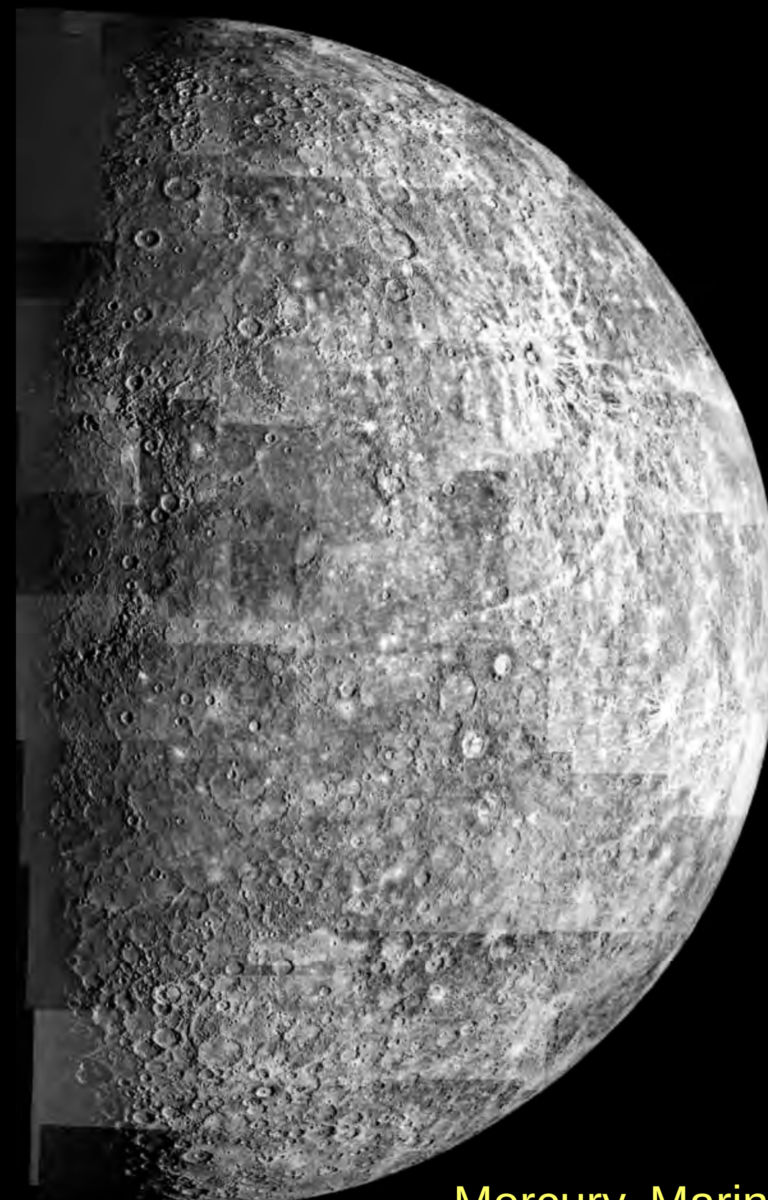
Moon and Mercury

The Moon, telescopic view

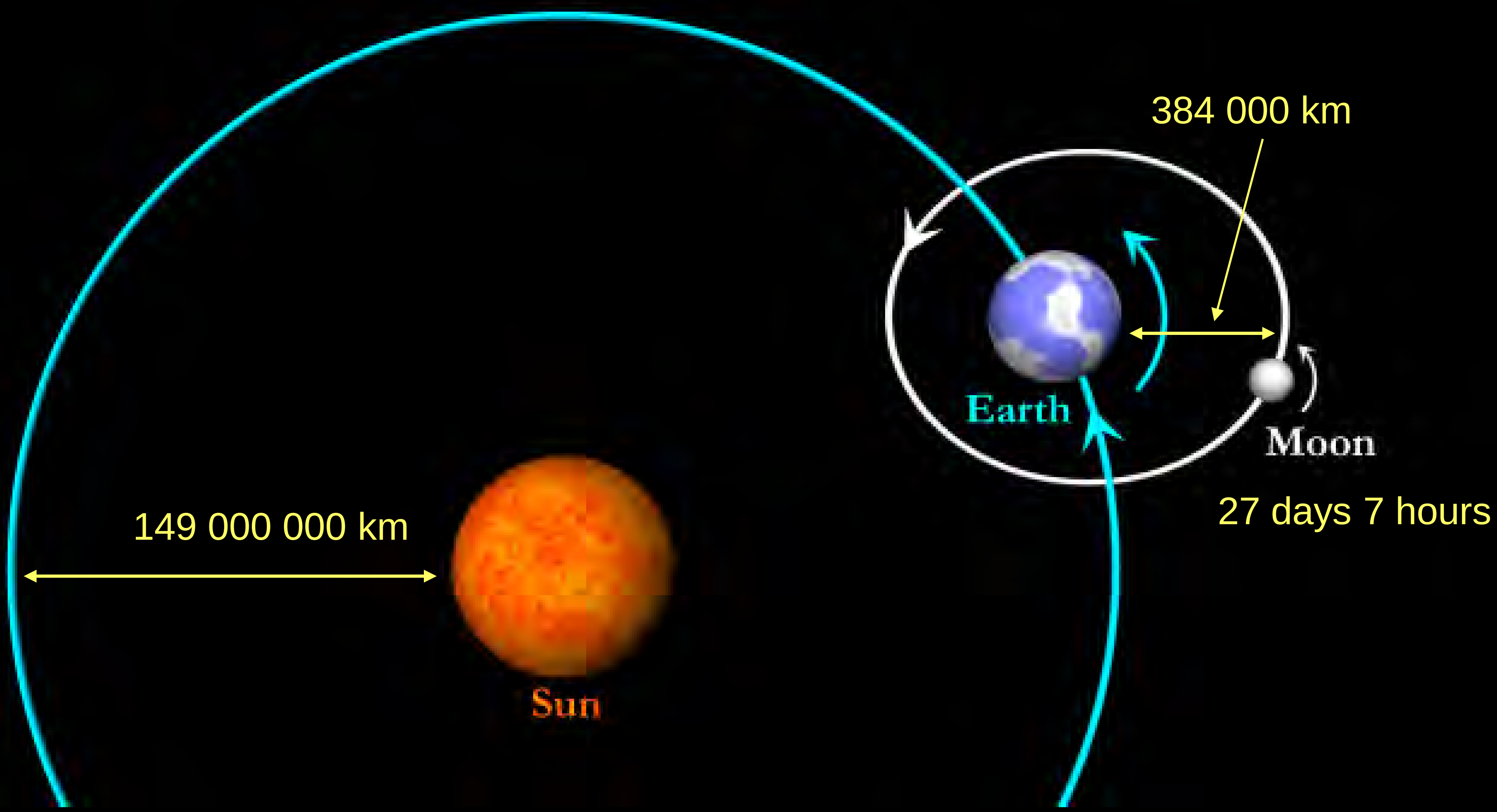


Mercury, Mariner 10

The Moon and Mercury: Their sizes in comparison with those of Earth, Venus and Mars

Earth Venus Mars Mercury The Moon

System Earth – the Moon



Historically the Moon, first, was, object of worship, then object of studies – astronomical, and then with the help of space flights

Selena,
Greek goddess
of the Moon

Chang'E,
Chinese
goddess
of the Moon

1564-1642

1904-1988

Galileo Galilei, Italian astronomer. He was first who reported on craters and mountains on the Moon.

Alexander Khabakov, Russian geologist. Published book on geology of the Moon, 1949

History of studies

Pre-telescope

Object in the sky

Telescopic observations

Galileo Galilei

What is present on lunar surface

Space flights to the Moon (Luna 1 => Chang’E-3)

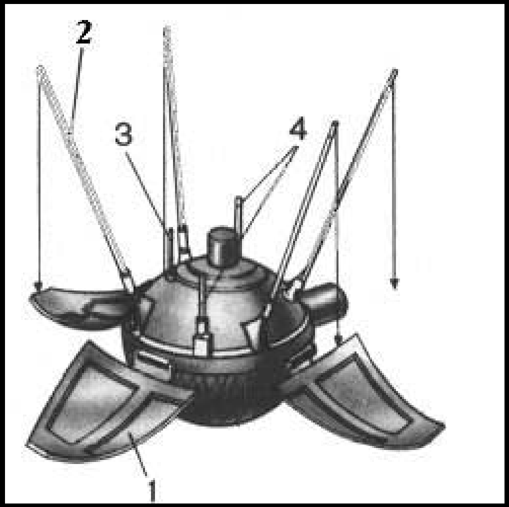
Close-up observations

Landing and *in-situ* studies

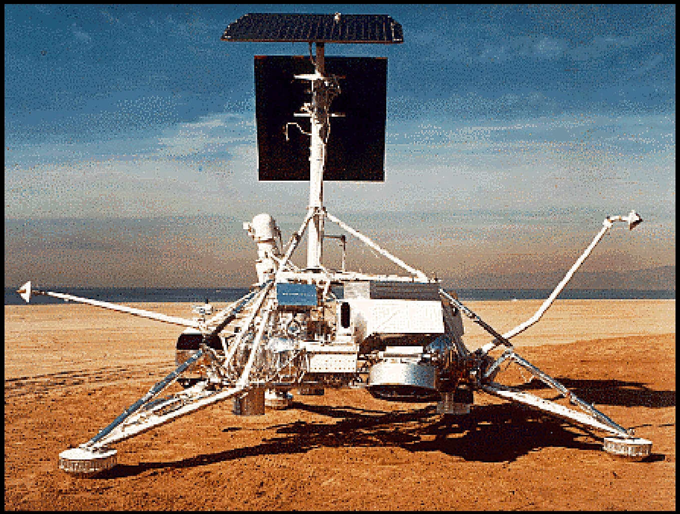
Samples delivered to Earth

Space flights to the Moon

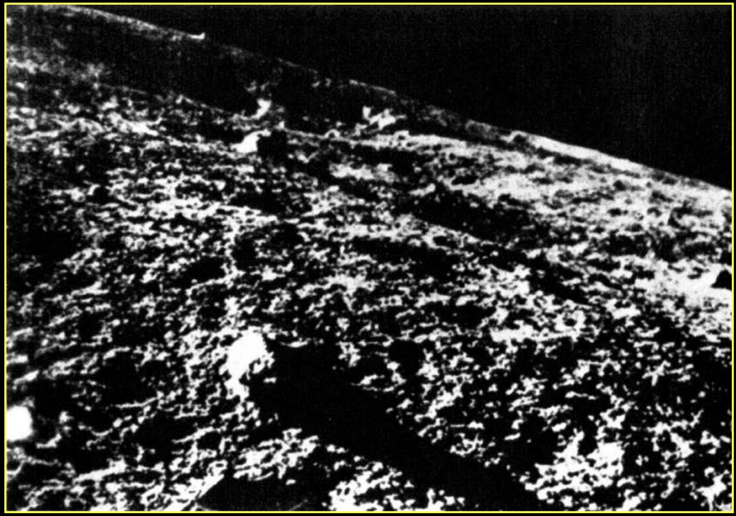
Problem of landing: To land and not to sink in the dust



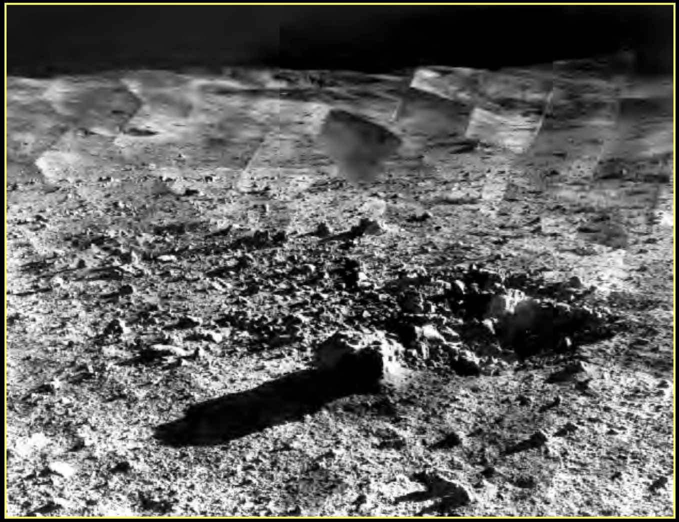
USSR Luna 9, 13 - 1966



USA Surveyor 1-7 1966-68



Fragment of Luna 9 TV panorama

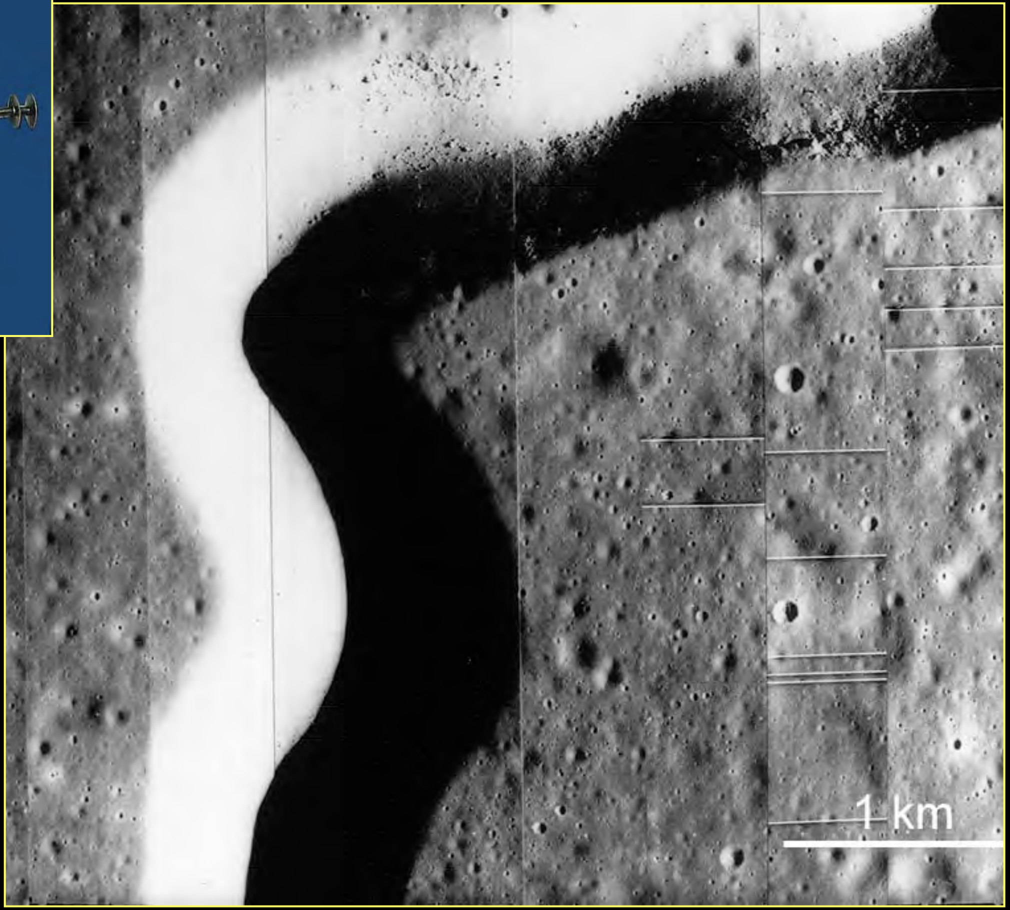


Fragment of Surveyor 1 TV panorama

Space flights to the Moon

Taking images of the surface

Part of image of Rima Hadley,
taken by КA Lunar Orbiter 5.
Landing site for Apollo 15.
Large (meters) boulders are seen



US Lunar Orbiter 1-5,
1966-1967
Selection of landing sites
for Apollo expeditions.
Geology of the Moon.
Image resolution up to 1-2 m

Space flights to the Moon

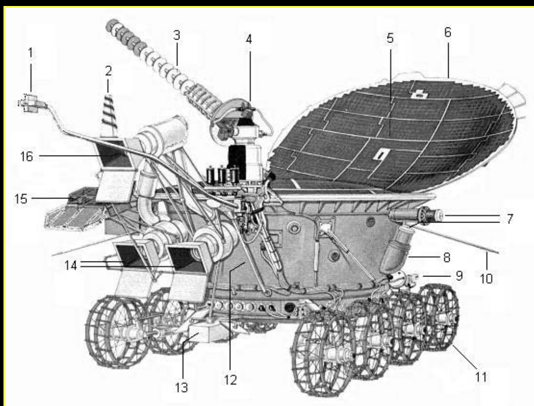
Apollo expeditions to the Moon: 1968-1972

April 16, 1972
Cape Canaveral,
Florida, USA
Apollo16 launch

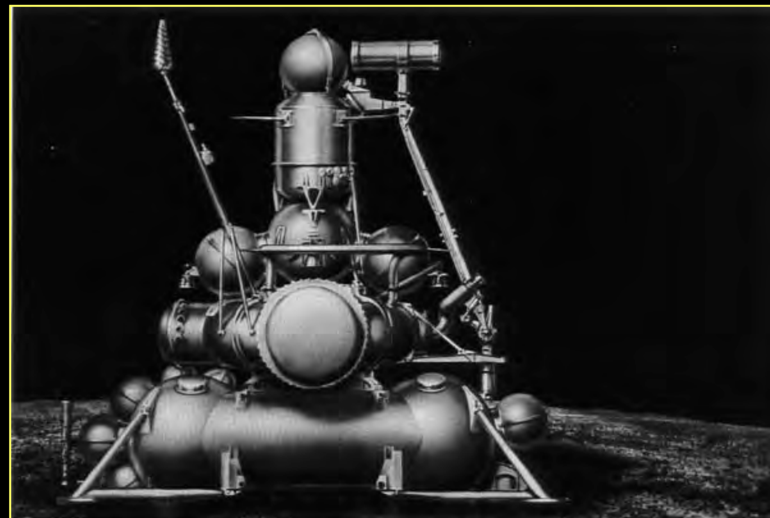
April 23 1972, Crater North Ray,
John Young collects samples

Space flights to the Moon

Soviet flights of Lunas –Lunokhods (1970-1976)

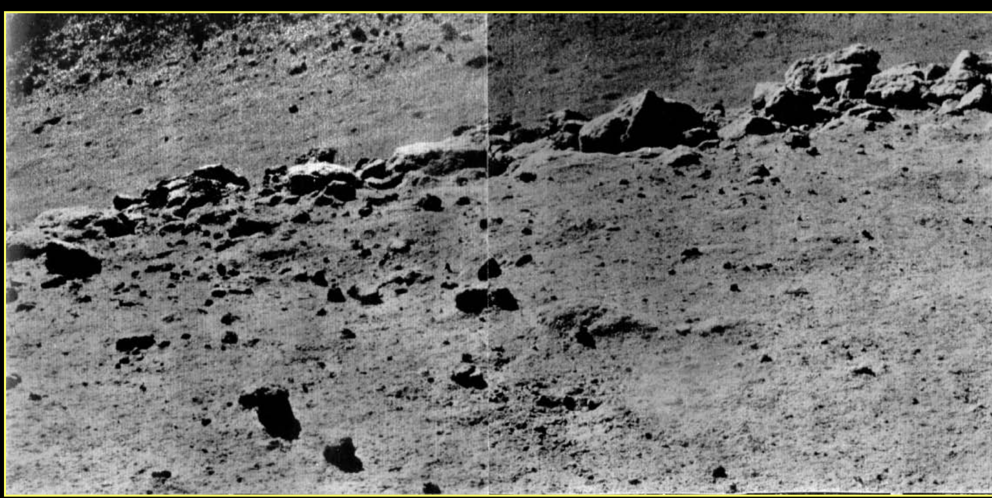


Lunokhod 2



Lander for Lunas - Lunokhods

Take off with samples



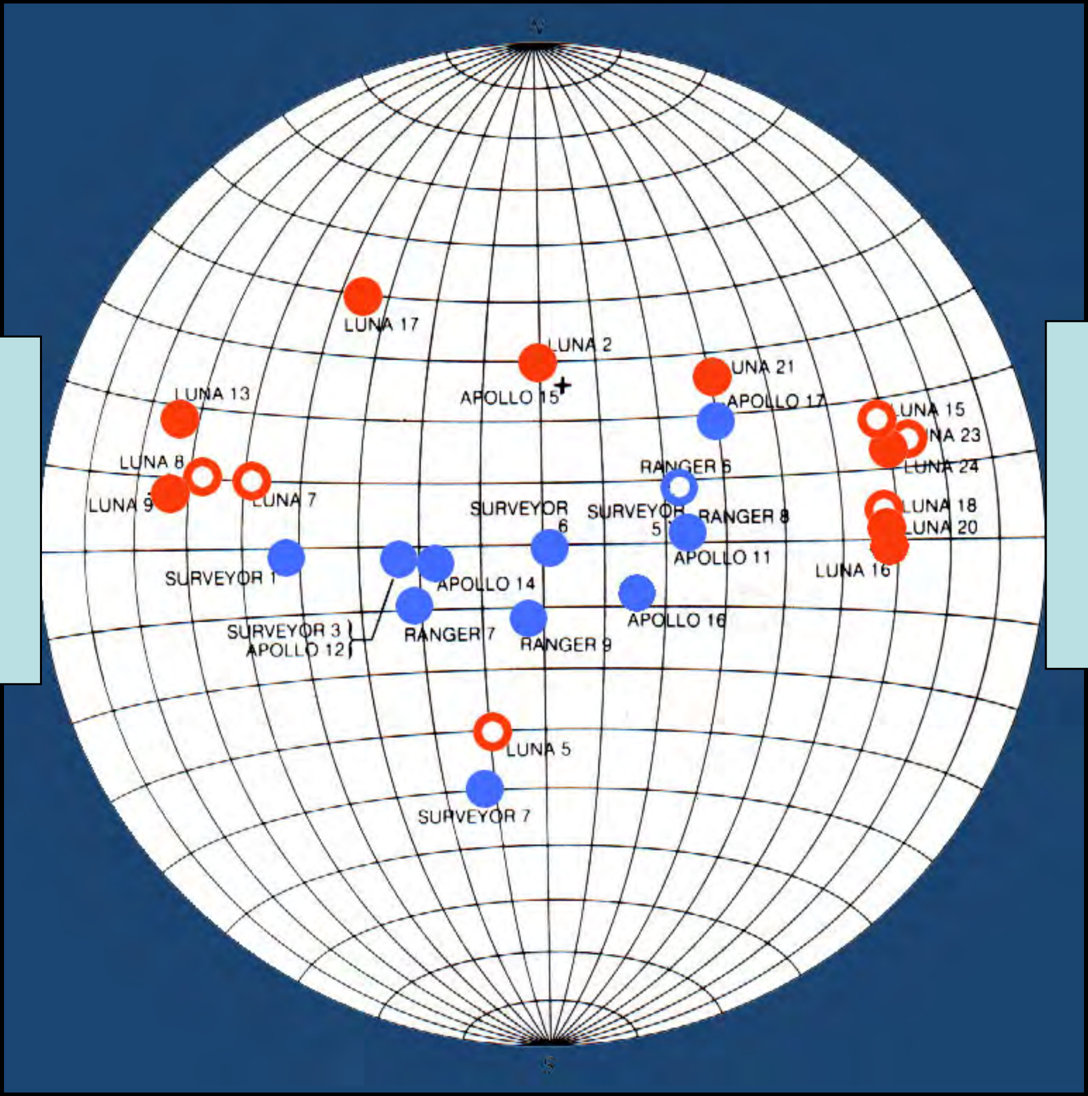
Lunokhod 2 in crater Le Monier

Luna 20 capsule with samples, W. Siberia

Lunar race

Flights to the Moon of the cold war time

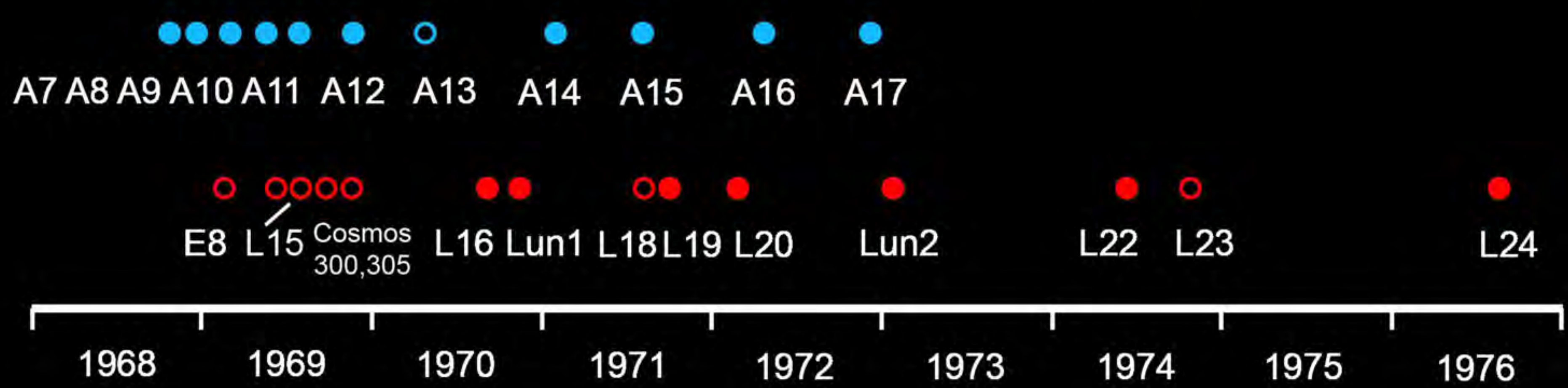
USSR
Attempts 48
Success 21



USA
Attempts 31
Success 22

From Huntress, Moroz, Shevalev, 2003

Space race 1968-1976: Lunas v.s. Apollo



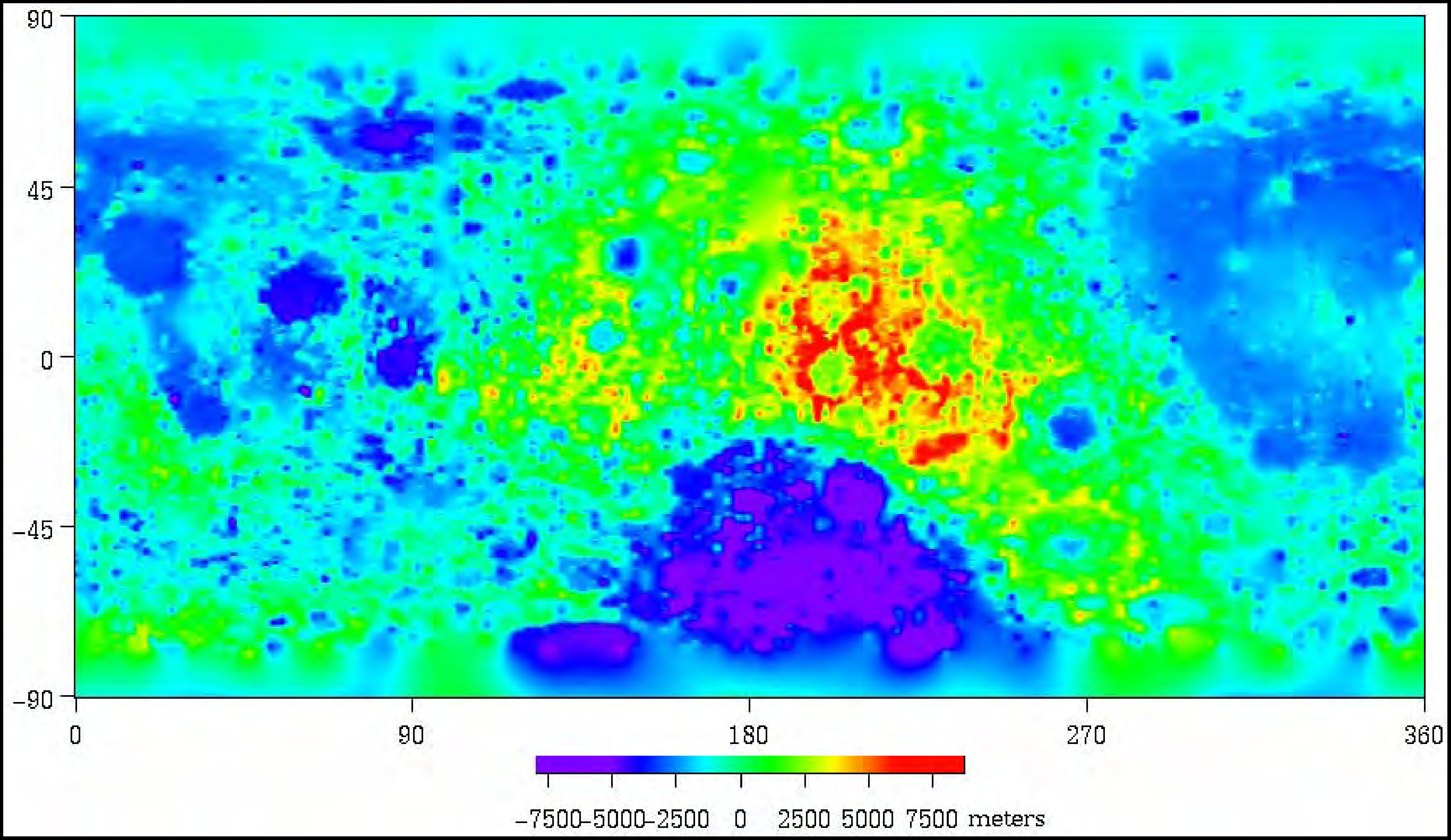
Name	Date of launch	Mission	Success
E8-201	Feb 19, 1969	Lunokhod 0	Crushed during liftoff
E8-5-402	June 14, 1969	Sample return	4^{th} stage rocket failed to ignite
Luna 15	July 13, 1969	Sample return	Crashed at landing on the Moon
Cosmos 300	Sept 23, 1969	Sample return	4^{th} stage rocket failed to ignite
Cosmos 305	Oct 22, 1969	Sample return	4^{th} stage misfired
Luna 16	Sept 12, 1970	Sample return	Sample from Mare Fecunditatis
Luna 17	Nov 10, 1970	Lunokhod 1	Lunokho
Luna 18	Sept 2, 1971	Sample return	Crashed
Luna 19	Sept 28, 1971	Lunar orbiter	Orbital s
Luna 20	Feb 14, 1972	Sample return	Sample f
Luna 21	Jan 8, 1973	Lunokhod 2	Lunokho
Luna 22	May 29, 1974	Lunar orbiter	Orbital s
Luna 23	Oct 28, 1974	Sample return	Crashed
Luna 24	Aug 8, 1976	Sample return	Sample /

Name	Date of launch	Mission	Success
Apollo 7	Oct 11, 1968	Prep. to land the Moon	Orbited Earth
Apollo 8	Dec 21, 1968	Prep. to land the Moon	Orbited the Moon
Apollo 9	March 3, 1969	Prep. to land the Moon	Orbited Earth
Apollo 10	May 18, 1969	Prep. to land the Moon	Orbited the Moon
Apollo 11	July 16, 1969	Landing on the Moon	Studied Mare Tranquilitatis
Apollo 12	Nov 14, 1969	Landing on the Moon	Studied Oceanus Procellarum
Apollo 13	April 11, 1970	Landing on the Moon	Aborted
Apollo 14	Jan 31, 1971	Landing on the Moon	Studied Fra Mauro
Apollo 15	July 26, 1971	Landing on the Moon	Studied Mare Imbrium/Apennine Front
Apollo 16	Apr 16, 1972	Landing on the Moon	Studied highland Decart Plateau
Apollo 17	Dec 7, 1972	Landing on the Moon	Studied Taurus Littrow

Missions of subsequent years

Clementine
DOD USA
1994

Imaging and spectrometry
Topography of farside and poles

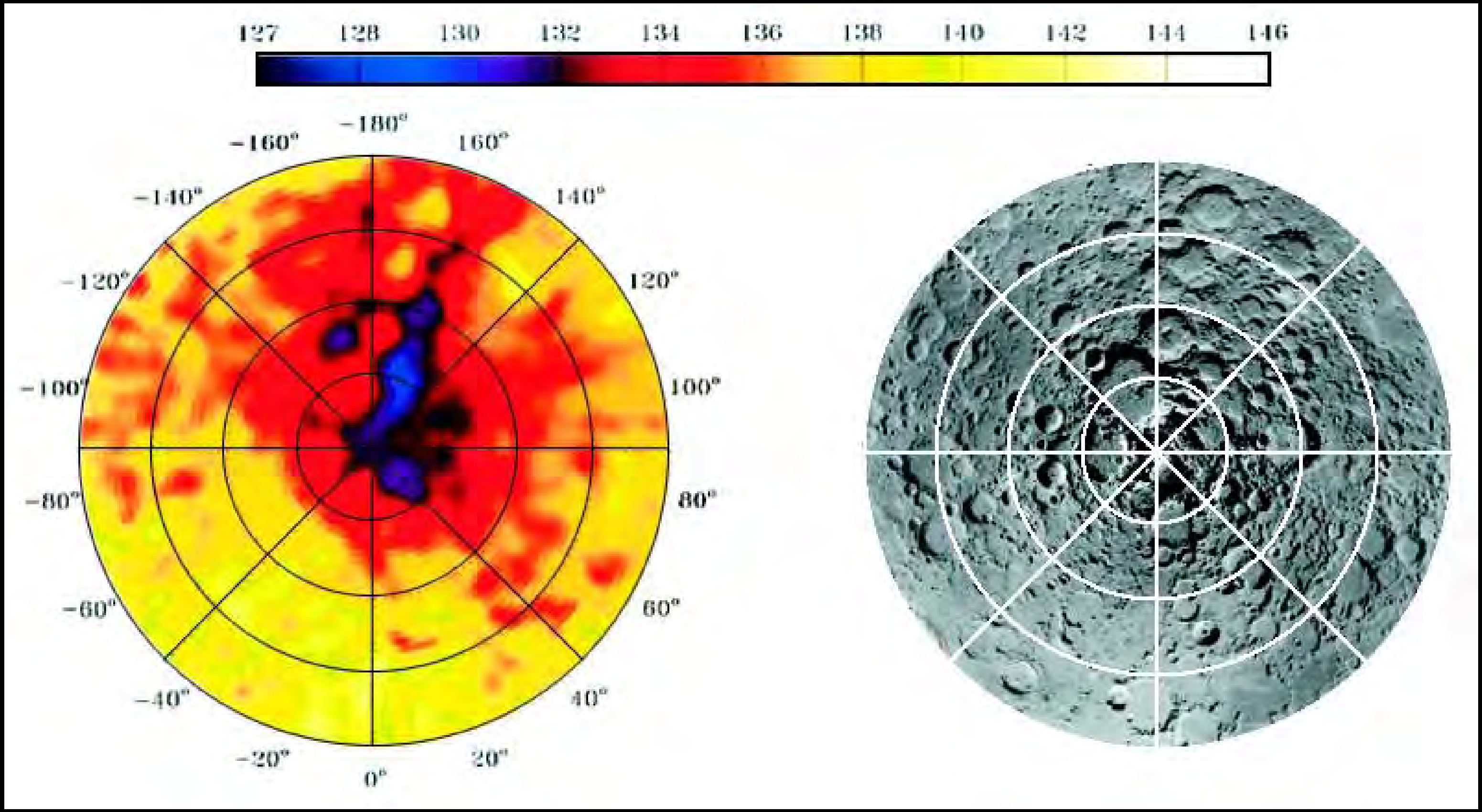


Missions of subsequent years

Lunar Prospector
NASA USA
1998-99

Gamma & X-ray spectrometry
- Surface geochemistry
- Water at the poles

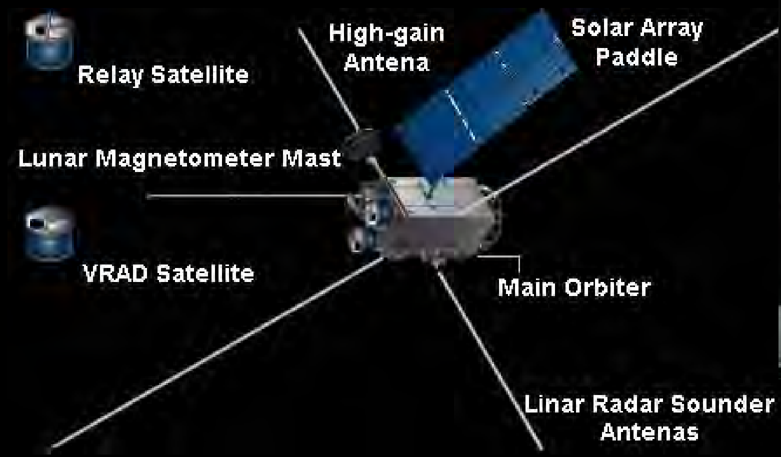
Gravity field
- Thickness of lunar crust



