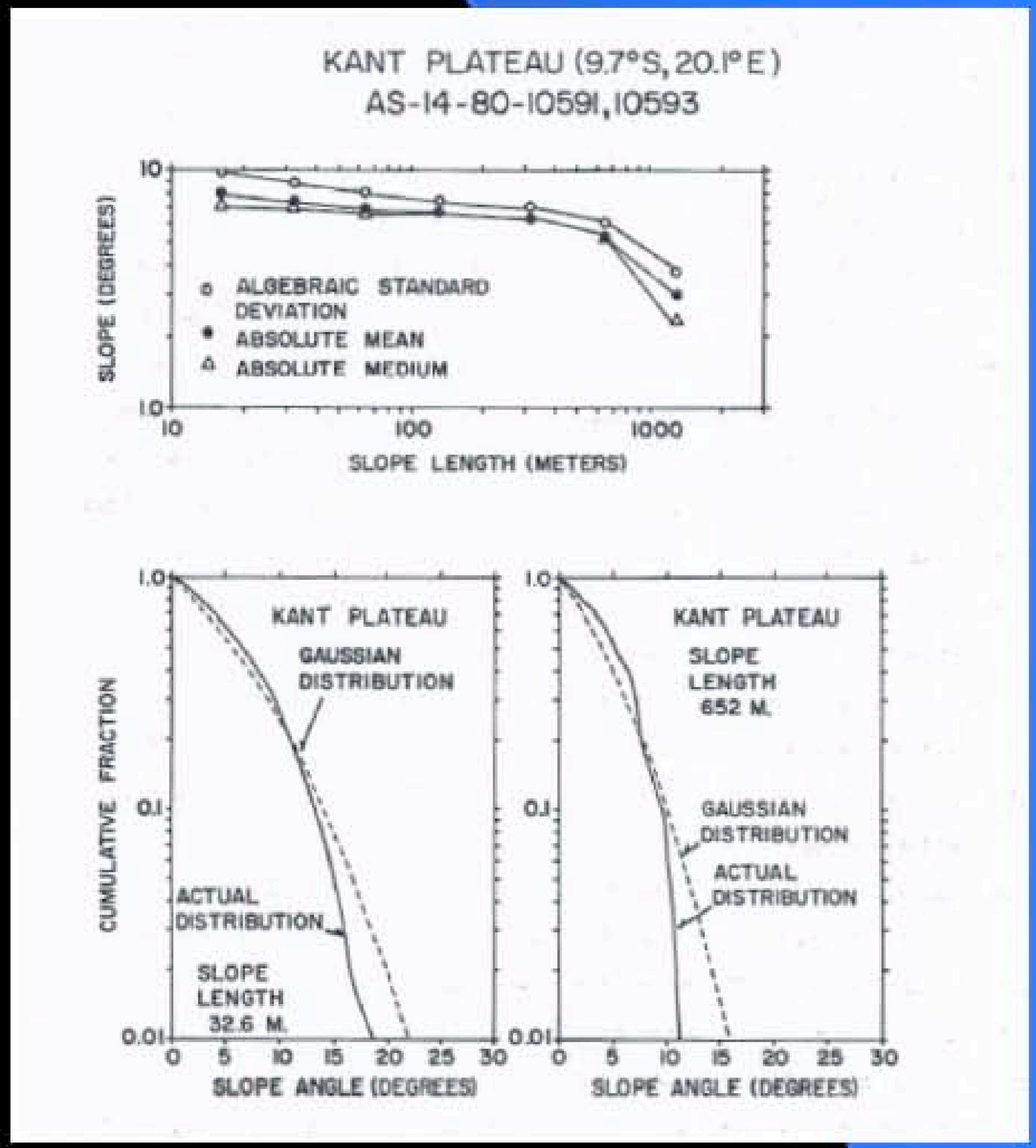
- Young mare; blocky crater rims
- Smooth flat surfaces
- Mean slopes < 5°; local slopes (in fresh crater walls) up to 25°





Highlands – Kant Plateau

- Ancient highlands; few blocks, but steep slopes
- Rolling to undulating plains
- Mean slopes ~ 10°; local slopes (inside craters) up to 30°



Surface Lighting

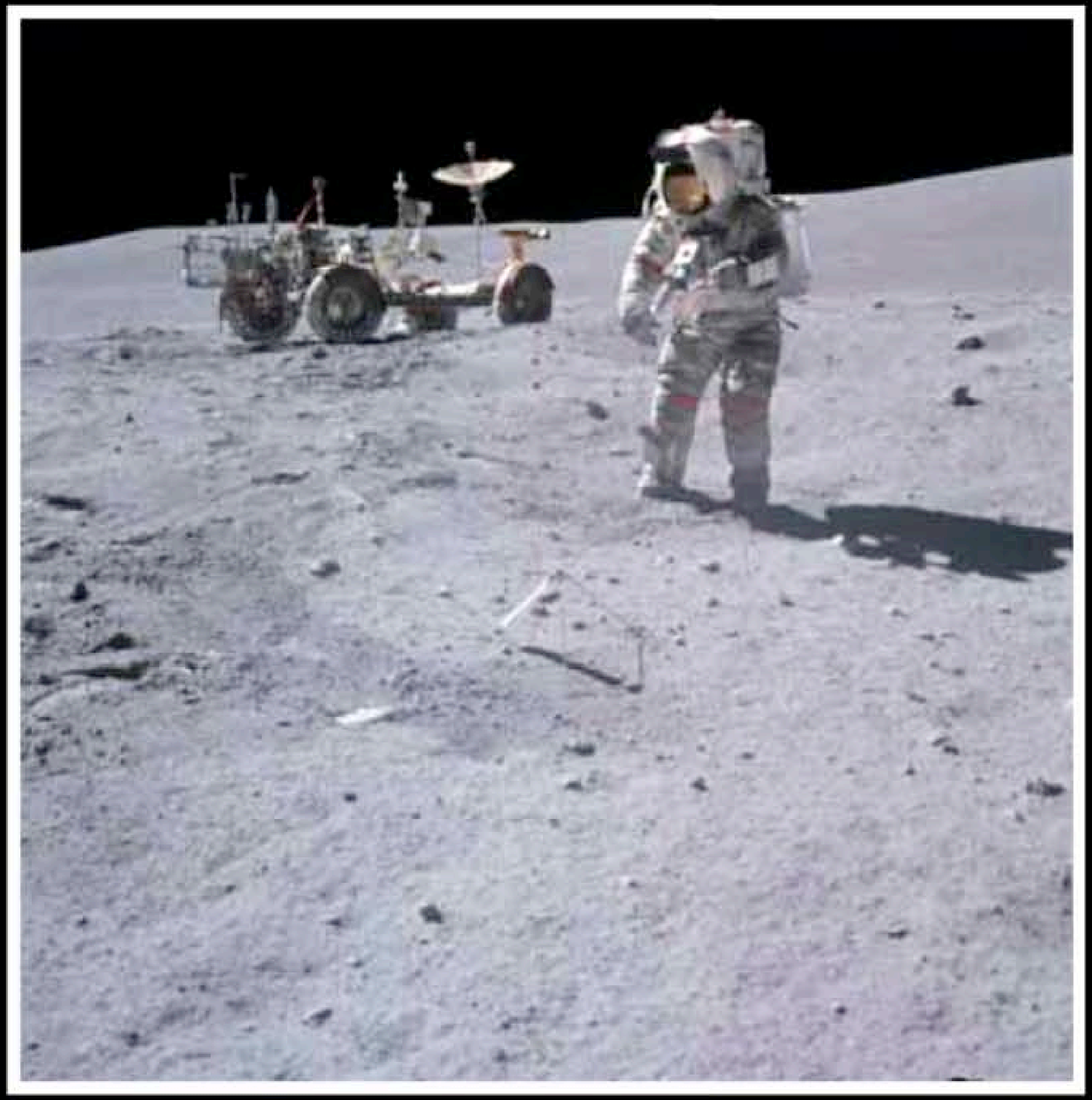
Mission	EVA 1	Local Time	EVA 2	Local Time	EVA 3	Local Time
Apollo 11	14.0°-15.4°	6.93-7.03				
Apollo 12	7.5°-9.5°	6.50-6.63	15.8°-17.8°	7.05-7.19		
Apollo 14	13.0°-15.5°	6.87-7.03	22.0°-24.3°	7.47-7.62		
Apollo 15	19.6°-22.9°	7.31-7.51	31.0°-34.7°	8.07-8.31	41.7°-44.3°	8.78-8.95
Apollo 16	22.2°-25.7°	7.48-7.71	34.1°-37.9°	8.27-8.53	45.8°-48.7°	9.05-9.25
Apollo 17	15.3°-19.0°	7.02-7.27	27.3°-31.2°	7.82-8.08	39.0°-42.6°	8.60-8.84

Time: Decimal hours with 6.00 as sunrise / 12.00 as noon.
Illumination: degrees above horizon
Apollo 12 EVA 1 had the lowest illumination angle
Apollo 16 EVA 3 had the highest illumination angle

Surface Lighting

AS12-46-6734

Apollo 12 EVA 1 - 7.5°

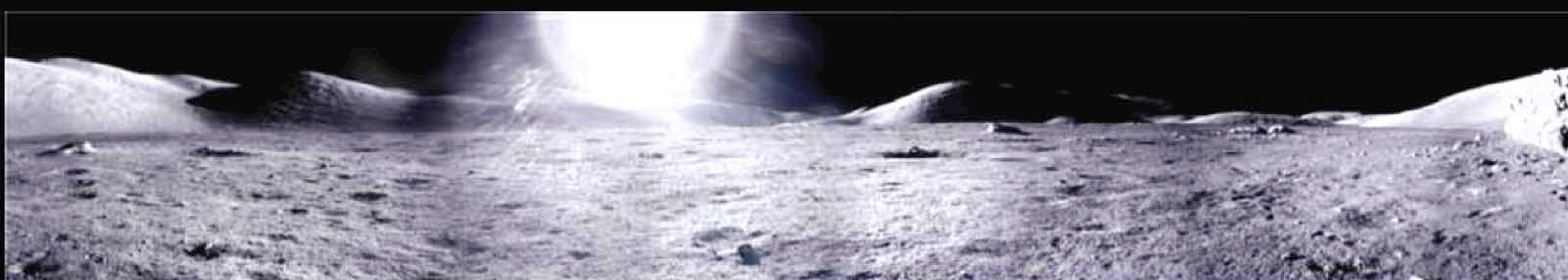


A16-117-18825

Apollo 16 EVA 3 - 46°

Surface Lighting

Apollo 12 EVA 1 down sun 7.5°



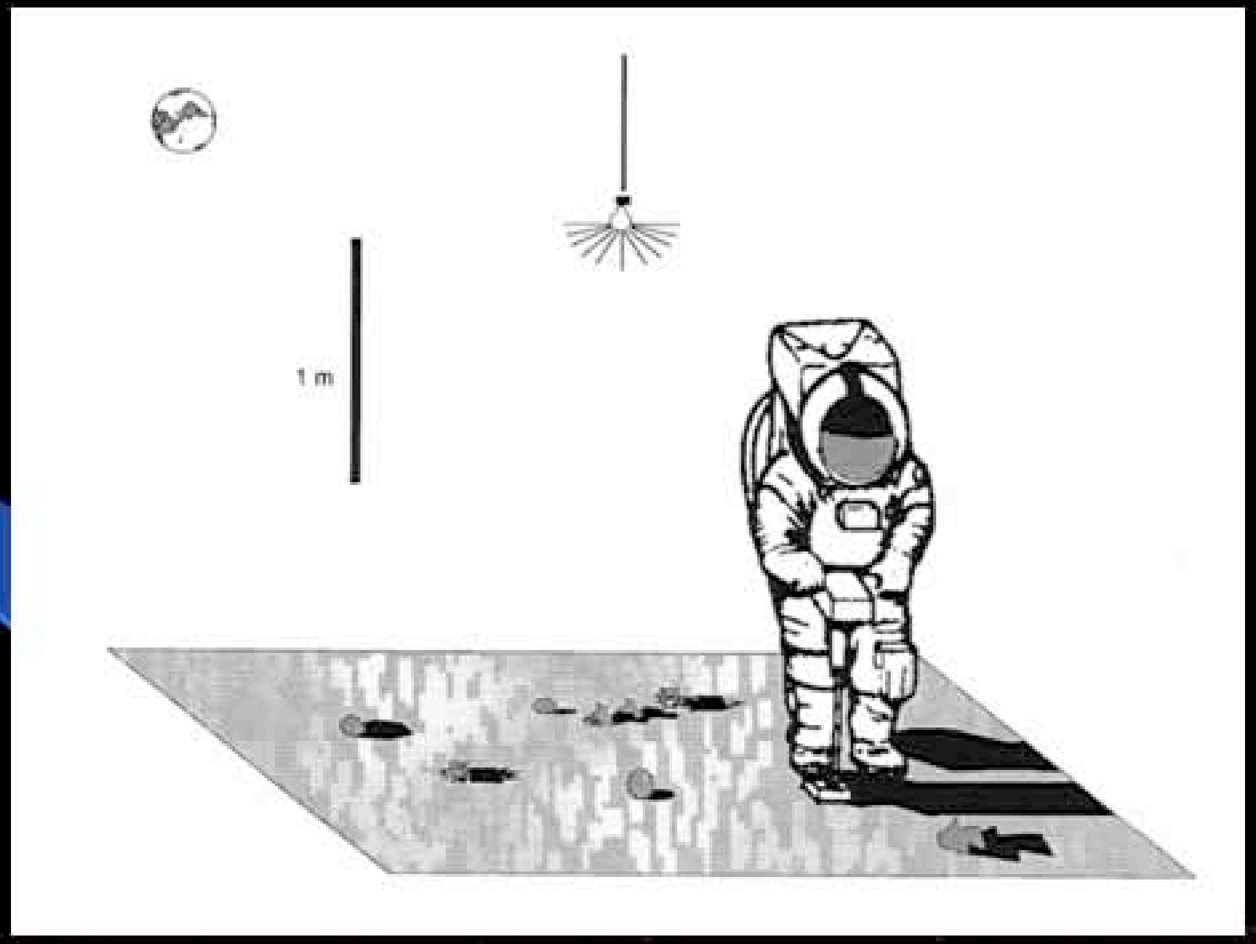
Apollo 17 EVA 1 up sun 16°

Working in the Dark
Earthlight and Artificial Illumination

Full disk Earth illumination equivalent to working in room lit by 60 W bulb 2.2 meters overhead

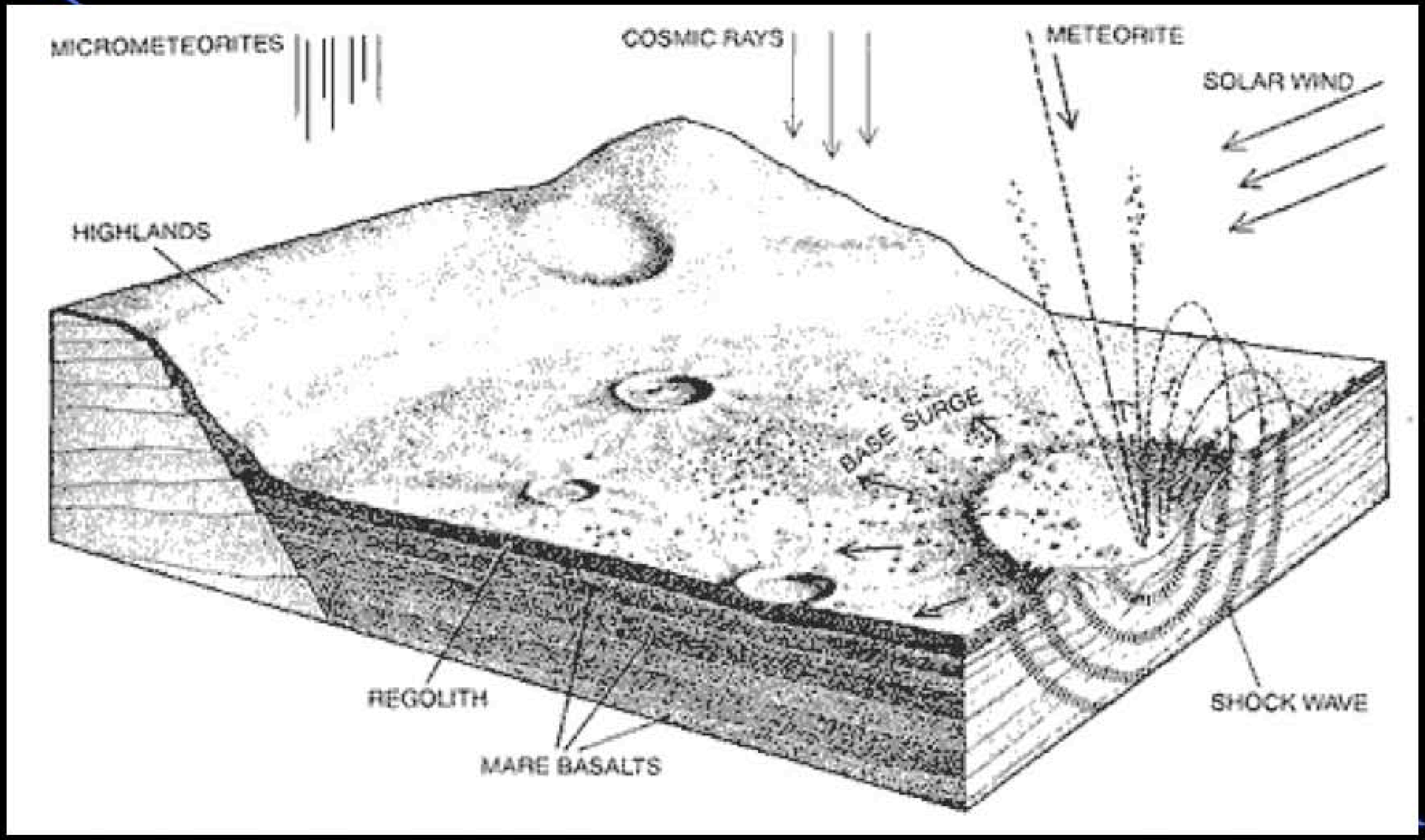
Thermal requirements will be greatly reduced for night work

