Introduction to the Moon

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Moon 101
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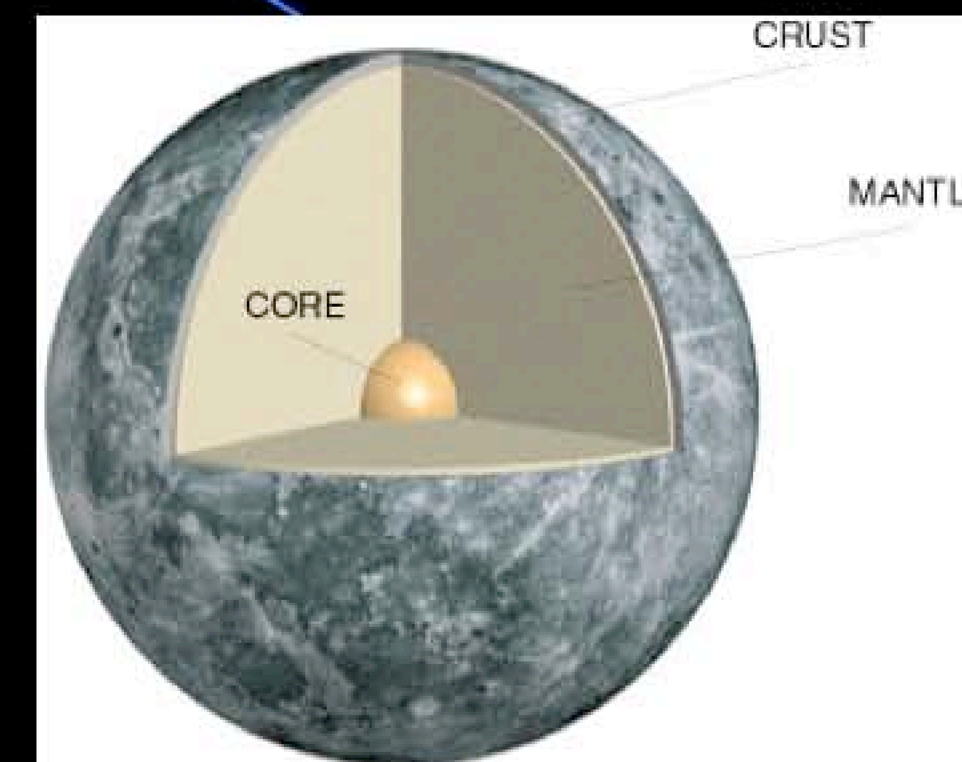
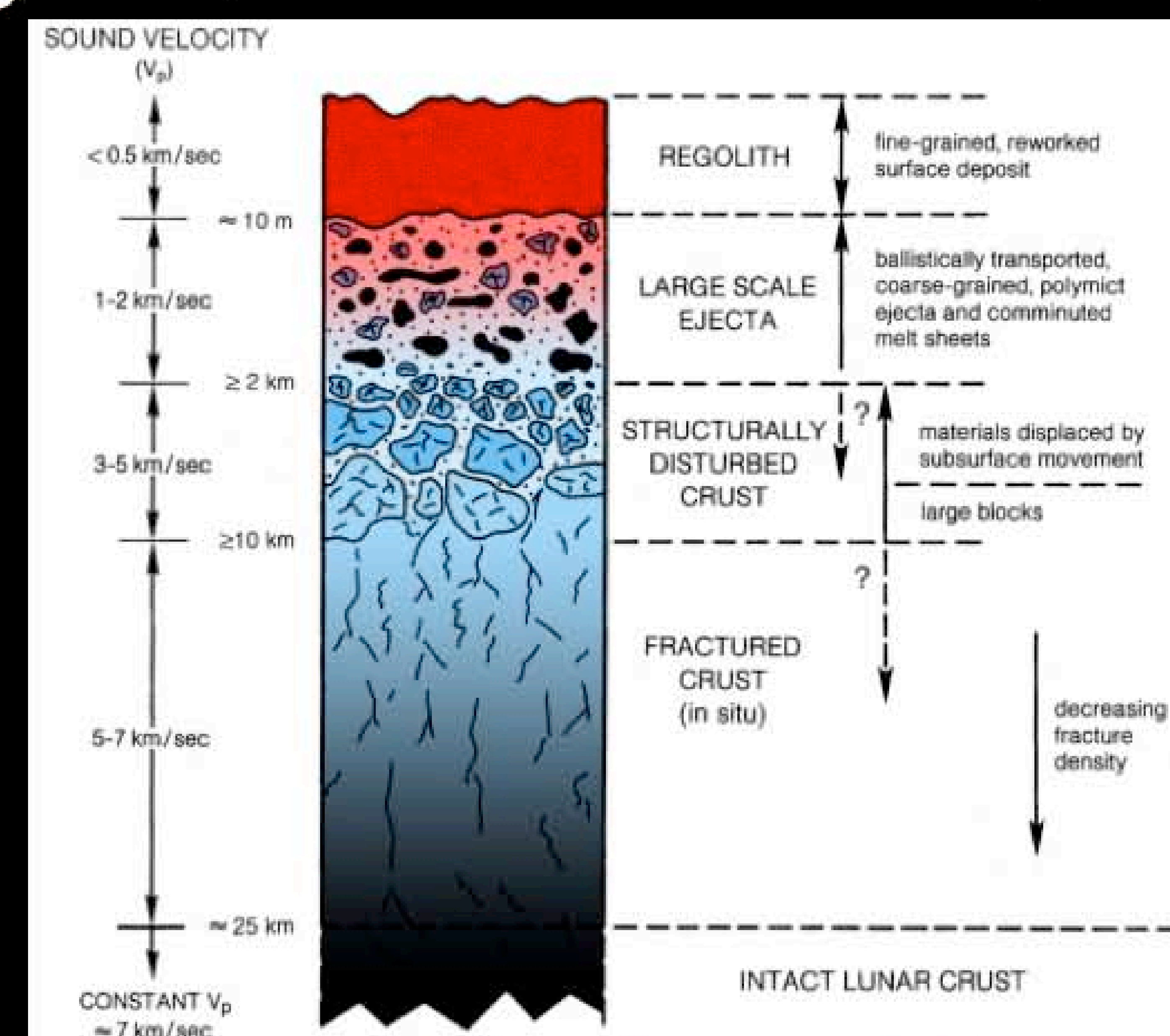
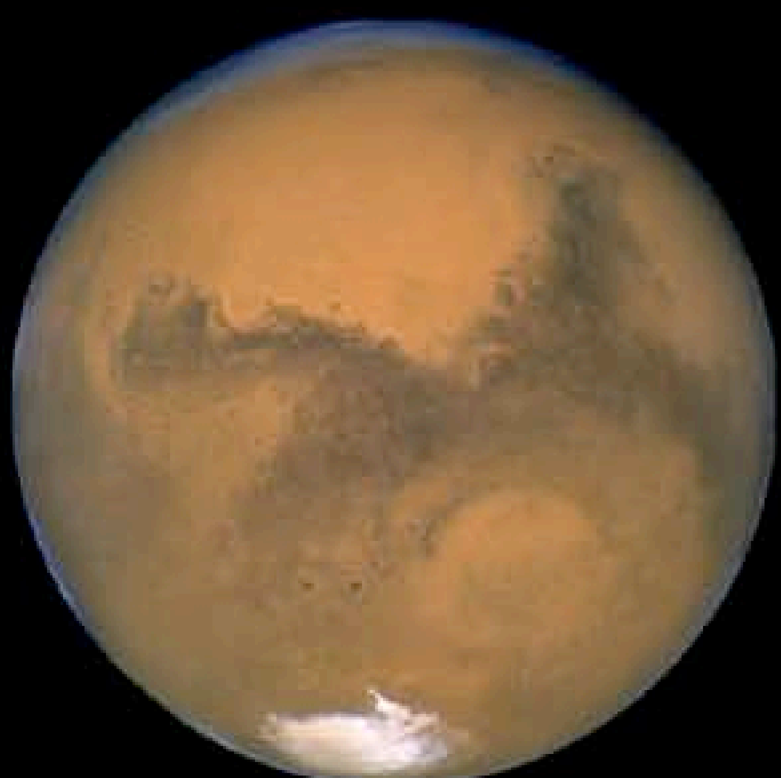
The Nature of the Moon

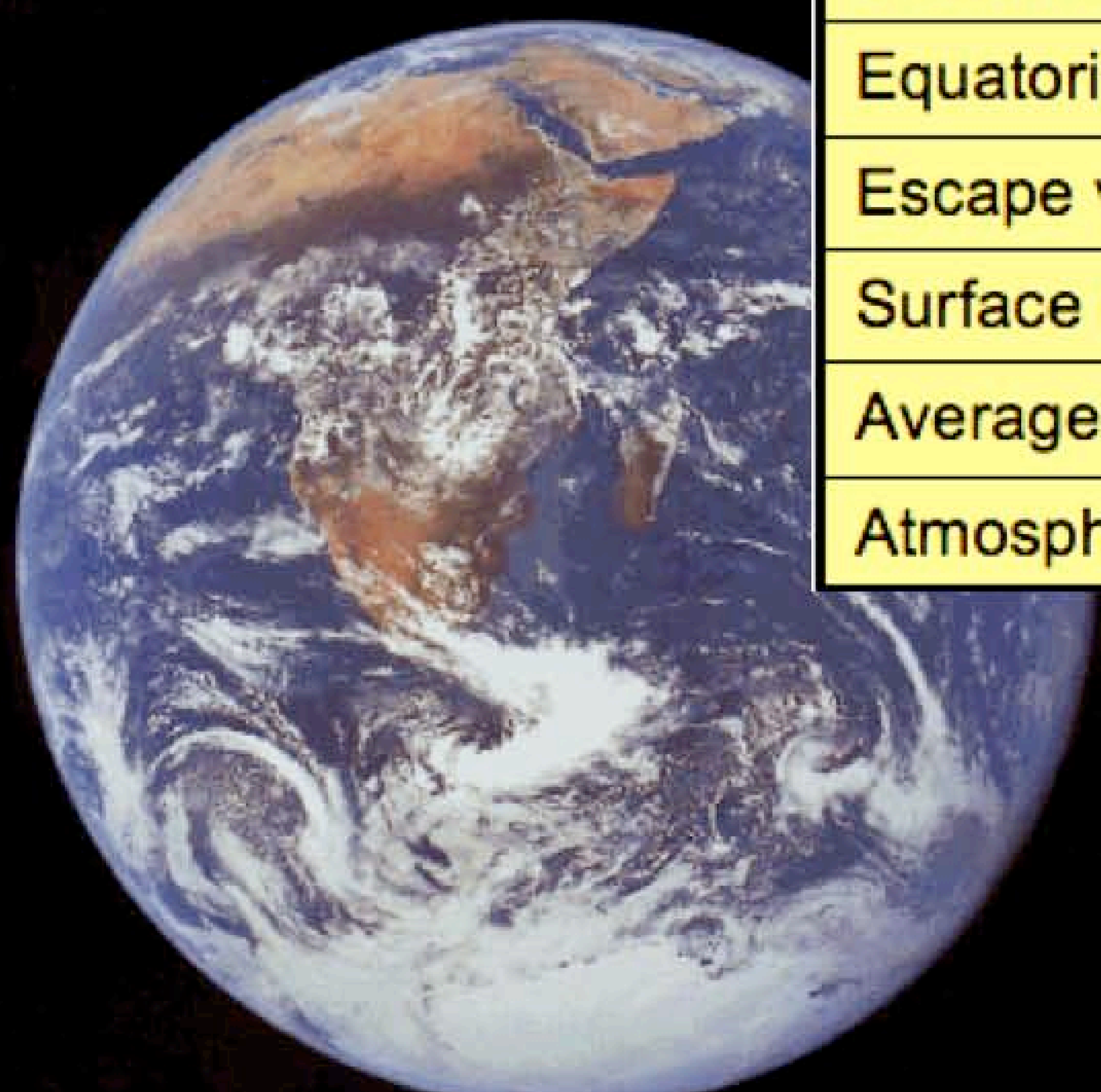
- A rocky planetary object, differentiated into crust, mantle, and core
- Heavily cratered surface; partly flooded by lava flows over 3 Ga ago
- Since then, only impacts by comets and asteroids, grinding up surface into chaotic upper layer of debris (regolith)
- Regolith is easily accessed and processed;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





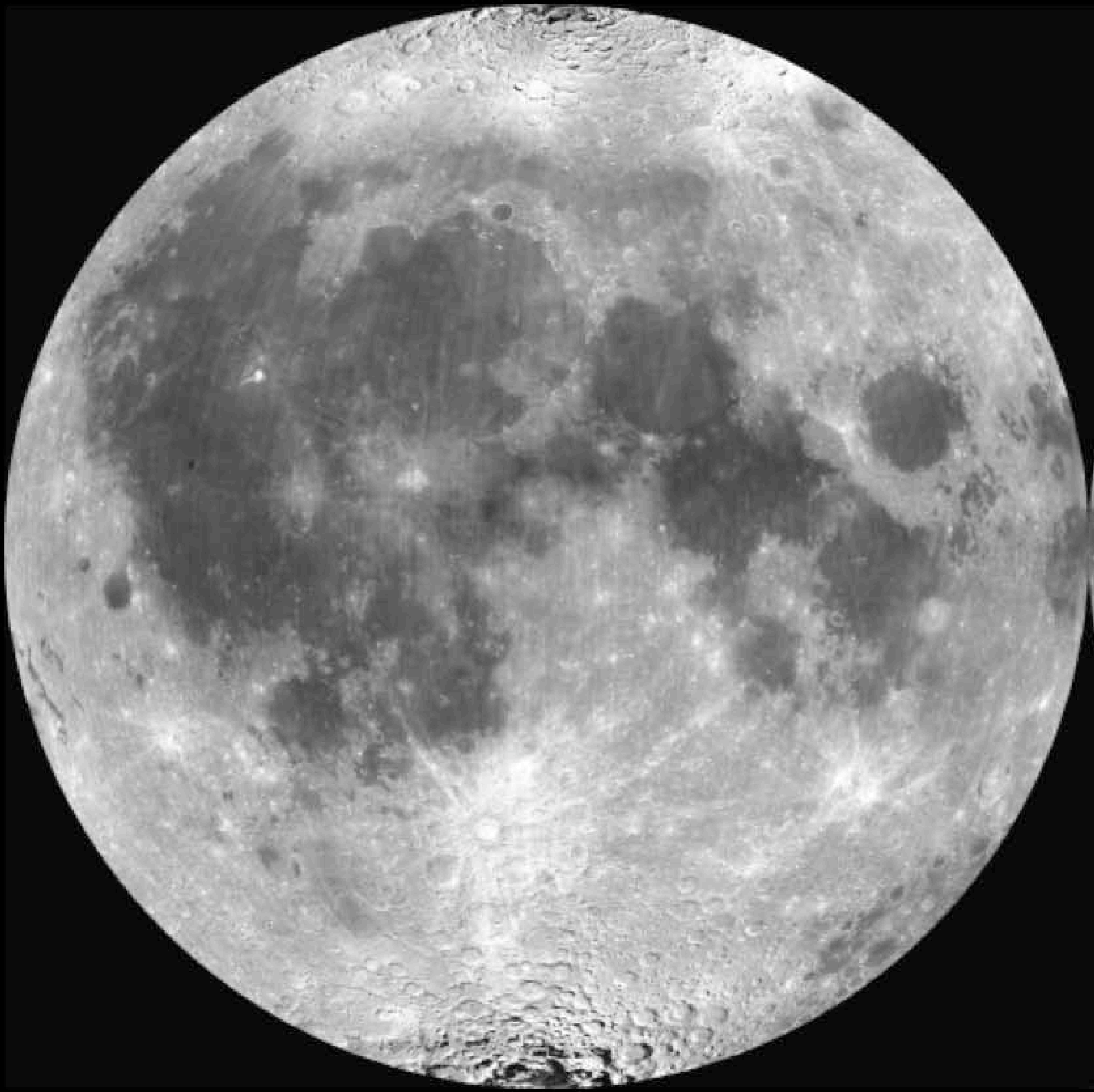
Some General Properties



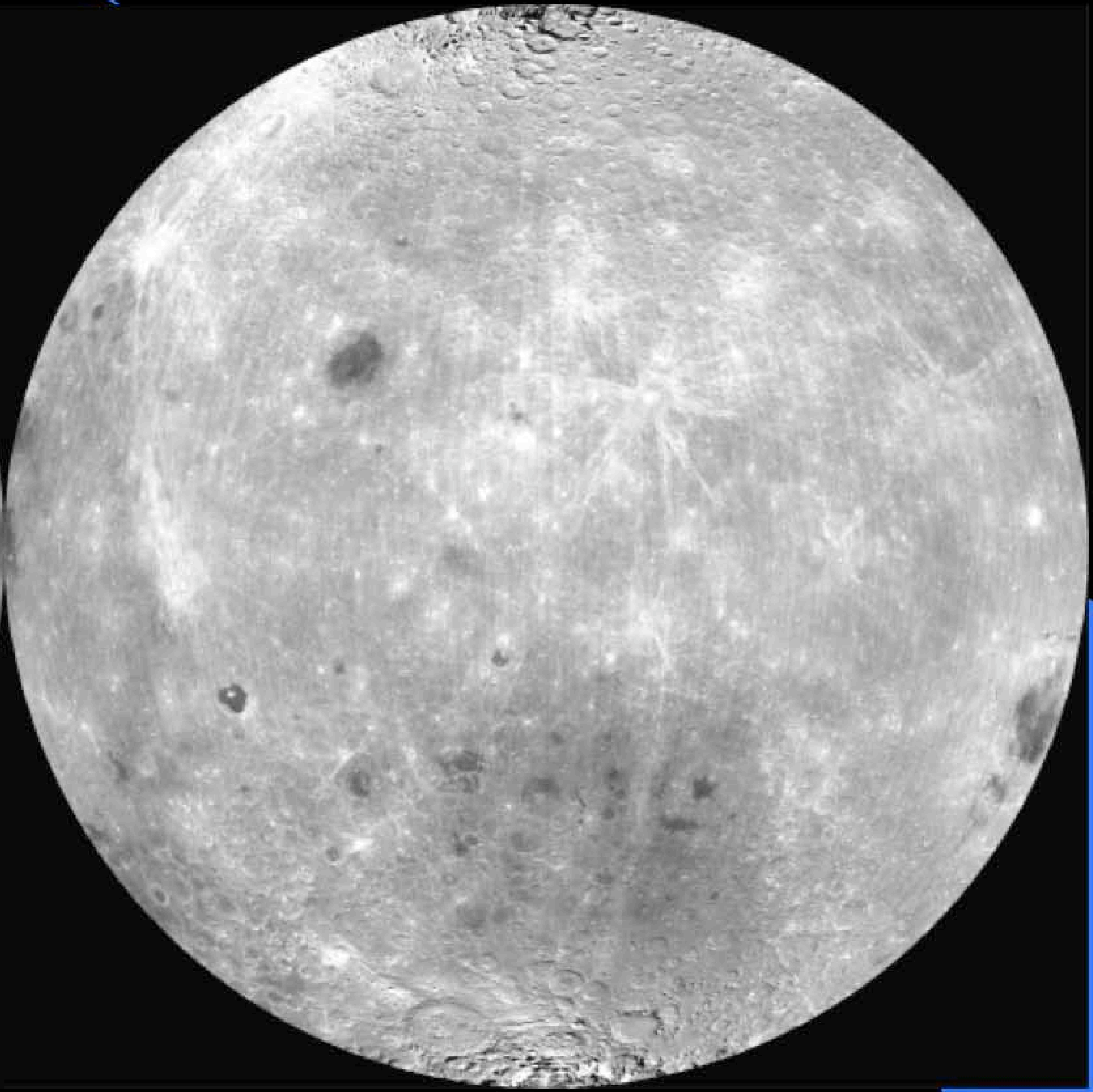


	Unit	Moon	Mars	Earth
Mass	10^{22} kg	7.34	64.2	598
GM	$kg^3 m^2$	4896.8	42828.2	398930.3
Density	$kg\ m^{-3}$	3340	3920	5520
Equatorial radius	km	1738	3393	6378
Volume	$10^{10} km^3$	2.2	16.3	108.2
Surface Area	$10^6 km^2$	37.9	144	511
Moment of Inertia		0.395	0.345-0.365	0.332
Equatorial gravity	$m\ s^{-2}$	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

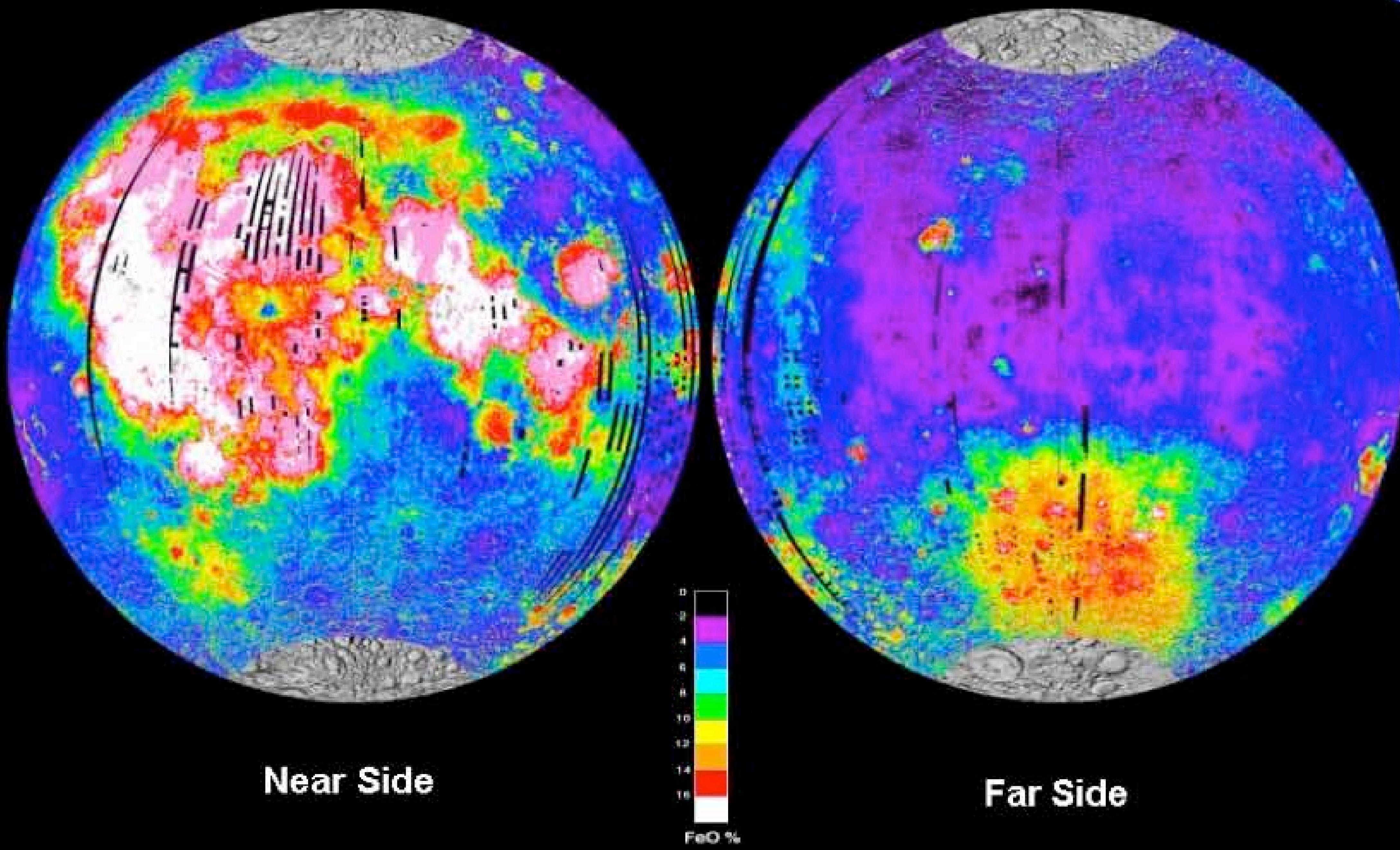


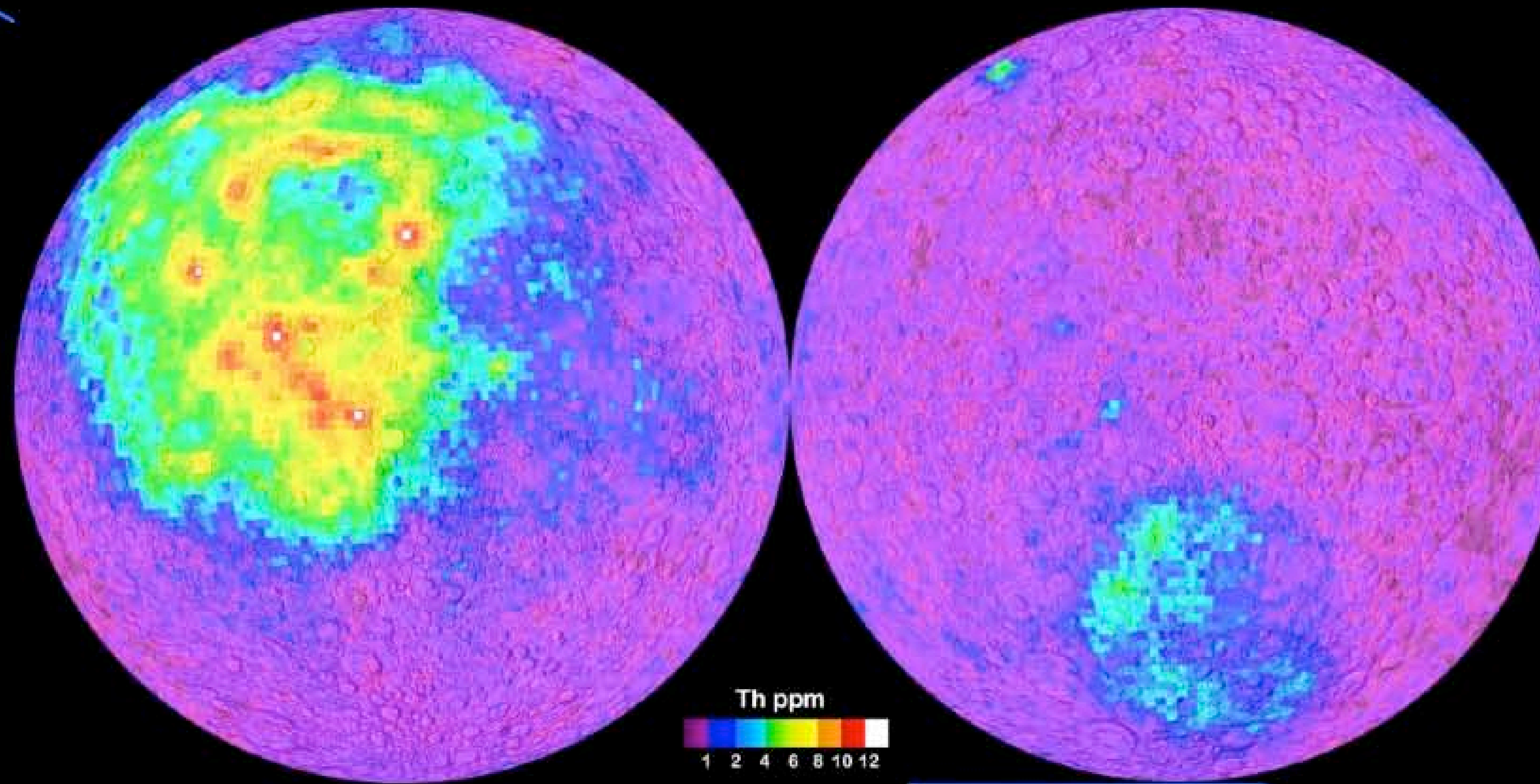
Near side

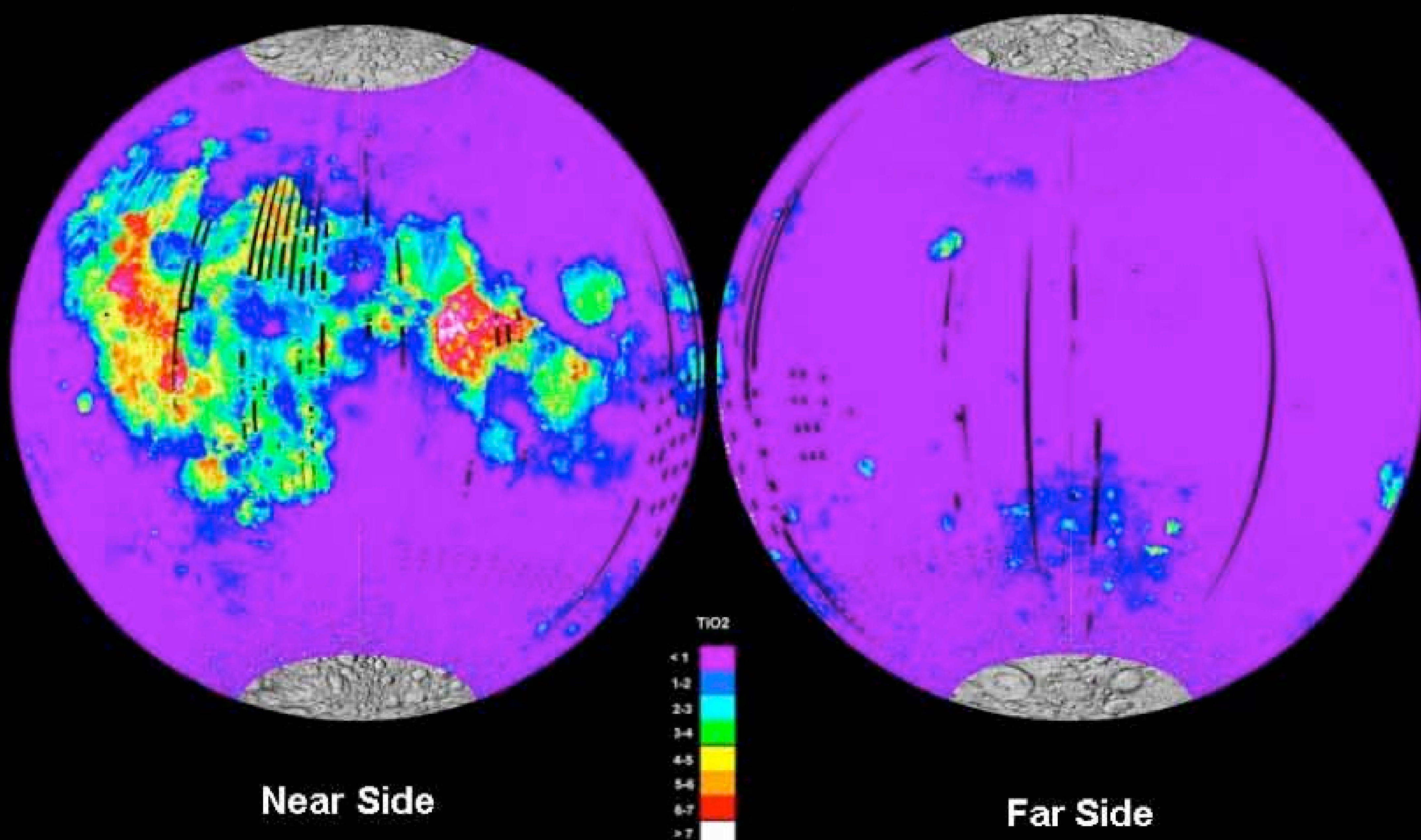


Far side

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

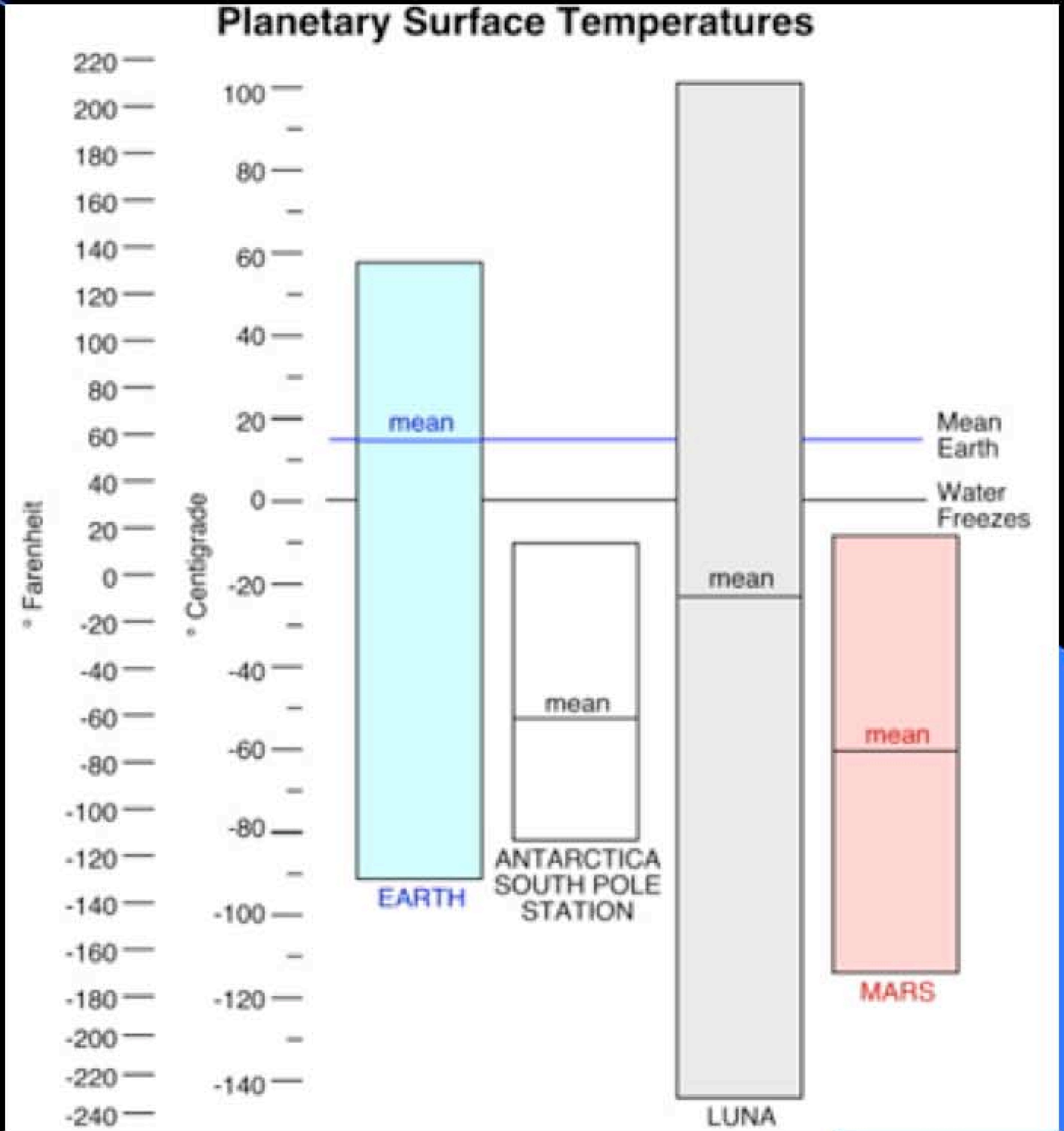
Thorium (Th) - asymmetrically distributed in western near side; maps KREEP