North Pole epithermal neutron flux. Feldman et al., 2002

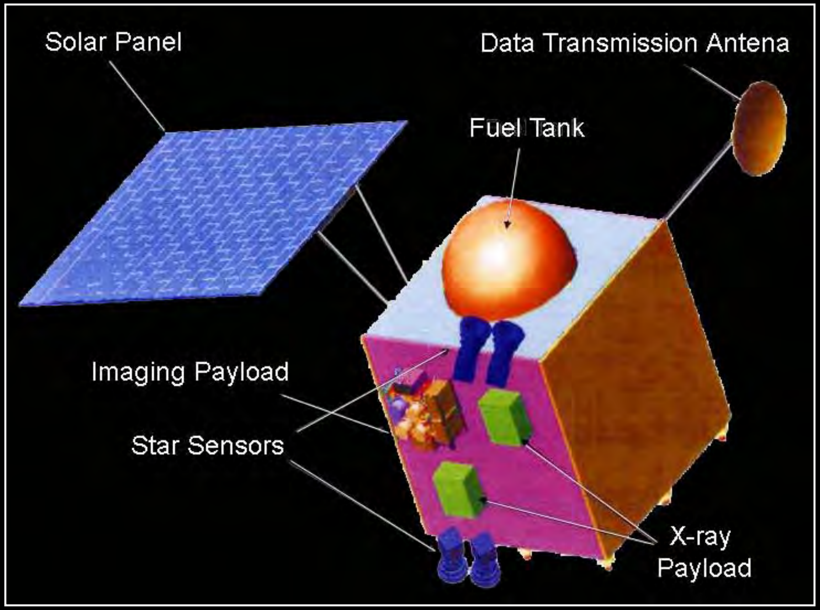
Missions of subsequent years

Kaguya, Japan, 2007-2009

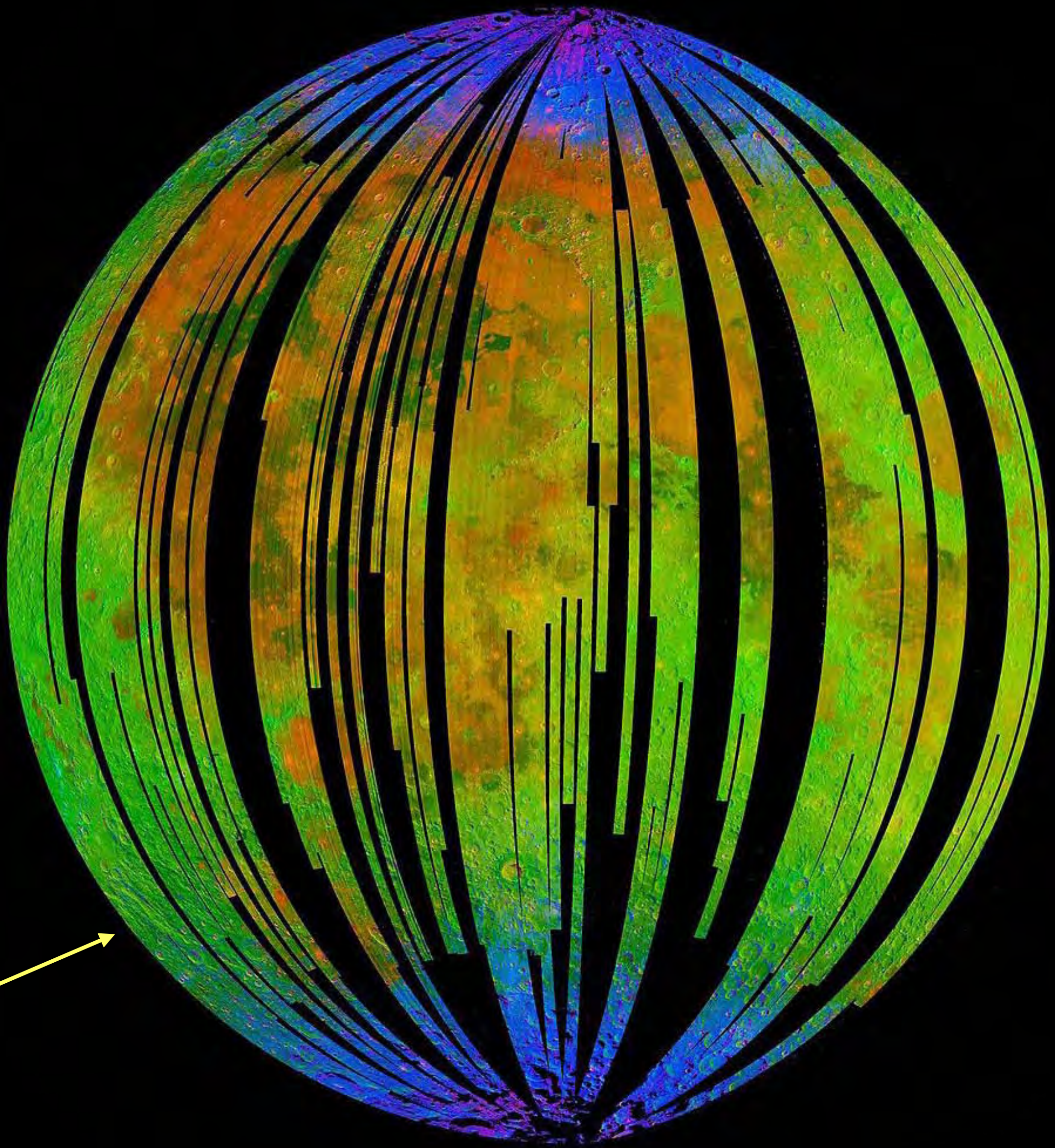


Chang-e 1, China, 2007-2009

Missions of subsequent years

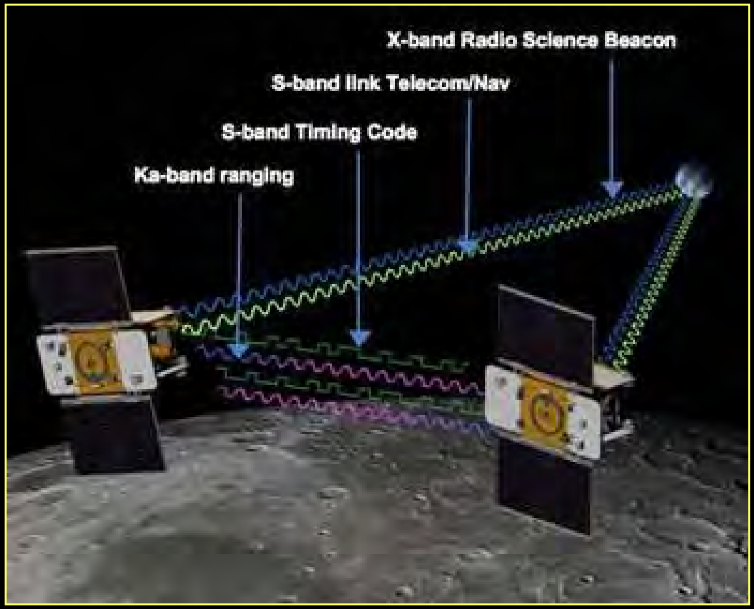


Chandrayaan 1, India
2008-2009

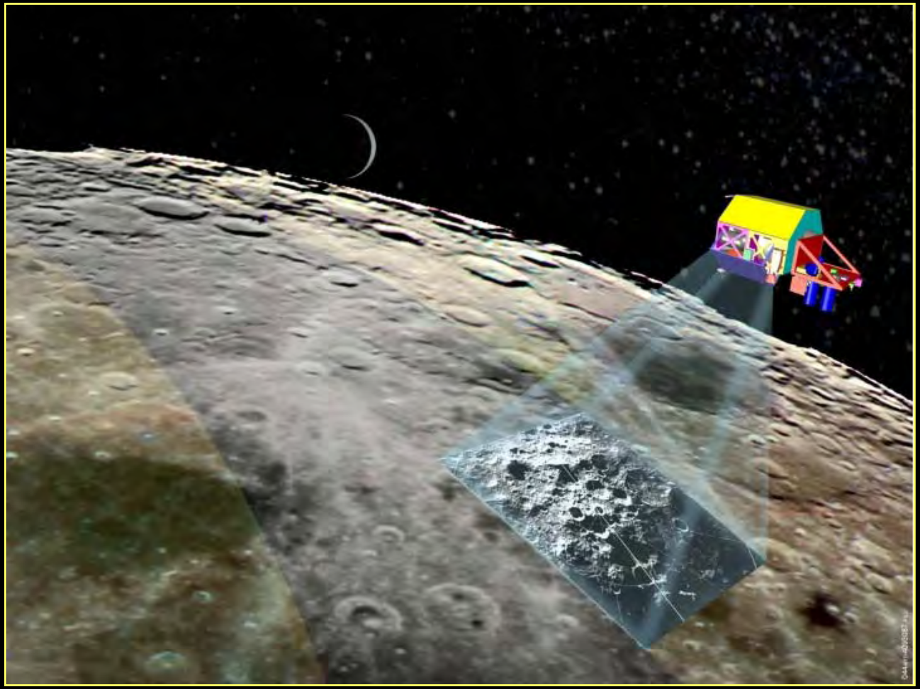


Moon Mineralogy Mapper
onboard Chandrayan 1
Surface water distribution

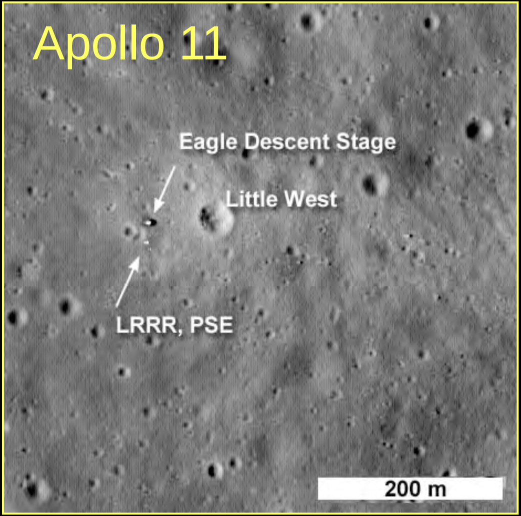
Very recent and current missions

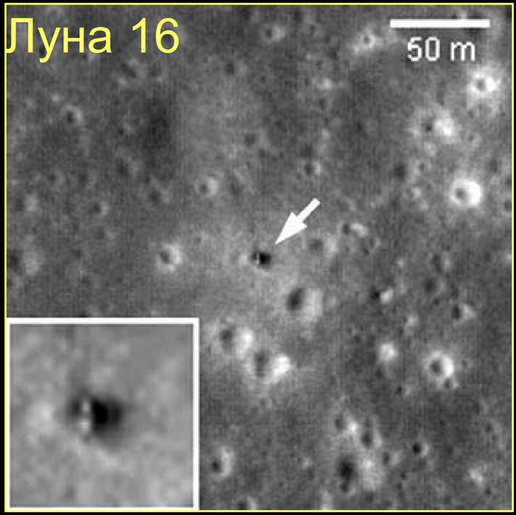


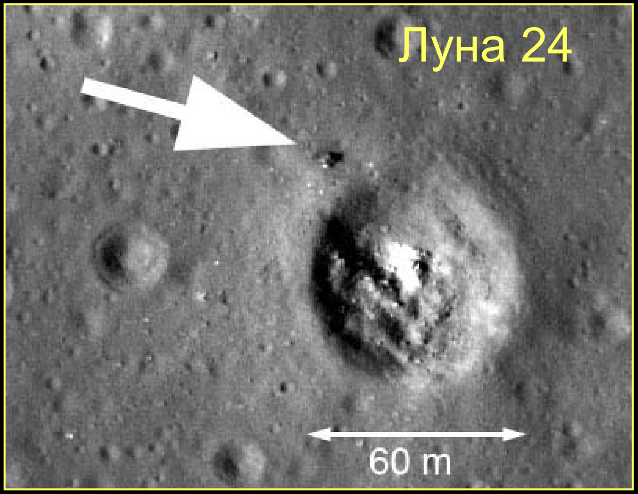
GRAIL = Gravity Recovery and Interior Laboratory, 2011



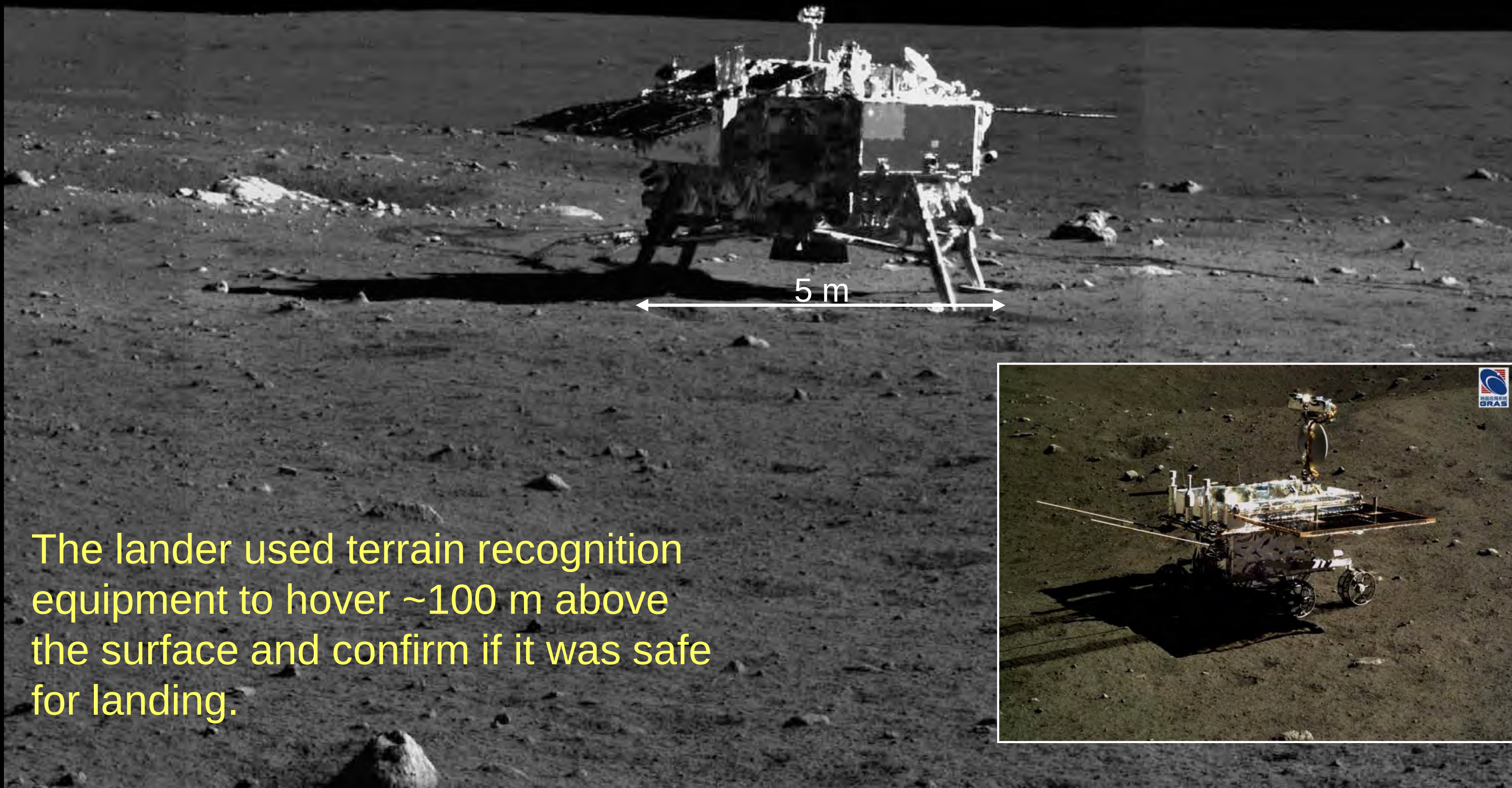
Lunar Reconnaissance Orbiter, USA, 2009





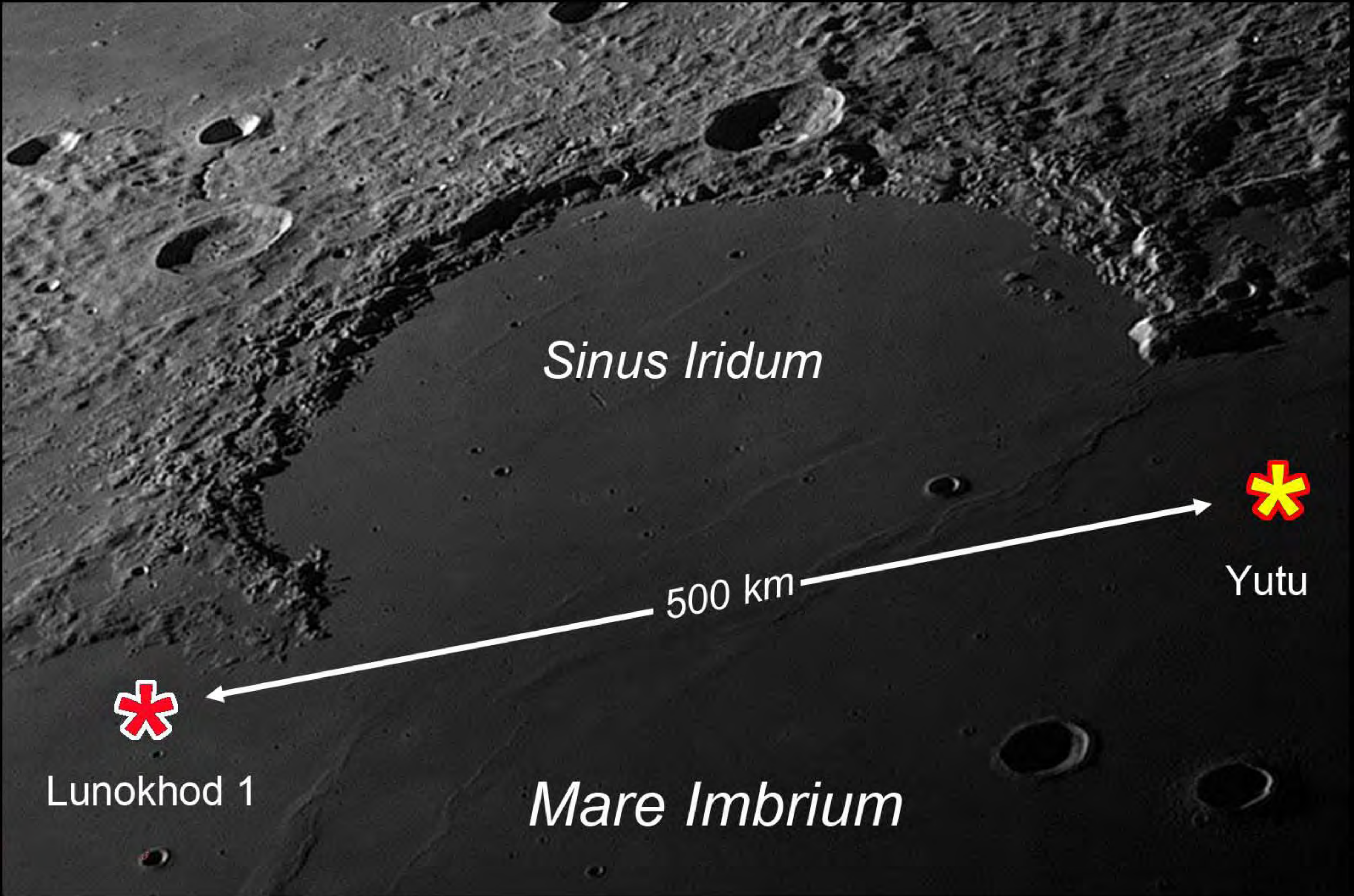


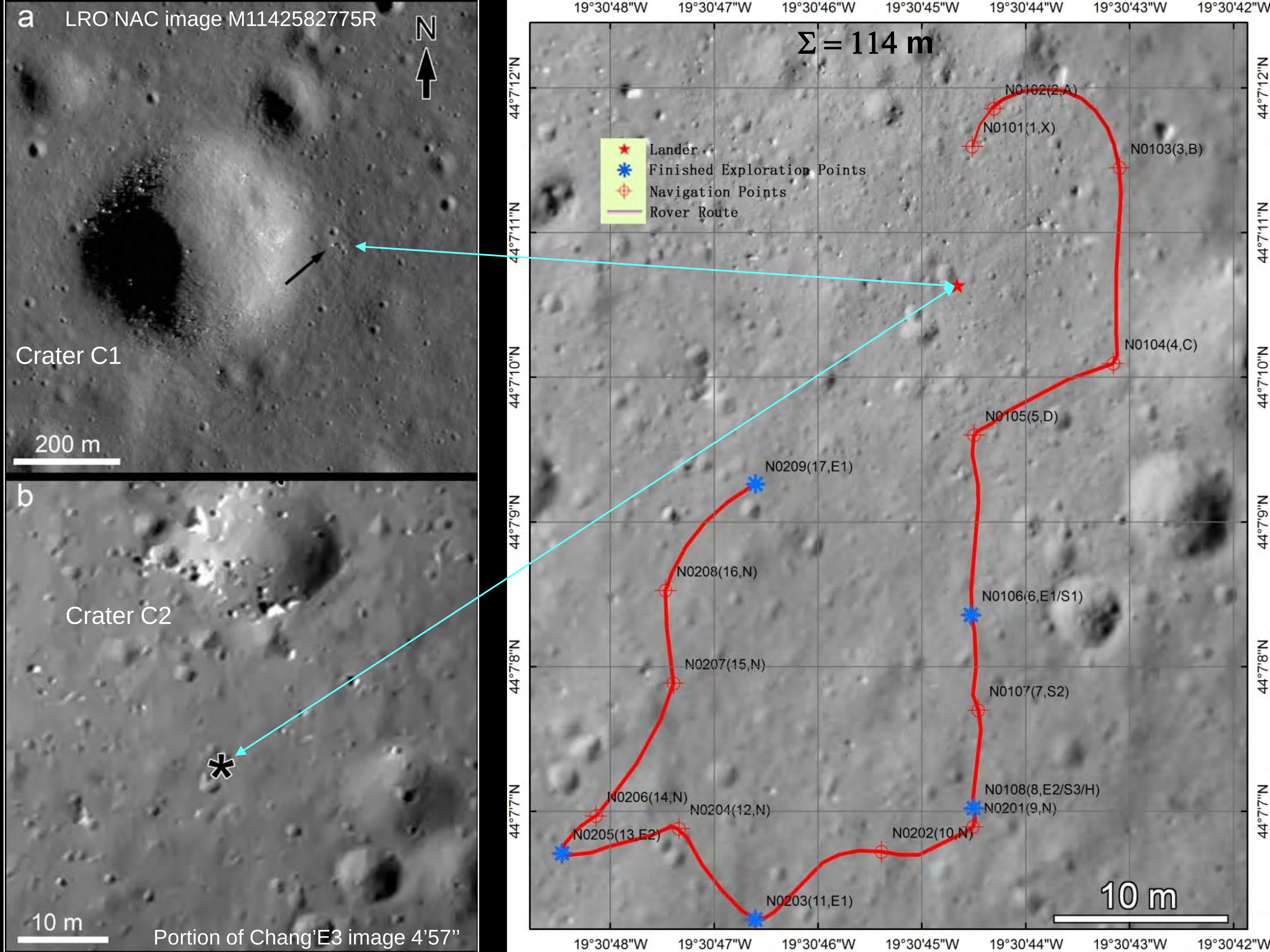
Very recent Chang'E-3



Chang'E-3 lander, which delivered Yutu rover (inlet) to the lunar surface. Portion of Yutu TV panorama (Dec 2013 – March 2015).

Area of work of Lunokhod-1 and Yutu rovers



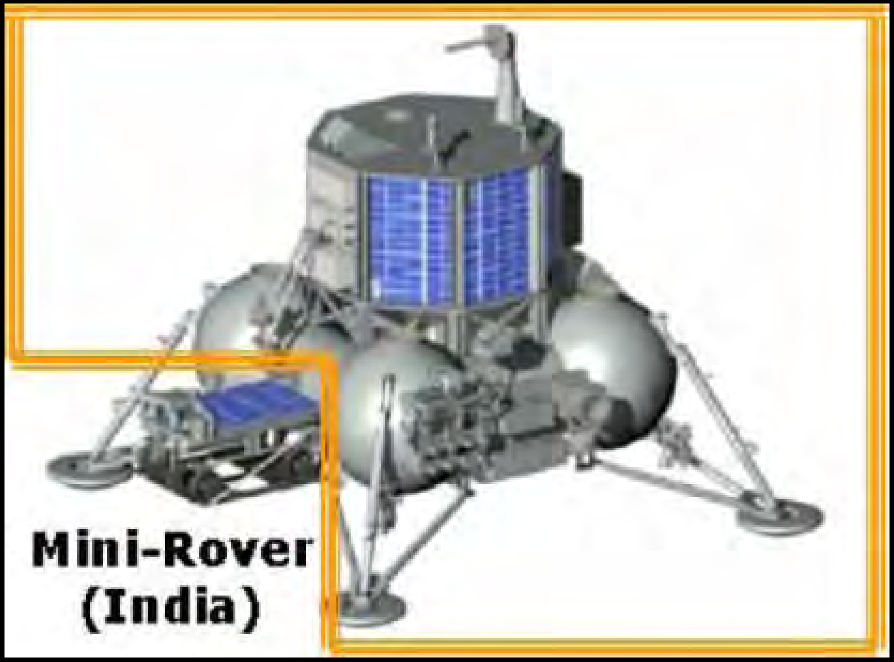


a
LRO NAC image M1142582775R
N
Crater C1
200 m
b
Crater C2
*
10 m
Portion of Chang'E3 image 4'57''
Σ = 114 m
Lander
Finished Exploration Points
Navigation Points
Rover Route
N0101(1,X)
N0102(2,A)
N0103(3,B)
N0104(4,C)
N0105(5,D)
N0106(6,E1/S1)
N0107(7,S2)
N0108(8,E2/S3/H)
N0201(9,N)
N0202(10,N)
N0203(11,E1)
N0204(12,N)
N0205(13,E2)
N0206(14,N)
N0207(15,N)
N0208(16,N)
N0209(17,E1)
10 m
19°30'48"W
19°30'47"W
19°30'46"W
19°30'45"W
19°30'44"W
19°30'43"W
19°30'42"W
44°7'12"N
44°7'11"N
44°7'10"N
44°7'9"N
44°7'8"N
44°7'7"N

Near-future Russian missions to the Moon
2018-2021

Luna Glob

Luna Resource



Landing in polar areas of the Moon, where in regolith there is present H_2O ice and other volatiles. Taking samples for analysis on-board of the lander. Drilling down to 1 m.

The Moon: Surface environment:

No atmosphere, $P_{\text{атм}} \sim 10^{-14}$ bar

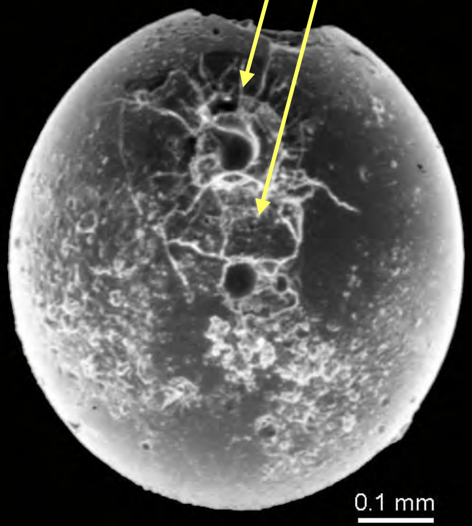
Temperature 120 – 410 K

$g = 162\ cm/s^2 = 1/6$ g Earth

Meteorite/ micrometeorite bombardment

Cosmic rays

Glass sphere from lunar soil with impact microcraters



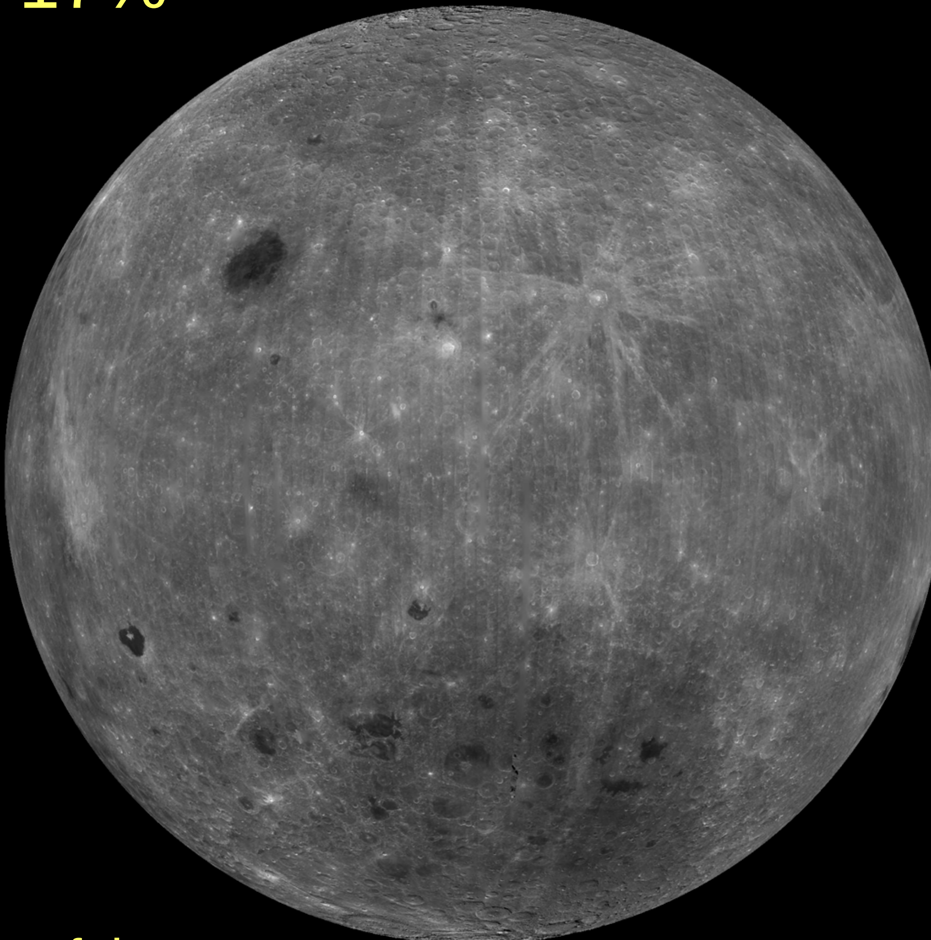
Apollo 14 astronaut installs TV camera

Surface morphology of the Moon:

Highlands – 83%
Mare – 17%

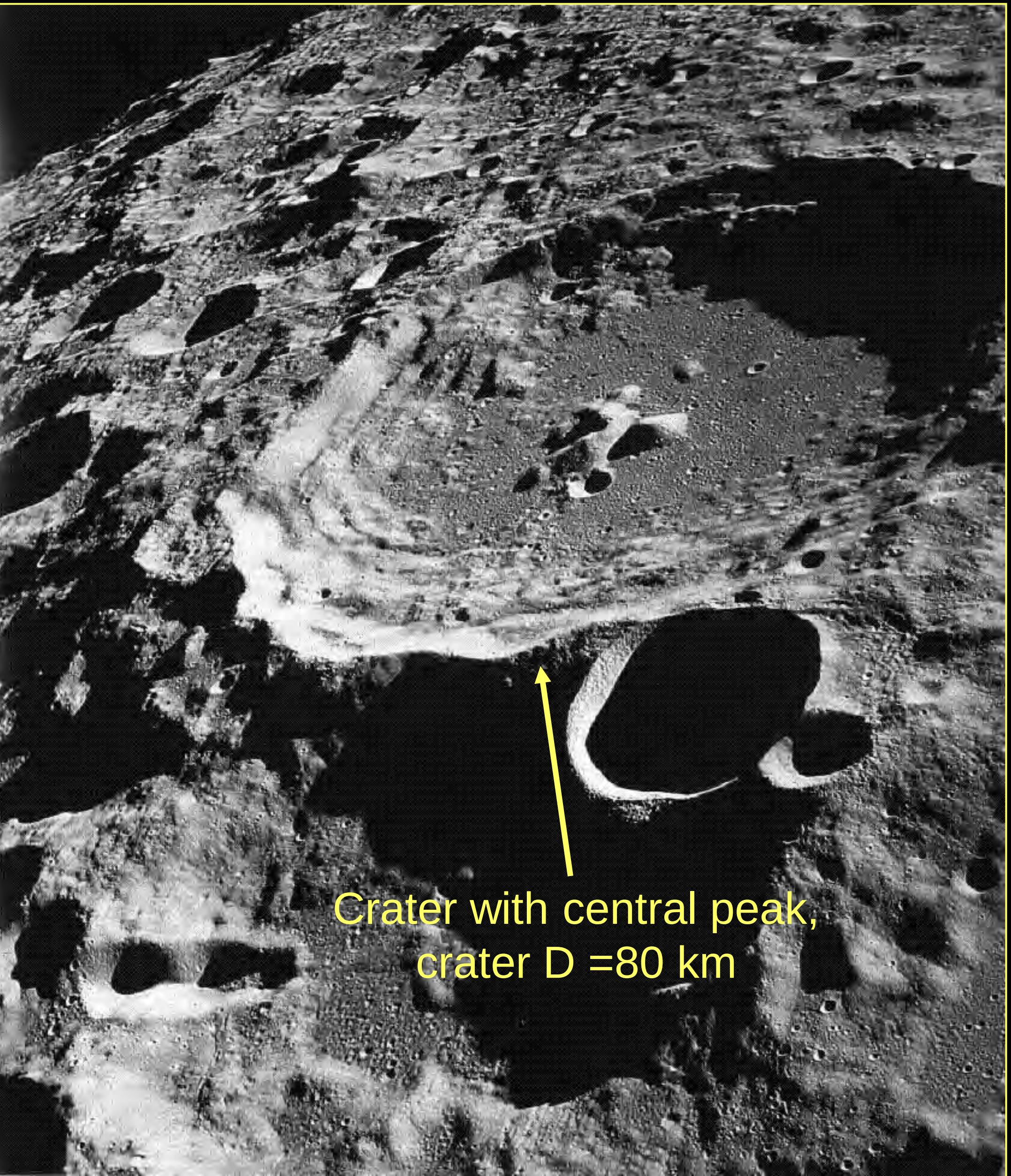
Near side

Mosaic of the Clementine images



Far side

Surface morphology of the Moon: Highlands / Mare



Types of lunar rocks

Maria

SiO_2 38-48%
TiO_2 0.5-13%
Al_2O_3 8-14%
FeO 18-20%
CaO 10-13%

SiO_2 44%
TiO_2 0.02%
Al_2O_3 36%
FeO 0.5%
CaO 19%

Highlands

Don’t believe the colors.
In reality all are grey.