Work near the poles will likely require artificial lighting in any event



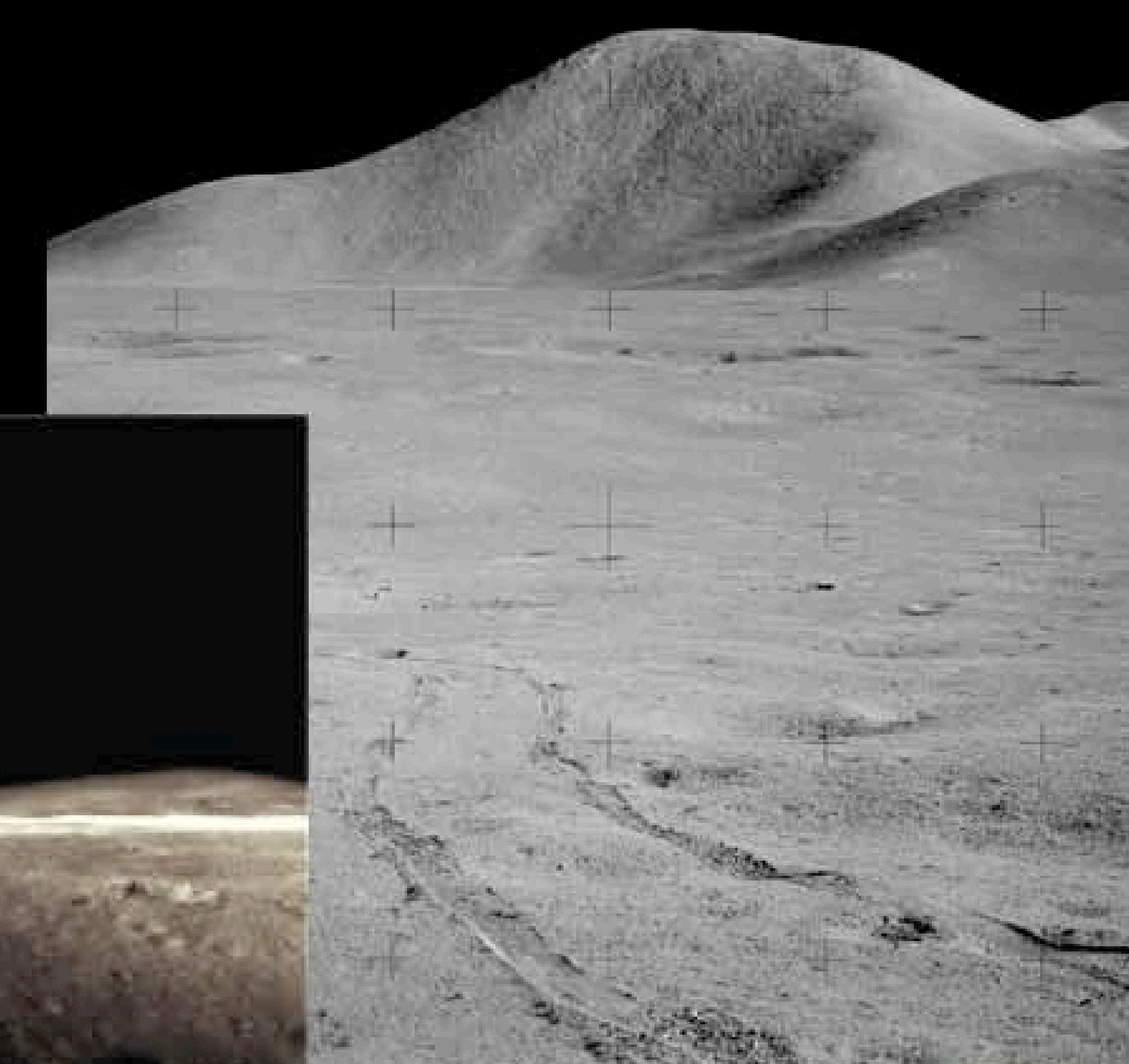
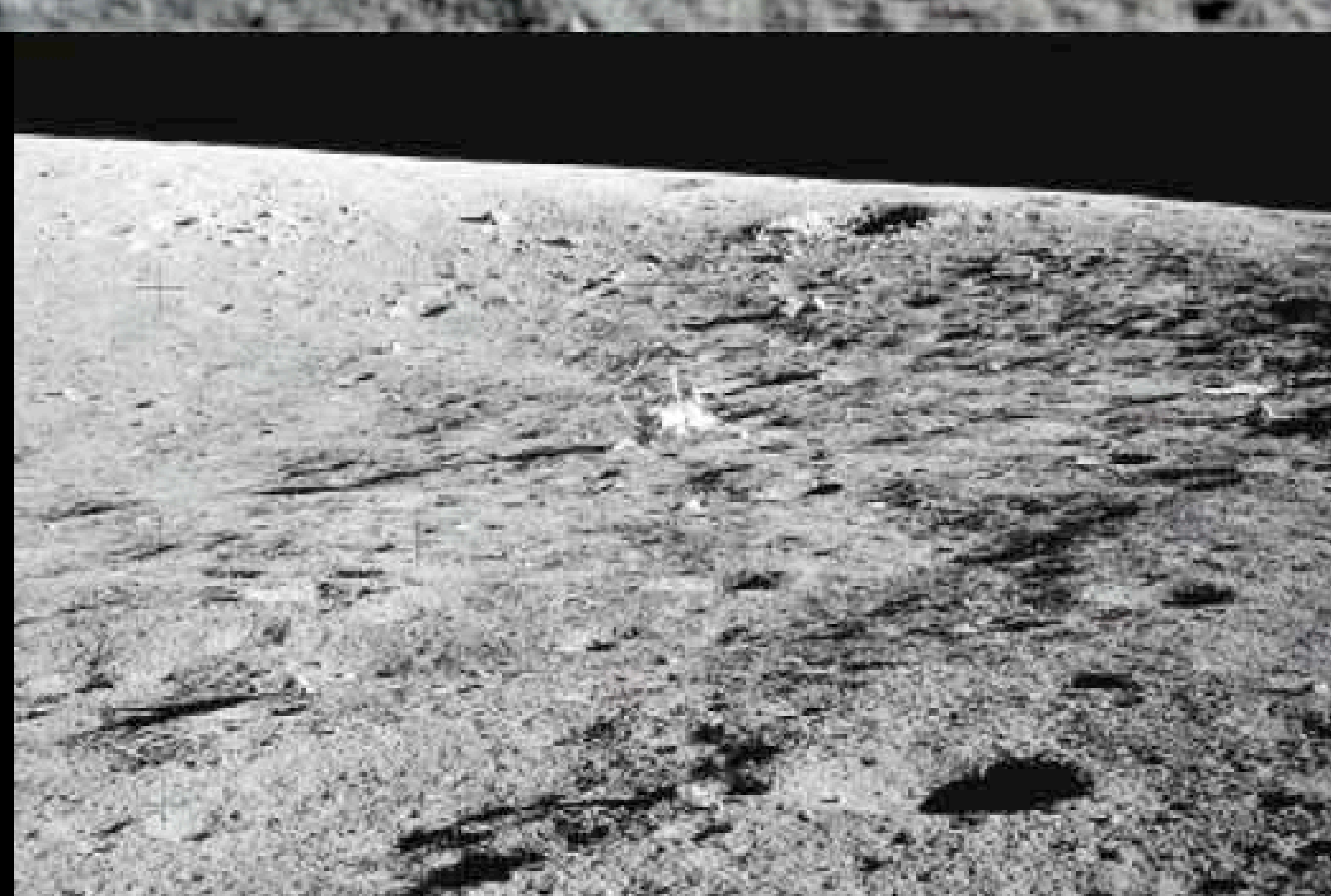
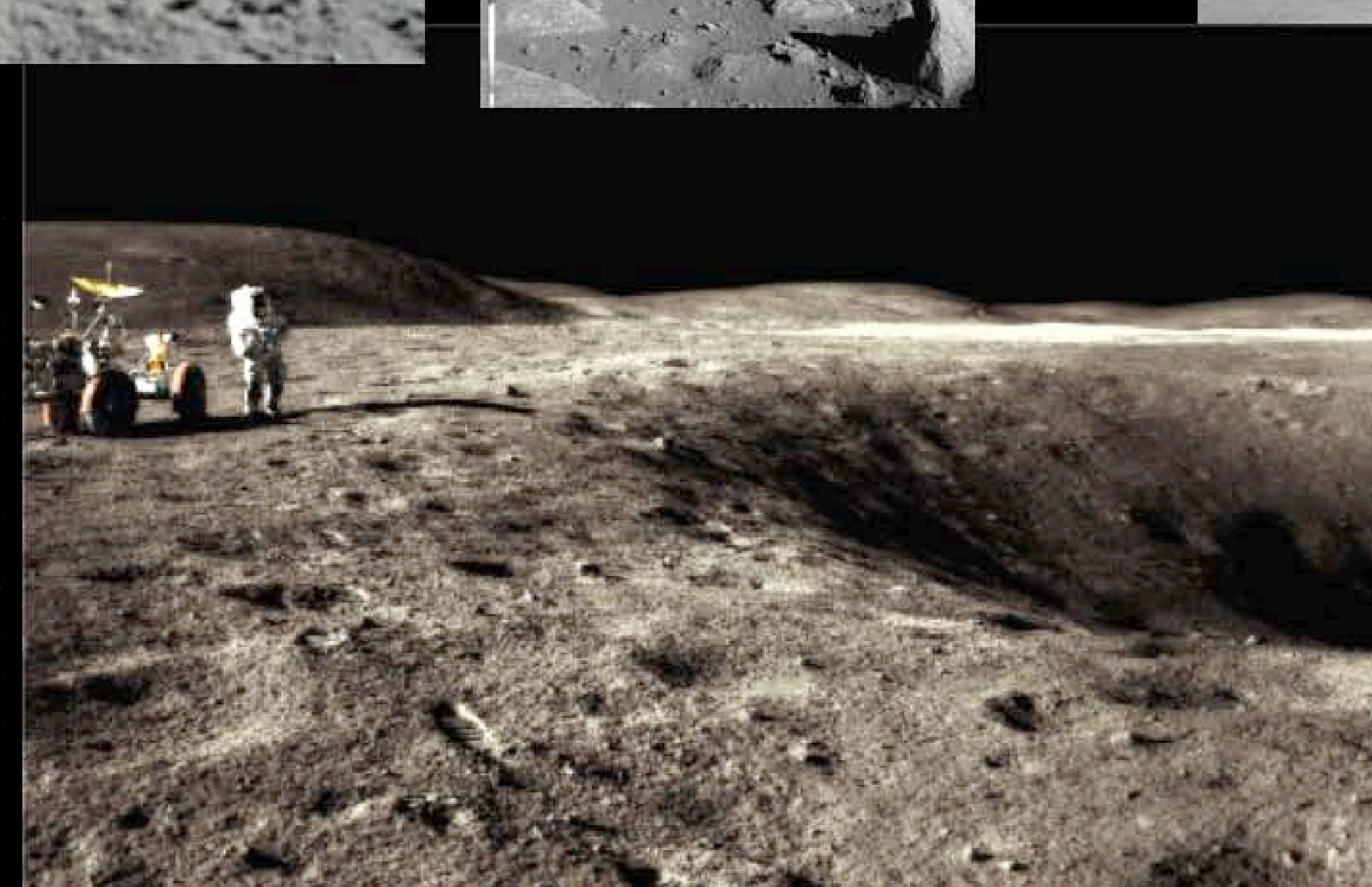
Regolith

The layer or mantle of loose incoherent rock material, of whatever origin, that nearly everywhere underlies the surface of the land and rests on bedrock. A general term used in reference to unconsolidated rock, alluvium or soil material on top of the bedrock. Regolith may be formed in place or transported in from adjacent lands.



Regolith



Regolith

Median particle size of 40-130 μm

- Average grain size 70 μm
- 10-20% of the soil is finer than 20 μm

Dust (<50 μm) makes up 40-50% by volume

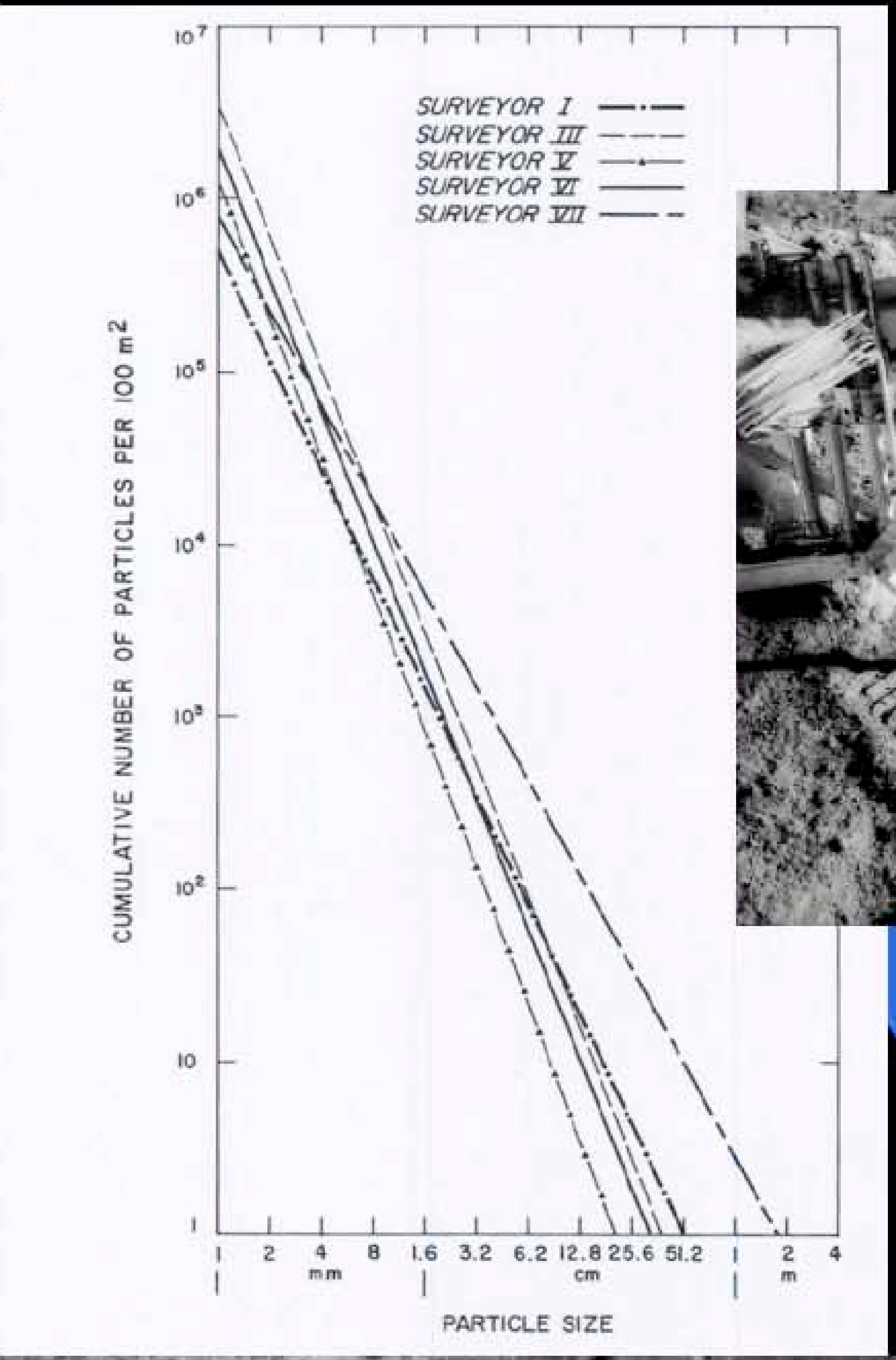
95% of lunar regolith is < 1 mm

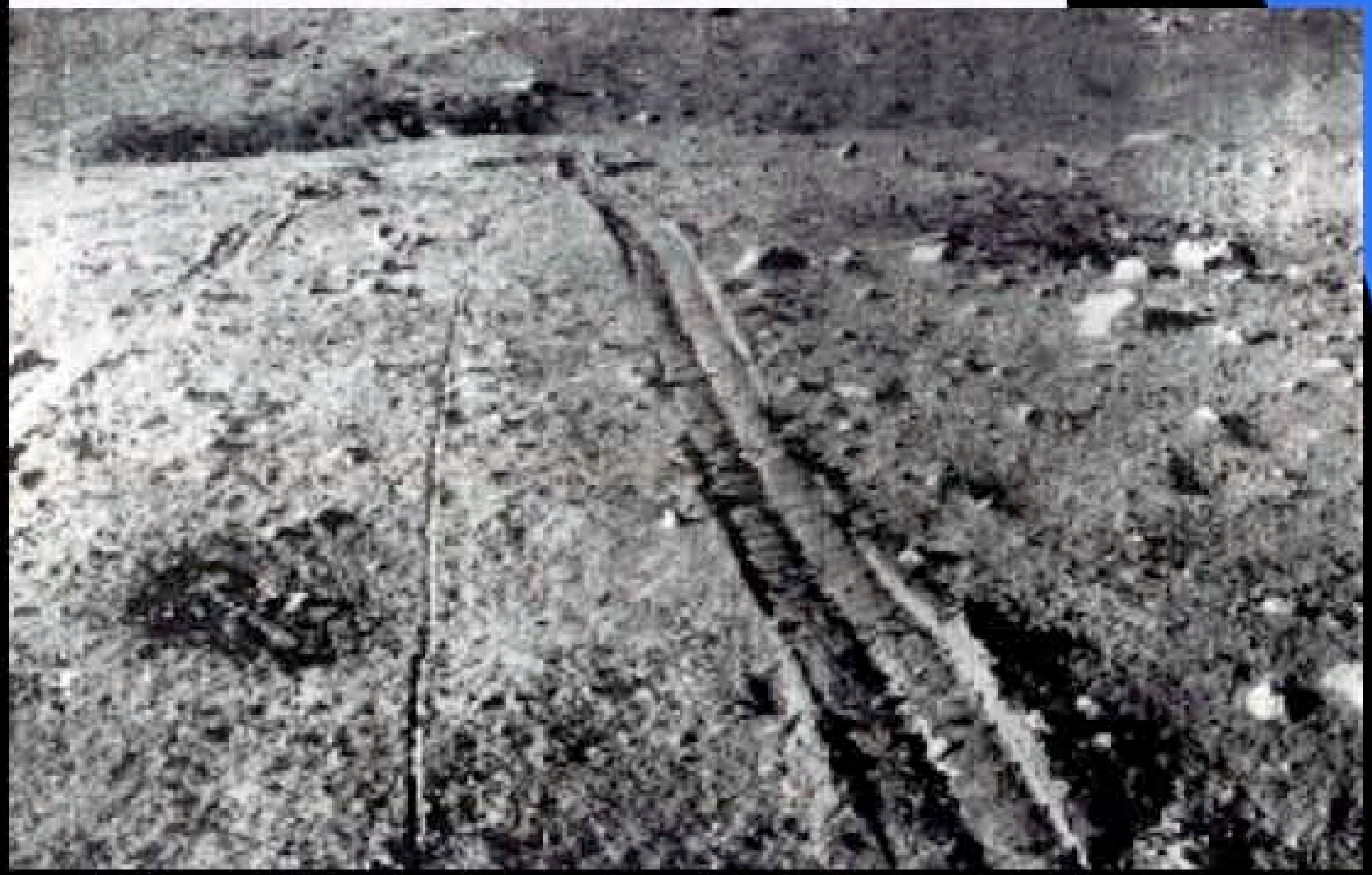
Soil particle size distribution very broad

- "Well graded" in geo-engineering terms
- "Very poorly sorted" in geologic terms

High specific surface area 0.5 m^2 gm^{-1}

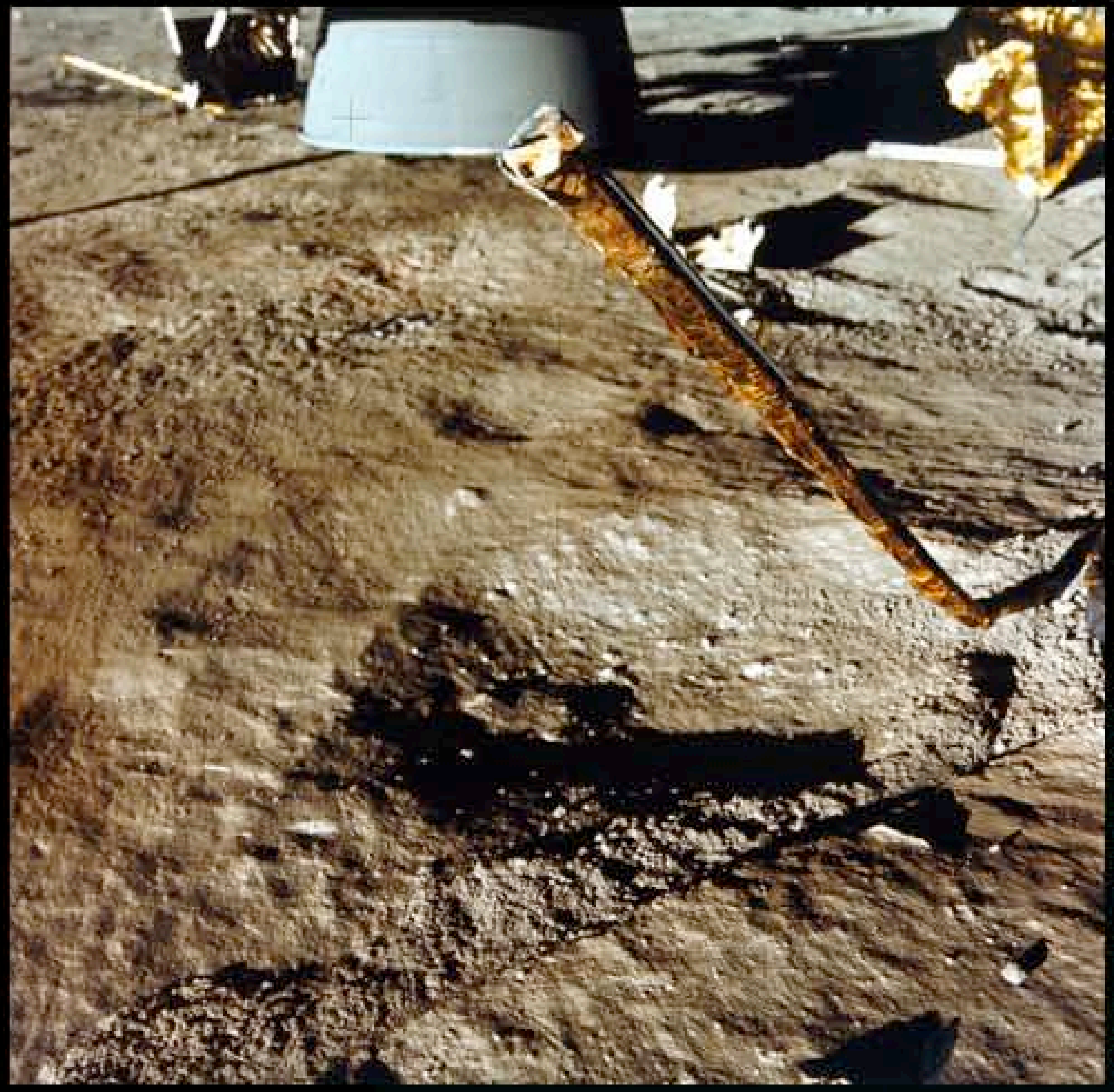
- 8X surface area of spheres with equivalent particle size distribution