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

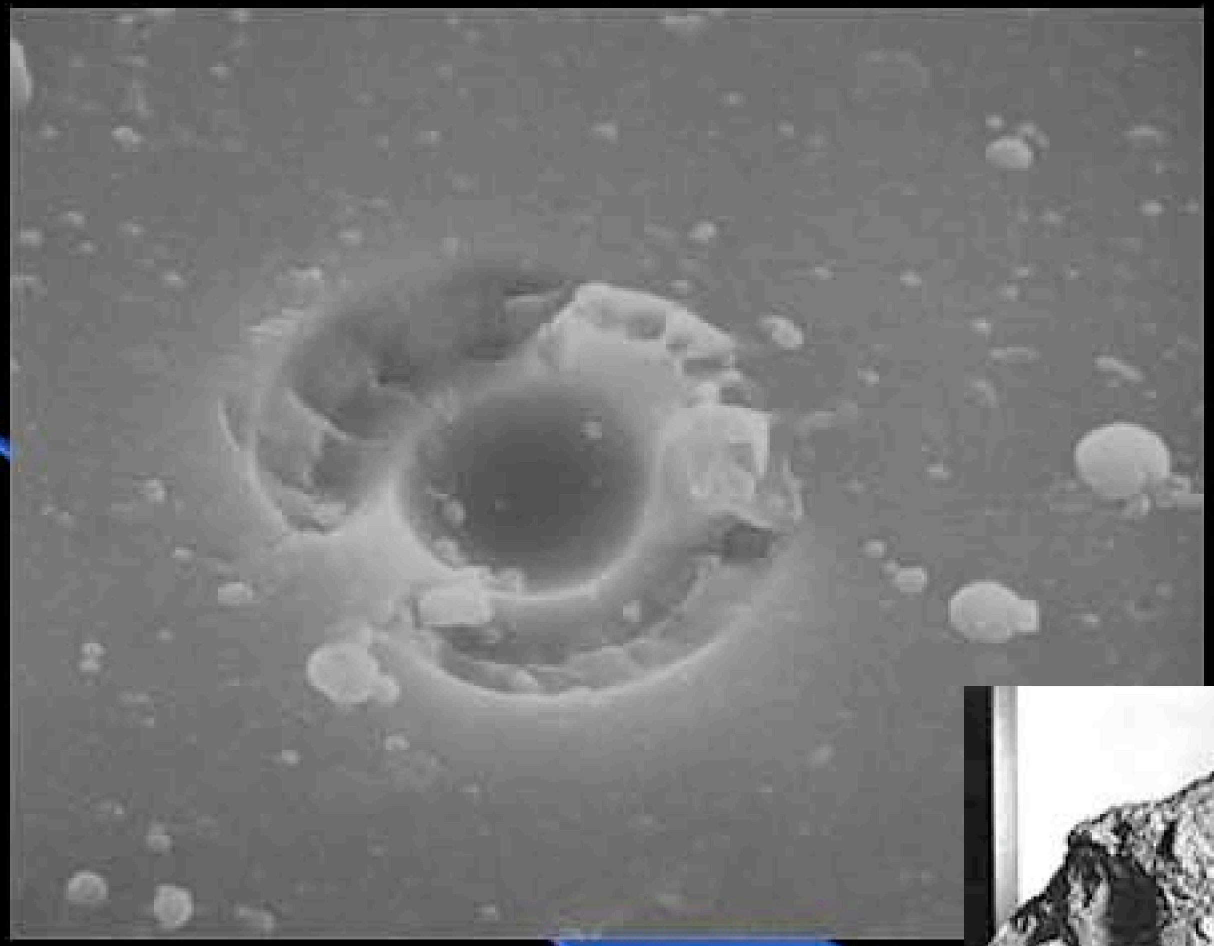
Estimated flux:

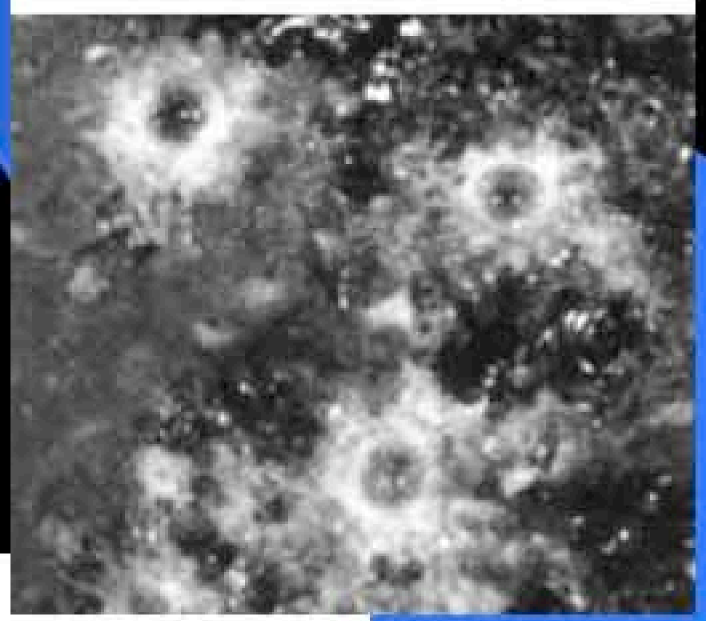
Crater Diameter (μm)	# craters / m^2 / yr
0.1	3×10^5
> 1	1.2×10^4
>10	3×10^3
>100	6×10^{-1}
>1000	1×10^{-3}

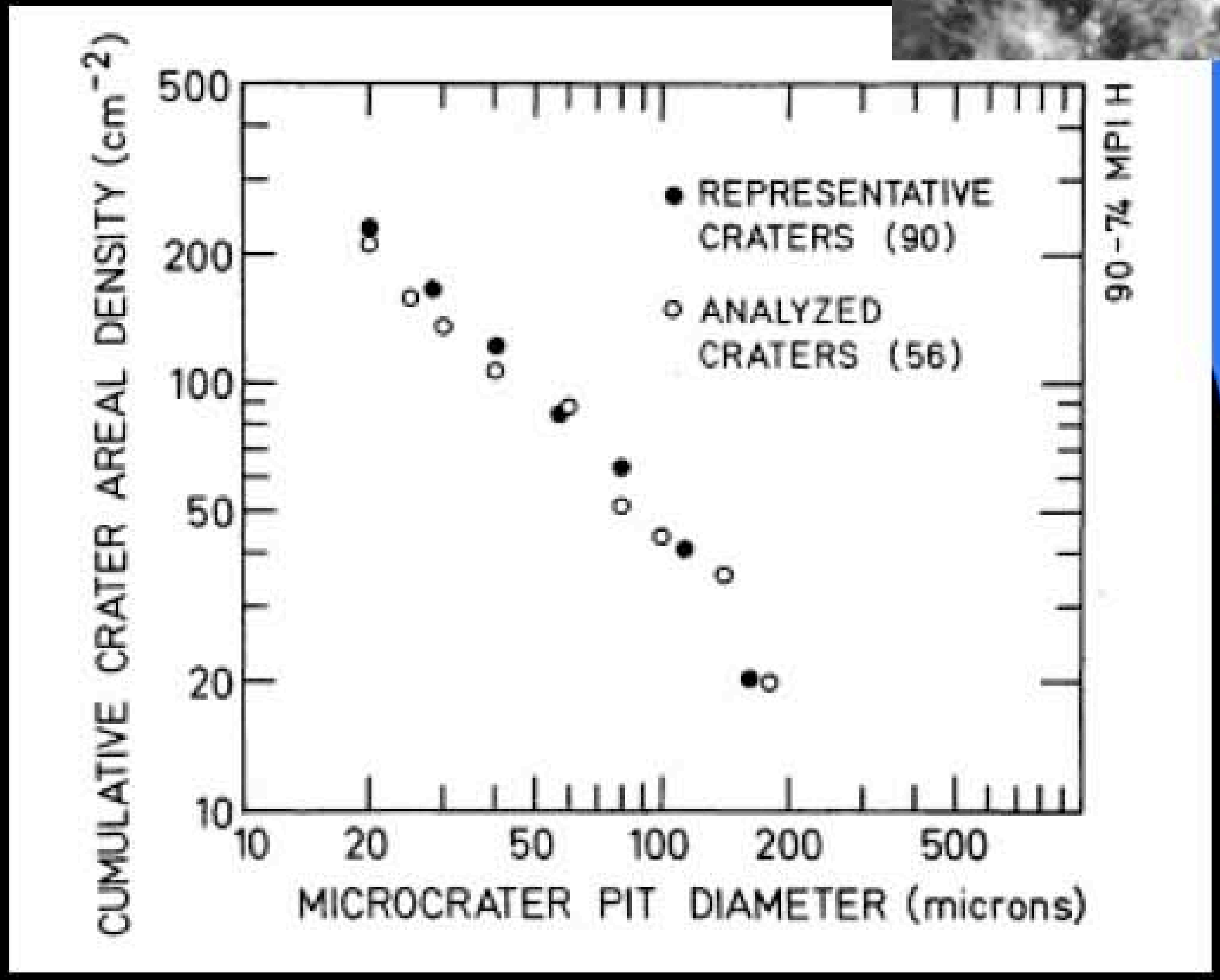
Microcraters from 1-10 μm will be common on exposed lunar surfaces

Craters ~100 μm dia. ~ 1 / m^2 / yr

Effects of secondary impact ejecta not well quantified

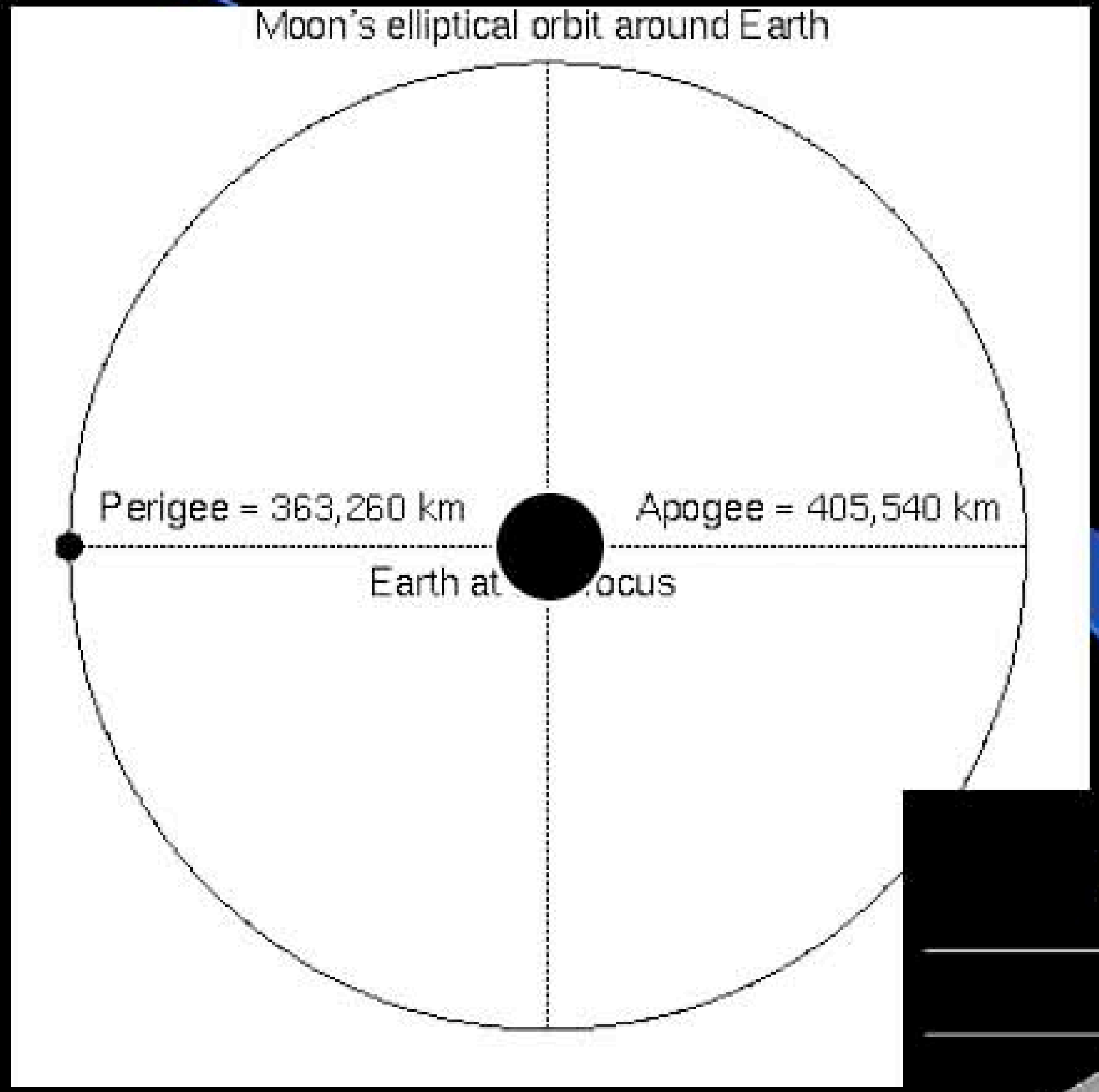


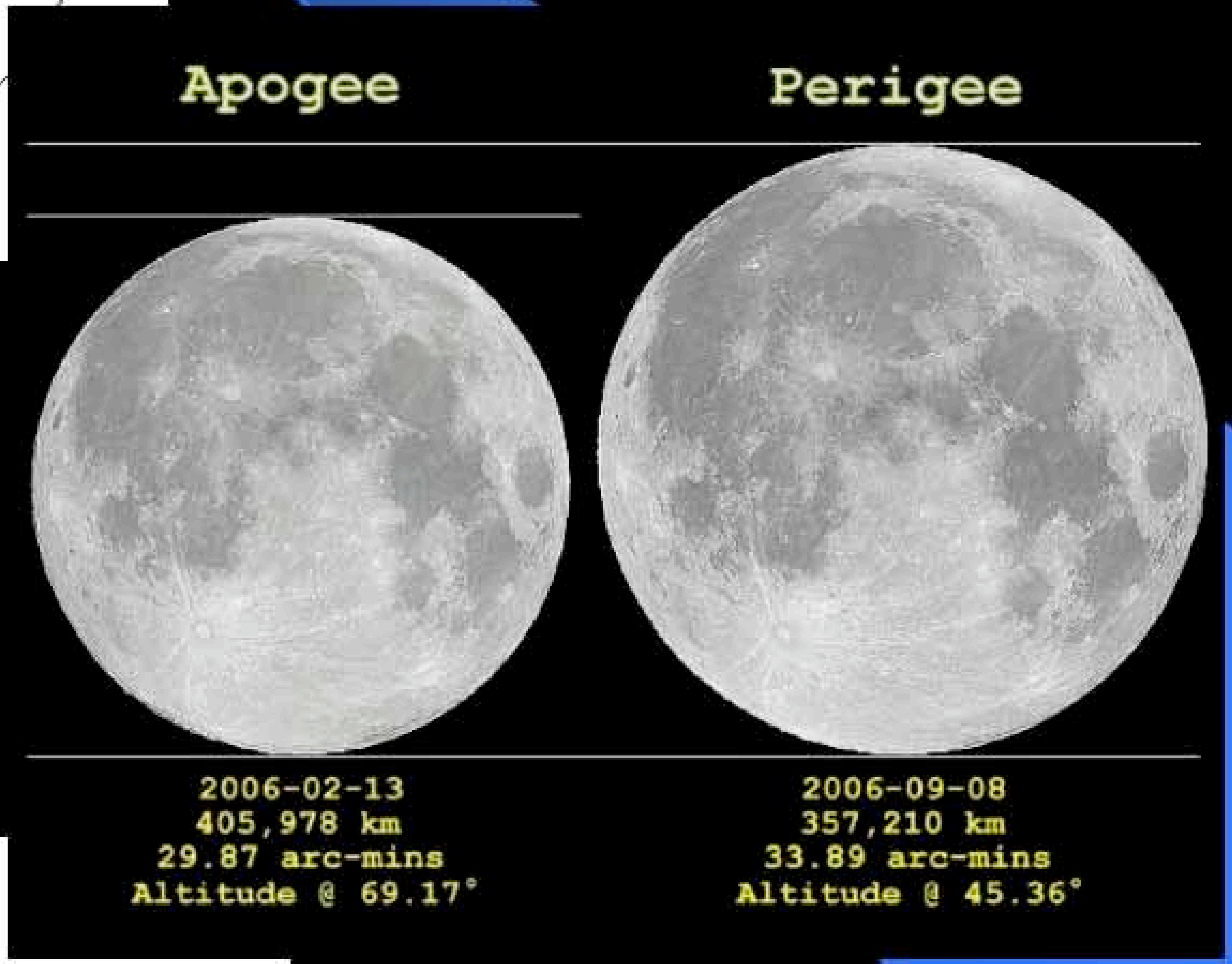


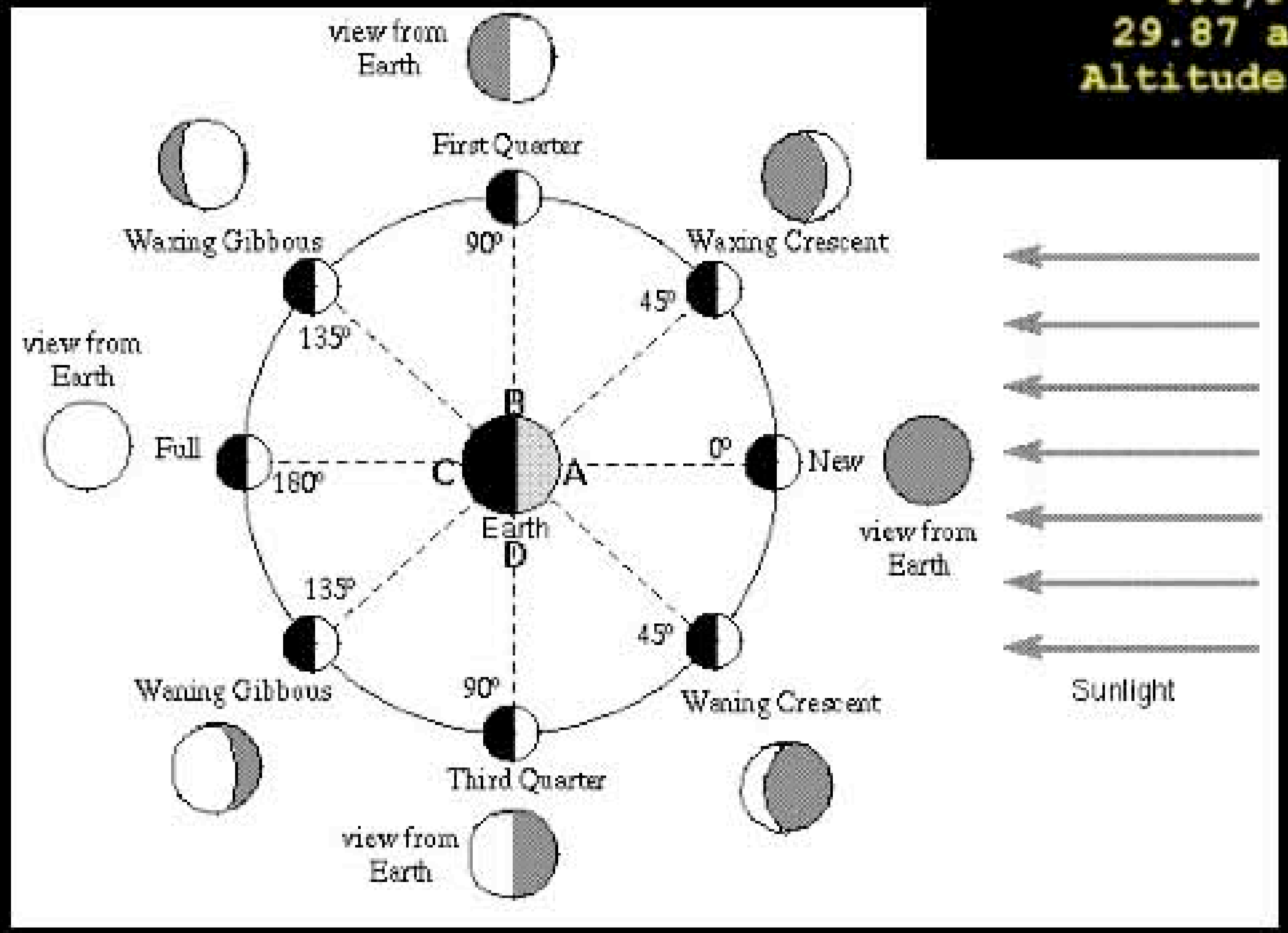


The Moon's Orbit

- 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

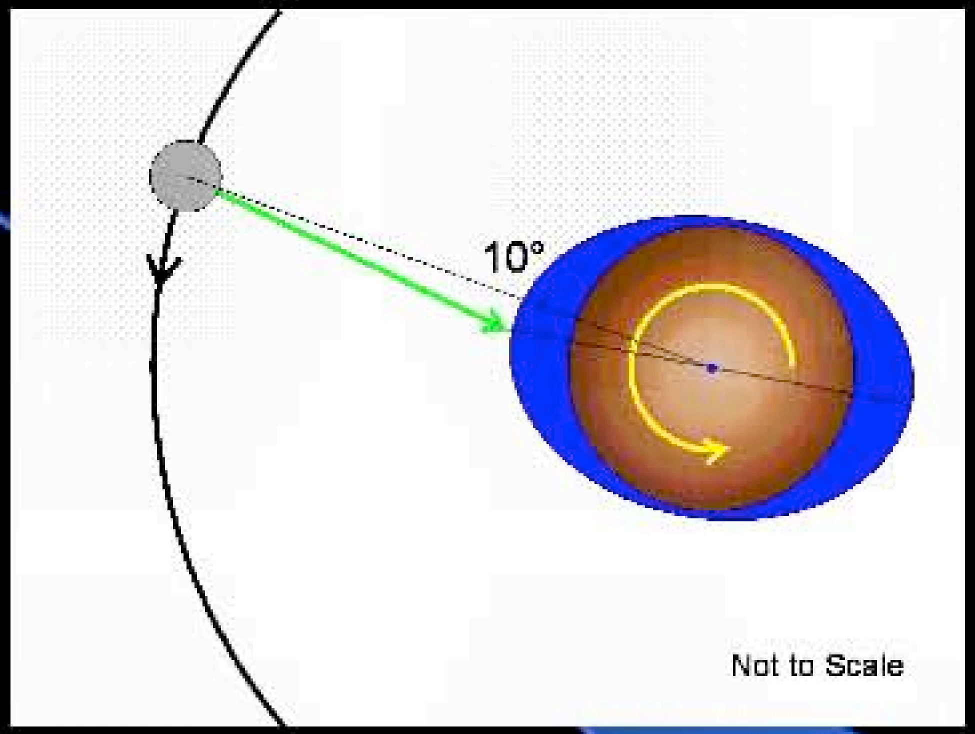


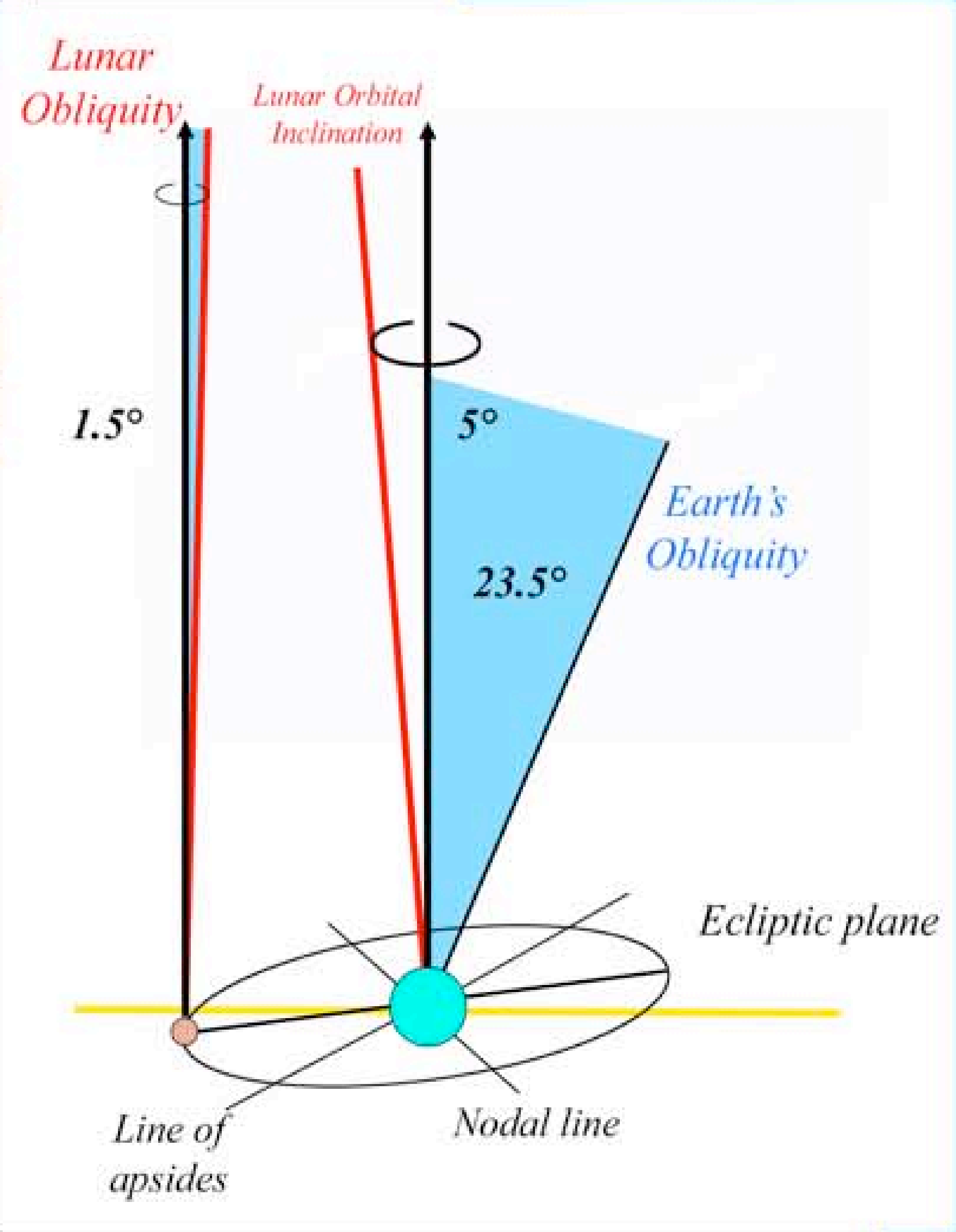




History of the Moon's Orbit

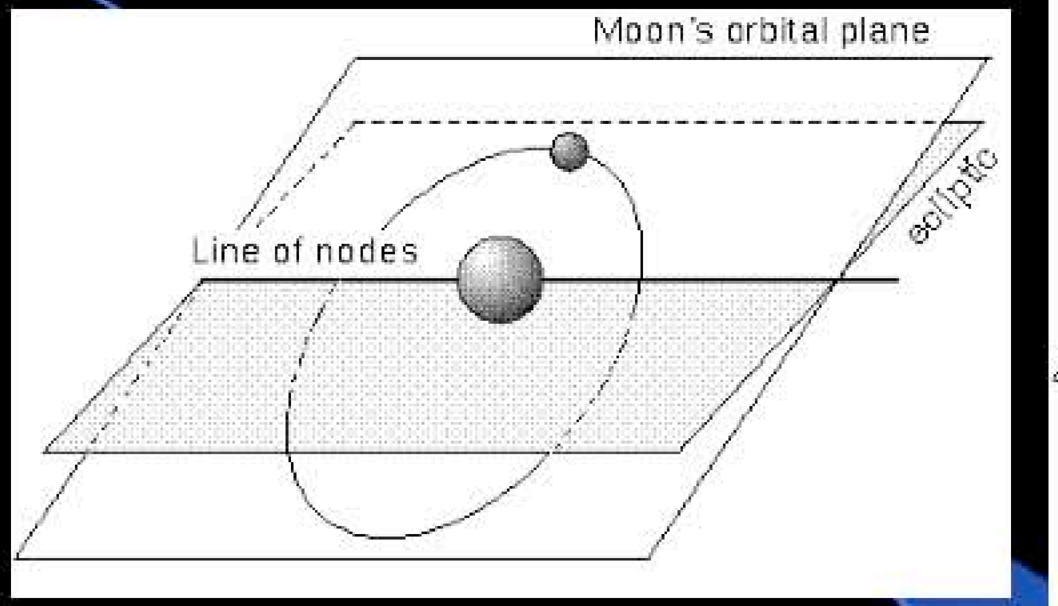
- Moon is receding from Earth at a rate of ~3.8 cm/year due to tidal braking
- Implication is that Moon was once much closer to Earth
  - Confirmed by growth rings of fossil corals
- History of orientation of orbital plane, spin axis uncertain; spin axis in current position for at least last 2 Ga