Lunar rocks

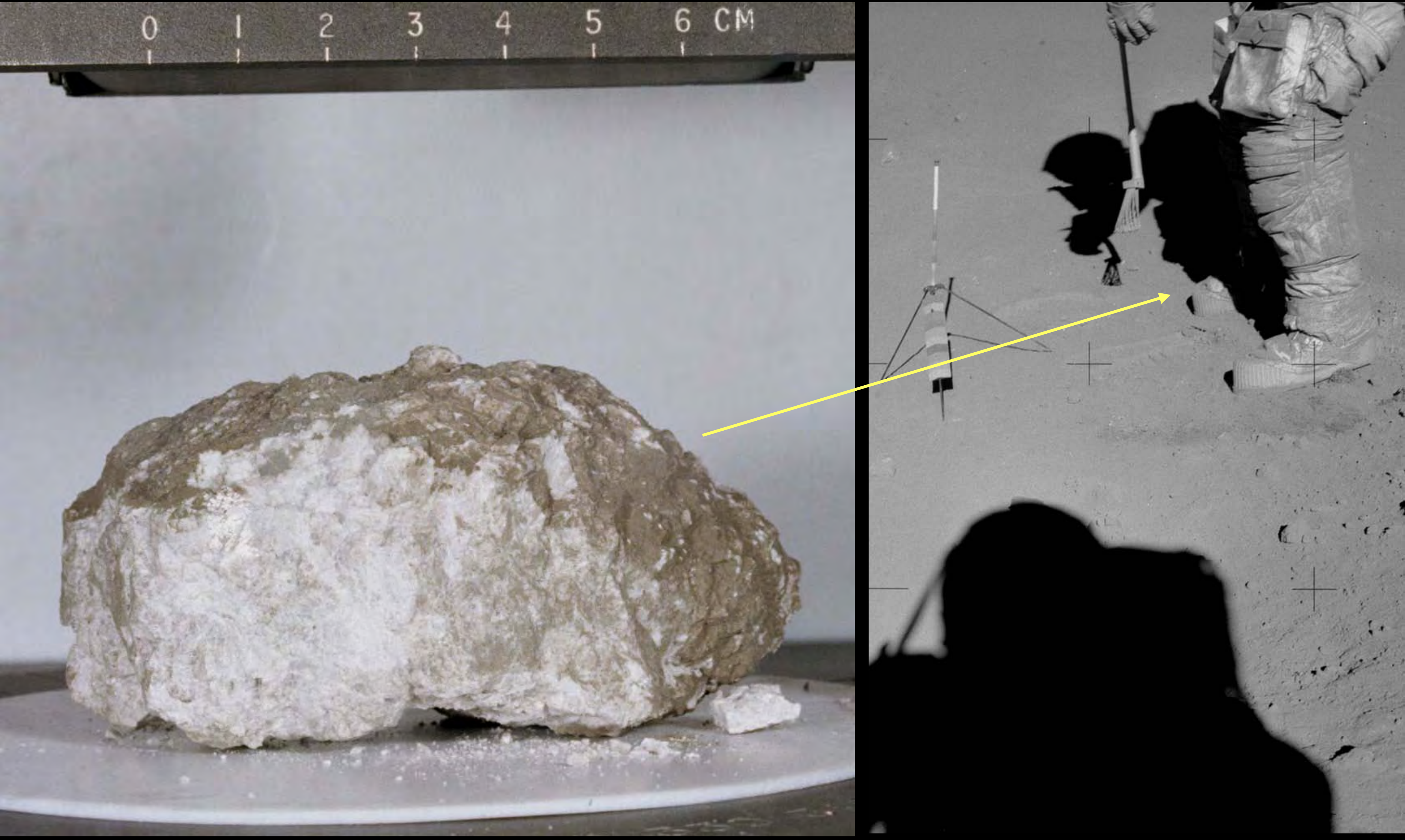
Mineral composition:

- Plagioclases (high-Ca), Olivines, Pyroxenes,
- Minerals with volatiles are absent

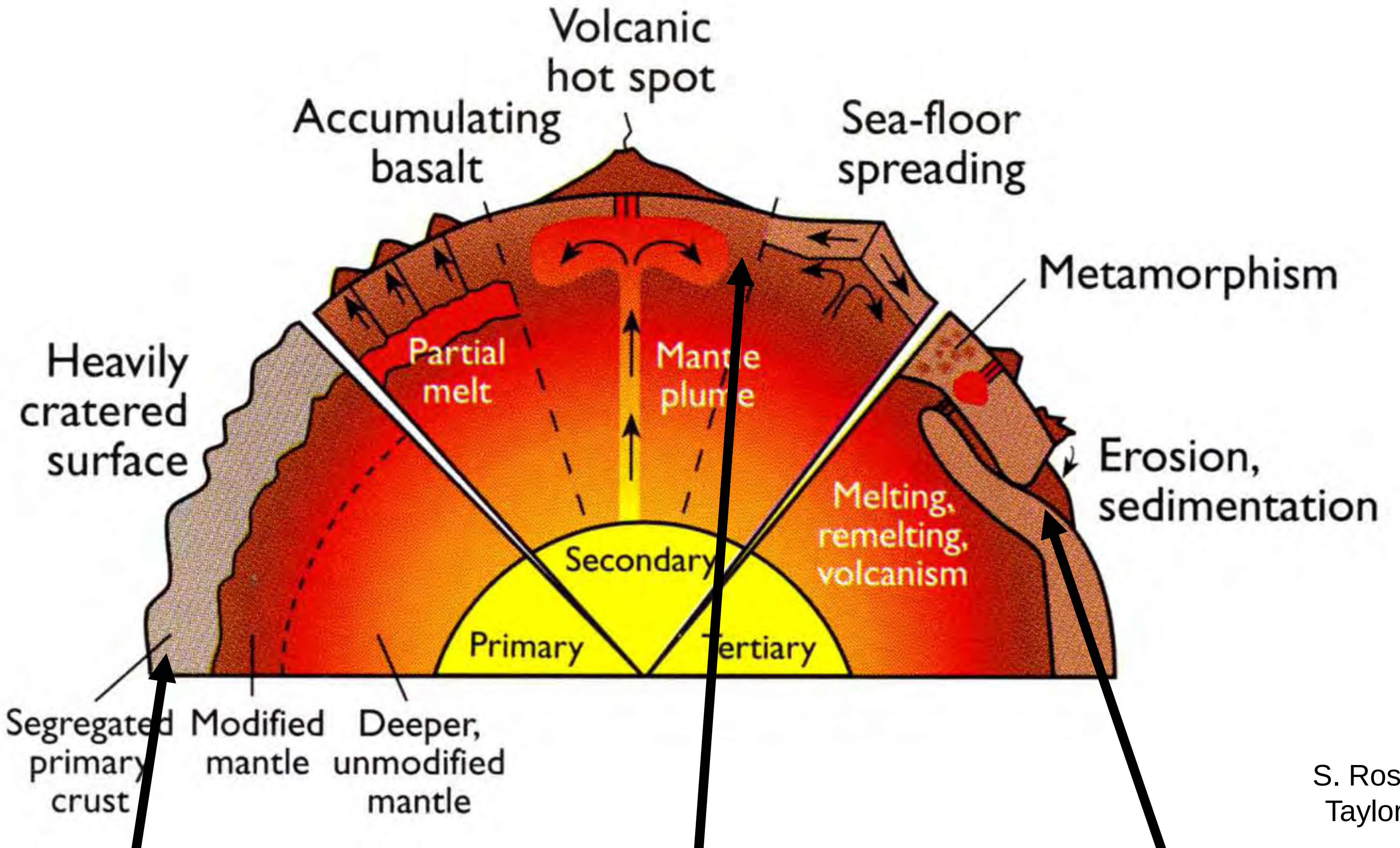
Rocks:

- Anorthosite-norite-troctolite (ANT) breccias in highlands,
- Basalts in lunar maria,
- No granites!

Apollo 15: “Genesis Rock” - Anorthosite



Three types of planetary crusts



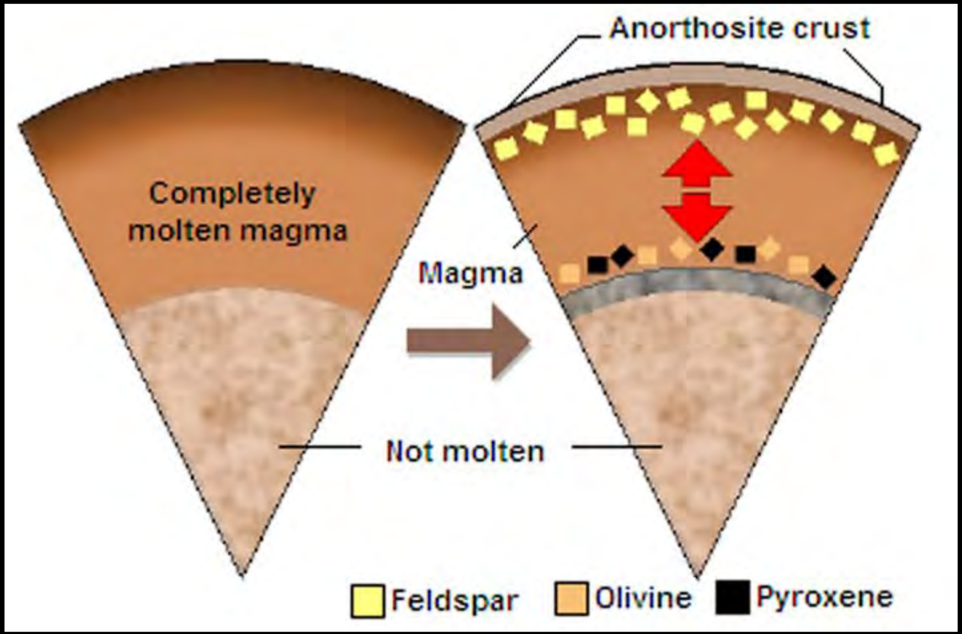
S. Ross Taylor

Primary:
Anorthositic
Crust of the Moon

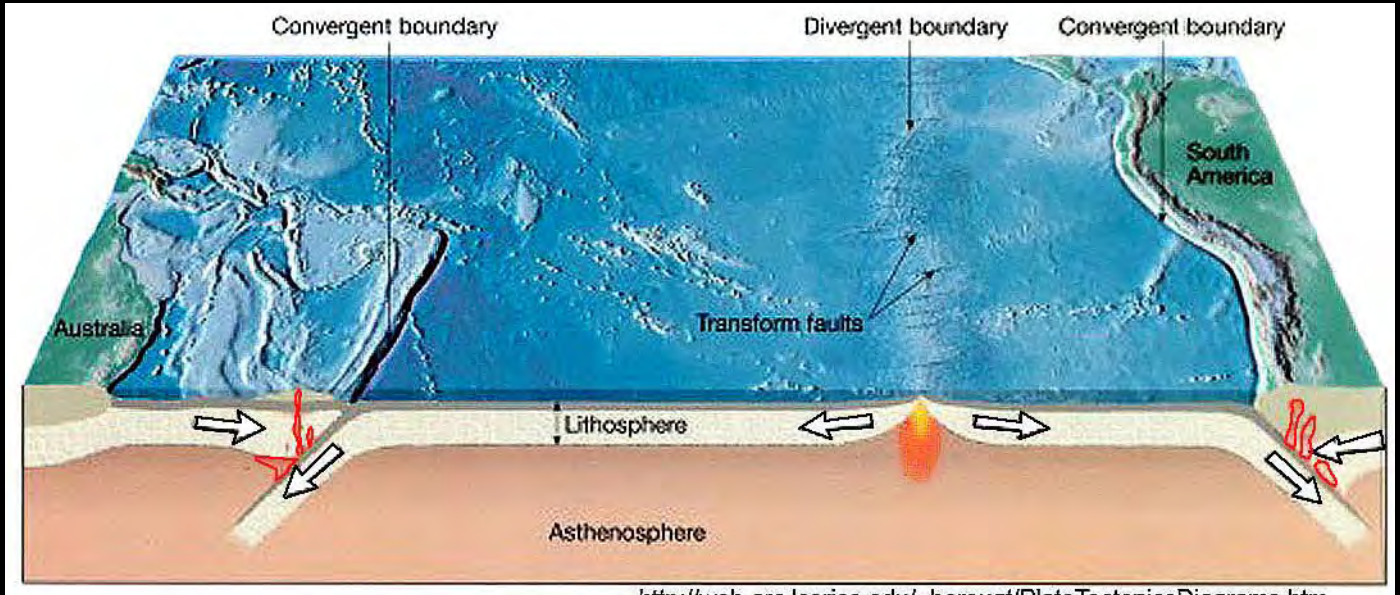
Secondary:
Oceanic crust of Earth,
Crust of the Moon in lunar maria

Tertiary:
Granitic crust
of the Earth continents

Primary anorthositic crust of the Moon



Secondary oceanic and tertiary continental crust of Earth



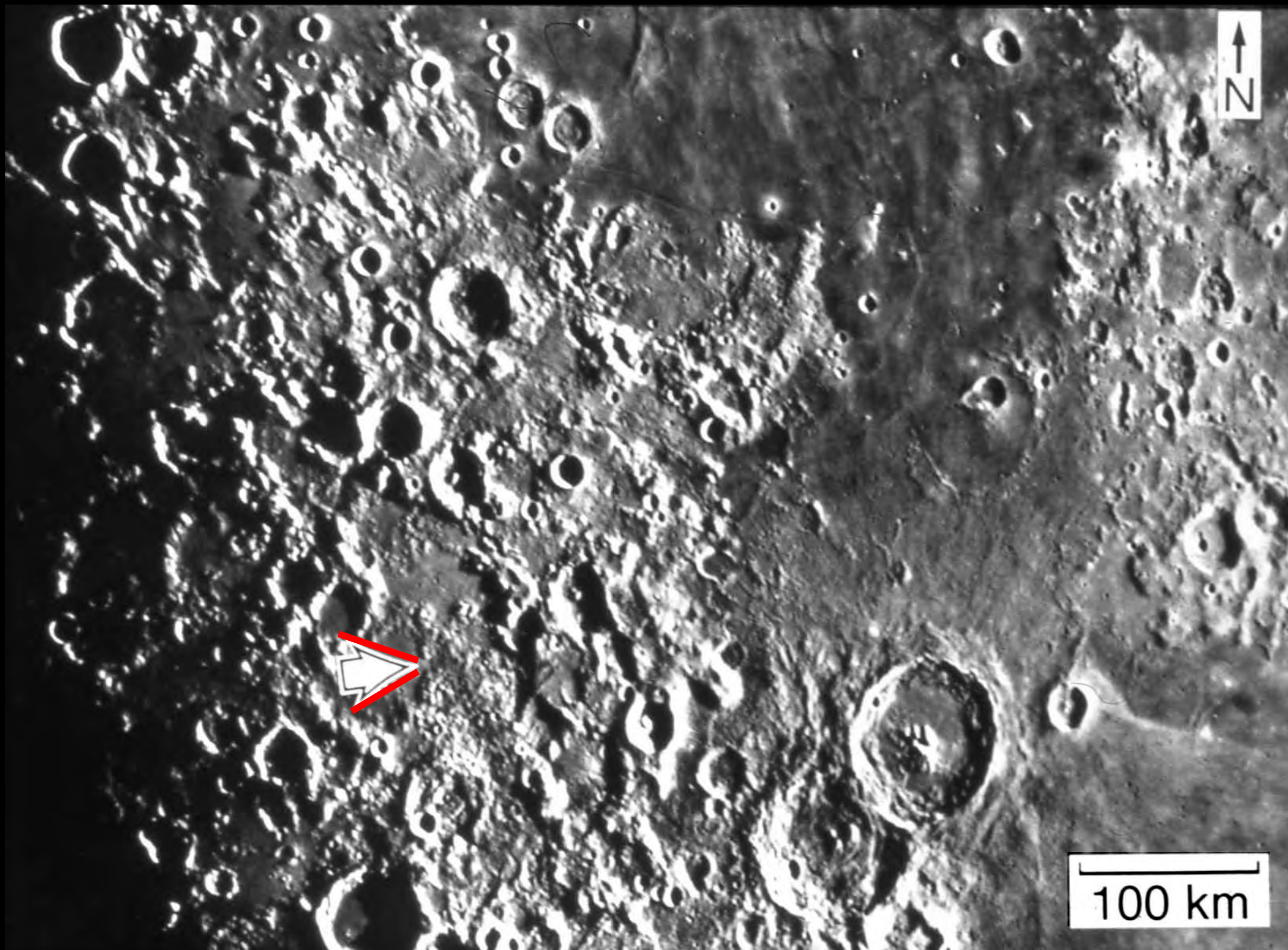
http://web.arc.losrios.edu/~borougt/PlateTectonicsDiagrams.htm

The Apollo 16 highland breccia, Fragments are seen

Don’t believe in color

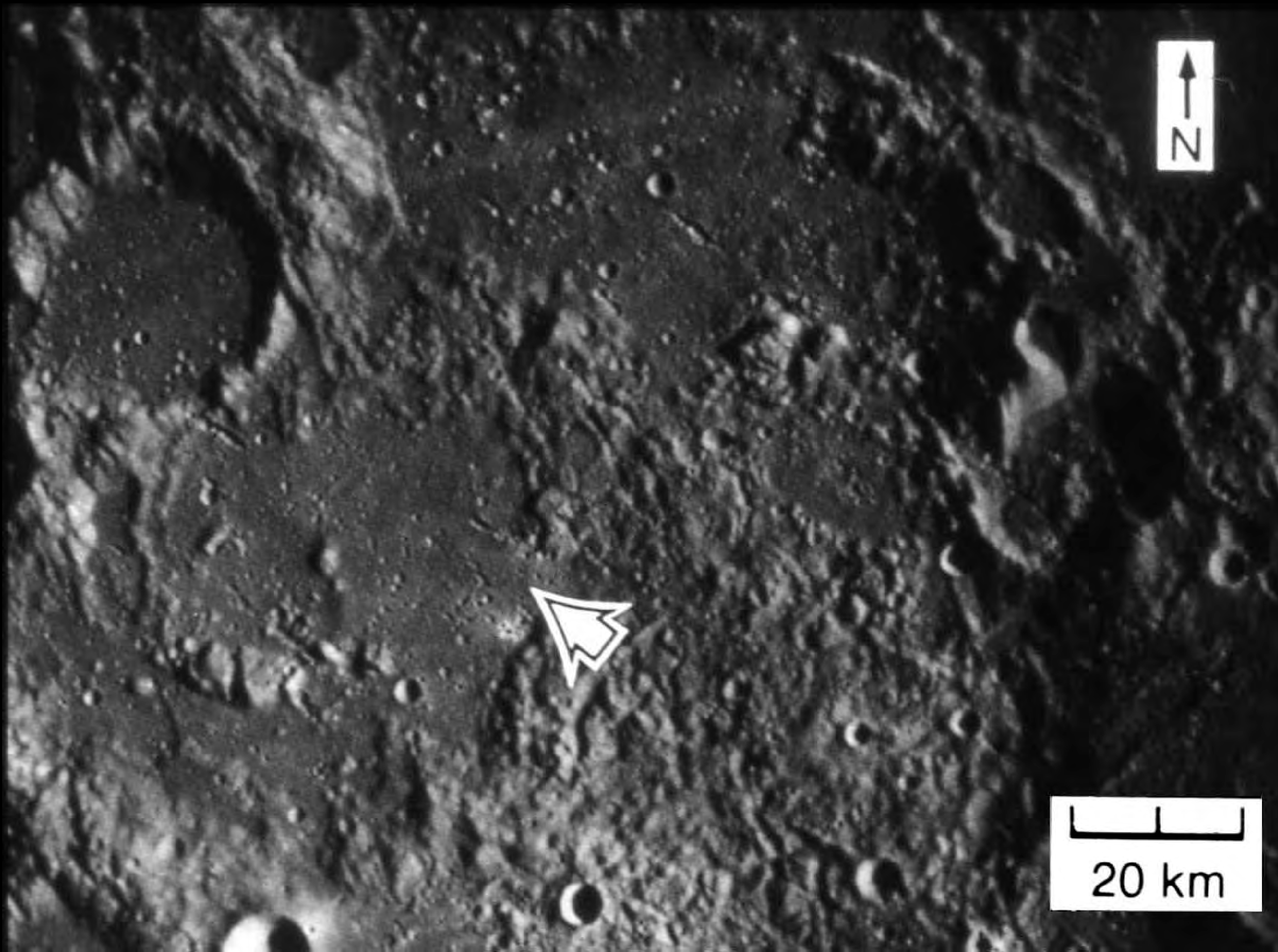
In the Apollo 16 site there are no lavas, only breccias

Apollo 16 landing site: Regional situation

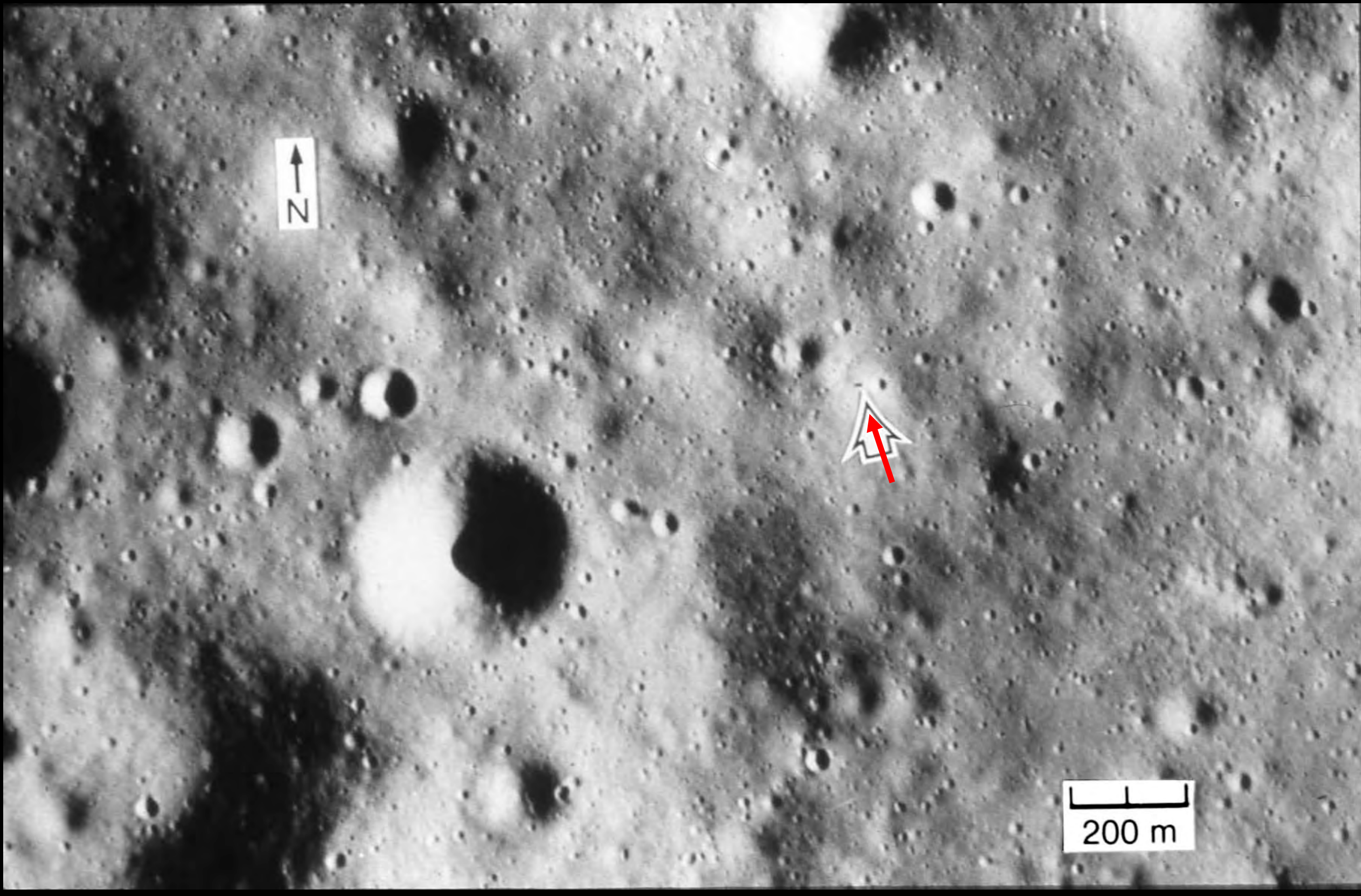


It was expected before landing that plains here were formed by the “highland” volcanism