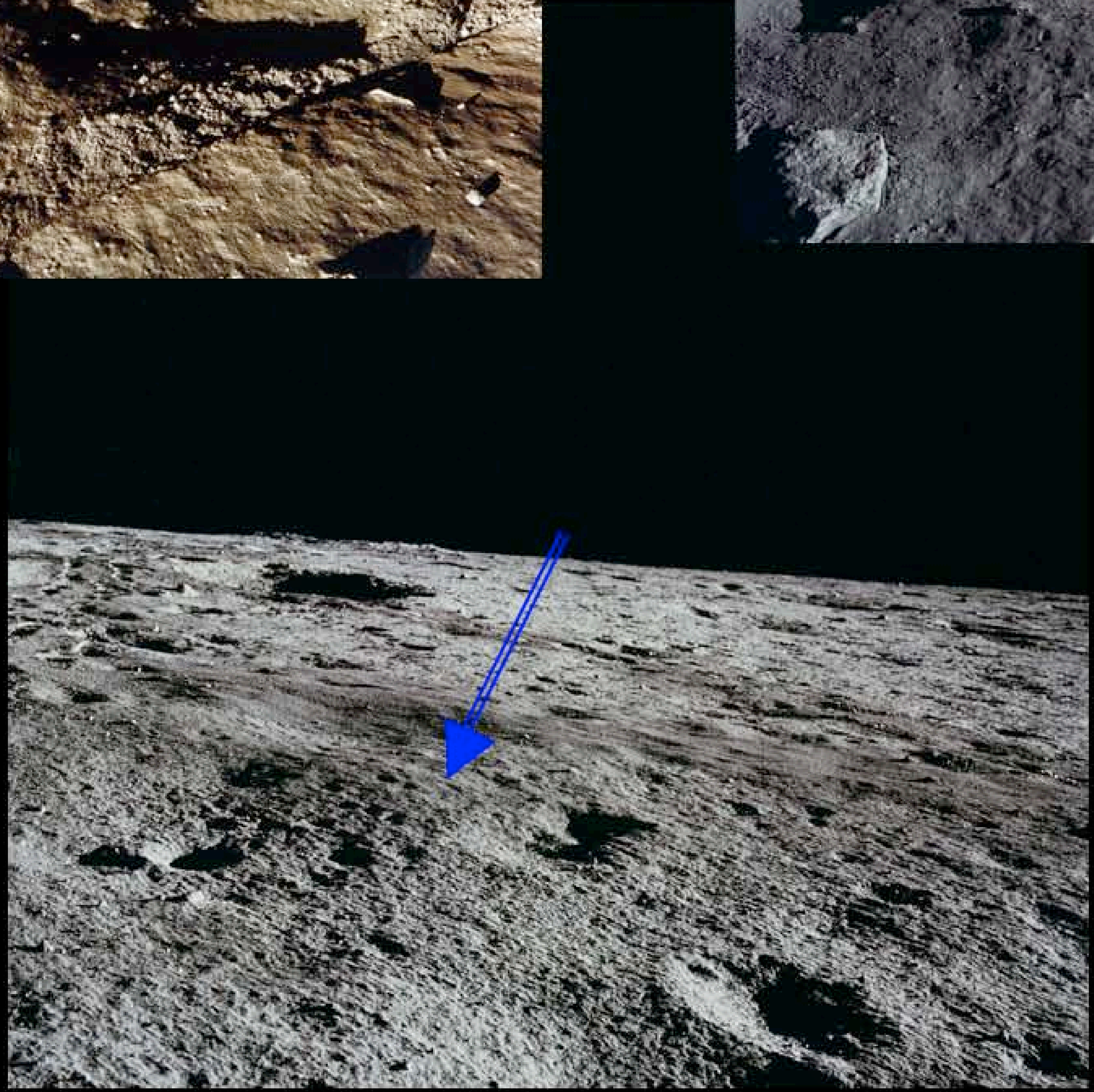




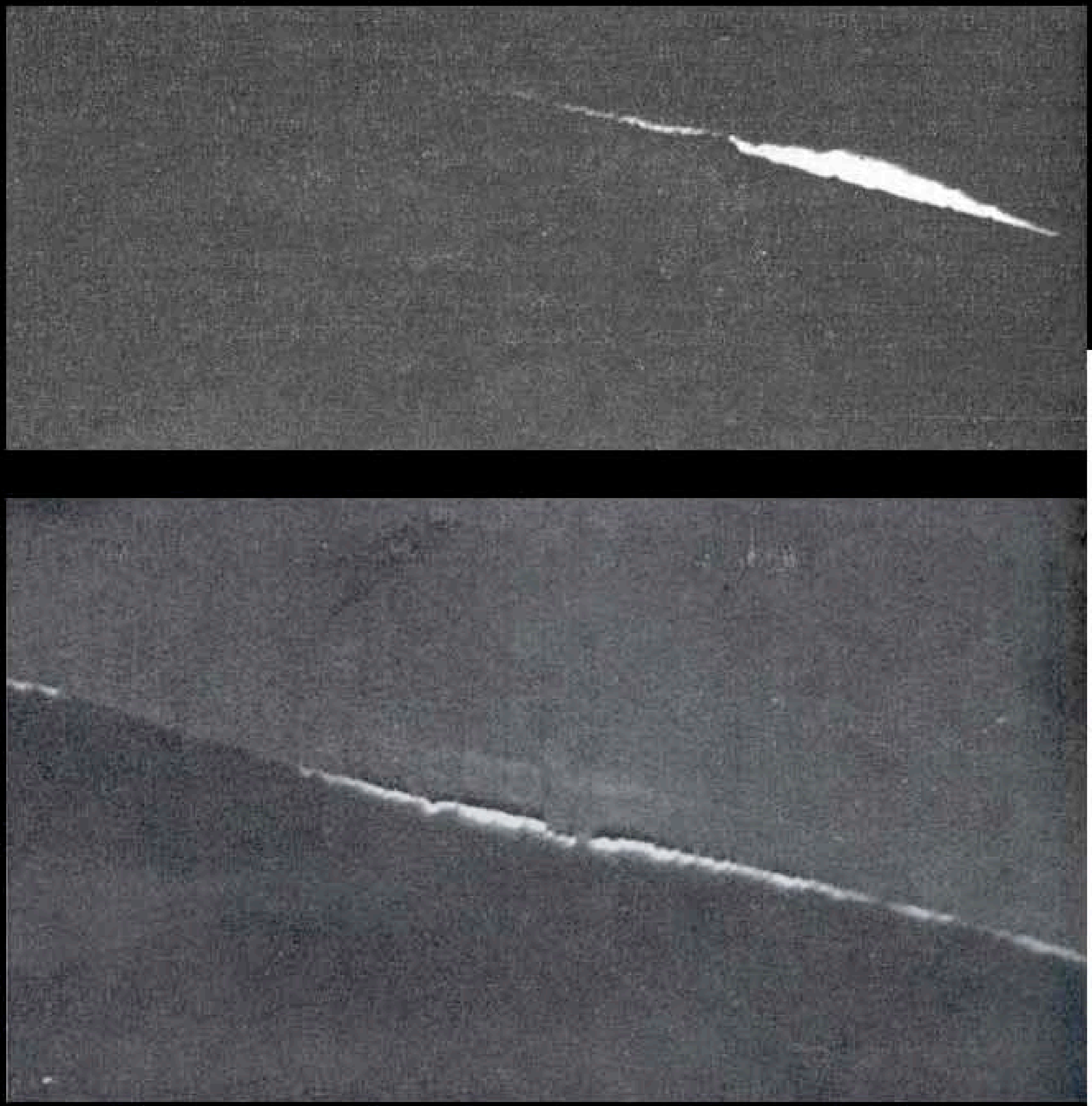
Dust

Loose Surficial Material

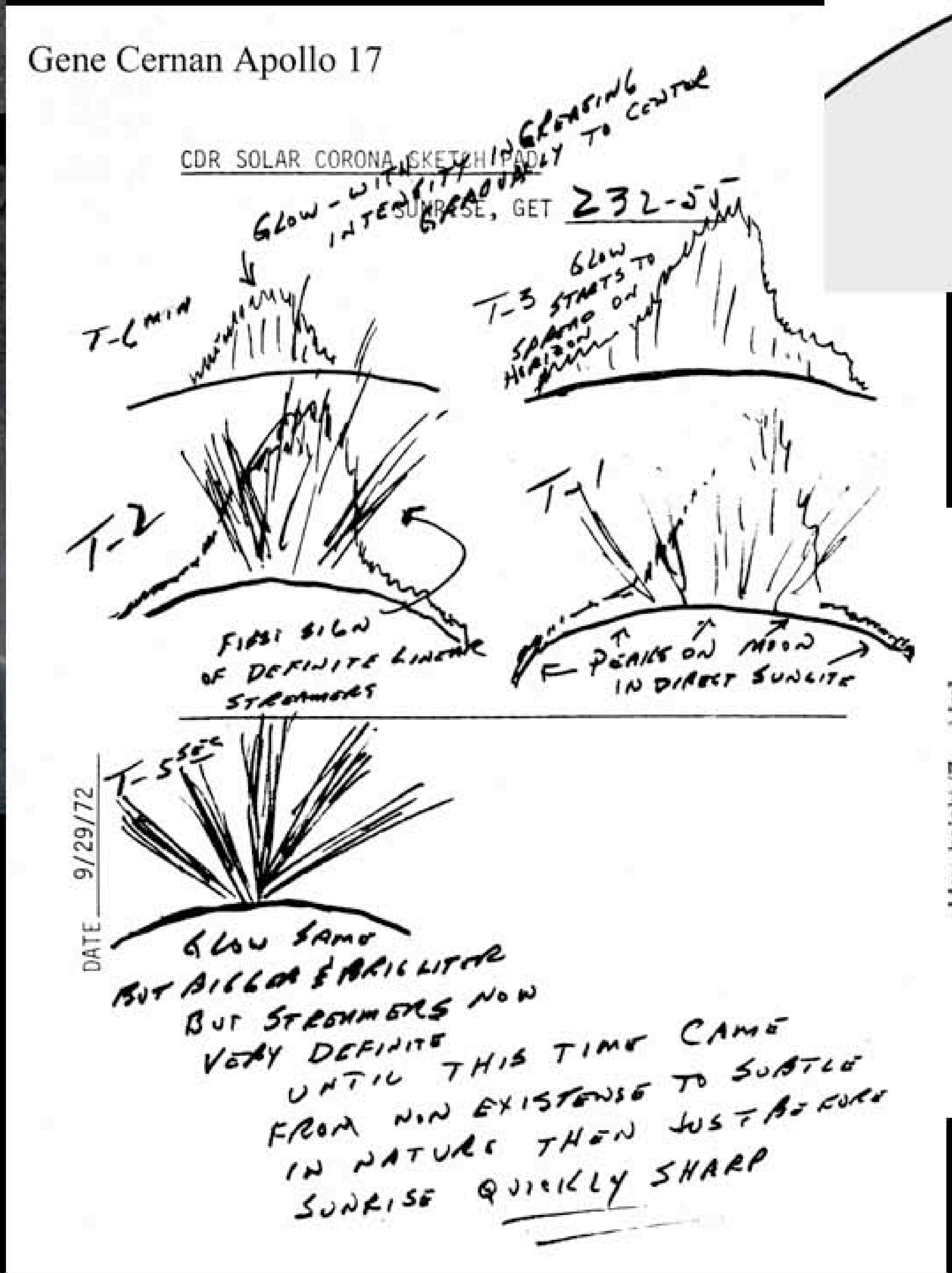


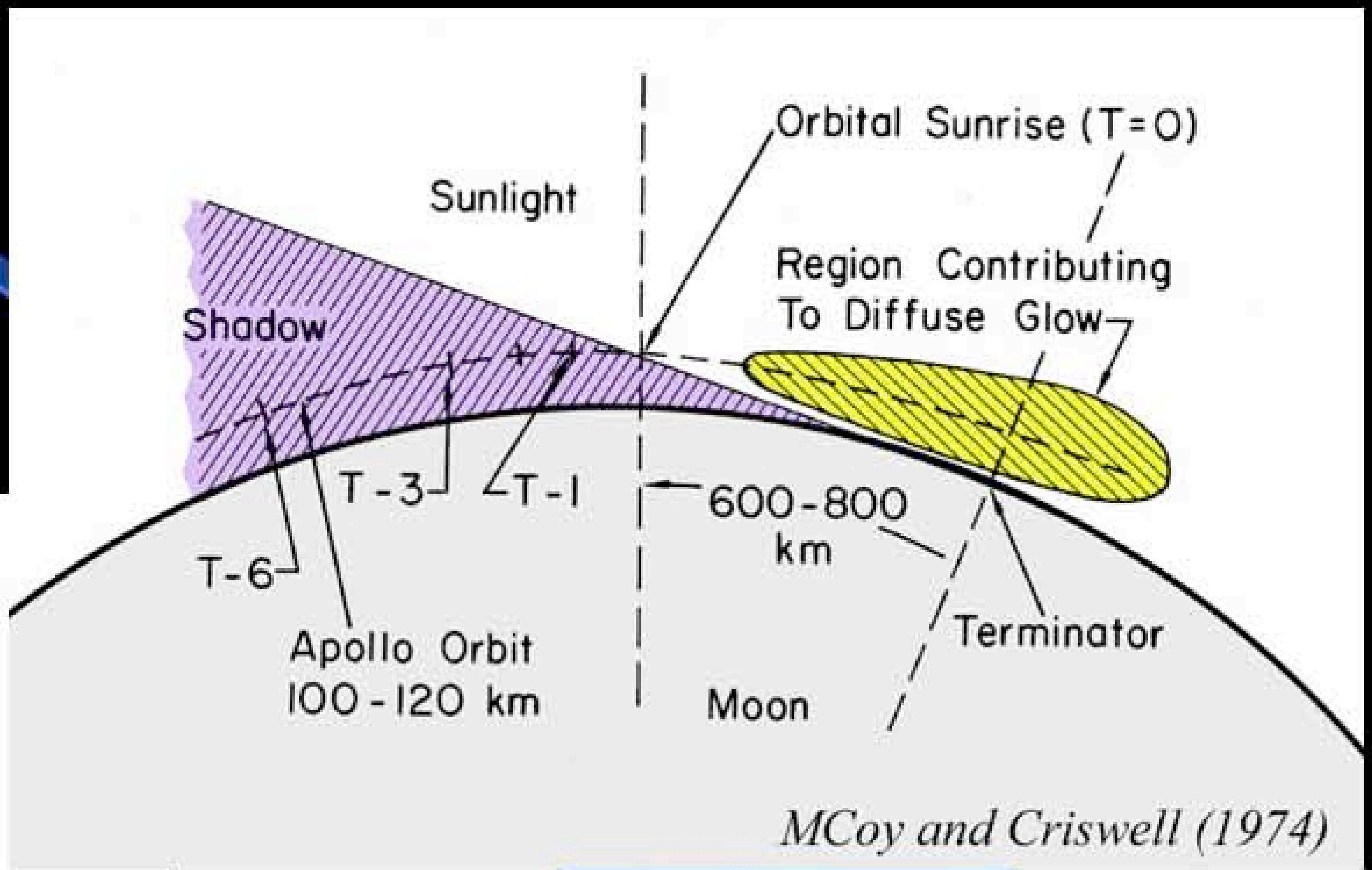


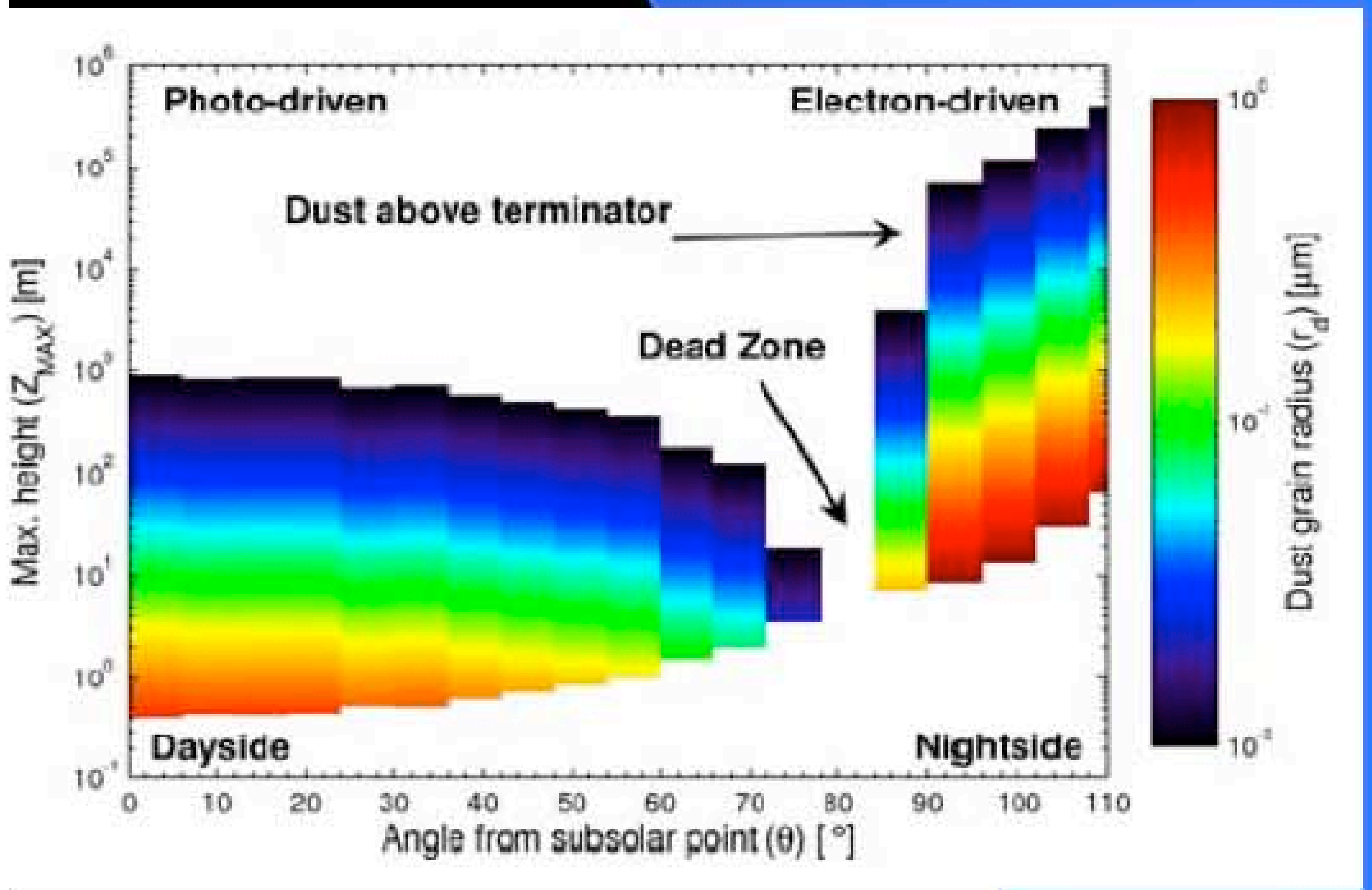
Levitated Dust?



