MSc – Planeten & Sonnensystem
Erdmond
WS 12/13

A. Deutsch

Erdmond Phasen der Erkundung

* Chinesen, Griechen, ...andere Kultur- und Naturvölker

-> Saros-Periode 18J + 11 1/3 Tage

(Zeitspanne, in der sich Sonne- und Mondfinsternisereignisse wiederholen)

Thales sagte nach Herodot eine totale Sonnenfinsternis für das Jahr 585 vor Ch. voraus, diese führte zum Abbruch einer Schlacht zwischen Lydiern und Mediern.

Erdmond Phasen der Erkundung

* Chinesen, Griechen, ...andere Kultur- und Naturvölker

-> Saros-Periode 18J + 11 1/3 Tage

* Teleskopische Beobachtungen 1609 – 1960

* Fernerkundung
Luna 1 am 2. Januar 1959 – Vorbeiflug am Mond

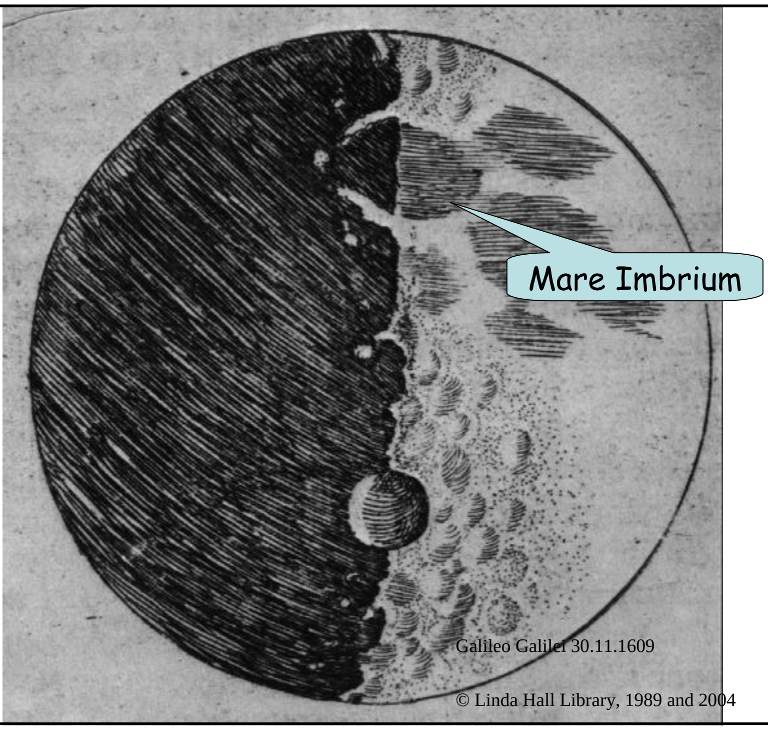
* Apollo – Luna
Erste bemannte Mondlandung: Apollo 11
20.7.1969 Neil Amstrong betritt den Mond

LUNA 24, Robotermission, landet am 9.8. 1976
170 g Proben aus 8 Bohrkernen

* Post-Apollo Missionen

Teleskopische Beobachtungen

Was sieht man?



Galileo Galilei 30.11.1609

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Albedo (von lat. albidus, weiß)

Verhältnis der ankommenden elektromagnetischen Energie, die von einem Objekt reflektiert wird, zu jener, welche vom Objekt aufgenommen wird.
Albedo = Maß für das Rückstrahlvermögen einer Oberfläche von 0 (keine Reflexion) bis 1 (alles Licht wird reflektiert).
Diese Werte werden auch in Prozent ausgedrückt (0 - 100%).

Johannes Kepler (1571-1630)

dunkel = Maria

Synonyme: Becken
Multiring-Becken
basins

hell = Terrae

Synonyme: Hochland
highland
upland
continents

Early nomenclature

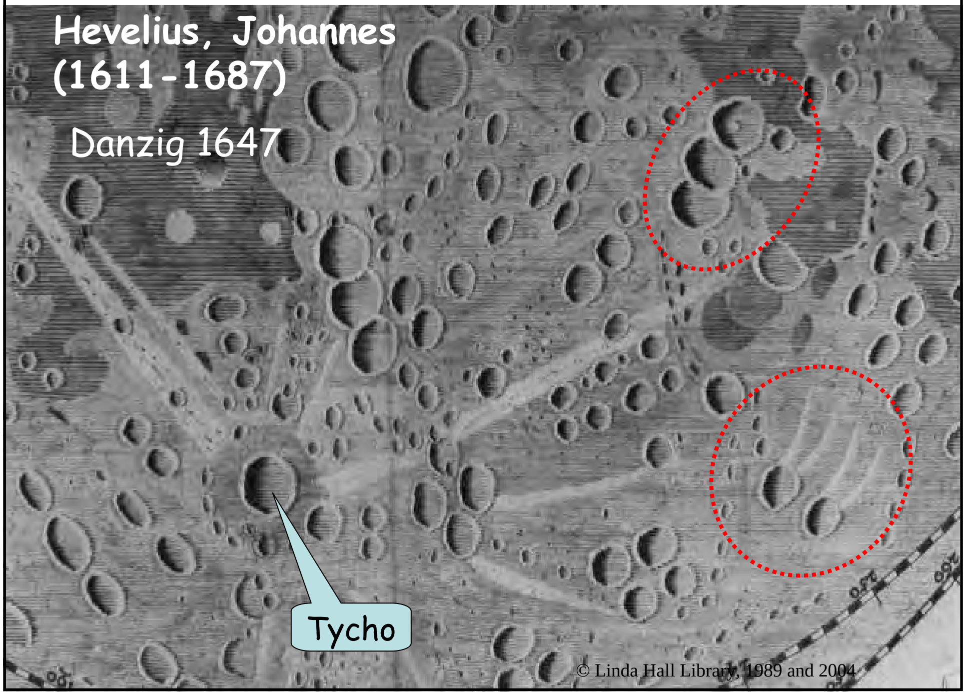
Planets were named by ancient people usually by names of gods and goddes (Mars, Venus, Jupiter).

Many of the names have survived to the present time.

The most chaotic nomenclature was developed for the Moon in the beginning of its systematic study.

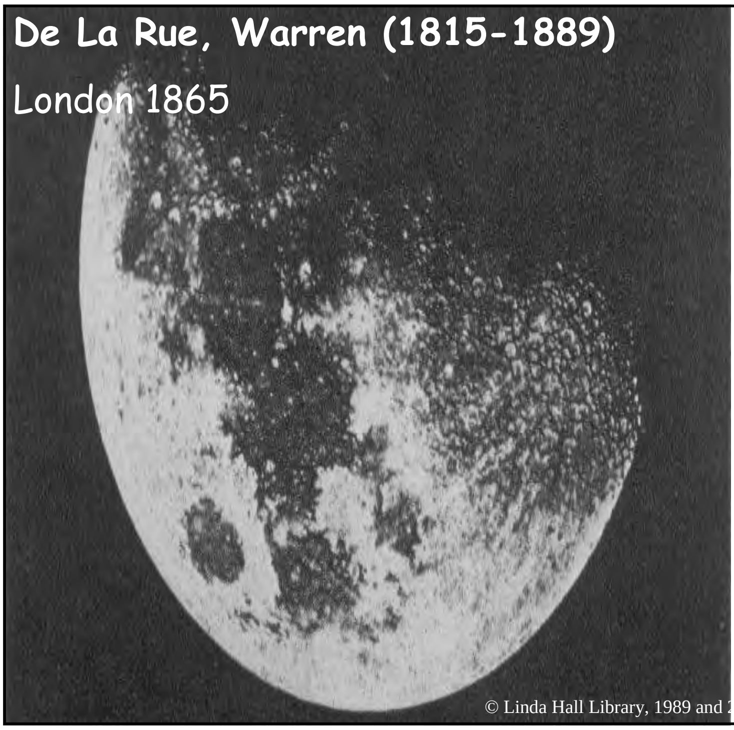
Hevelius, Johannes (1611-1687)

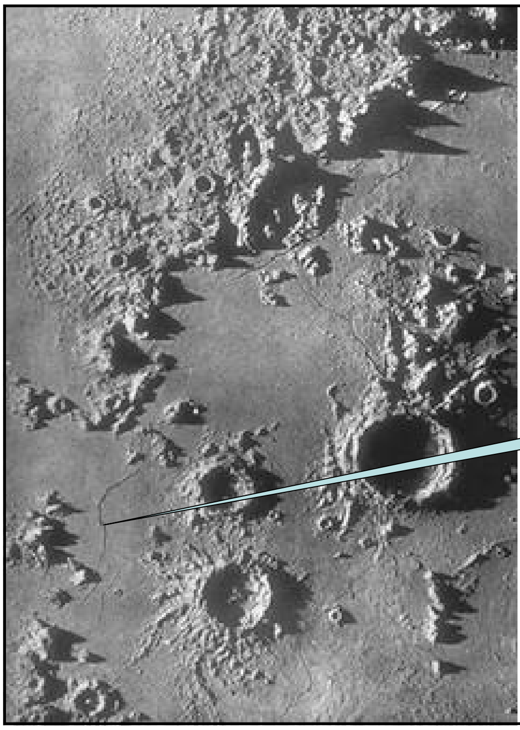
Danzig 1647



De La Rue, Warren (1815-1889)

London 1865





Nasmyth, James Hall (1808-1890) & Carpenter, James (1840-1899)

London 1874

Fotographien von Gipsmodellen

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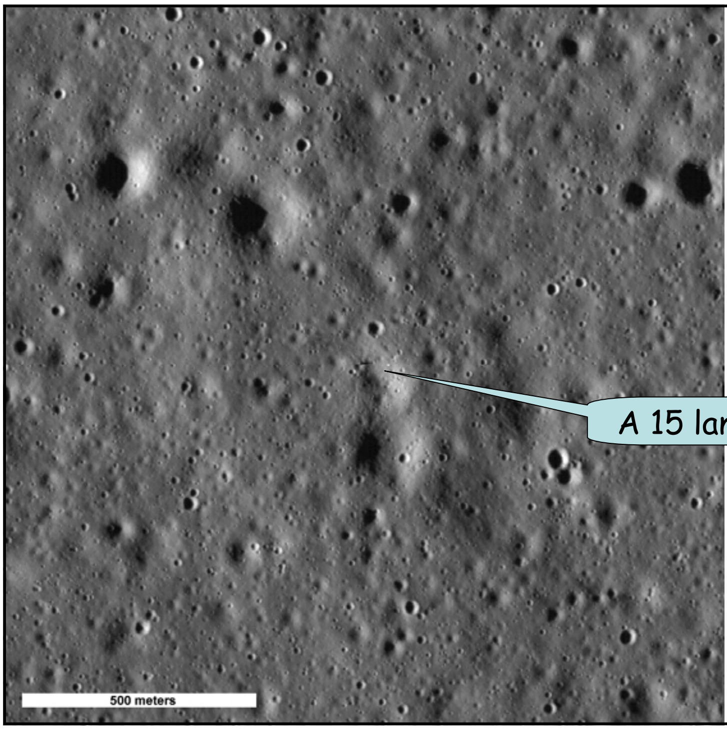

LRO July 2009

G. Karl Gilbert
1843 – 1918

In 1891 Gilbert, chief geologist for the U.S. Geol. Survey, decided to test wheter the crater in Arizona was created by the impact of a meteorite or the result of volcanic activity (explosion of superheated steam).

Johann Friedrich Julius Schmidt (1825-1884)

~~Vulkanische Krater am Mond??~~

Impaktkrater!!
G. Karl Gilbert

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How to explore a solid body

* Remote sensing …

* Robotic missions

  – "in situ" measurements (Mars rover …)

  - robotic sample return missions
    Luna (UdSSR), Hayabusa (Asteroid Itokowa),
    Stardust

* Human activities on the surface (Apollo missions)
(?Asteroid; ?Mars)

What do we want to know?

* Surface properties

* Composition of the surface

* Composition of the interior

* Geologic history …

Data needed to understand origin and evolution of the Moon

* Geochemistry – Thorsten Kleine

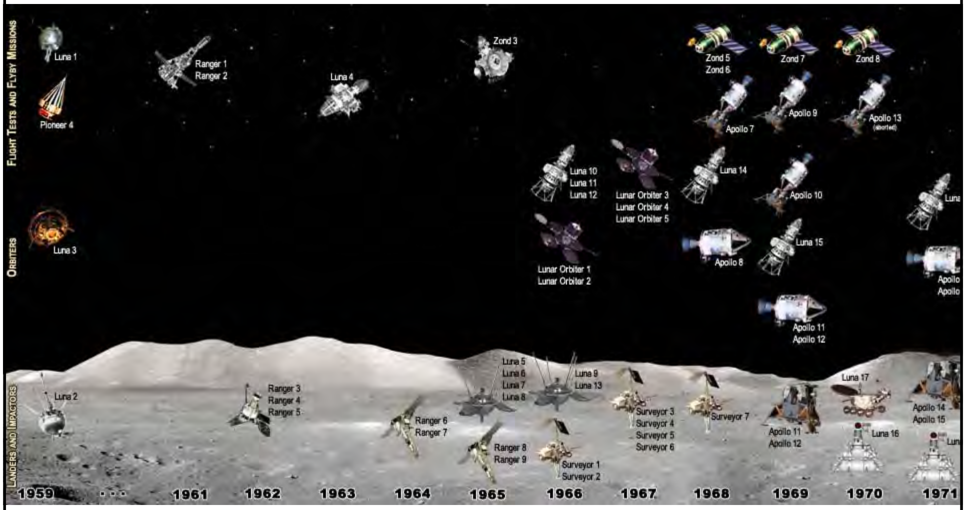
* What else?