Apollo 16 landing site: Approaching

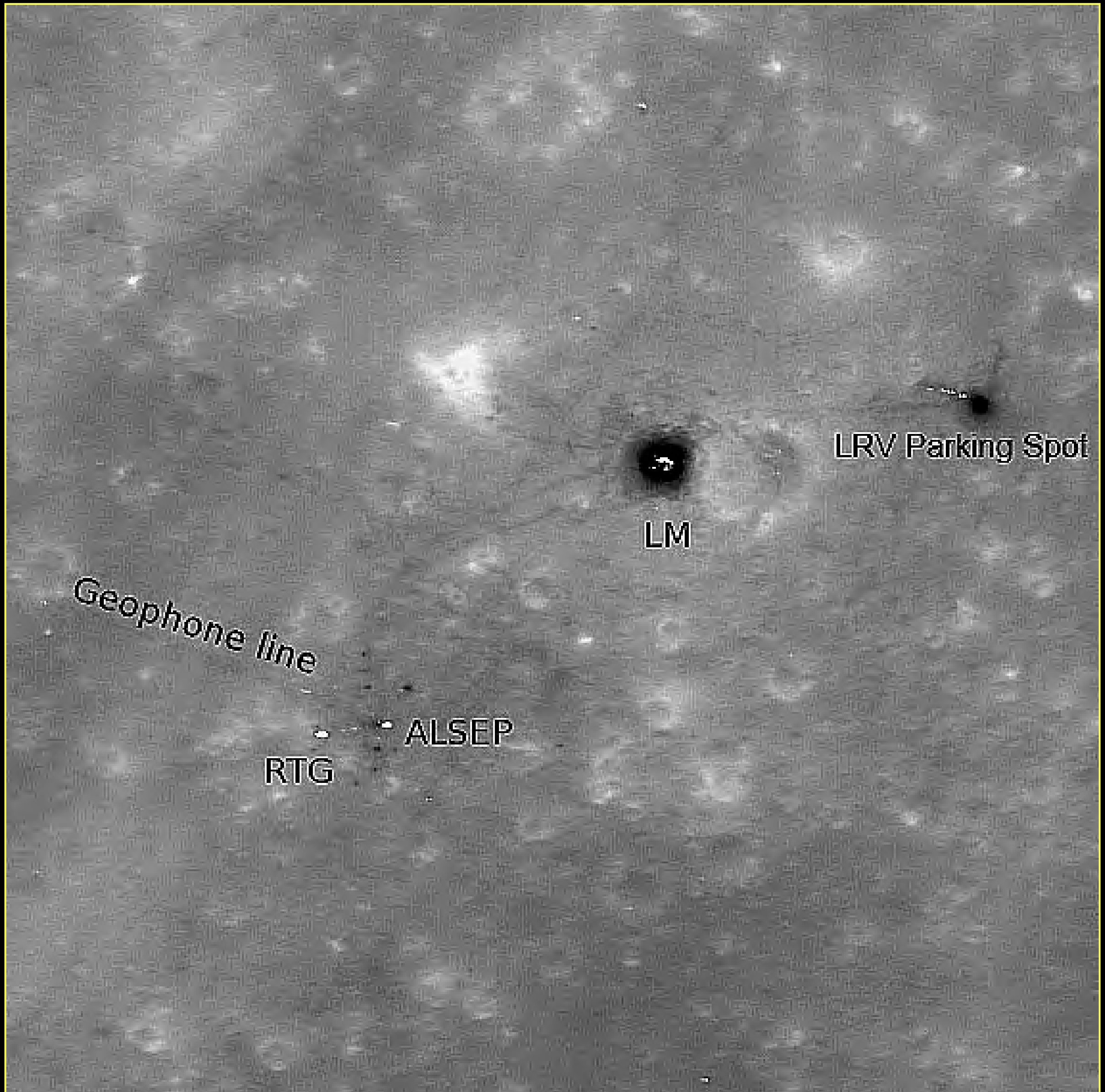


Apollo 16 landing site: Local situation

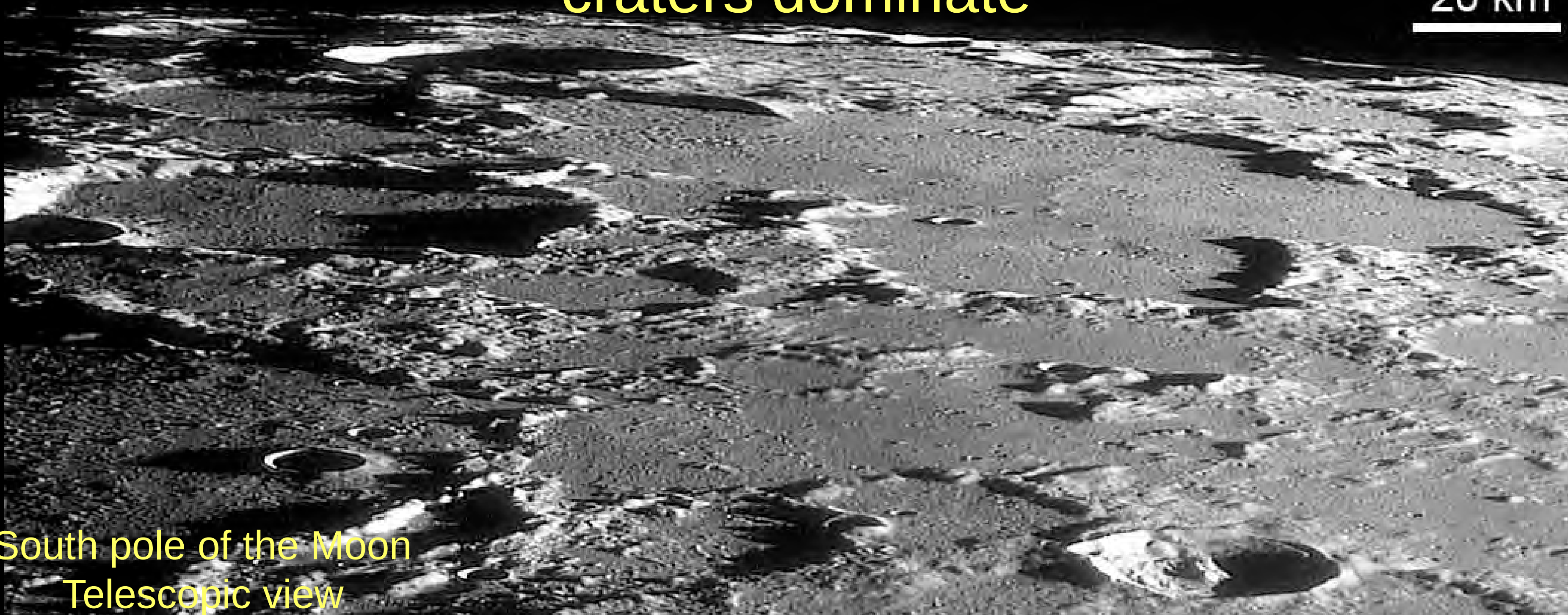


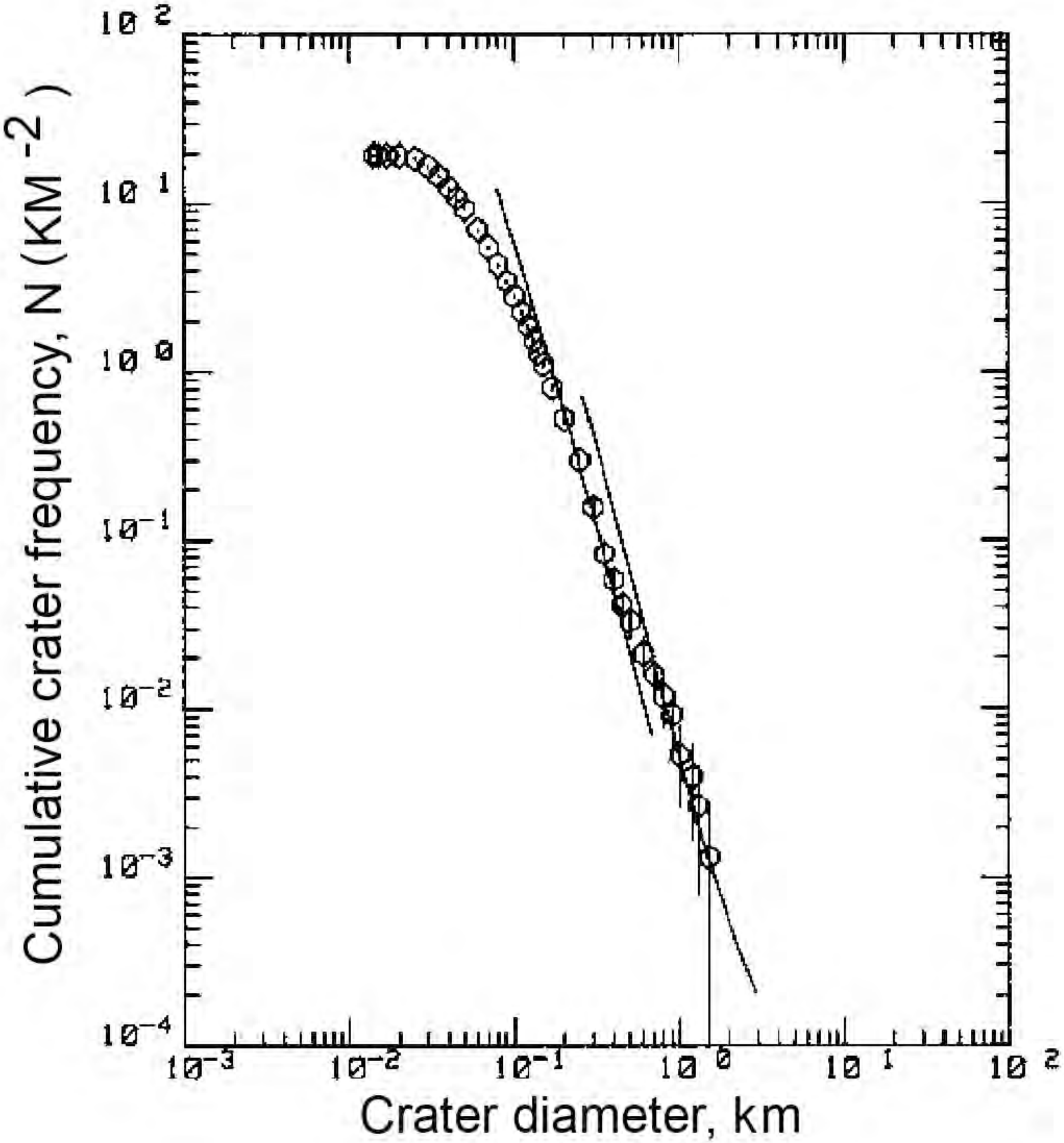
Apollo 16 landing site, LROC NAC image

The landing module, parked rover and astronauts' foot traces are seen



In surface morphology of the Moon craters dominate



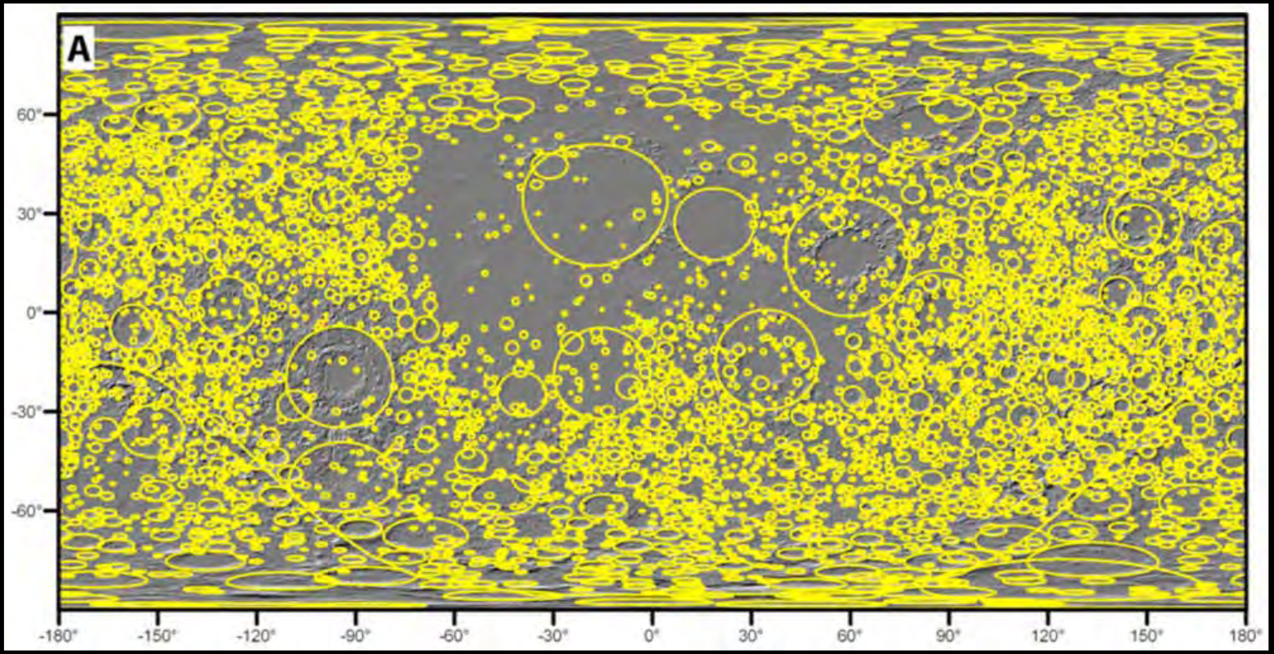


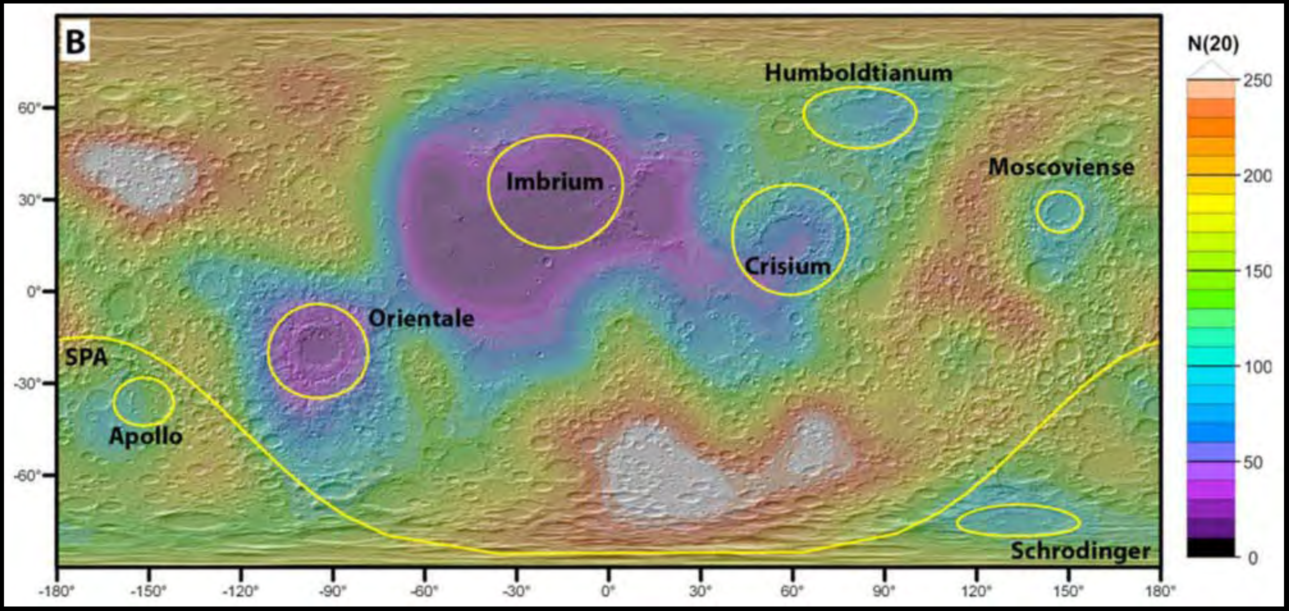
Amount of craters (N) per area unit of the surface depends on their diameter (D) and the surface age

N(D) is, as a rule, a power function with power degree between -2 and -3.

Global distribution of craters >20 km in diameter.

Data of LOLA, superposed on image.

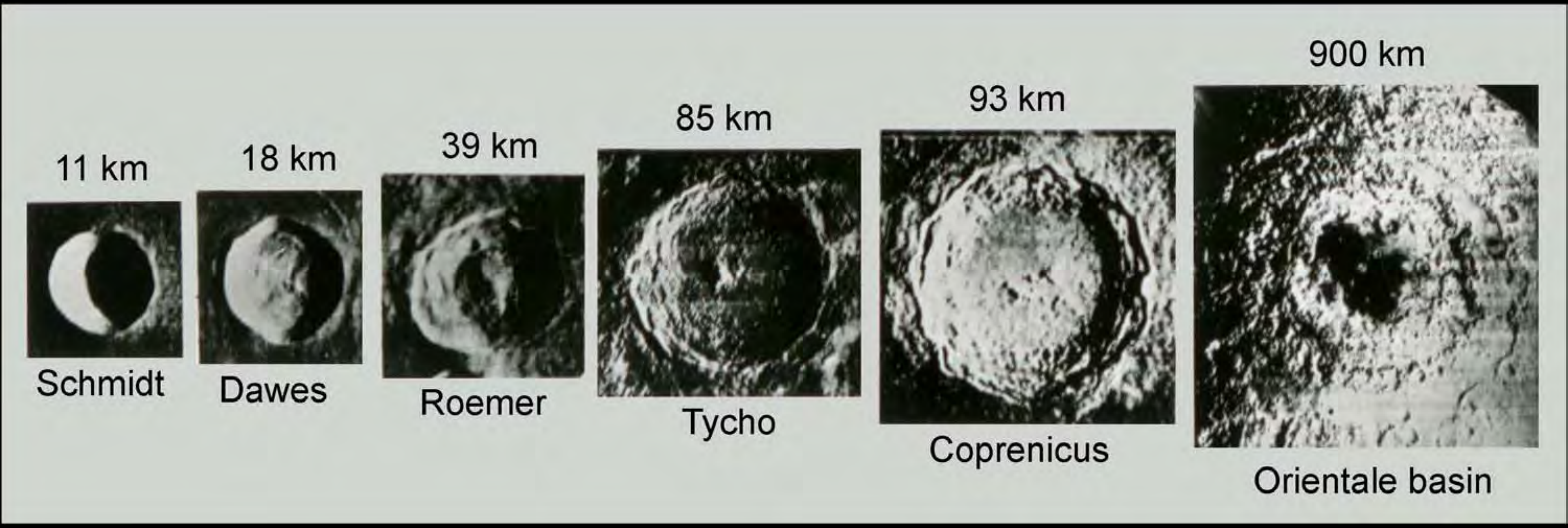




Head, 2011

Morphology of lunar craters depends on their diameter

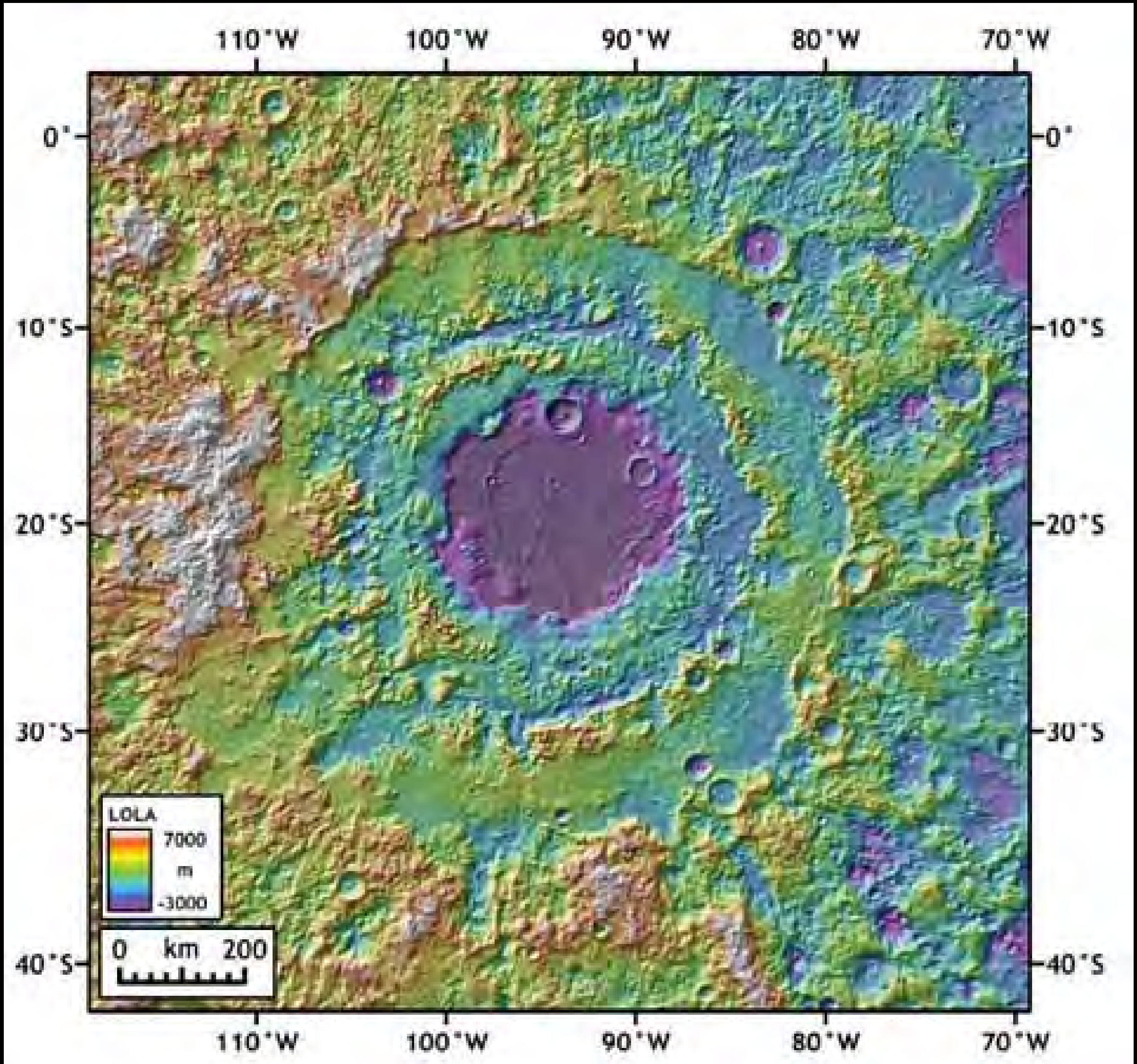
Smaller than 10 km – bowl-shaped
15-20 km – transition to central-peaked craters
20-90 km – central-peaked craters
Larger than 90 km – ringed basins



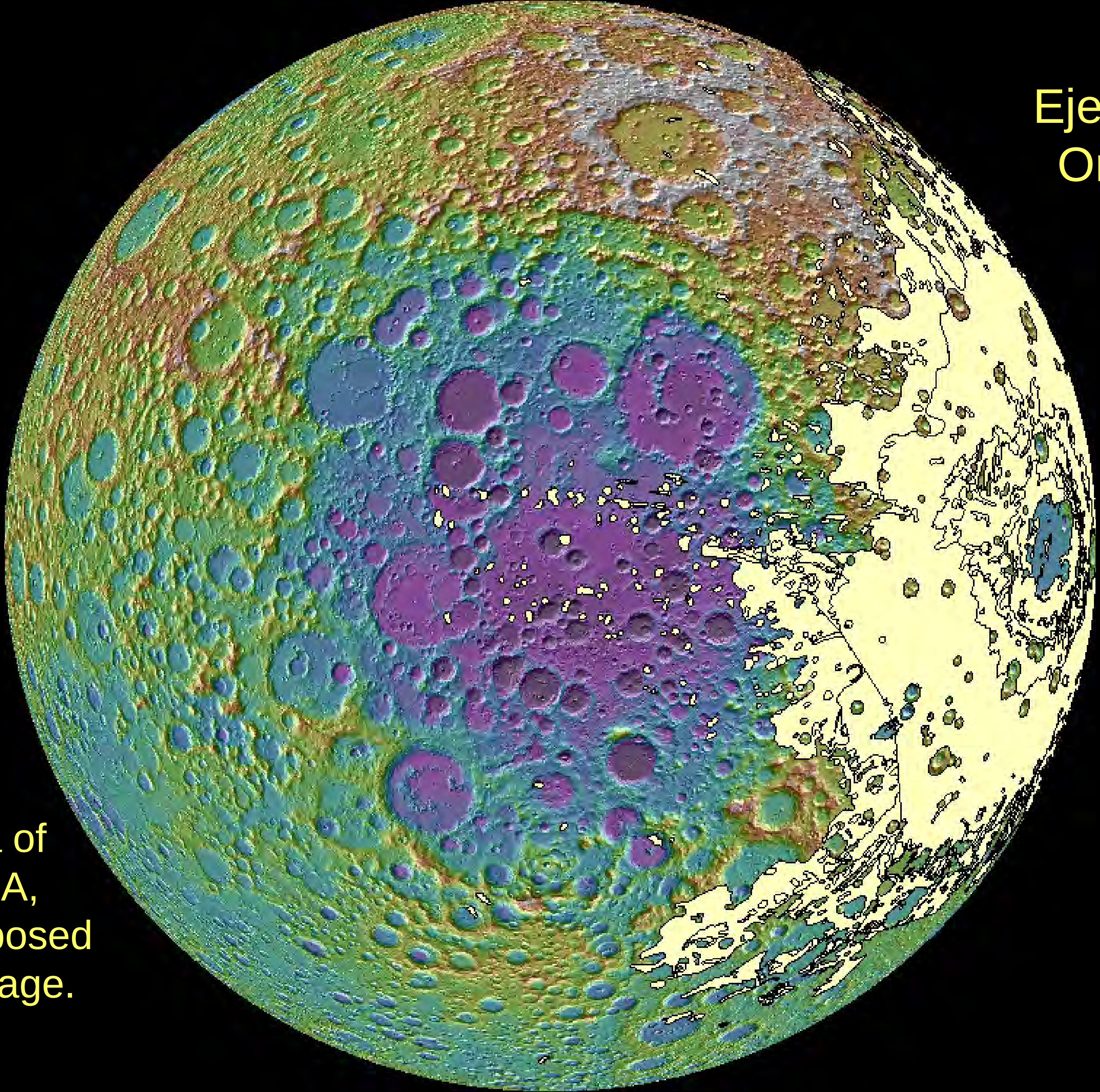
Basilevsky & Grebennik, 1980

Orientale basin – the youngest impact basin of the Moon

Data of LOLA, superposed on image.



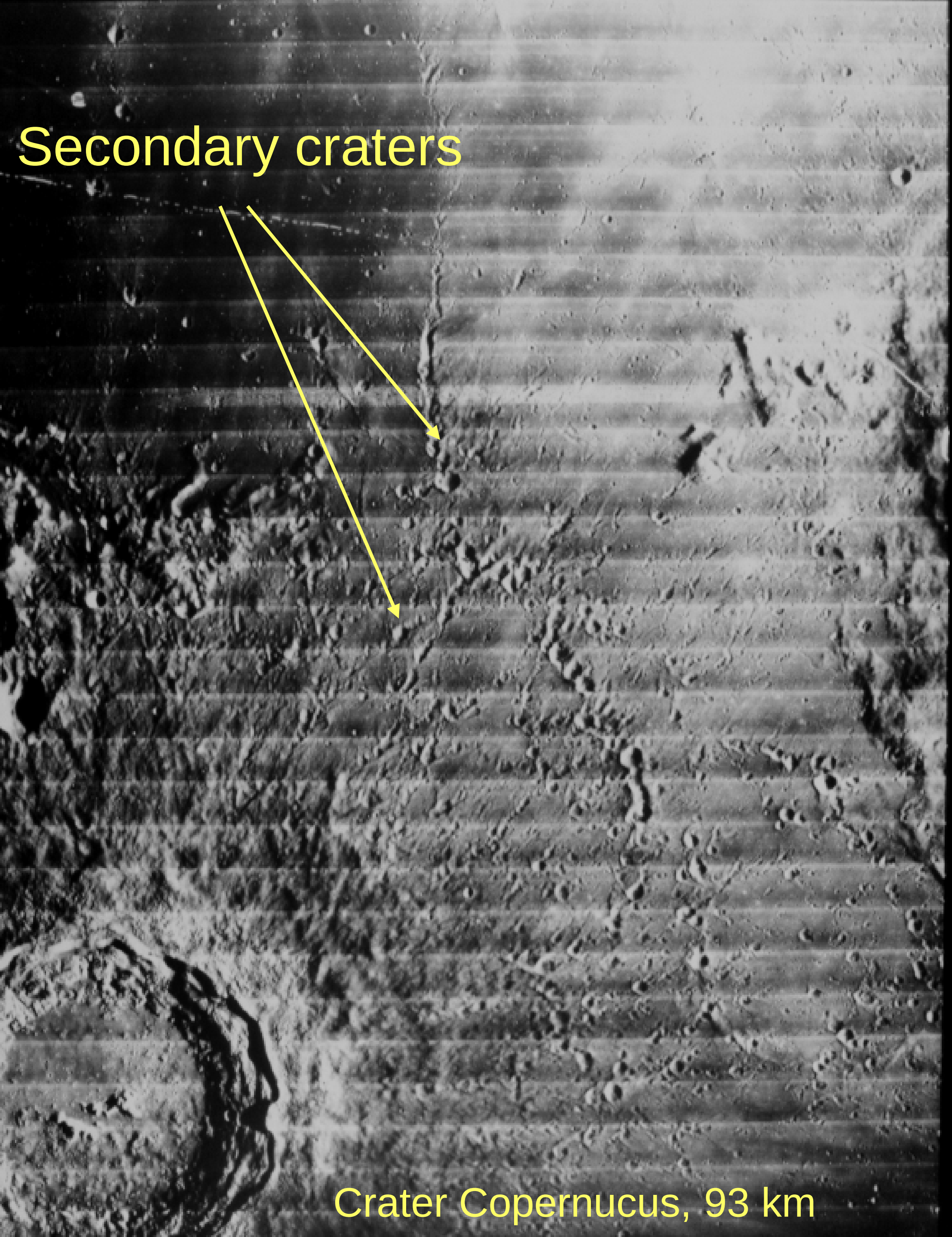
Head, 2011



Ejecta from Orientale basin

Data of LOLA, superposed on image.

Head, 2011



Origin of lunar craters:

Morphology suggests an "explosion". But which explosion?

Impact of meteorite
or
Volcanic explosion?

Lunar samples delivered to Earth answered this question:
Meteorite impact

Geochemical specifics

Observations:

- Practical absence of volatiles H_2O, CO_2
- Deficit of moderately volatile components (K,Na)
- Enrichment in refractories (Ca, Al).

What follows from this:

- Explosions were not volcanic: craters are impact.
- High temperature and possibility to loose volatiles – openness into space => Hypothesis of Giant impact.

Observations :

- Deficit of siderophiles (Pt, Ir) – only for primary magmatic rocks; regolith while highland breccias are enriched in siderophiles

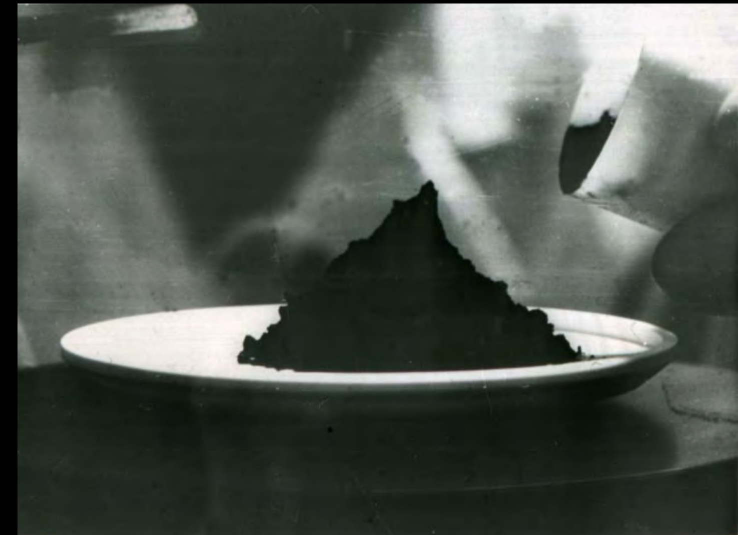
What follows from this :

Siderophiles did sink to the core. But it is small.

=> Hypothesis of Giant impact

Regolith

Loose, moderately cohesive soil
Composition – minerals, rocks, glasses, agglutinates
Admixtute of meteorite material

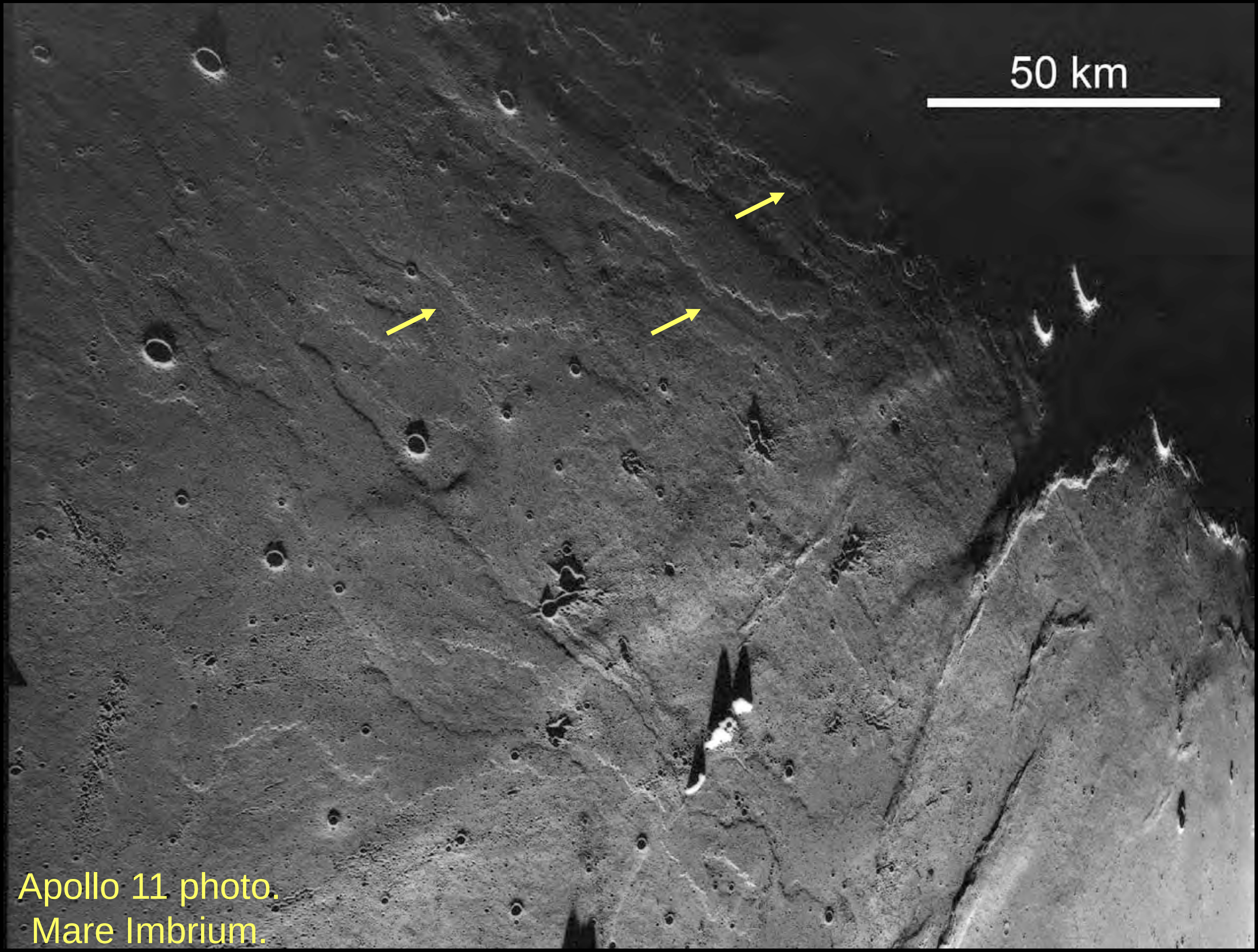


Luna16 soil

Apollo 11 astronaut footprint

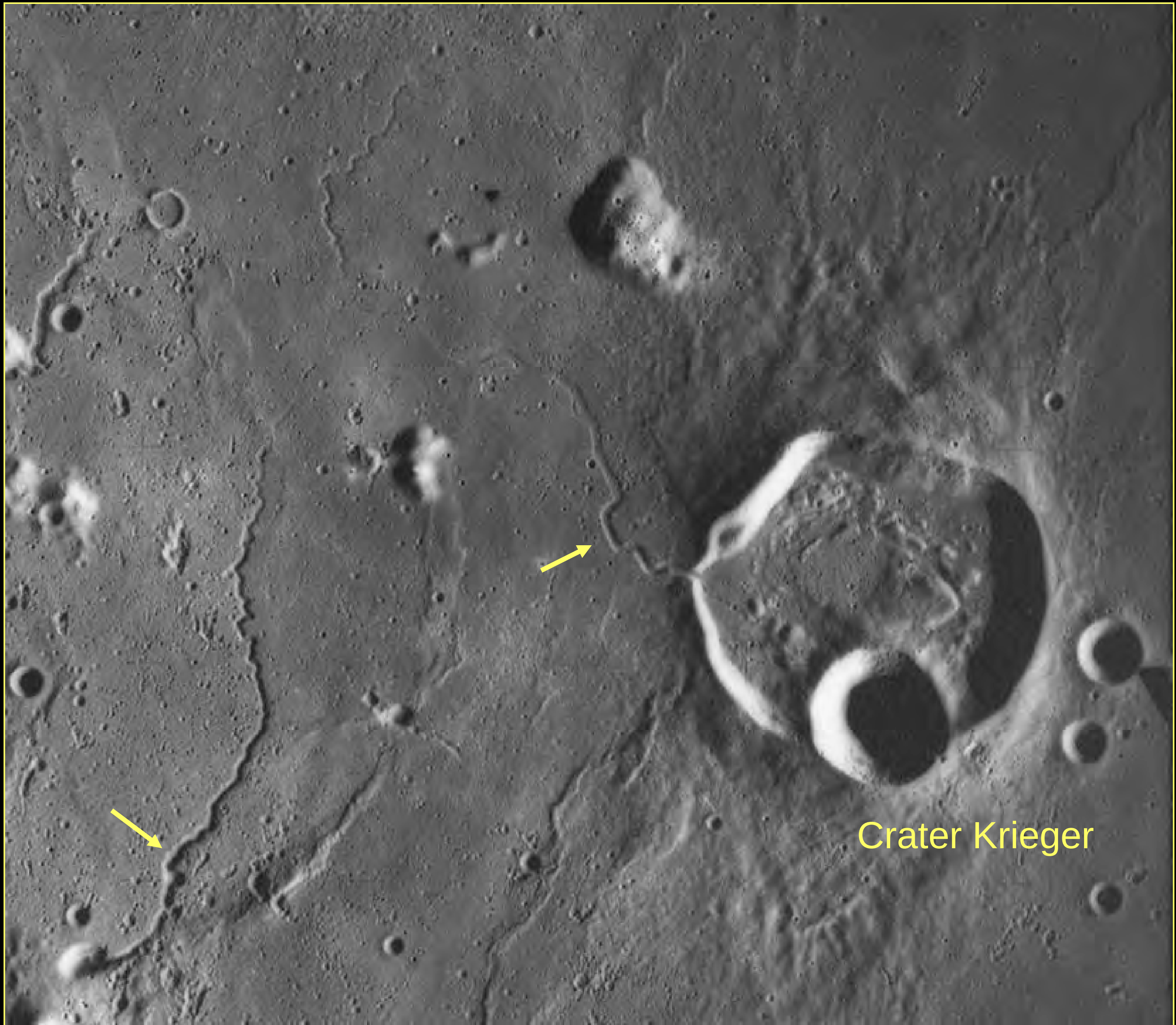
Particles of Luna 16 regilith

Lunar volcanism



Plains-forming basaltic lavas fill lunar maria.

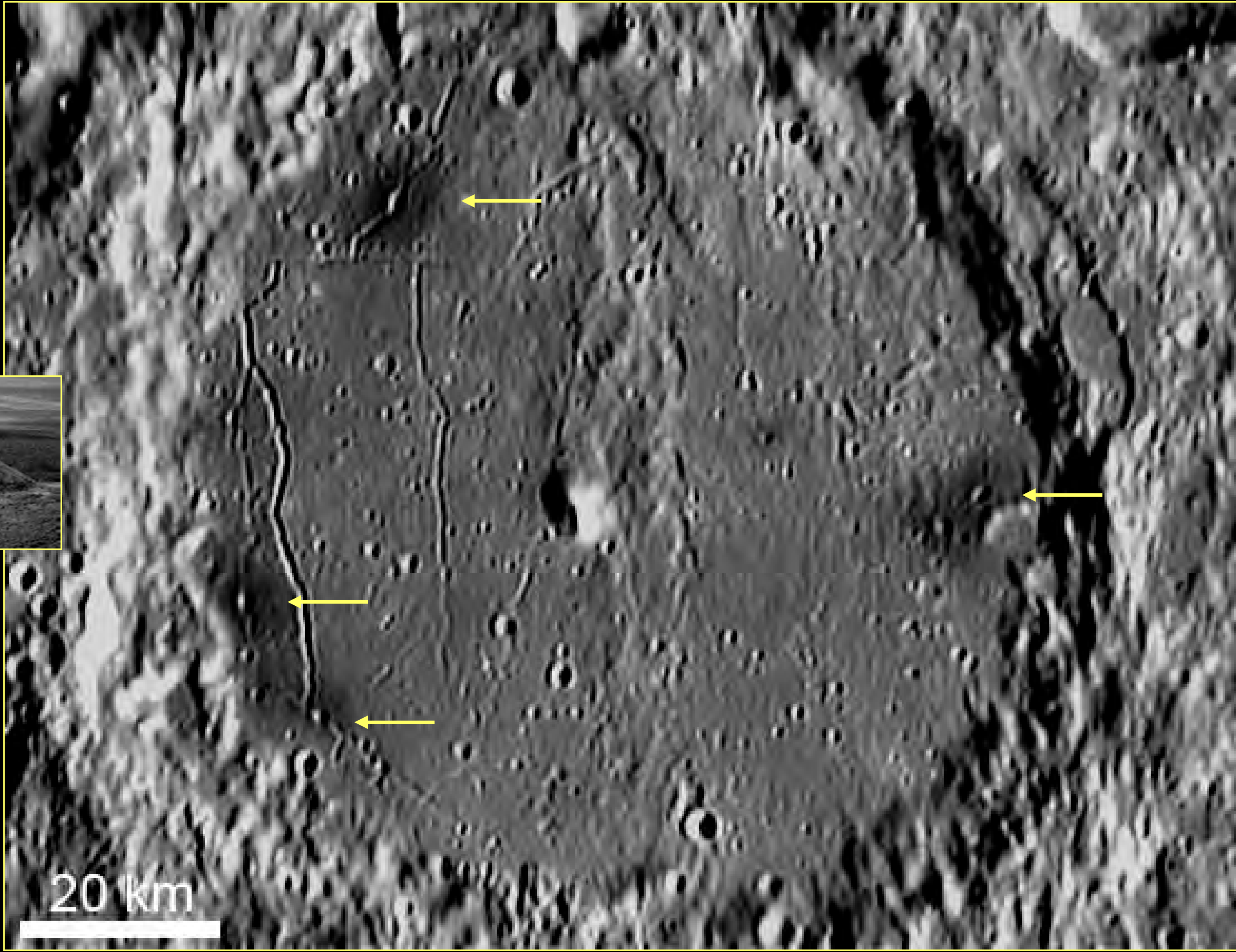
Sinuous rilles – erosion by the flowing hot lava



108-km crater Alphonsus. Fractures and small dark-halo craters – pyroclastic deposits?