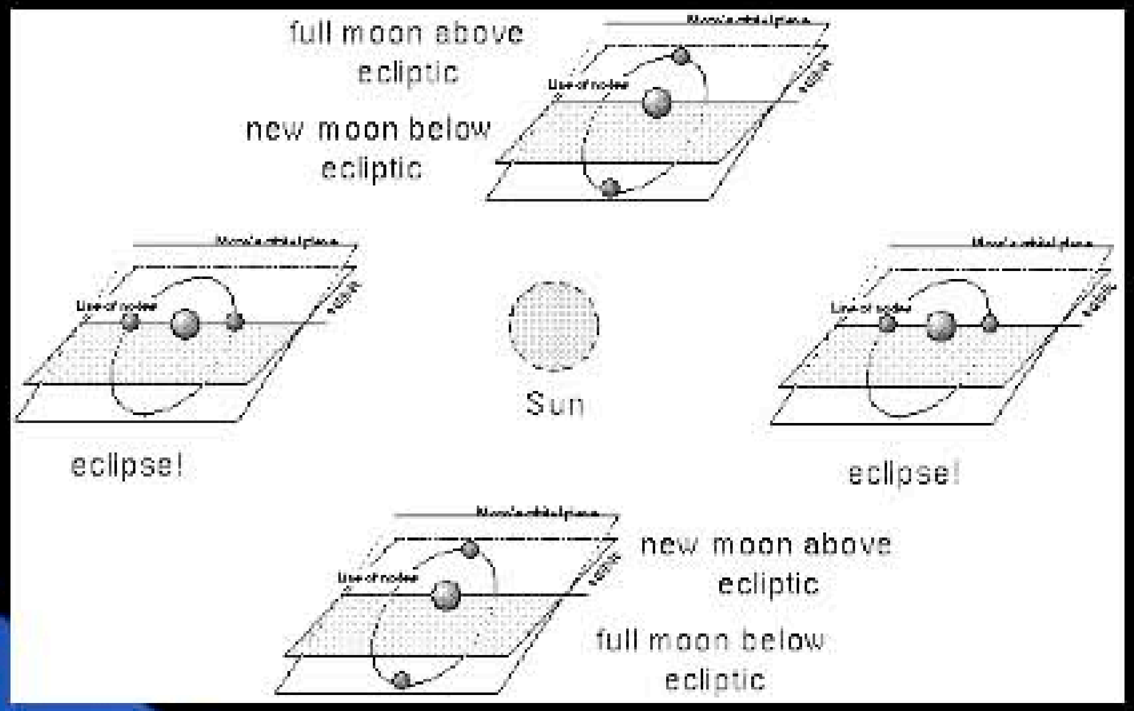


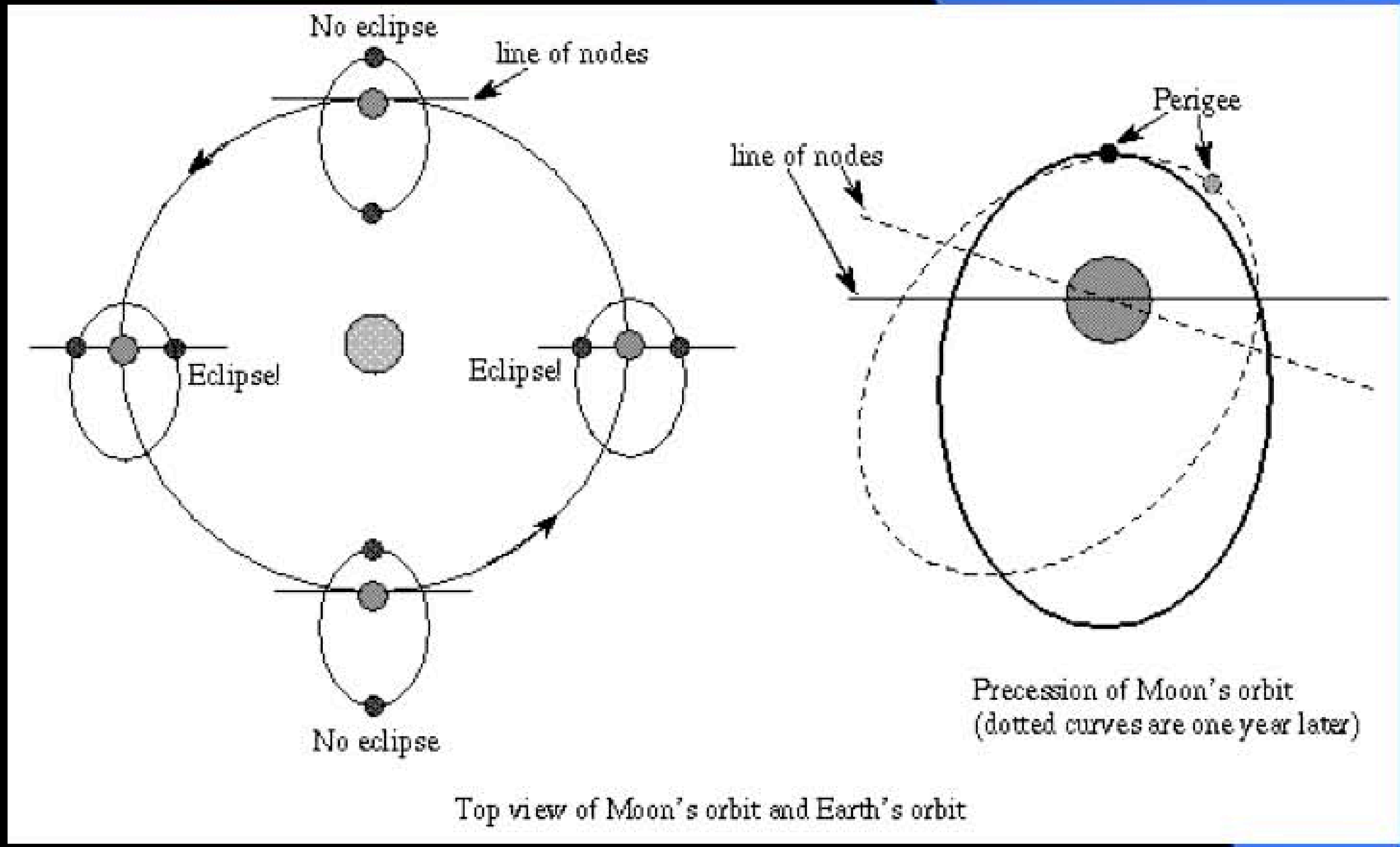


Moon's Orbit and Eclipses

- 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







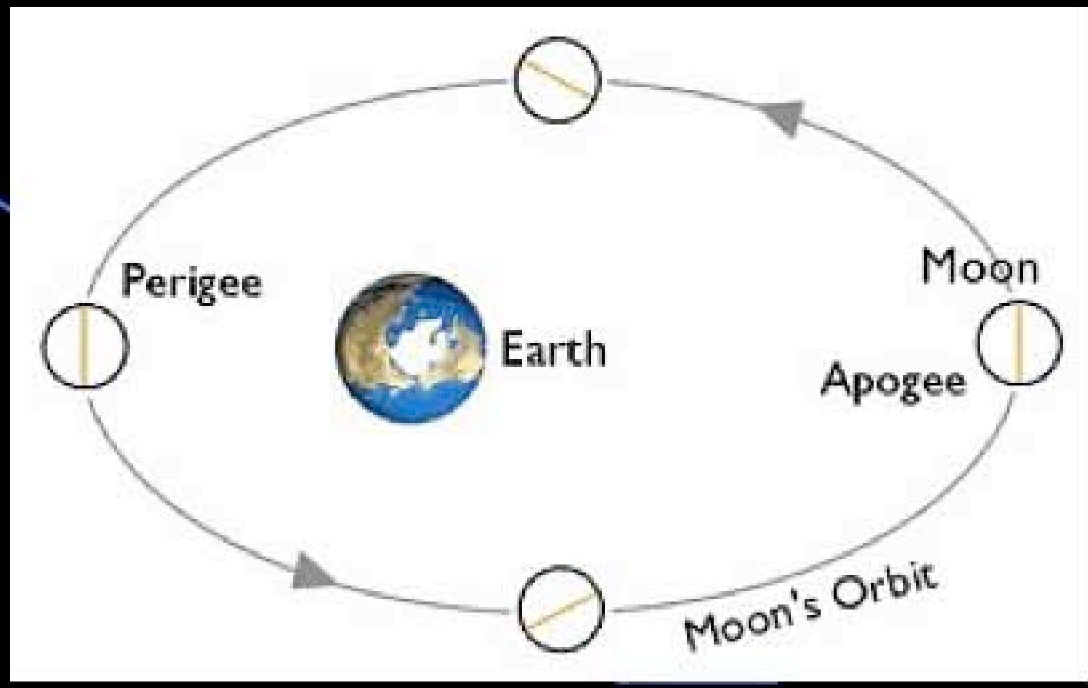
Libration

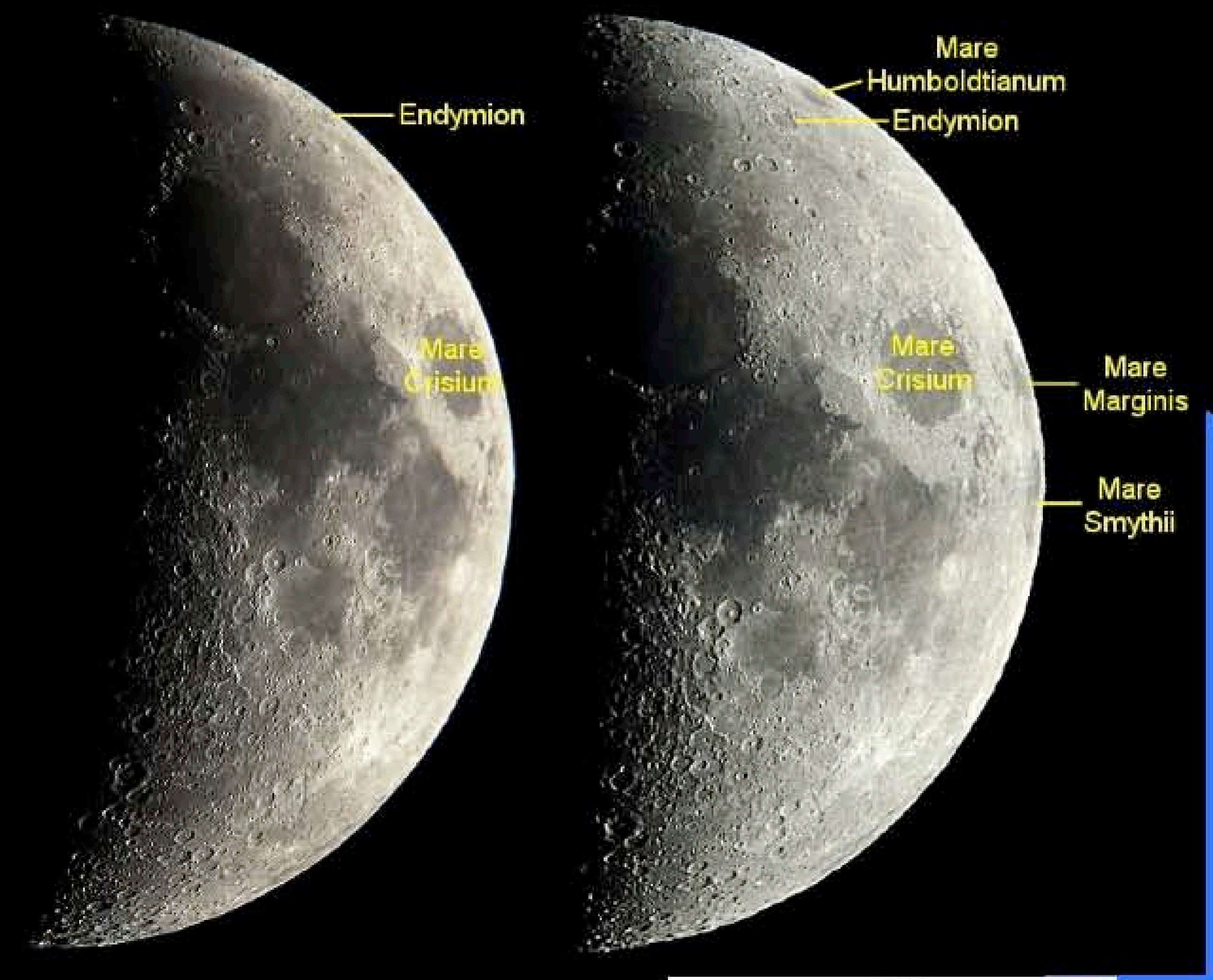
Longitudinal

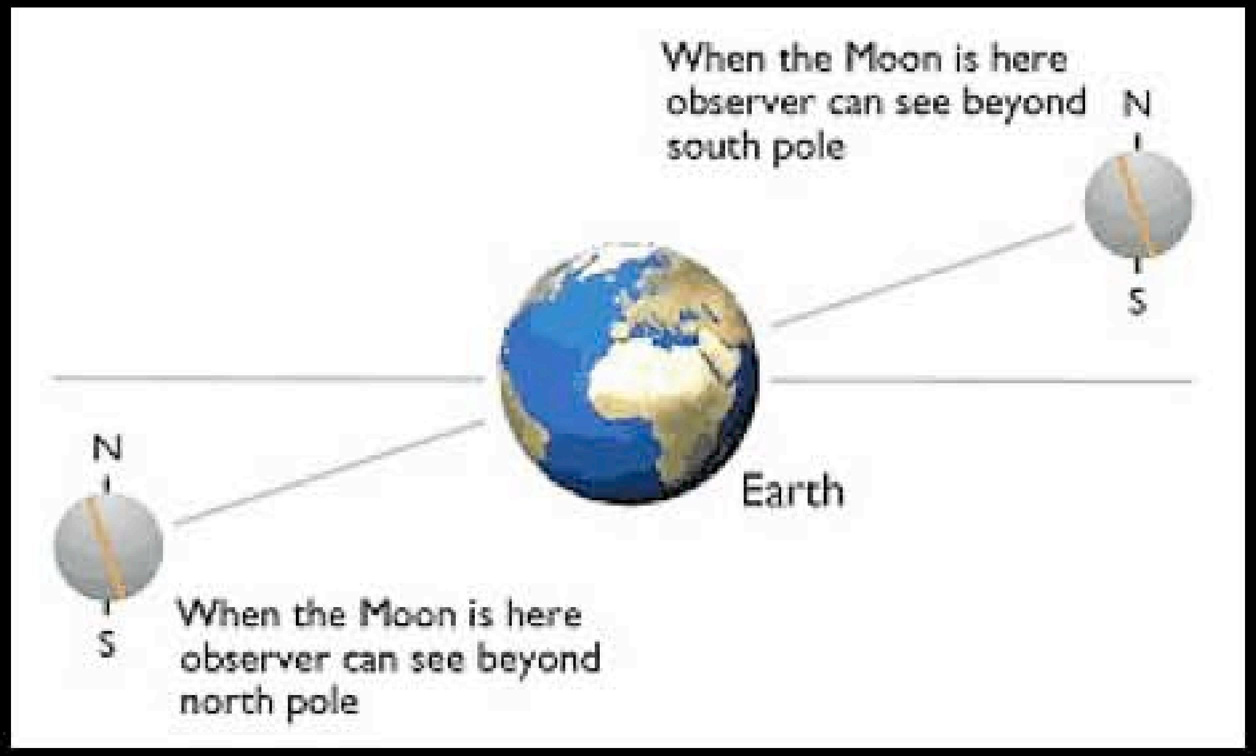
- Caused by Moon's elliptical orbit
- Can see approx. 8° beyond 90° W and 90° E limbs
- Diurnal parallax of observer ~1° due to diameter of Earth

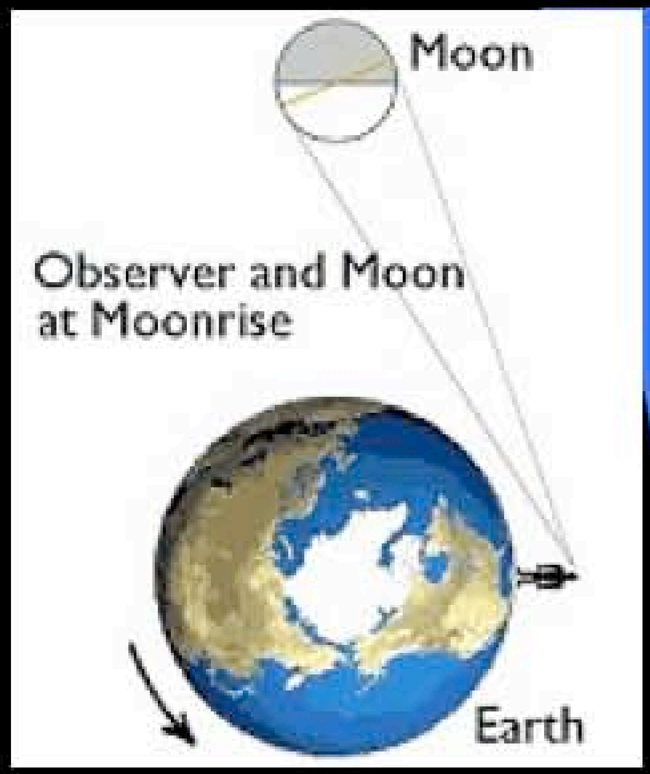
Latitudinal

- 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

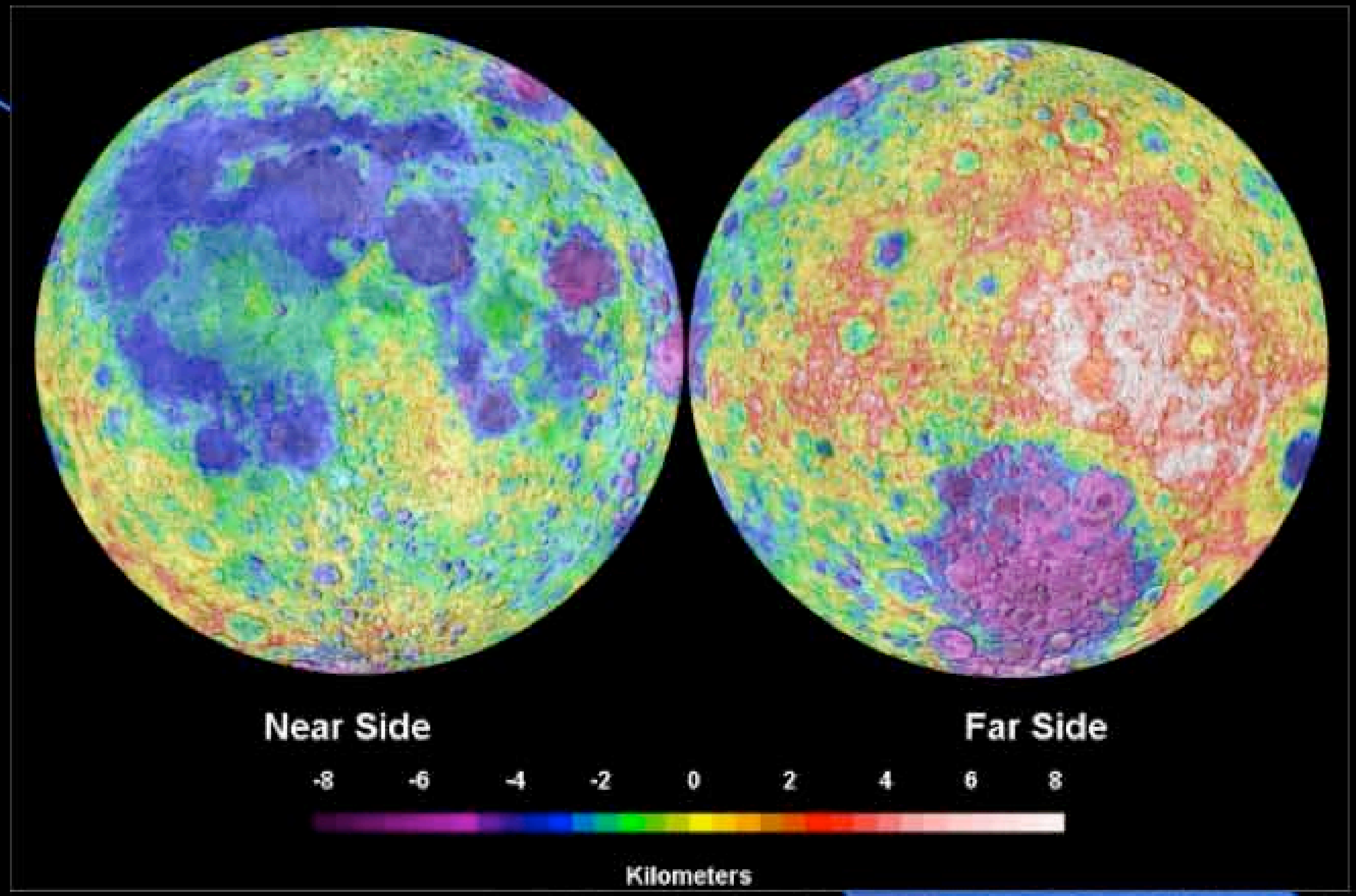
Moon is very "bumpy"; extremes of elevation + 8 km to –9 km (same dynamic range as Earth, sea floor to mountains)

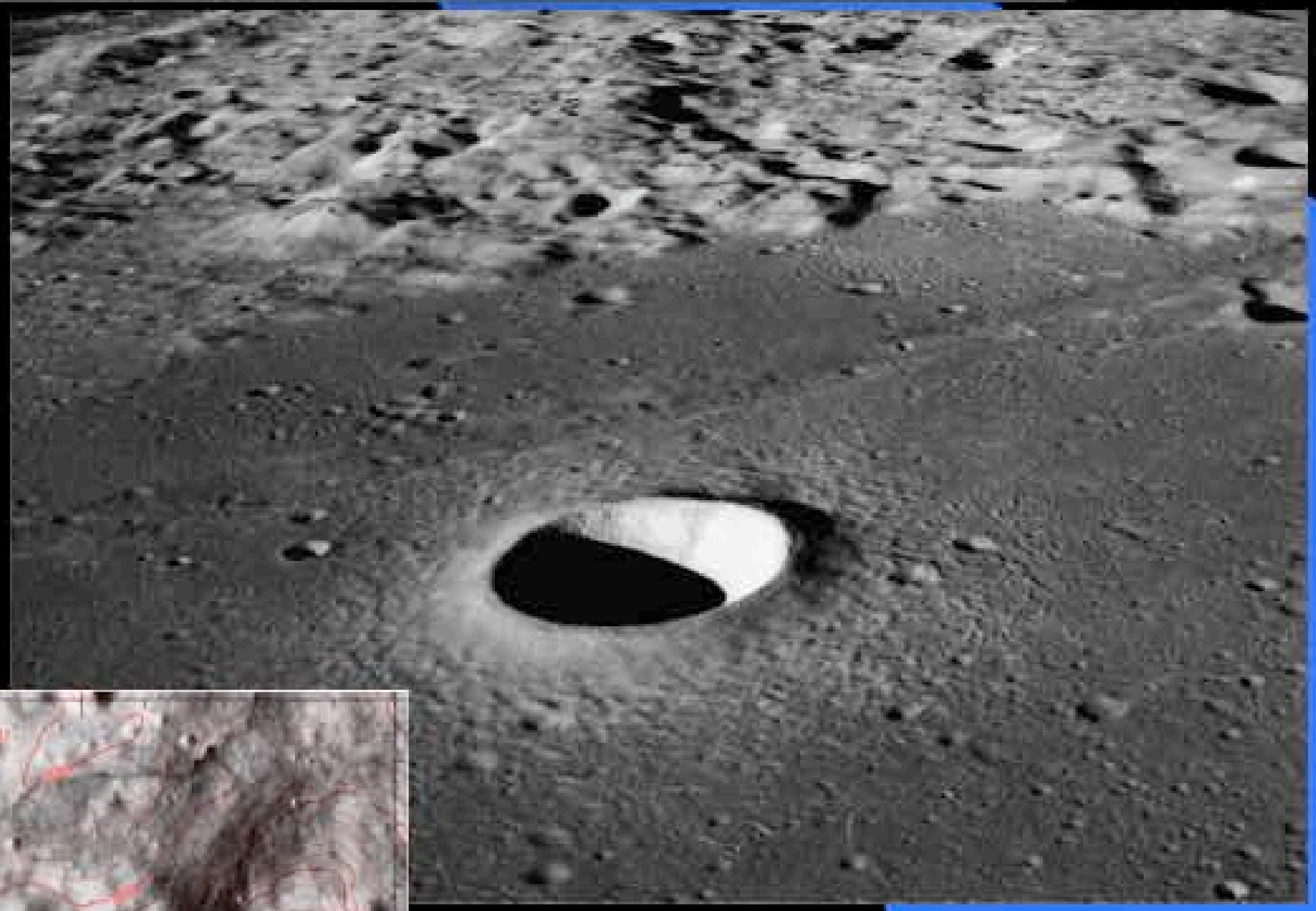
Physiography divided into rough, complex bright highlands (terra) and relatively flat, smooth dark lowlands (maria)

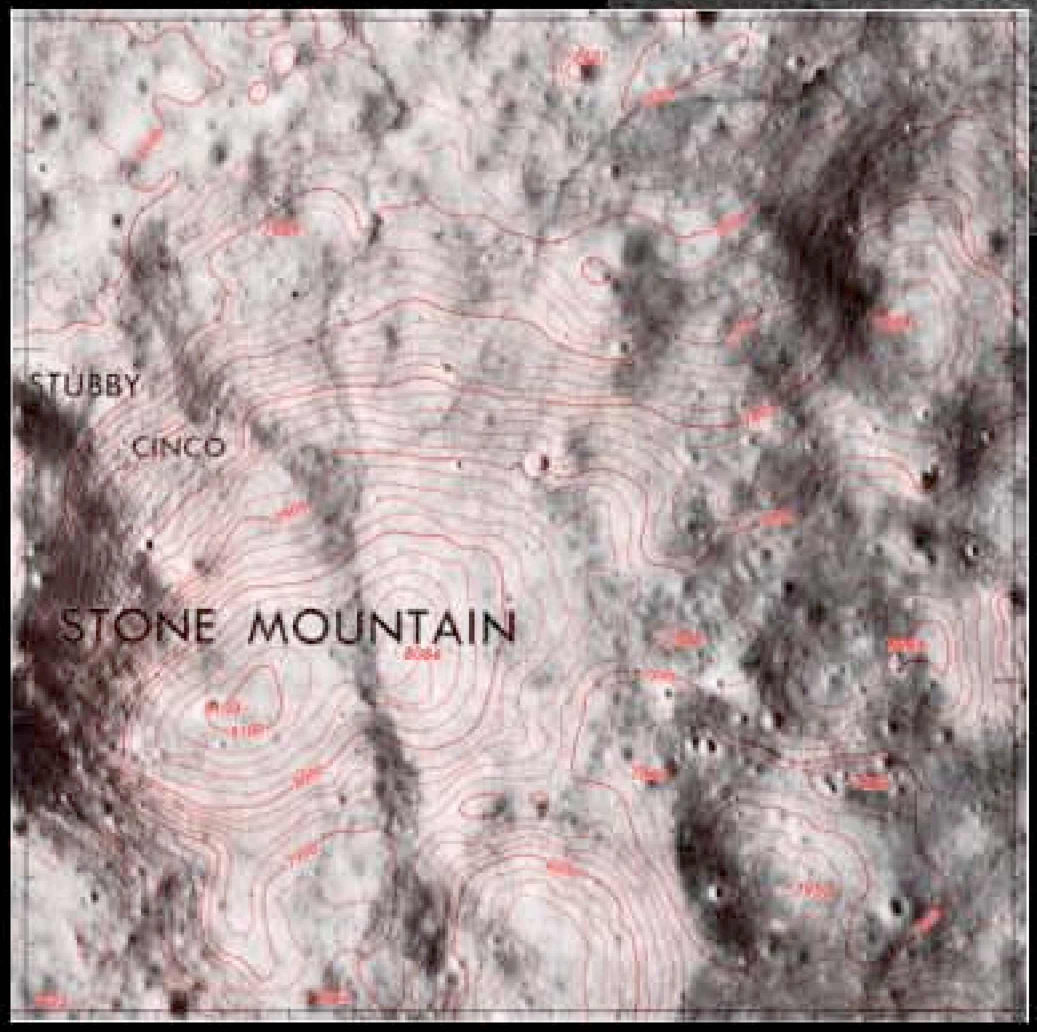
Landforms dominated by craters, ranging in size from micrometers to thousands of km across

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

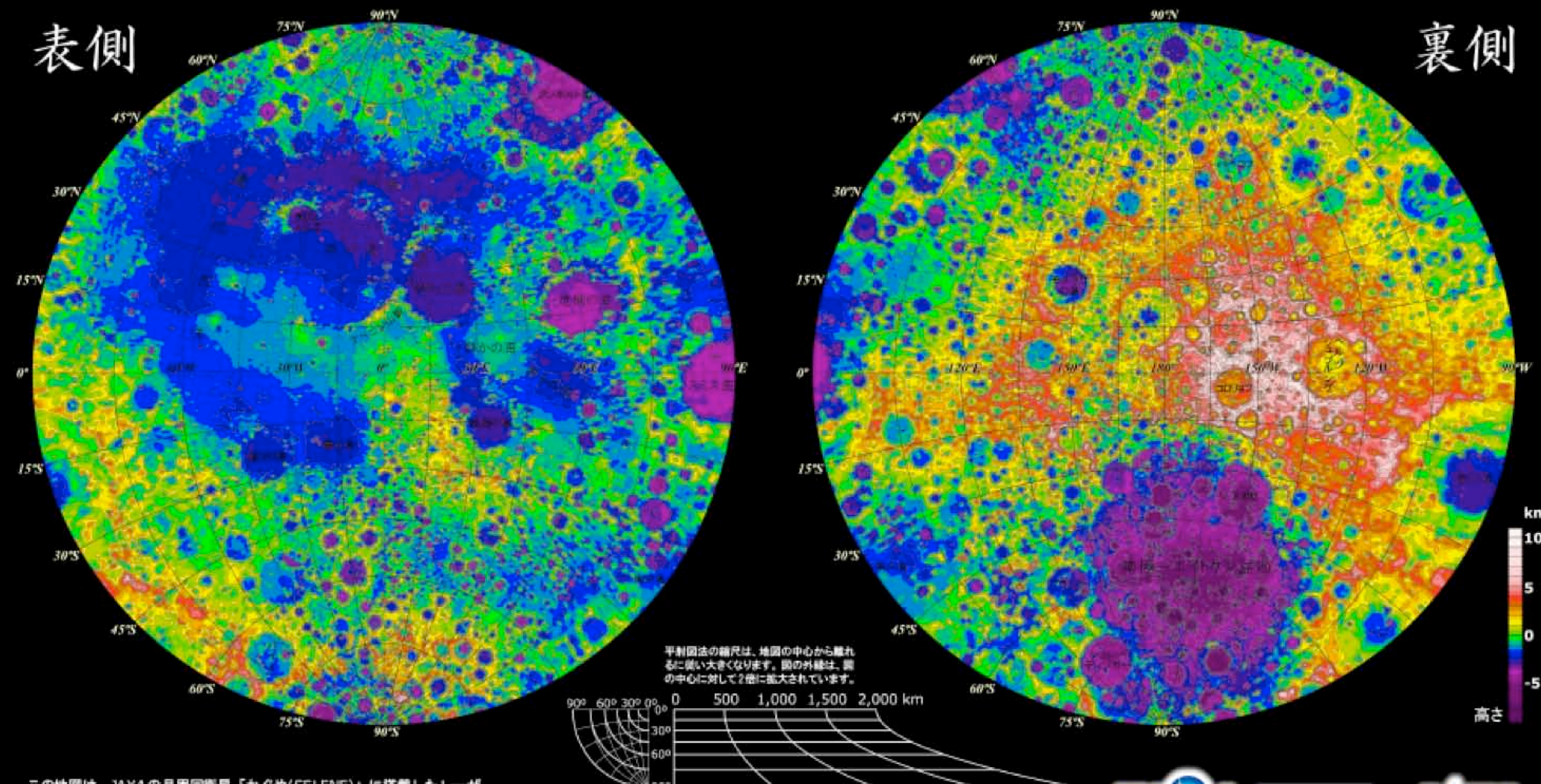






New Kaguya Topographic Map

「かぐや」が見た月の地形



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。

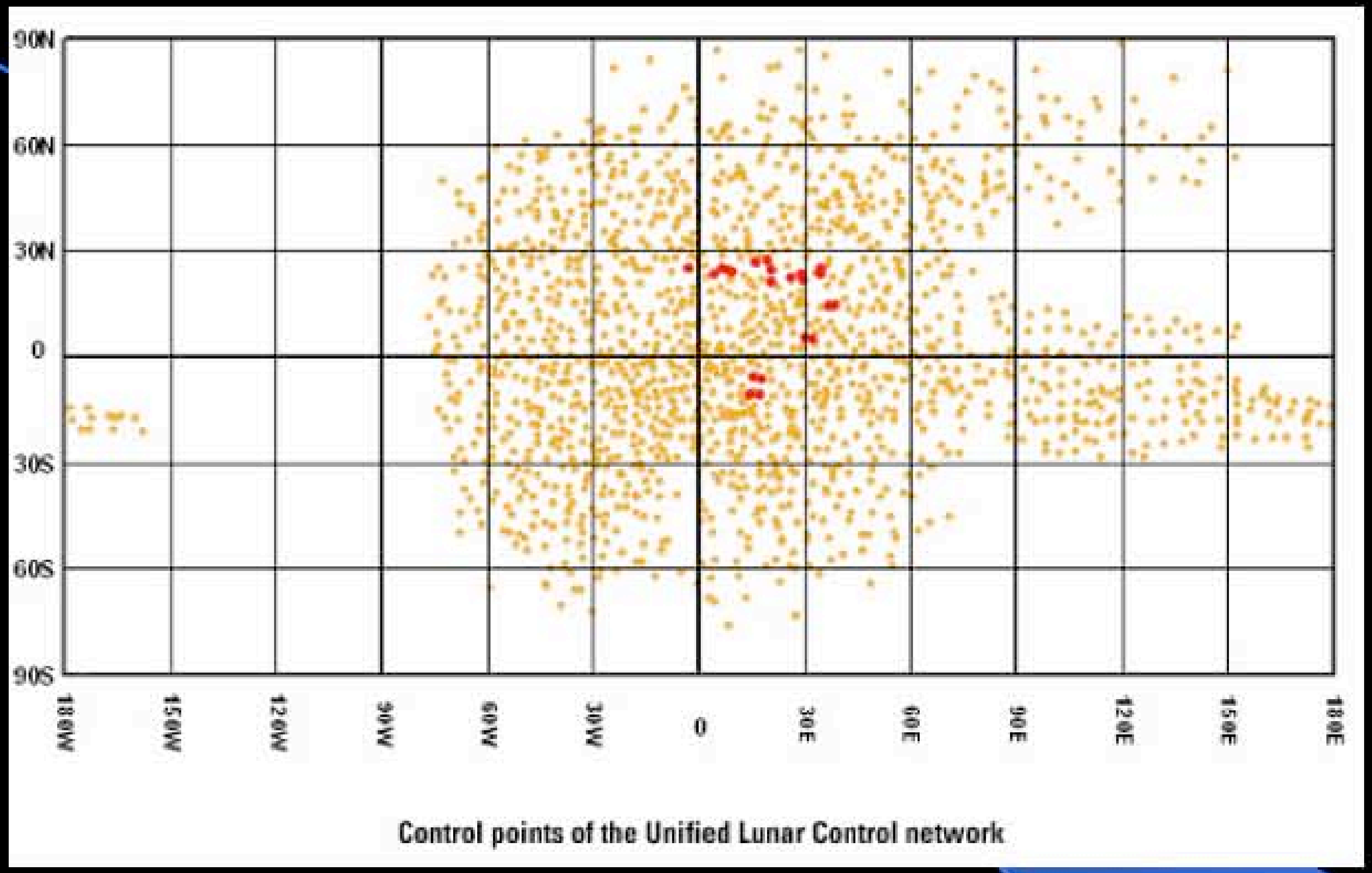
また裏側の南半球には、南極－エイトケン盆地と呼ばれる直径約2,500kmもある巨大な衝突盆地があり月面で最も低い地域です。海は円形もしくは楕円形をしているものが多く、衝突盆地の窪みに溶岩が噴出して溜まったものと考えられています。しかし南極－エイトケン盆地は海にはなっていません。これは地殻の厚さや岩石の組成が表側と違うためではないかと考えられています。

LALTのデータ処理・解析　自然科学研究機構 国立天文台

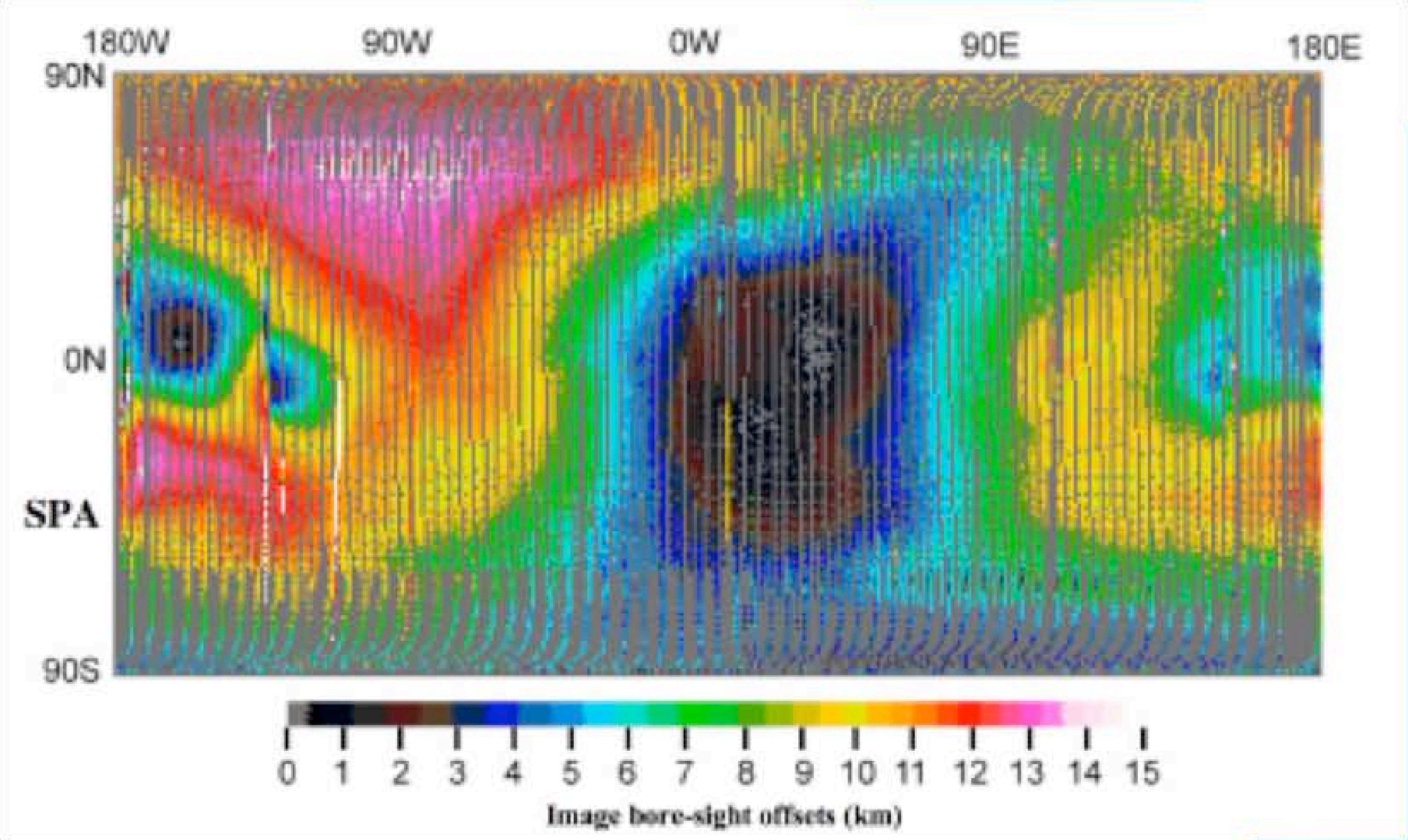
地形図の作成　国土交通省 国土地理院

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

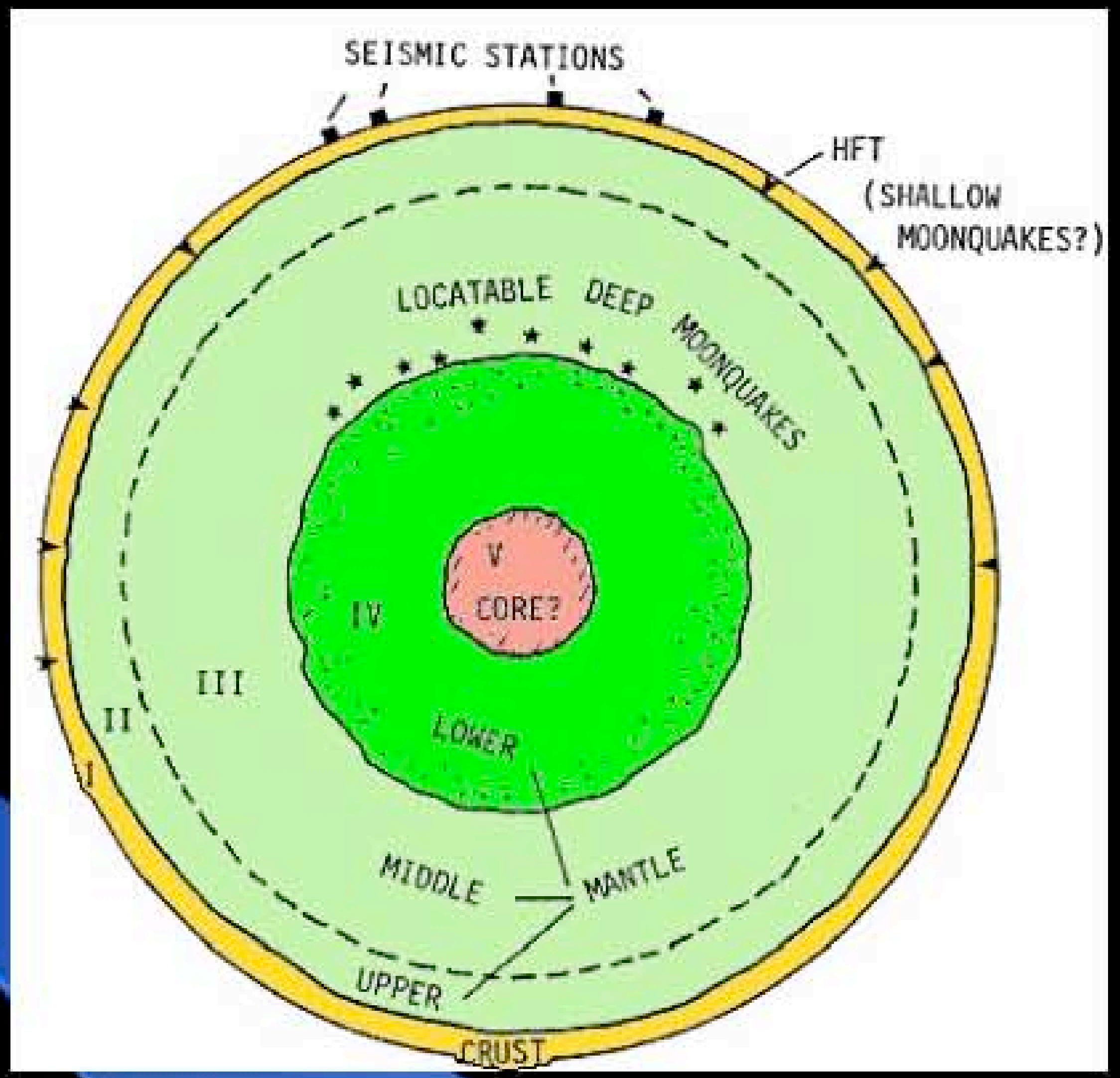


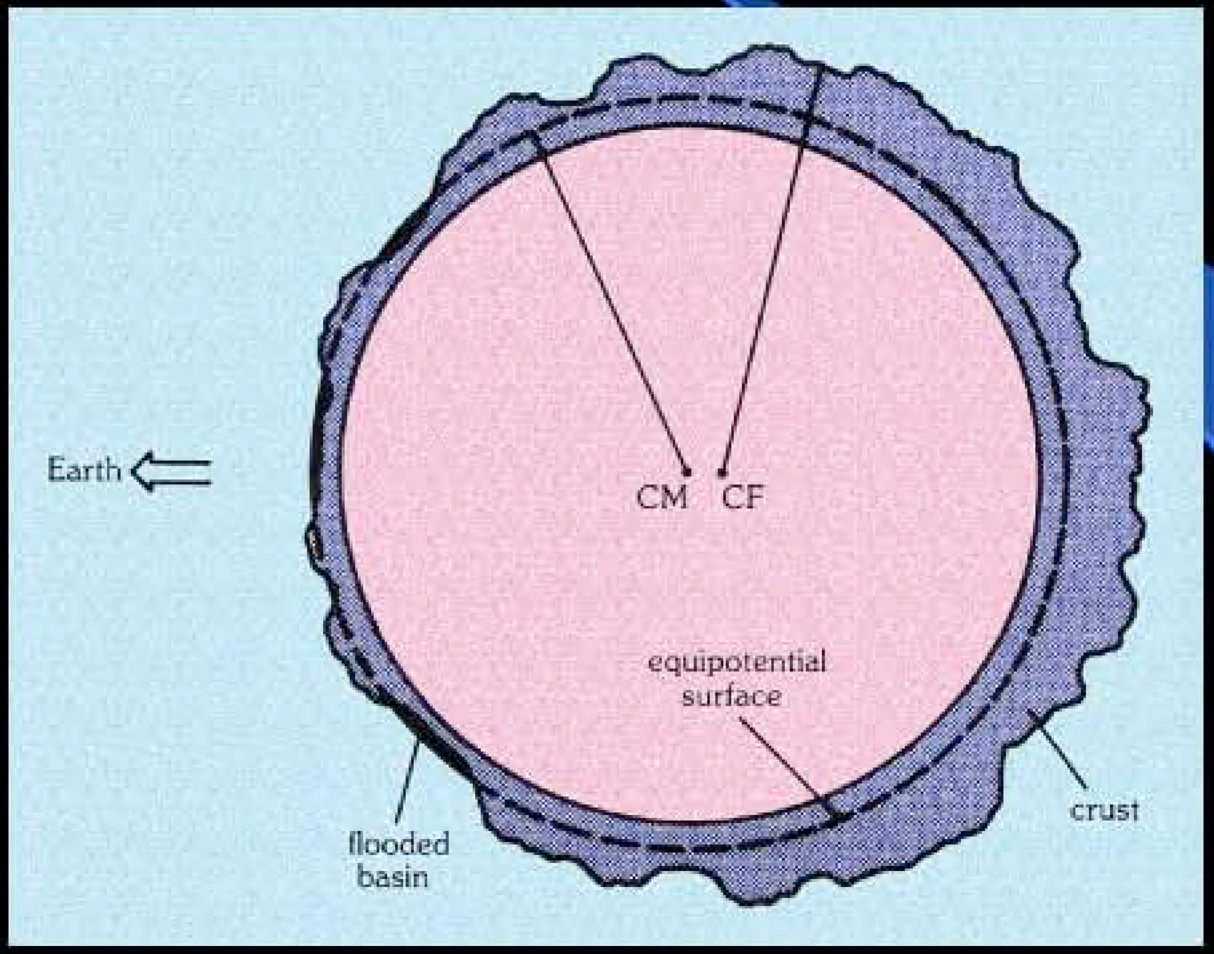
Control points of the Unified Lunar Control network