* Age

* The interior

- distribution of mass – composition of the mantle
- presence of a core
- temperature history

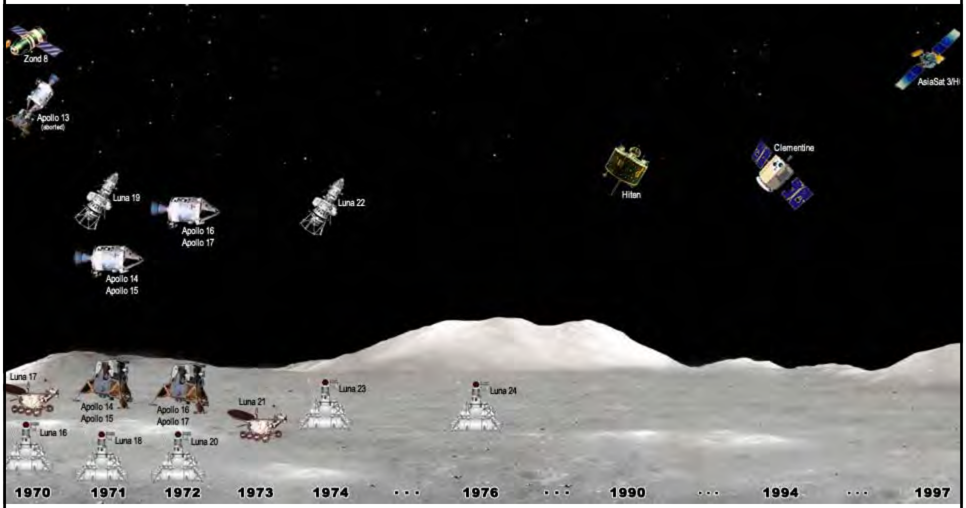
Missions to the Moon



http://www.lpi.usra.edu/lunar/missions/

http://nssdc.gsfc.nasa.gov/planetary/lunar/lunartimeline.html

Missions to the Moon



http://www.lpi.usra.edu/lunar/missions/

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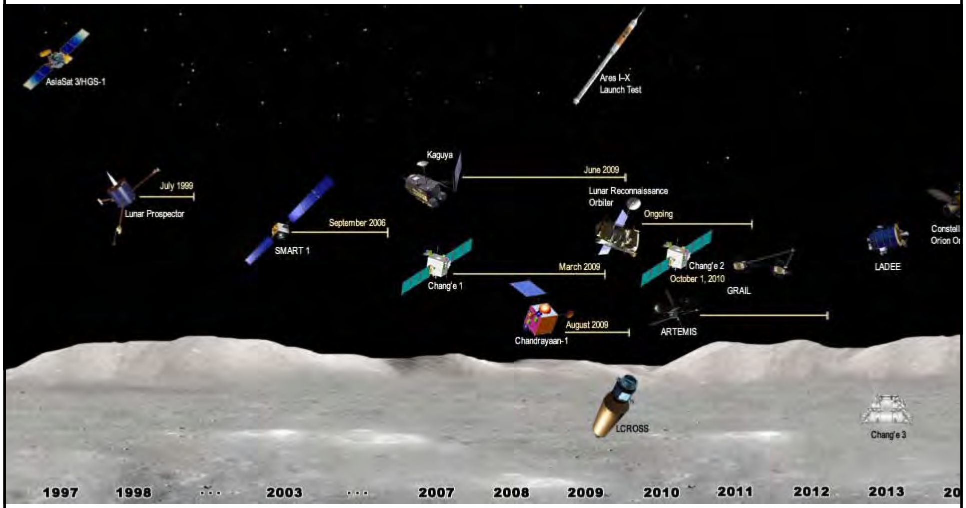
Missions to the Moon



http://www.lpi.usra.edu/lunar/missions/

http://nssdc.gsfc.nasa.gov/planetary/lunar/lunartimeline.html

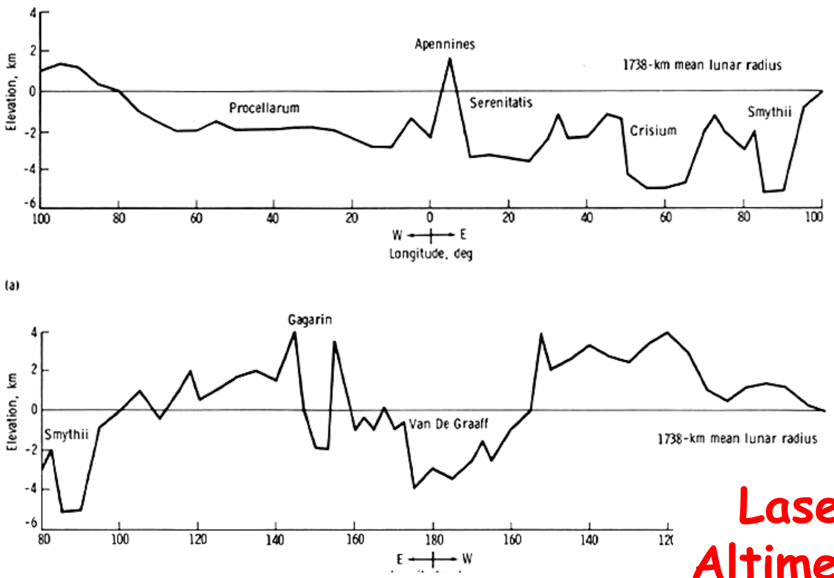
Missions to the Moon (1958 - 2006)

Luna 1959 -1976	UdSSR
Zond 1965 - 1970	UdSSR
Ranger 1961 - 1965	NASA
Surveyor 1966 - 1968	NASA
Lunar Orbiter 1966 - 1967	NASA
Apollo Program 1963 - 1972	NASA
Galileo 1990, 1992	NASA mission to Jupiter
Hiten 1990 - 1993	ISAS (Japanese Space Agency)
Clementine 1994	NASA
Lunar Prospector 1998	NASA
SMART-1 2003 - 2006	ESA

Apollo Lunar manned missions

Orbital experiments

- Window Meteoroid Detector
- Metric and Panoramic Photography
- Laser Altimeter
- Infrared Radiometer
- Ultraviolet Spectrometer
- Alpha Particle Spectrometer
- Lunar Sounder
- Subsatellite
- Bistatic Radar
- X-Ray Fluorescence Spectrometer
- Gamma-Ray Spectrometer



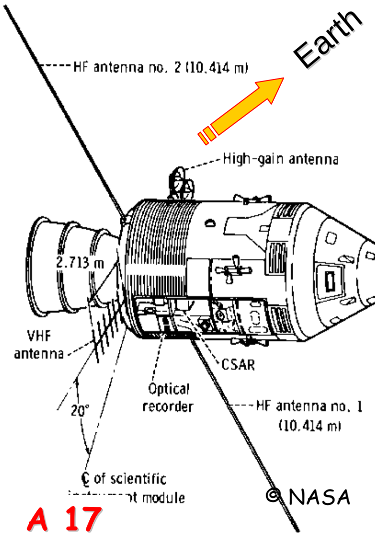
Topographic range (km) Moon 16 - Earth 20
Volumetric mean radius (km) M 1738 - E 6371

Laser Altimeter

orbital

Lunar Sounder

orbital



A 17

Objective: electrical conductivity, lunar topography (upper 2 km)

Technique: 3-wavelength synthetic aperture radar (SAR); the very long wavelengths penetrate deep into the Moon because it is very dry.

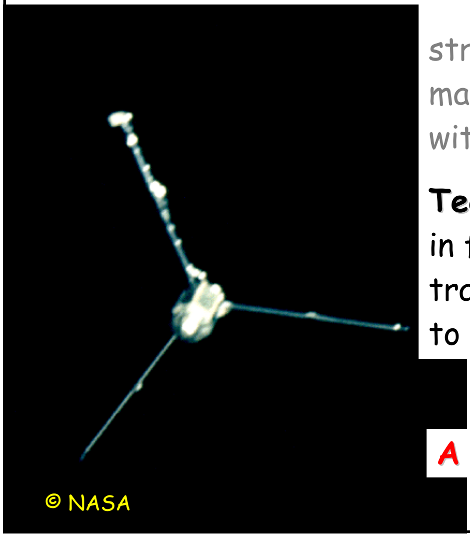
A similar experiment on the space shuttle mapped ancient river valleys beneath the Sahara Desert.

Results:

- layered basalts, e.g., Mare Crisium
- origin of wrinkle ridges due to motions along faults

Subsatellite

orbital


© NASA

Objective: details of the gravity field ➔ distribution of mass in the Moon's interior

strength and orientation of the magnetic field near the Moon [lies within the Earth's magnetic field]

Technique: magnetometer, changes in frequency of radio waves transmitted from the spacecraft to Earth [Doppler effect]

A 14, A 15, A 16, A 17

Apollo Lunar manned missions

Surface experiments

- Solar Wind spectrometer
- Solar Wind composition by Foil Entrapment
- Cold Cathode Ion Gauge
- Lunar Atmospheric Composition
- Lunar Neutron Probe
- Soil Mechanics
- Laser Ranging Retroreflector
- Lunar Passive Seismic Experiment
- Lunar Active Seismic Experiment + Seismic Profile

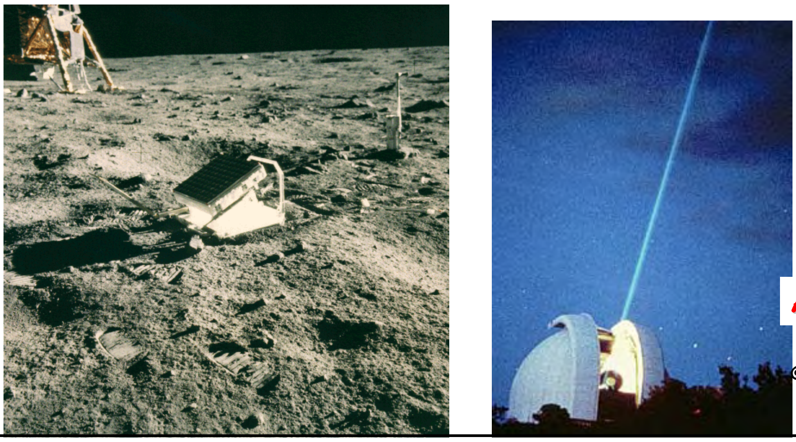
- ~ 400 kg samples

- Lunar Surface Magnetometer
- Traverse Gravimeter
- Lunar Ejecta and Meteorites
- Surveyor 3 analysis

Laser Ranging Retroreflector

Objective: precise measurement of Earth-Moon distance, motion of the Moon's center of mass, lunar radius

Technique: Laser beams from Earth are reflected back to their point of origin (-> Ø 7 km -> 20 km)



A 11

© NASA

Laser Ranging Retroreflector

Objective: precise measurement of earth-moon distance, motion of the Moon's center of mass, lunar radius

Results:

- Earth ↔ Moon ~385,000 km; accuracy of ~ 3 cm
- Moon is receding from Earth ~ 3.8 cm yr-1
  tides accelerate the Moon ➔ radius is increasing, orbital period is decreasing
- variations in Moon's rotation related to the mass distribution inside the Moon ➔ core with r ≤ 350 km
- improved knowledge of Earth's rotation rate, precession of its spin axis

Passive Seismic


© NASA

A 11

Objective: surface activities, including tidal deformations, impacts, interior structure

Techniques: 2 seismometers

Results:

- moonquakes at depths of 800 – 1000 km, mag. 2
- Moon has a crust, mantle, and core (r <450 km?)
- average crustal thickness 60-70 km, upper 20 km heavily fractured
- 1700 impacts recorded

„Moon"-Quakes - Meteoroid impact

Moonquake
13:09 hr, May 23, 1970

Meteoroid impact
8:09 hr, April 8, 1970

Passive seismic experimens total observation time close to 8 yrs.