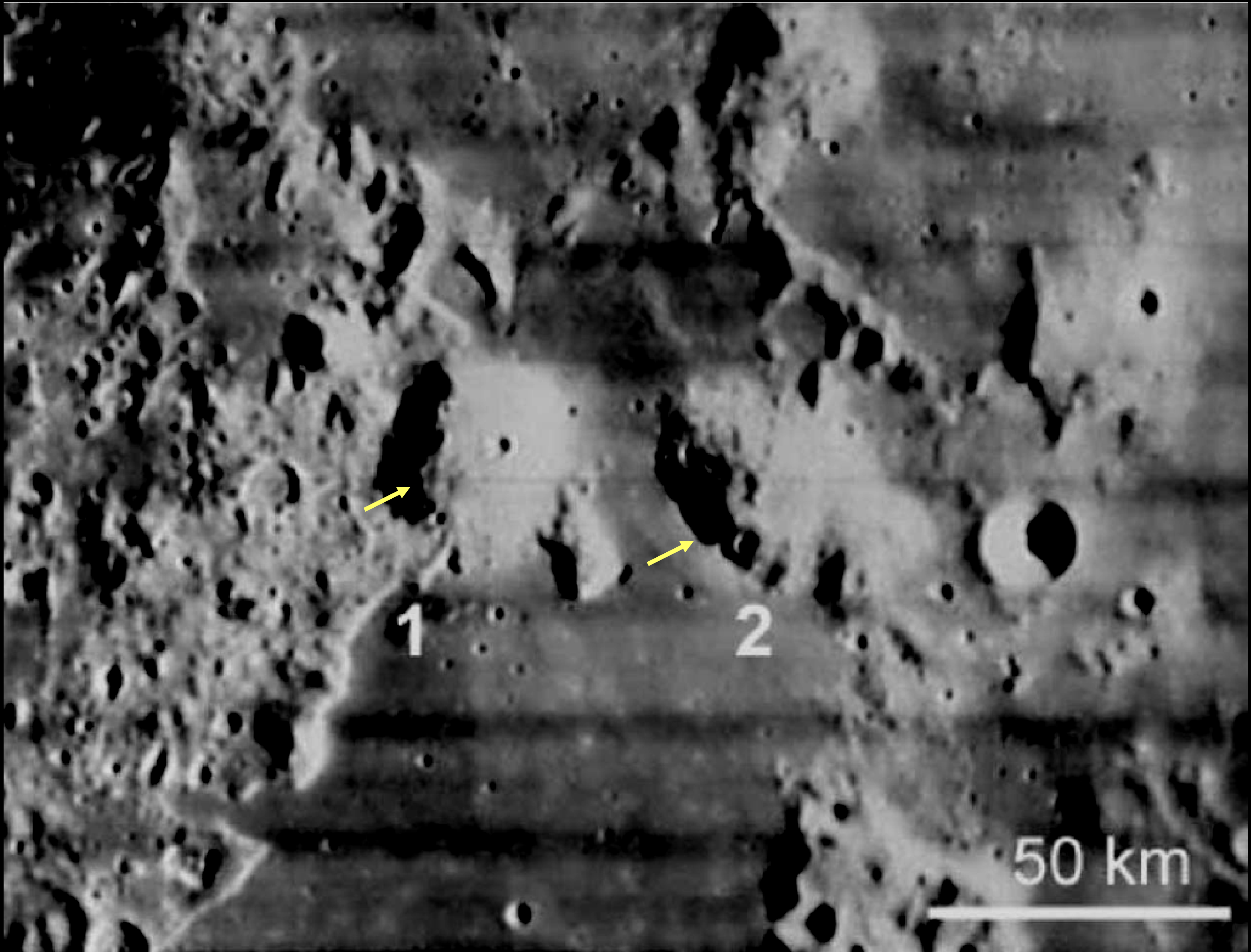
No cinder cones are observed on the Moon

Too small gravity



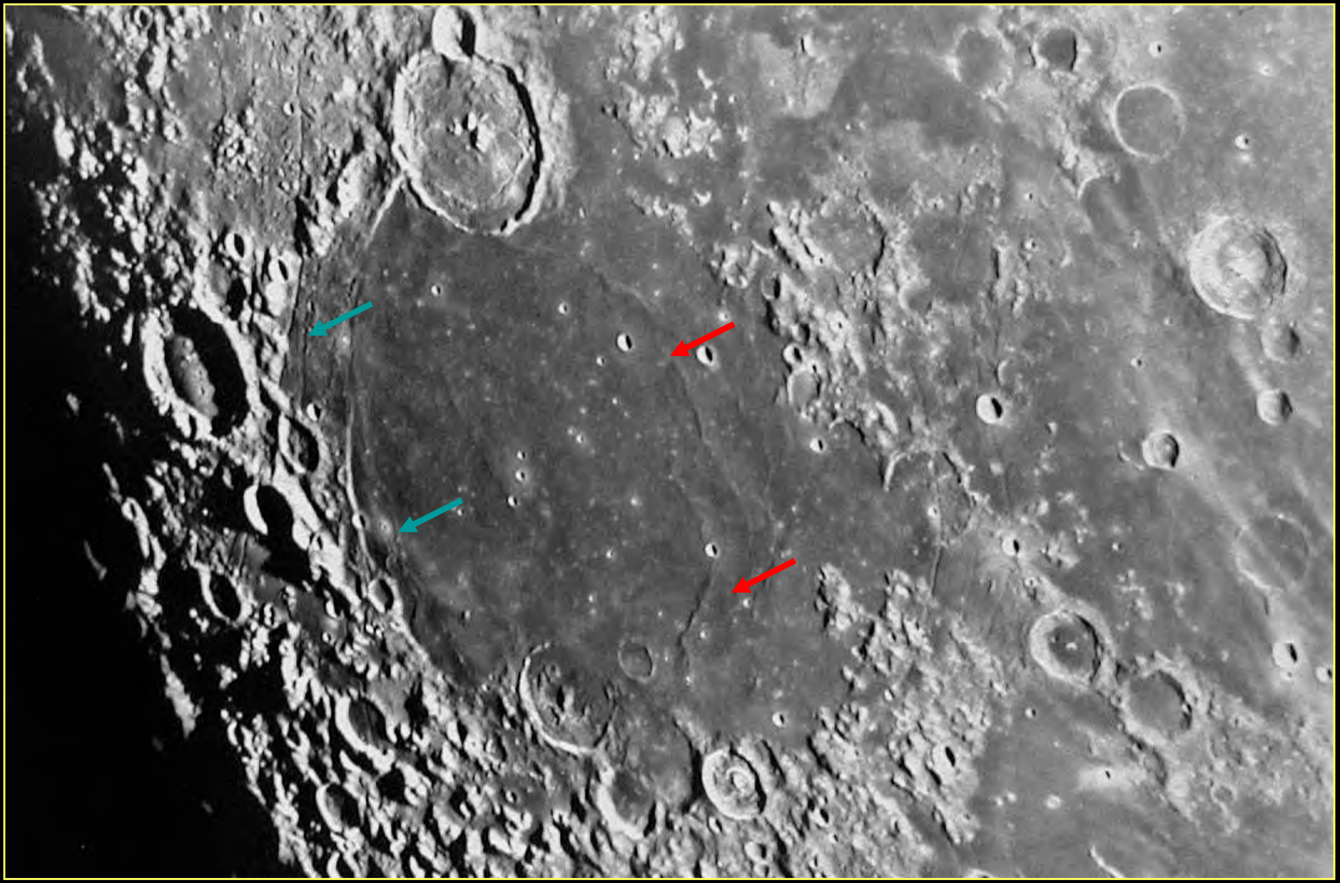
In 1958 Soviet astronomer N. Kozyrev observed here release of gas

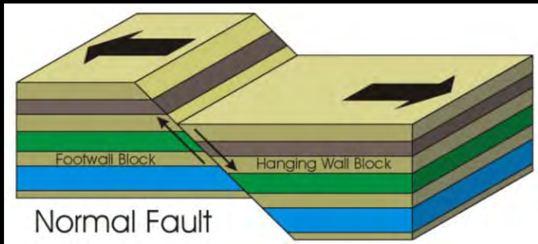
Gruithuisen domes – non-basaltic volcanism?



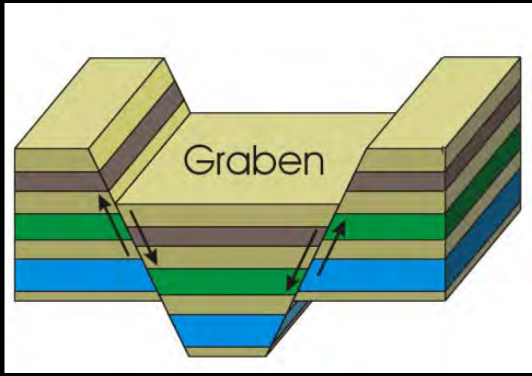
Tectonics (subordinate significance)

- Structures of tension (extension): faults, graben, fissures
- Structures of compression: sinuous rilles
- Influence of large impacts

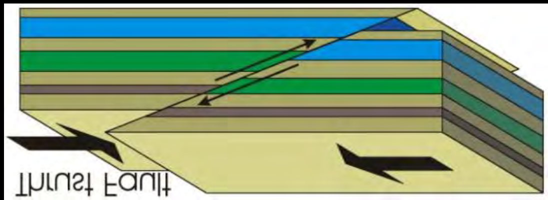




Normal fault – Tension structure

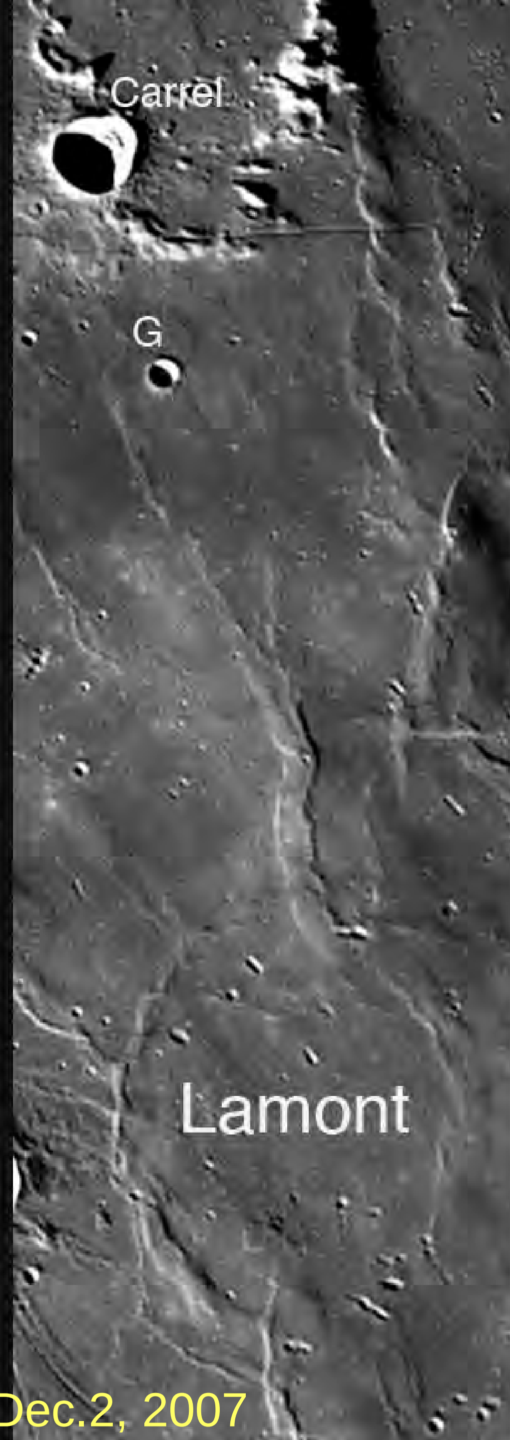


Graben– Tension structure



Upthrust – compression structure

http://facweb.bhc.edu/acadrmics/science/harwoodr/Geol101



Sinuous rilles in lunar maria are compressional structures.

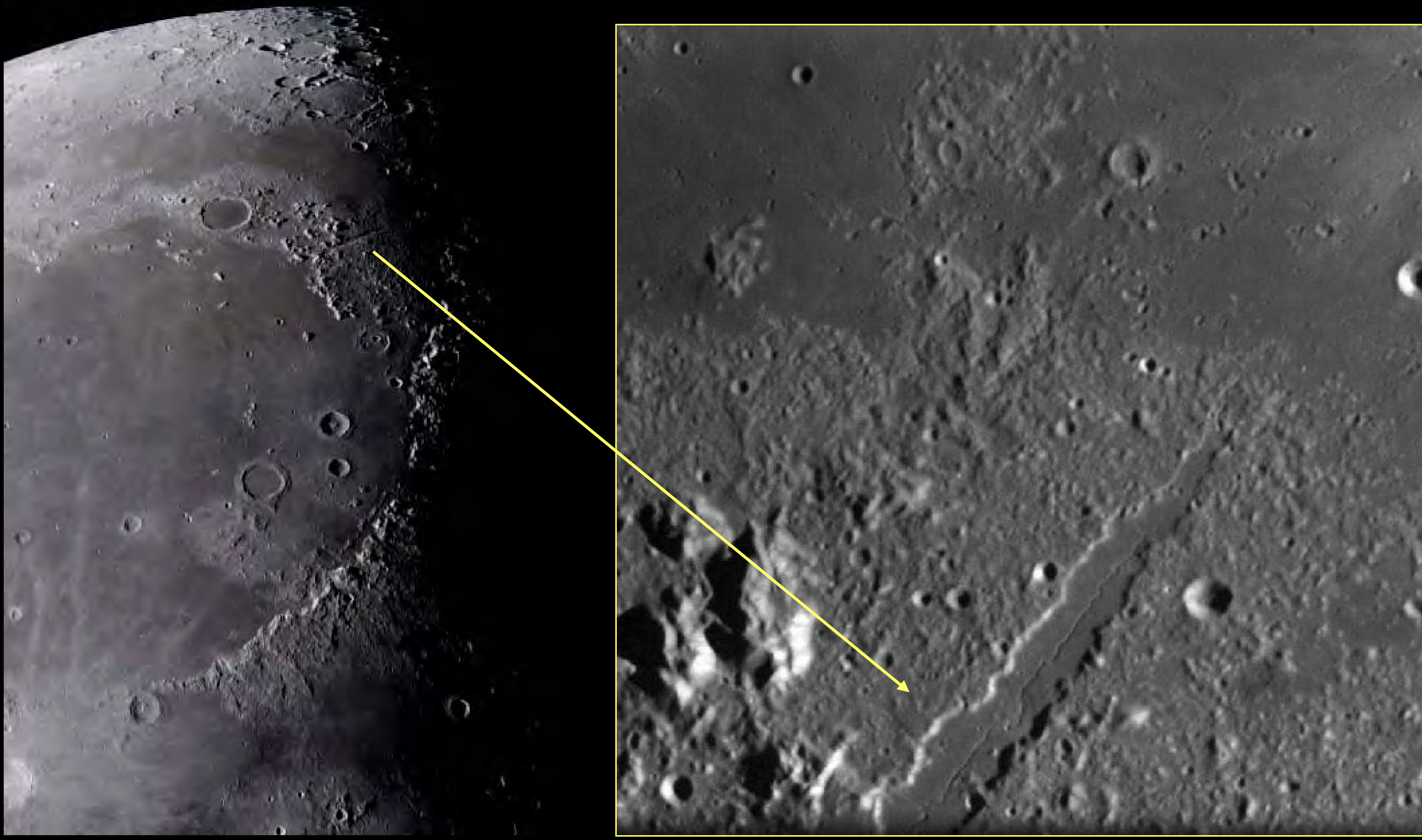
Similar structures are observed on the plains of Venus and Mars.

Rare on Earth: Meckering ridges, Australia.

Courtesy of LPOD image of the Day, Dec.2, 2007

Lunar graben – tension (extension) structures

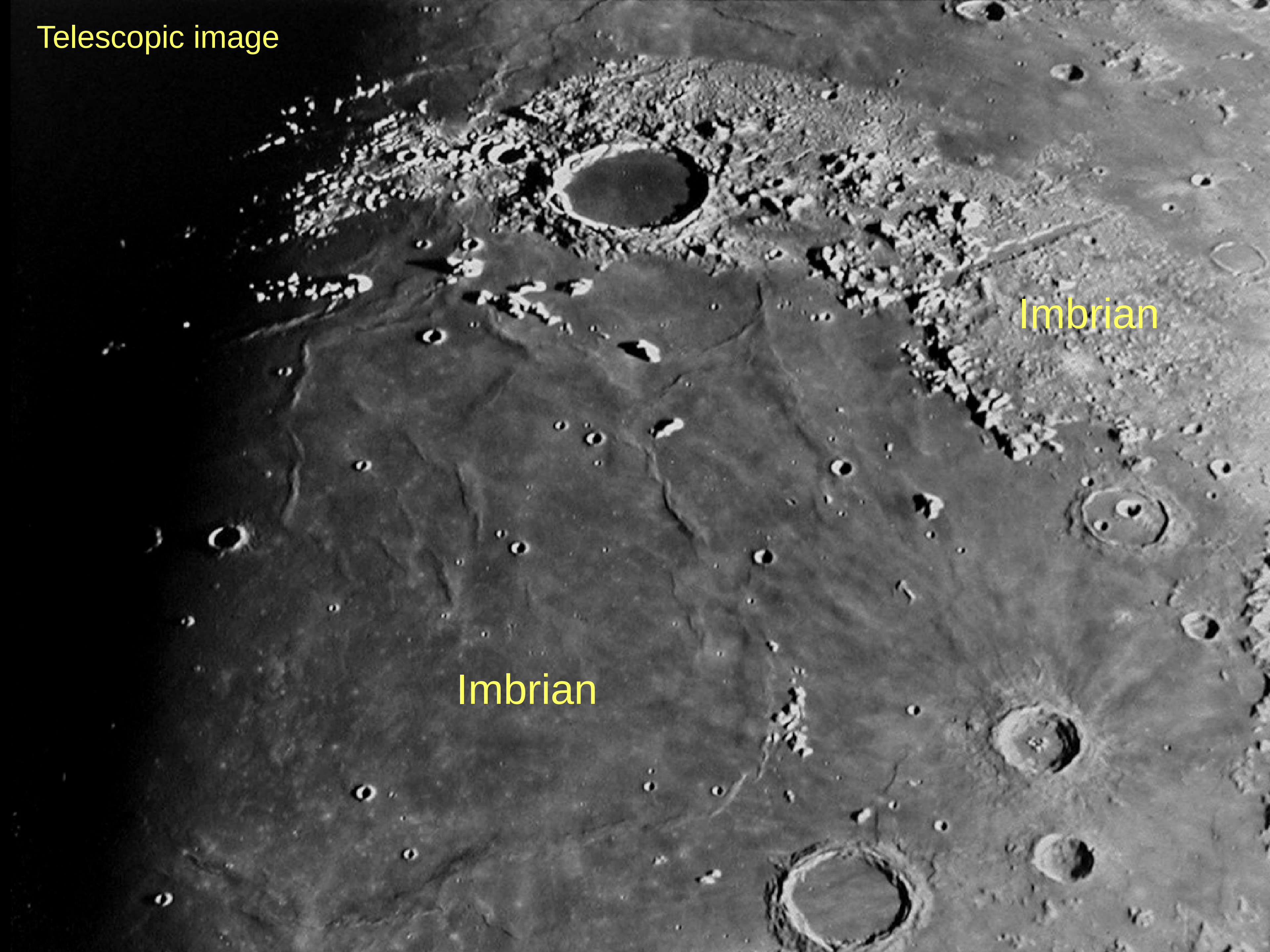
Influence of large impacts:
Radial graben in the ring of Imbrium basin

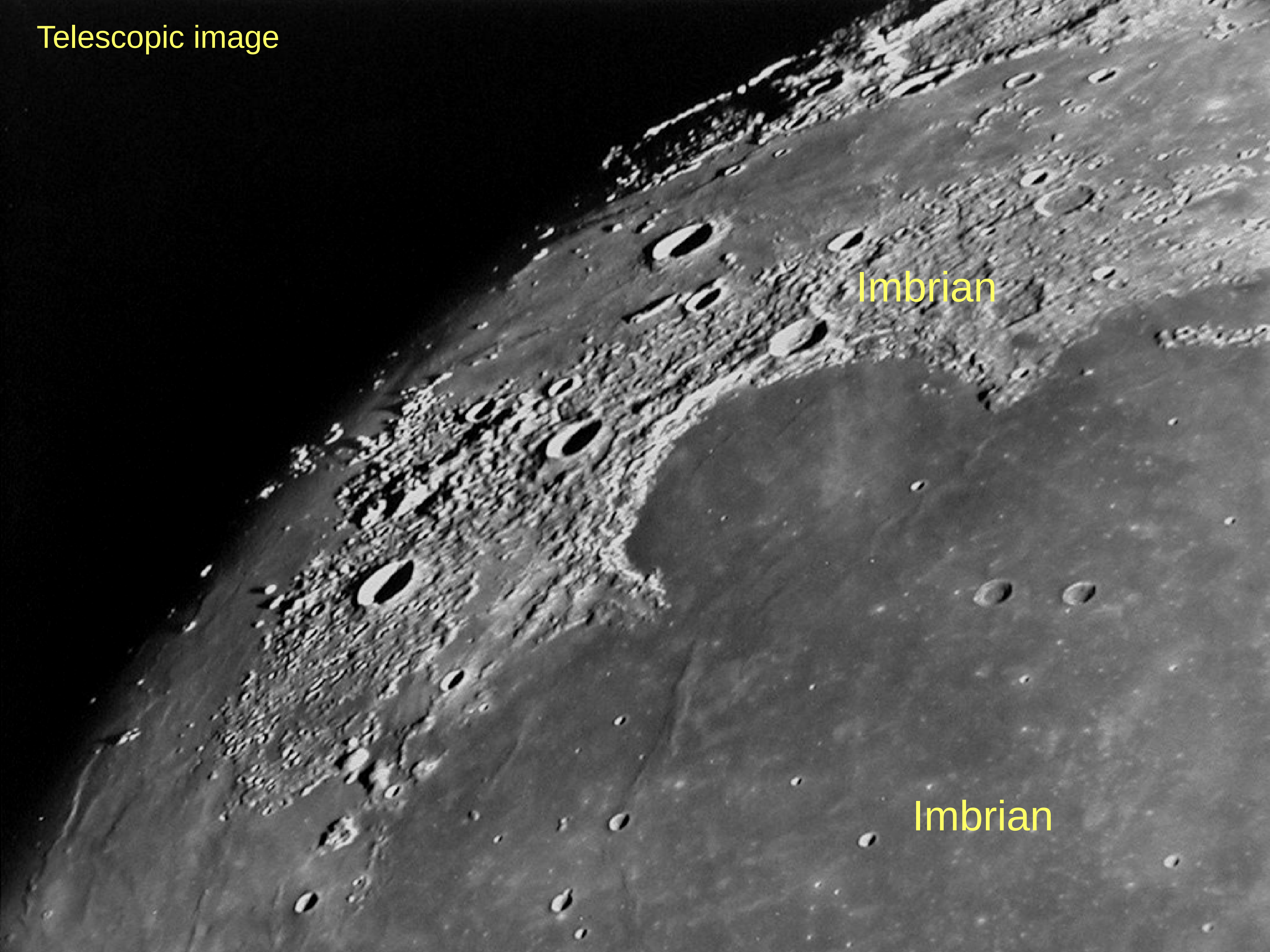


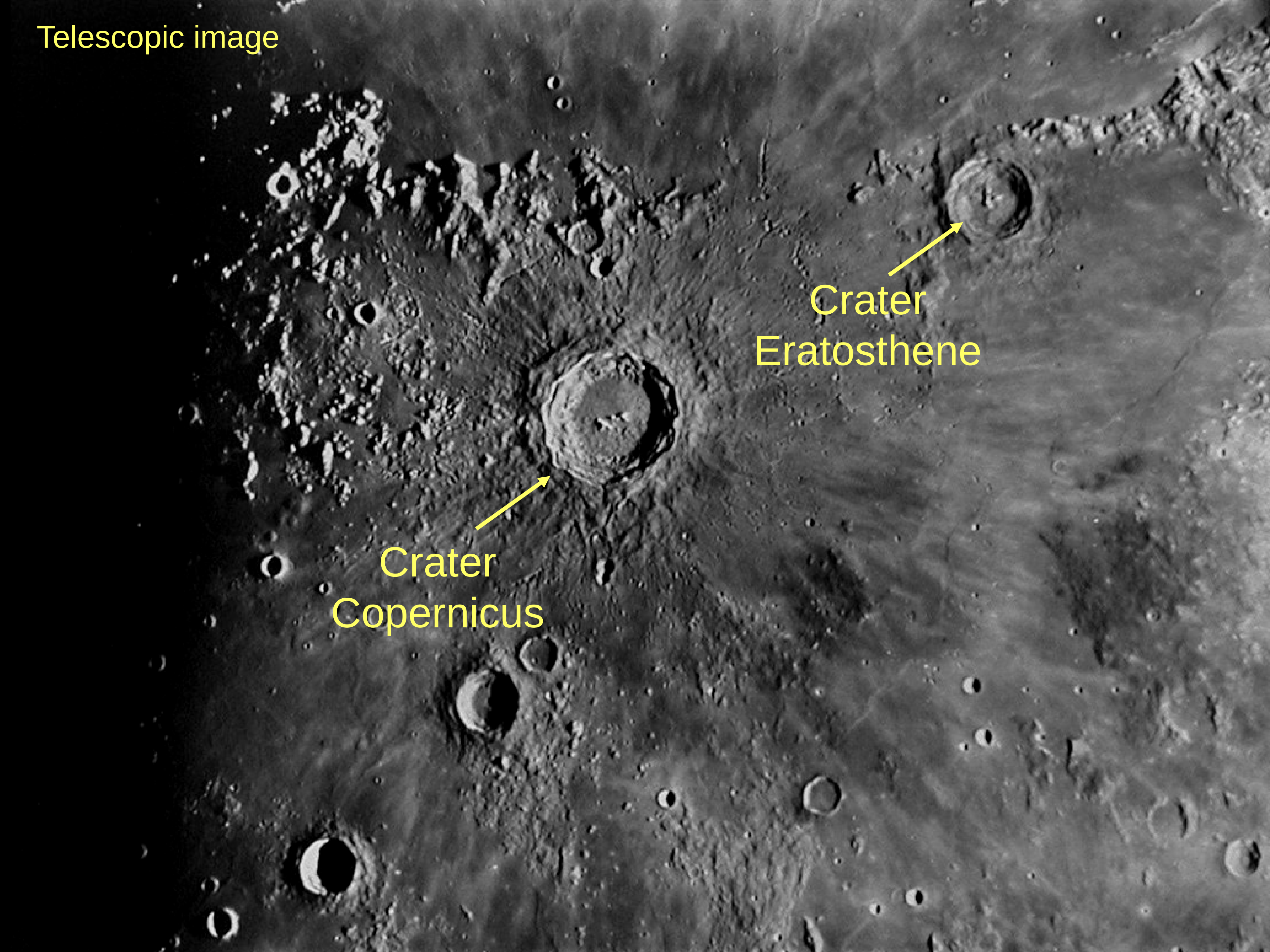
Geological history of the Moon

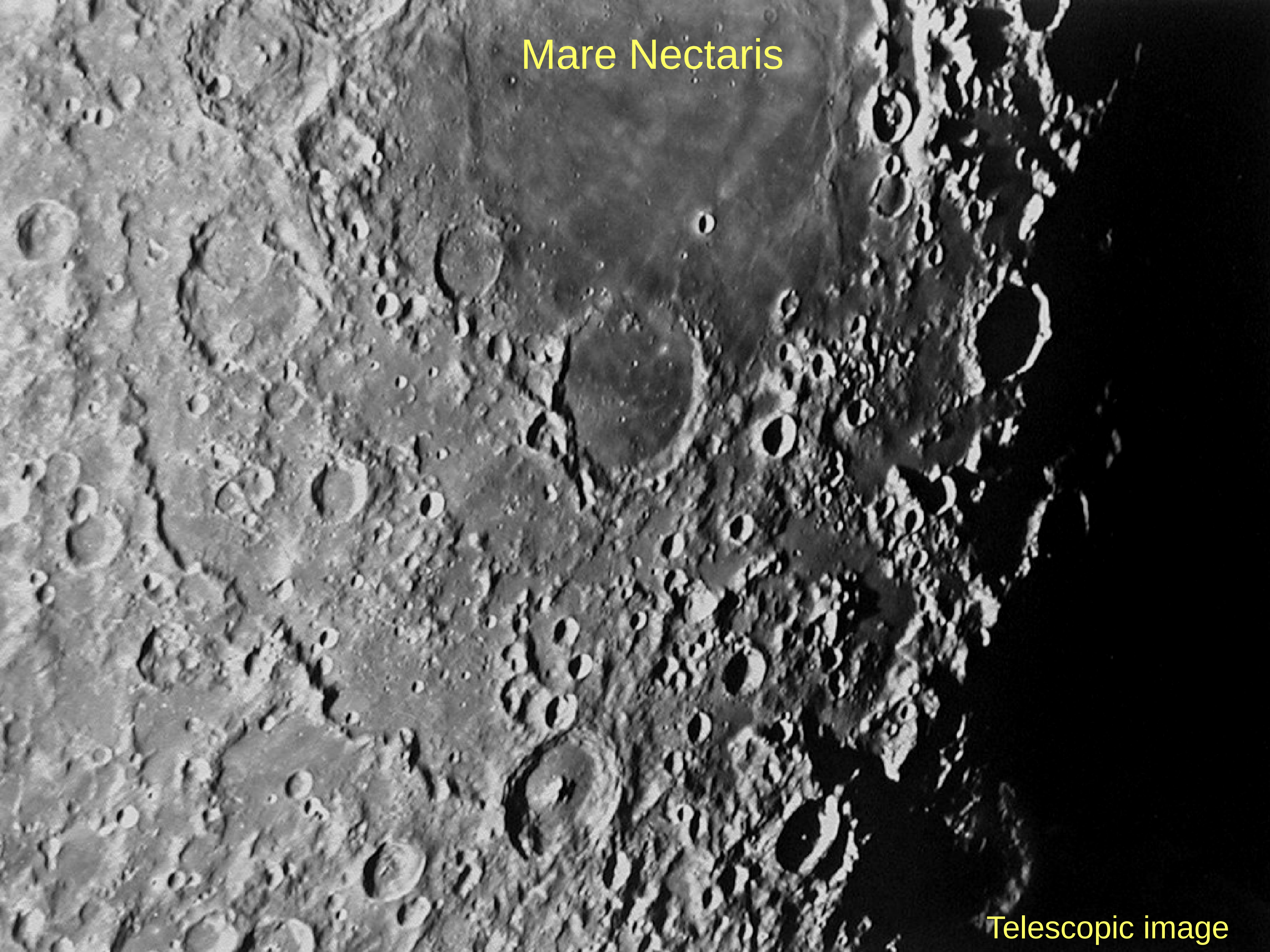
Major stages of geological evolution were determined based on analysis of telescopic images.

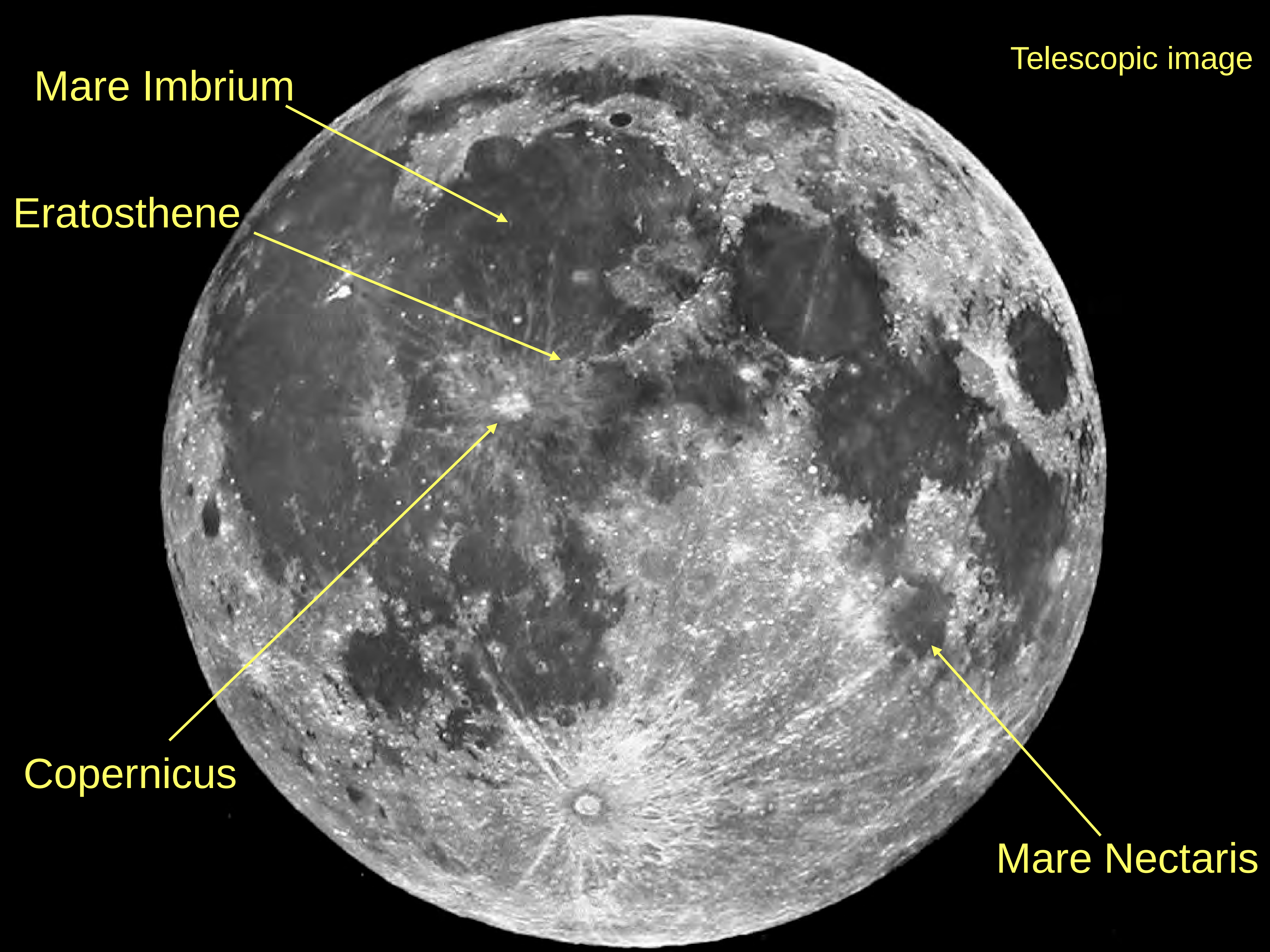
But types of geological processes and absolute dating of events became understandable only based on analysis of data acquired in space missions.