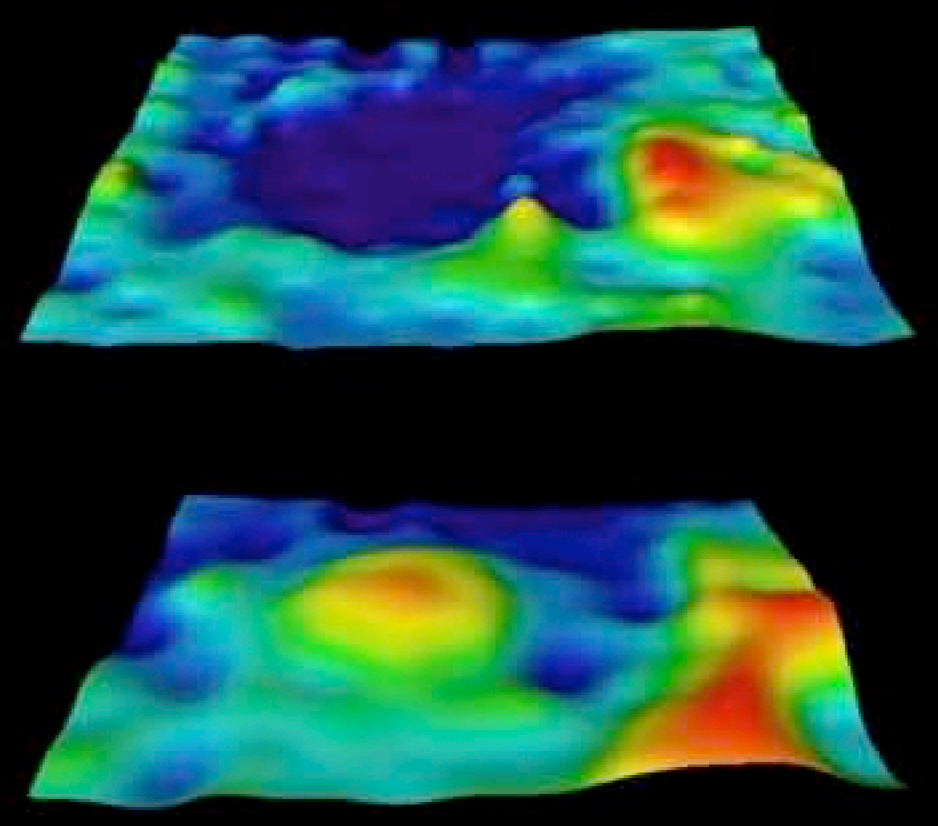
Moment of Inertia and CM-CF

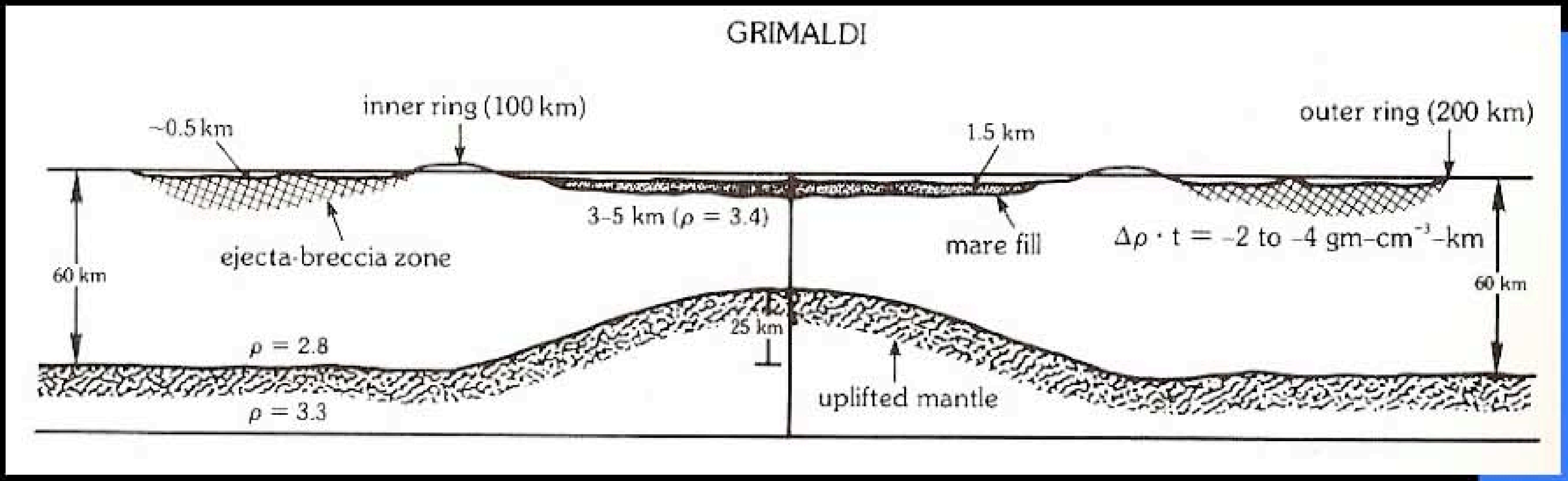
- Lunar Moment of Inertia 0.395 ± 0.0023 (core < 400 km radius)
- Center of Mass is offset ~2 km towards Earth from Center of Figure
  - Result of thicker far side crust (?)
  - Responsible for more maria on near side?
- Mass distribution asymmetric in outer few tens km (mascons)
  - Mass concentrations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





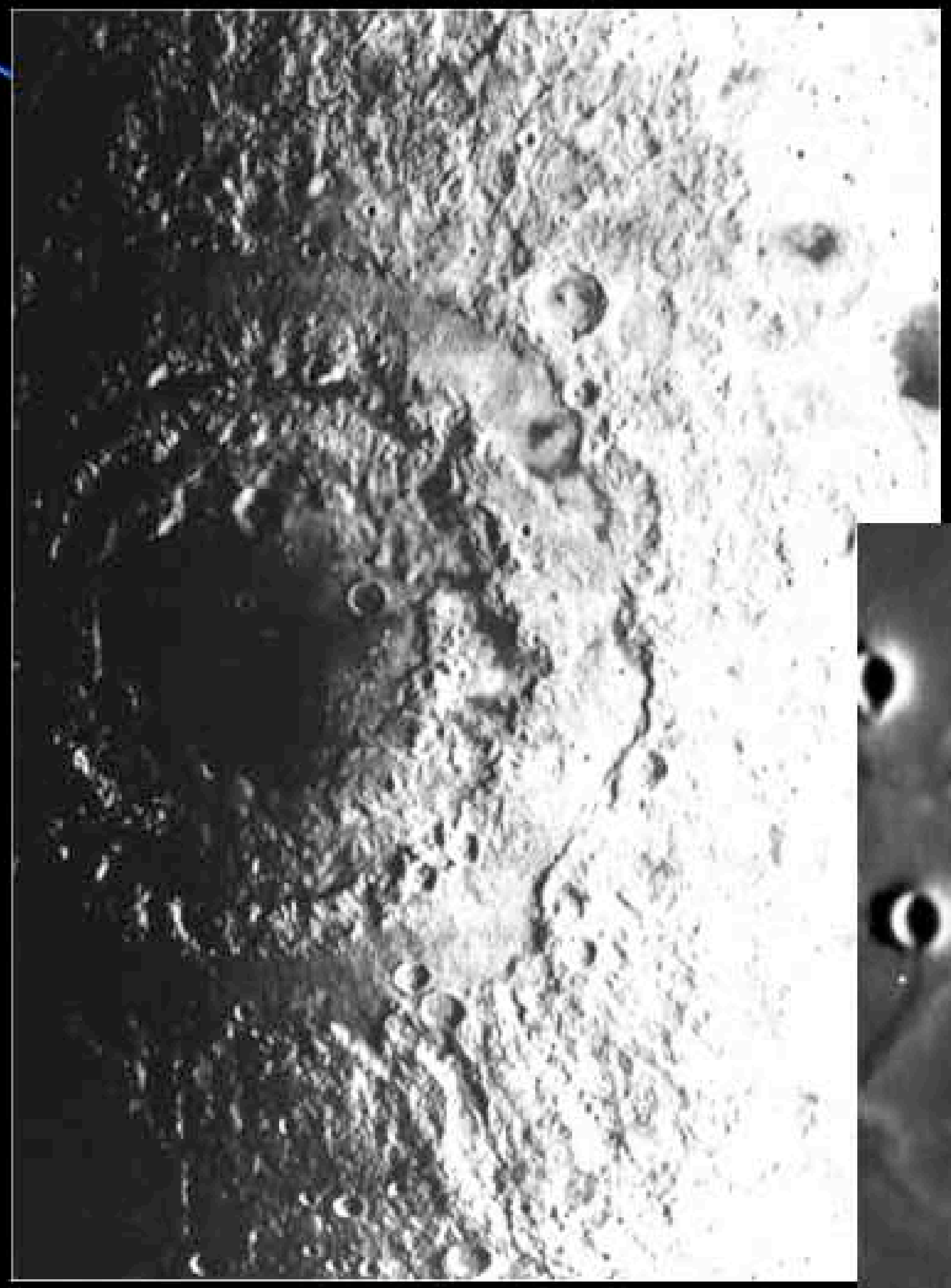
MARE SMYTHII

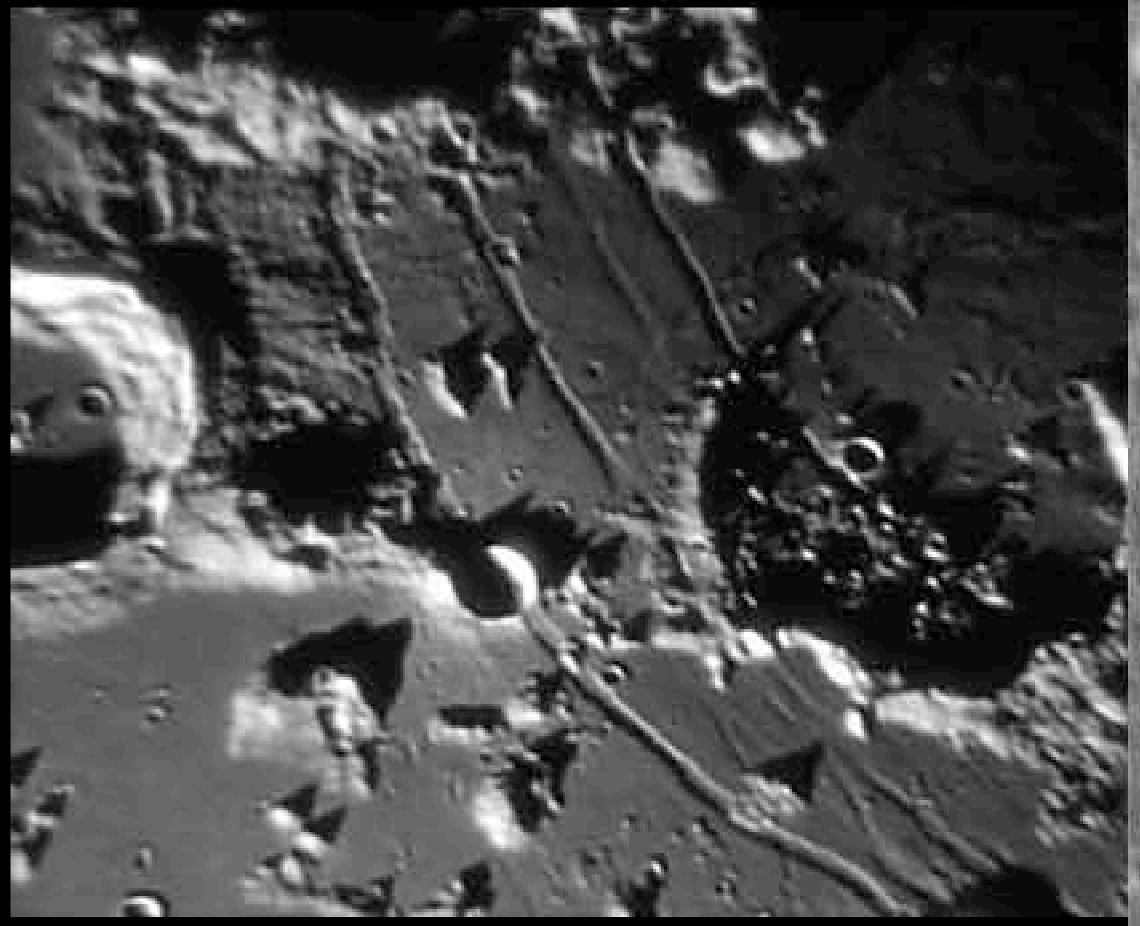
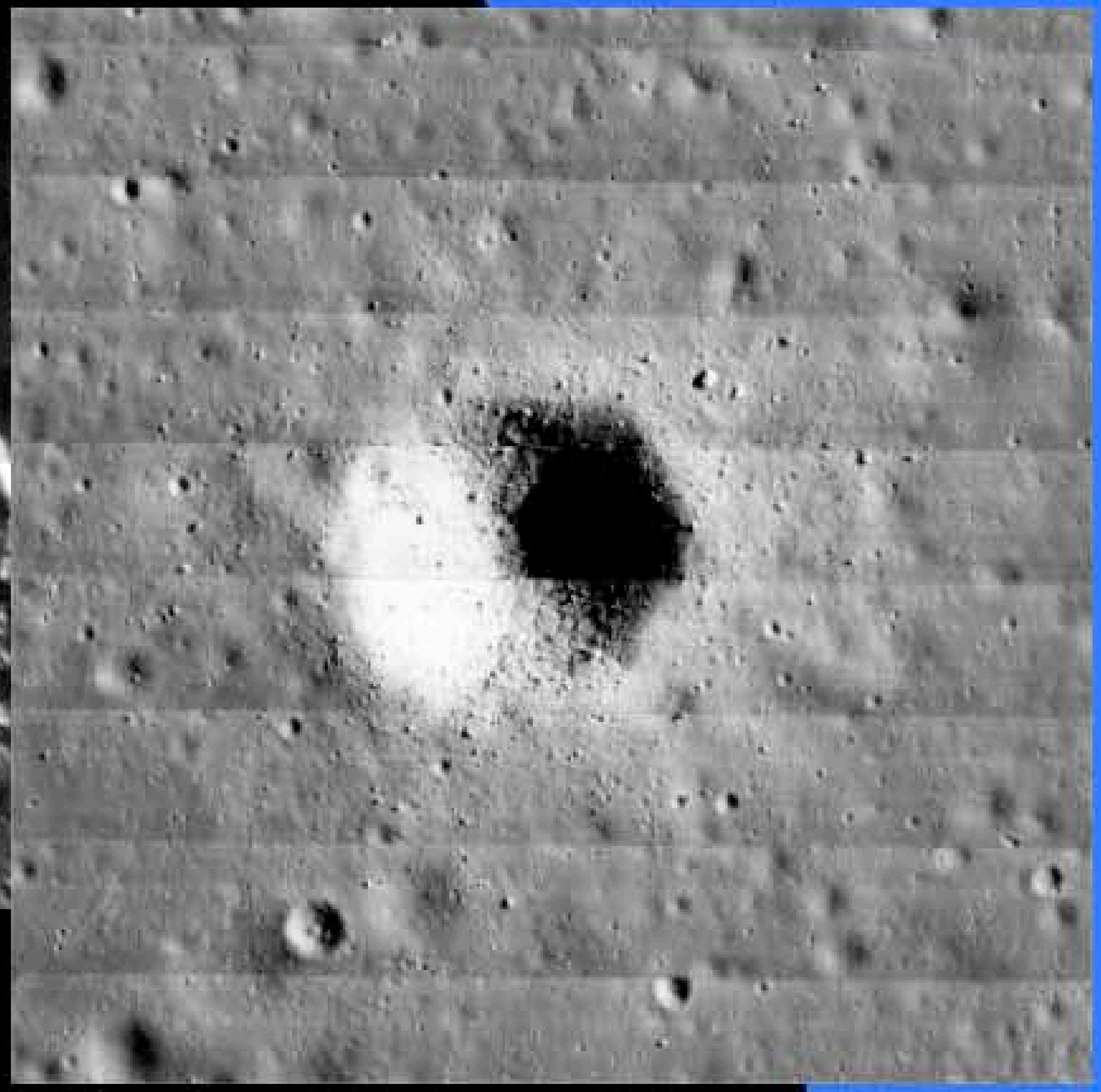




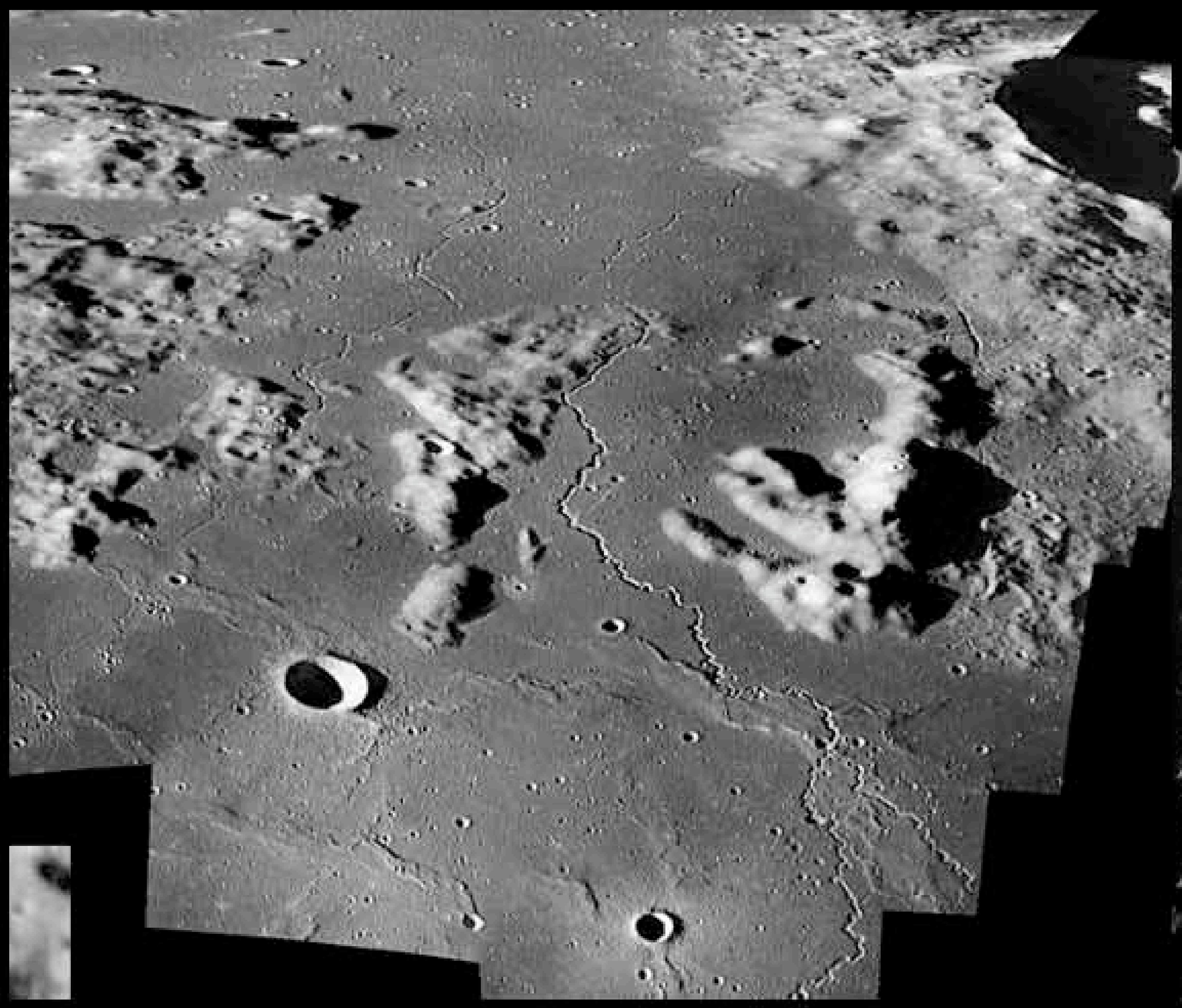
Surface Morphology and Physiography

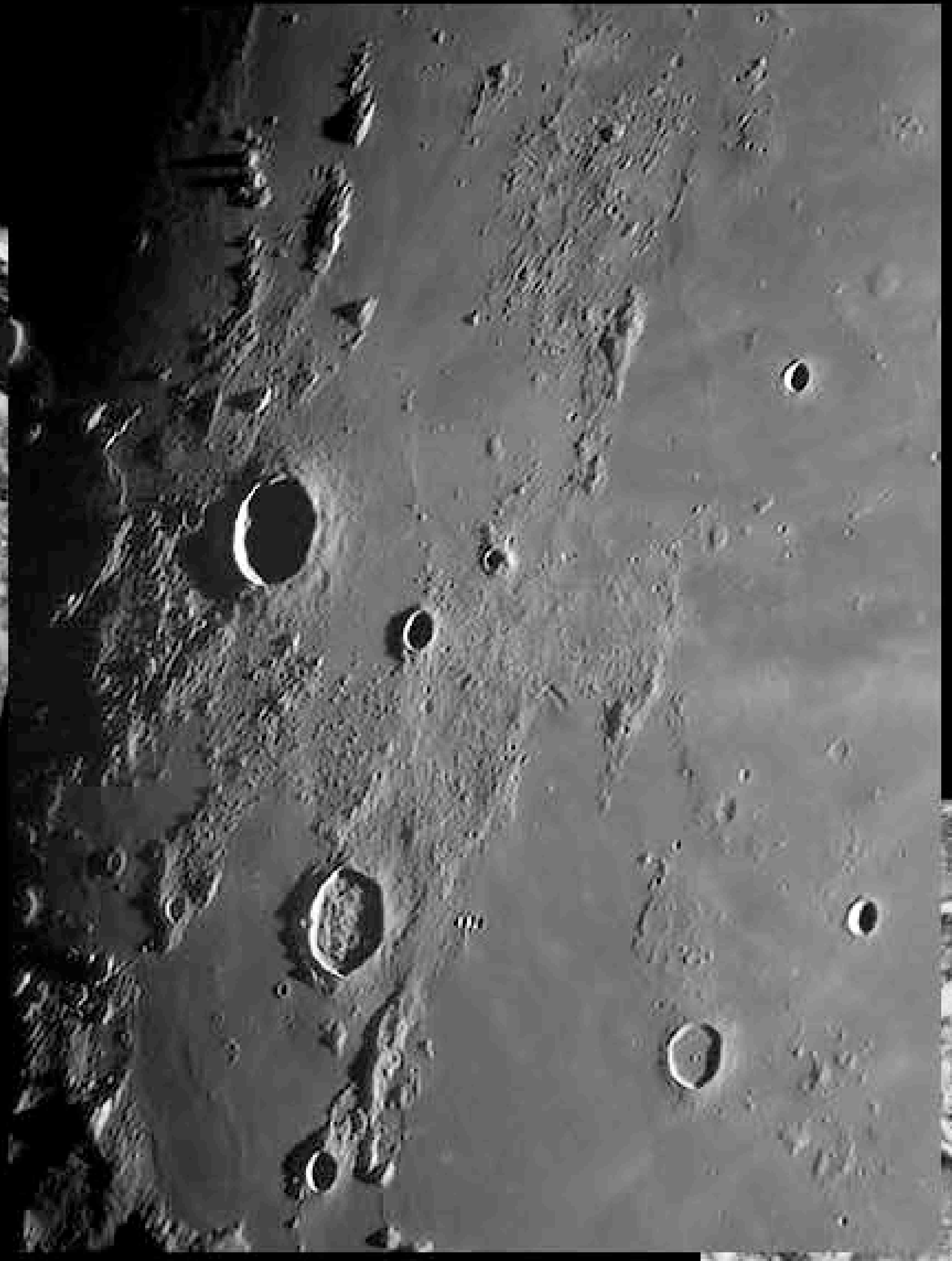
- Craters dominate all other landforms
  - Range in size from micro- to mega-meters
  - Shape and form change with increasing size (bowl shaped to central peaks to multiple rings)
- Maria are flat-lying to rolling plains, with crenulated ridges
  - Low relief, all mostly caused by post-mare craters
-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