Artifical impacts 9

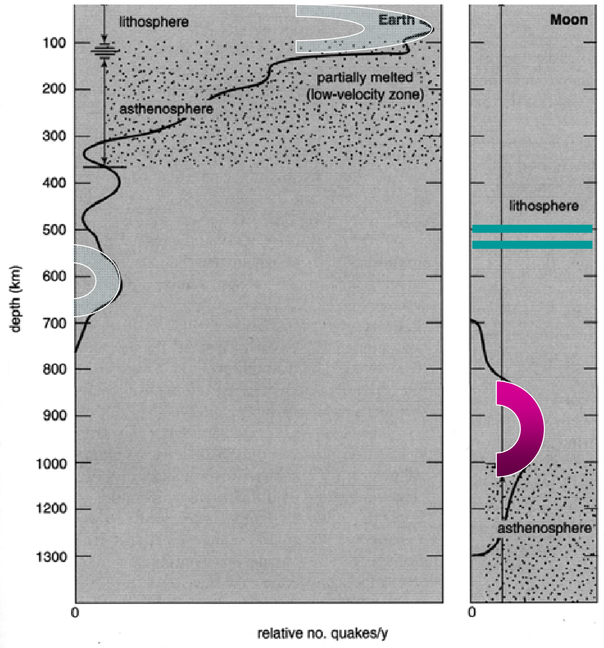
Meteoroid impacts 1700

Deep moonquakes 980

Unclassified events 7300

Lunar Source Book

HARTMANN 1999 Moons and Planets



Depth distributions of Earth- & „Moon“-Quakes

Seismic discuntinuity

Earth mag. up to 9+

total seismic energy released yr-1

5×10^{17}

Moon mag. 1-2

total seismic energy released yr-1

10^{7}

Active Seismic Experiment

Lunar Seismic Profiling

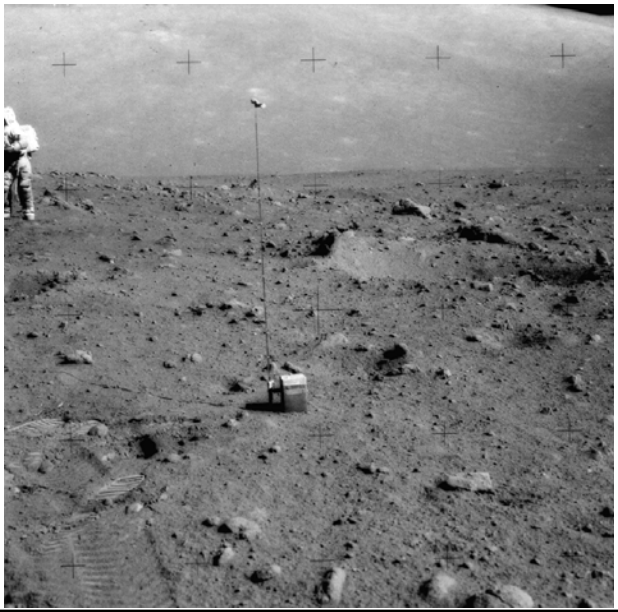
Objective: characteristics of lunar materials down to 3 km

Technique: 90-meter-long geophone line, detonation of explosive charges (≤2.7 kg!; Apollo 16 - 3 mortar shells) by radio control after LM left the Moon

Results:

- upper x00m of the crust - seismic velocity (P wave) 0.1 – 0.3 km s-1 ➔ much lower than observed for intact rocks, consistent with highly fractured/brecciated material
- A 17 landing site - surface basalt layer 1.4 km thick

Lunar Seismic Profiling



A 17

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Missions to the Moon (1958 - 2006)

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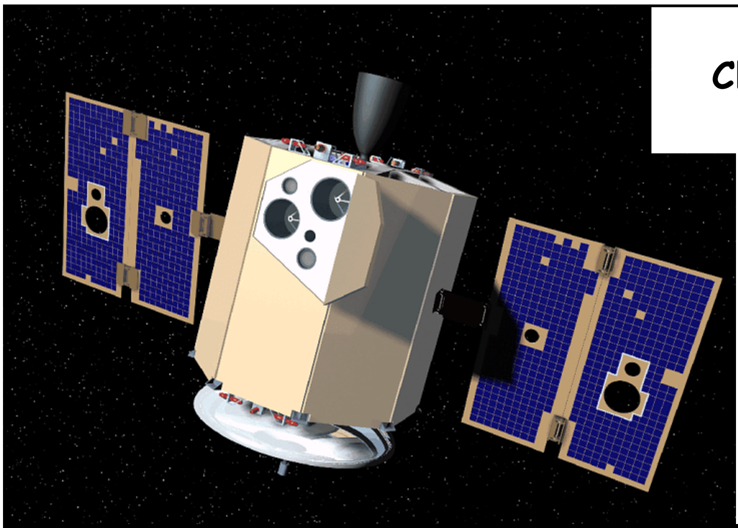
Hiten 1990 - 1993	ISAS (Japanese Space Agency)
Clementine 1994	NASA
Lunar Prospector 1998	NASA
SMART-1 2003 - 2006	ESA

Clementine (1994)



http://www.lpi.usra.edu/expmoon/clementine/clementine.html
http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1994-004A

Clementine (1994)

Objectives:

- global composition and mineralogy
- global topographic and gravitational field mapping
- improved determination of the magnetic field
- high-resolution imaging of selected areas
- observation of near-Earth asteroid 1620 Geographos - failed

71 days in polar orbit
orbital period ~ 5 hours
transit from south to north pole ~90 min

Clementine (1994)

Joint project between the Strategic Defense Initiative Organization and NASA

designed, integrated, operated by the Naval Research Lab

solid rocket motor for injection towards the Moon

not designed as scientific mission
yet testing of new cameras, solar panels, …

Star Wars

costs ~80 m US$

http://www.nrl.navy.mil/clm/

Clementine - Orbital experiments

- Star Tracker Camera
- Ultraviolet/Visible CCD Camera (UV/Vis)
- Near-Infrared CCD Camera (NIR)
- Long-Wavelength Infrared Camera (LWIR)
- High-Resolution Camera (HIRES)
- Charged Particle Telescope
- Laser Image Detection and Ranging (LIDAR) System
- Bistatic Radar Experiment
- S-Band Transponder Doppler Gravity Experiment

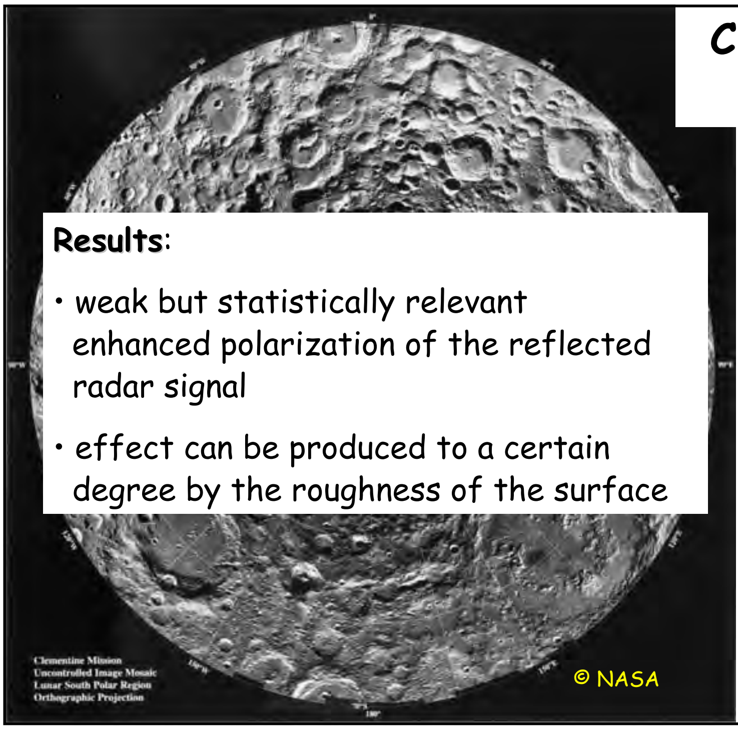
Bistatic Radar Experiment

Objective: search the Moon's polar regions for evidence of ice in permanently shadowed craters

Technique: transmission of a radio signal from the spacecraft at a point on the target body, reflected signals were received on Earth Deep Space Network (DSN) at Goldstone (USA), Madrid, and Canberra.

Properties of the received reflections (echo magnitude very high for radar-transparent materials such as frozen volatiles compared to silicates, circular polarization) give information on the target surface.

Clementine (1994)



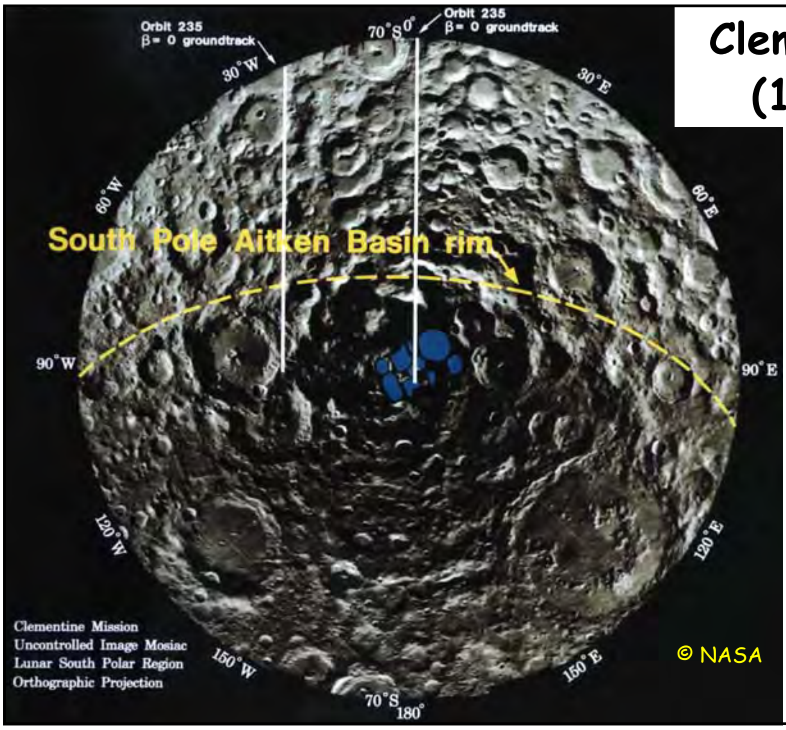
Results:

- weak but statistically relevant enhanced polarization of the reflected radar signal
- effect can be produced to a certain degree by the roughness of the surface

Pentagon announced on Dec 3, 1996

Clementine data indicates the presence of ice in the bottom of a crater located on the Moon's South pole

Clementine (1994)



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S-Band Transponder Doppler Gravity Experiment

Objective: lunar gravity field

Technique: perturbations in the motion of Clementine; tracking in Pomonkey, and NASA Deep Space Network.

Measurement of the frequency of the S-band*) transmission every 10 s, Doppler shift ➔ relative velocity of Clementine towards/away from Earth converted to gravity effects on the spacecraft, accuracy of velocity measurements: Pomonkey 3 mm s-1 Deep Space Network stations: 0.3 mm s-1

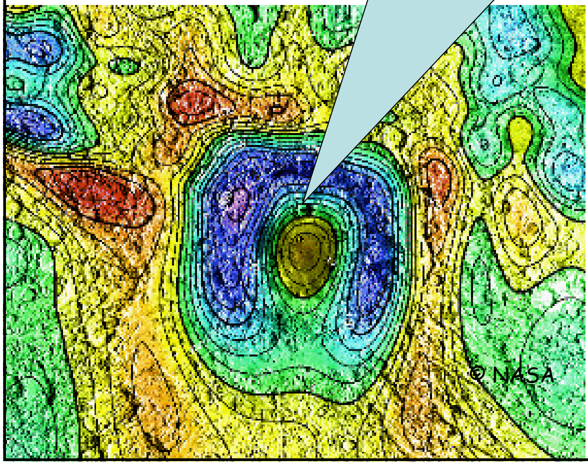
>361,000 observations, ~ 57,000 at ≤ 1000 km altitude

tracking was not possible on most of the lunar farside

*)Short wave frequencies range from 2 to 4 GHz

Clementine (1994)

gravity signature of Mare Orientale
data from Clementine, Lunar
Orbiters 2-5, Apollo 15 subsatellite



© NASA

gravity high = yellow
in the center of the basin

gravity high → mass concentration, "**mascon**"

gravity low = purple associated with one of the basin rings that → significant mass deficit beneath the surface

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Missions to the Moon (1958 - 2006)

Luna 1959 -1976	UdSSR
Zond 1965 - 1970	UdSSR
Ranger 1961 - 1965	NASA
Surveyor 1966 - 1968	NASA
Lunar Orbiter 1966 - 1967	NASA
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Galileo 1990, 1992	NASA mission to Jupiter
Hiten 1990 - 1993	ISAS (Japanese Space Agency)
Clementine 1994	NASA
Lunar Prospector 1998	NASA
SMART-1 2003 - 2006	ESA

Lunar Prospector (1998)

http://nssdc.gsfc.nasa.gov/planetary/lunarprosp.html

Lunar Prospector (1998)

- low polar orbit, mapping of surface composition and possible polar ice deposits …
- 19 month mission will allow construction of a detailed map of the surface composition of the Moon, and will improve our understanding of the origin, evolution, current state, and resources of the Moon.
- no on-board computer
- 31 July 1999 - Lunar Prospector impacted the Moon near the south pole in a controlled crash to look for evidence of water ice - none was observed

Doppler Gravity Experiment (DGE)

Lunar Prospector
(1998)

Objective:

surface and internal mass distribution of the Moon; nearside gravity map with a resolution of 200 km and a precision of 5 mgal

Results:

- LP's gravity data, improved by a factor of ~5 over, indicate existence of a lunar core (iron?) with r ≥300 km
- well-known lunar gravity field → benefits of modeling long-term spacecraft orbits about the Moon, → more accurate planning of fuel needs