Telescopic image
Imbrian
Imbrian


Telescopic image
Imbrian
Imbrian


Telescopic image
Crater
Eratosthene
Crater
Copernicus


Mare Nectaris
Telescopic image


Telescopic image
Mare Imbrium
Eratosthene
Copernicus
Mare Nectaris

Geological periods:

Pre-Nectarian – most ancient

Nectarian

Imbrian

Eratosthenian

Copernican – the youngest

Typical rocks

Pre-Nectarian – Highland breccias

Nectarian – Highland breccias

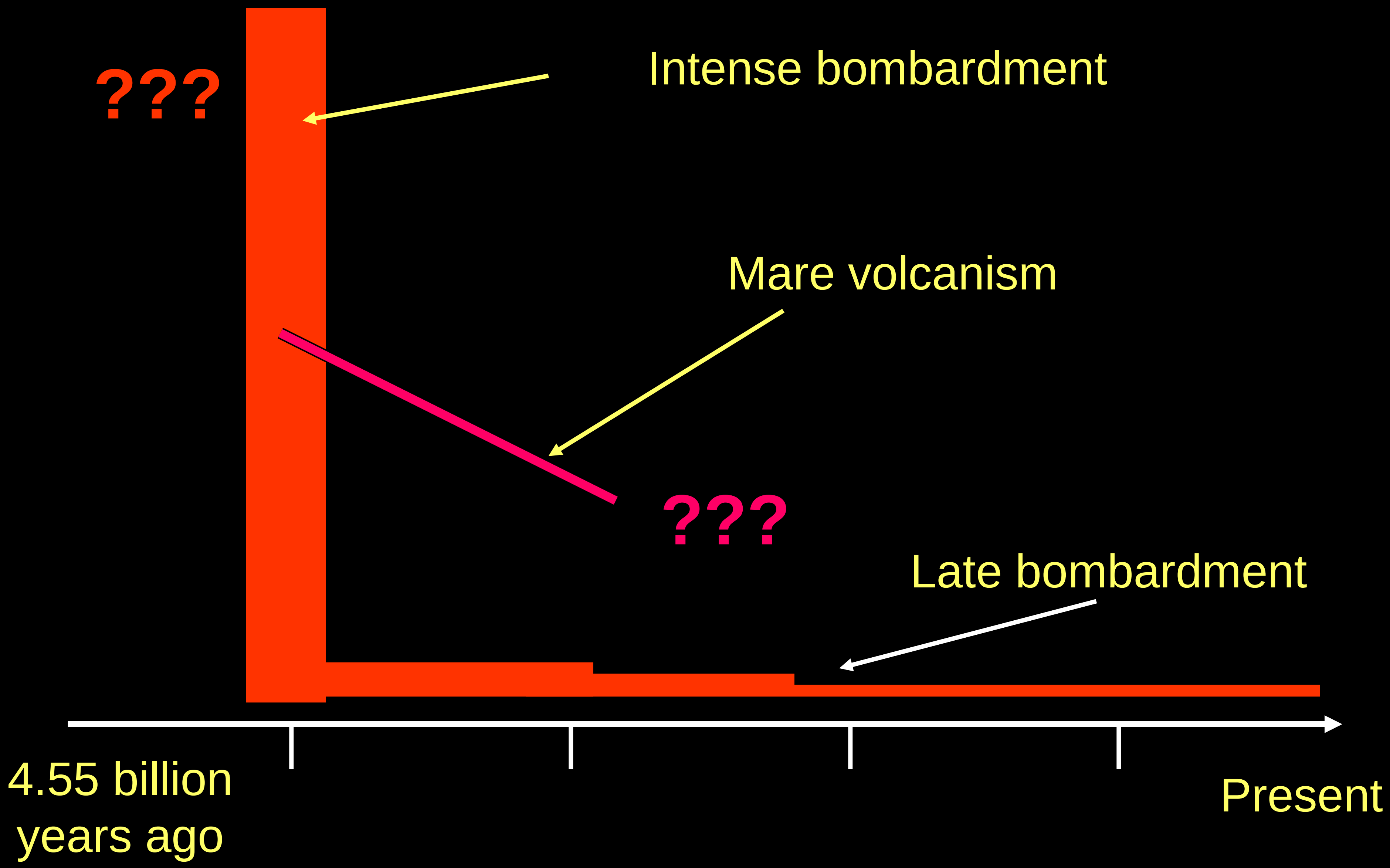
Imbrian – Highland breccias
and mare basalts

Eratosthenian – Mare basalts (not much)
and rocks of craters

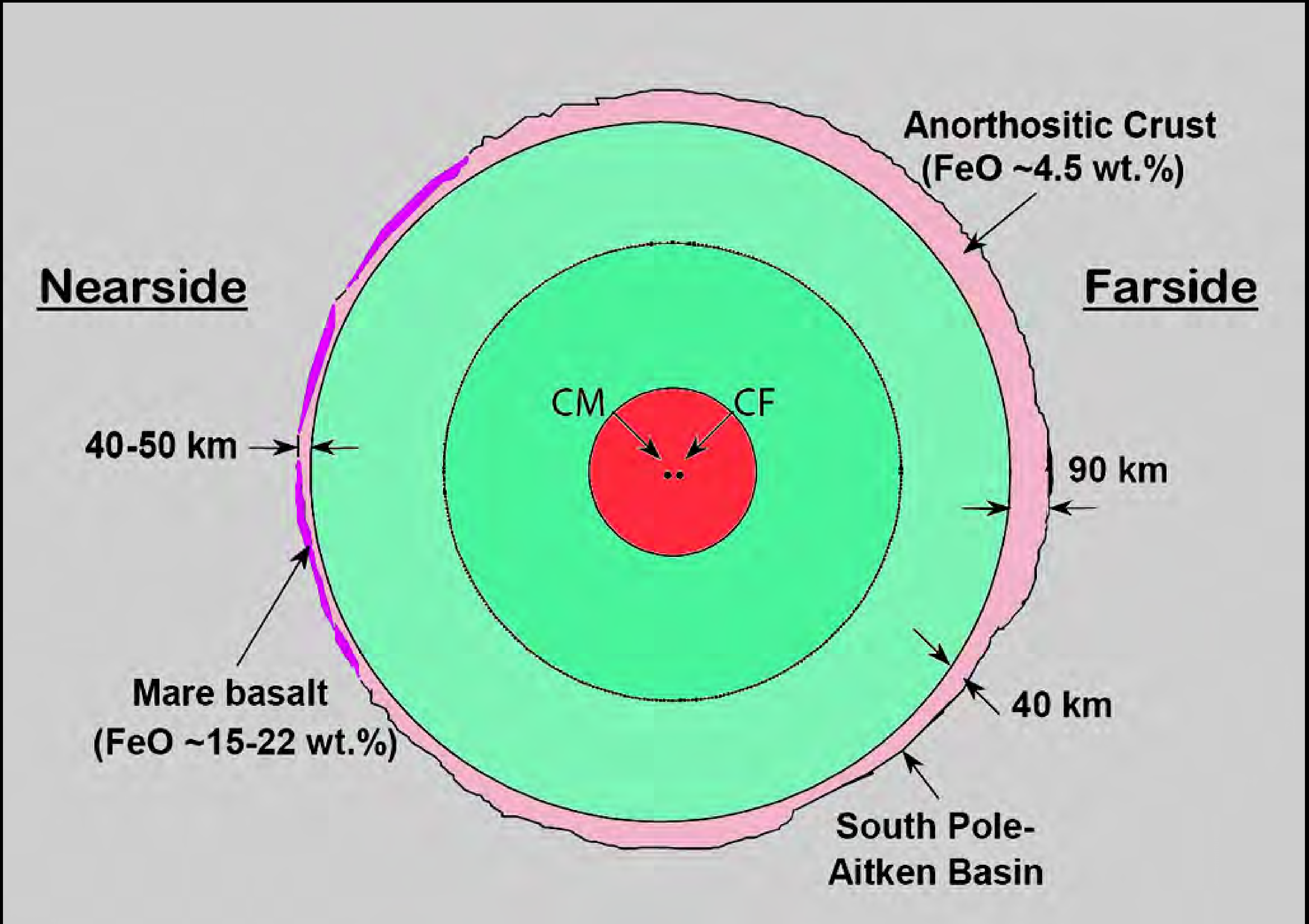
Copernican – Rocks of craters

Absolute ages of lunar rocks

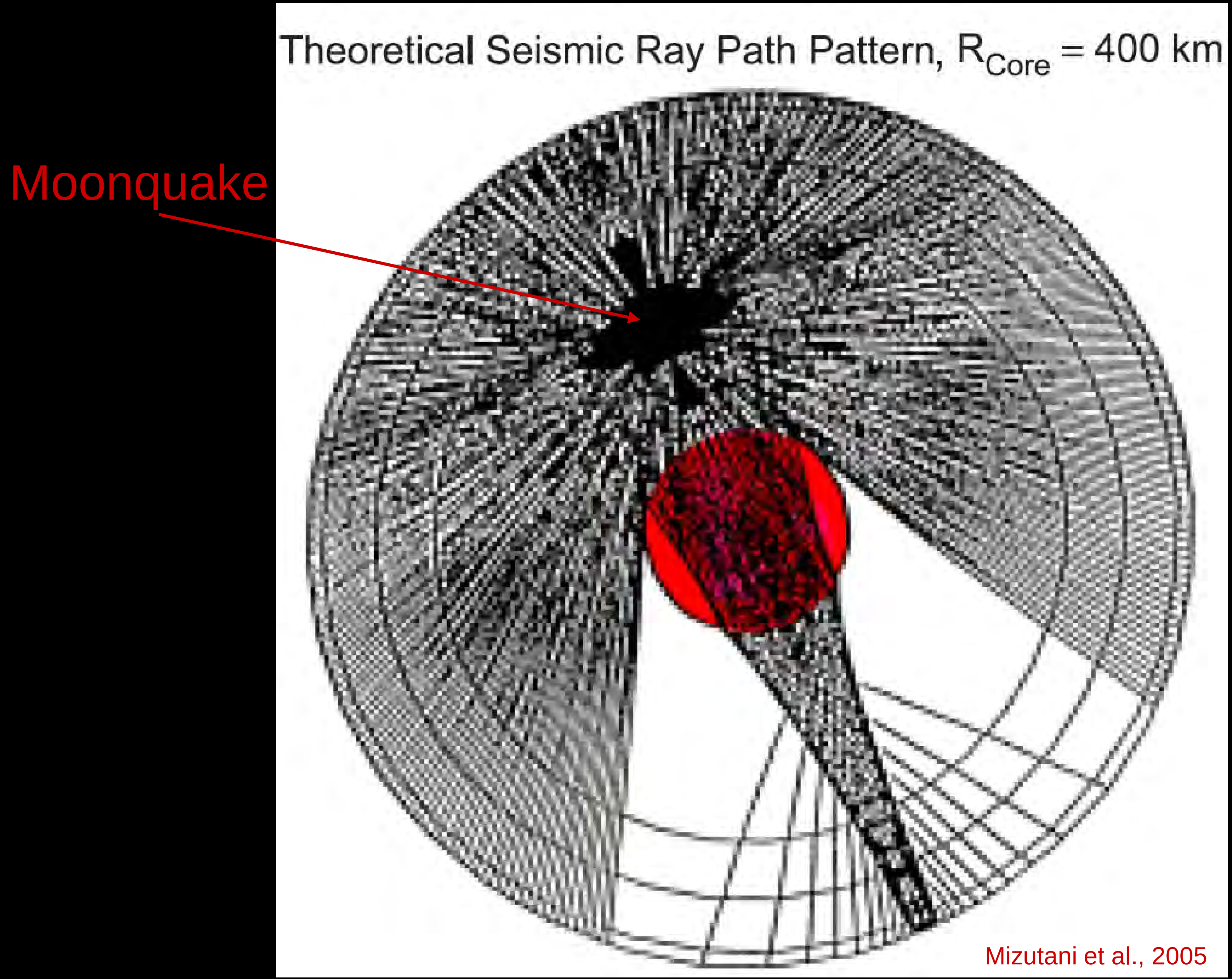
Geological history of the Moon



Structure of lunar interior: Seismic sounding, gravity + topography



Seismic sounding and monitoring

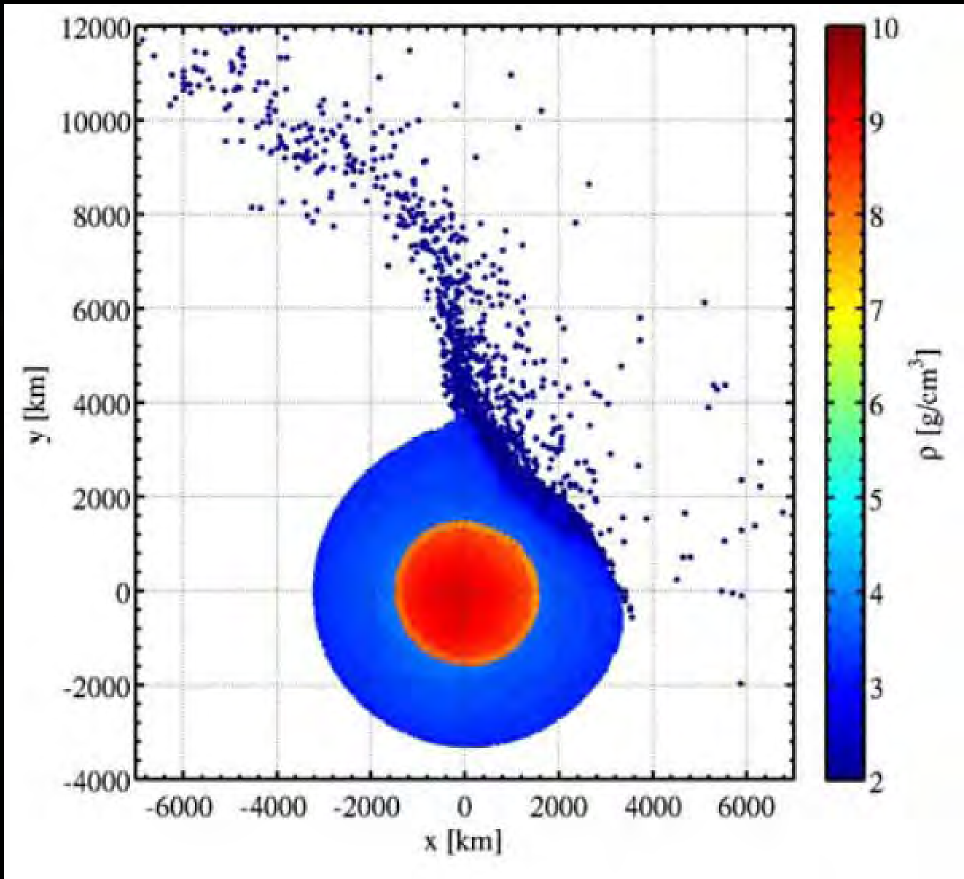


Origin of the Moon: Hypothesis of giant impact

Mars-size body

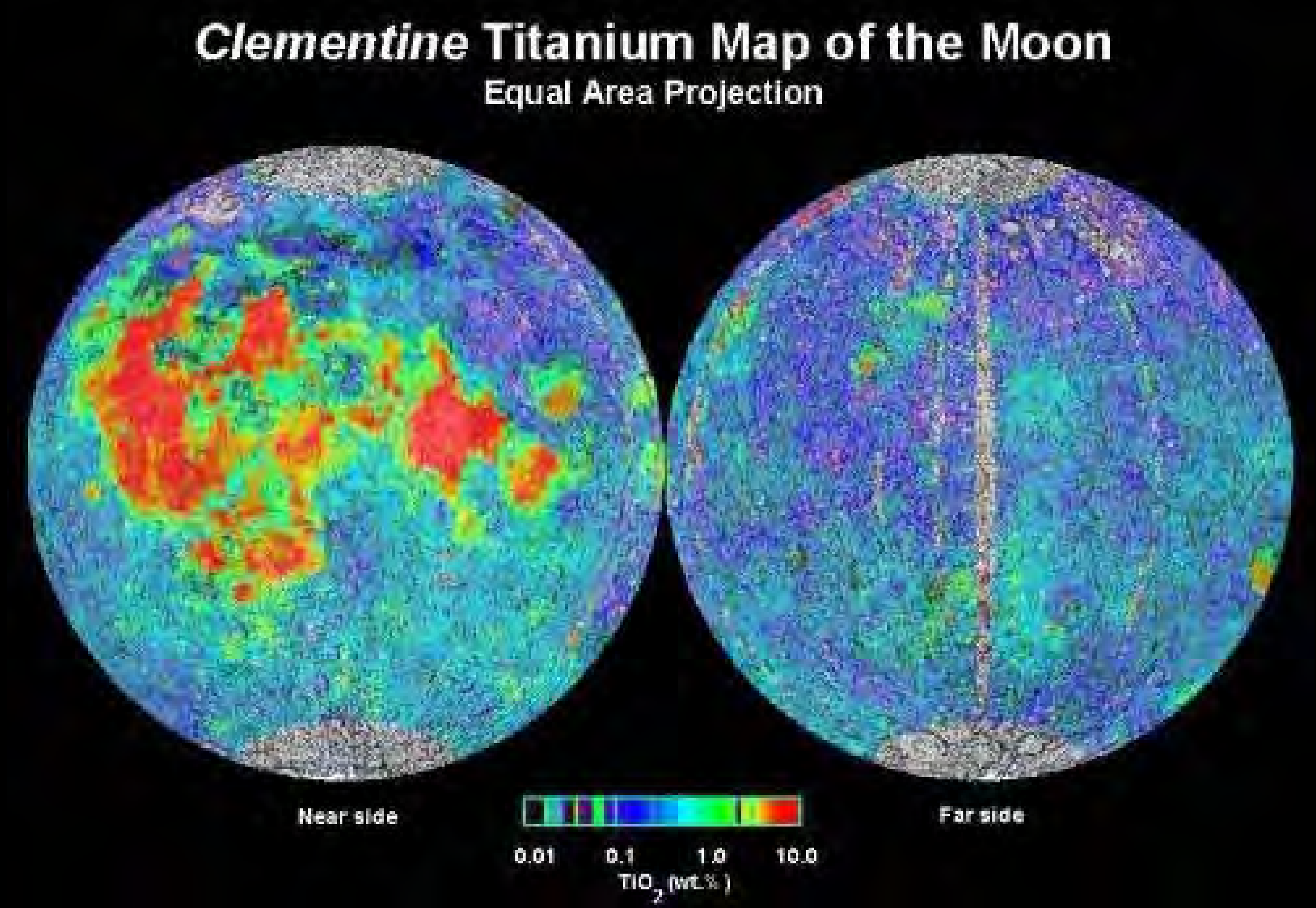
Proto-Earth

The Moon formed as
a result of accretion
of ejecta from the impact
on near-Earth orbit??



Lunar resources

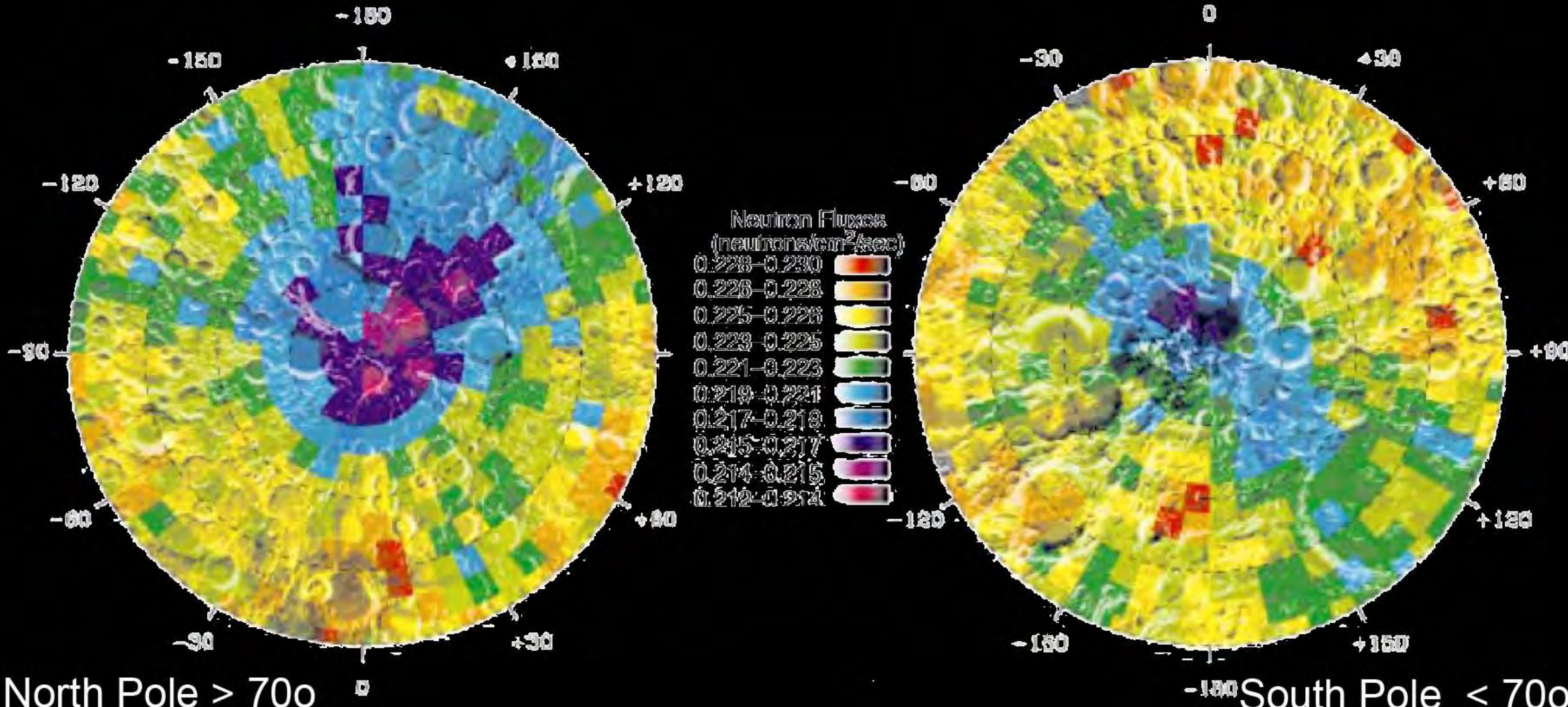
Helium-3 on the Moon



Maximum contents of He-3 are found in samples of regolith, formed on high-Ti basalts

Lunar resources

Polar deposits on the Moon as a source of water



Low neutron flux = high content of hydrogen

In which form hydrogen is?:

Water ice, ammonia, organics, captured protons?

How large are resources?

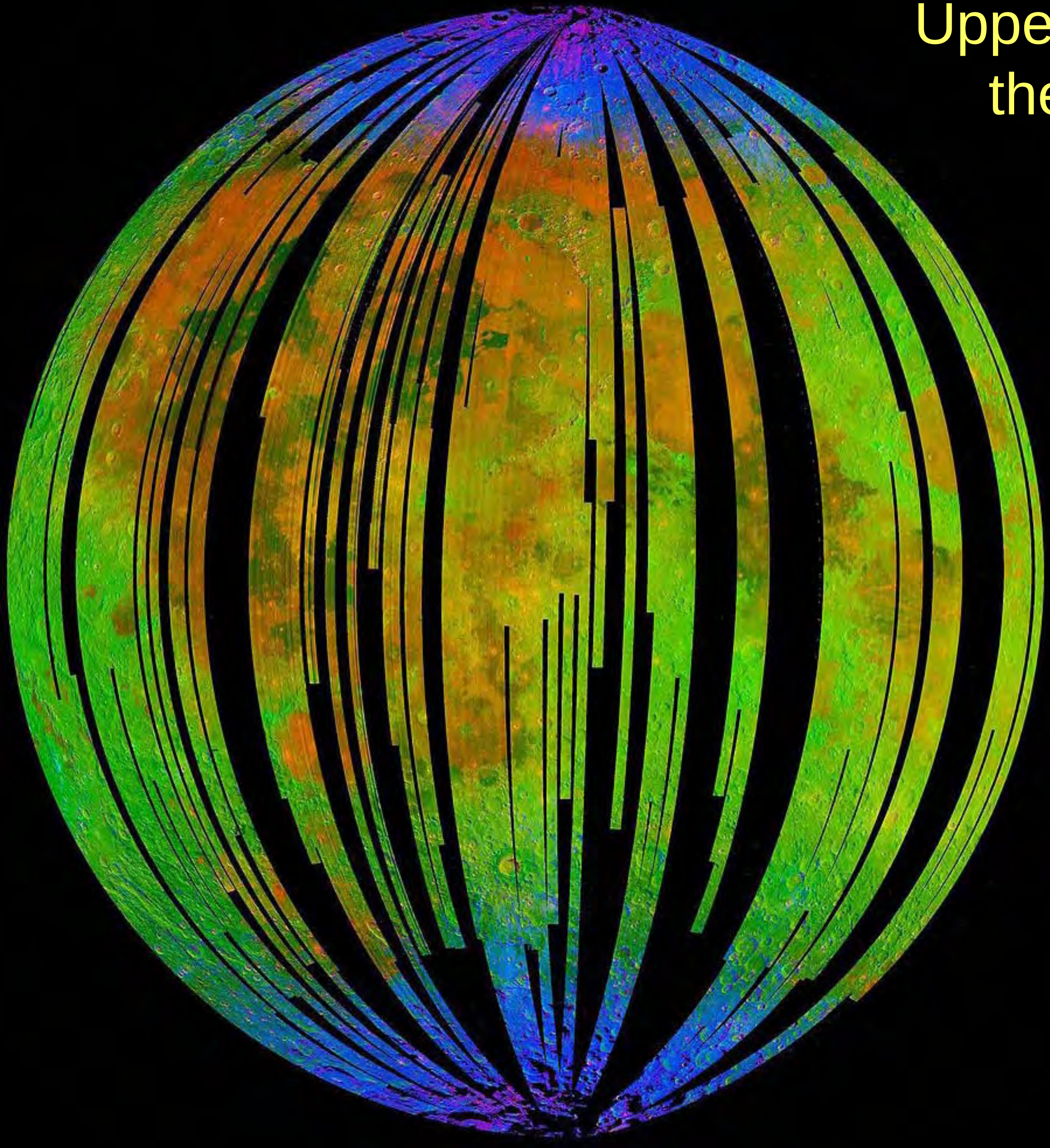
The Moon: What we know and what we do not know?

- Polar “caps” => Volatiles in permanent shadow => What are they?
- He-3 in lunar regolith => How to determine resources?
- Up to which time lunar volcanism occurred?
- Problem of non-basaltic volcanism.
- What was going on the Moon during the first 600 million years?
- Structure of lunar interiors – know badly.
- Origin of the Moon: Giant impact / Accretion?

New data on water on the Moon:

Water on the surface of soil particles - spectral data:

Upper 1-2 mm, varies during the lunar day.

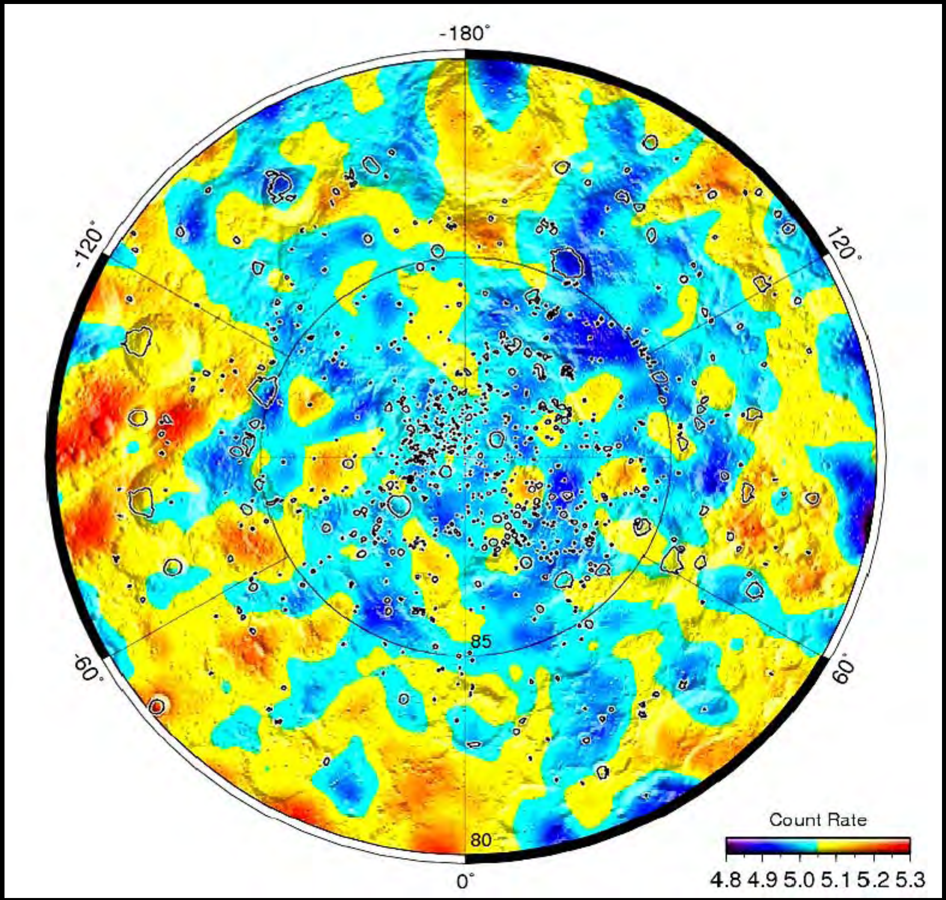


Map of distribution of H_2O and OH on the lunar surface based on *Pieters et al.* (2009) results with corrections on red continium from *Clark et al.* (2010).

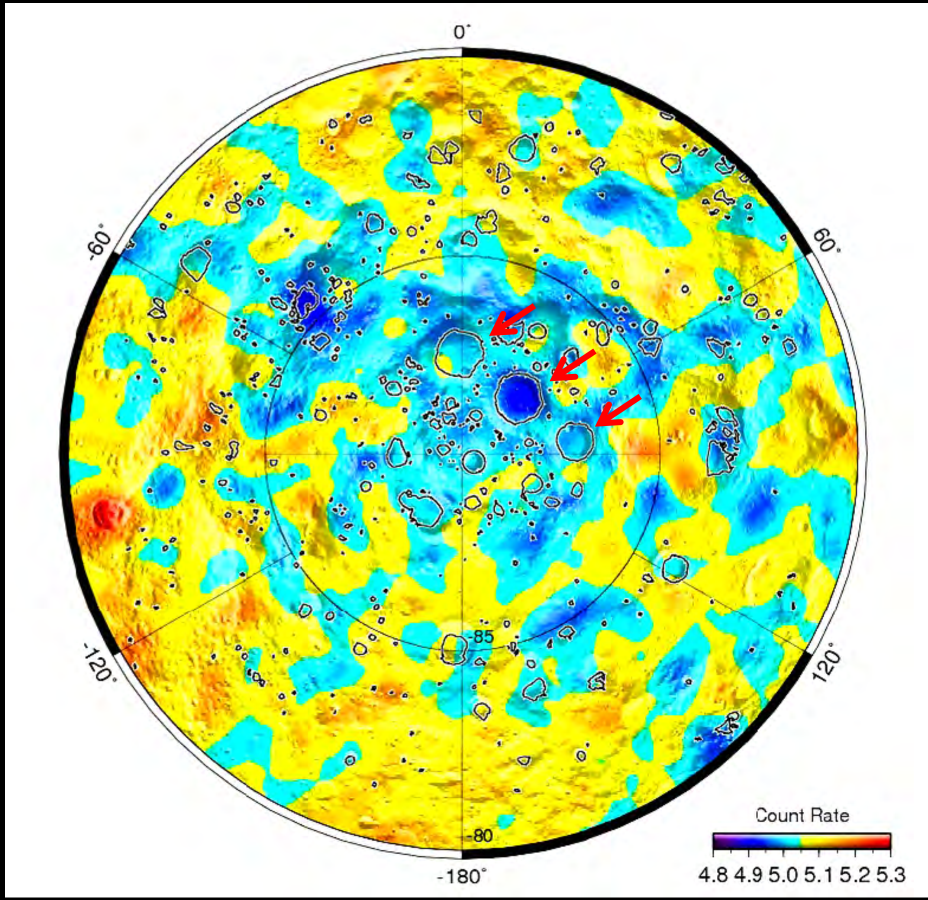
Blue and purple colors indicate on presence of H_2O and/or OH, while red, green, yellow and orange – on absence of H_2O and OH.

New data on water on the Moon:

Water in polar areas: LEND experiment



North pole

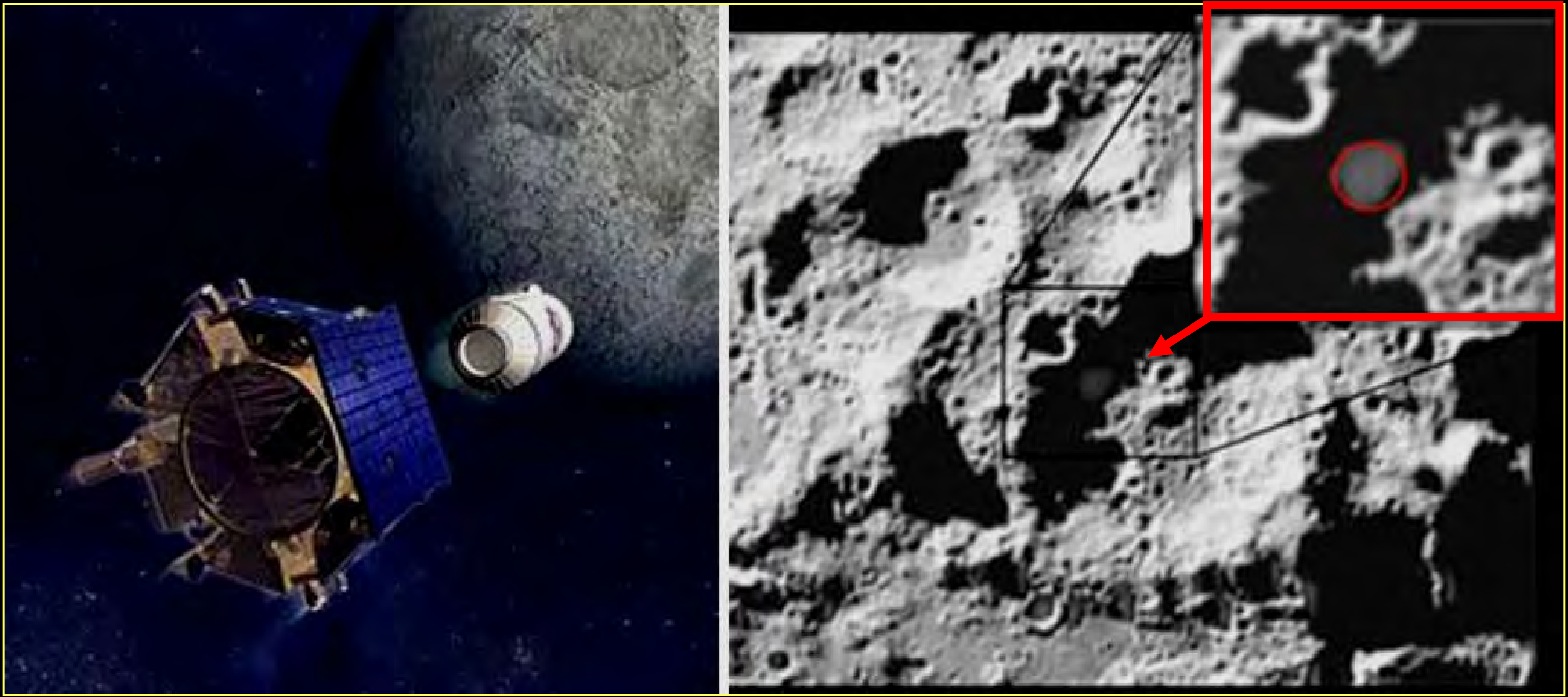


South pole

Lower flux of epithermal neutrons = higher contents of hydrogen (water) not always coincides with permanently dark areas (Mitrofanov et al., 2010, 2011).