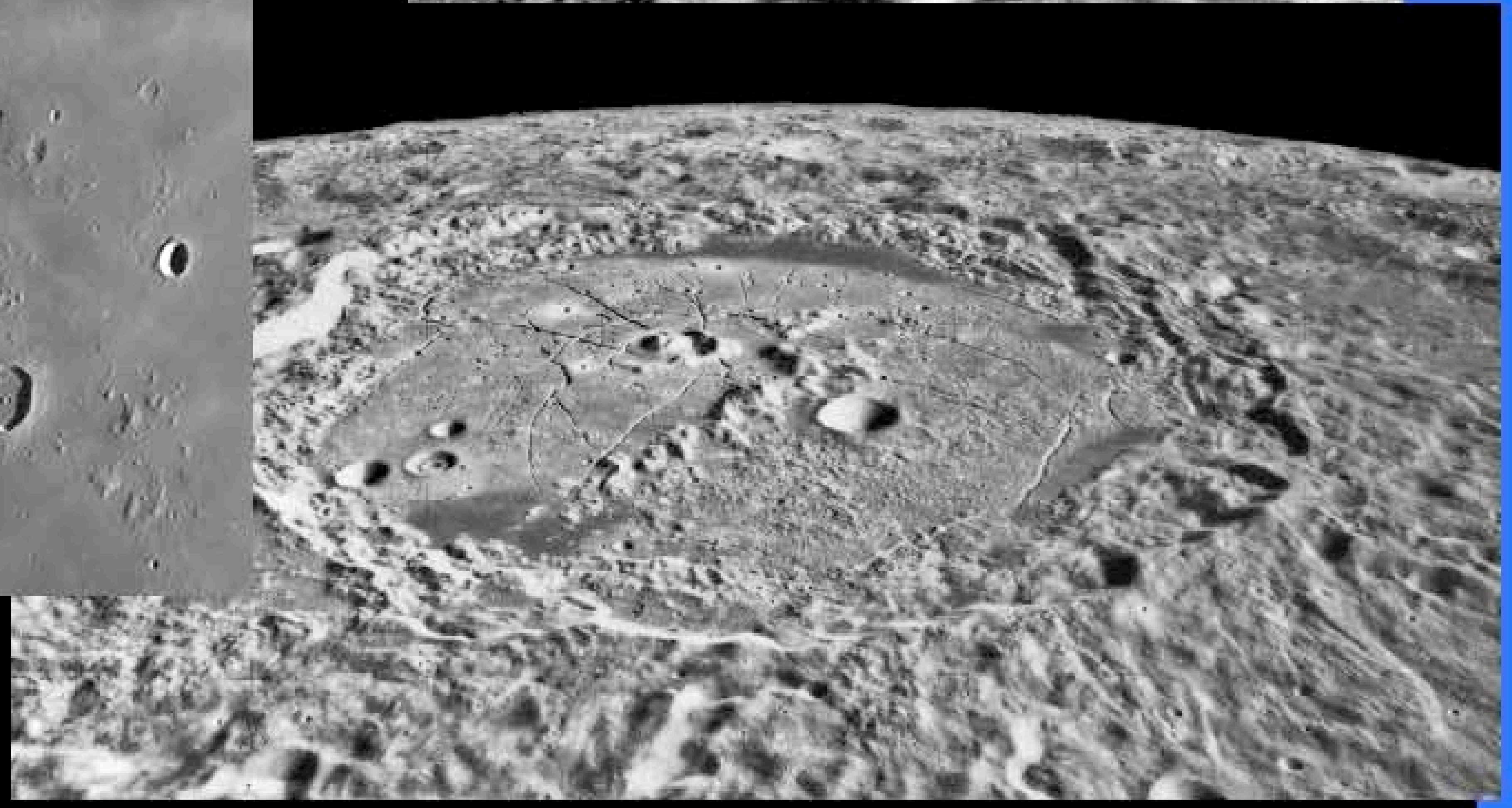


Some Lunar Landscapes







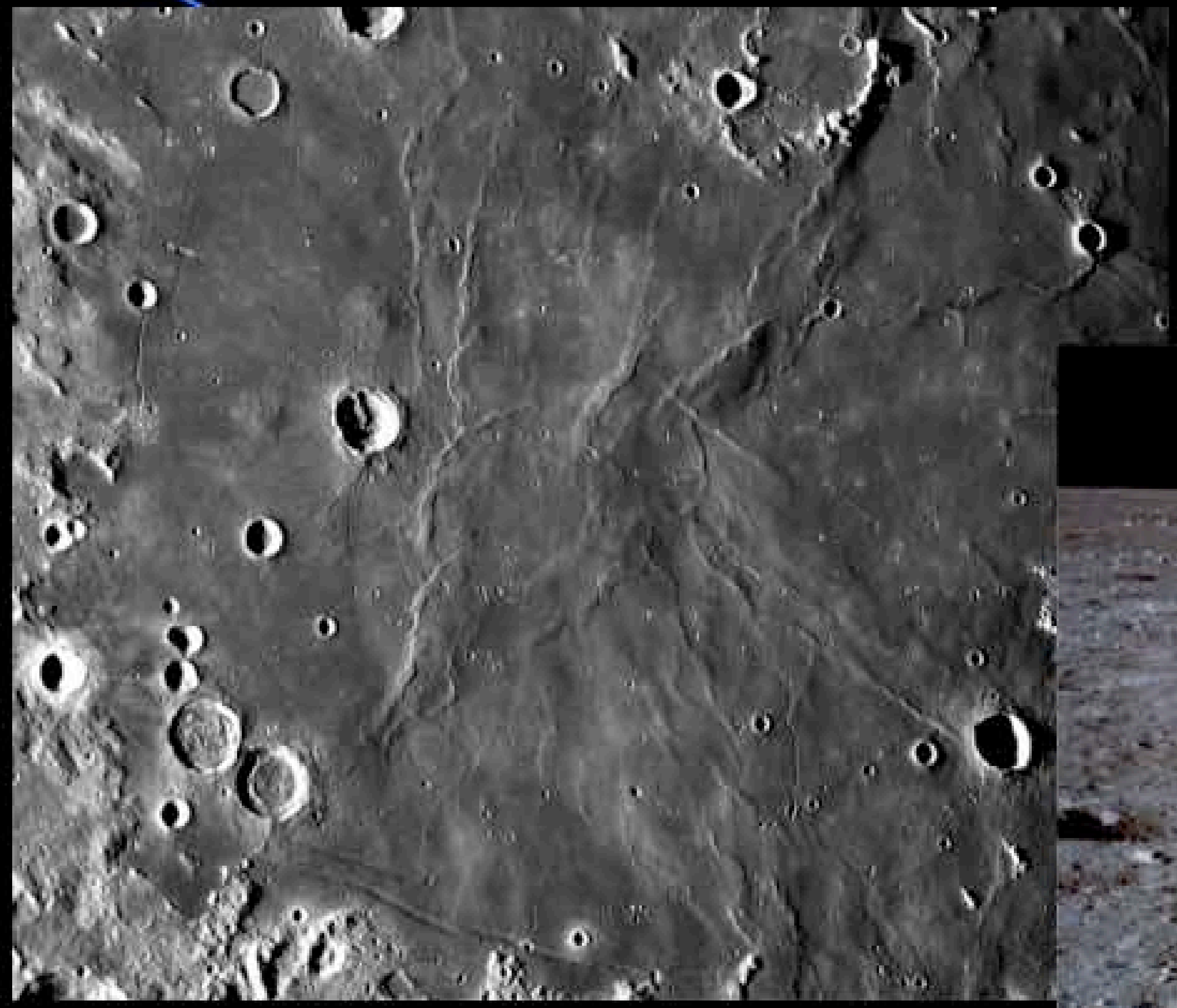
Lunar Terrains

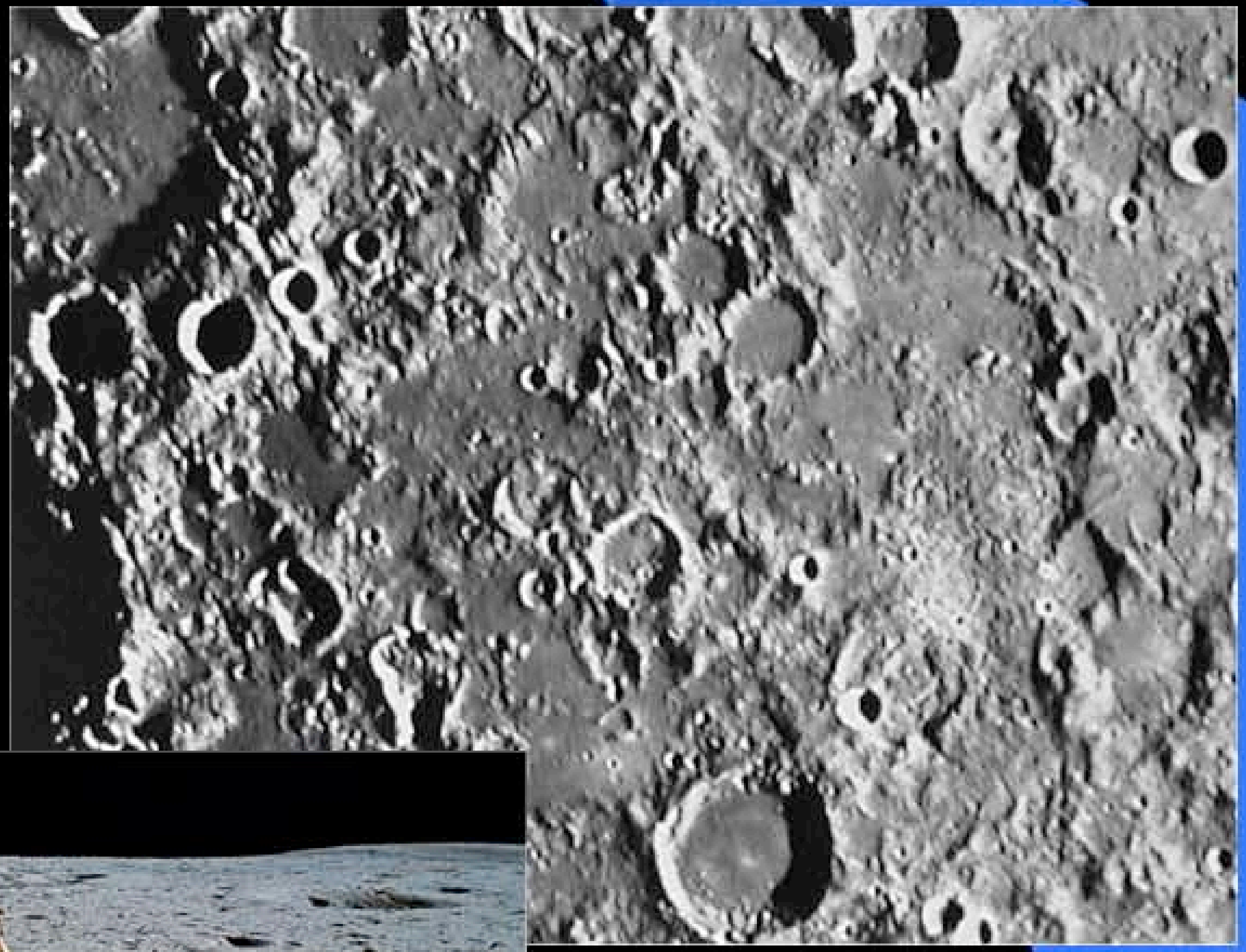
Maria

- 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°

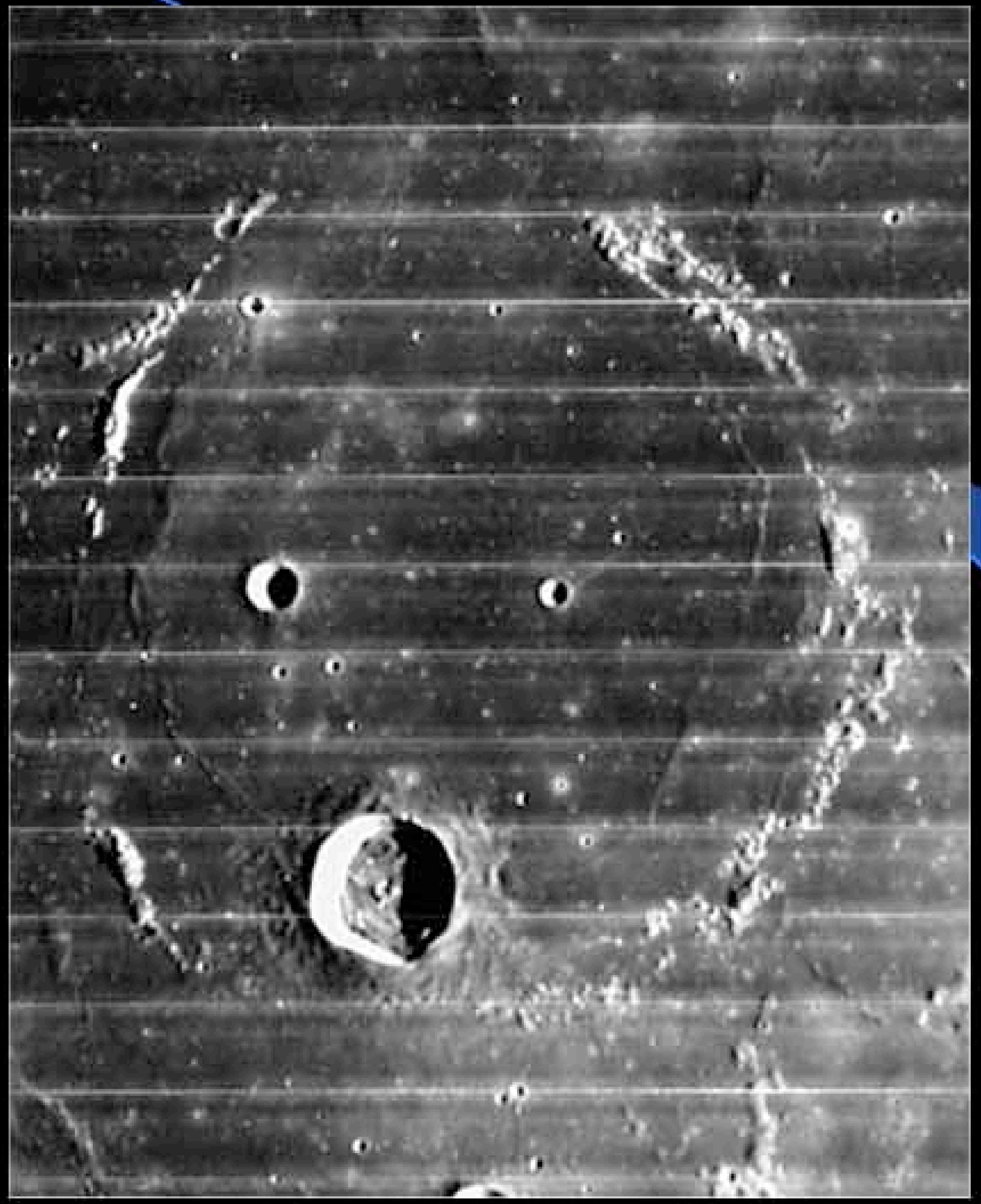


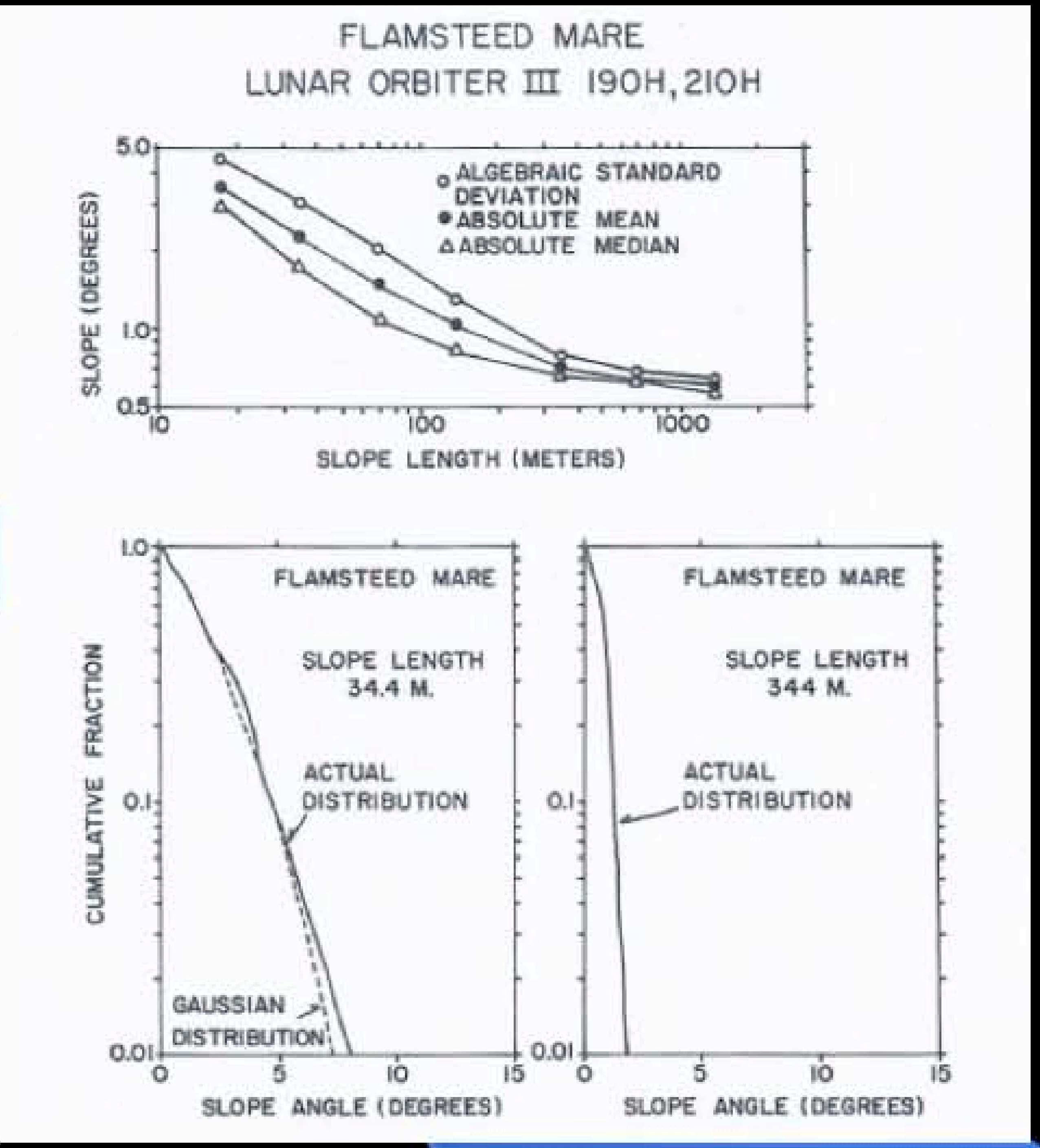



Terrain Slopes

Mare – Flamsteed ring mare

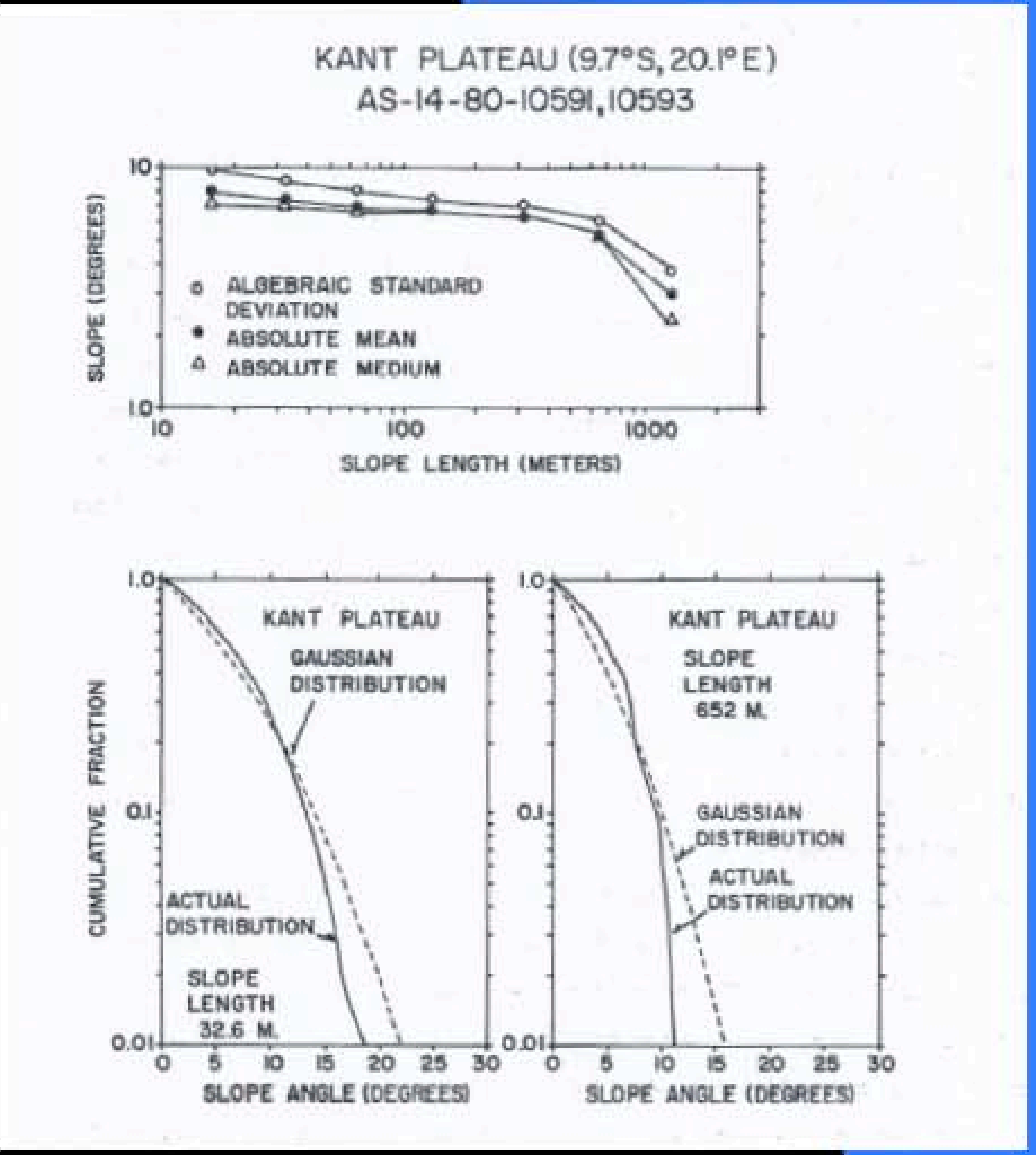
- Young mare; blocky crater rims
- Smooth flat surfaces
- Mean slopes < 5°; local slopes (in fresh crater walls) up to 25°





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

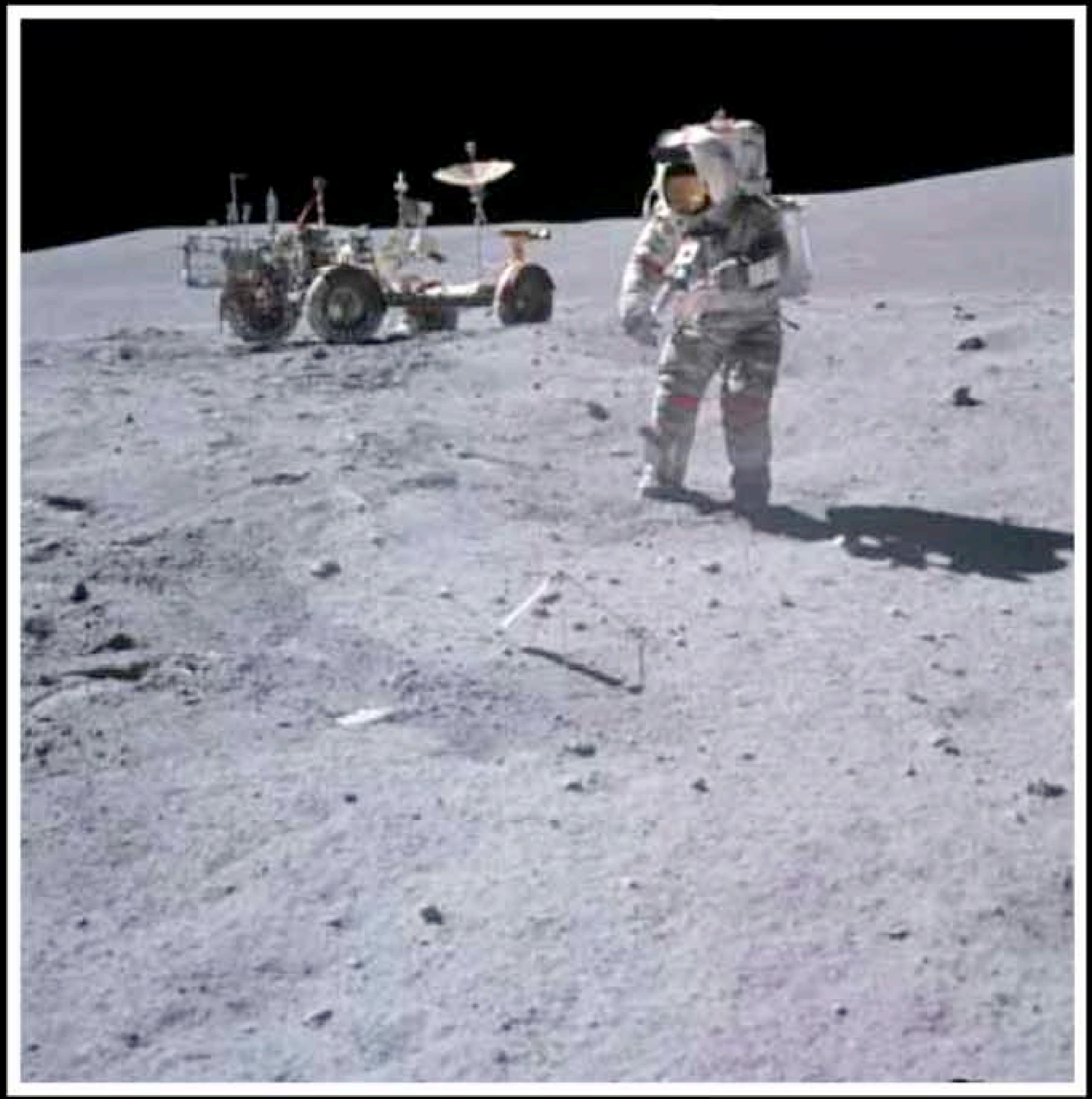
Apollo 12 EVA 1 had the lowest illumination angle

Apollo 16 EVA 3 had the highest illumination angle

Surface Lighting

AS12-46-6734

Apollo 12 EVA 1 - 7.5°



A16-117-18825

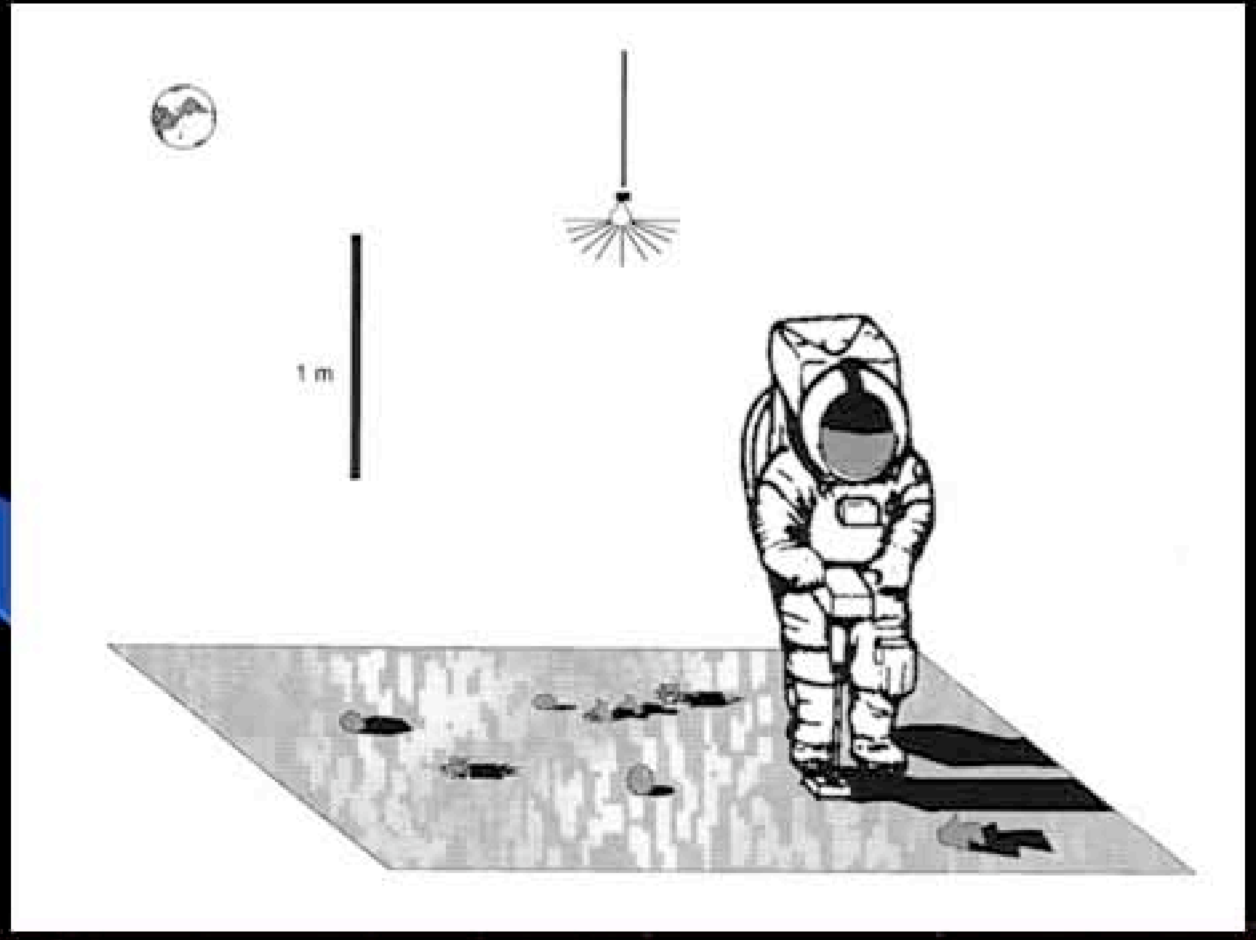
Apollo 16 EVA 3 - 46°

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



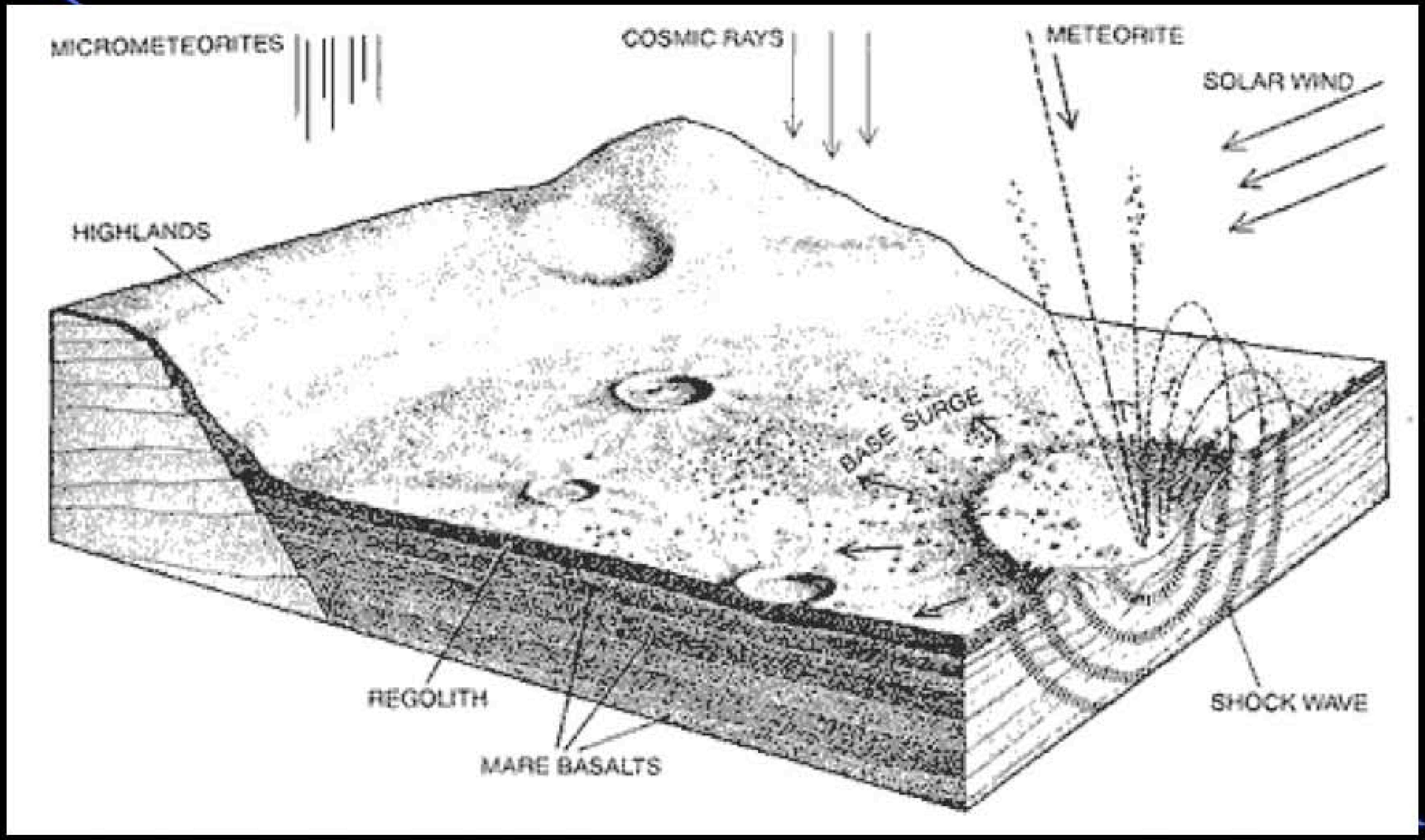
Full disk Earth illumination equivalent to working in room lit by 60 W bulb 2.2 meters overhead

Thermal requirements will be greatly reduced for night work

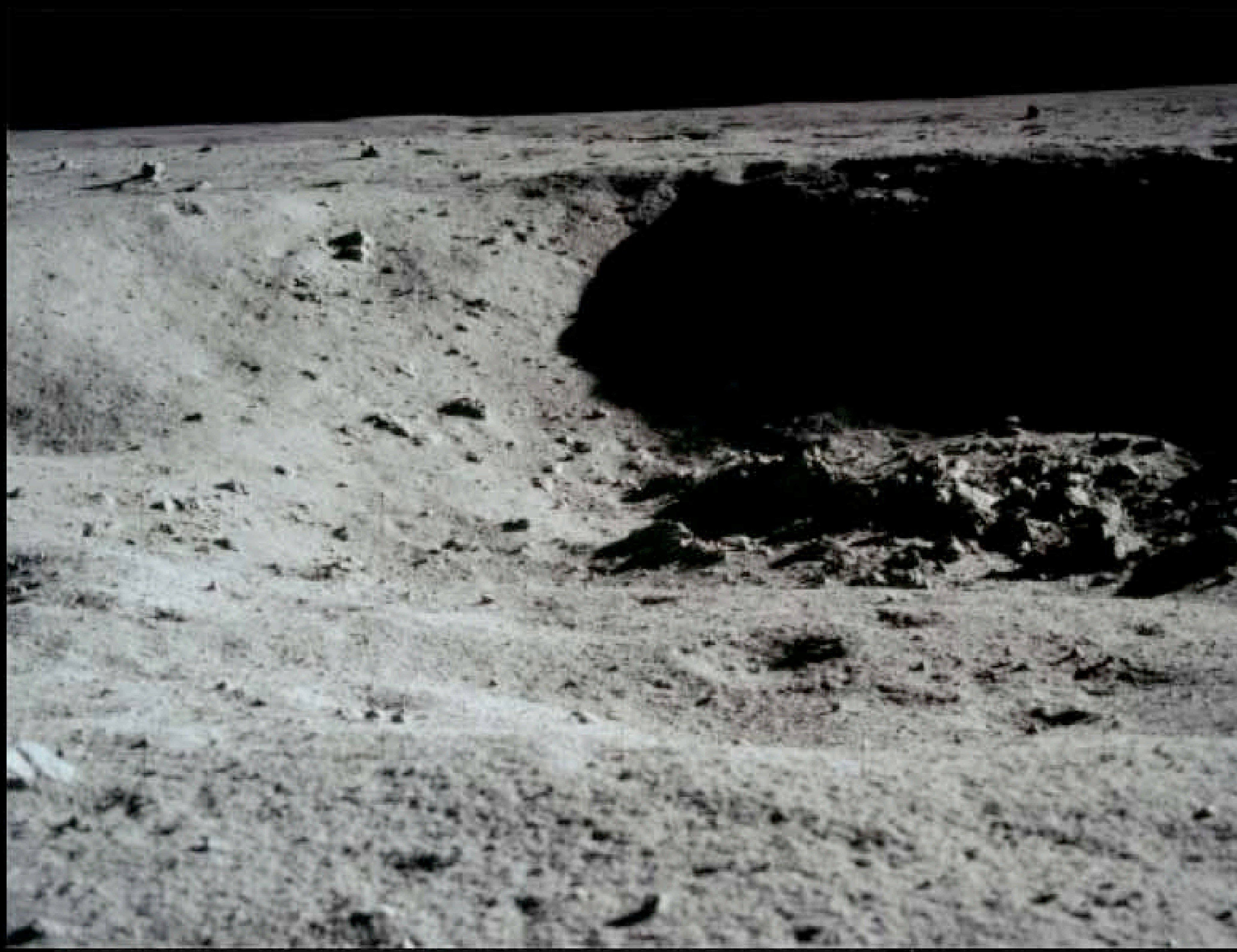
Work near the poles will likely require artificial lighting in any event

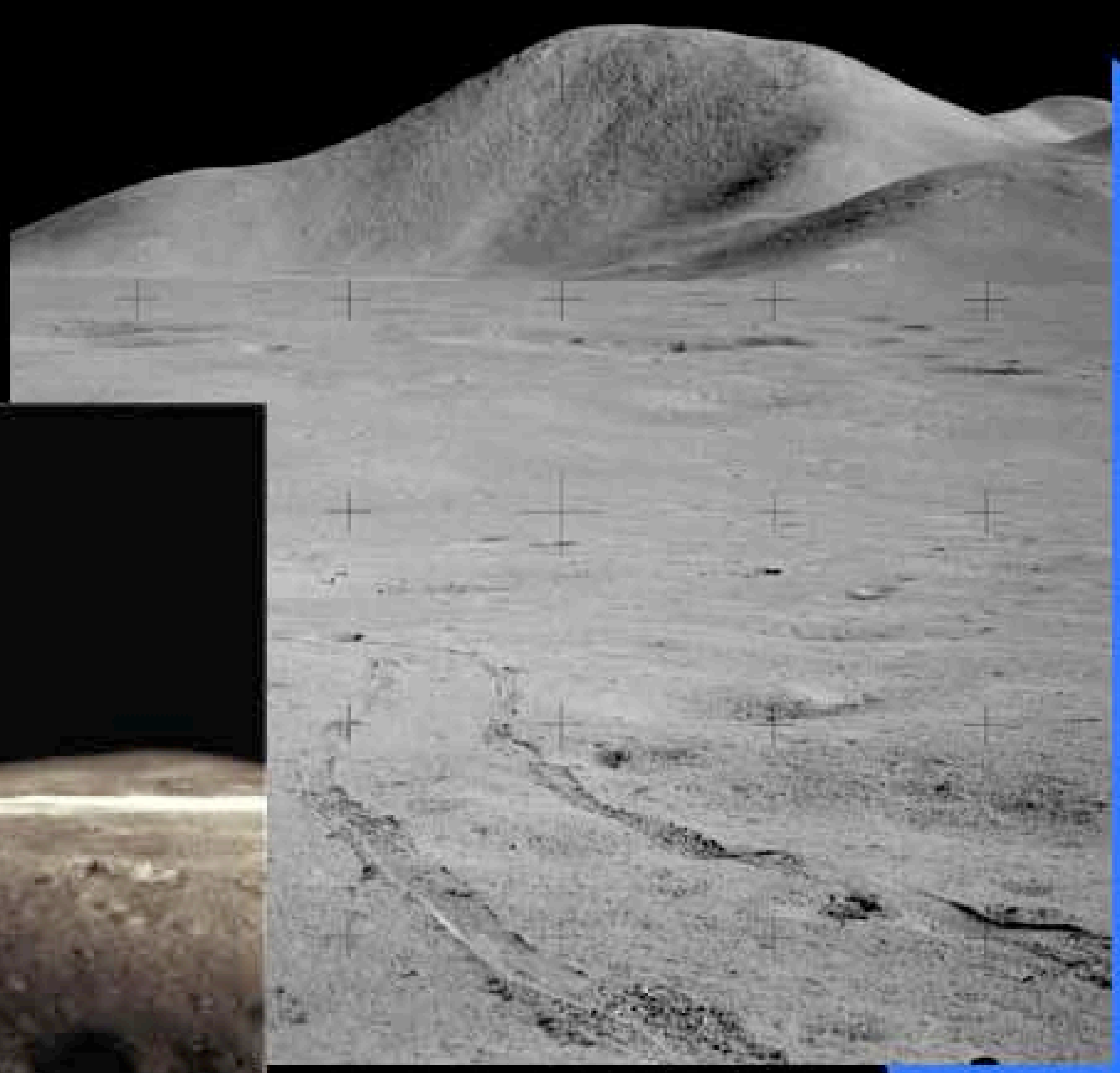
Regolith

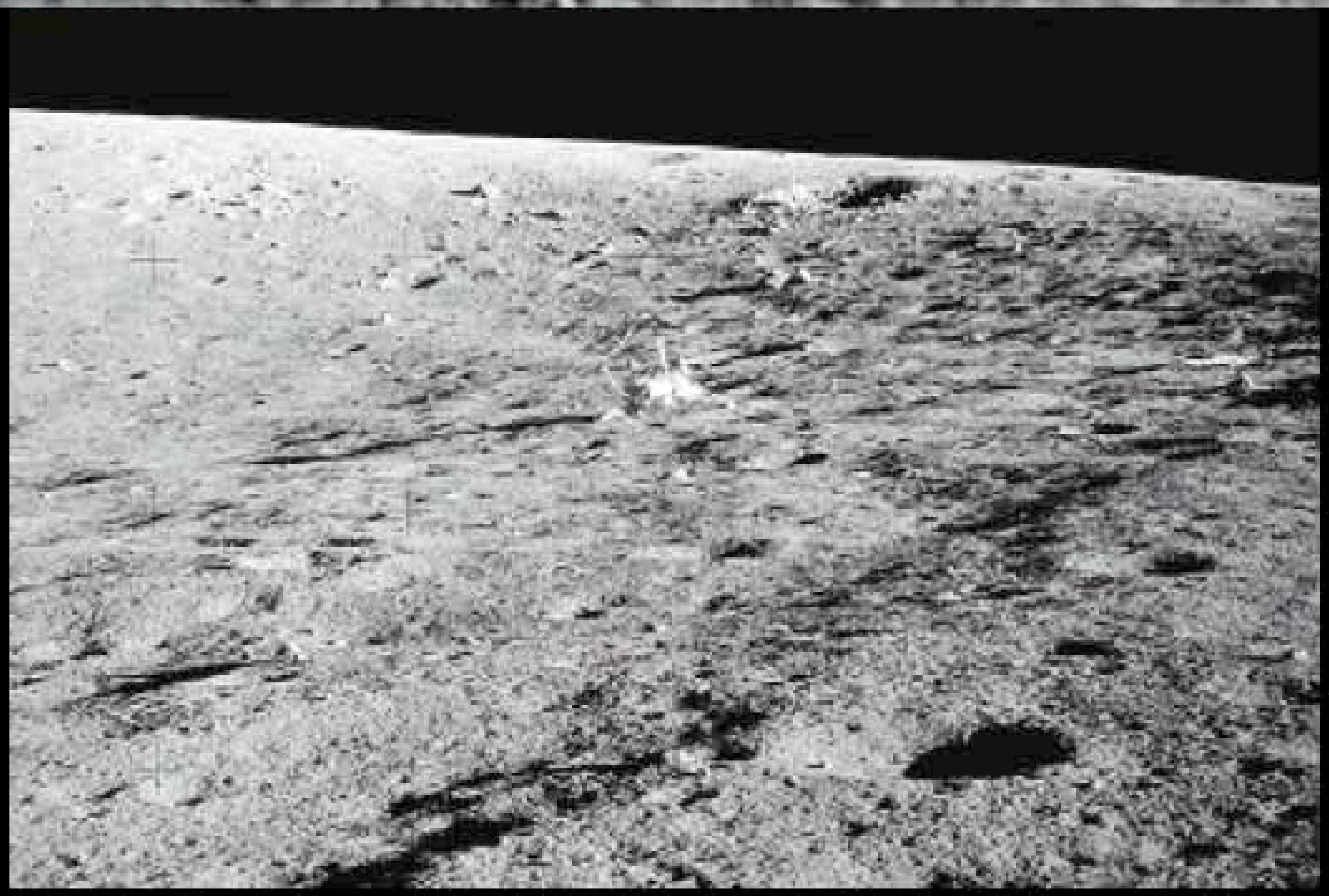
The layer or mantle of loose incoherent rock material, of whatever origin, that nearly everywhere underlies the surface of the land and rests on bedrock. A general term used in reference to unconsolidated rock, alluvium or soil material on top of the bedrock. Regolith may be formed in place or transported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