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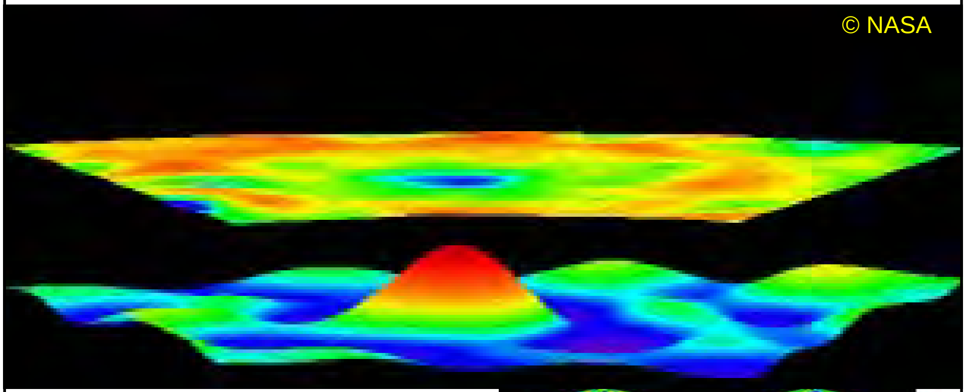
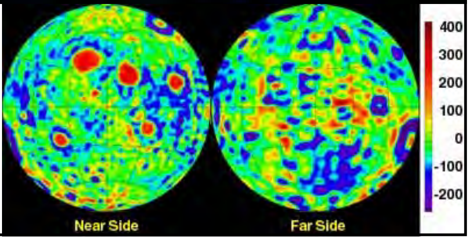
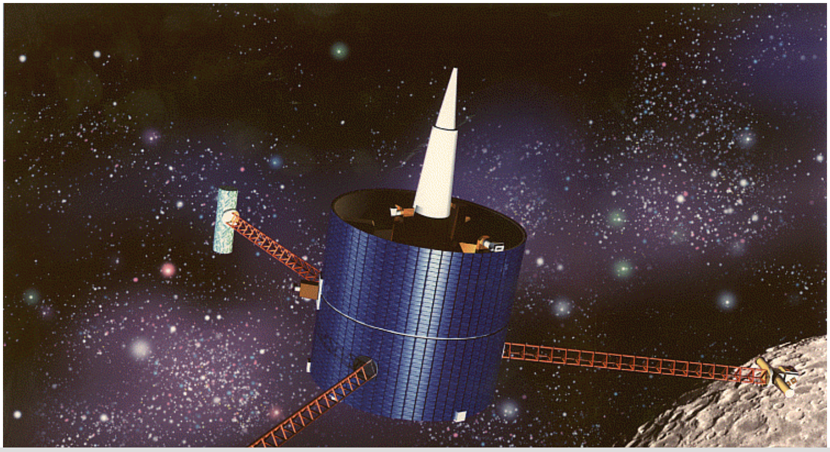
Prospector Doppler Gravity Experiment



upper = fairly flat low topography
lower = corresponding gravity field
→ "**mascon**"
red = high, blue = low gravity



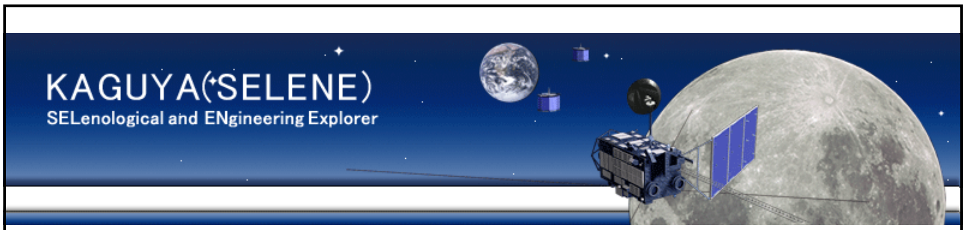
Lunar Prospector (1998)



Tonight, the ashes of Eugene M. Shoemaker are to be launched in a memorial capsule aboard Lunar Prospector to the moon. The polycarbonate capsule is carried in a vacuum-sealed, flight-tested aluminum sleeve mounted deep inside the spacecraft.

Missions to the Moon (2004 – 201X)

Clementine 1994	NASA
Lunar Prospector 1998	NASA
SMART-1 2003 - 2006	ESA
Chang'e 1 2007 – 2009	China Nat. Space Admin.
SELENE (KAYUGA) 2007/08	JAXA
Chandrayaan-1 2008/09	ISRO
LCROSS Juni – Okt. 2009	NASA
LRO Juni 2009 – …	NASA
Chang'e 2 2009 - 2013	China Nat. Space Admin
GRAIL 2012 - …	NASA


KAGUYA(SELENE)
SELenological and ENgineering Explorer


Satellites and Spacecraft
SELenological and ENgineering Explorer "KAGUYA" (SELENE)

http://www.kaguya.jaxa.jp/en/index.htm

Four way Doppler measurements by Relay satellite and Main Orbiter transponder,
Differential VLBI Radio Source (RSAT,VRAD)

Objective: Four-way Doppler and ranging to determine the lunar gravity field (at the lunar far side) …

Results:

SCIENCE VOL 323 13 FEBRUARY 2009

Seeing the Missing Half

Gregory A. Neumann[1] and Erwan Mazarico[1,2]

Results from the Japanese SELENE mission shed light on differences between the far and nearsides of the Moon.

Farside Gravity Field of the Moon from Four-Way Doppler Measurements of SELENE (Kaguya)

Noriyuki Namiki,[1*] Takahiro Iwata,[2] Koji Matsumoto,[3] Hideo Hanada,[3] Hirotomo Noda,[3] Sander Goossens,[3] Mina Ogawa,[4] Nobuyuki Kawano,[3] Kazuyoshi Asari,[3] Sei-itsu Tsuruta,[3] Yoshiaki Ishihara,[3] Qinghui Liu,[3] Fuyuhiko Kikuchi,[3] Toshiaki Ishikawa,[3] Sho Sasaki,[3] Chiaki Aoshima,[5] Kosuke Kurosawa,[6] Seiji Sugita,[6] Tadashi Takano[7]

KAGUYA
2007-09

Four way Doppler measurements by Relay satellite and Main Orbiter transponder, Differential VLBI Radio Source (RSAT,VRAD)

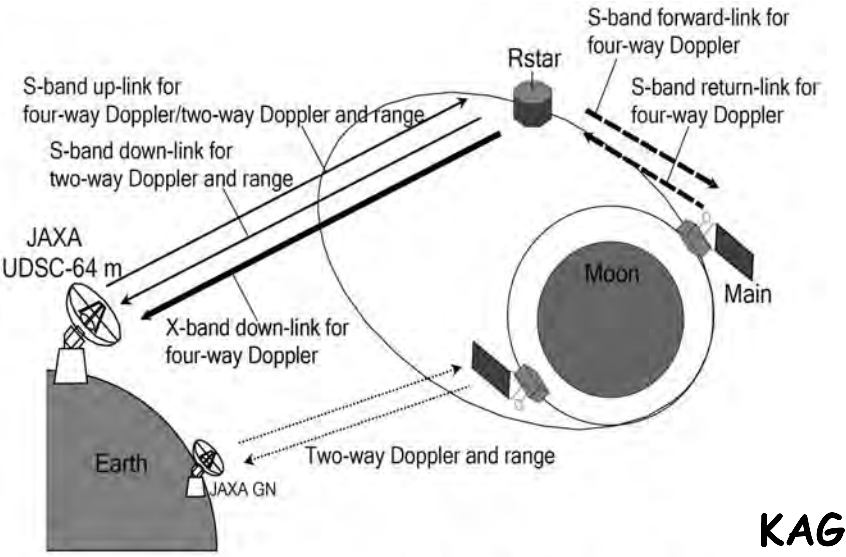
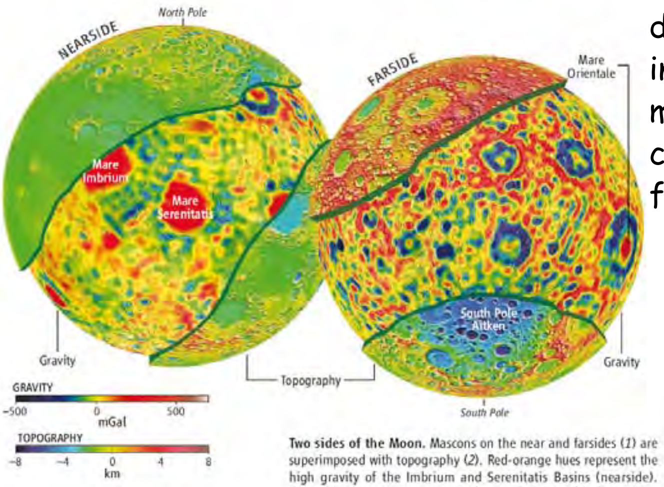


Fig. S1. Schematic diagram of the four-way Doppler measurements

KAGUYA
2007-09

Four way Doppler measurements by Relay satellite and Main Orbiter transponder, Differential VLBI Radio Source (RSAT,VRAD)



Two sides of the Moon. Mascons on the near and farsides (1) are superimposed with topography (2). Red-orange hues represent the high gravity of the Imbrium and Serenitatis Basins (nearside). Green-blue hues represent gravity lows and topographic depressions such as the large South Pole–Aitken Basin (bottom right). Note the different character between the nearside mascons and the farside mascons with their large negative anomaly rings.

Results: mass distribution indicates cooler, more rigid conditions at the farside

Namiki et al. 2009 SCIENCE 323

KAGUYA
2007-09

Lunar Global Shape and Polar Topography Derived from Kaguya-LALT Laser Altimetry

H. Araki,[1]* S. Tazawa,[2] H. Noda,[1] Y. Ishihara,[2] S. Goossens,[2] S. Sasaki,[2] N. Kawano,[2]
I. Kamiya,[3] H. Otake,[4] J. Oberst,[5] C. Shum[6]

A global lunar topographic map with a spatial resolution of finer than 0.5 degree has been derived using data from the laser altimeter (LALT) on board the Japanese lunar explorer Selenological and Engineering Explorer (SELENE or Kaguya). In comparison with the previous Unified Lunar Control Network (ULCN 2005) model, the new map reveals unbiased lunar topography for scales finer than a few hundred kilometers. Spherical harmonic analysis of global topographic data for the Moon, Earth, Mars, and Venus suggests that isostatic compensation is the prevailing lithospheric support mechanism at large scales. However, simple rigid support is suggested to dominate for the Moon, Venus, and Mars for smaller scales, which may indicate a drier lithosphere than on Earth, especially for the Moon and Venus.

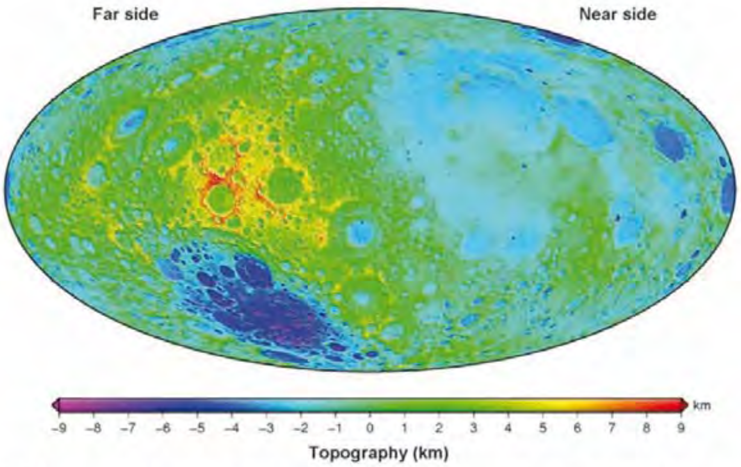


Fig. 1. Lunar global topographic map obtained from LALT altimetry data shown in Hammer equal-area projection. Lunar coordinates are based on the mean Earth/polar axis system. Reference of the height is a sphere whose radius is 1737.4 km and whose origin is set to the center of mass (*19*). The map center is 270°E, with the nearside on the right and the farside on the left. Full range of the topography is about 19.81 km. The highest point is on the southern rim of the Dirichlet-Jackson basin (−158.64°E, 5.44°N, +10.75 km), and the lowest point is inside Antoniadi crater (−172.58°E, 70.43°S, −9.06 km) in the South Pole–Aitken Basin.