View of horizon glow from Surveyor



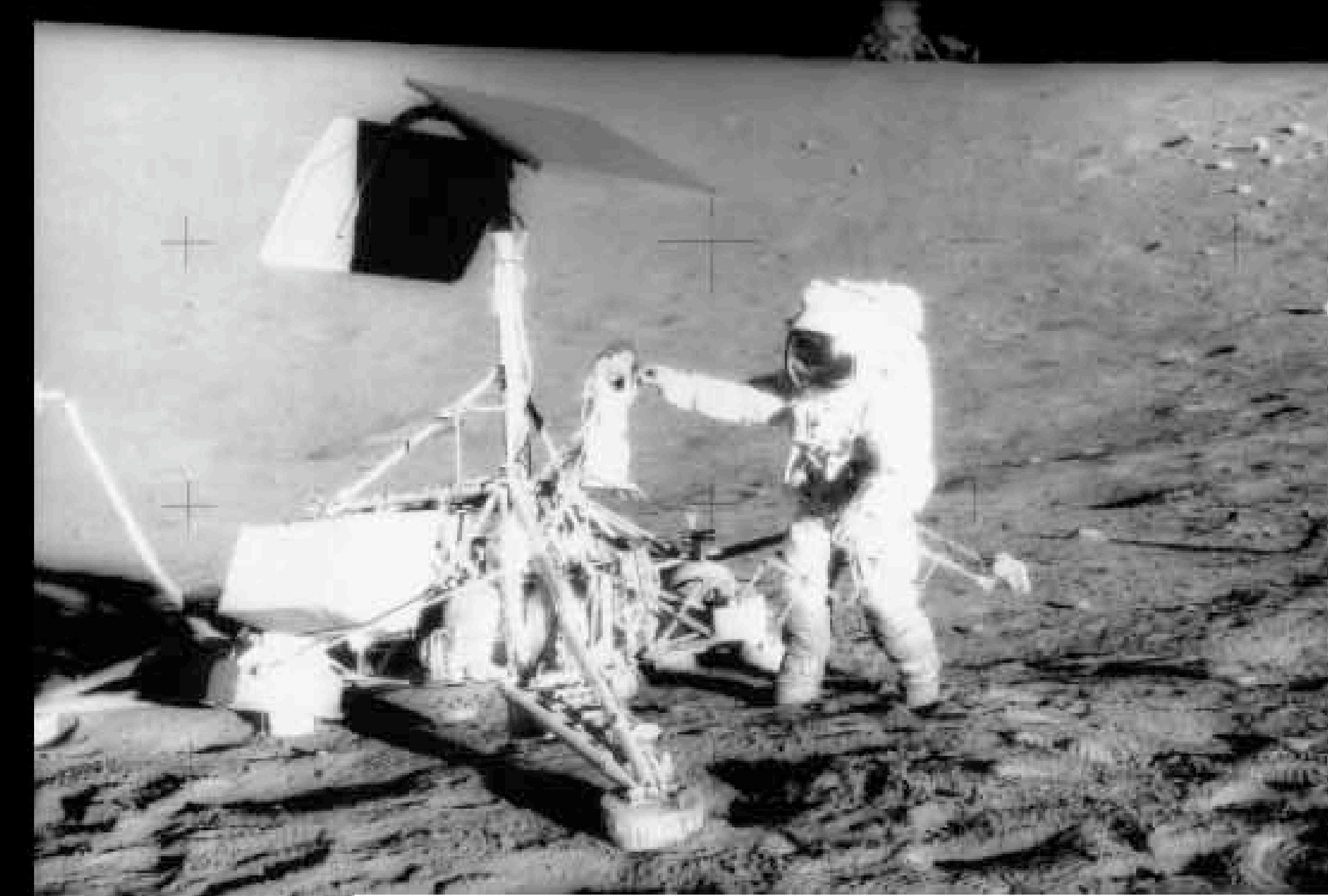


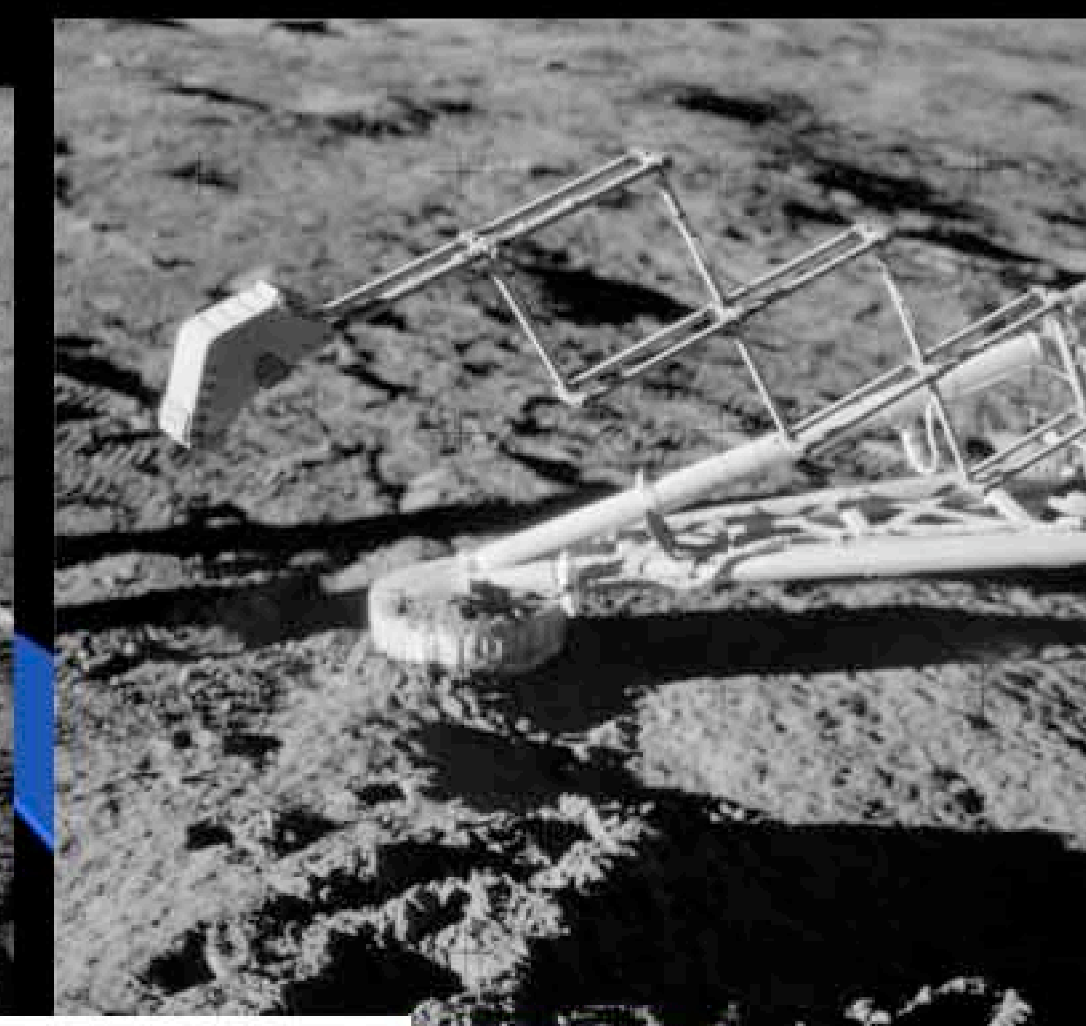


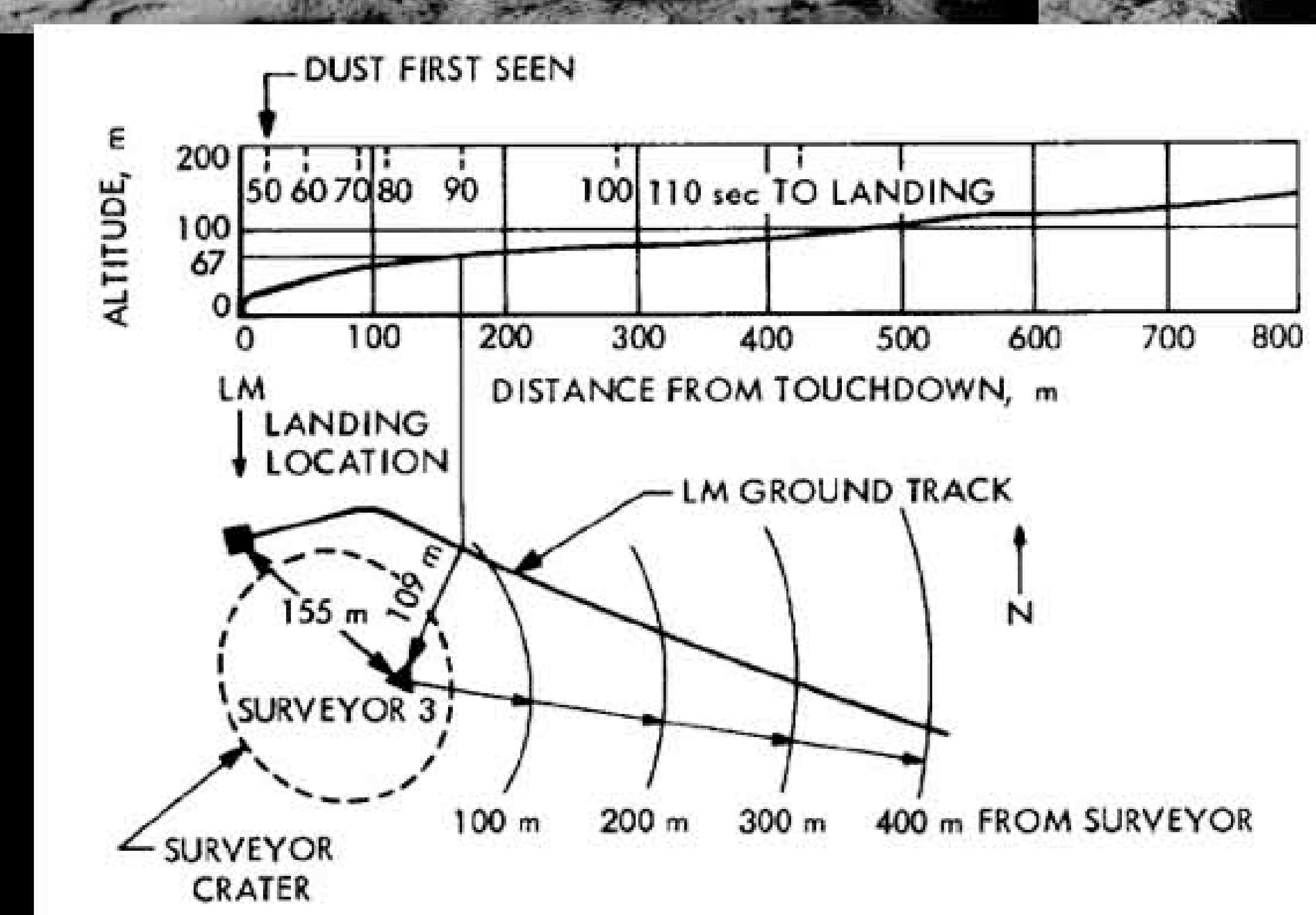
Vondrak

Surveyor 3 Spacecraft

- Spent 31 months on Moon prior to arrival of Apollo 12 astronauts
- Some dust coating on parts noted, but patterns indicated the coatings occurred during Surveyor landing and subsequent Apollo 12 Lunar Module landing
- No evidence of "levitated dust" settling on spacecraft
- Care will have to be taken to assure landing spacecraft do not spread dust over deployed equipment and instruments on surface



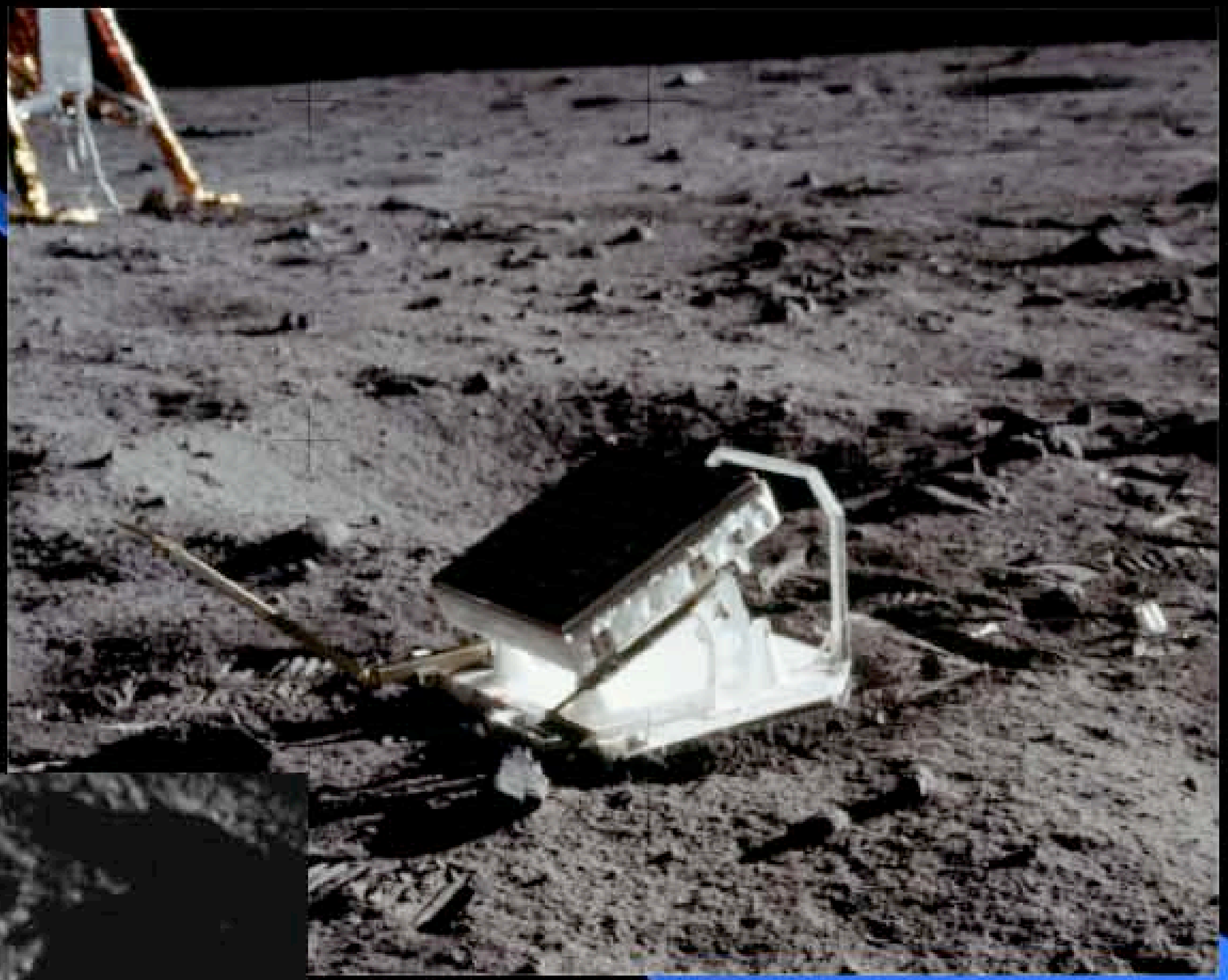


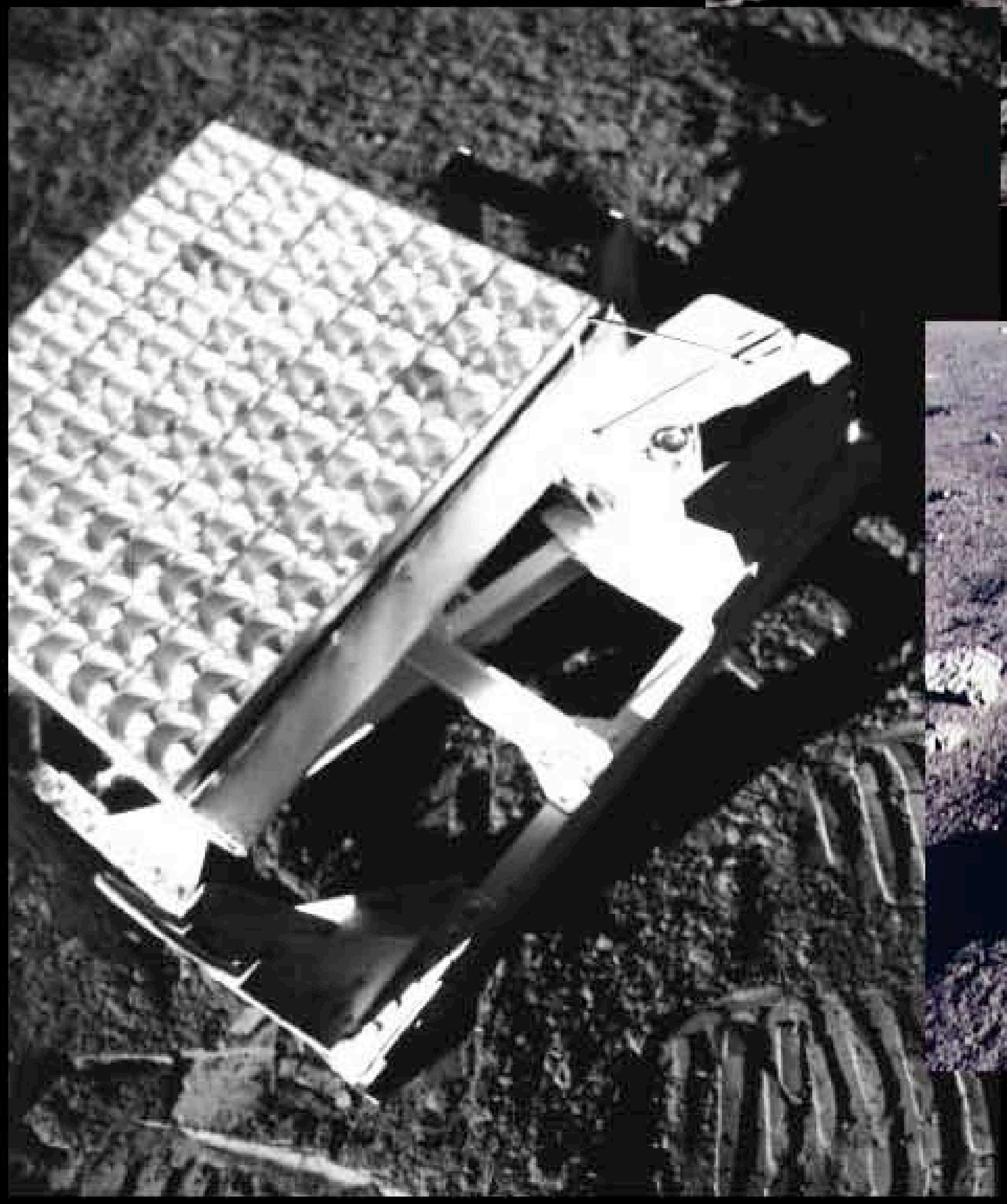


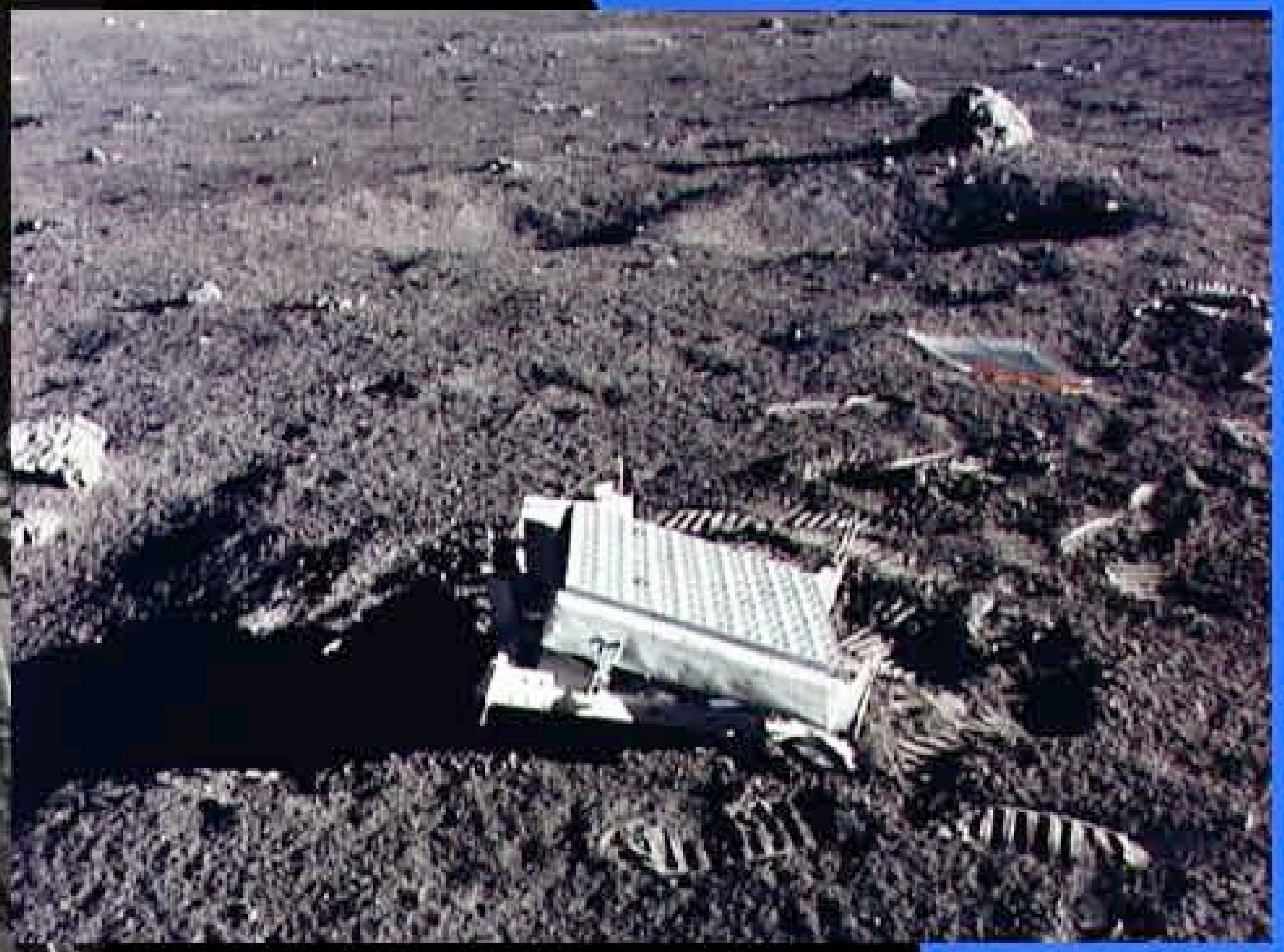
"The observed dust, therefore, originated from both the Surveyor and LM landings, with each contributing a significant amount to various surfaces. "Lunar transport" seems to be relatively insignificant, if evident at all." – W. F. Carroll and P.M. Blair (1972)
ANALYSIS OF SURVEYOR 3 MATERIAL AND PHOTOGRAPHS
NASA SP-284, p. 28

Laser Ranging Retroreflectors

- Flown on Apollo 11, 14, and 15
- Array of glass cube corner reflectors, deployed ~30 cm above lunar surface
- Astronauts deployed carefully, minimizing dust disturbance
- Laser returns received immediately and arrays continue in operation today
- No evidence of any degradation in laser signal return over lifetime of arrays (Apollo 11 LRRR on surface for 37 years now)