New data on water on the Moon:

Water in polar areas: LCROSS experiment

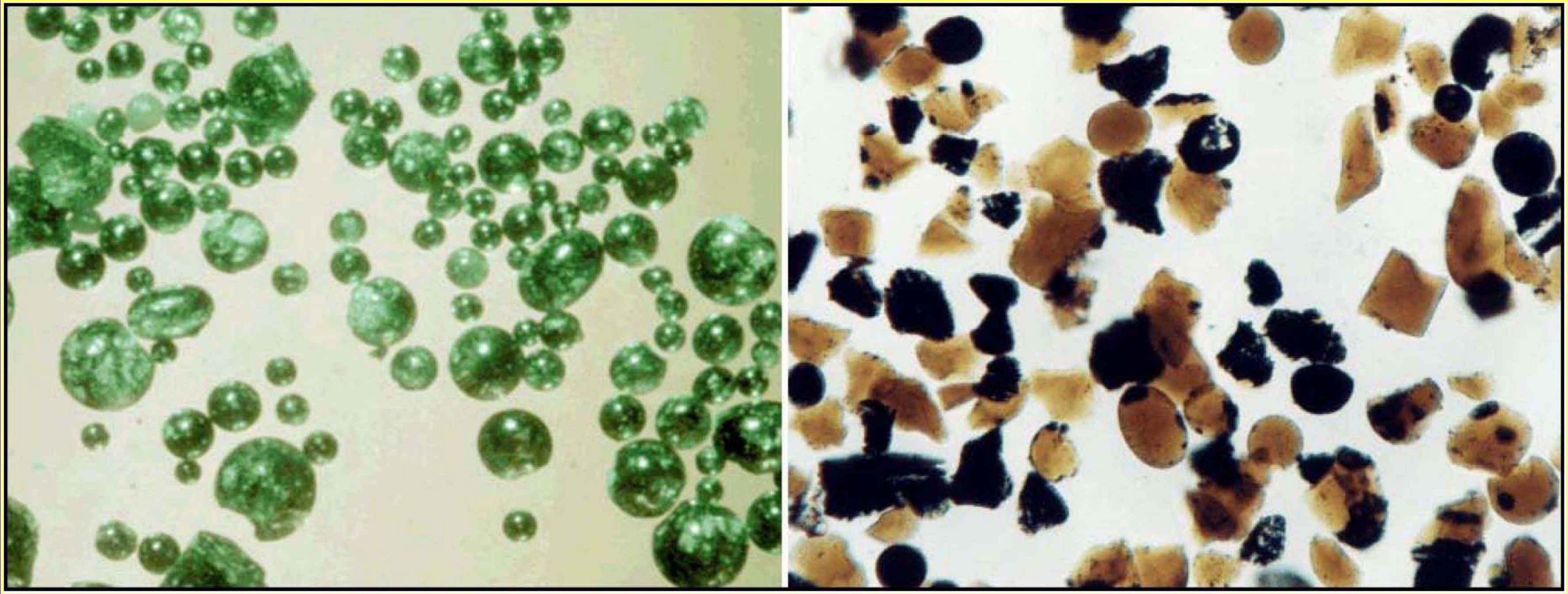


H_2O content in the impact place 5.6 ± 2.9 % (mass.)

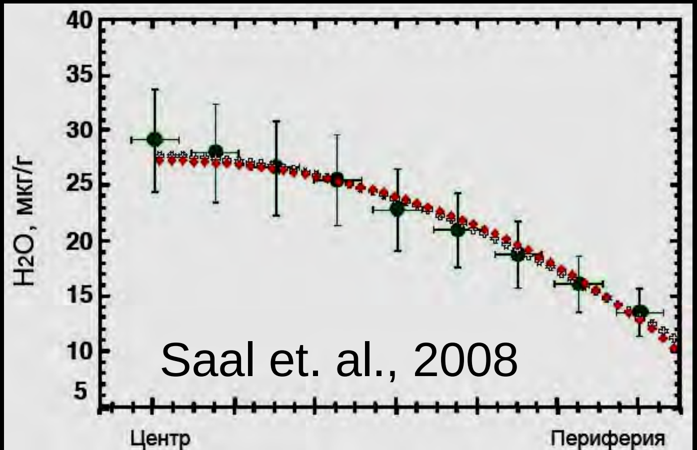
Compound	Molecules cm^{-2}	% Relative to H_2
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

New data on water on the Moon:

Water in pyroclastic deposits



Microscopic view of spherules of green and orange glass collected by Apollo15 and Apollo 17. 1 x 1.5 mm field of view. Photo NASA

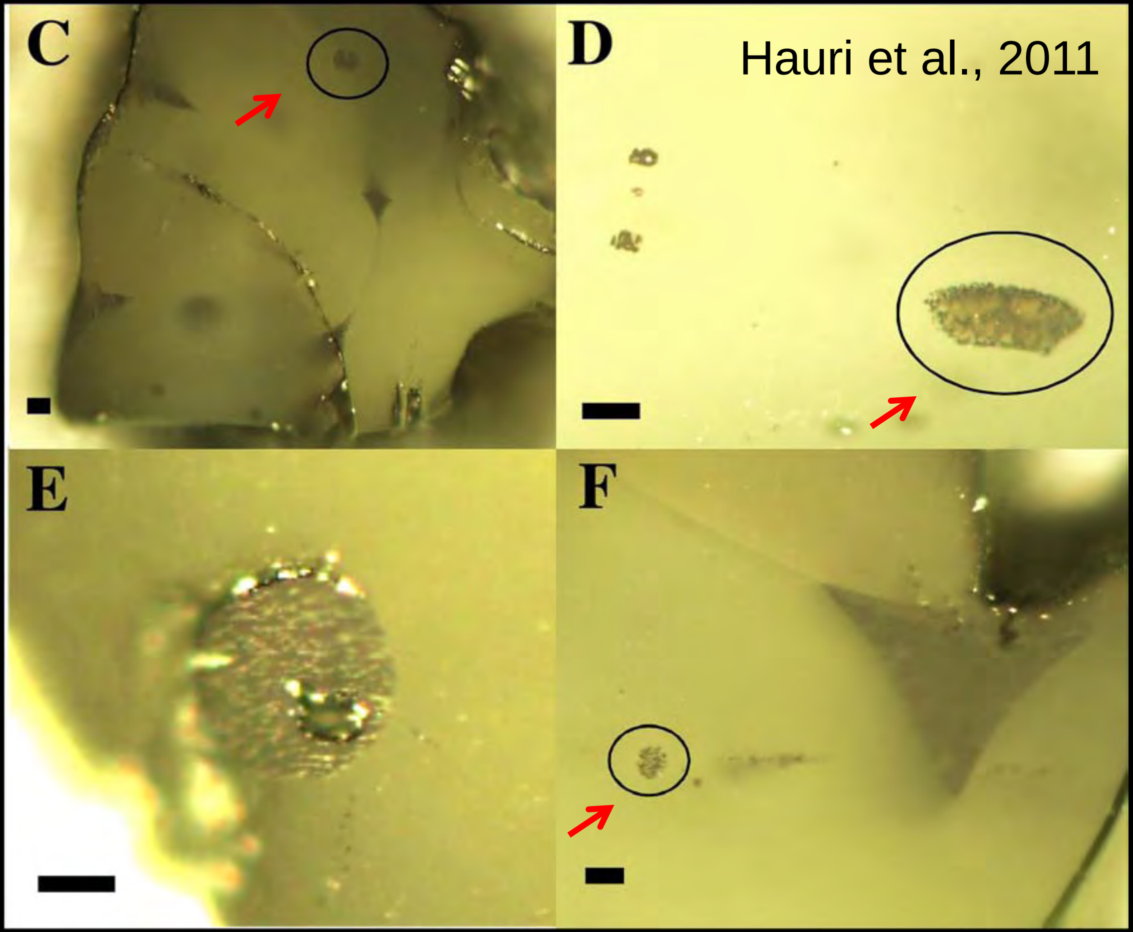


Model estimation of water content in the magma = 700 – 1000 mkg/g, as in magmas of mid-oceanic ridges of Earth.:

So the Moon interiors are not absolutely dry, as it was thought until recent time.

New data on water on the Moon:

Water in pyroclastic deposits

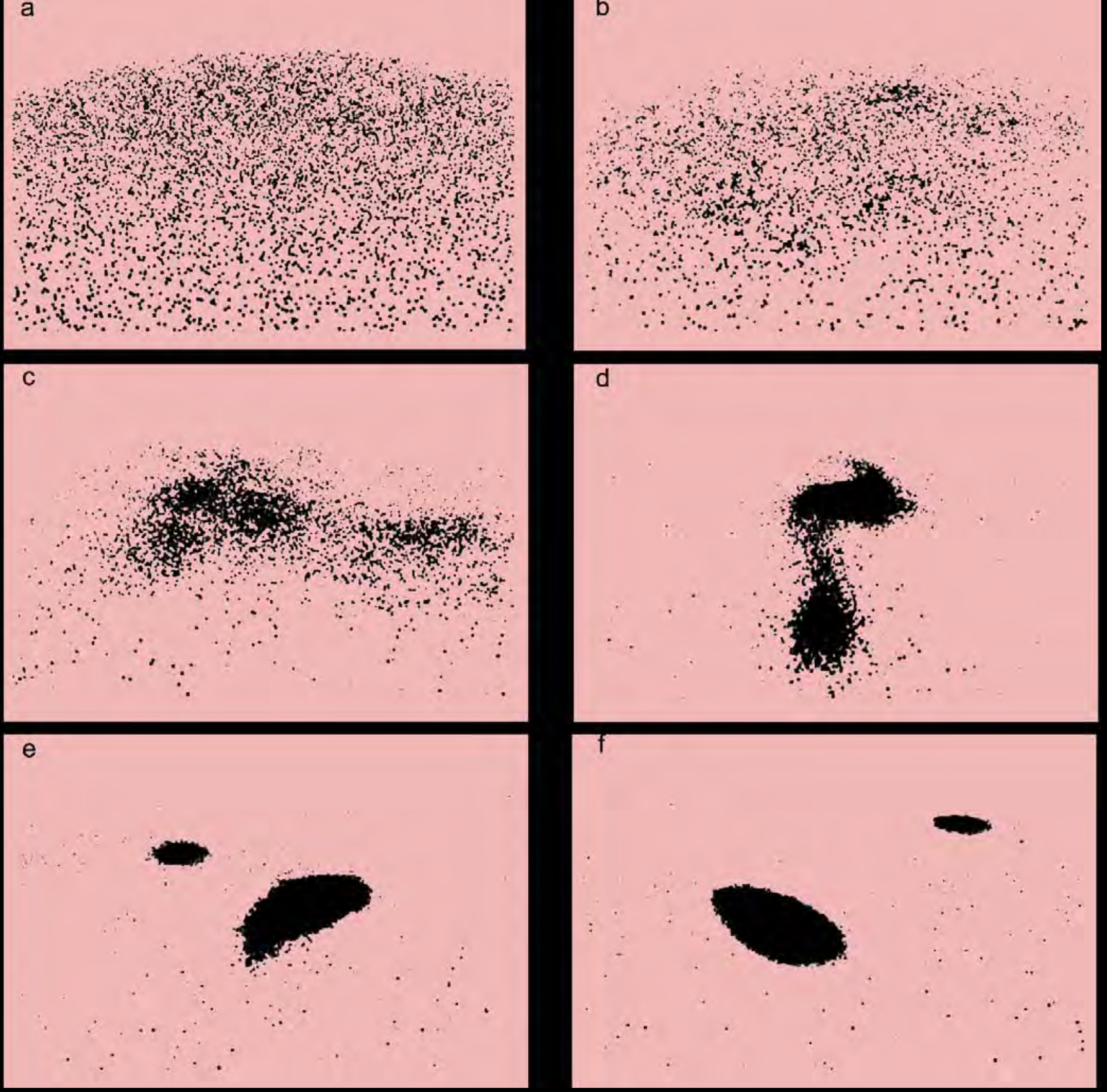


Inside circles are melt inclusions in olivine which, in turn, are inclusions in Apollo 17 orange glass spherules, sample 74220.

Melt inclusions contain 615–1410 ppm water, and high amounts of fluorine (50–78 ppm), sulfur (612–877 ppm) and chlorine (1.5–3.0 ppm). These volatile contents are very similar to primitive terrestrial mid-ocean ridge basalts and indicate that some parts of the lunar interior contain as much water as Earth's upper mantle.

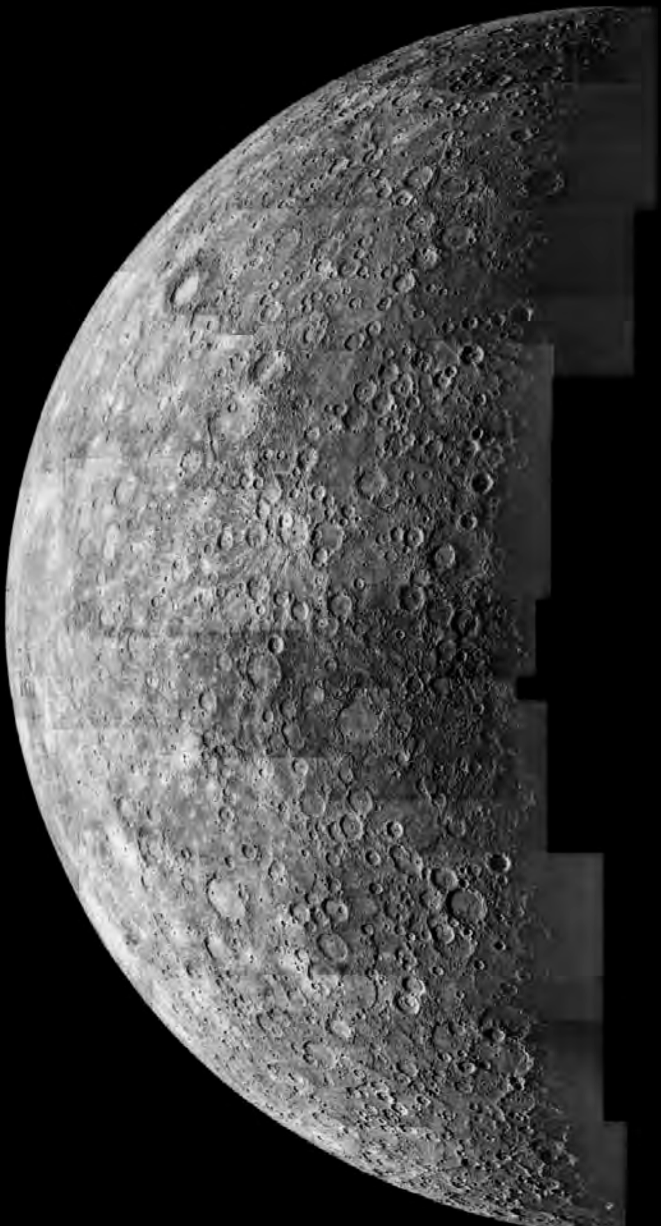
But if lunar interiors are not seriously depleted in water, this rises doubts in the Giant impact hypothesis of origin of the Moon and forces to work out other hypotheses, e.g., the hypothesis of parallel accumu-lation of the Moon and Earth from one swarm of particles.

Галимов, 1998; Галимов и Кривцов, 2005



Separation of the swarm into two parts: future Earth and future Moon

Mercury



Planet closest to the Sun

No satellites

Mercury year = 88 Earth days

Period of rotation = 59 Earth days

Solar day = 176 Earth days

D = 4878 km = 0.38 D of Earth

M = 0.055 M of Earth

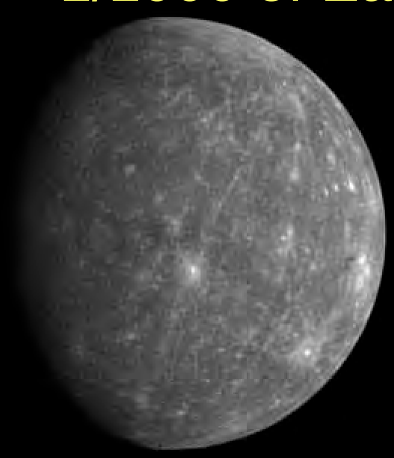
Mean density ρ = 5.44 g/cm^3

(ρ Earth= 5.52 г/см^3)

Magnetic field = Dipole

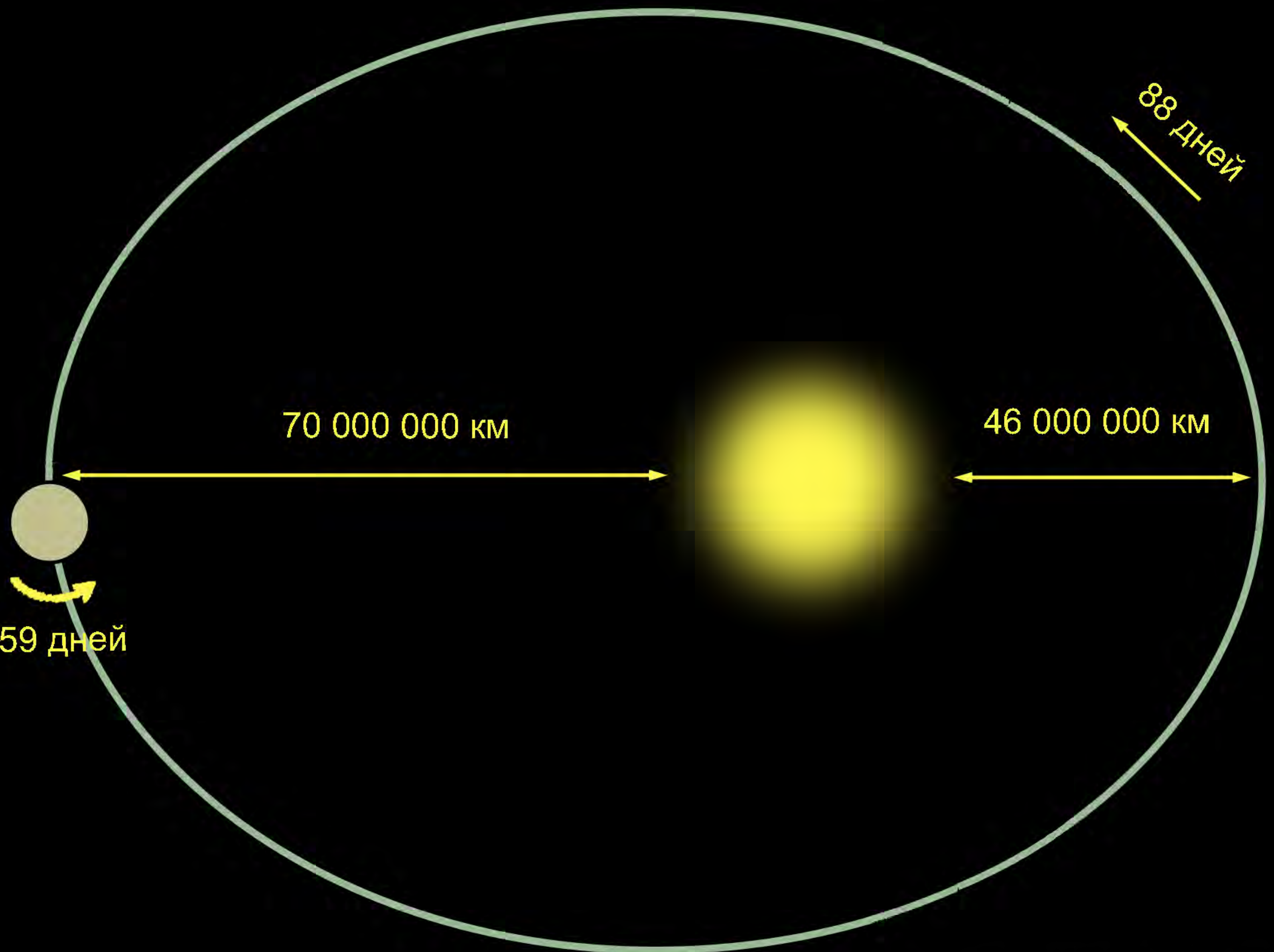
= 1/1000 of Earth's

The Moon



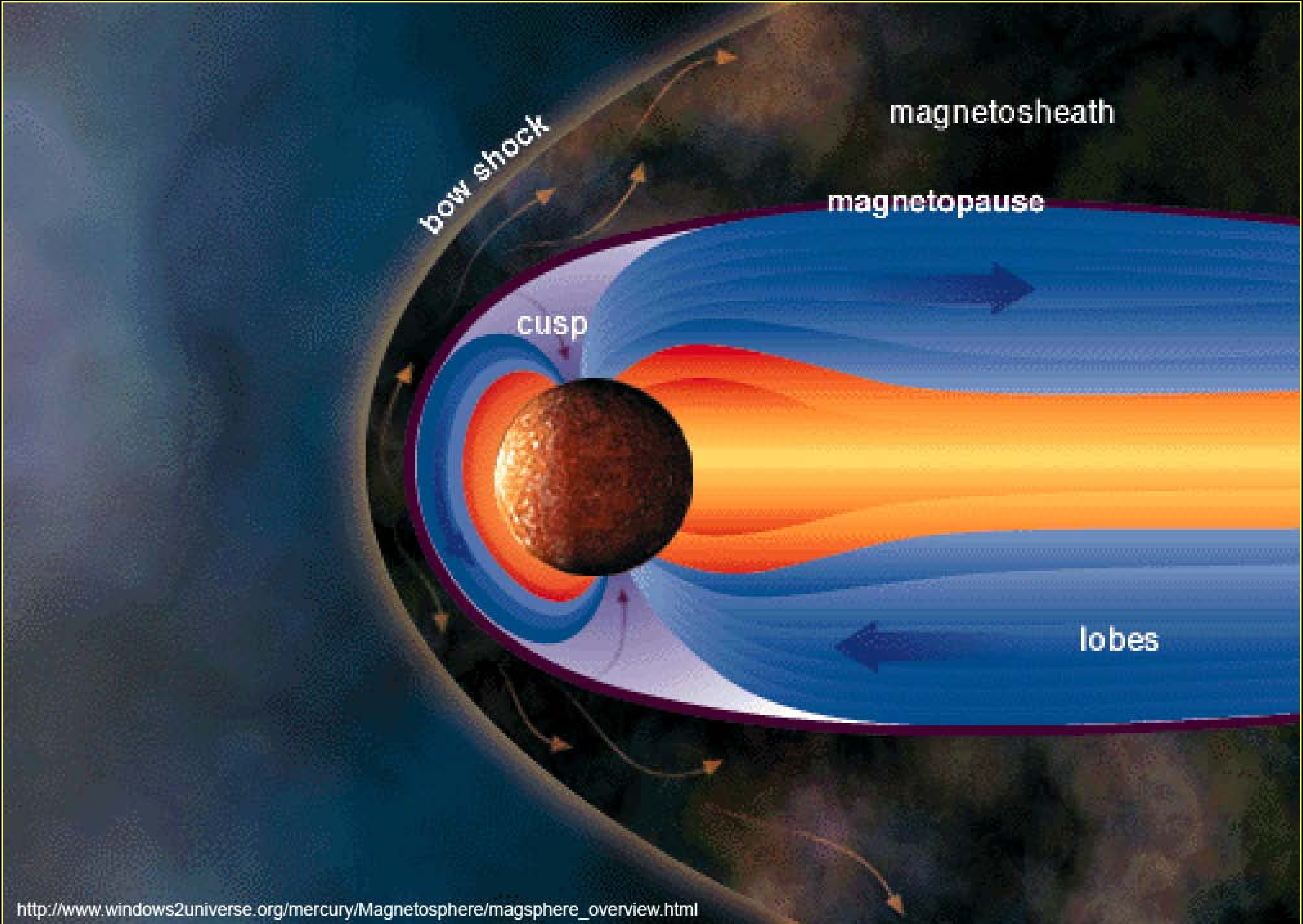
Mercury

Mercury orbit
(large excentricity)



http://en.wikipedia.org/wiki/File:Mercury%27s_orbital_resonance.svg

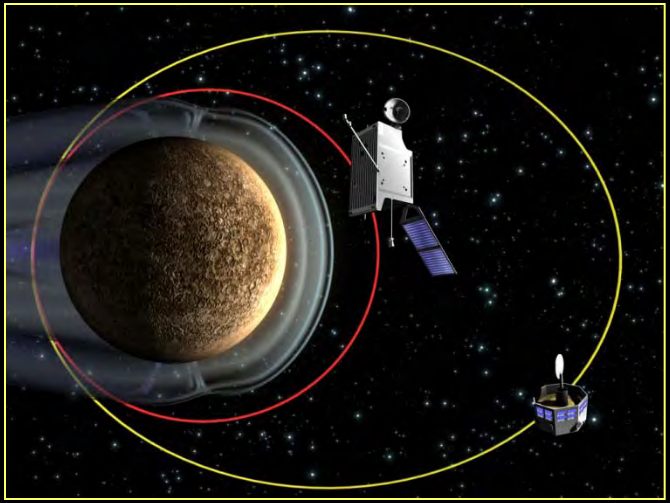
Mercury magnetosphere



History of studies:

- Telescopic studies from Earth are difficult:
  only 28 angle degrees from the Sun
- Mariner 10 (USA): 3 flybys, TV coverage 45%,
  resolution 1 km, (1% - 100 – 500 m); UV and IR
  spectra; magnetic observations.
- Messenger (USA) 3 flybys,
  satellite orbit since - 18.03.2011.
- Beppi Colombo (ESA): Launch January 2017

Messenger



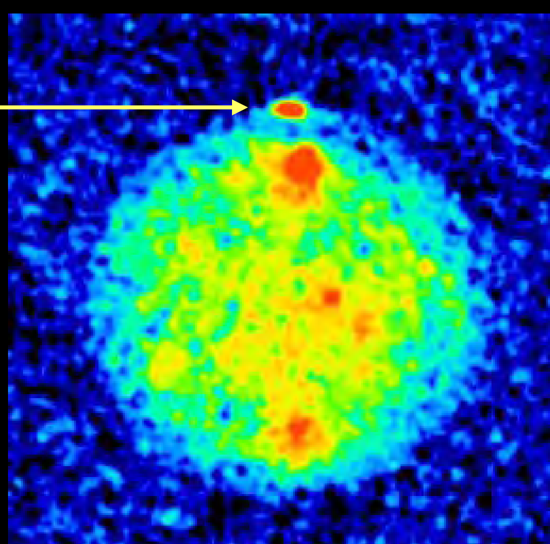
Beppi Colombo

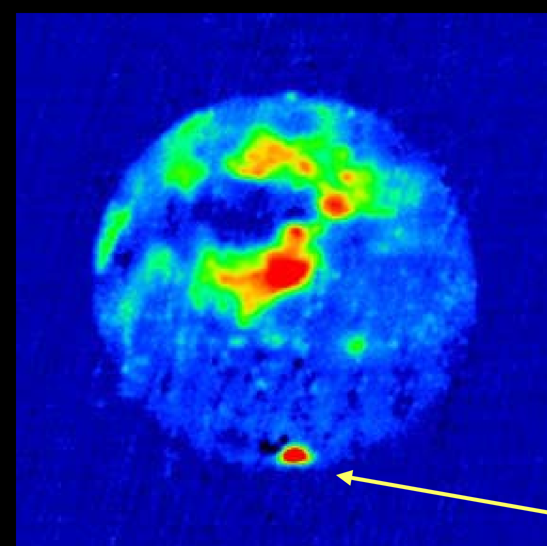
Surface environment:

- Surface temperature100-110 K => 500-700 K
- Atmosphere absent: traces of He, H, O, Na, K
- Surface gravity = 378 cm/s^2 = 0.38 g of Earth = 2.3 g of the Moon

Polar deposits

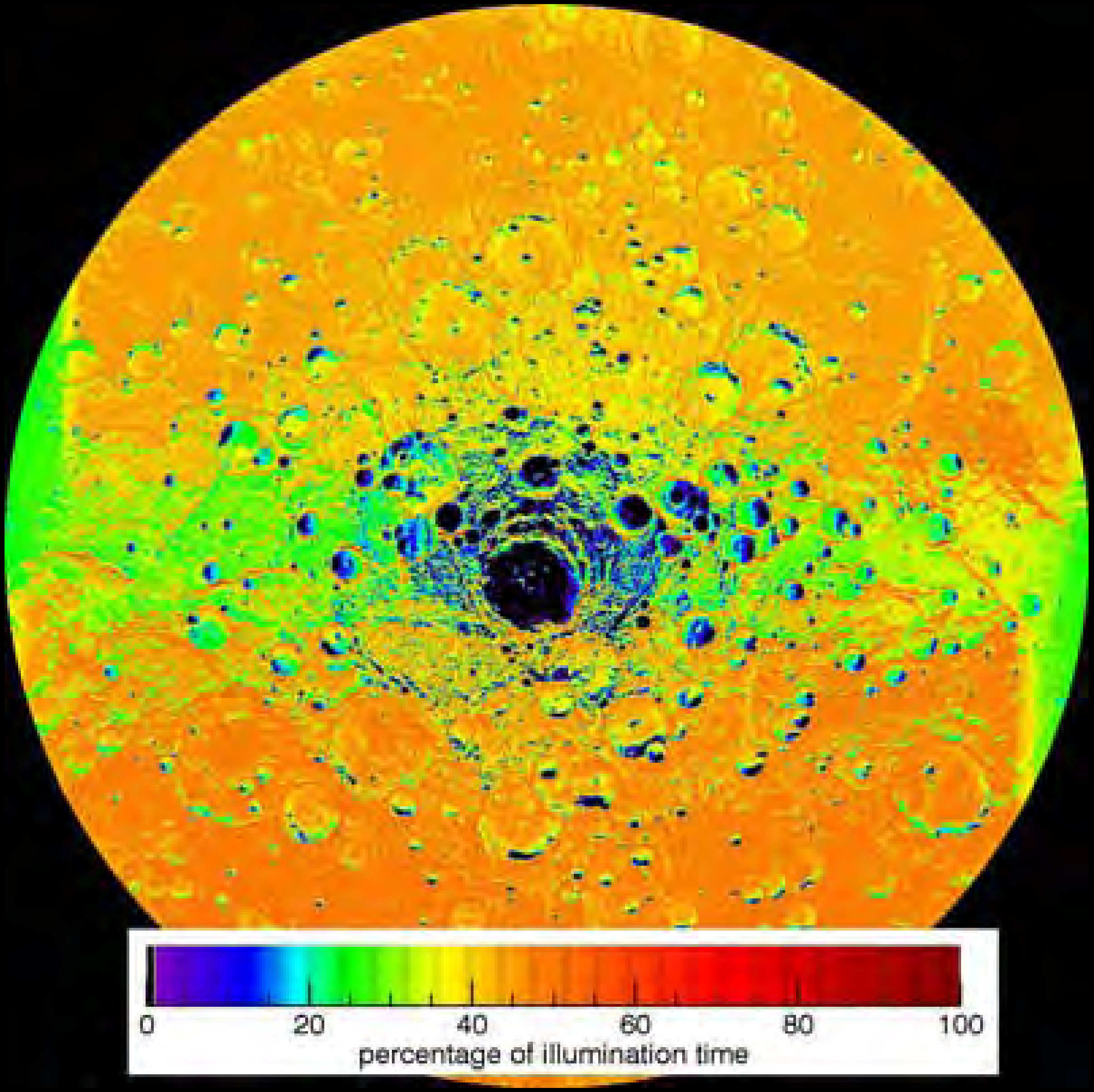
- Discovered by Earth-based radar studies
- Radio-bright spots in polar areas
- Radio-physical characteristics are close to those of polar caps of Mars and surface of Jupiter icy satellites
- Snow / ice H_2O or elementary S





http://www.aoc.nrao.edu/intro/planets.html

Map of illumination of Mercury based on the Messenger data



http://news.sciencemag.org/sciencenow/2011/10/scienceshot-dark-ice-on-a-hot.html?ref=hp

Surface morphology

- Cratered terrains resemble lunar highlands
- Smooth plains resemble lunar maria
- Craters resemble lunar ones, but their rims are higher, and secondary craters are closer to primary crater
  - effect of higher gravity accelleration