19.81 km

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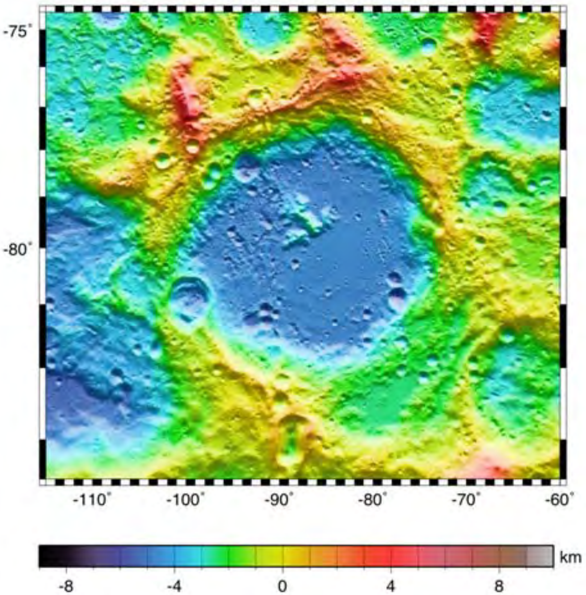
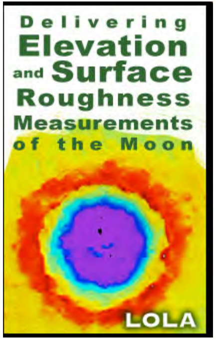
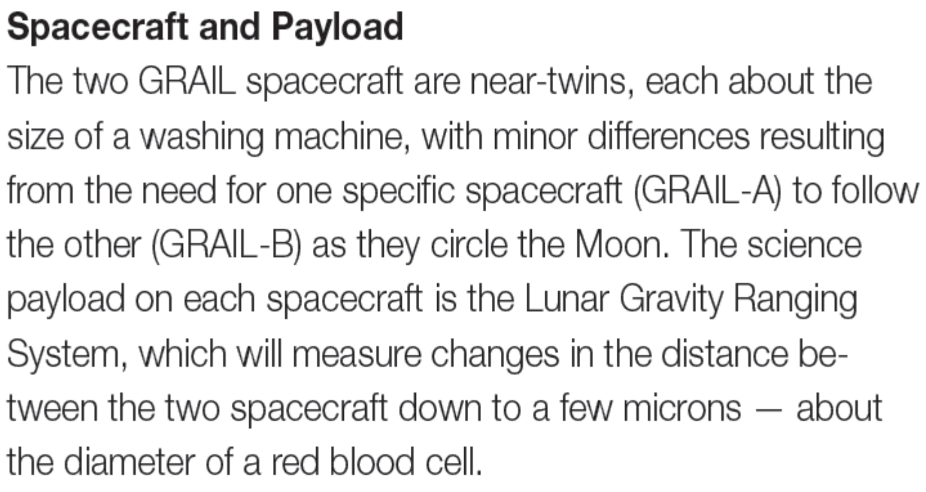




Drygalski Crater
(Ø 149 km),
located near the
lunar south pole

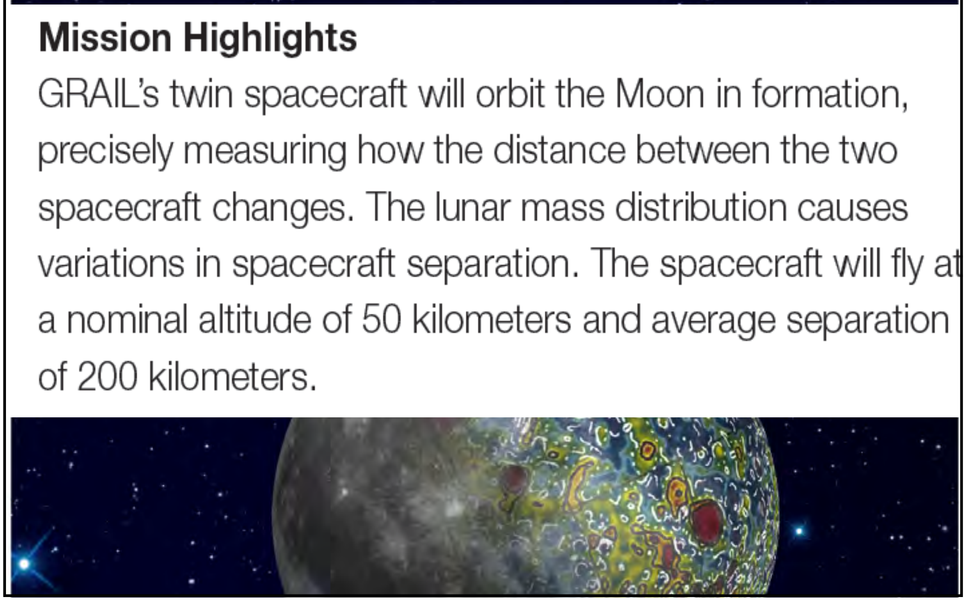
NASA's Gravity Recovery and Interior Laboratory
GRAIL



Spacecraft and Payload

The two GRAIL spacecraft are near-twins, each about the size of a washing machine, with minor differences resulting from the need for one specific spacecraft (GRAIL-A) to follow the other (GRAIL-B) as they circle the Moon. The science payload on each spacecraft is the Lunar Gravity Ranging System, which will measure changes in the distance between the two spacecraft down to a few microns — about the diameter of a red blood cell.

NASA's Gravity Recovery and Interior Laboratory GRAIL



Mission Highlights

GRAIL's twin spacecraft will orbit the Moon in formation, precisely measuring how the distance between the two spacecraft changes. The lunar mass distribution causes variations in spacecraft separation. The spacecraft will fly at a nominal altitude of 50 kilometers and average separation of 200 kilometers.

	Moon	Earth	Ratio Moon/Earth
Mass (M - 10^{24} kg)	0.07349	5.9736	
Volume (V - 10^{10} km3)	2.1958	108.321	0.0203
Equatorial radius (r - km)	1738.1	6378.1	0.2725
Polar radius (km)	1736.0	6356.8	0.2731
Ellipticity (Flattening)	0.0012	0.00335	0.36
Mean density (kg/m3)		5515	0.607
Surface gravity (m/s2)	1.62	9.80	0.165
Escape velocity (km/s)	2.38	11.2	0.213
Topographic range (km)	19.8	20	0.99
Moment of inertia I (M r2)	0.394	0.3308	1.191
point mass M at a distance r from the axis of rotation.			

http://nssdc.gsfc.nasa.gov/planetary/factsheet/

Moment of Inertia (I = inertia, J)

Trägheitsmoment

Body	*I*
hollow sphere	0.667
homogeneous sphere	0.400
sphere with core with ½ of the total radius and 2x density of the mantle	0.347
mass concentrated entirely at center	0.000

Body	*I*
Moon	0.391
Mars	0.365
Earth	0.3307
Neptune	0.29
Jupiter	0.26
Uranus	0.23
Saturn	0.20
Sun	0.06

Moment of Inertia (I = inertia, J)

Trägheitsmoment

Interpretation
Moon - quite homogeneous distribution, small Fe core
Mars - some central concentration, Fe core
Earth – large Fe core
gaseous giants + Sun – I / Mr² “inflated“ by light gases, reducing I

Body	*I*
Moon	0.391
Mars	0.365
Earth	0.3307
Neptune	0.29
Jupiter	0.26
Uranus	0.23
Saturn	0.20
Sun	0.06

HARTMANN 1999 Moons and Planets

Object	Magnetic field (nT)[a]
Sun	200 000[b]
Mercury	220
Venus	<30
Earth	30 500
Moon	
3.3 Gy ago	2 000
Today	10
Mars	40

Magnetic field of selected bodies in the solar system

1 nT (Tesla) =
10^{-9} T = 1 Gamma = 10^{-5} Gauss

	MERCURY	VENUS	EARTH	MOON	MARS
Diameter (km)	4879	12,104	12,756	3475	6794
Density (kg/m^3)	5427	5243	5515	3340	3933
Rotation Period (hours)	1407.6	-5832.5	23.9	655.7	24.6

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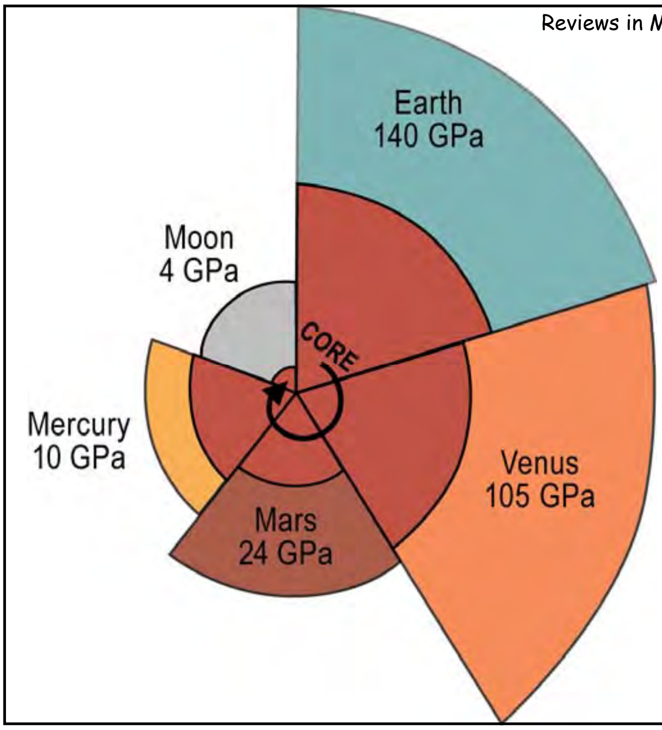
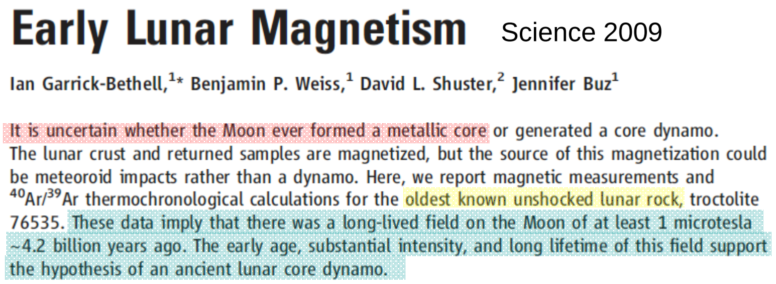


Wieczorek et al. 2006

A **core dynamo** on the Moon? YES, at 4.2 Ga



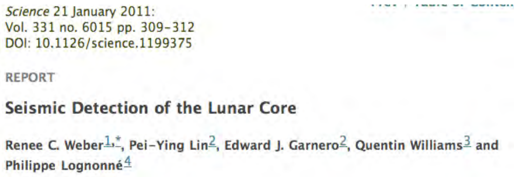
Early Lunar Magnetism

Science 2009

Ian Garrick-Bethell,[1]* Benjamin P. Weiss,[1] David L. Shuster,[2] Jennifer Buz[1]

It is uncertain whether the Moon ever formed a metallic core or generated a core dynamo. The lunar crust and returned samples are magnetized, but the source of this magnetization could be meteoroid impacts rather than a dynamo. Here, we report magnetic measurements and $^{40}Ar/^{39}Ar$ thermochronological calculations for the oldest known unshocked lunar rock, troctolite 76535. These data imply that there was a long-lived field on the Moon of at least 1 microtesla ~4.2 billion years ago. The early age, substantial intensity, and long lifetime of this field support the hypothesis of an ancient lunar core dynamo.

A **liquid core** in the Moon today? YES



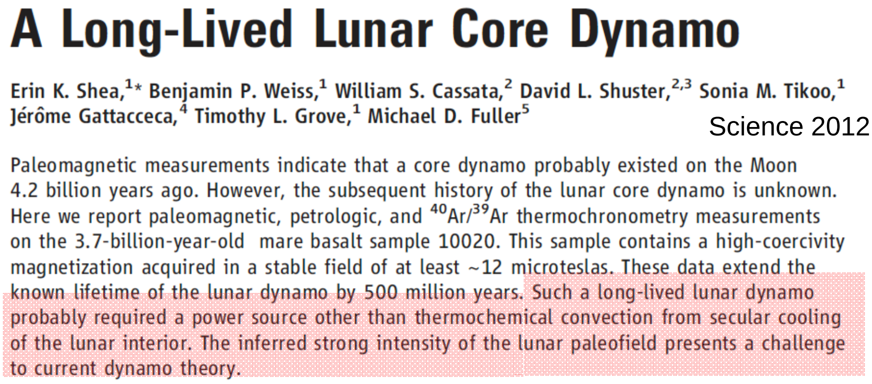
Science 21 January 2011:
Vol. 331 no. 6015 pp. 309–312
DOI: 10.1126/science.1199375

REPORT

Seismic Detection of the Lunar Core

Renee C. Weber[1,*], Pei-Ying Lin[2], Edward J. Garnero[2], Quentin Williams[3] and Philippe Lognonné[4]

small (330 km radius), solid core (40% vol), liquid core (60%)



A Long-Lived Lunar Core Dynamo

Erin K. Shea,[1]* Benjamin P. Weiss,[1] William S. Cassata,[2] David L. Shuster,[2,3] Sonia M. Tikoo,[1] Jérôme Gattacceca,[4] Timothy L. Grove,[1] Michael D. Fuller[5]

Science 2012

Paleomagnetic measurements indicate that a core dynamo probably existed on the Moon 4.2 billion years ago. However, the subsequent history of the lunar core dynamo is unknown. Here we report paleomagnetic, petrologic, and $^{40}Ar/^{39}Ar$ thermochronometry measurements on the 3.7-billion-year-old mare basalt sample 10020. This sample contains a high-coercivity magnetization acquired in a stable field of at least ~12 microteslas. These data extend the known lifetime of the lunar dynamo by 500 million years. Such a long-lived lunar dynamo probably required a power source other than thermochemical convection from secular cooling of the lunar interior. The inferred strong intensity of the lunar paleofield presents a challenge to current dynamo theory.

Core dynamo at the Moon at 3.7 Ga!