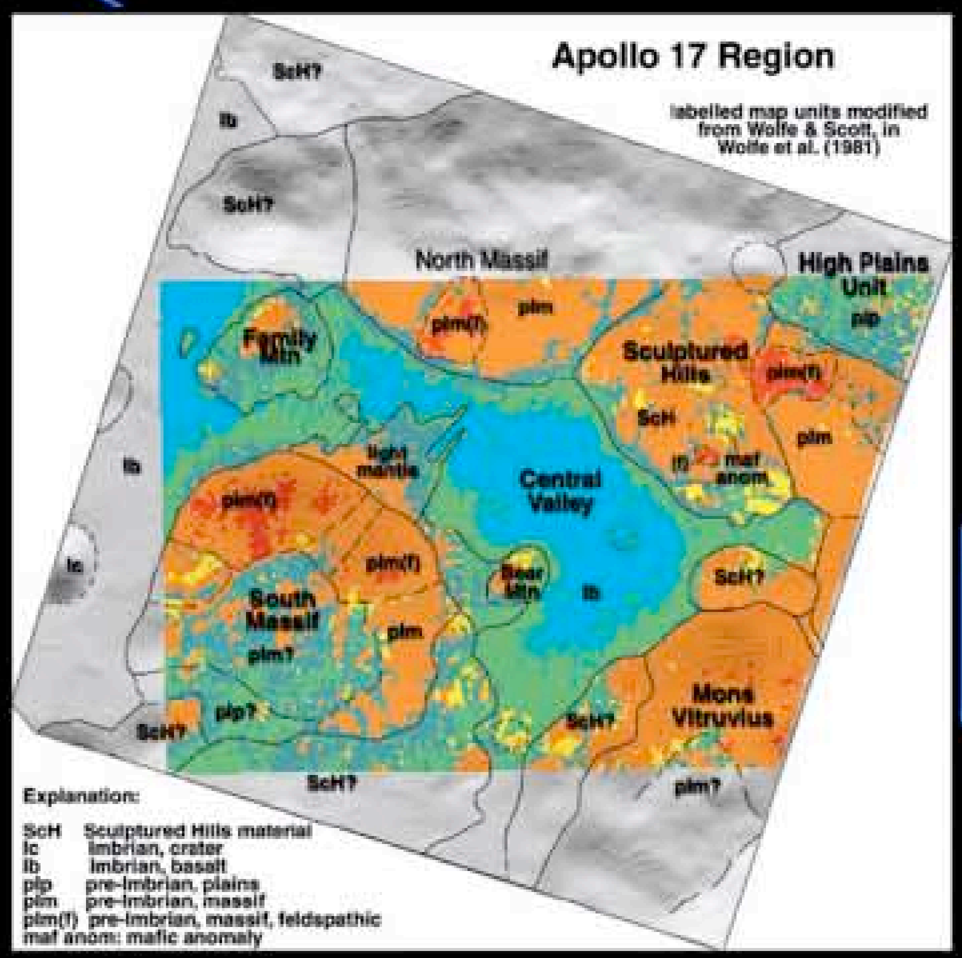




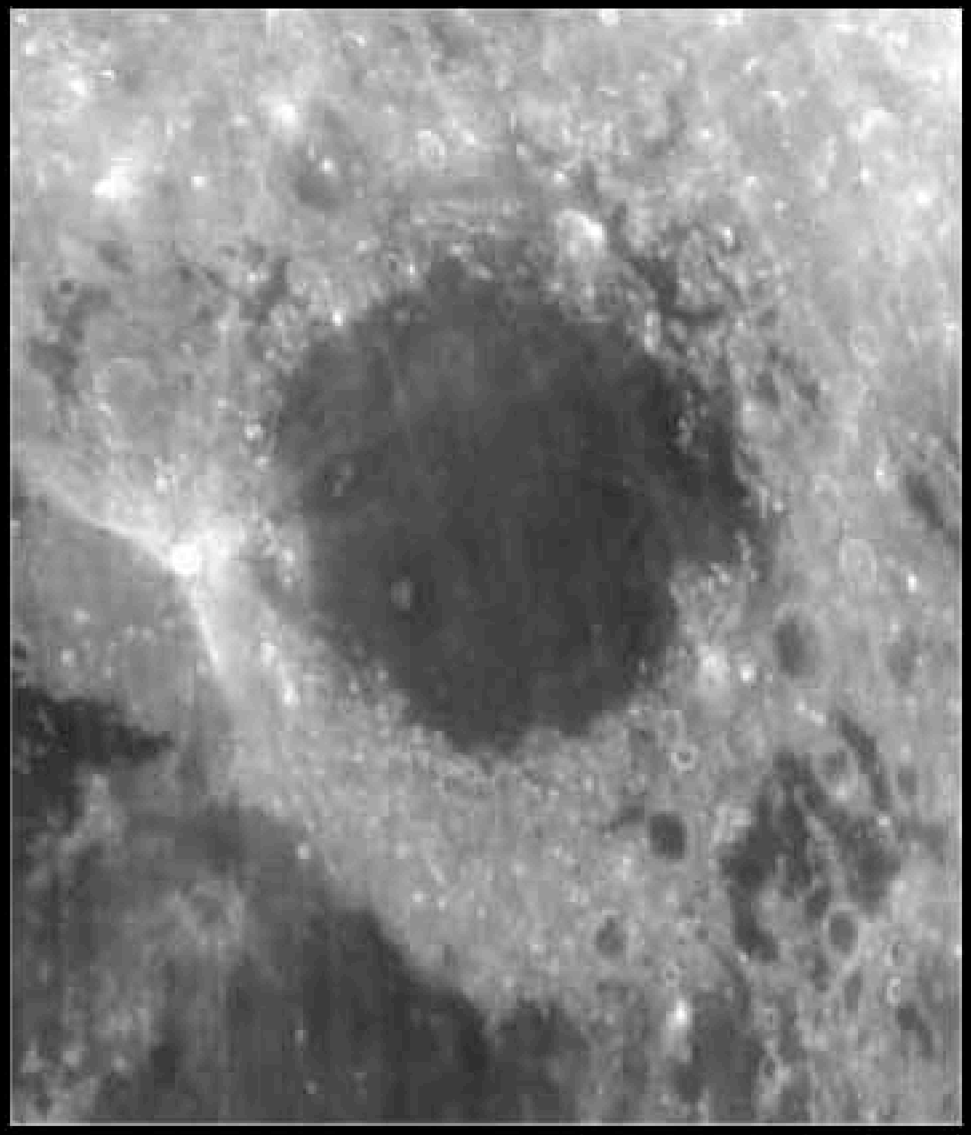


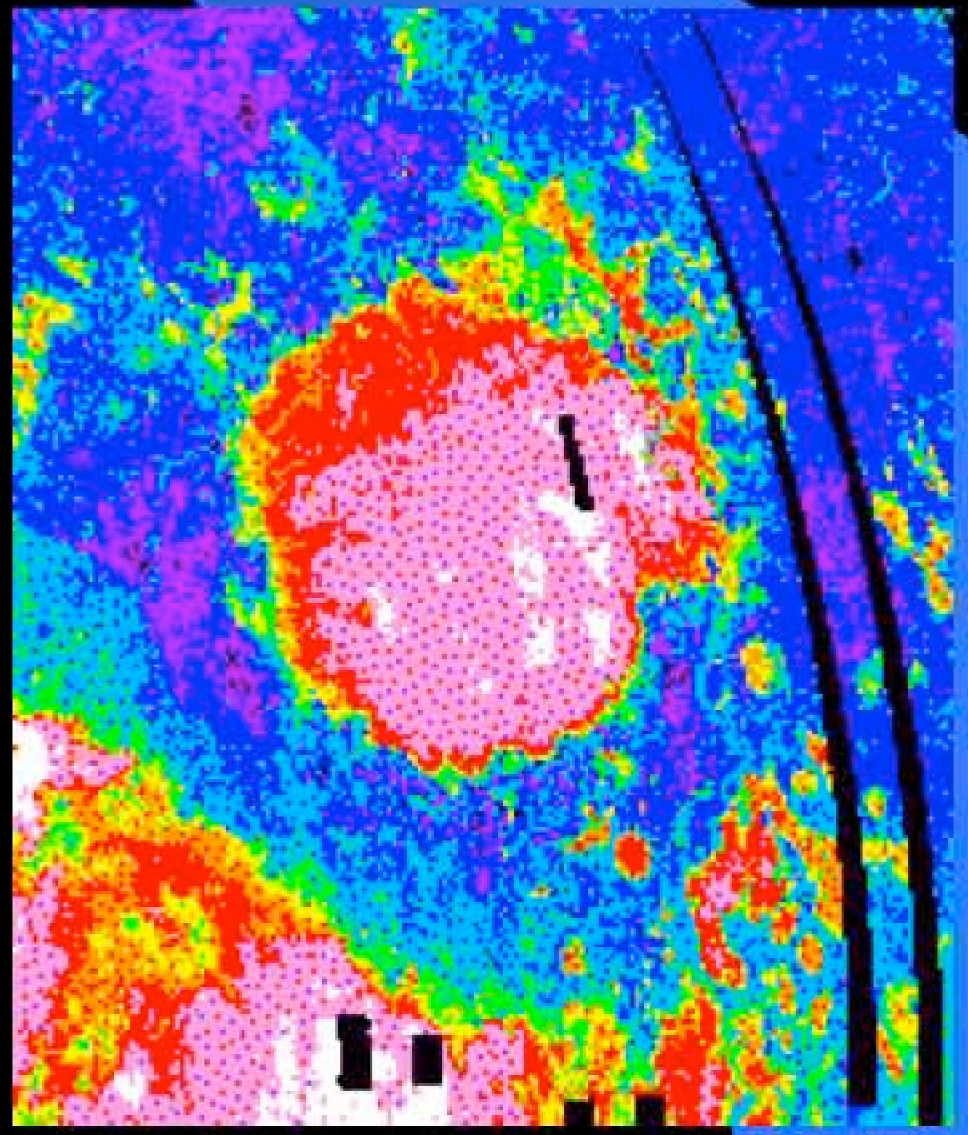
Lateral Dust Transport?

- Levitated dust could move laterally, coating optics and equipment – does it?
- Lateral transport on Moon appears to be very inefficient
- Compositional gradients at Apollo sites are abrupt and well-preserved
- Sharp contacts preserved in remote-sensing data, showing that extensive lateral transport does not occur on the Moon
- Surface rocks have clean surfaces; no evidence of deposited dust layer



Robinson and Jolliff, 2002





Mare Crisium – albedo and Fe concentration

Origin of the Moon

The traditional models

Intact capture

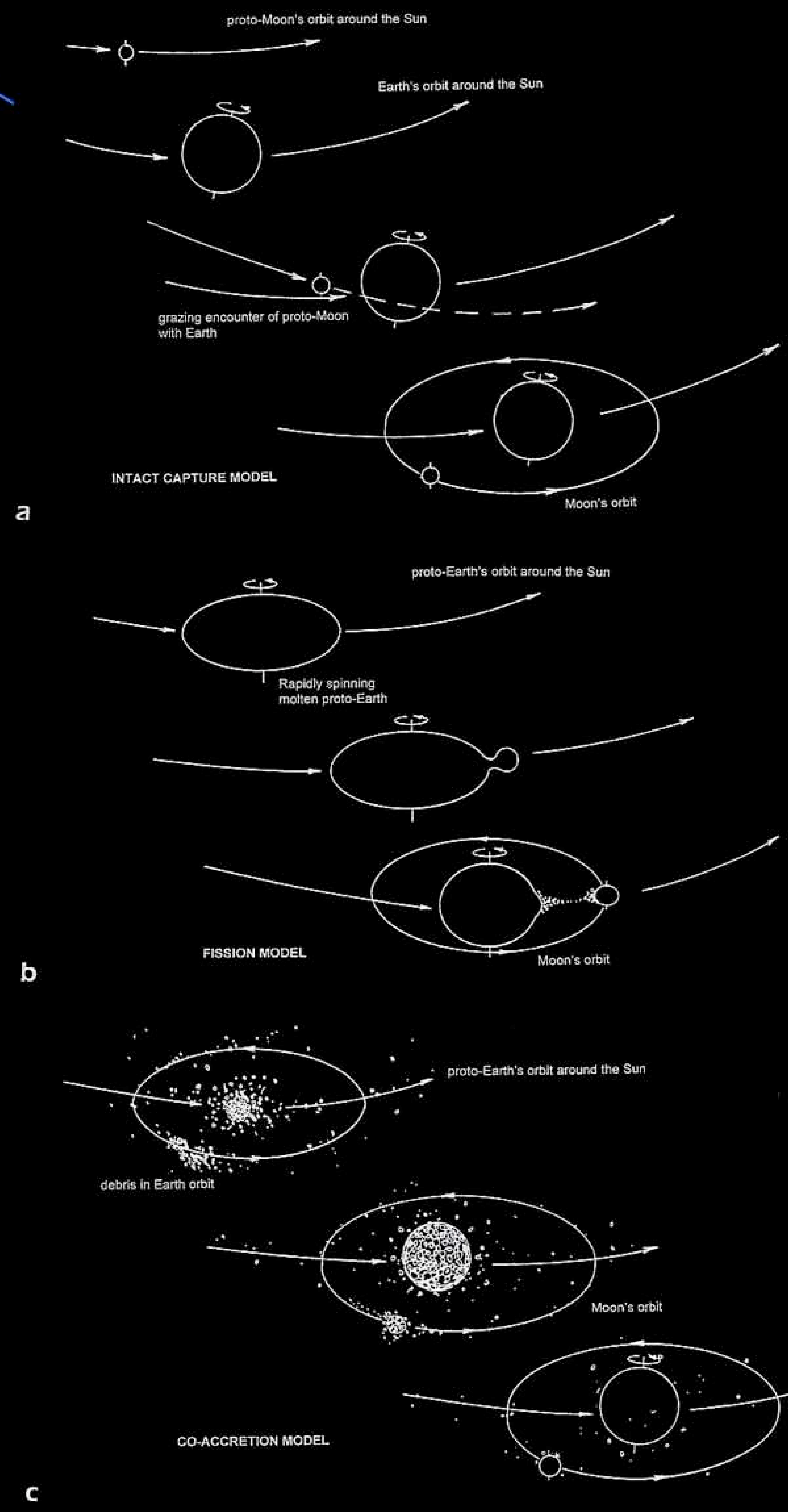
Moon formed elsewhere and was captured during a close passage by Earth

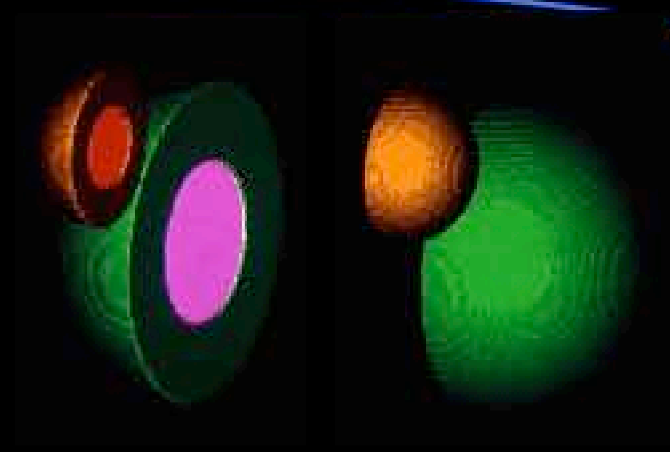
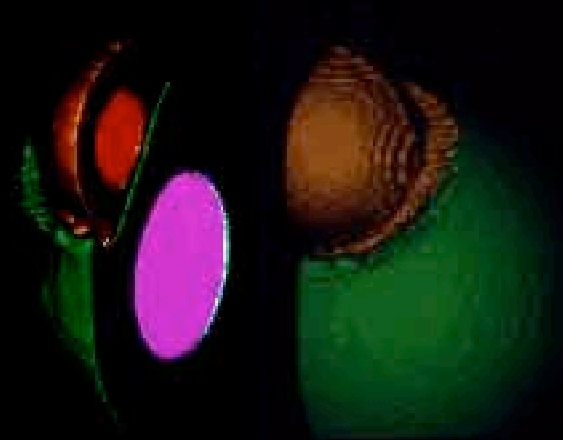
Fission