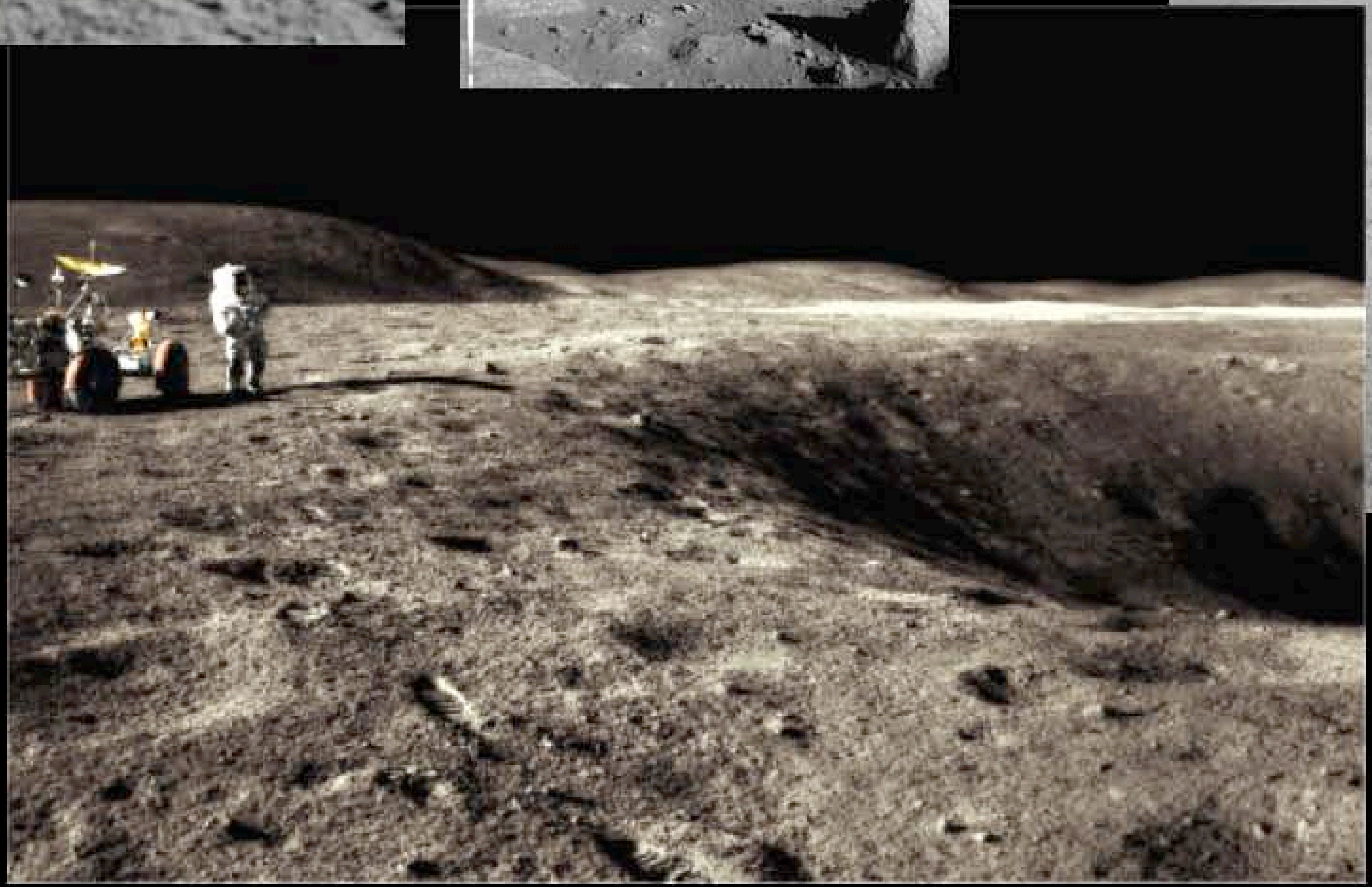


Regolith



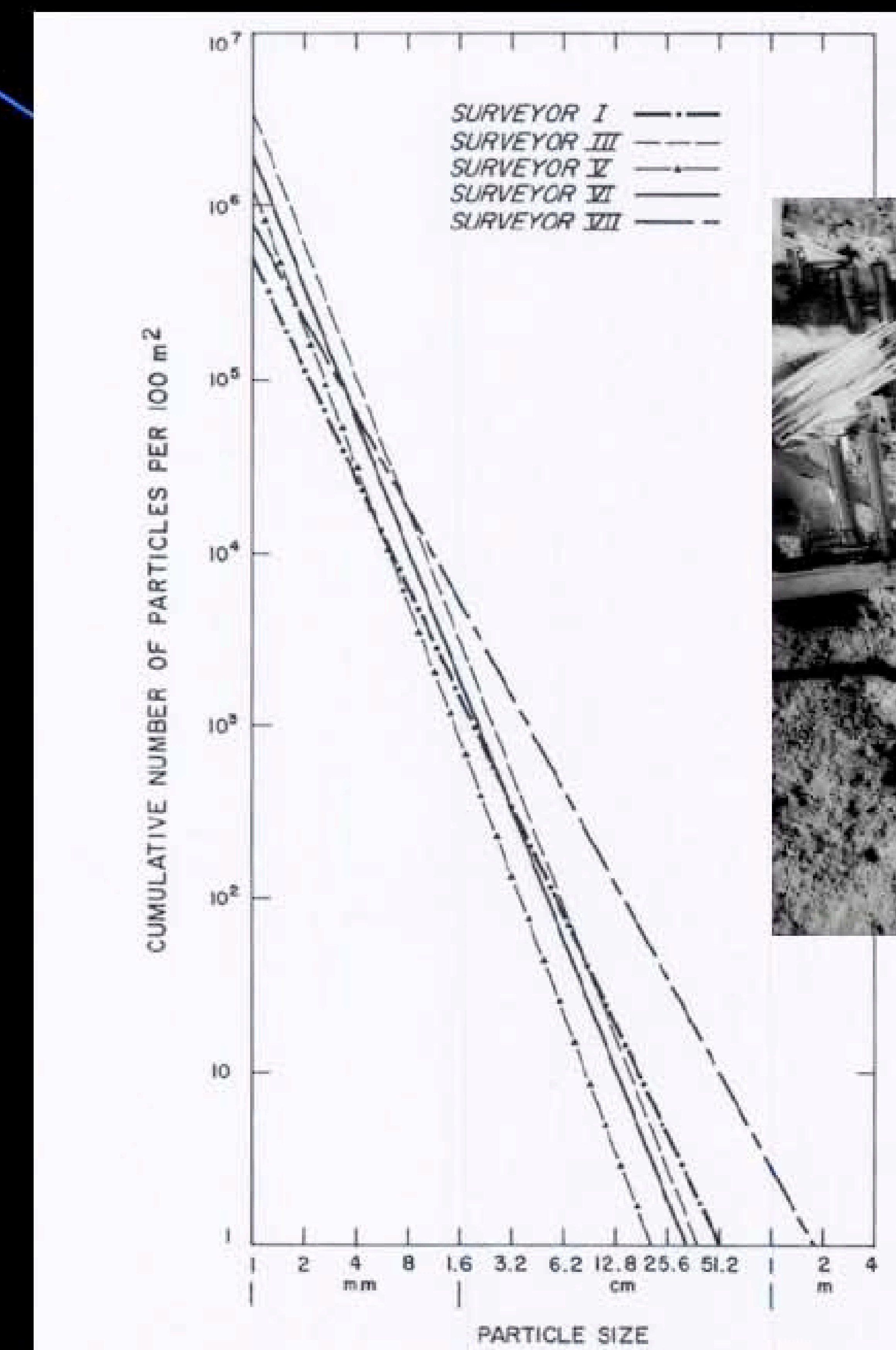






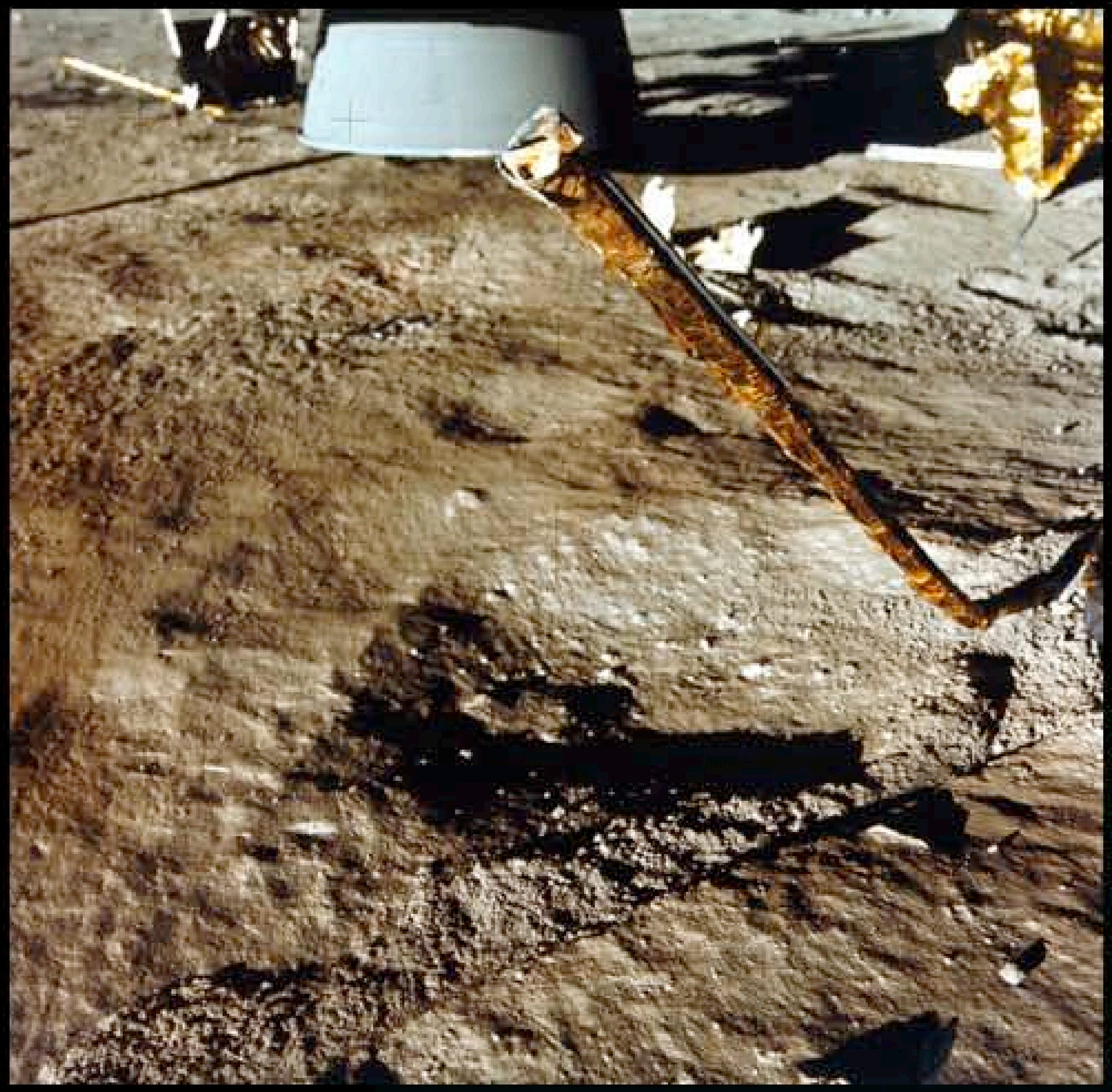
Regolith

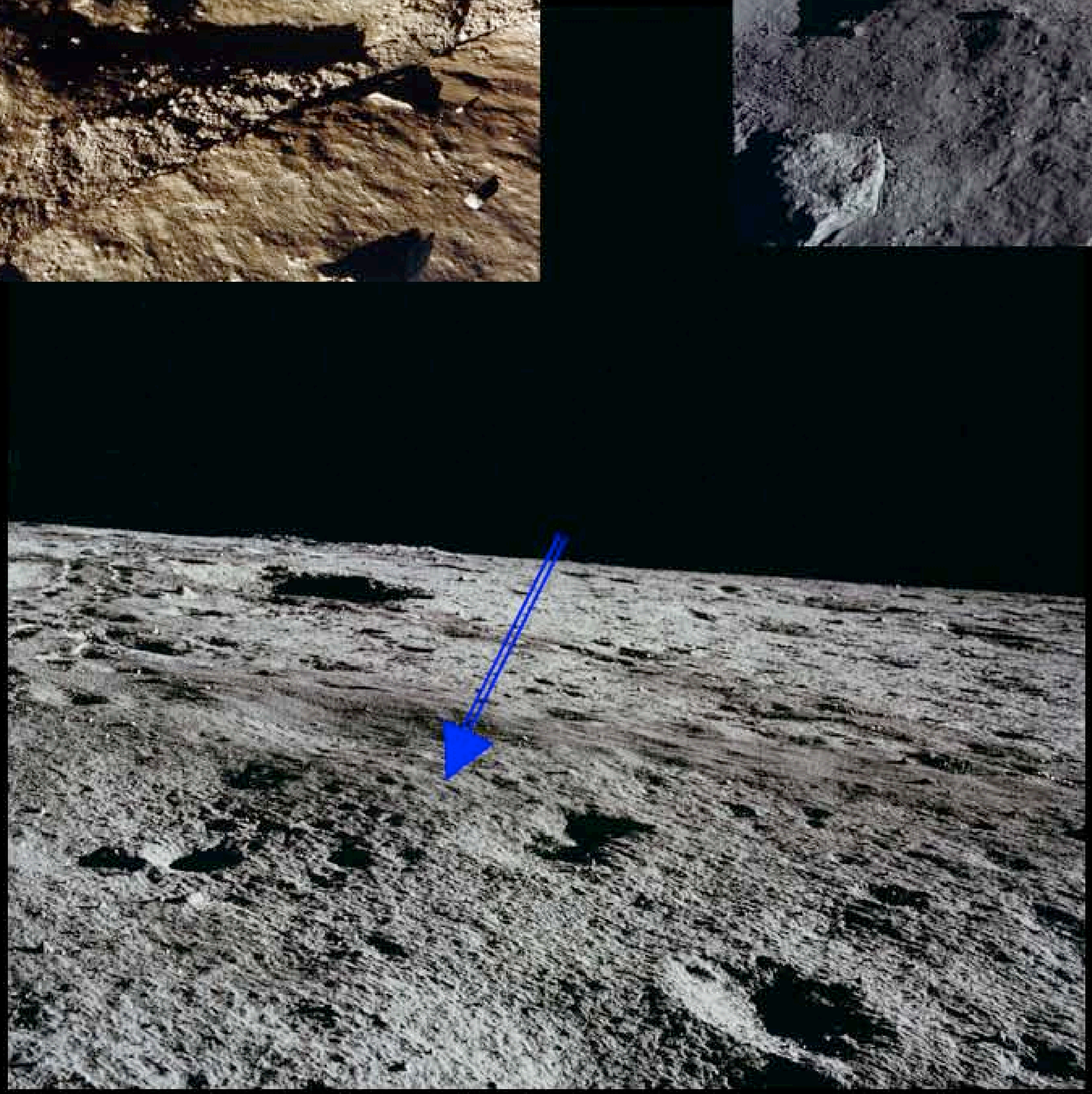
- **Median particle size of 40-130 μm**
  - Average grain size 70 μm
  - 10-20% of the soil is finer than 20 μm
- **Dust (<50 μm) makes up 40-50% by volume**
- **95% of lunar regolith is < 1 mm**
- **Soil particle size distribution very broad**
  - "Well graded" in geo-engineering terms
  - "Very poorly sorted" in geologic terms
- **High specific surface area 0.5 m^2 gm^{-1}**
  - 8X surface area of spheres with equivalent particle size distribution



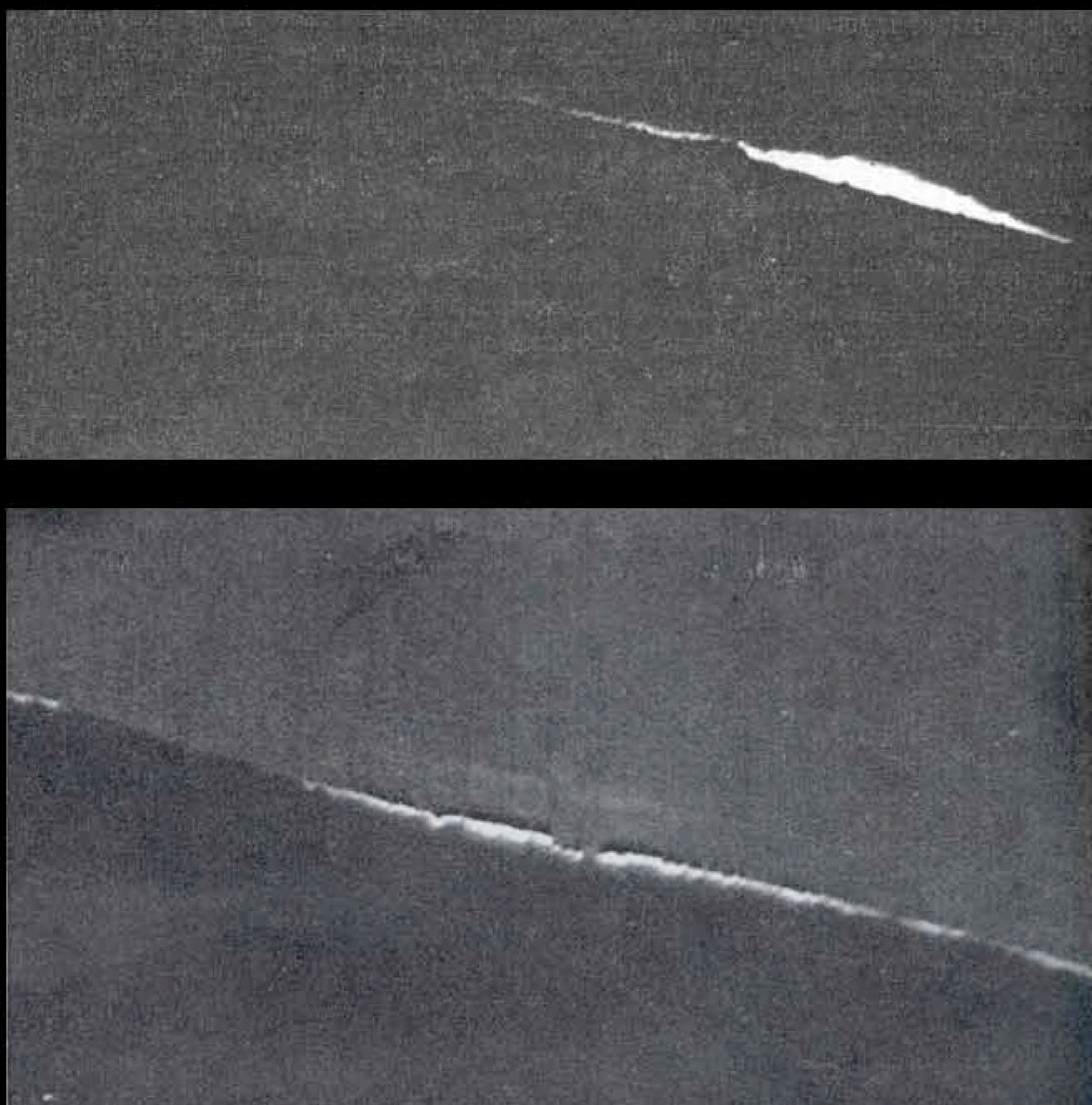
Dust

Loose Surficial Material



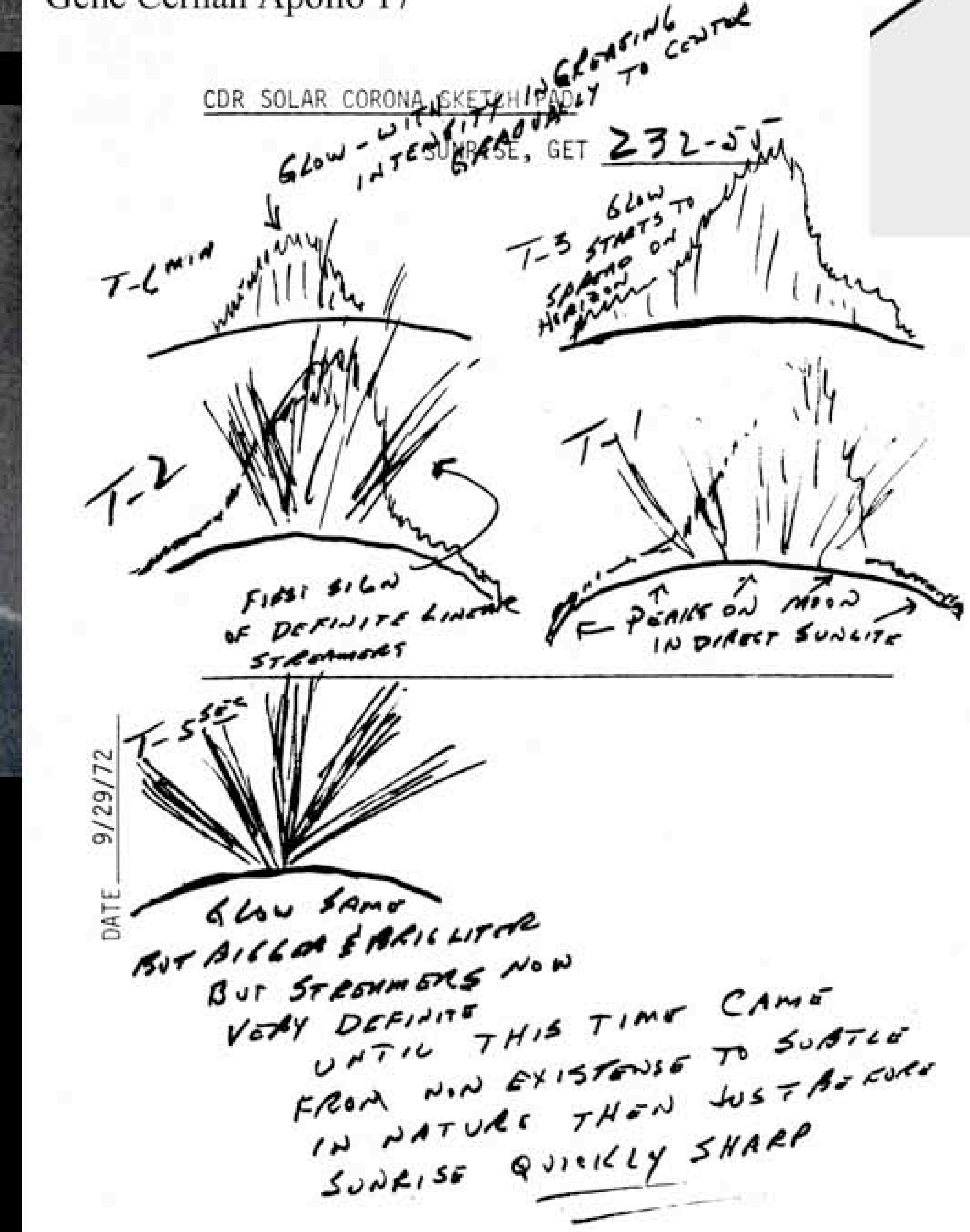


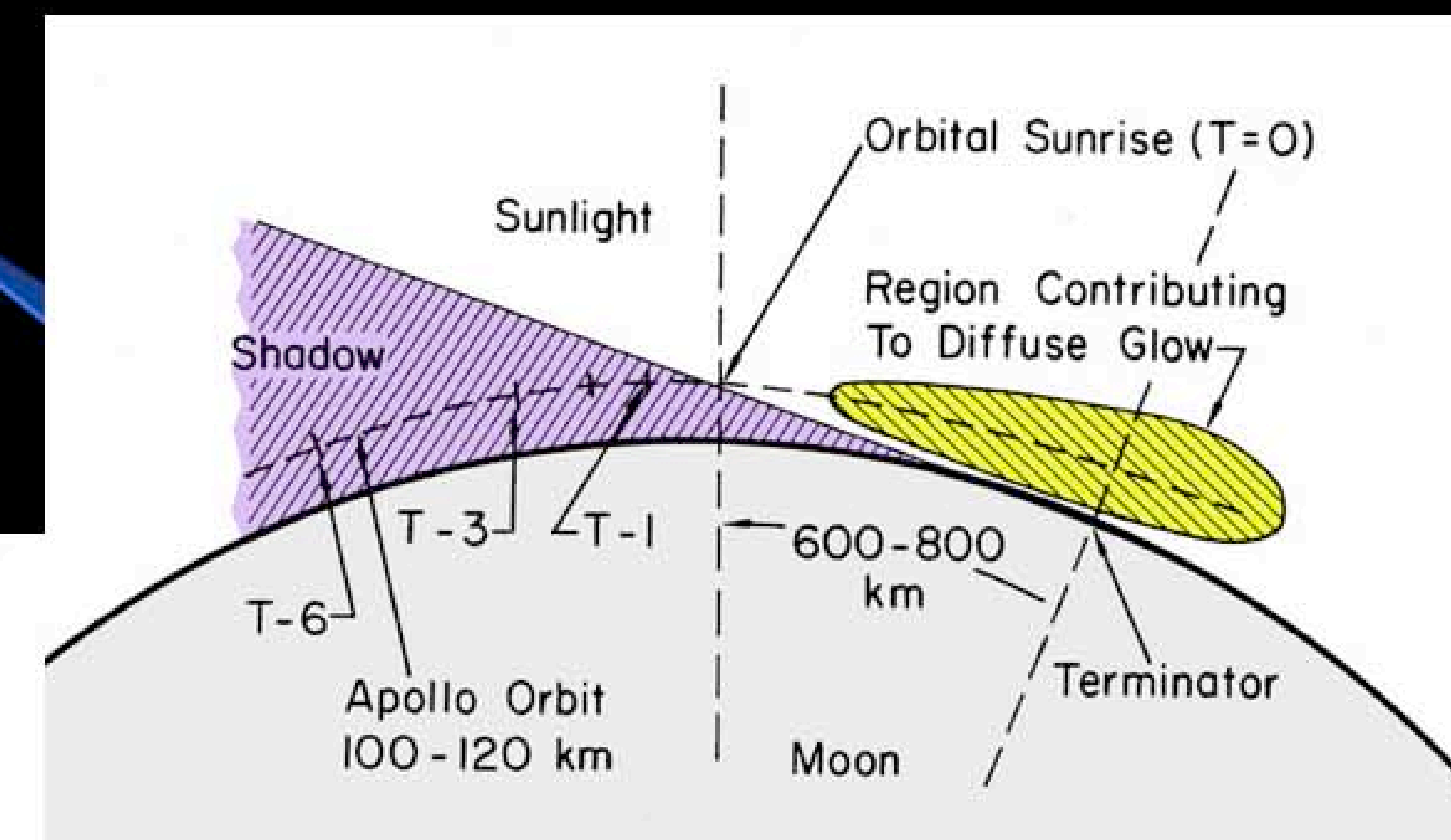
Levitated Dust?



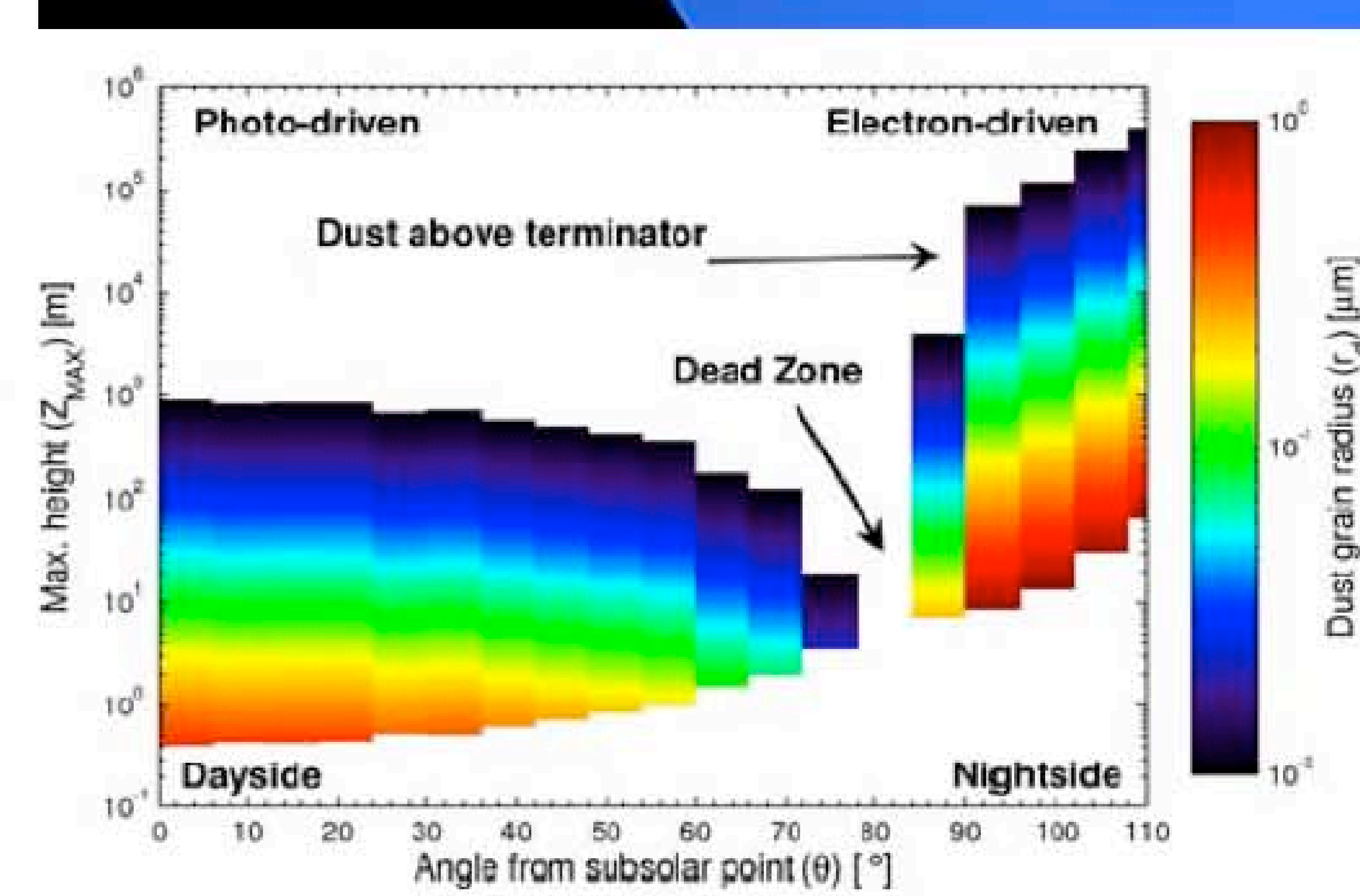
View of horizon glow from Surveyor

Gene Cernan Apollo 17





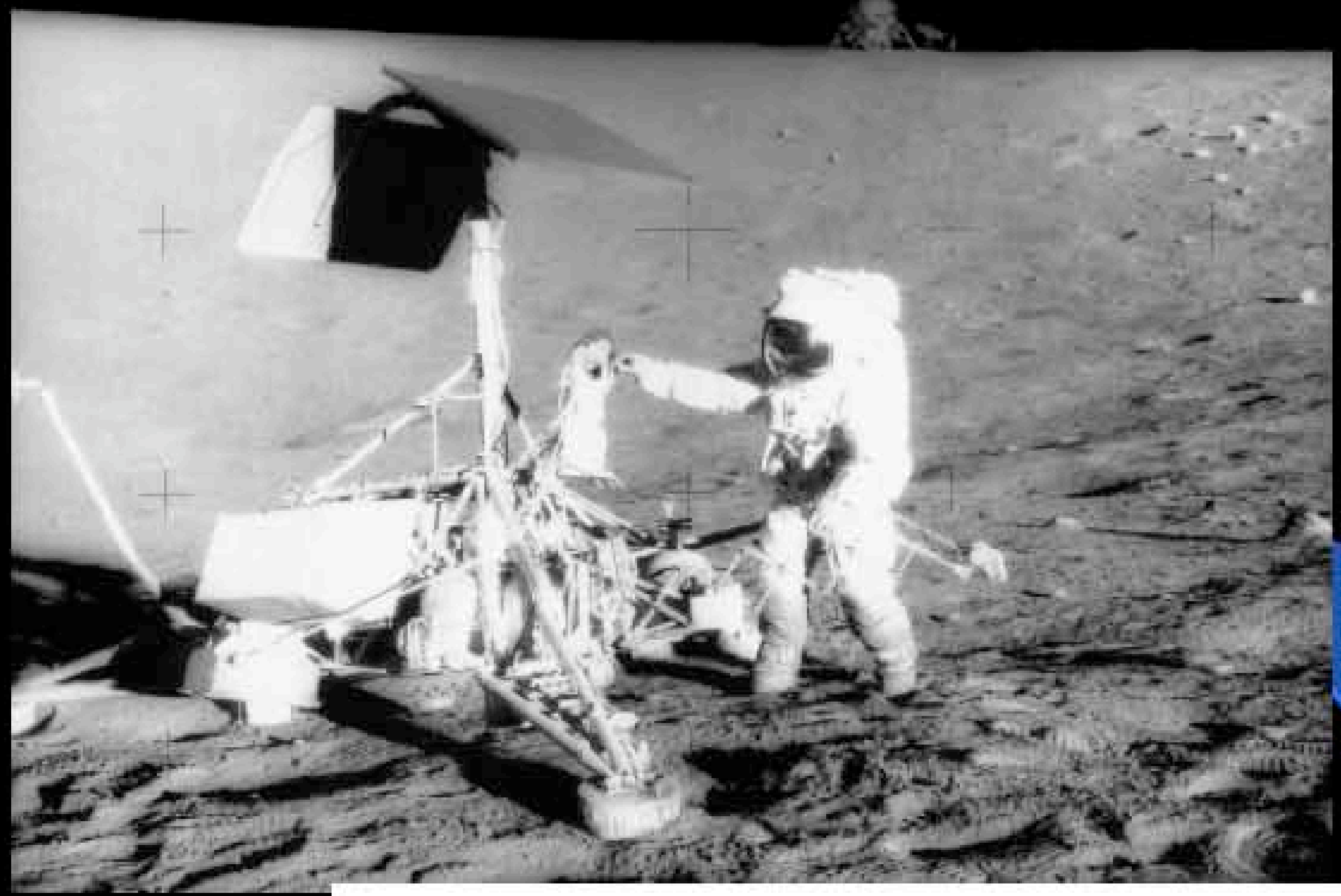
MCoy and Criswell (1974)