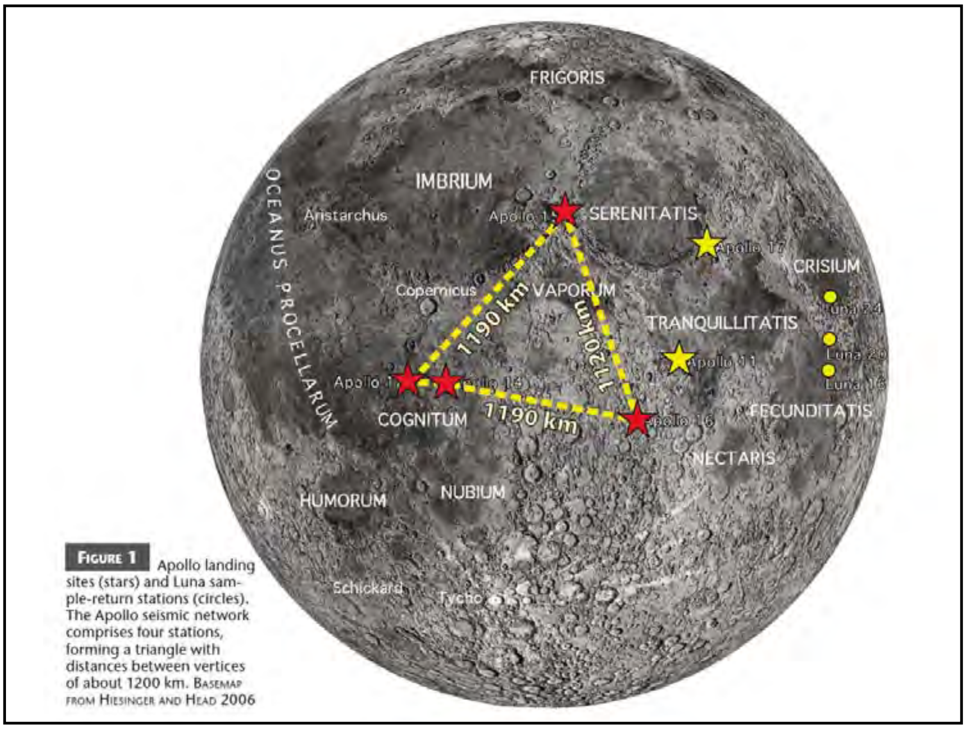
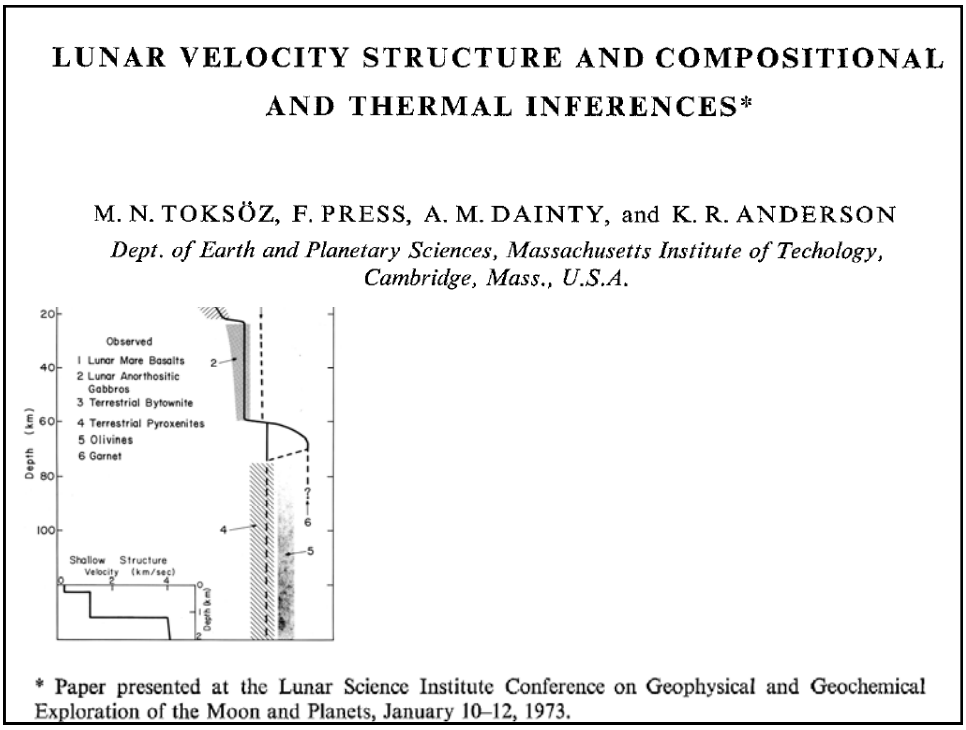


FIGURE 1 Apollo landing sites (stars) and Luna sample-return stations (circles). The Apollo seismic network comprises four stations, forming a triangle with distances between vertices of about 1200 km. BASEMAP FROM HIESINGER AND HEAD 2006



LUNAR VELOCITY STRUCTURE AND COMPOSITIONAL AND THERMAL INFERENCES*

M. N. TOKSÖZ, F. PRESS, A. M. DAINTY, and K. R. ANDERSON

Dept. of Earth and Planetary Sciences, Massachusetts Institute of Techology,
Cambridge, Mass., U.S.A.

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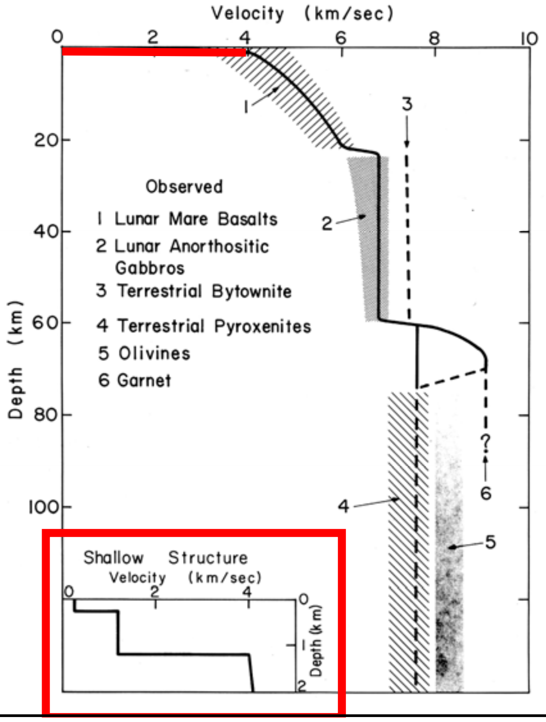
* Paper presented at the Lunar Science Institute Conference on Geophysical and Geochemical Exploration of the Moon and Planets, January 10–12, 1973.



SR TAYLOR 1975 Lunar Science
Post-Apollo View

Velocity profile (Vp) of the lunar crust and the upper mantle

based on seismic measurements

U Kiel

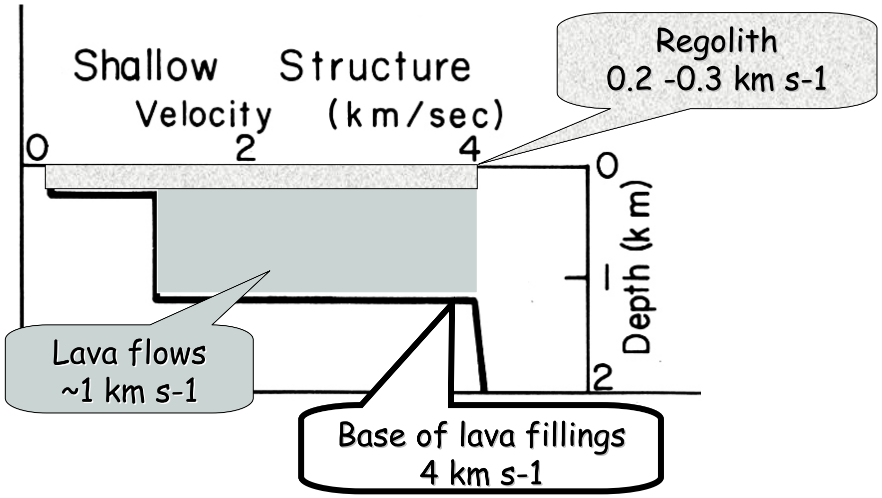
P-[redacted]-waves	
Material	**V_p km s^{-1}**
air	**0,3**
water	**1,45**
	Sediments
sand, clay	**1,5 - 2,5**
limestone	**3,5 - 5,5**
sandstone	**1,8 - 3,0**
	Metamorphic rocks
gneiss	**6,6 - 7,0**
amphibolite	**6,9 - 7,0**
peridotite	**7,9 - 8,1**
eclogite	**7,8 - 8,1**
	Magmatite
granite	**5,6 - 6,3**
gabbro	**6,5 - 6,8**

SR TAYLOR 1975 Lunar Science Post-Apollo View

Velocity profile (Vp)of the upper 2 km of the lunar crust

based on seismic measurements + gravity data

A 17 Taurus-Littrow Site



Regolith
0.2 -0.3 km s-1

Lava flows
~1 km s-1

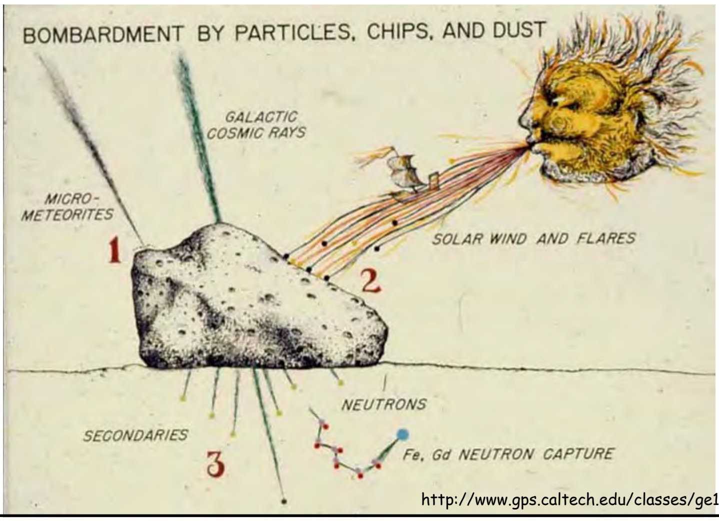
Base of lava fillings
4 km s-1

Regolith

- typische geologische Formation auf allen planetaren Körpern ohne Atmosphäre
- reflektiert Untergrund-Zusammensetzung
- schützt unterliegende Gesteine
- liegt auf Mega-Regolith
- max. 20 m mächtig; mittlere Mächtigkeit Mare-Ebenen ~4-5 m, Hochland 10-15 m
- wird von lunar Soils bedeckt

Lunarer Regolith

- hohe Gehalte an Sonnenwind (Edelgase)
  alle Komponenten zeigen Strahlenschäden



http://www.gps.caltech.edu/classes/ge151/albee/s37.jpg

Lunar Radar Sounder Observations of Subsurface Layers Under the Nearside Maria of the Moon

Science 323, 2009

Takayuki Ono,[1] Atsushi Kumamoto,[1] Hiromu Nakagawa,[1] Yasushi Yamaguchi,[2]
Shoko Oshigami,[2] Atsushi Yamaji,[3] Takao Kobayashi,[4] Yoshiya Kasahara,[5] Hiroshi Oya[6]

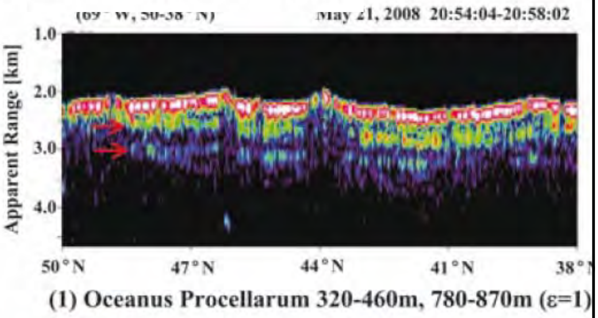
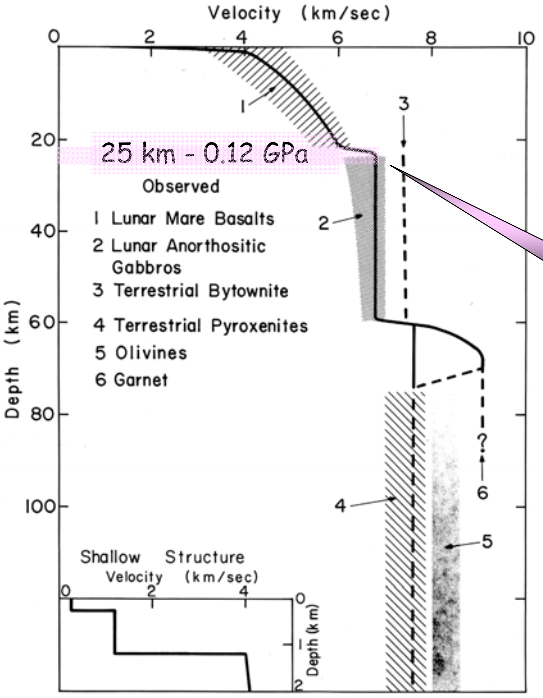


Fig. 1. B-scan (*10*) displays with obvious subsurface echoes (red arrows). Doppler focusing was not applied to the data. Observation ground tracks are plotted on the topographic map (center left panel) that was generated using the LRS as an altimeter. A spherical surface with a radius of 1737.4 km is used as the reference for the vertical coordinates.