Moon spun off from molten, rapidly rotating Earth

Binary (co-) accretion

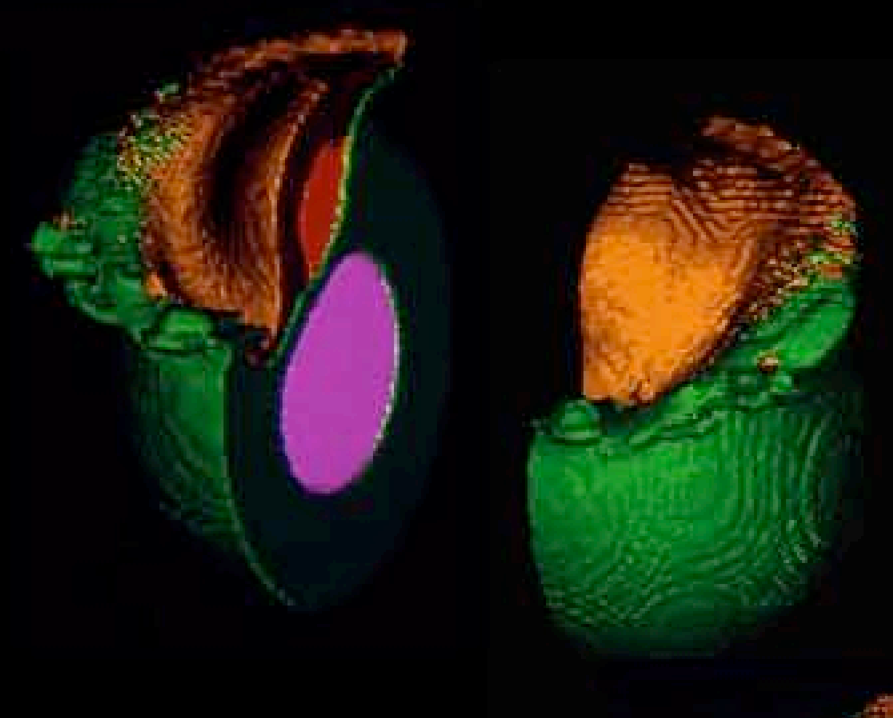
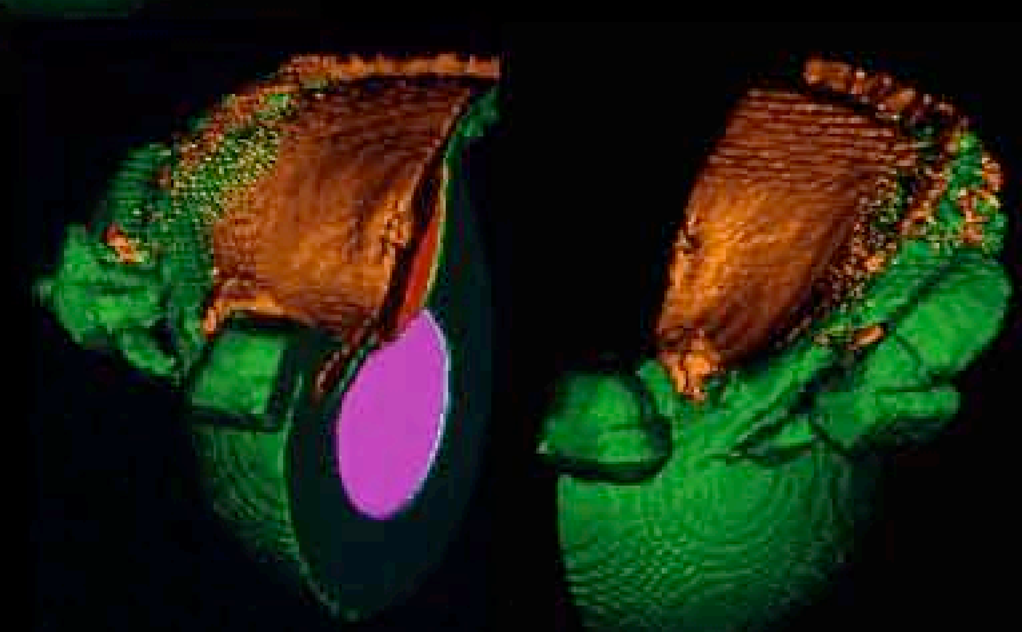
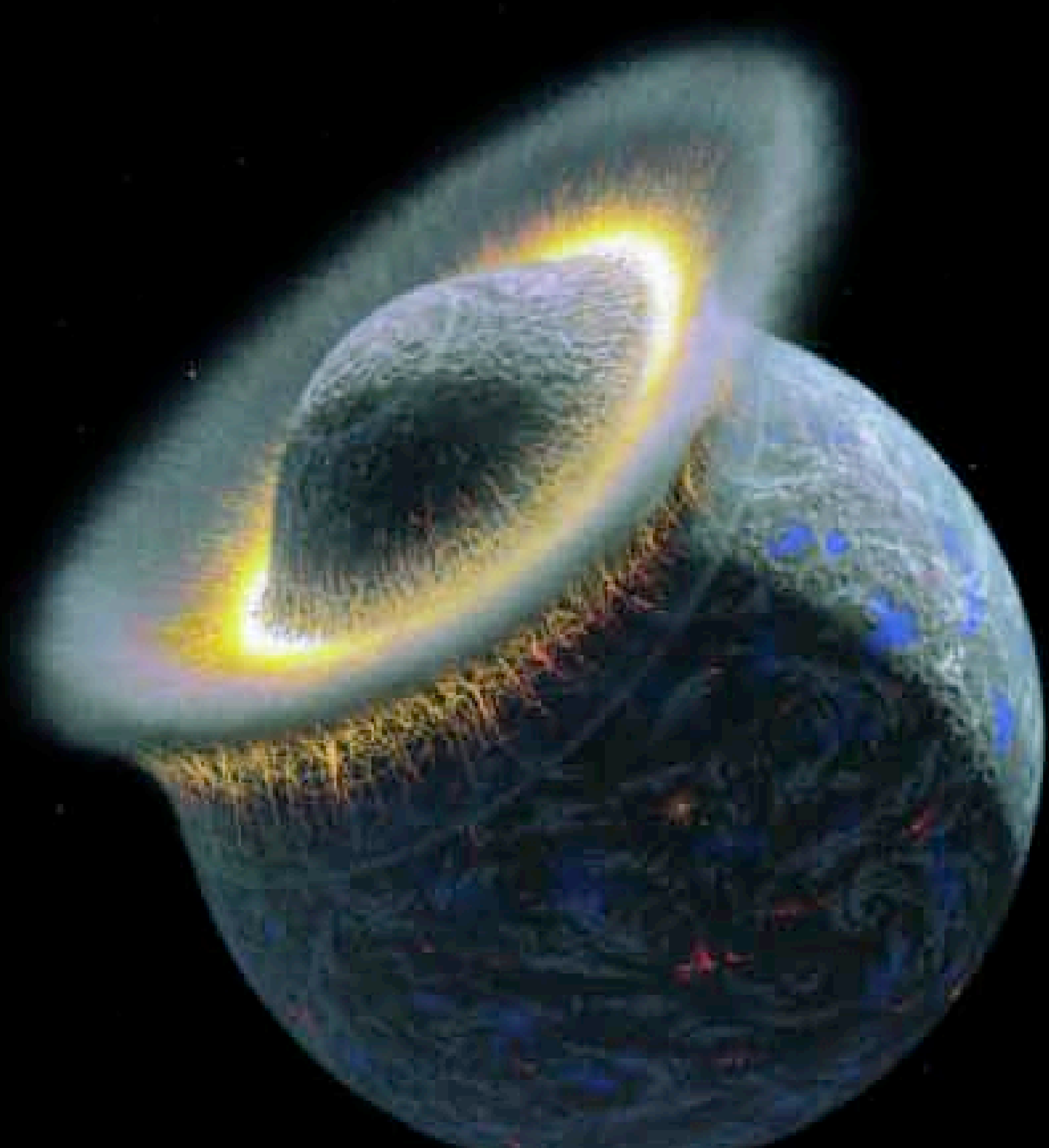
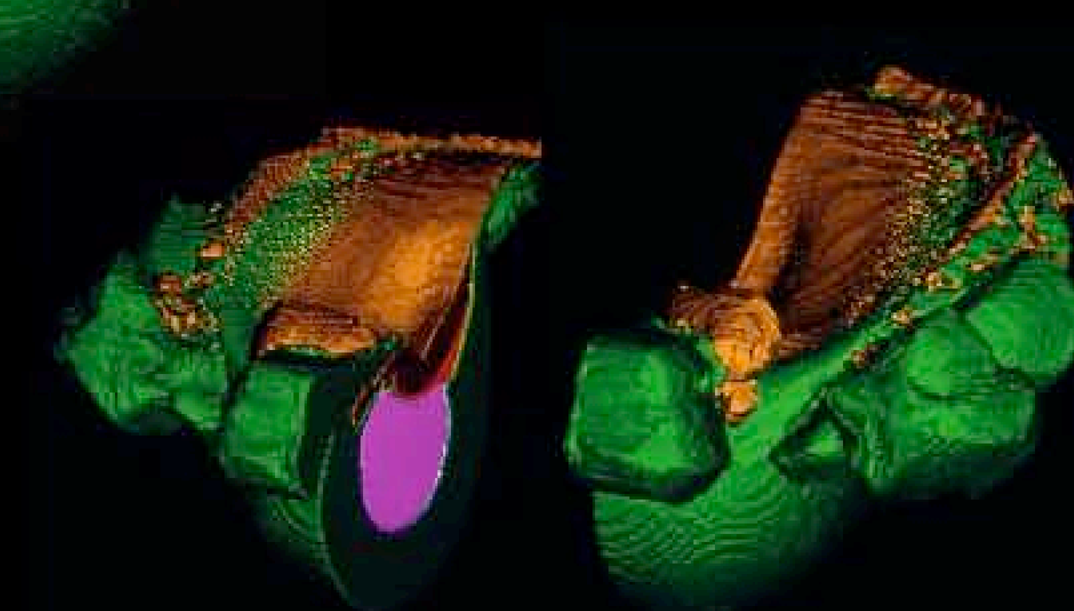
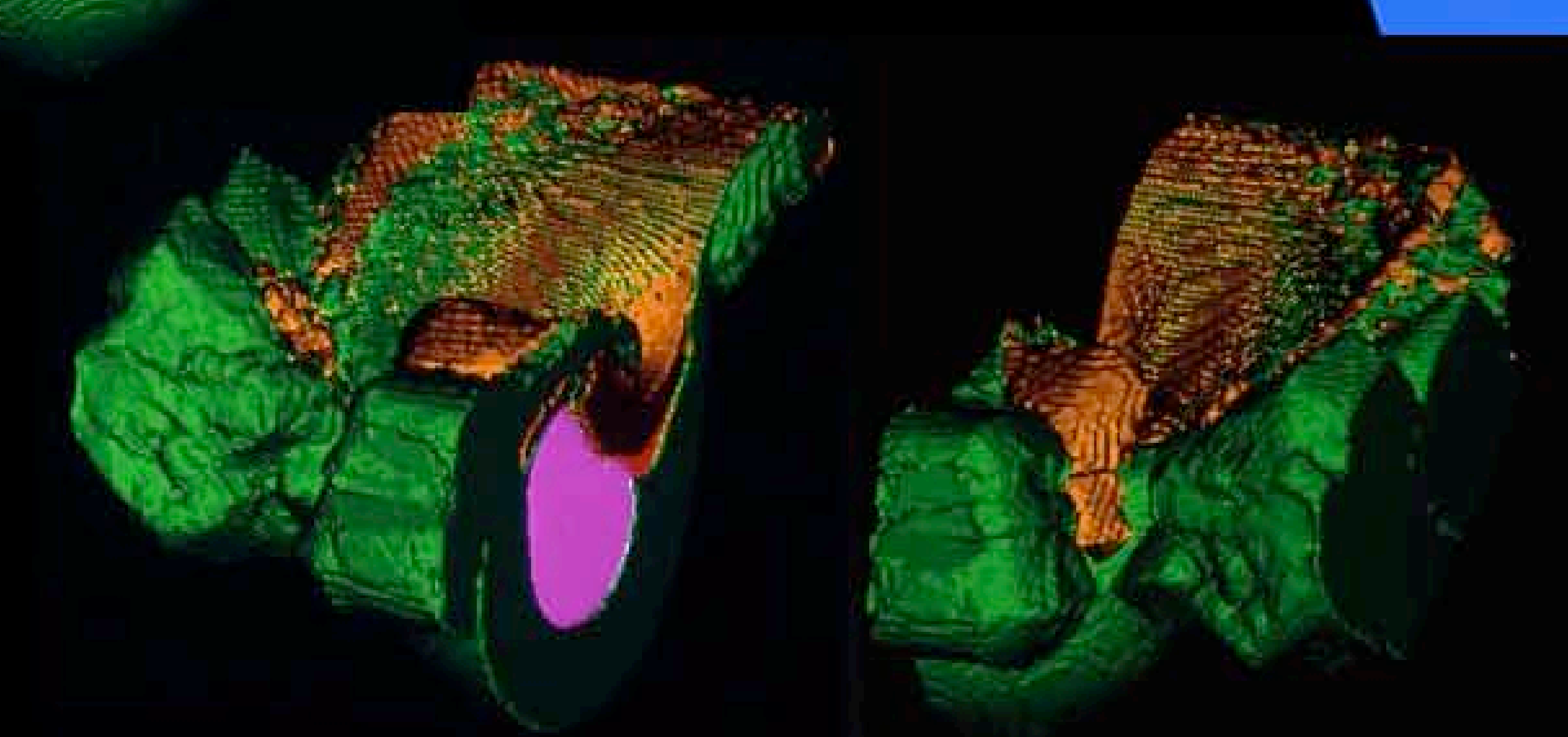
Both Earth and Moon accreted from small bodies at same position from sun