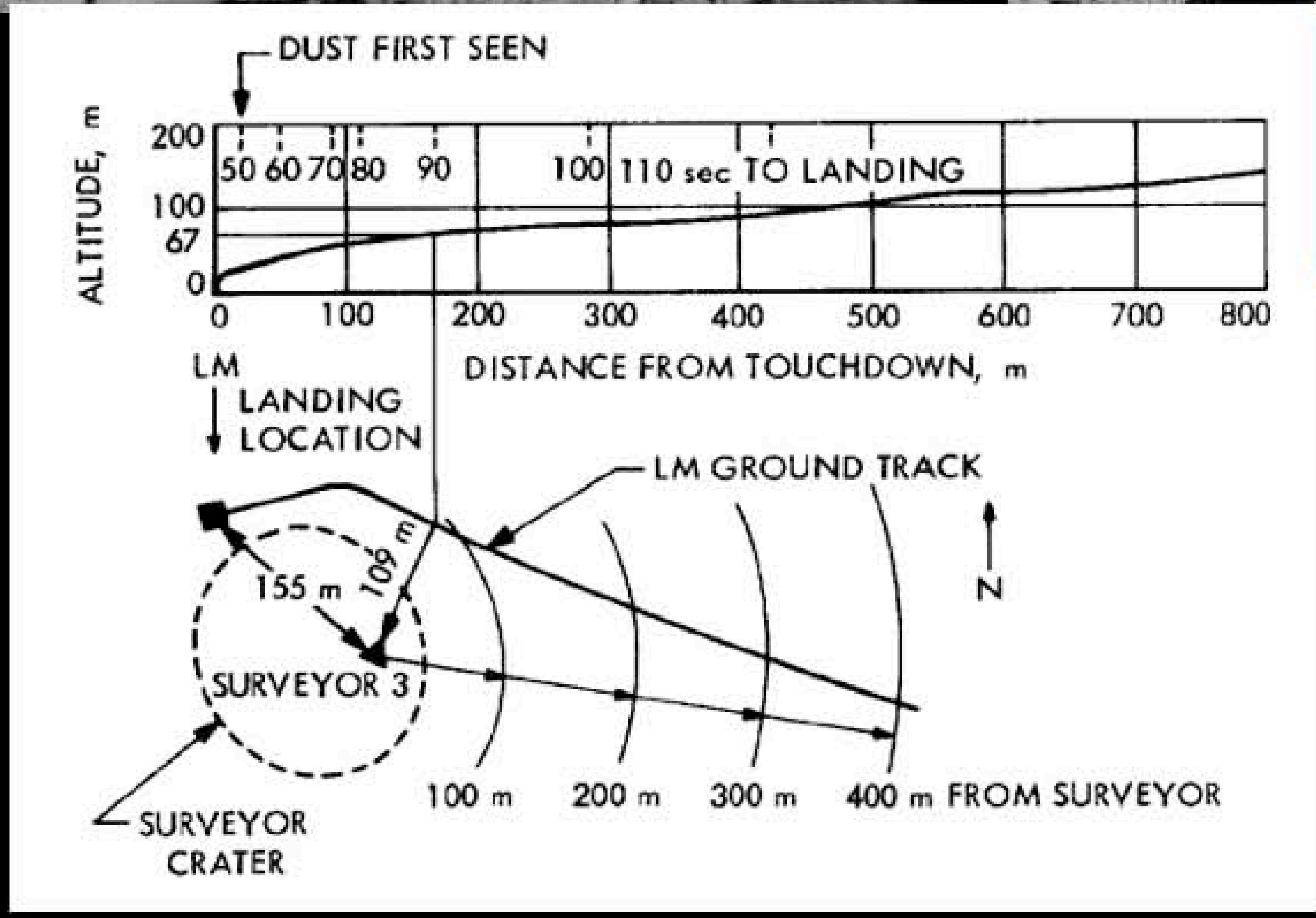


Vondrak

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

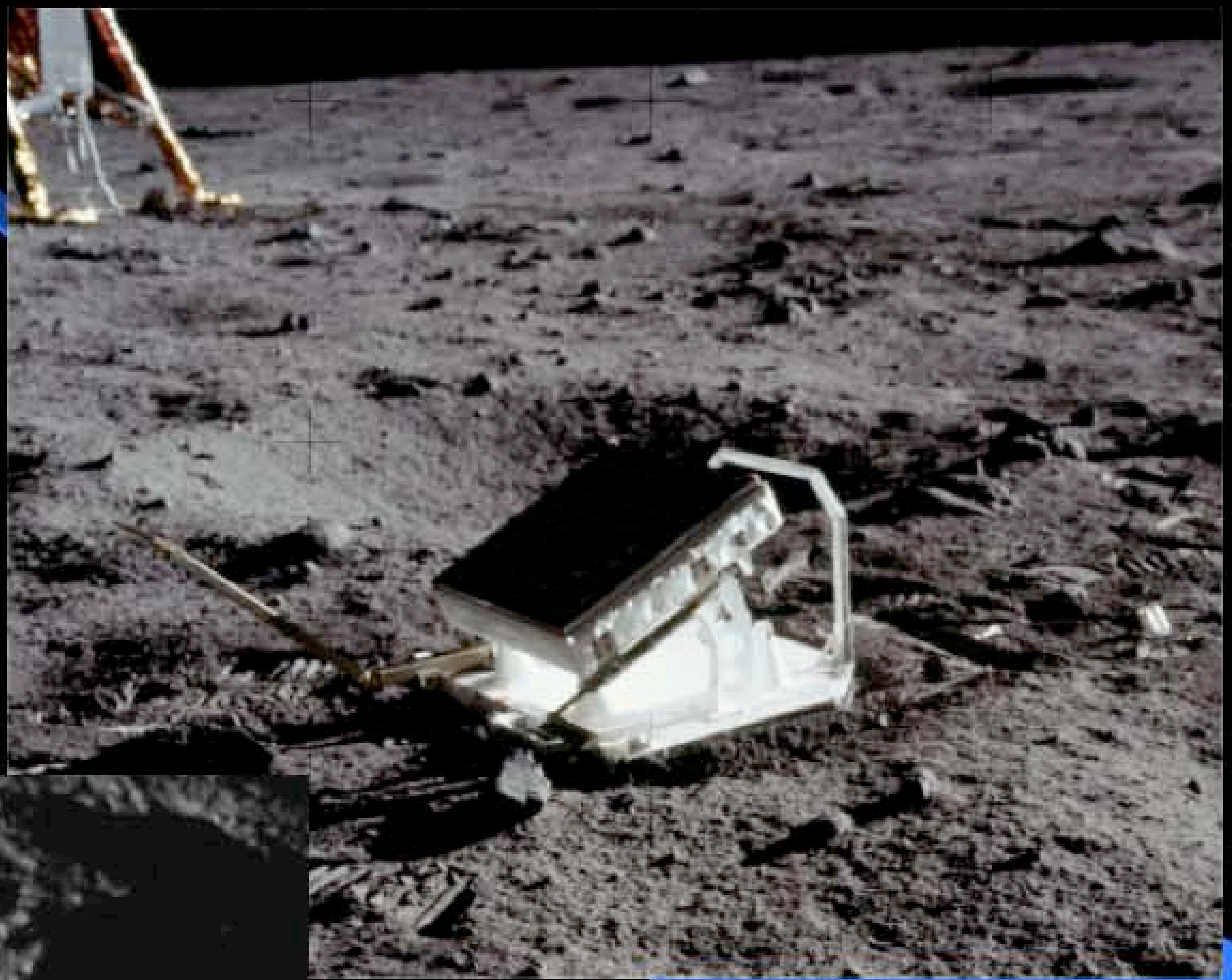


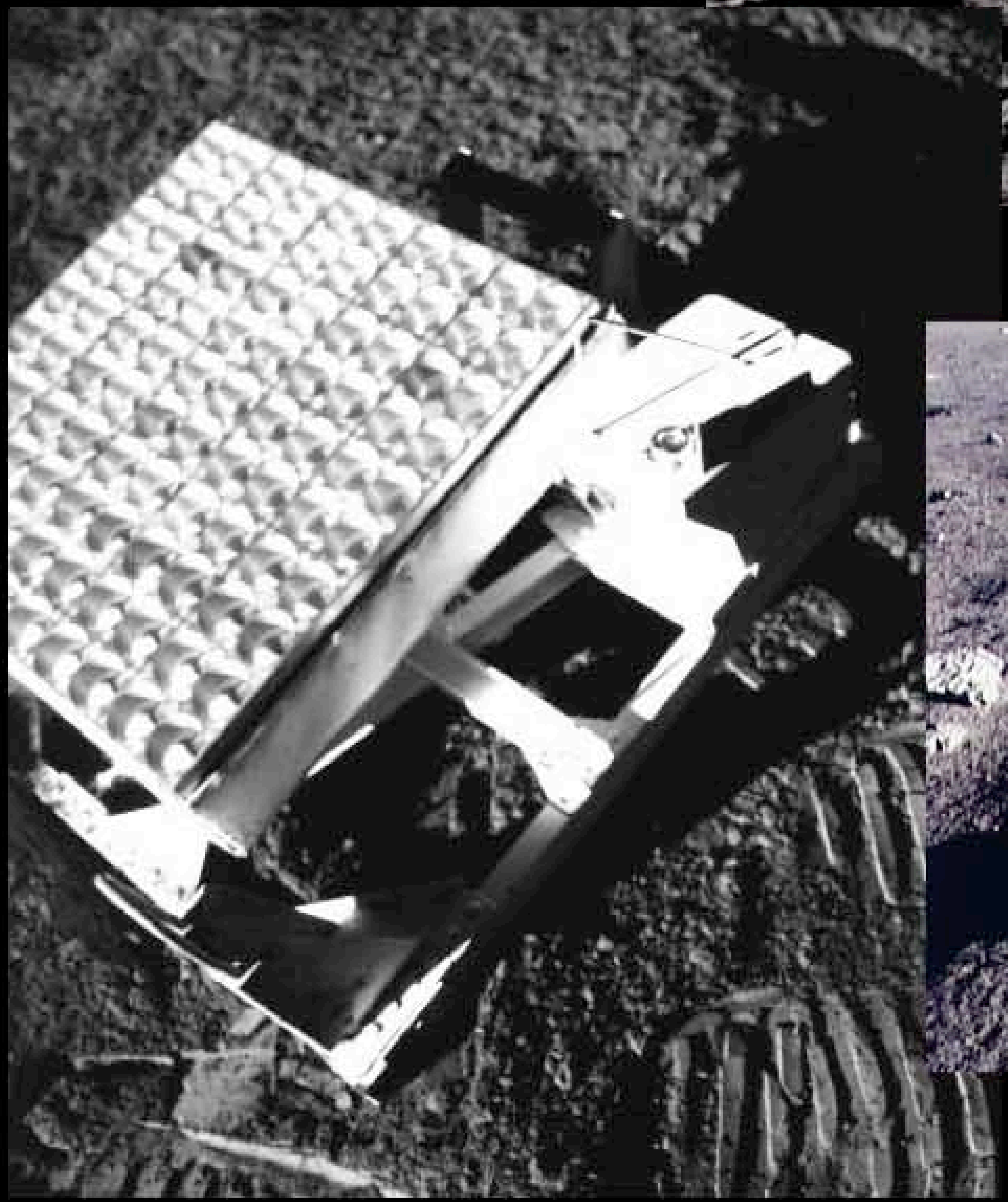


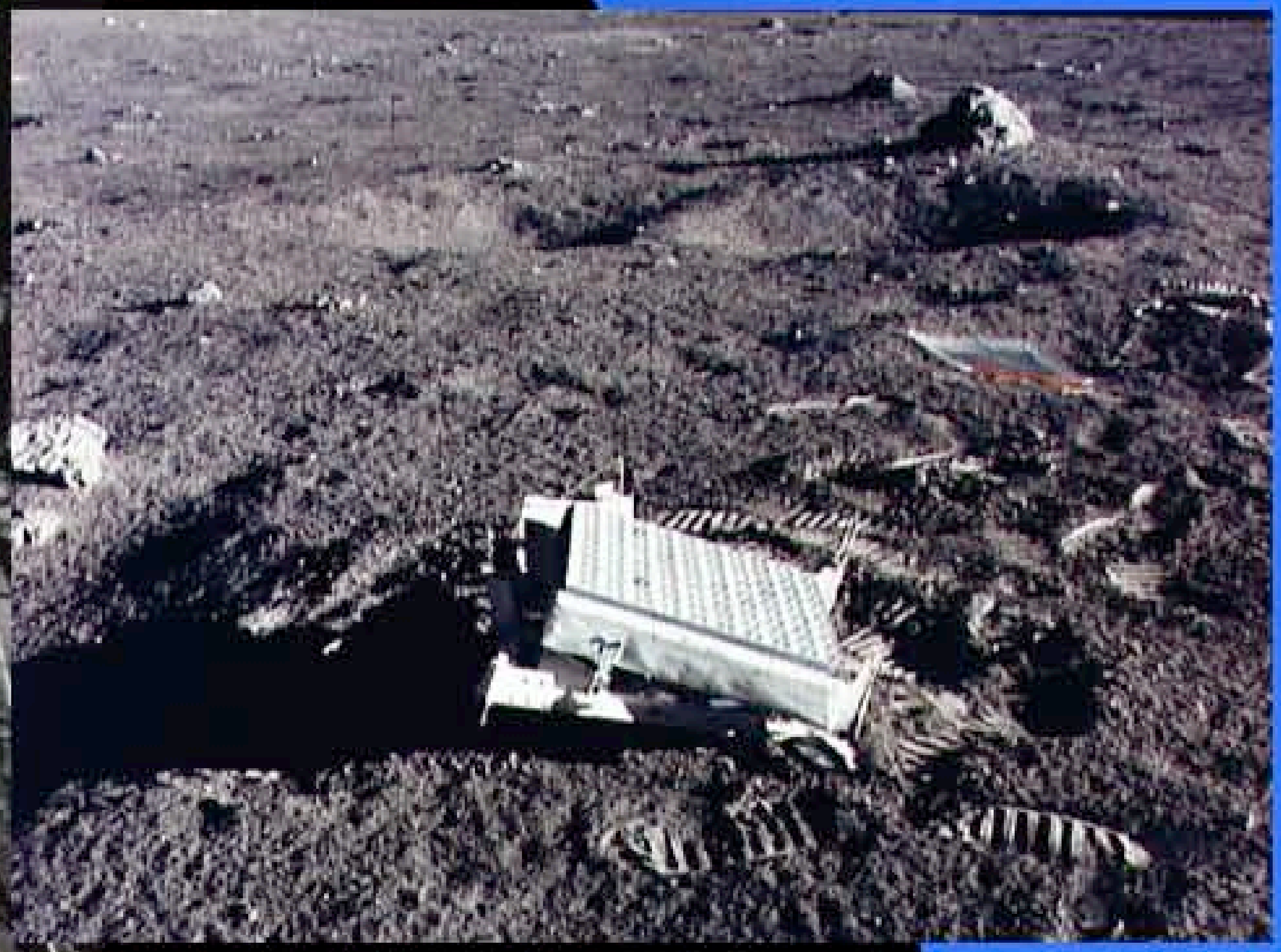
"The observed dust, therefore, originated from both the Surveyor and LM landings, with each contributing a significant amount to various surfaces. "Lunar transport" seems to be relatively insignificant, if evident at all." – W. F. Carroll and P.M. Blair (1972)
ANALYSIS OF SURVEYOR 3 MATERIAL AND PHOTOGRAPHS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

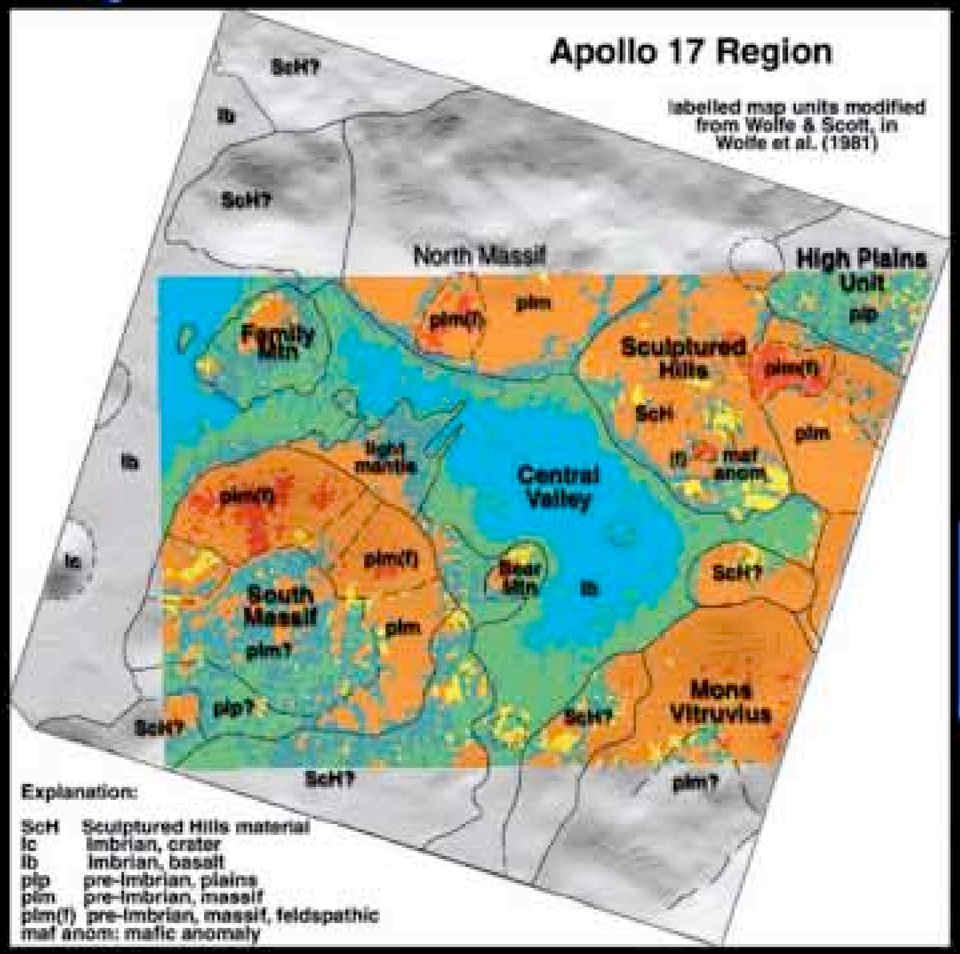




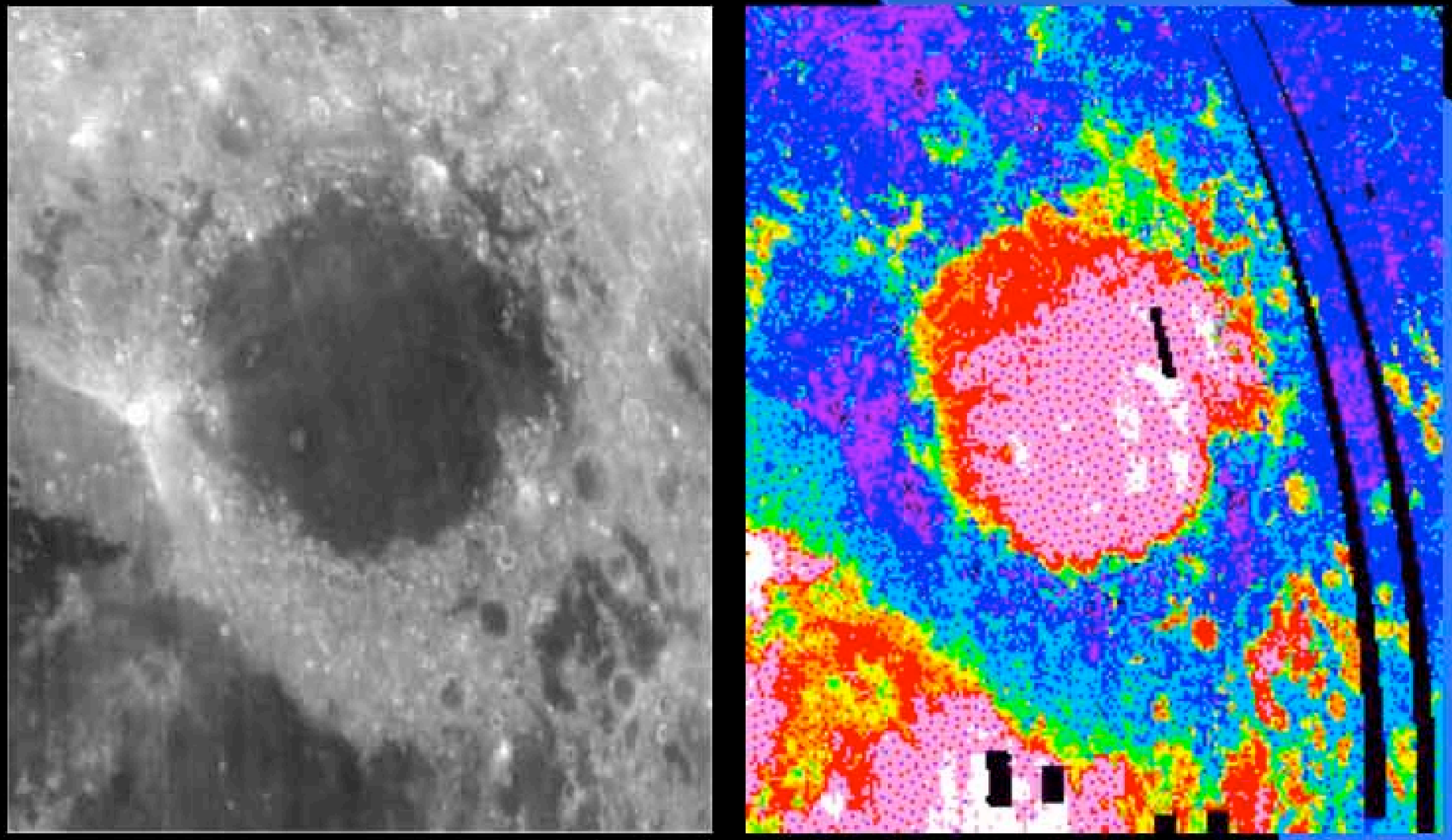


Lateral Dust Transport?

- 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

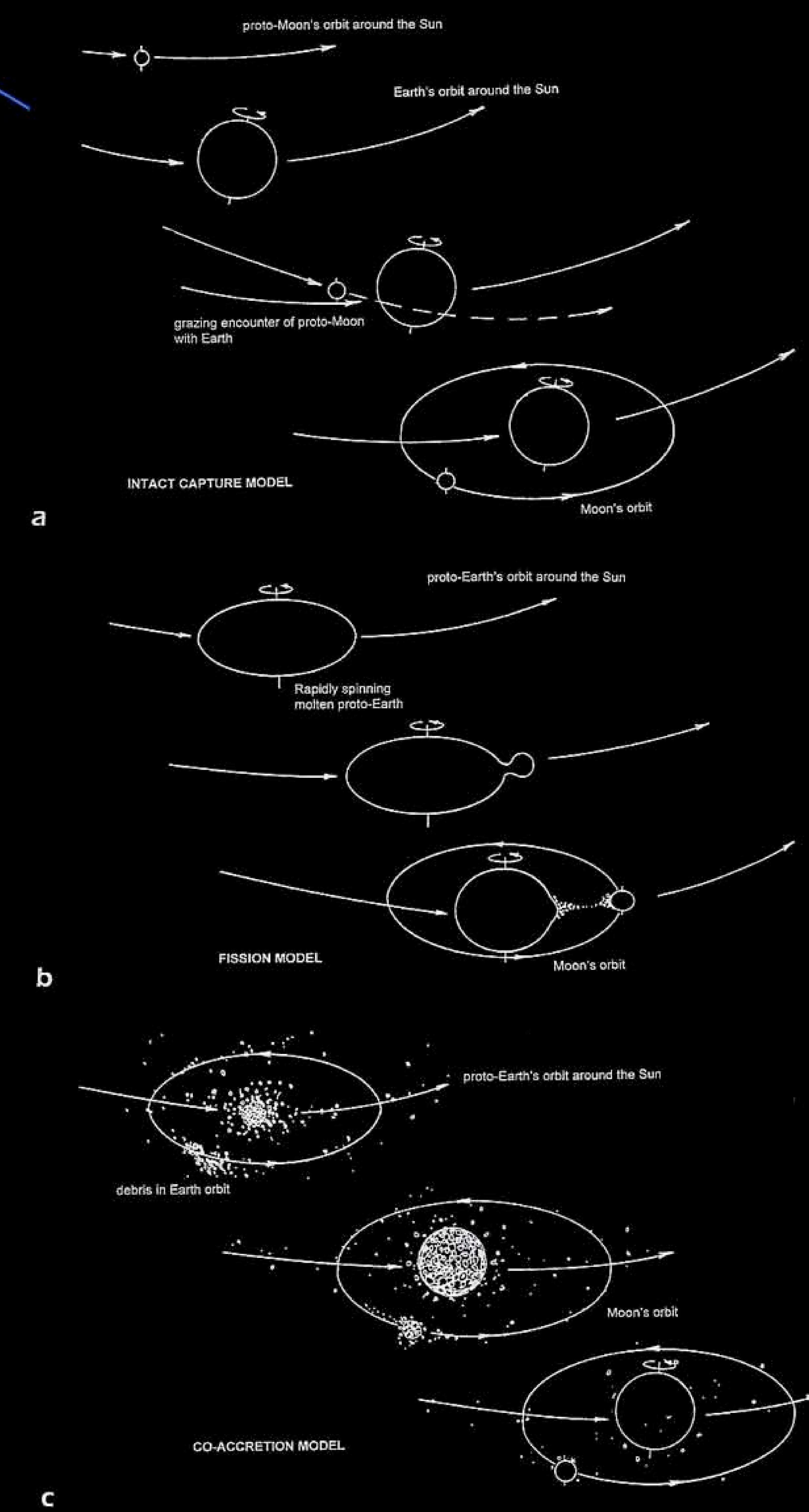
Moon formed elsewhere and was captured during a close passage by Earth

Fission

Moon spun off from molten, rapidly rotating Earth

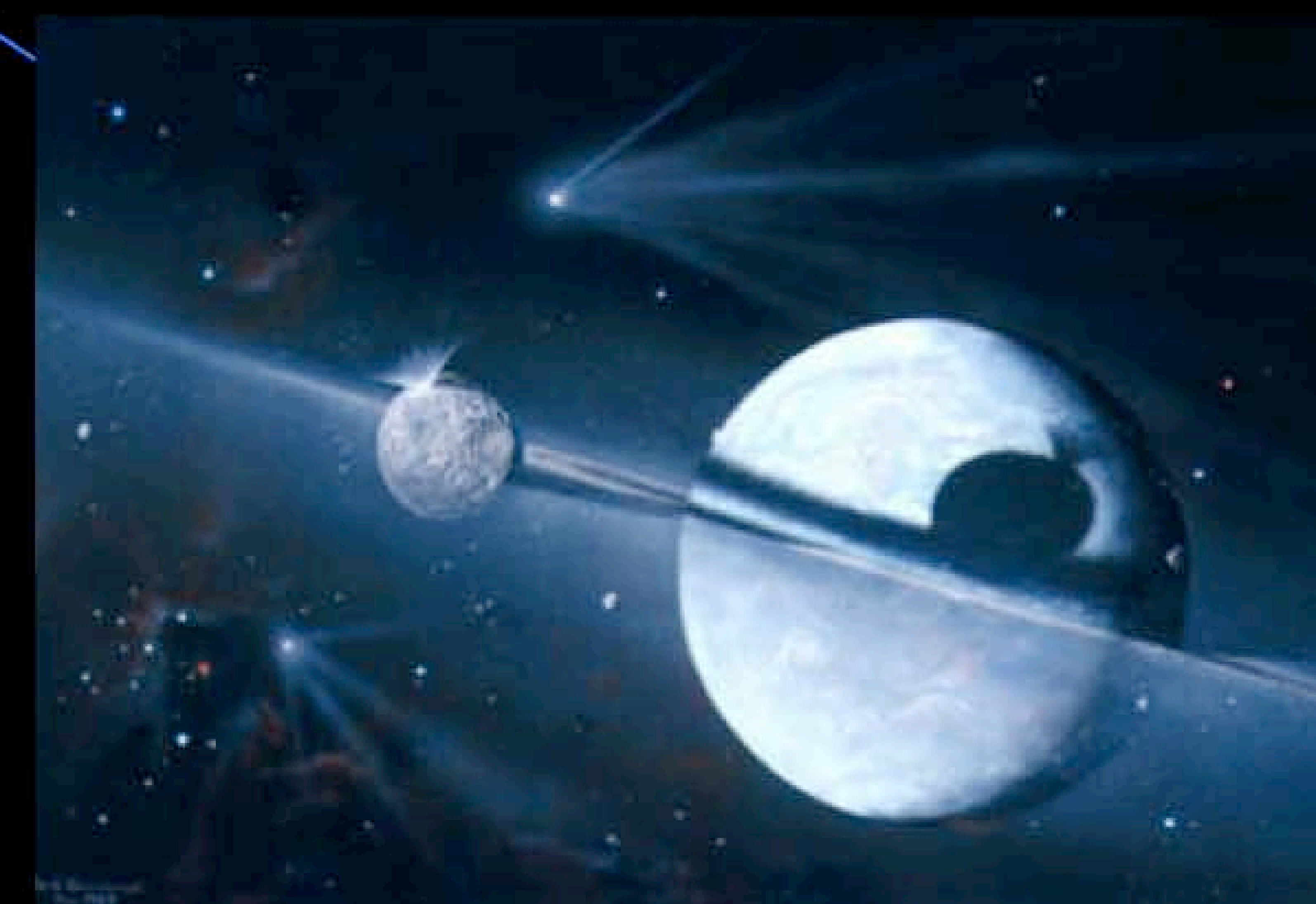
Binary (co-) accretion

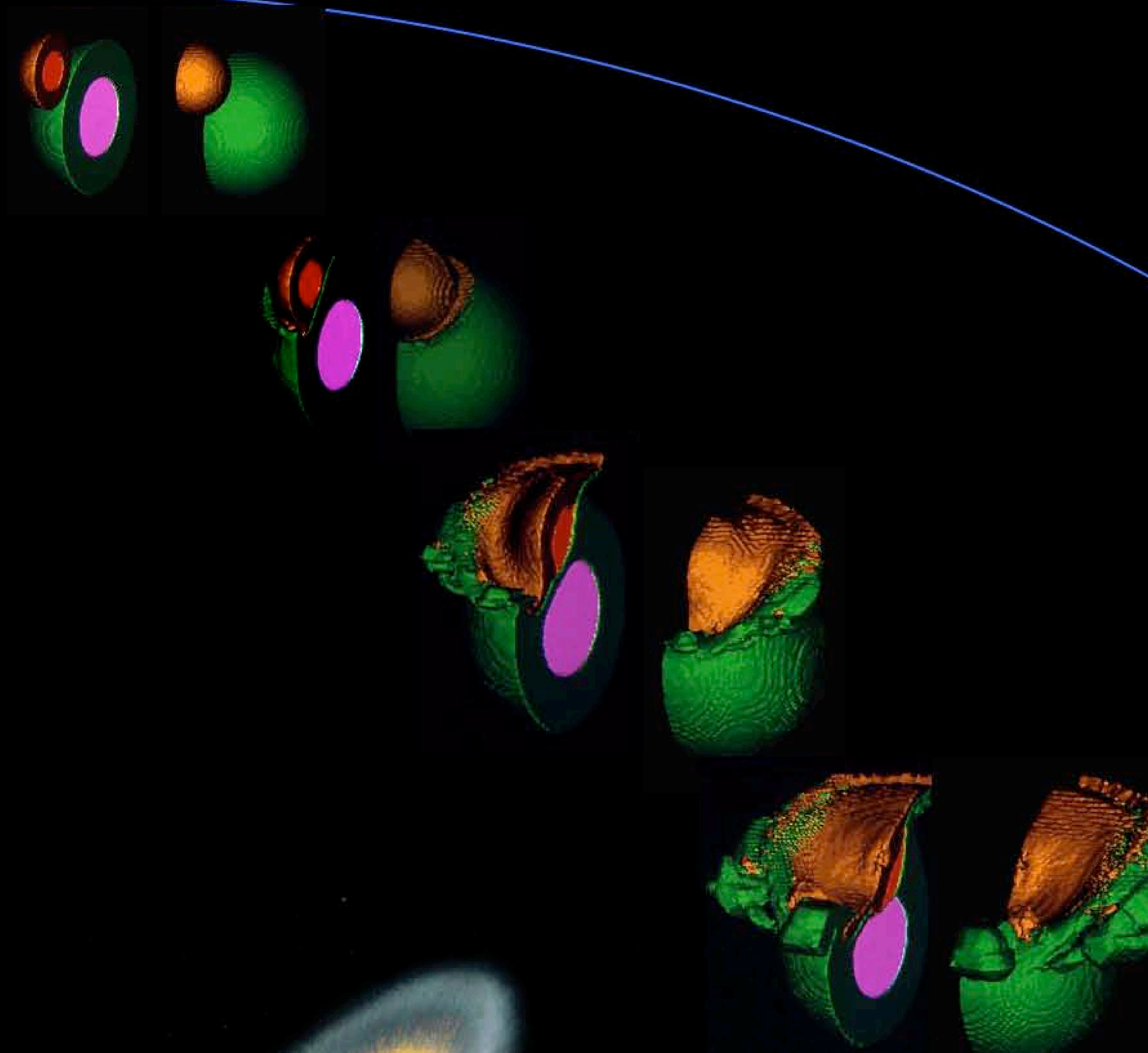
Both Earth and Moon accreted from small bodies at same position from sun