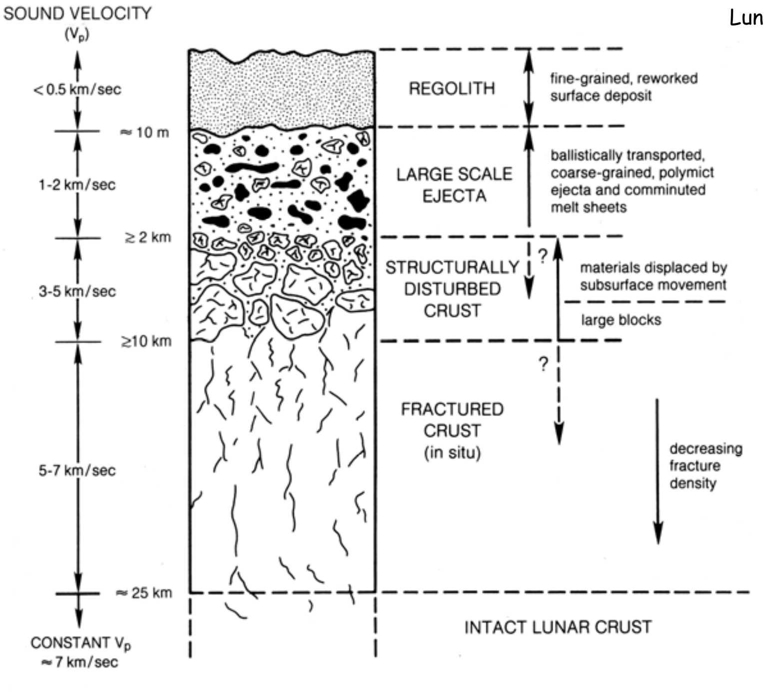
SR TAYLOR 1975 Lunar Science
Post-Apollo View

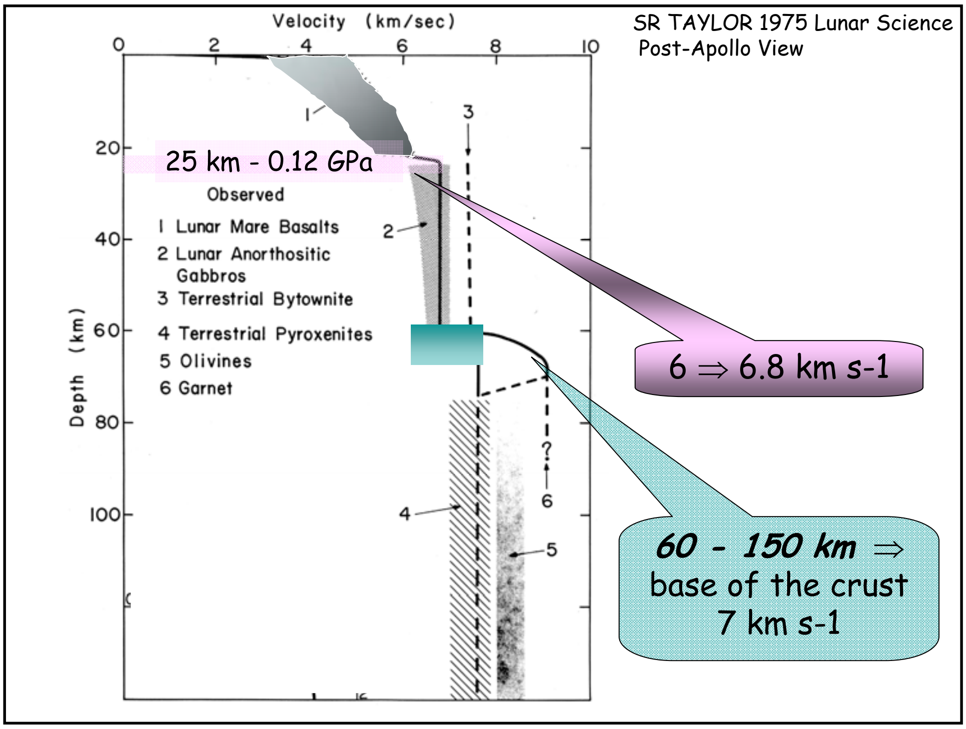
Velocity profile (Vp) of the lunar crust and the upper mantle



6 ⇒ 6.8 km s-1

Lunar Source Book



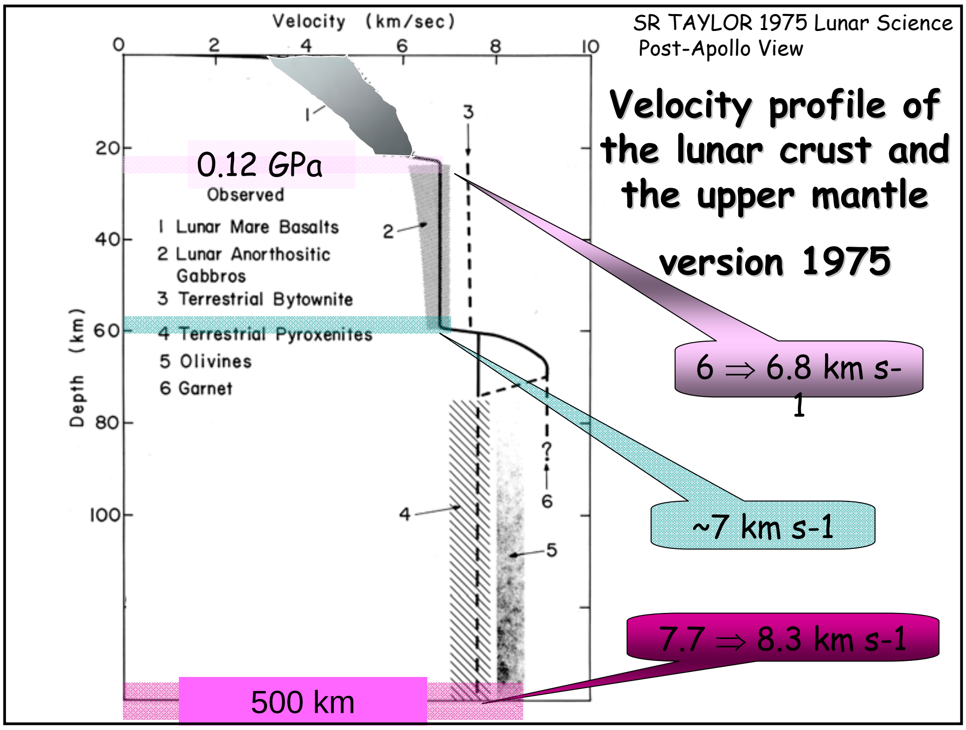


SR TAYLOR 1975 Lunar Science
Post-Apollo View

25 km - 0.12 GPa

6 ⇒ 6.8 km s-1

60 - 150 km ⇒
base of the crust
7 km s-1



SR TAYLOR 1975 Lunar Science
Post-Apollo View

Velocity profile of the lunar crust and the upper mantle

version 1975

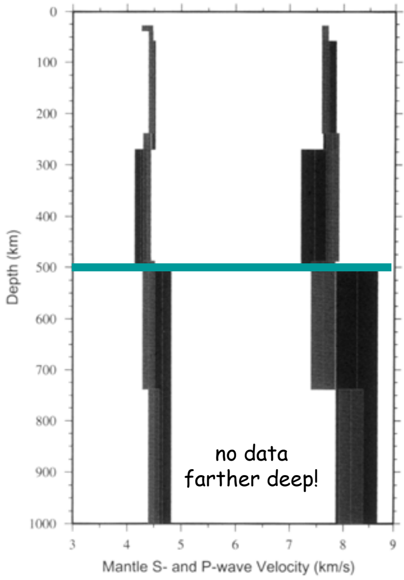
0.12 GPa

6 ⇒ 6.8 km s-1

~7 km s-1

7.7 ⇒ 8.3 km s-1

500 km



no data
farther deep!

Figure 3.21. P- and S-wave velocity profiles of the lunar mantle based on the studies of Lognonné et al. (2003) (gray) and Nakamura et al. (1982) (black) with 1-σ uncertainties. Note the different velocity scale with respect to Figure 3.19.

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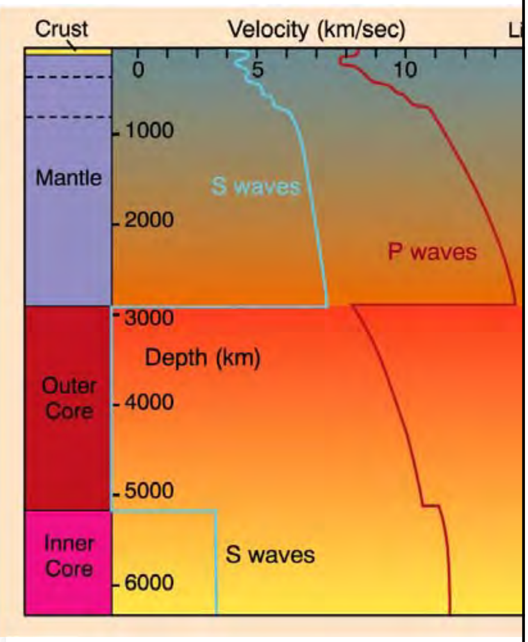

Earth

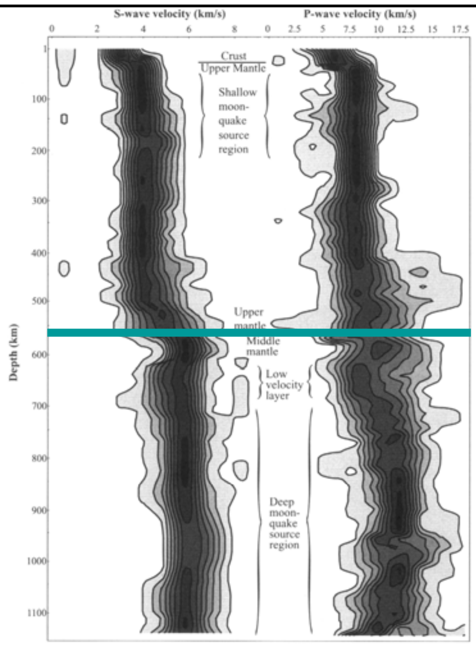

Figure 3.19. P and S-wave velocity profiles of the lunar mantle based on the Bayesian inversion of Khan et al. (2000). The marginal probability of the seismic velocity is plotted at one-kilometer depth intervals, and the contours define nine equally sized probability intervals. [Used by permission of the American Geophysical Union, from Khan et al. (2000), *Geophysical Research Letters*, Vol. 27, Fig. 1a, p. 1592.]

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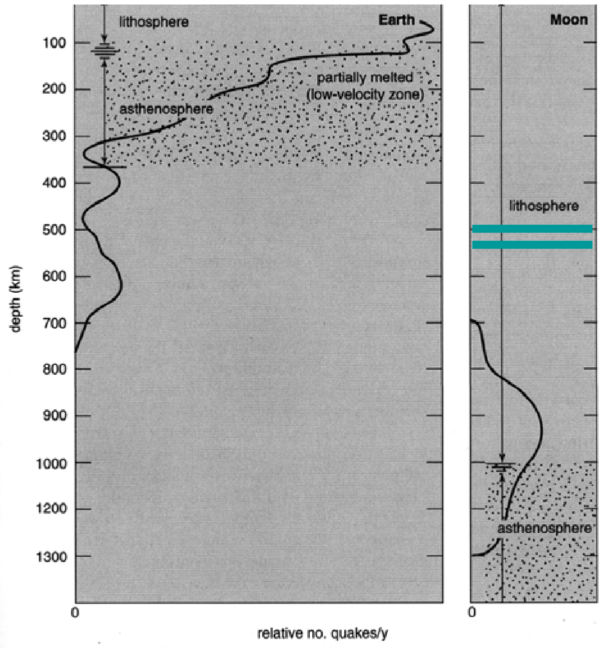
Velocity profile of the lunar interior

2006 version 2

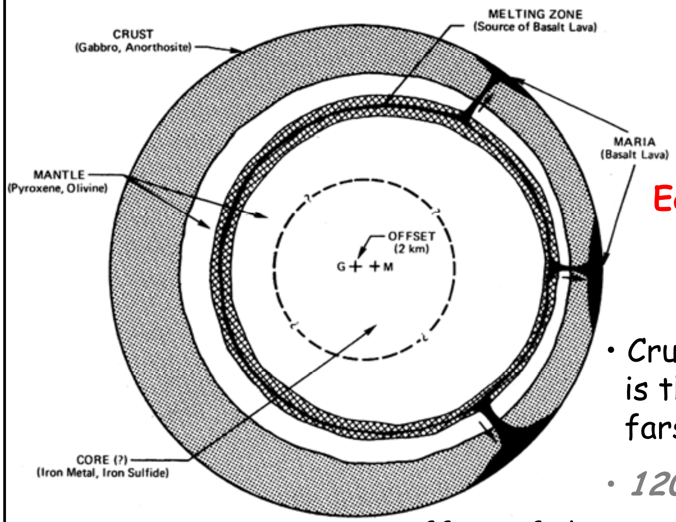
HARTMANN 1999 Moons and Planets

Seismic discontinuity



THE LUNAR INTERIOR

BM FRENCH 1977 The Moon Book

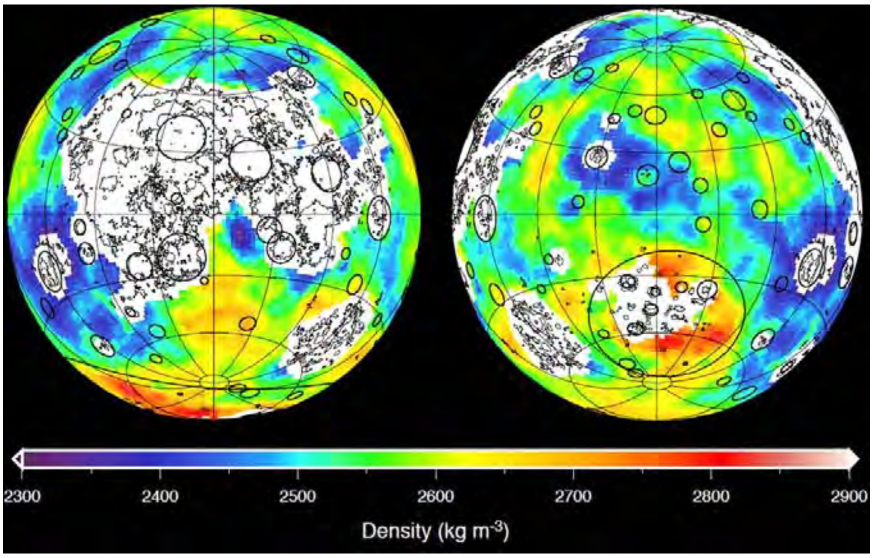


Earth →

- Crust at the nearside is thinner than at the farside.
- *120 – 20* km
- offset of the mass center from the geometric center by ~2 km