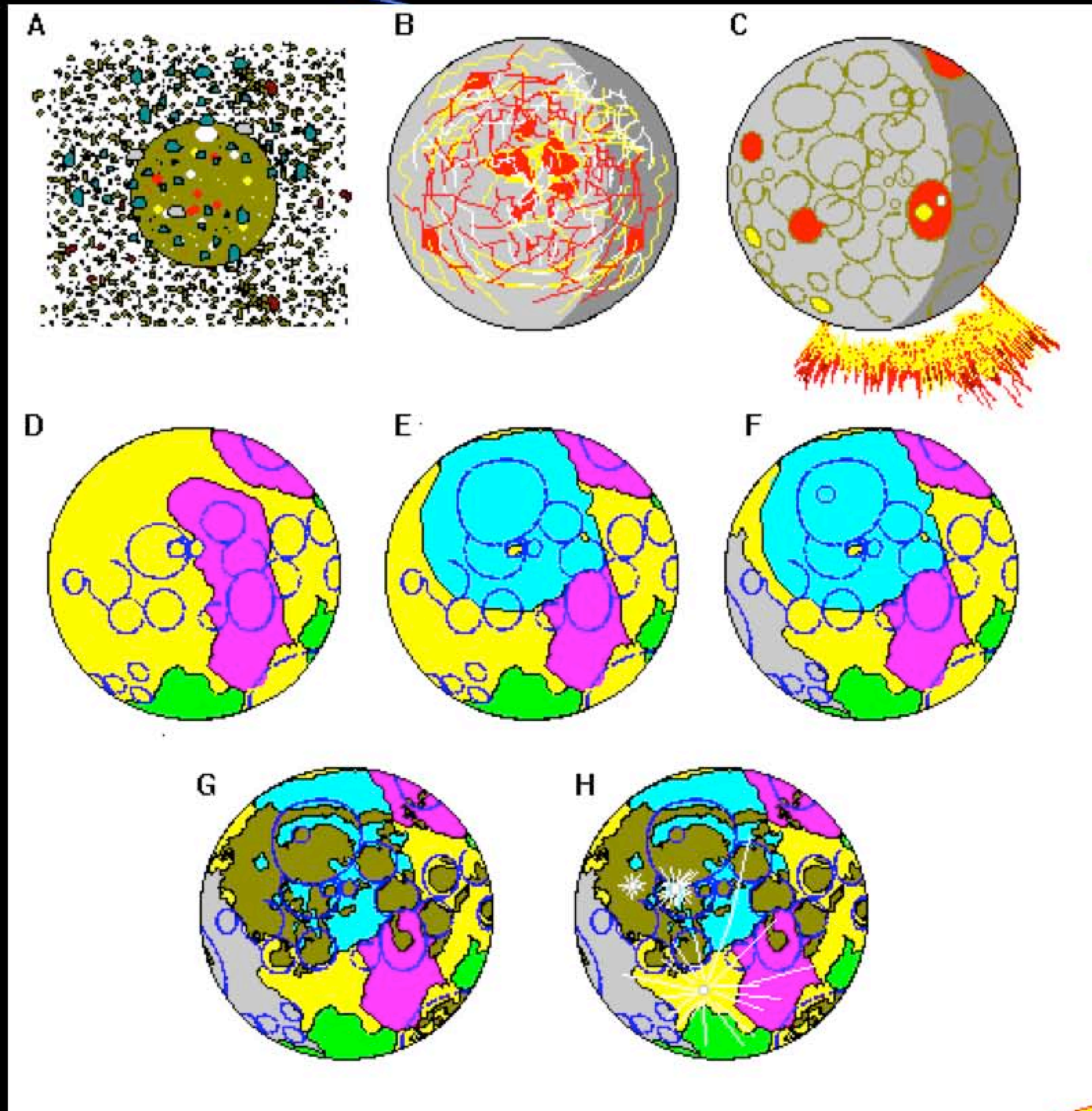


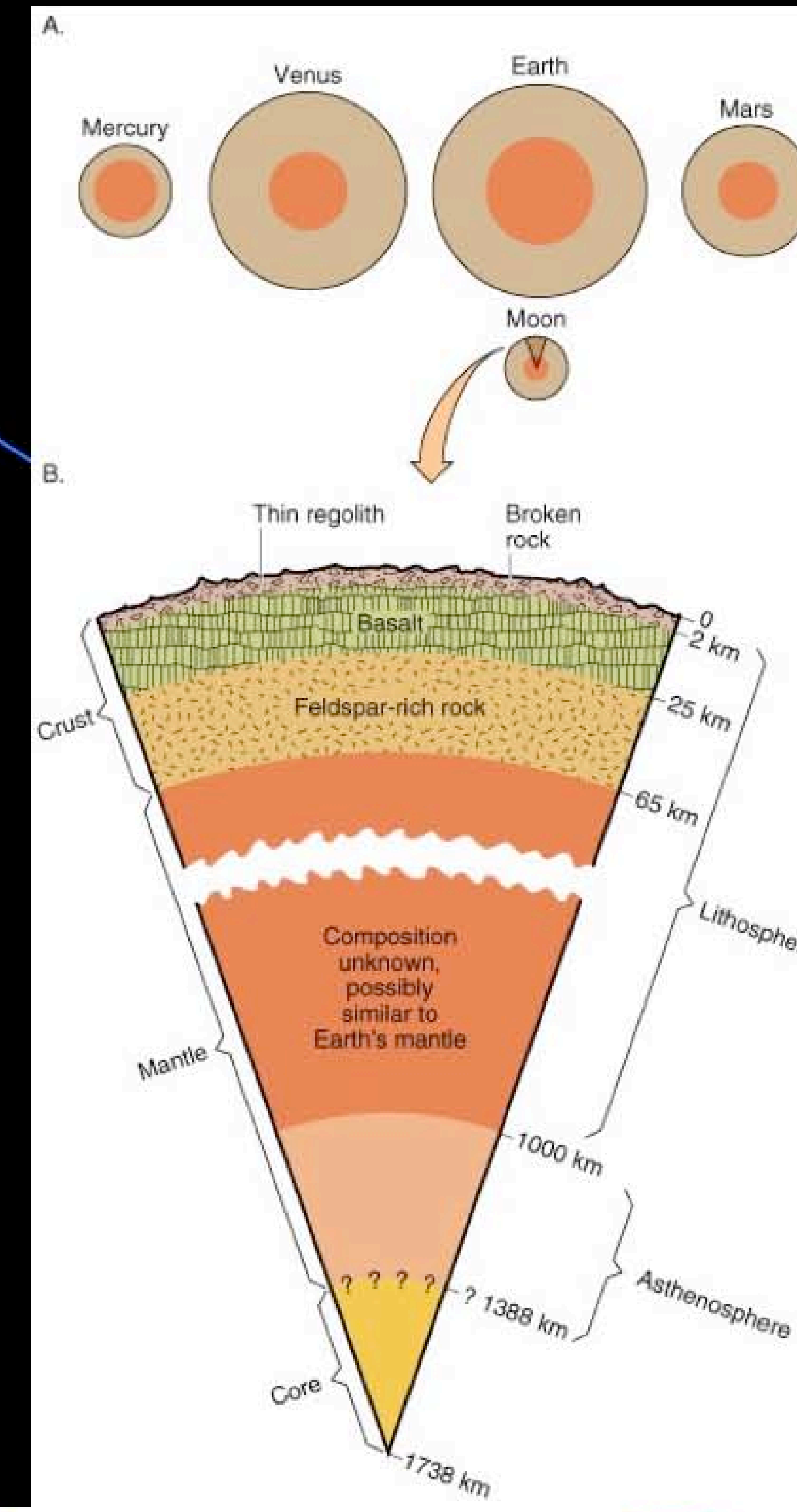



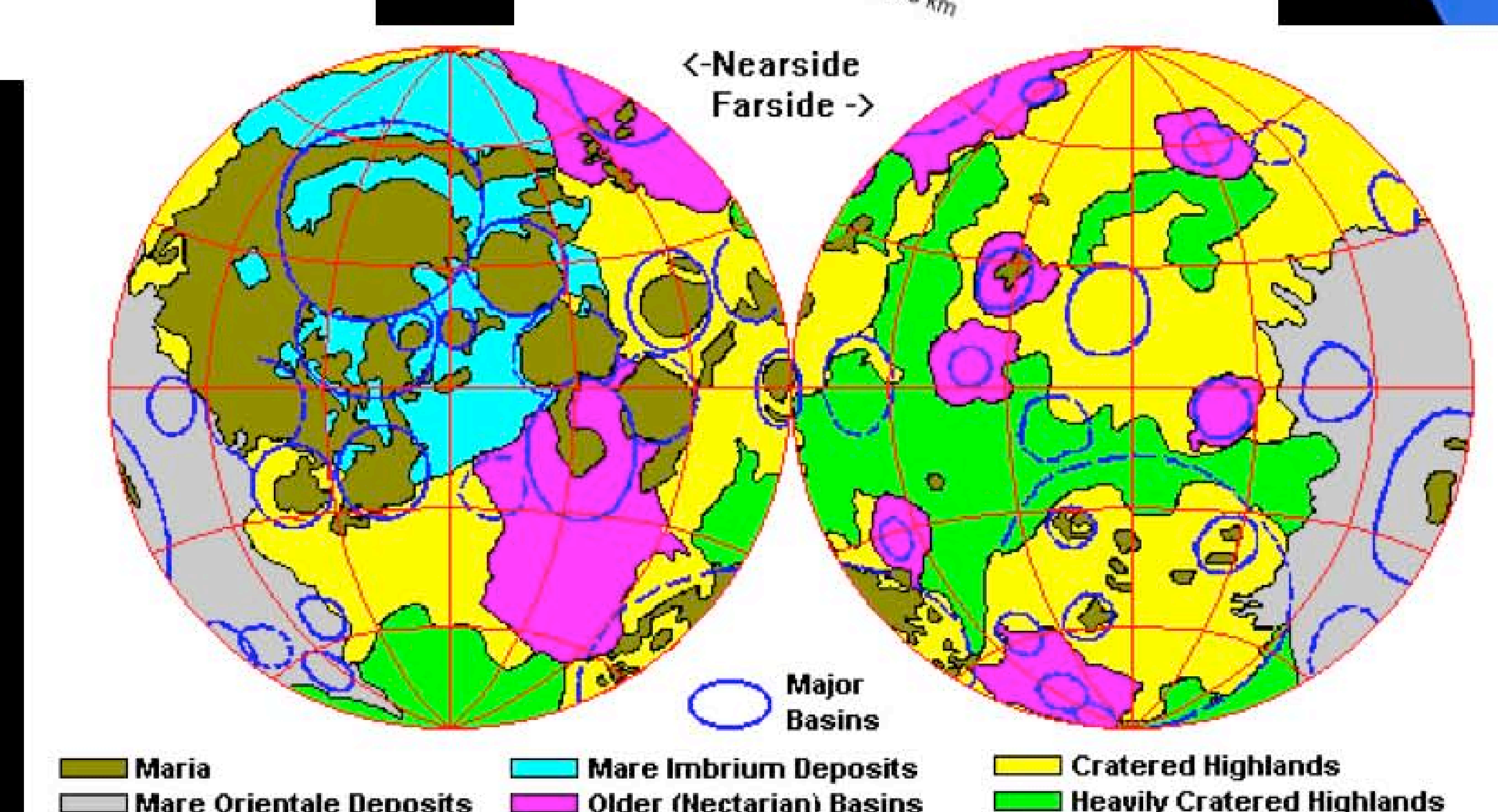
Lunar Origin

Giant Impact Hypothesis



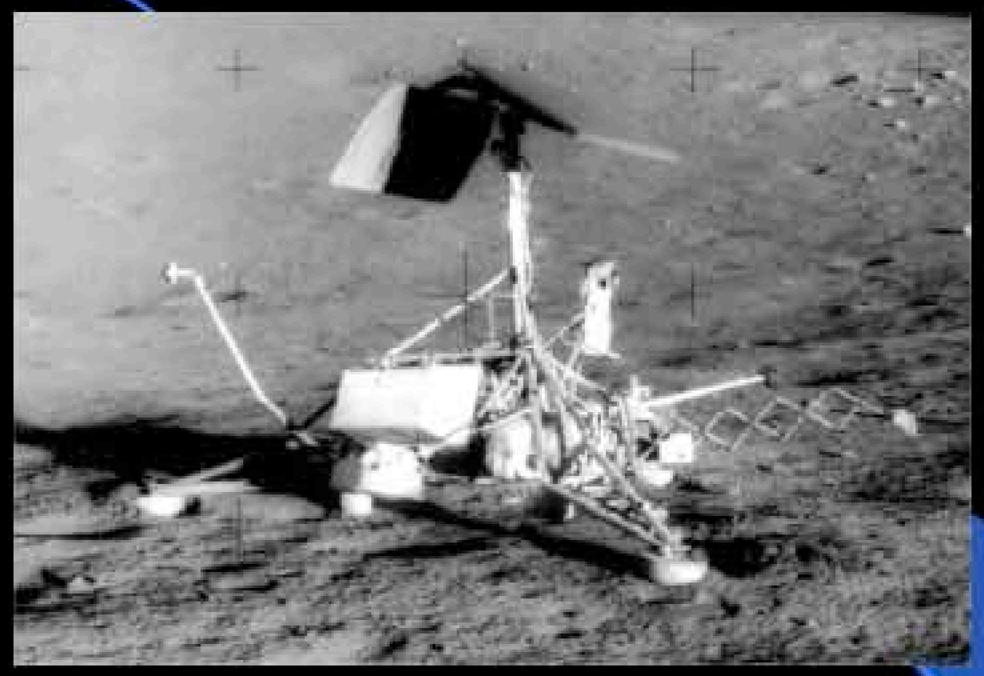
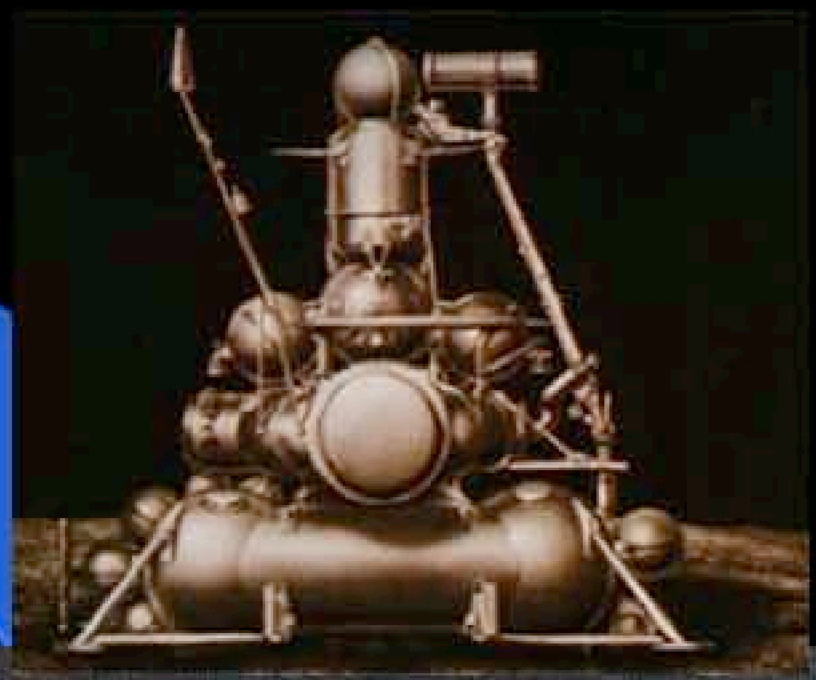
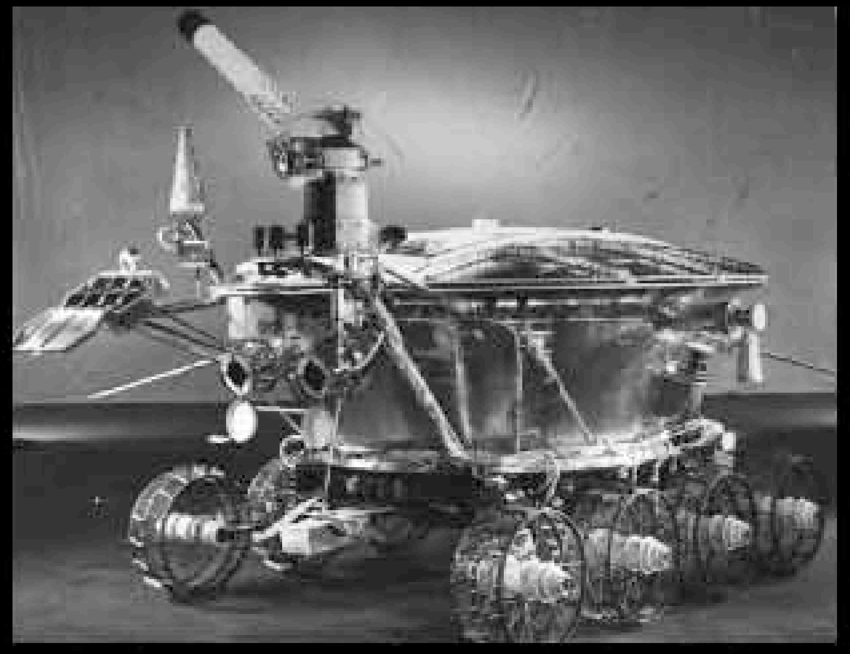
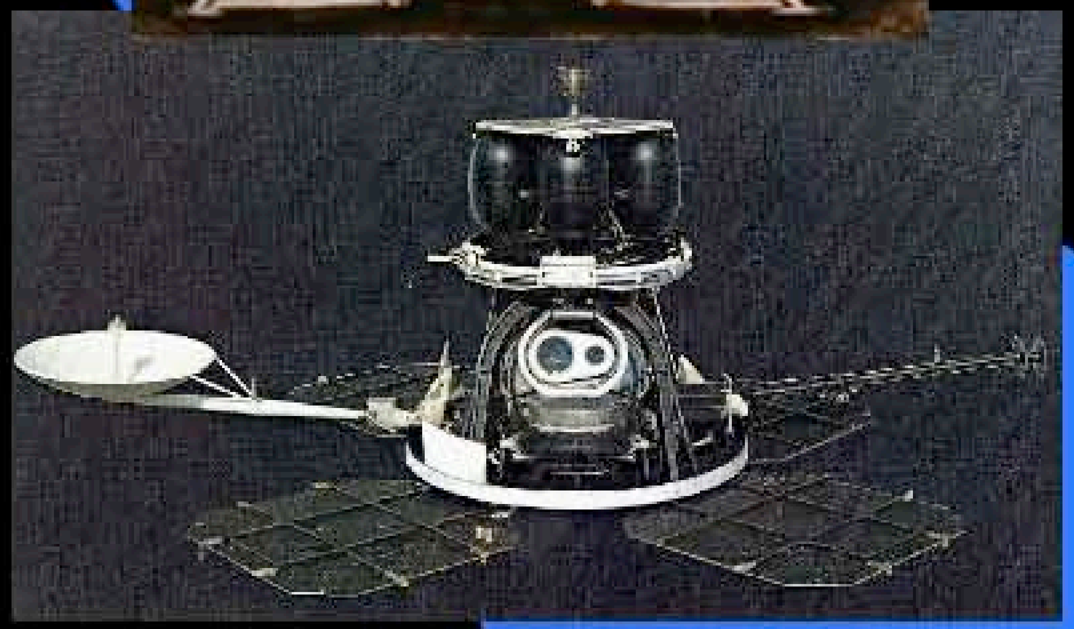
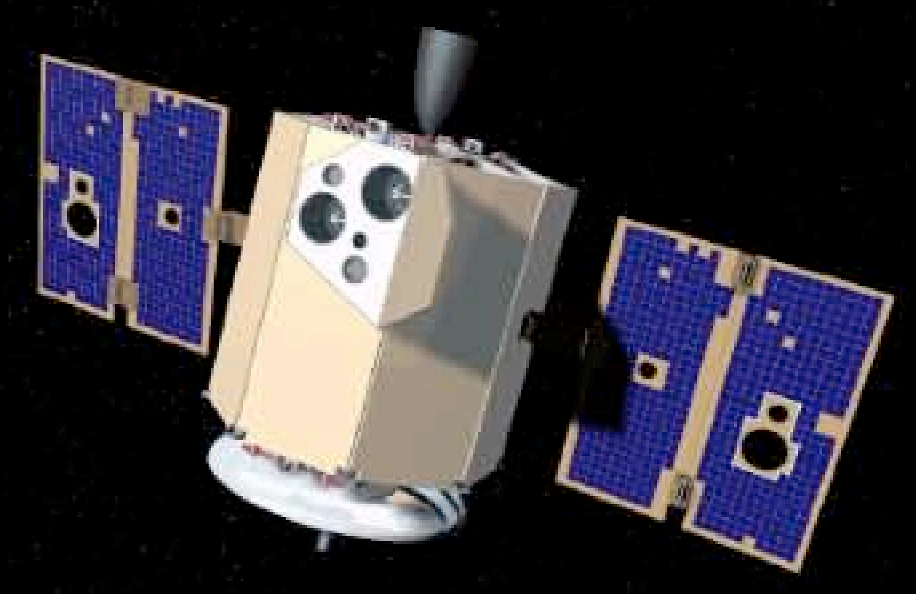
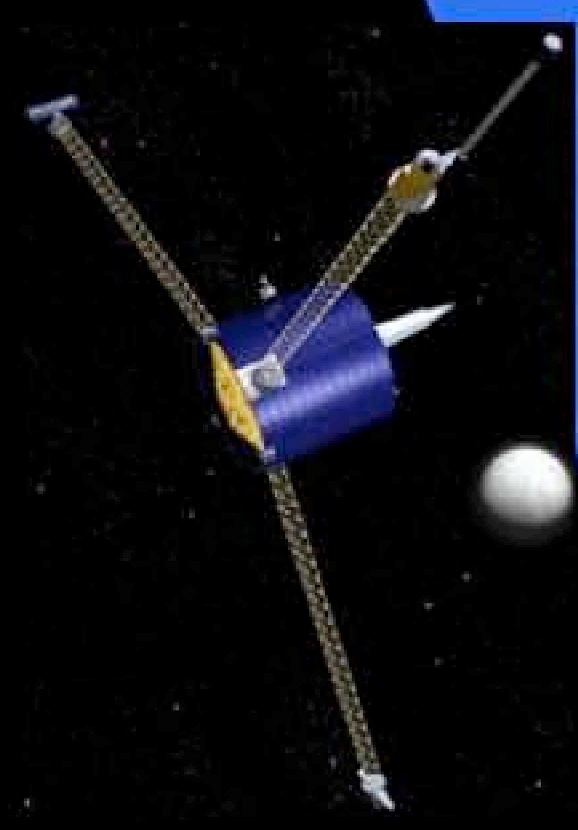




Lunar History and Evolution

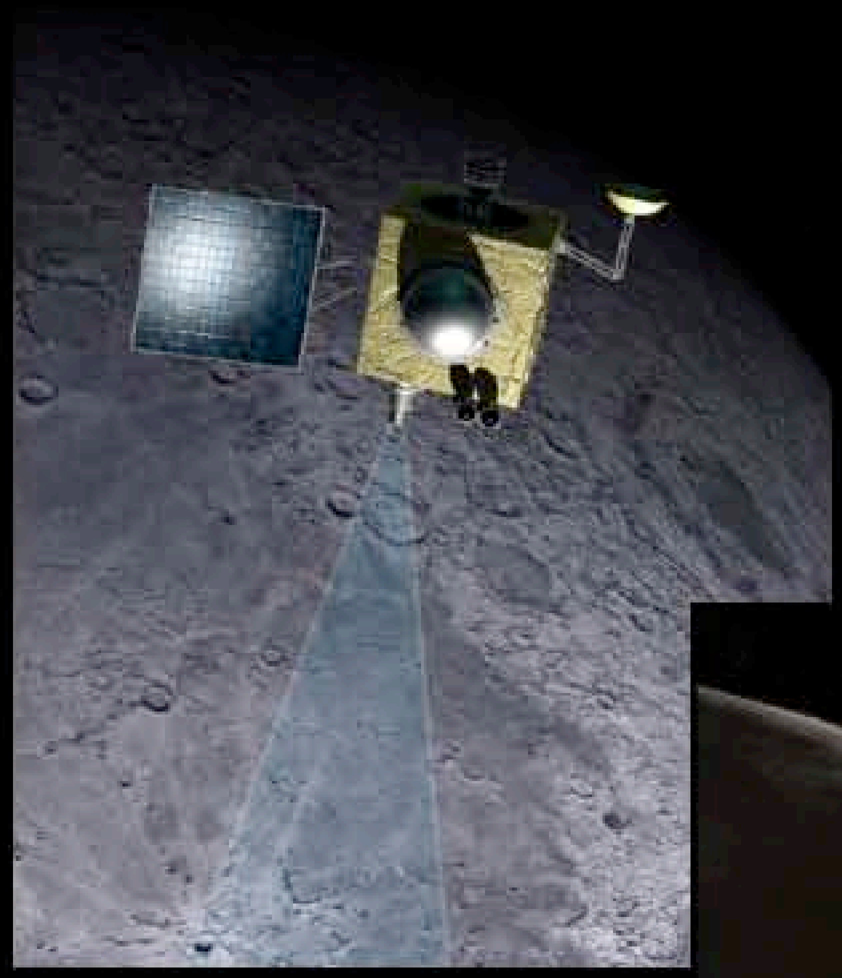
Lunar Robotic Missions

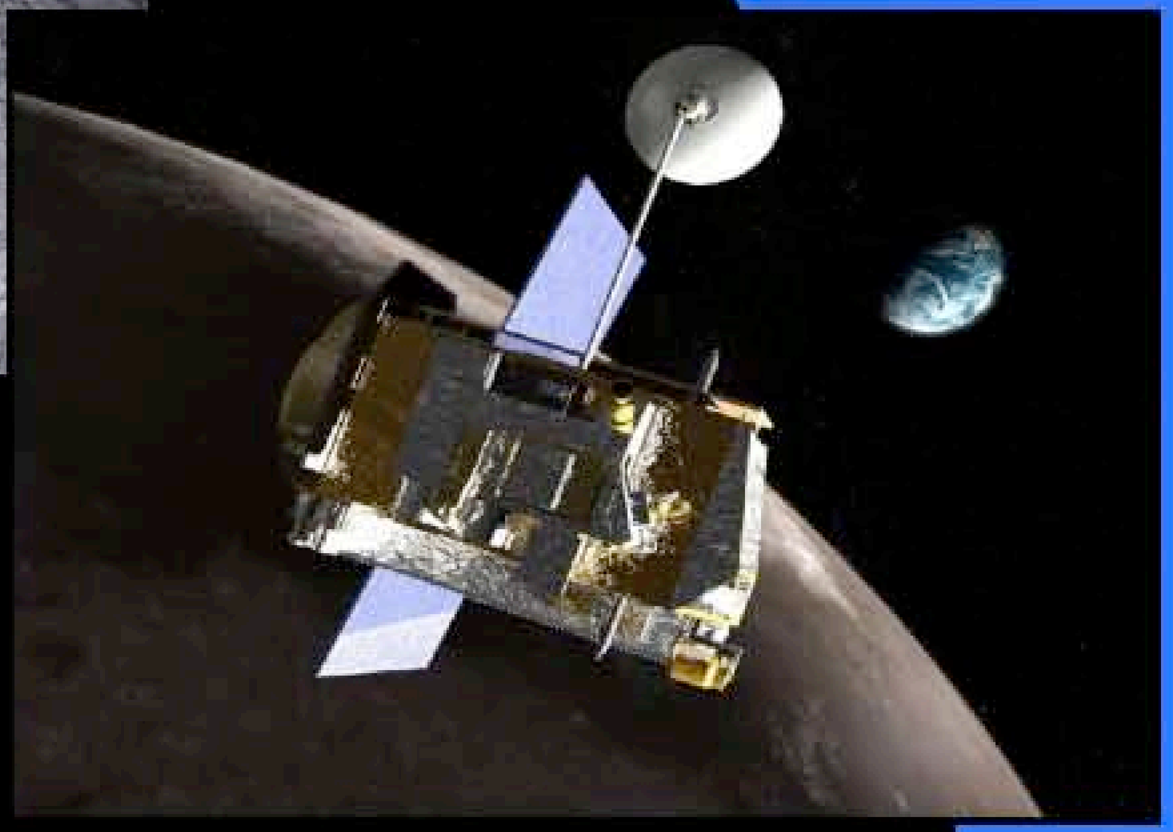
- Impactors
  - Ranger - imaging
- Soft landers
  - Surveyor - imaging and chemical analysis
  - Luna 16, 20, 24 -sample return
  - Lunakhod - long-range rover
- Orbiters
  - Lunar Orbiter - global and site mapping
  - Clementine - global mapping
  - Lunar Prospector - global mapping
  - SMART-1 - technology demo


Current Lunar Missions

- All polar orbiting global mappers, 100 km altitude (200 km for Change'E; 50 km for LRO), 1-2 yr duration
- Kaguya (SELENE)
  - Every remote-sensor known to man
- Chang'E
  - Imaging, microwave radiometry
- Chandrayaan-1
  - Imaging, altimetry, mineralogy, SAR
- Lunar Reconnaissance Orbiter
  - Geodesy, thermal IR, neutron, SAR





Existing and Future Lunar Data

Coverage and Resolution

Property	Present	Future
Topography	30 km H; 50 m V	10 m H; 2 m V
Geodesy	0.5 to 15 km	global < 100 m
Morphology	200 m; 5 bands	5 m; 8 bands
Chemistry	Th, Fe, Ti; 30 km	All majors; 15-30 km
Mineralogy	Ol, Px, Plg; 200 m	All; 80 m
Gravity	near; 40 km ± 30 mgal	global; 30 km ± 10 mgal
Magnetic field	global; 100 km ± 5 nT	global; 100 km ± 1 nT
Atmosphere	detected; species ± 10%	global; temporal ~days; species ± 1%

Suggested Reading

Wilhelms D.E. (1987) *Geologic History of the Moon*. USGS Prof. Paper 1348, 302 pp. Available at: http://ser.sese.asu.edu/GHM/

Heiken G., Vaniman D. and French B., eds. (1991) *Lunar Sourcebook*, Cambridge Univ. Press, 756 pp. CD-ROM version available; details at: https://www.lpi.usra.edu/store/products.cfm?cat=8

Spudis P.D. (1996) *The Once and Future Moon*, Smithsonian Institution Press, Washington DC, 308 pp. http://www.amazon.com/Future-Smithsonian-Library-Solar-System/dp/1560986344/ref=sr_1_1?ie=UTF8&s=books&qid=1212426761&sr=1-1

Wood C.A. (2003) *The Modern Moon*, Sky Publishing, Cambridge MA, 209 pp. http://www.amazon.com/Modern-Moon-Personal-View/dp/0933346999/ref=pd_bbs_sr_1?ie=UTF8&s=books&qid=1212426952&sr=1-1

Bussey B. and Spudis P.D. (2004) *The Clementine Atlas of the Moon*, Cambridge Univ. Press, Cambridge UK, 376 pp. http://www.amazon.com/Clementine-Atlas-Moon-Ben-Bussey/dp/0521815282/ref=pd_sim_b_title_3

Moon 101 - A Look Ahead

June 4, 2008 Introduction (Spudis) – motions, history of orbit/axis tilt, surface conditions, general properties, proposed origin.