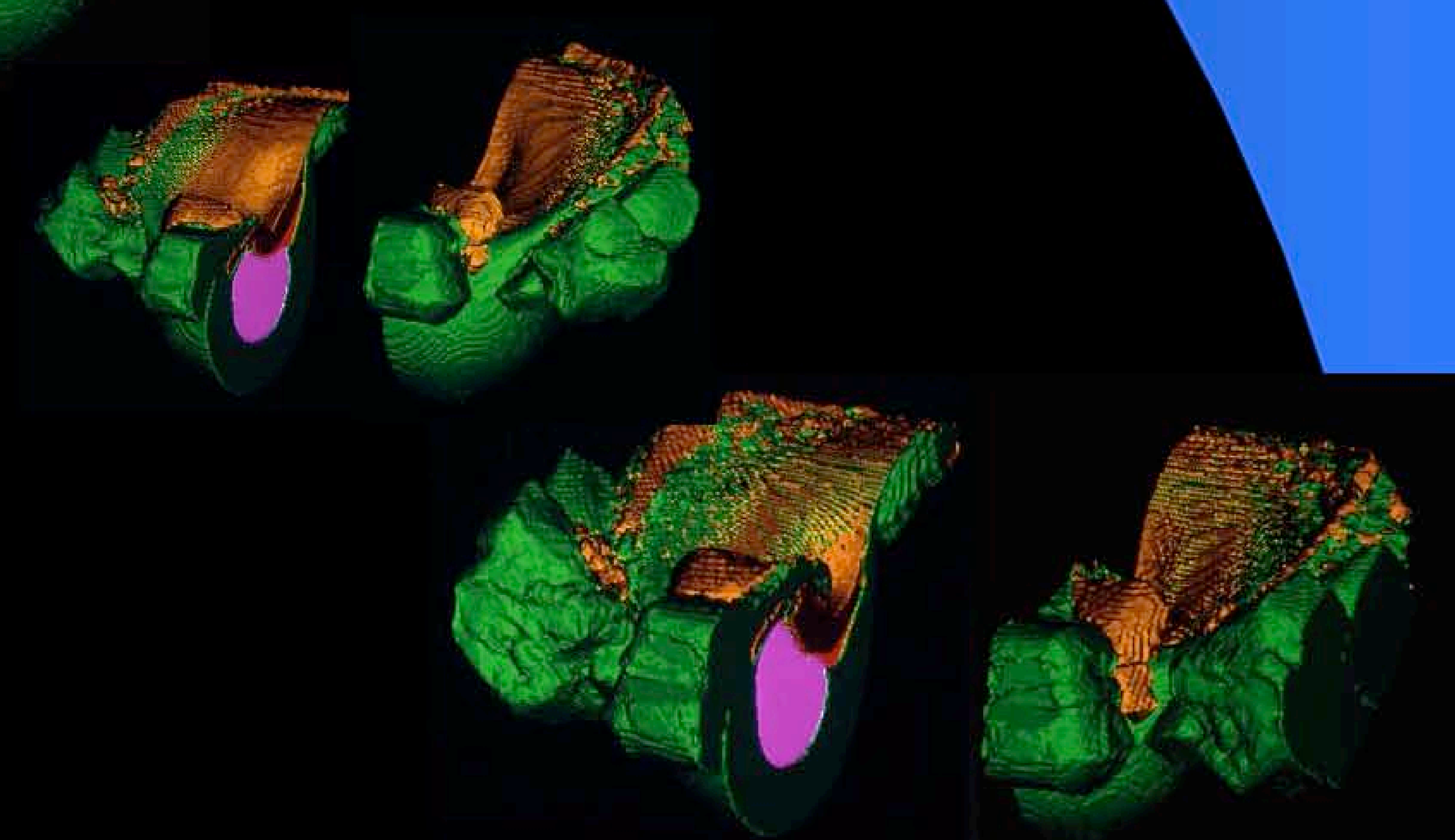


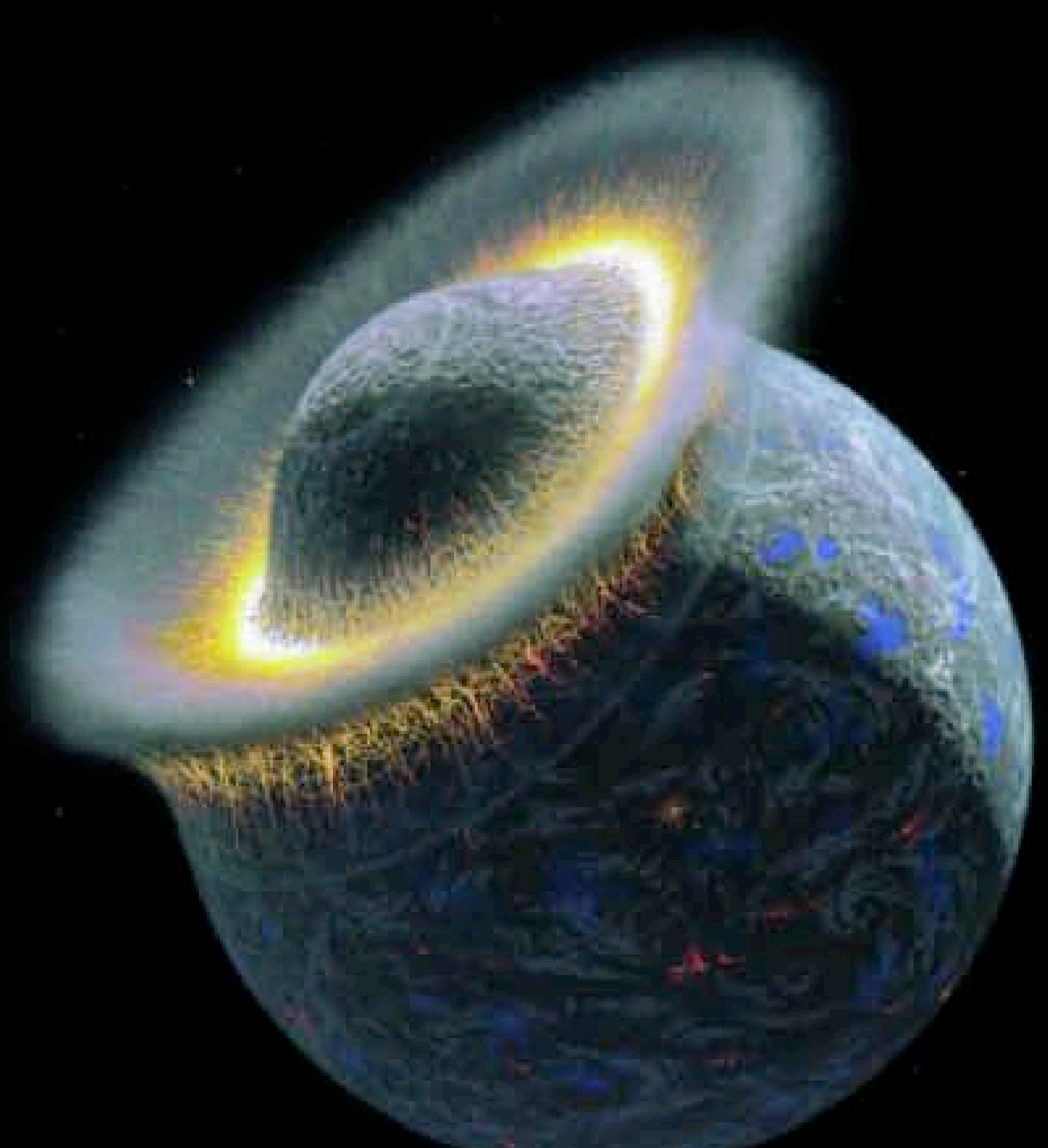
Lunar Origin

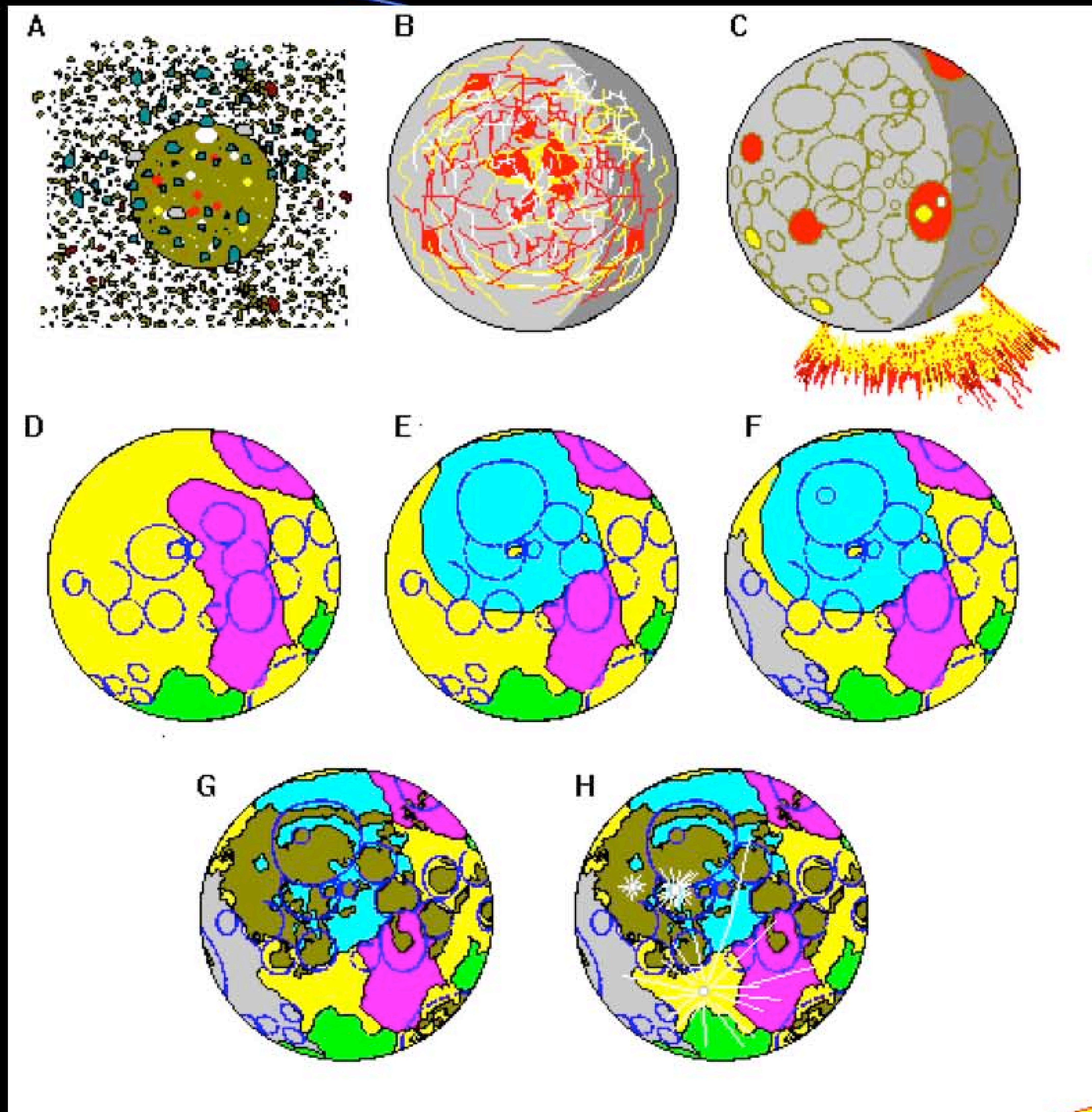
Giant Impact Hypothesis

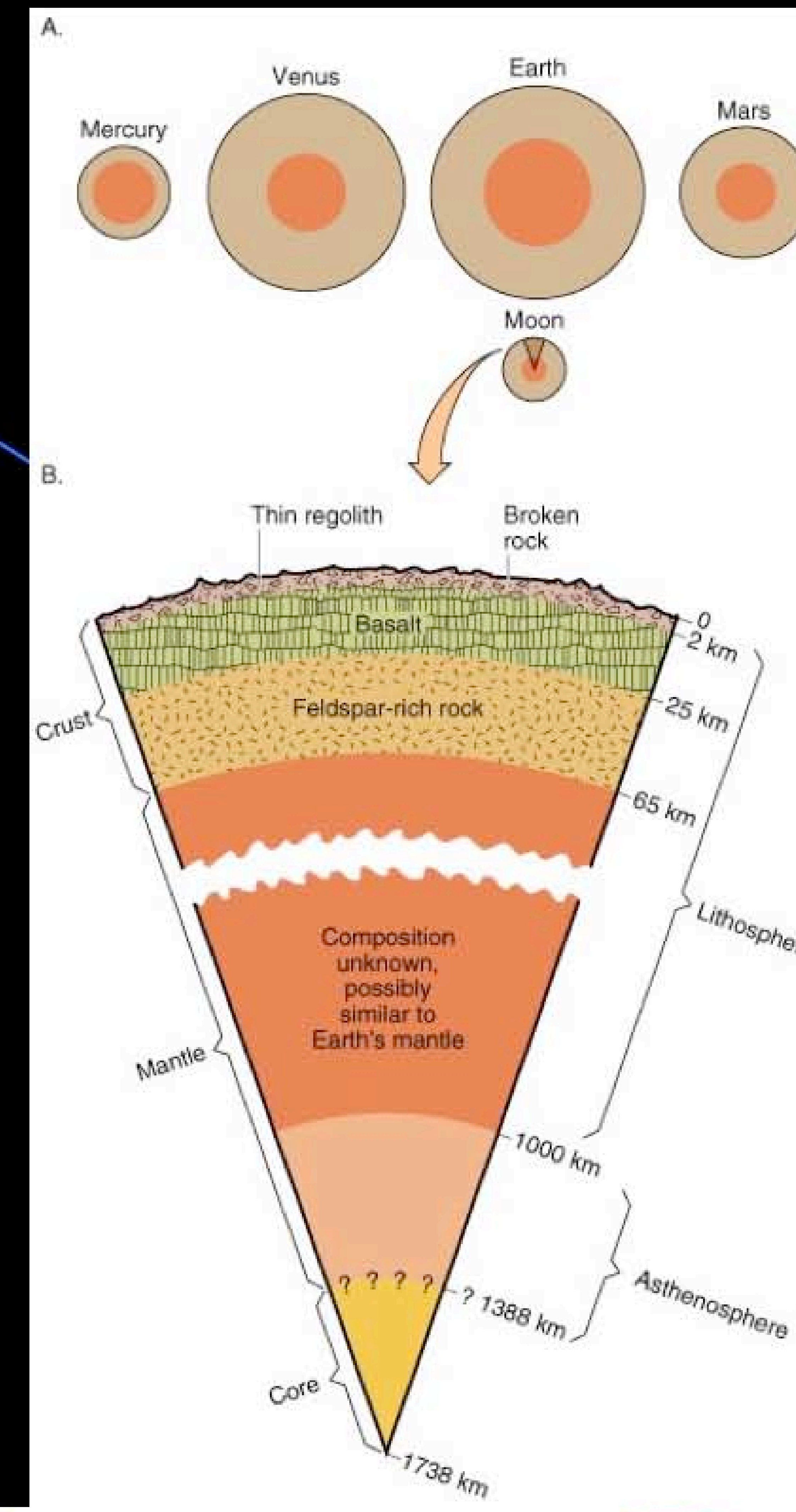


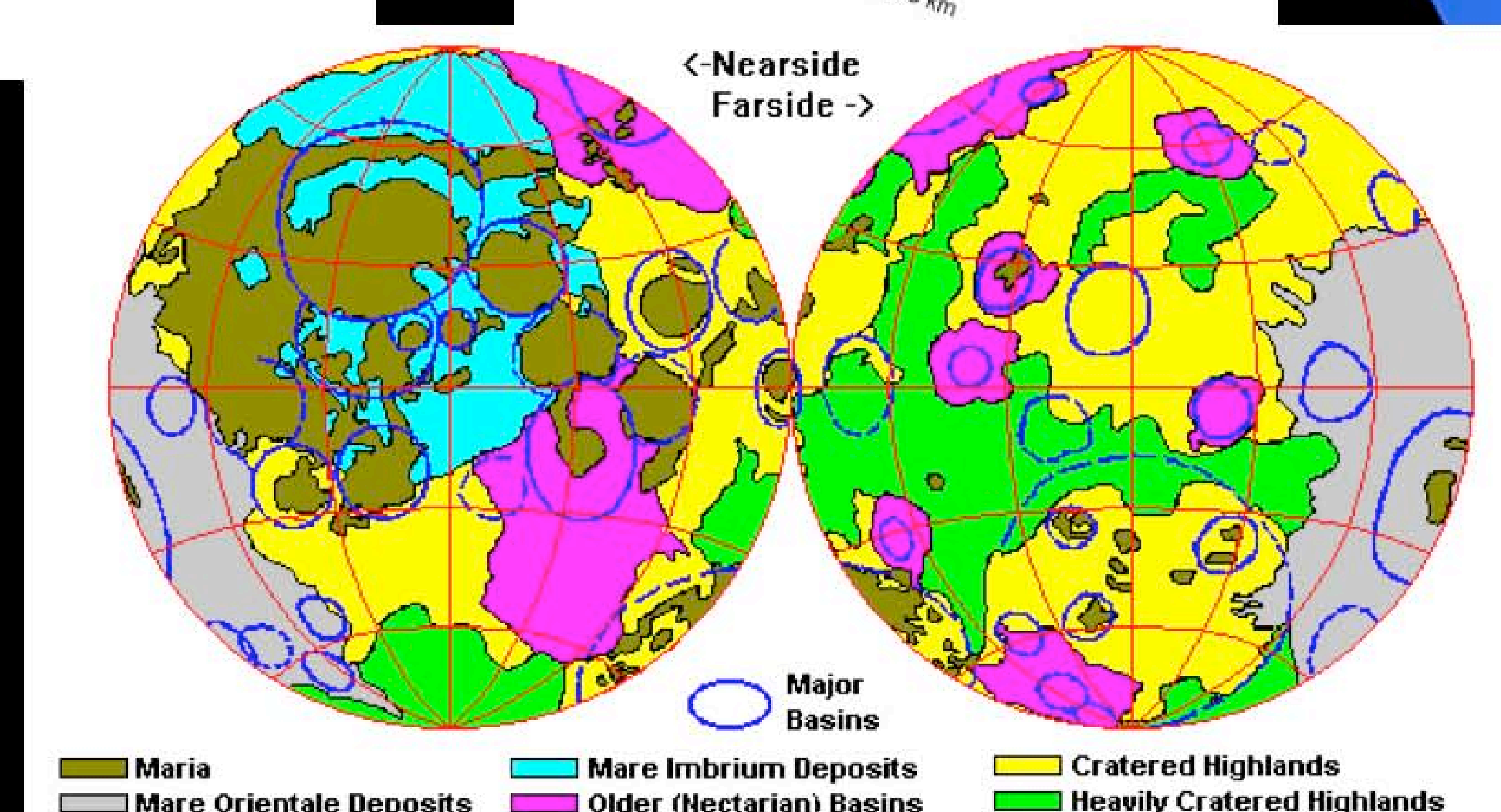












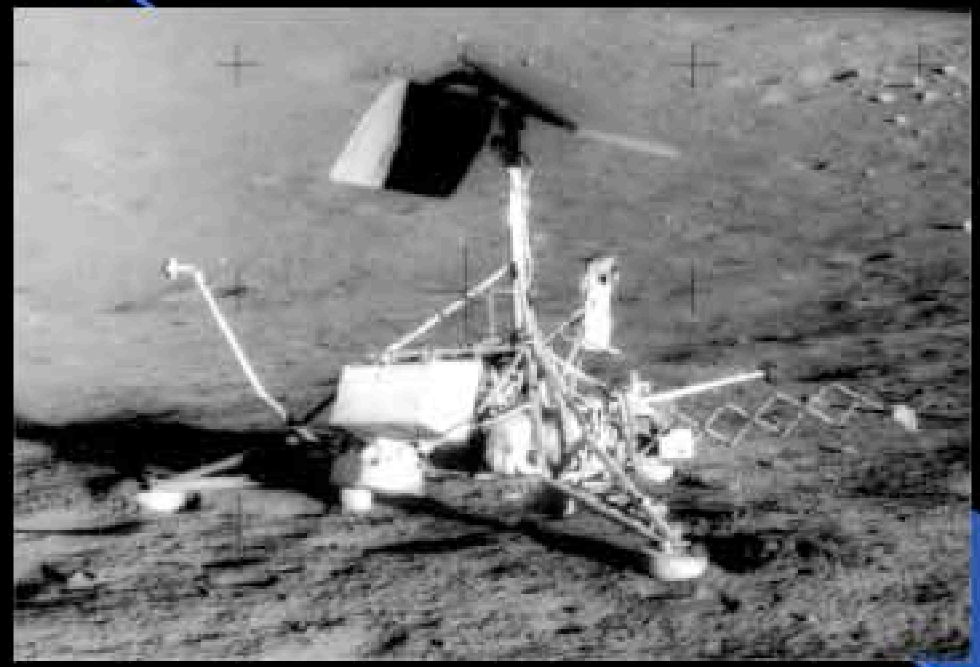
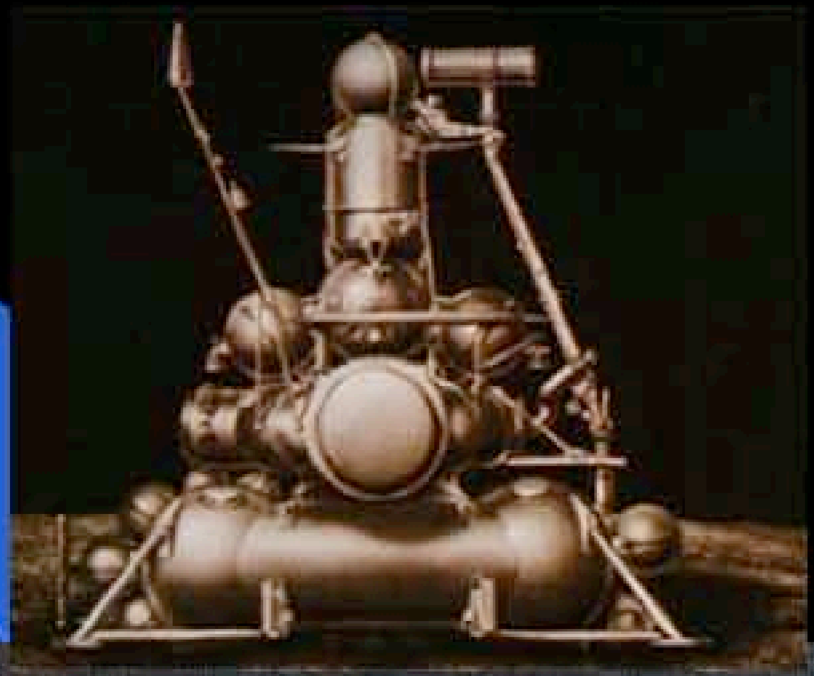
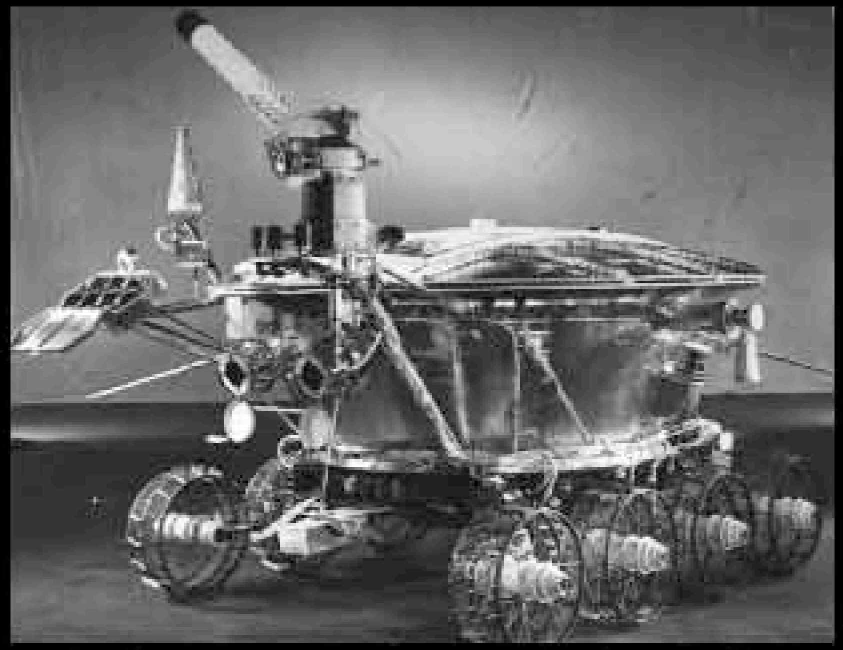
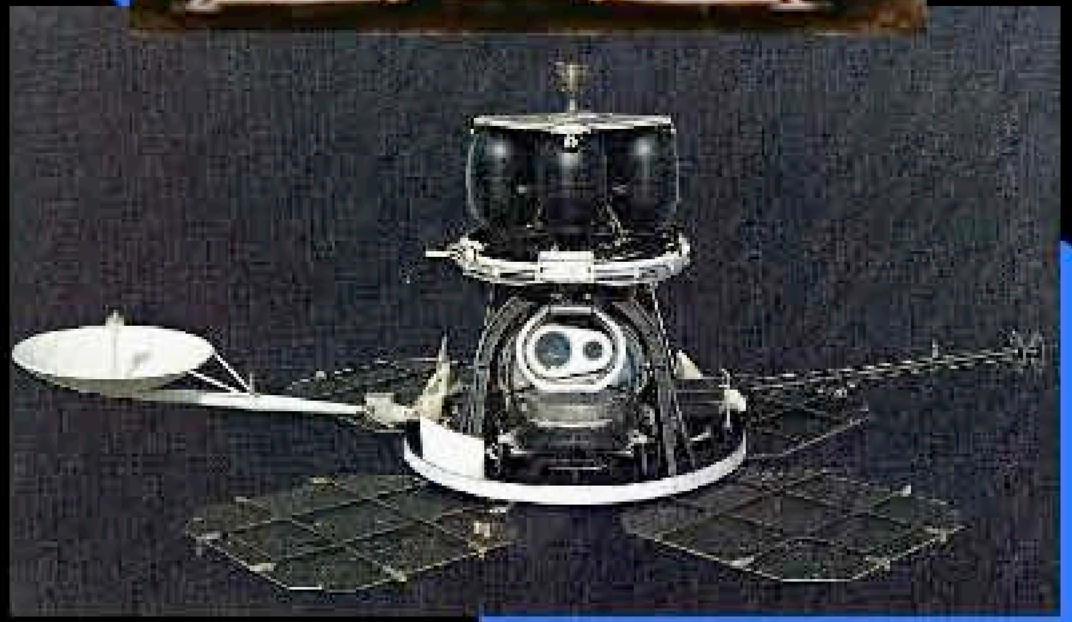
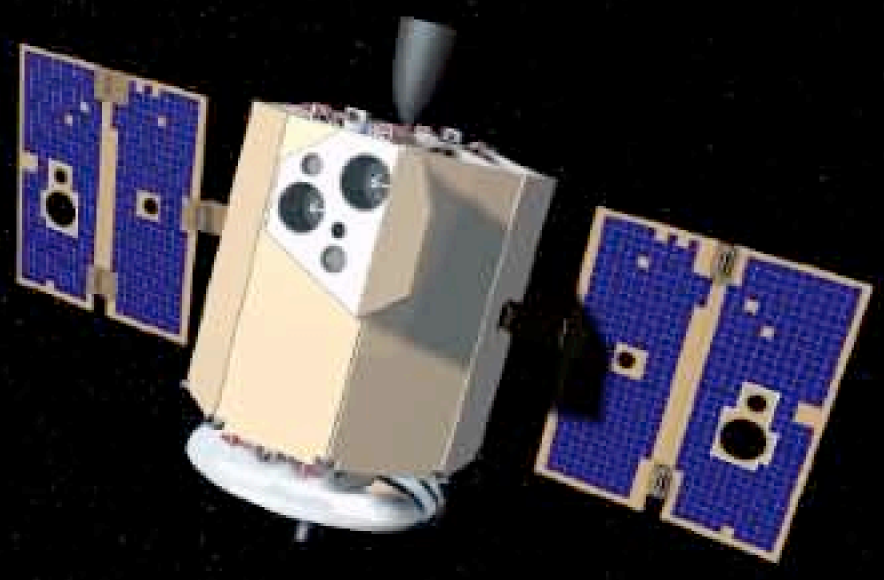
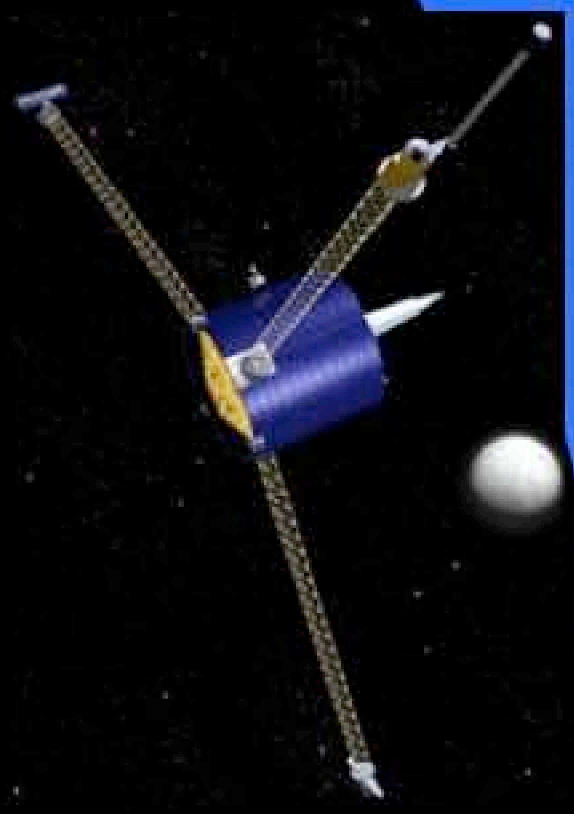
Lunar History and Evolution

Lunar Robotic Missions

Impactors
- Ranger - imaging

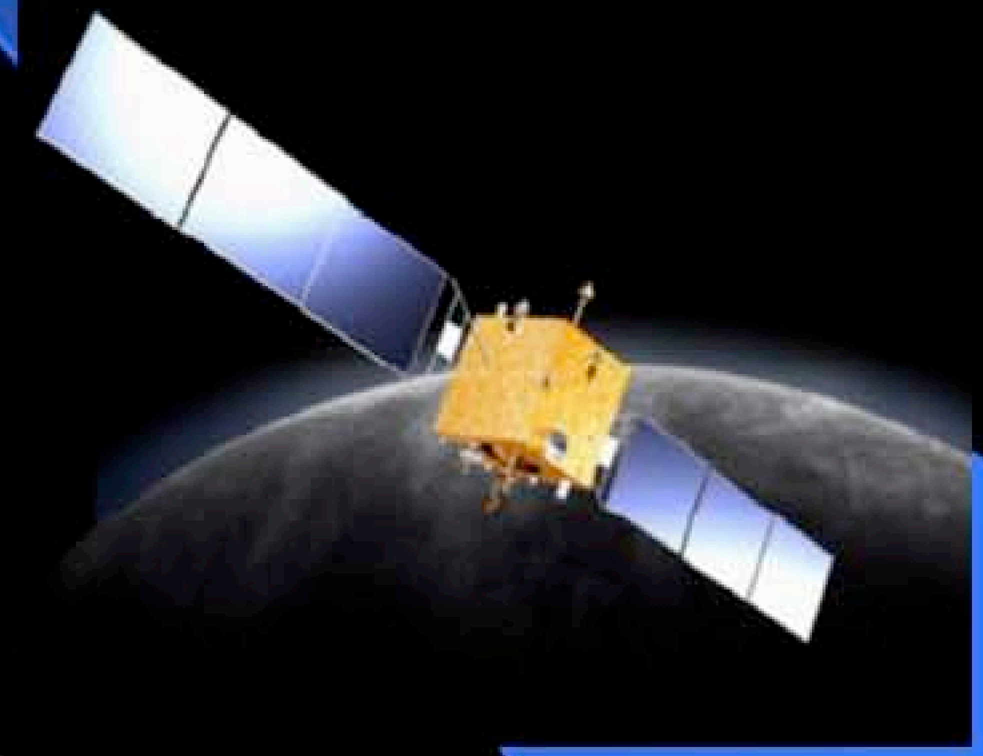
Soft landers
- Surveyor - imaging and chemical analysis
- Luna 16, 20, 24 -sample return
- Lunakhod - long-range rover

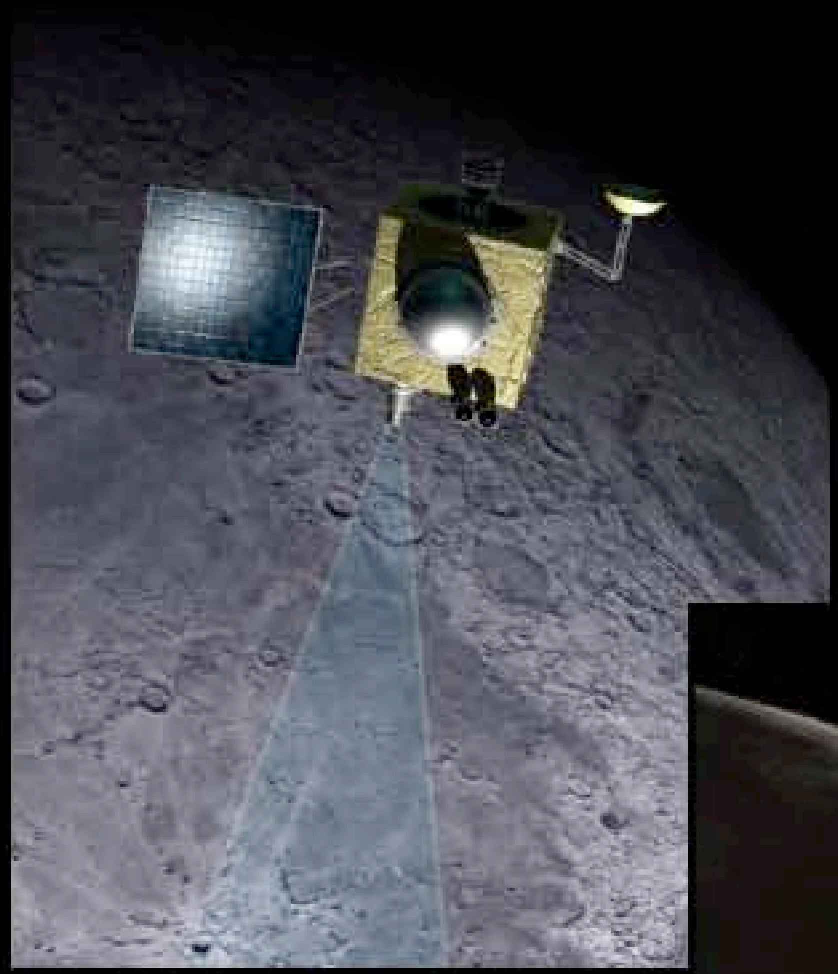
Orbiters
- Lunar Orbiter - global and site mapping
- Clementine - global mapping
- Lunar Prospector - global mapping
- SMART-1 - technology demo

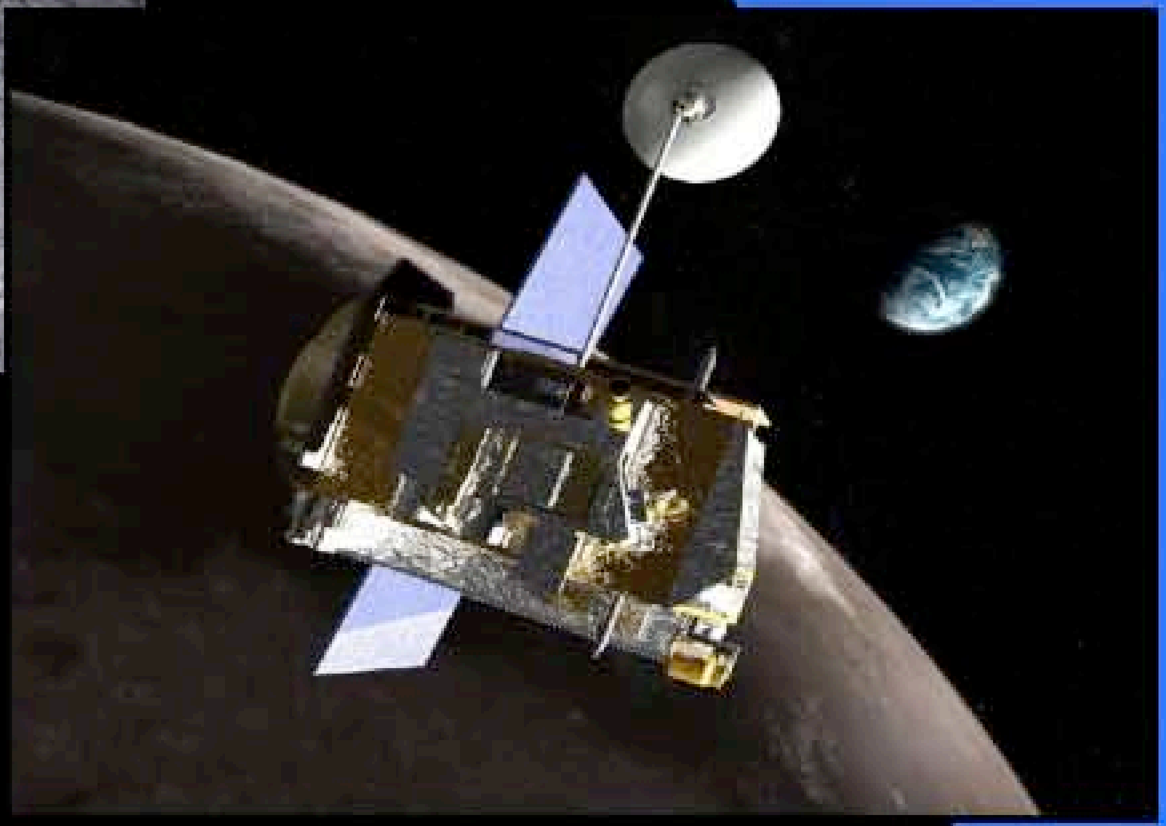









Current Lunar Missions

- 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

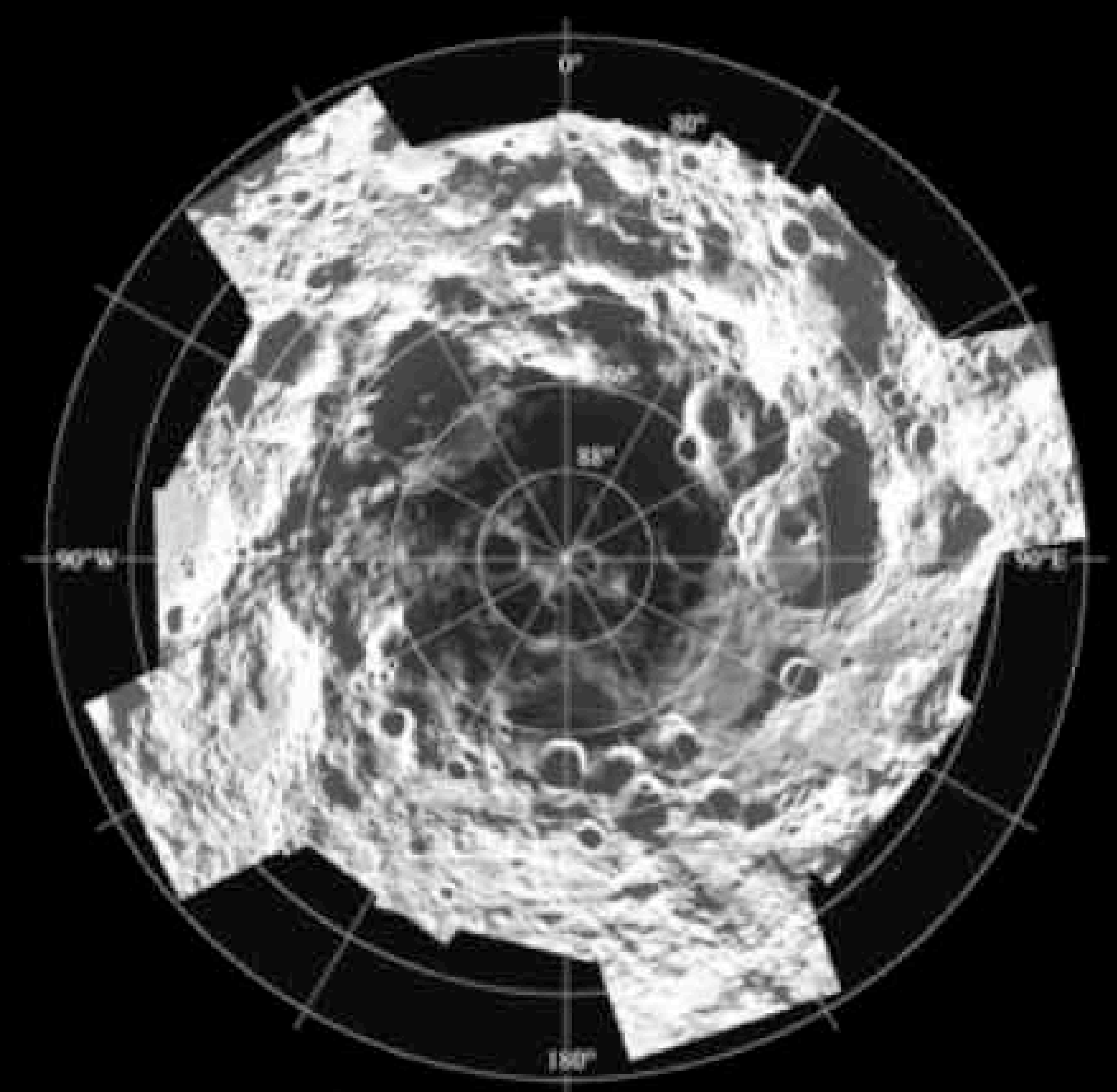
For more information, go to:

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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