NASA - GRAIL

Bulk density of the lunar crust



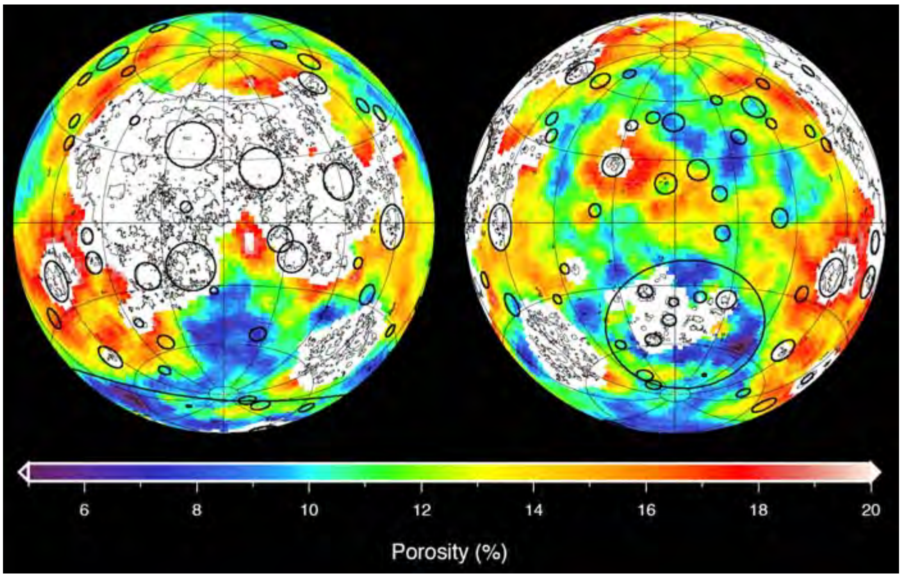
near

far

Wieczorek et al. 2012 Science Dec 6

NASA - GRAIL

Porosity of the lunar crust



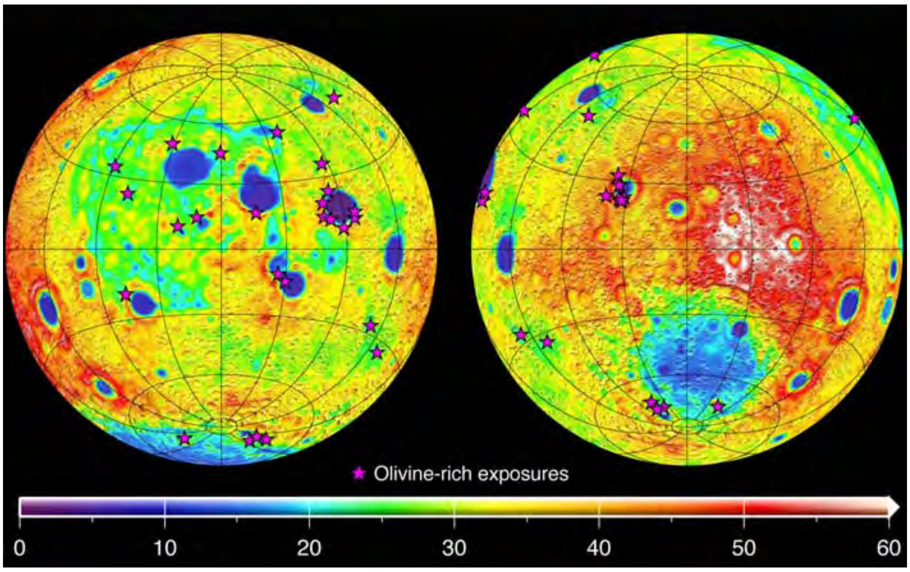
near

far

Wieczorek et al. 2012 Science Dec 6

NASA - GRAIL

Crustal thickness of the Moon



near

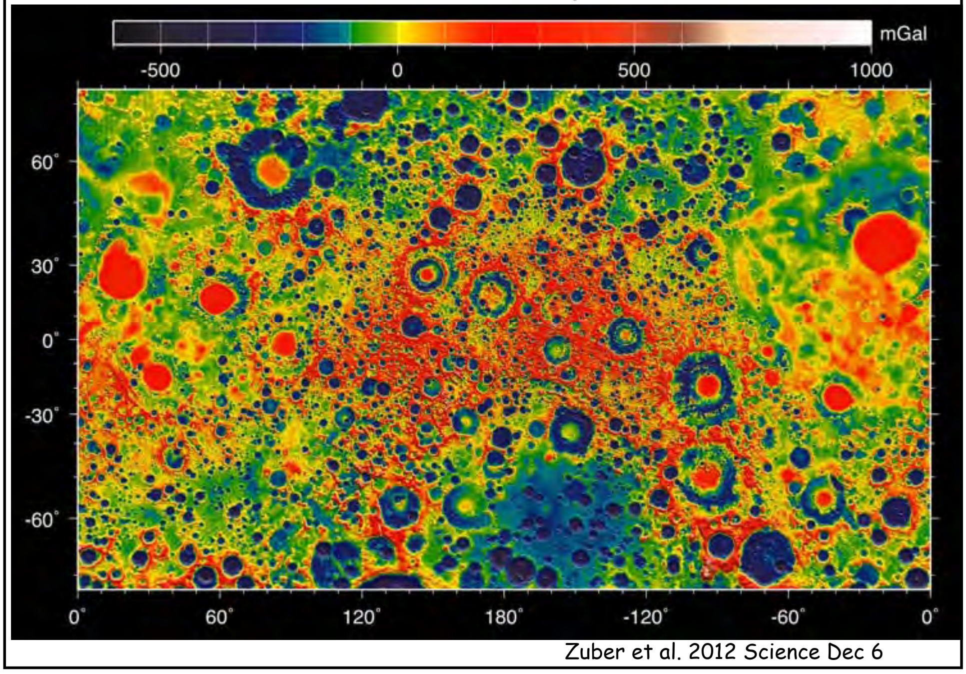
far

Moscoviense Basin < 1 km

Wieczorek et al. 2012 Science Dec 6

NASA - GRAIL

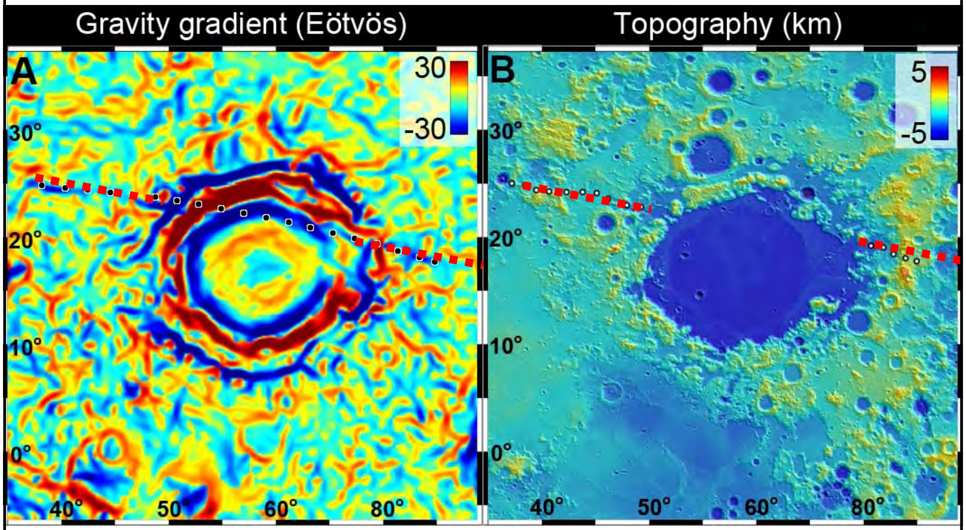
Gravity field of the Moon



Zuber et al. 2012 Science Dec 6

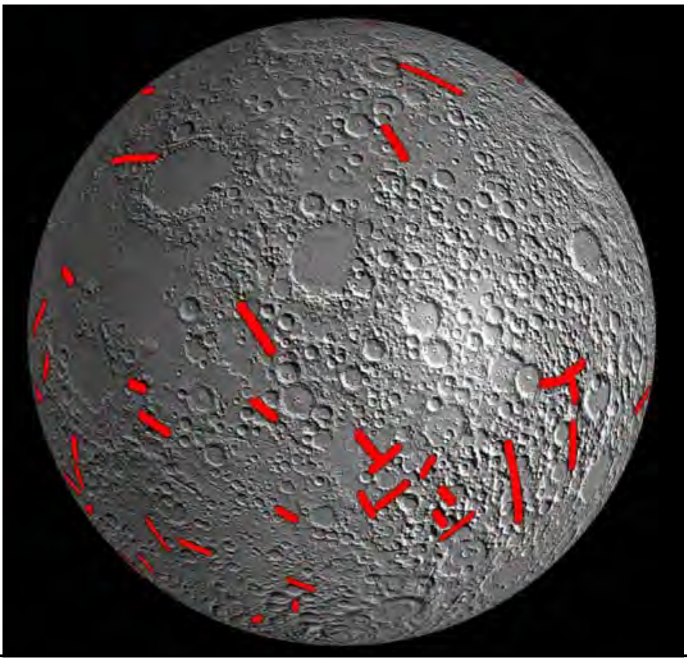
NASA - GRAIL

Linear gravity anomaly truncated by the Crisium basin



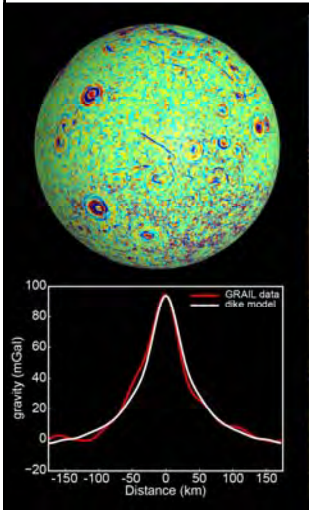
NASA - GRAIL

Dyke map of the Moon



NASA - GRAIL

Dyke map of the Moon

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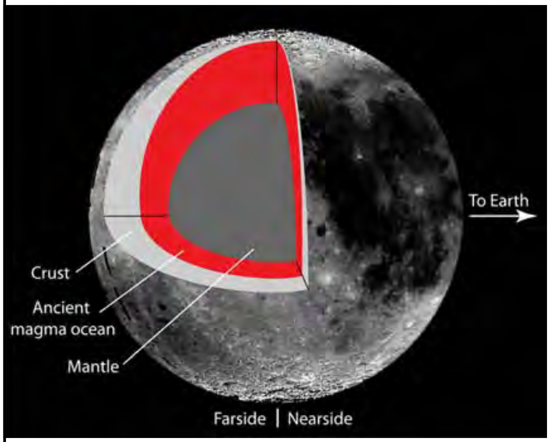
NASA's Gravity Recovery and Interior Laboratory GRAIL



Earth →

- Crust at the nearside is thinner than at the farside.
- 60 – 2 km

T. SPOHN Planetologie

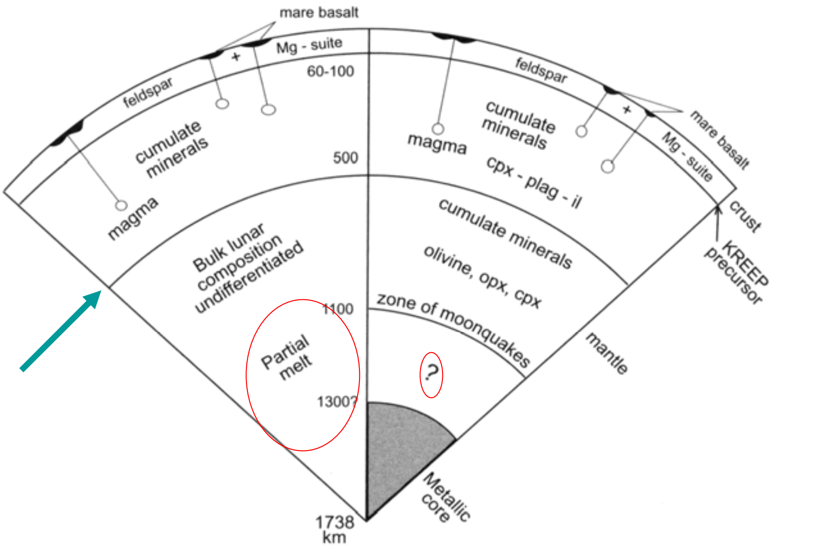


Figure 7.1. Two alternatives for the internal structure of the Moon. On the left, only half the Moon melted and differentiated and the deep interior has primitive lunar composition. Some partial melting has occurred due to the presence of K, U, and Th. This model is consistent with the lunar free oscillation periods (Amir Kahn, Univ. of Copenhagen personal communication). On the right, the Moon was totally melted and differentiated, forming a small metallic core (adapted from Taylor 2001).

Doppler Gravity Experiment (DGE)

Lunar Prospector (1998)

gravity map of the Moon:

upper: fairly flat low topography

lower: corresponding strong gravity field → "**mascon**"