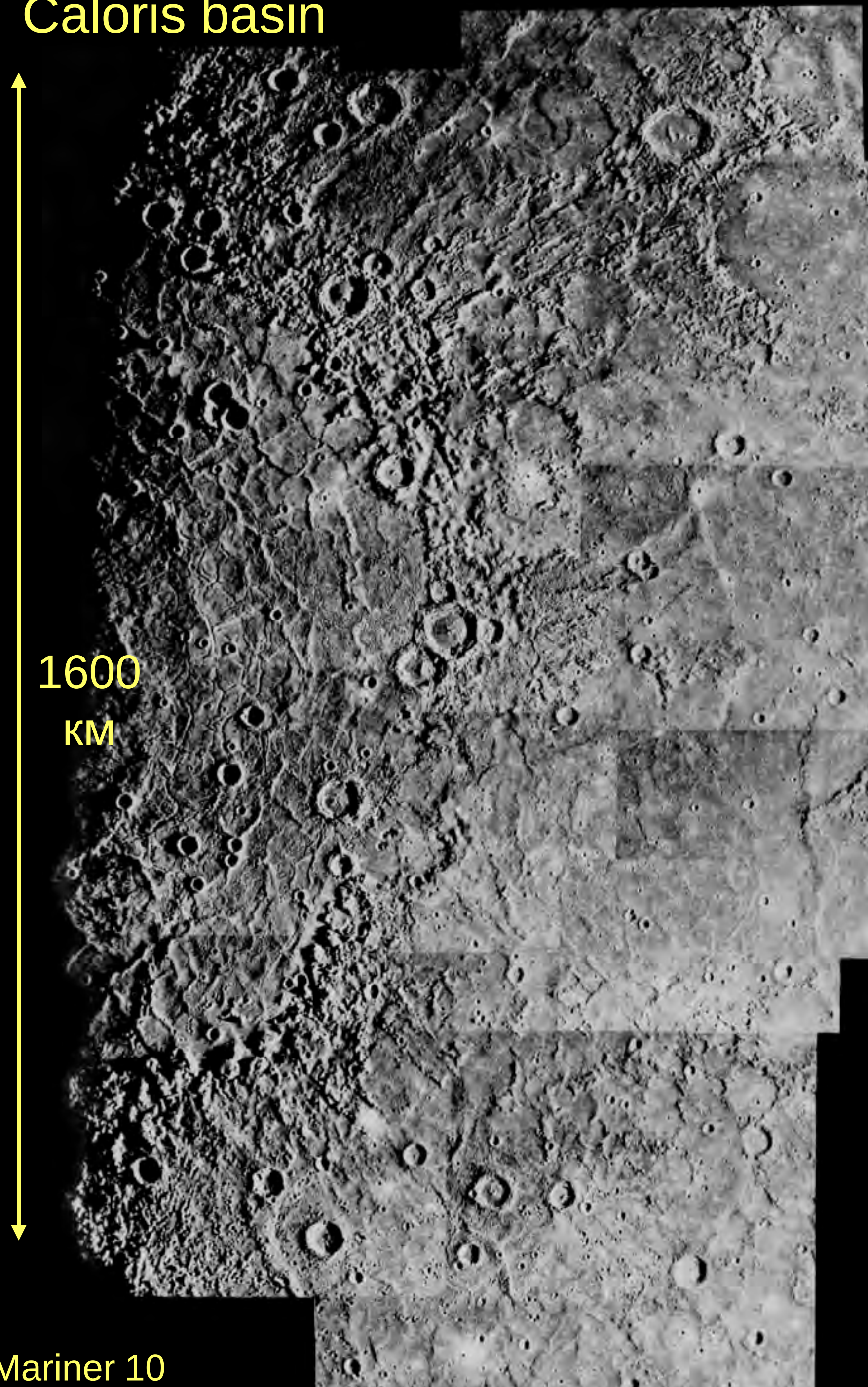
South pole of Mercury

Plains looking similar to lunar maria

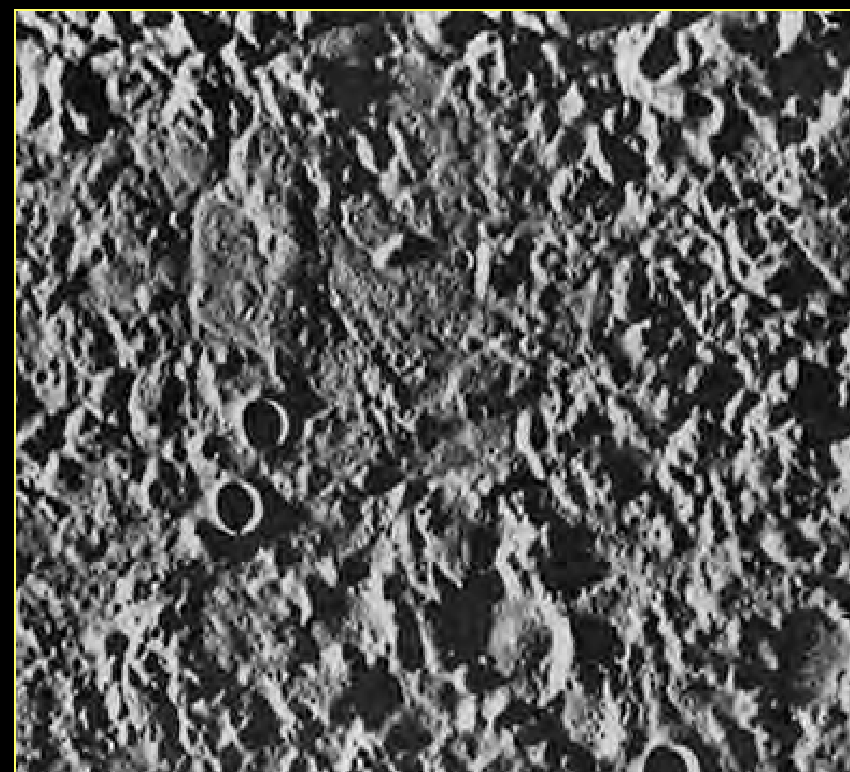
Messenger, NASA

Impact basin Caloris (D = 1300 km) and antipodal region of chaotic terrain – result of focusing of seismic waves from the impact – amplitude of vertical movement = 1 km

Caloris basin



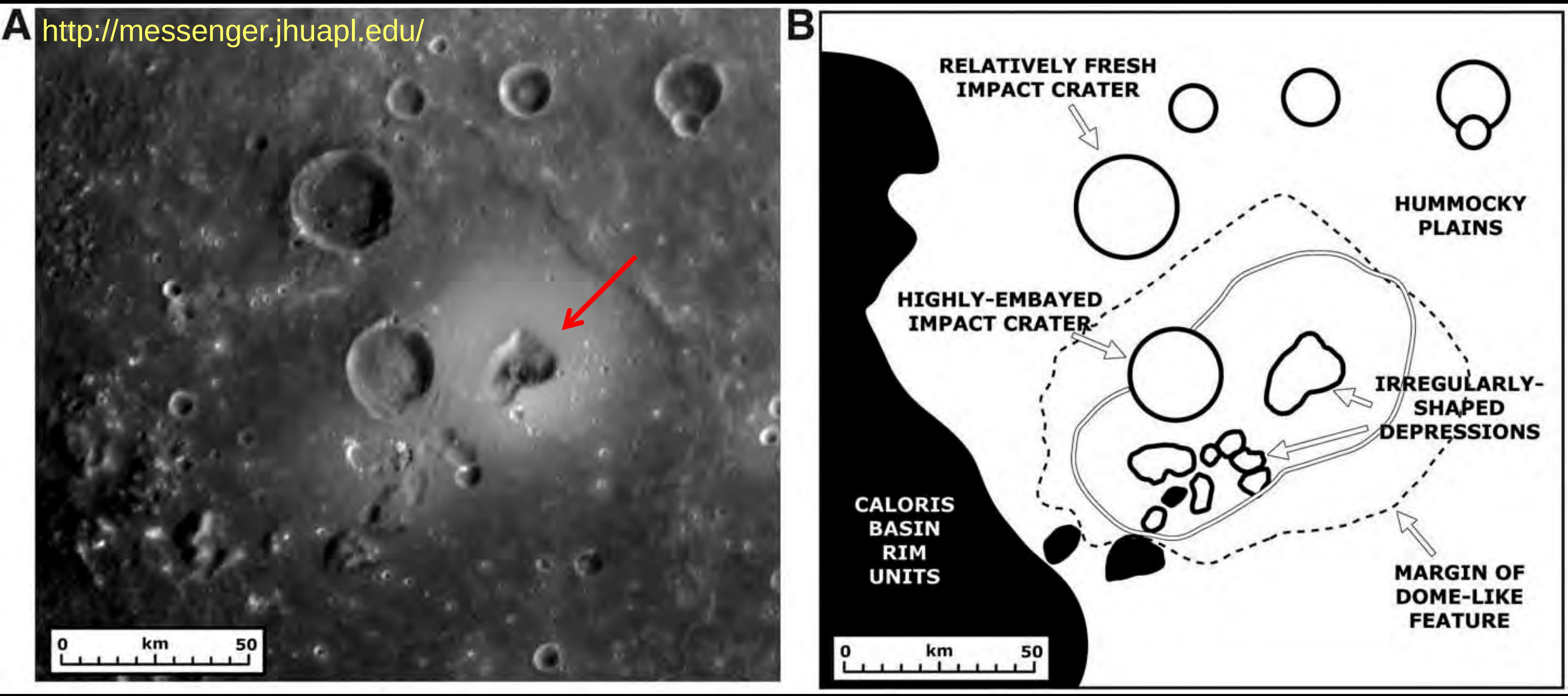
Mariner 10



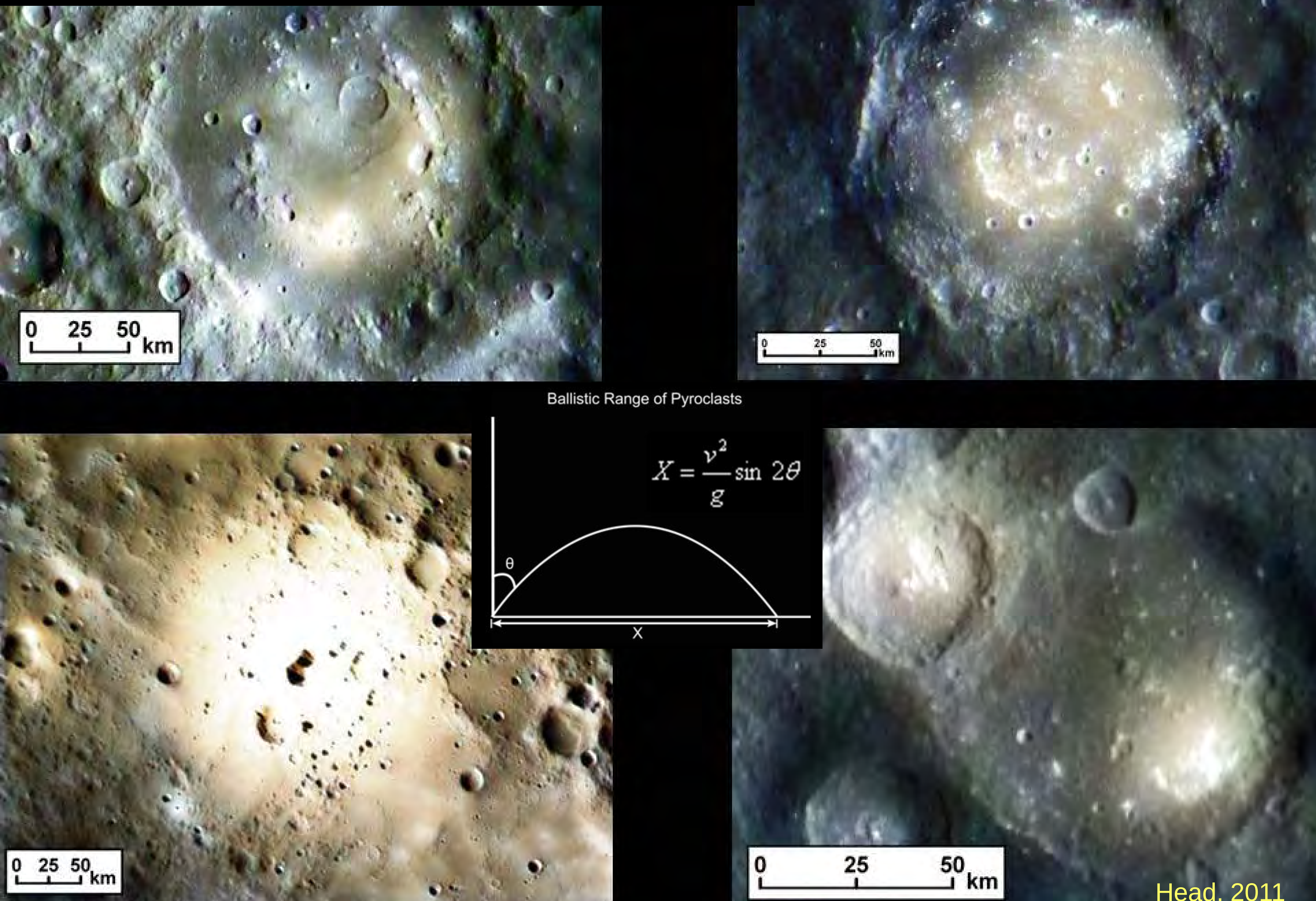
Antipodal region

Volcano in Caloris basin

- Depressions of irregular form with no rims are seen (arrow)
- Around volcano are seen many “normal” craters
- On volcano surface are only rare small craters
  => large difference in the time of formation
- Source of lava is not the impact melt

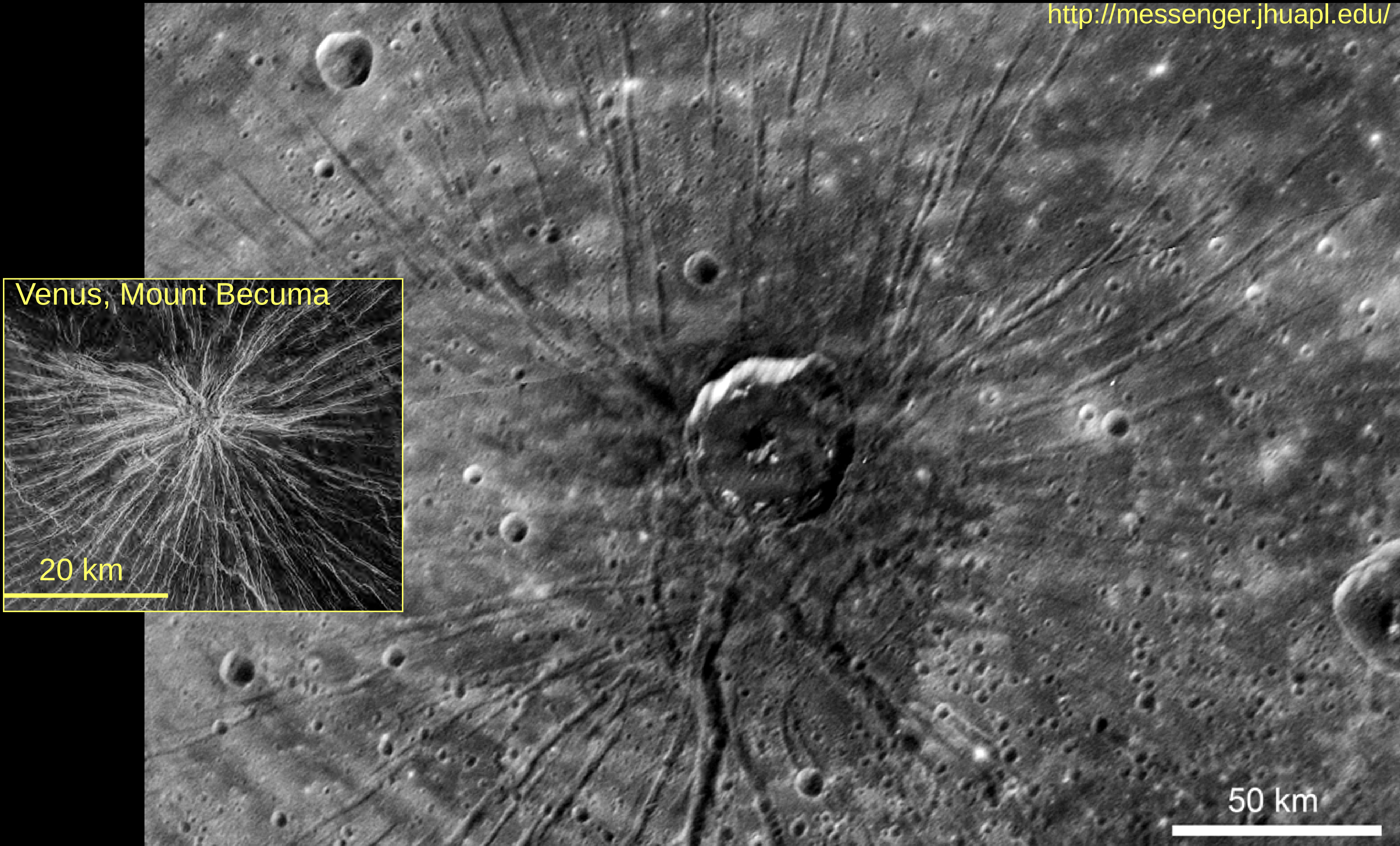


Pyroclastic deposits



Radial faults

Similar features on Venus are due to volcanism
Crater in the center, probably impact, superposed accidentally



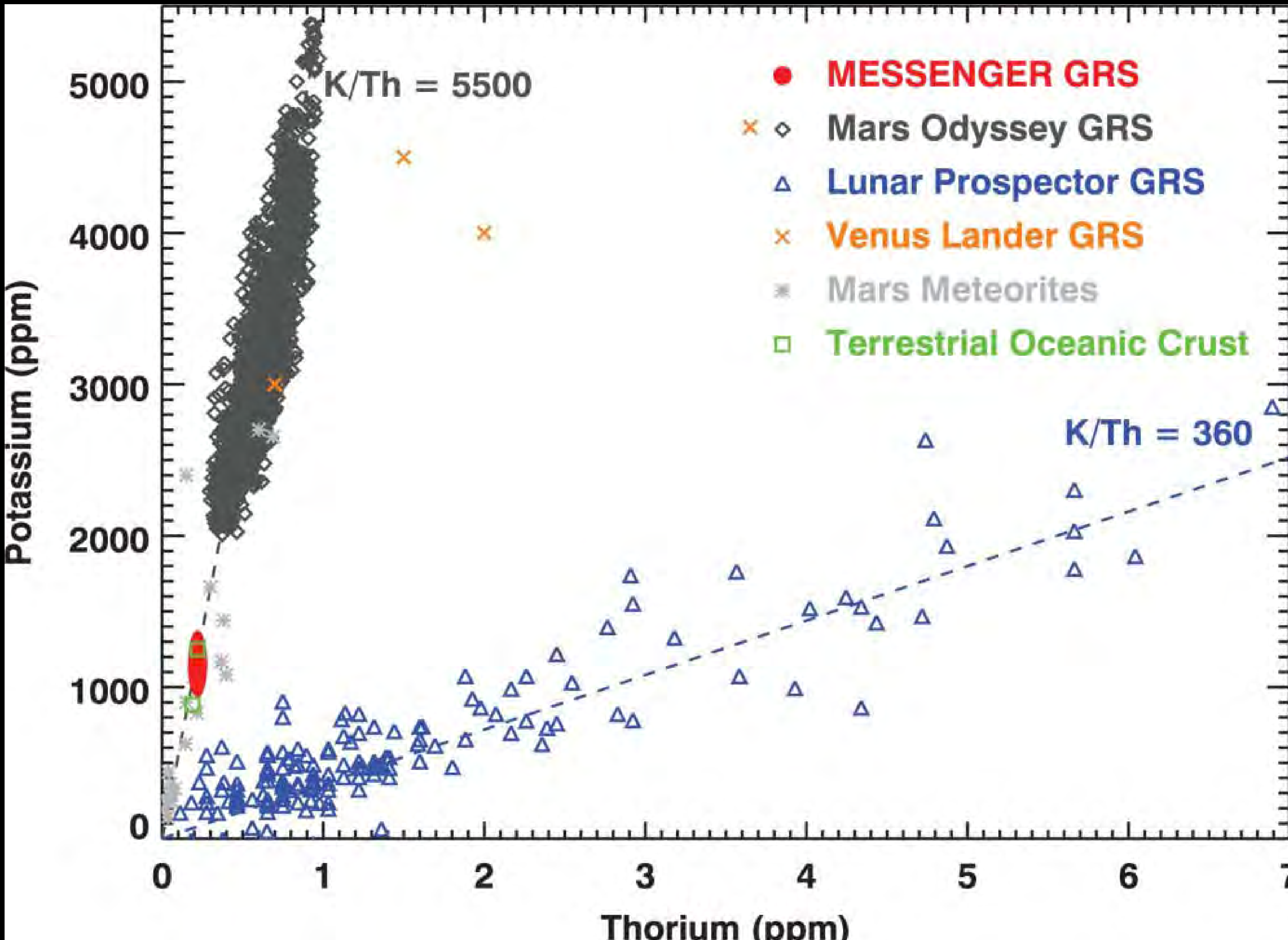
Composition of surface rocks:

- Spectra resembling lunar ones, studied badly
- Surface in visual is twice lighter than lunar one, and twice darker in UV
- Fe content ~ 6%, like for lunar highlands, and by factor 3 lower comparing to lunar basalts
- Messenger spectrometer MASCS: 325 - 1300 nm (VIRS) и 220 - 320 nm (UVVS). No one spectra VIRS showed the 1-micron absorption band.
- Absence of this band is one more evidence that Fe^{+2} is present in minimum contents.

Volcanism:

- Dark plains ~ 40% of imaged surface - low-Fe basalts?
- On the Moon albedo highlands / mare ~ 2, on Mercury ~ 1.4

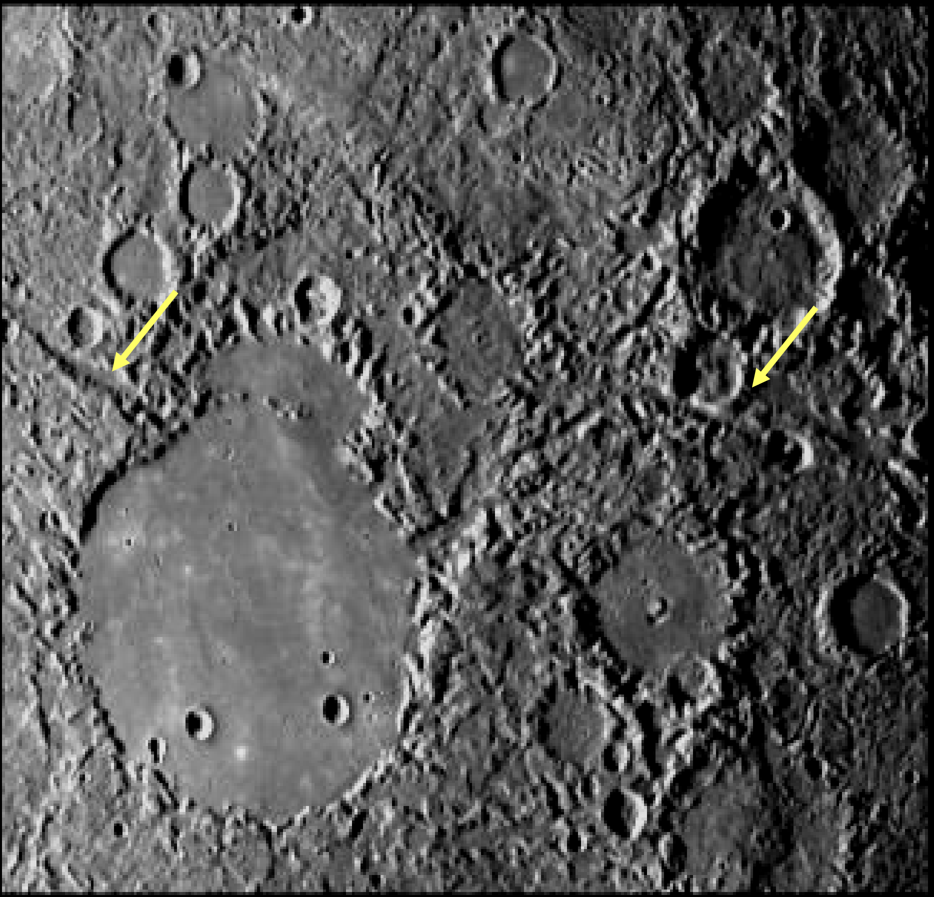
MESSENGER gamma-spectrometry results



P. Peplowski et al., Science.

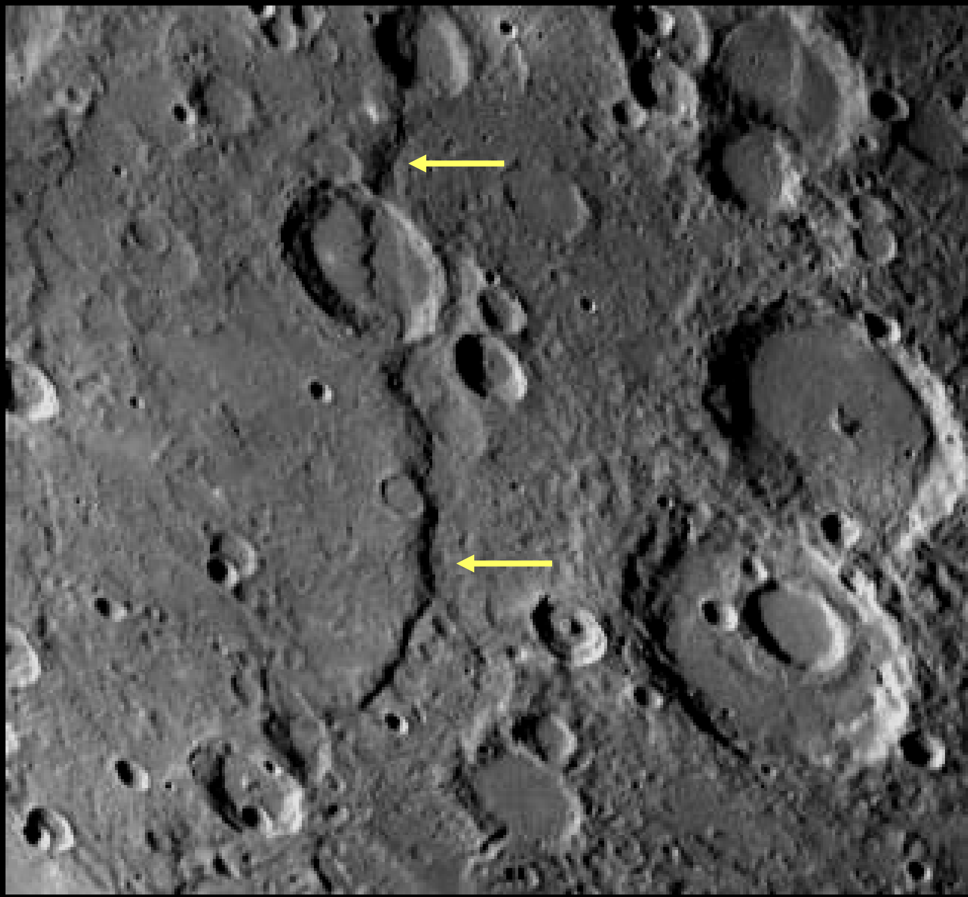
Tectonics:

- Ridges and graben: compression and extension
- Long scarps (upthrusts) => Compression of the whole planet with radius decrease by 2 km



Graben

Mariner 10 images



Scarps

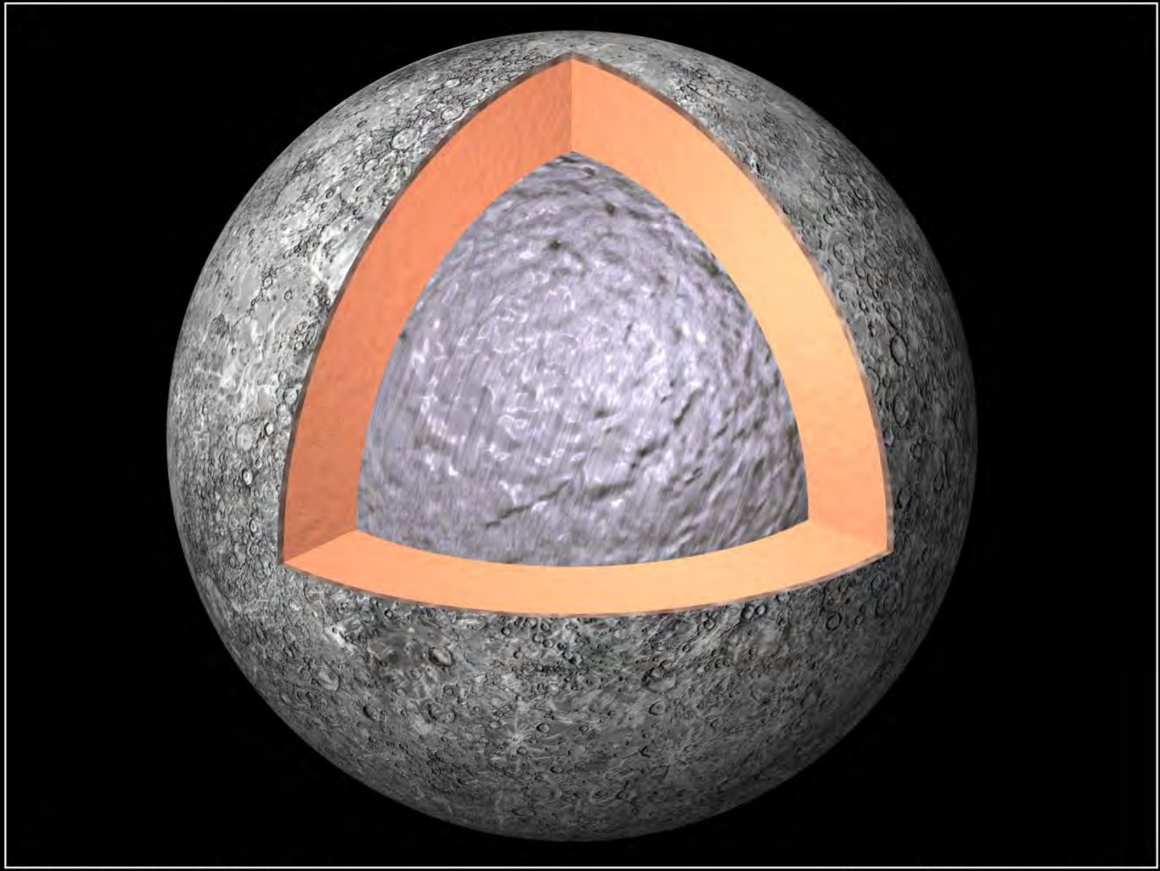
Internal structure:

- Mercury $\rho = 5.44$ g/cm^3, consider compression 5.3 g/cm^3
  Earth $\rho = 5.52$ g/cm^3, consider compression 4.4 g/cm^3

- Fe in the core R = ¾ R of Mercury (for Earth ½ R)

- Magnetic field
  => liquid core

- Admixture of S supports liquid state

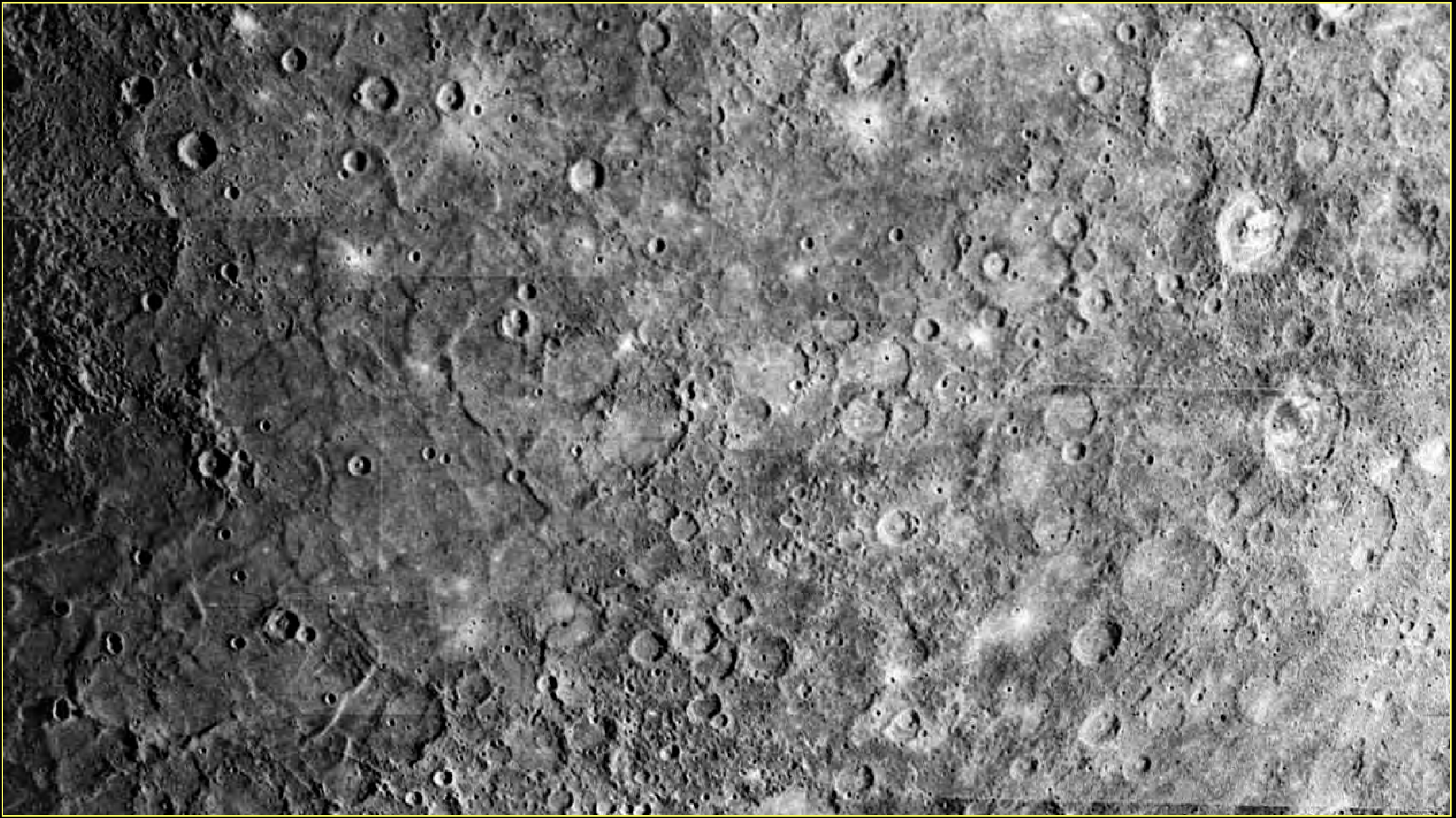


The Interior of Mercury

Geologic history

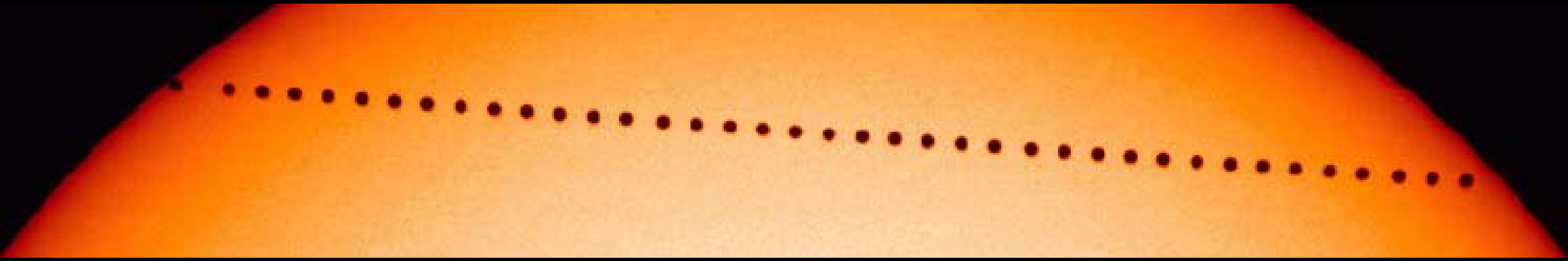
- Early bombardment ~ 4 billion years ago?
- Plains forming volcanism ~ 3.8 billion years ago?
- Then - period of endogenic calmness

Mariner 10 images



Unresolved problems

- Large core - why?
- Chronology of events
- Surface rock composition
- Nature of polar caps
- Origin of Mercury – was it satellite of Venus?



Passage of Mercury on the Sun disk in 2003