June 18, 2008 Environment (Mendell) – thermal, radiation, plasma, electrical (including interactions with Earth's magnetosphere), exosphere

July 2, 2008 Physiography and geology (Spudis) – terrains, landforms, topography (photogeology). Impact crater formation, excavation, ejecta emplacement, secondaries, impact melting and shock metamorphism, lunar meteorites. Flux through time; cataclysm, periodicity, correlation with terrestrial record and other planets

July 16, 2008 Surface (Lindsay) – dust, rocks, slopes, trafficability (geotechnical properties). Formation and evolution of regolith, interface with bedrock. Crater size-frequency distributions, exotic components, highland/mare mixing, vertical and lateral transport of material. Chemical and mineral composition, physical state, properties, characteristics

July 30, 2008 Crust (Lofgren) – formation and evolution, highland rocks types and magmatism, rock provinces and terranes; Volcanism: magma types, flood v. central vent eruptions, pyroclastics, number of flows, thicknesses, changes in composition with time, history; deformation and tectonic history

August 13, 2008 Interior (Plescia) – megaregolith, crustal thickness and variation, near side/far side dichotomy, mantle/core size, composition, heat flow, lunar magnetism, bulk composition

August 27, 2008 Poles (Bussey) – environment, sunlight and shadow, volatiles, opportunities and difficulties of living and working at the poles

September 10, 2008 The Apollo Program (Eppler) - architecture, capabilities, evolution, surface exploration, rover experience, advanced Apollo (cancelled missions)

September 24, 2008 Exploration (Eppler/Spudis)– geological reconnaissance and field work, surveys, traverses, transects, stratigraphy and the third dimension, bedrock on the Moon

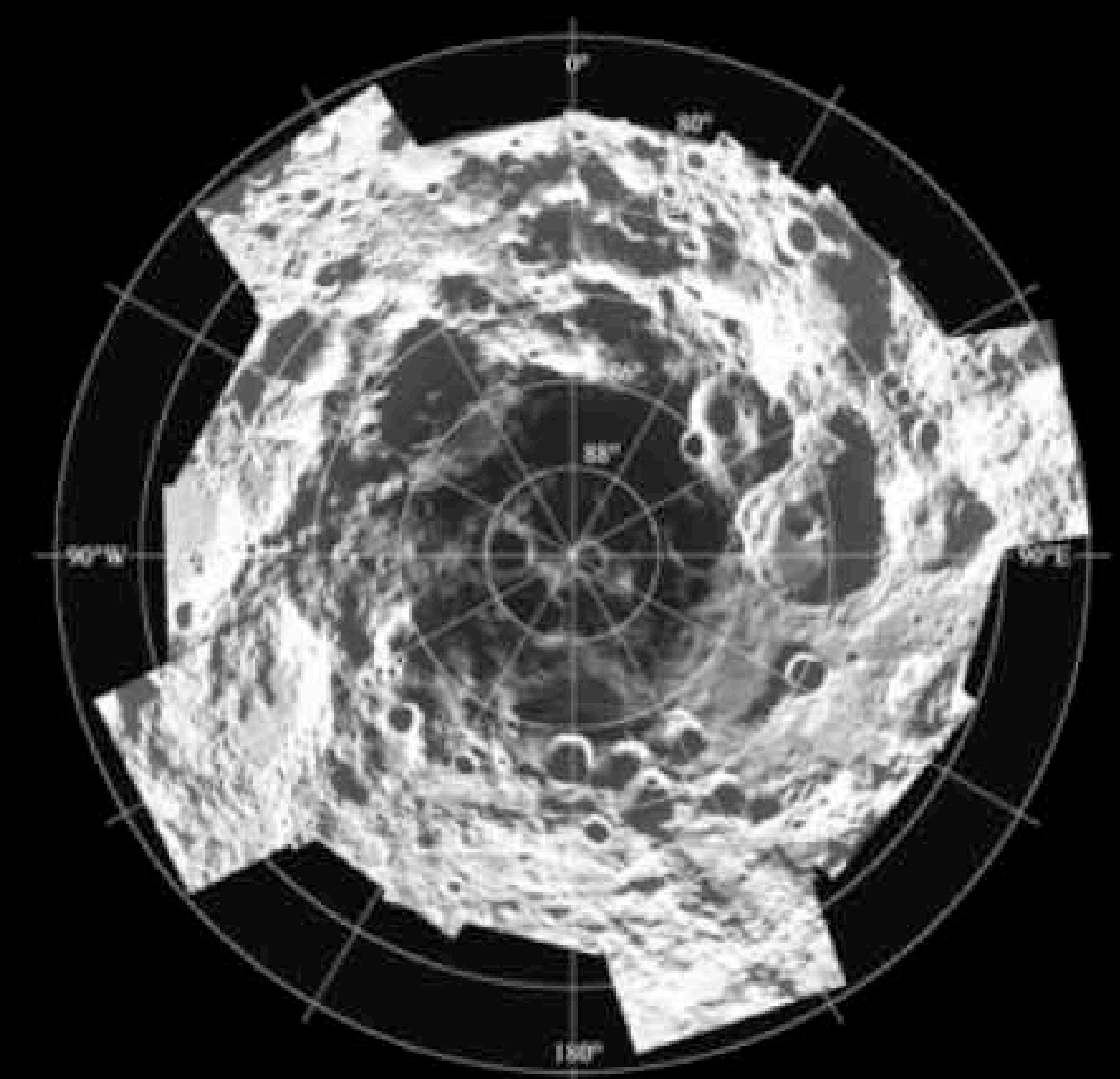
October 8, 2008 Stations and observatories (Eppler/Spudis) – site selections and surveys, networks, emplacement, construction, alignment, maintenance

For more information, go to:
http://www.spudislunarresources.com

Spudis Lunar Resources

Using the Moon to learn how to live and work productively in space

What's this web site all about?



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spudis@lpi.usra.edu

THE ROCK THAT FELL TO EARTH

When an asteroid was spotted heading towards our planet last October, researchers rushed to document a cosmic impact from start to finish for the first time. **Roberta Kwok** tells the tale.

Around midnight on 6 October 2008, a white dot flitted across the screen of Richard Kowalski's computer at an observatory atop Mount Lemmon in Arizona. Kowalski had seen hundreds of such dots during three and a half years of scanning telescope images for asteroids that might hit Earth or come close. He followed the object through the night and submitted the coordinates, as usual, to the Minor Planet Center in Cambridge, Massachusetts, which keeps track of asteroids and other small bodies. When the sky began to brighten, he shut down the telescope, went to the dorm down the mountain and fell asleep.

The only thing that had puzzled Kowalski about the midnight blip was the Minor Planet Center's response to his report. Its website posted the discovery right away but when he tried to add more data, the system stayed silent.

Tim Spahr, the Minor Planet Center's director, found out why the following morning. The centre's software computes orbits automatically, but this asteroid was unusually close to Earth. "The computer ran to me for help," says Spahr. He did some quick calculations on Kowalski's data to figure out the path of the asteroid, which was now named 2008 TC_3. "As soon as I looked at it and did an orbit manually, it was clear it was going to hit Earth," he says.

The brightness of 2008 TC_3 suggested it was only a few metres across and, assuming it was a common rocky asteroid, would probably split into fragments soon after entering the atmosphere. But safe as that might seem, Spahr had procedures to follow. He called Lindley Johnson, head of NASA's Near Earth Object Observations programme in Washington DC, on his BlackBerry — a number only to be used in emergencies.

"Hey Lindley, it's Tim," said Spahr. "Why would I be calling you?"

Johnson's response: "We're going to get hit?"

Spahr also called astronomer Steve Chesley of the Jet Propulsion Laboratory (JPL) in Pasadena, California, who at the time was hustling his kids out of the door for school. Chesley hurried into the office, ran a program to calculate the asteroid's orbit and "was astounded to see 100% impact probability", he says. "I'd never seen that before in my life." Chesley calculated that the asteroid would hit Earth's atmosphere less than 13 hours later, at 2:46 UT the next day; the impact site would be northern Sudan, where the local time would be 5:46 a.m.. He sent his results to NASA headquarters and the Minor Planet Center, which circulated an electronic bulletin to a worldwide network of astronomers. A group called NEODys in Pisa, Italy, also confirmed that an impact was nearly certain.

> "Listen guys, this is happening, this is going to happen tonight." — Alan Fitzsimmons

Although several small objects such as 2008 TC_3 hit Earth each year, researchers had never spotted one before it struck. Kowalski's discovery, therefore, provided a unique chance to study an asteroid and its demise in real time, if astronomers could mobilize resources around the world quickly enough.

Soon e-mails and phone calls were flying across the globe as scientists raced to coordinate observations of the incoming asteroid. "IMPACT TONIGHT!!!" wrote physicist Mark Boslough of Sandia National Laboratories in Albuquerque, New Mexico, to colleagues, including a Sandia engineer responsible for monitoring US government satellite data.

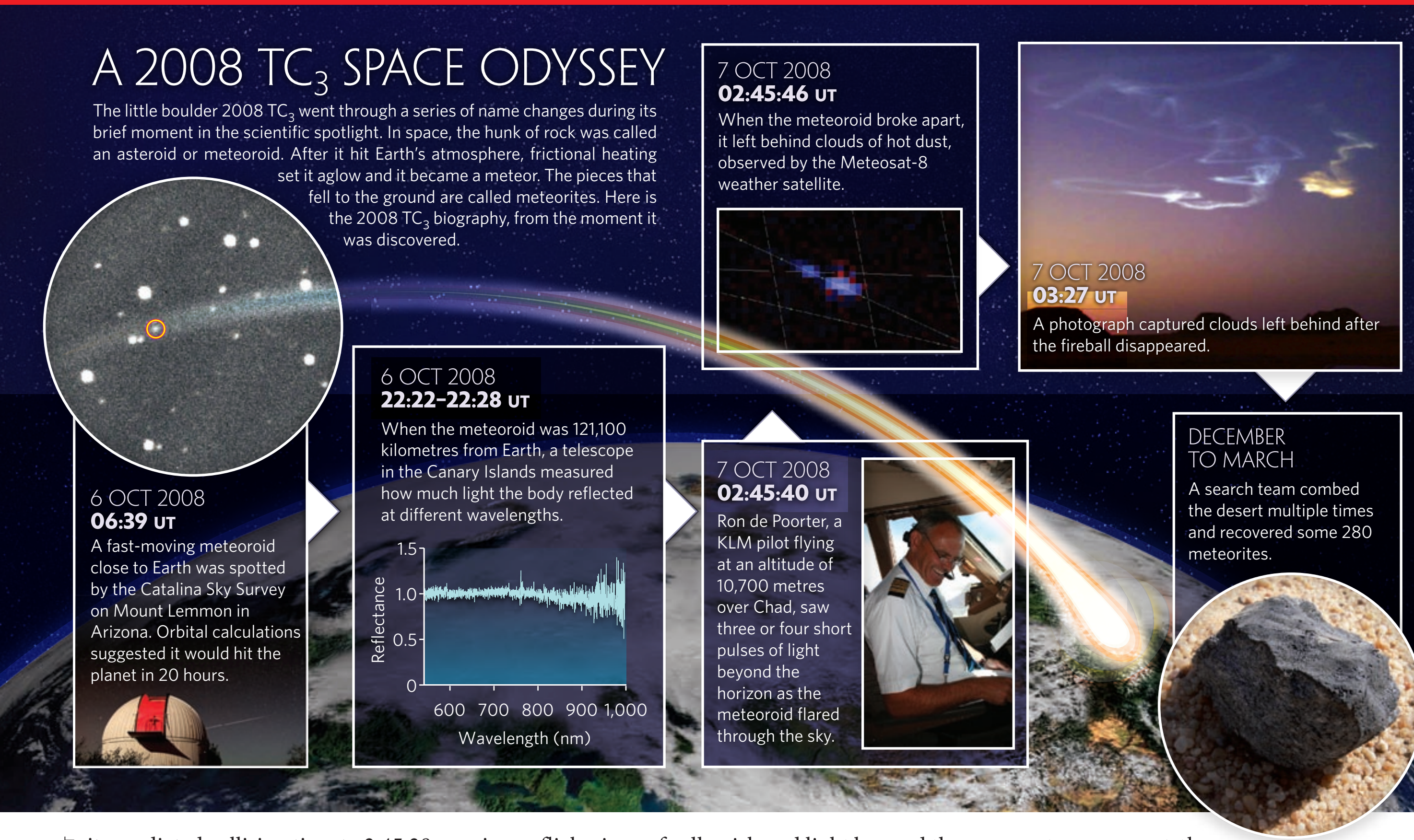
Countdown to impact

Peter Brown, an astronomer at the University of Western Ontario in Canada who heard the news from JPL, ran to his local observatory, fired up the telescope and began tracking the asteroid, which looked like "a very small, faint, fast-moving streak", he says. Alan Fitzsimmons at Queen's University Belfast in Northern Ireland called two of his colleagues, who had just arrived at the William Herschel Telescope at La Palma on the Canary Islands and were not scheduled to use the telescope until the next day.

"Listen guys, this is happening, this is going to happen tonight," he told the researchers, who arranged to borrow an hour of observing time from another astronomer.

All day, observations poured into the Minor Planet Center, which released new data and orbit calculations several times an hour. NASA notified other government agencies, including the state and defence departments, and issued a press release that afternoon saying that the collision could set off "a potentially brilliant natural fireworks display". About an hour before impact, the asteroid slipped into Earth's shadow and out of view to optical telescopes. By then, astronomers from 26 observatories worldwide had already captured and submitted about 570 observations, allowing JPL to refine

P. JENNISKENS



NASA/UNIV. ARIZONA; FULL MOON PHOTOGRAPHY; A. FITZSIMMONS, QUEEN'S UNIV. BELFAST

R. DE POORTER; EUMETSAT & CHMI (Z. CHARVAT); COURTESY OF M. E. ABDELATIF MAHIR/M. H. SHADDAD/P. JENNISKENS; P. JENNISKENS

its predicted collision time to 2:45:28 UT, give or take 15 seconds.

As the countdown progressed, Jacob Kuiper fretted. Kuiper, an aviation meteorologist on the night shift at the Royal Netherlands Meteorological Institute in De Bilt, had seen an e-mail about the incoming asteroid. And he was worried that no one would see the explosion in the sparsely populated Nubian Desert.

With less than 45 minutes left, Kuiper realized he could notify Air France-KLM — the airline to which he routinely issued weather reports — which probably had planes flying over Africa. About ten minutes later, pilot Ron de Poorter received a message print-out in the cockpit of KLM flight 592, flying north from Johannesburg to Amsterdam. The message gave the latitude and longitude of the predicted asteroid impact. De Poorter calculated that he would be a distant 1,400 kilometres from the collision. Still, at the appointed time he and his co-pilot dimmed the instrument lights and peered northeast.

Far above the plane, asteroid 2008 TC_3 hit the top of the atmosphere at about 12,400 metres per second. The collision heated and vaporized the outside of the rock, ripping material from its surface. The impact of rock atoms with air molecules created a brilliant flash that lit the desert below. Less than 20 seconds after 2008 TC_3 entered the atmosphere, calculations suggest, pressure on the rock triggered a series of explosions that shattered it, leaving a trail of hot dust.

From the cockpit of his plane, de Poorter saw flickerings of yellowish-red light beyond the horizon, like distant gunfire. The flash woke a station manager at a railway outpost in Sudan. In a village near the Egyptian border, people returning from morning prayers saw a fireball that brightened and flared out, according to accounts collected later by researchers.

Electronic eyes watched, too. US government satellites spotted the rock when it was 65 kilometres above the ground. Moments later, it was picked up by a European weather satellite, which caught two dust clouds and light from the fireball. An array of microbarometers in Kenya normally used to monitor for nuclear explosions detected low-frequency sound waves from the blast, which Brown later calculated would be equivalent to about 1–2 kilotonnes of TNT, roughly one-tenth the size of the atomic bomb dropped on Hiroshima.

> **"We have never had such concrete affirmation all the machinery works."**
> — Steve Chesley

Tracking of the fireball's trajectory by US satellites showed that JPL accurately predicted the object's location within a few kilometres and a few seconds. "We have never had such a concrete affirmation that all the machinery works," says Chesley.

But for Peter Jenniskens, an astronomer at the SETI Institute in Mountain View, California, the spectacular light show was not enough. For weeks after the asteroid hit, Jenniskens, who studies meteor showers, waited to hear whether someone had found the fallen meteorites. No news emerged. "Somebody needed to do something," he says.

Jenniskens flew to Sudan in early December and met with Muawia Hamid Shaddad, an astronomer at the University of Khartoum who had already obtained pictures of the fireball's trail from locals. Together, they drove north from Khartoum to the border town of Wadi Halfa, asking villagers where the fireball had exploded in the sky. These eyewitness accounts convinced Jenniskens that the rock had disintegrated high in the atmosphere — in good agreement with US satellite data — and that any fragments were most likely to be found southwest of Station 6, a tiny railroad outpost in the Nubian Desert.

Desert search

On 6 December 2008, Jenniskens and Shaddad set out with a group of 45 students and staff from the University of Khartoum to scour the area. Team members lined up about 20 metres apart over a kilometre-wide strip, facing a sea of sand and gravel interspersed with hills, rocky outcrops and dry winding riverbeds. Flanked by two pairs of cars and trailed by a camera crew from news network Al Jazeera, the line of searchers began marching slowly east, like the teeth of a massive comb being dragged through the desert.

Towards the end of the day, a car approached Jenniskens with news that a student might have found a meteorite. "I remember thinking, 'oh no, not again,'" says Jenniskens, who had already fielded several false alarms. Still, he jumped in the car and drove to the student, who presented him with a small square fragment, about a centimetre and a half across with a thin, glassy outer layer. The surface resembled the crust that meteorites form after being melted and solidified, and the rock's deep black colour suggested it was freshly fallen. It was the team's first meteorite — and the first time that scientists had ever recovered a meteorite from an asteroid detected in space (see page 485).

The next day, the team walked 8 kilometres and found 5 meteorites, all very dark and rounded. On the third day, a trek of 18 kilometres yielded larger meteorites nearly 10 centimetres across. A few weeks later, a team of 72 students and staff found 32 more, and the most recent field campaign, completed in March, brought the tally to about 280 fragments weighing a total of several kilograms.

Jenniskens couriered a sample to Mike Zolensky, a cosmic mineralogist at the NASA Johnson Space Center in Houston, Texas. Examining the rock, Zolensky discovered that it contained large chunks of carbon and glassy mineral grains resembling sugar crystals. Tests at other labs confirmed that the sample was a ureilite, a type of meteorite thought to come from asteroids that have melted during their time in space. Only 0.5% of objects that hit Earth yield fragments in this category. But 2008 TC$_3$'s pieces are strange even for ureilites: they are riddled with an unusually large number of holes, says Zolensky. "It boggles the mind that something that porous could survive as a solid object," he says.

The findings suggest that 2008 TC$_3$ broke from the surface of a larger asteroid, as the pores would have been crushed if they were near the rock's centre, says Zolensky. He suggests that future studies of the meteorites' chemistry could help reveal the history of its parent asteroid. Moreover, the new finds might eventually yield clues to how planets form, he says, because the asteroid had melted during its history, a process that young planets go through.

2008 TC$_3$ gave astronomers a rare chance to connect a dot in the sky with rocks in their hands. "We have a lot of meteorites on the ground and a whole lot of asteroids up there, and forging a link is not easy," says Don Yeomans, manager of NASA's Near-Earth Object Program Office at JPL.

Jenniskens and his team concluded the asteroid belonged to a group called F-class asteroids. These asteroids reflect very little light, and scientists had been unsure what they were made of. The new evidence "opens a huge window", says Glenn MacPherson, a meteorite curator at the Smithsonian Institution in Washington DC, who was not involved in the studies of 2008 TC$_3$. Although not all F-class asteroids may be the same, he says, the data suggest at least some of them may contain the same material as ureilites, such as carbon and iron.

Clark Chapman, a planetary scientist at the Southwest Research Institute in Boulder, Colorado, says the connection between F-class asteroids and ureilites does not surprise him. But, he adds, "this is a proven link and we don't have many of those".

"It's like finding a man in a dark grey suit 50% farther away than the Moon" — Richard Kowalski

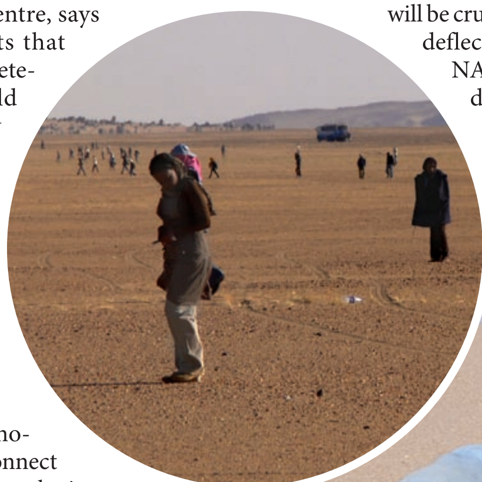
Scientists have tried to figure out the composition of asteroids by studying how they reflect various wavelengths of light and matching these features to meteorite samples in the lab. But such connections are often tenuous unless the reflection signature is very distinct. The most secure example is an asteroid called 4 Vesta, which has been associated with a group of igneous meteorites. No missions have yet returned asteroid fragments to Earth, although a NASA spacecraft orbited the asteroid Eros for a year and landed on it in 2001. Japan's Hayabusa mission attempted to collect a sample from the asteroid Itokawa in 2005; scientists will find out whether it succeeded when the spacecraft returns next year.

Knowing what asteroids are made of will be crucial if we ever need to deflect one, says Yeomans. NASA aims to provide decades of warning if any killer asteroids are headed for Earth so that a strategy can be devised to avoid a collision. That strategy will differ for various asteroids, which can range from "wimpy ex-cometary fluffballs", to solid rock, to slabs of nickel-iron, says Yeomans.

With the advent of new surveys, scientists could spot objects hurtling towards Earth more frequently. Today's surveys have found almost 90% of near-Earth objects with a diameter of 1 kilometre or larger, says Yeomans, but smaller rocks can easily slip by unnoticed. Discovering 2008 TC$_3$ was like finding "a man in a dark grey suit 50% farther away than the Moon", says Kowalski, who is part of the Catalina Sky Survey, an effort that discovers 70% of all the near-Earth objects found every year. The detection rate will increase with the next generation of surveys, perhaps up to a few Earth-bound asteroids per year, says Alan Harris, a planetary astronomer at the Space Science Institute who is based in La Canada, California. The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) in Hawaii will officially begin observations with its prototype system this year, and the Large Synoptic Survey Telescope in Chile is scheduled to begin full operations in 2016.

In the meantime, Kowalski and his colleagues are still on the job. The night after spotting asteroid 2008 TC$_3$, Kowalski headed back up Mount Lemmon, heated his dinner and settled down in the telescope's control room. As his discovery plunged towards the desert on the other side of the world, Kowalski was surveying another part of the sky, waiting for the next white dot. ■

Roberta Kwok is a news intern in *Nature*'s Washington DC office.



P. JENNISKENS

Peter Jenniskens (above) led the search for meteorite fragments in the Sudan desert (inset).