Lunar Science by Kaguya

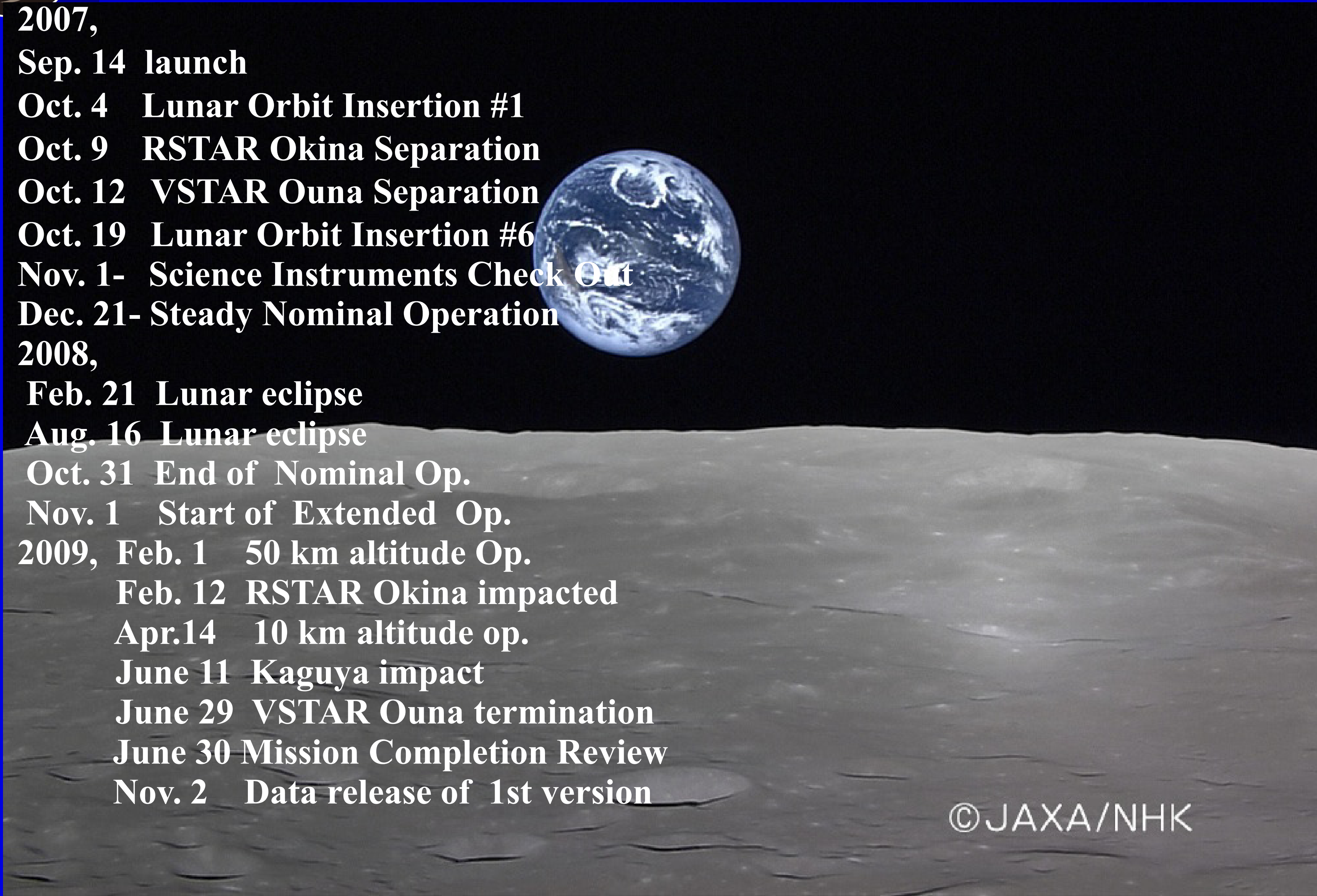
SELenological and ENgineering Explorer

M. Kato, S. Sasaki, Y. Takizawa and the Kaguya team

Jan. 5, 2011

Kaguya's Sequence of Events

2007,
Sep. 14 launch
Oct. 4 Lunar Orbit Insertion #1
Oct. 9 RSTAR Okina Separation
Oct. 12 VSTAR Ouna Separation
Oct. 19 Lunar Orbit Insertion #6
Nov. 1- Science Instruments Check Out
Dec. 21- Steady Nominal Operation
2008,
Feb. 21 Lunar eclipse
Aug. 16 Lunar eclipse
Oct. 31 End of Nominal Op.
Nov. 1 Start of Extended Op.
2009, Feb. 1 50 km altitude Op.
Feb. 12 RSTAR Okina impacted
Apr.14 10 km altitude op.
June 11 Kaguya impact
June 29 VSTAR Ouna termination
June 30 Mission Completion Review
Nov. 2 Data release of 1st version



Kaguya (SELENE) Science Mission and Instruments

X-ray Spectrometer (XRS)	Global mapping of Al, Si, Mg, Fe distribution using **100 cm^2 CCD, spatial resolution 20 km**, Energy range 0.7-8 keV, 5 μm Be film, Solar X-ray monitor
Gamma-ray Spectrometer (GRS)	Global mapping of U, Th, K, major elements, distribution using **250 cm^3 large pure Ge crystal, Spatial resolution 160 km**, Energy range 0.1-10 MeV
Multi-band Imager (MI)	UV-VIS-NIR CCD & InGaAs imager, spectral bandwidth from0.4 to 1.6 microns, 9 bands filters, spectral resolution 20-30 nm, **spatial resolution 20-60 m**
Spectral Profiler (SP)	Continuous spectral profile ranging from 0.5 to 2.6 microns, spectral resolution 6-8 nm, **spatial resolution 500 m**
Terrain Camera (TC)	High resolution stereo camera, **spatial resolution 10 m**
Lunar Radar Sounder (LRS)	Mapping of subsurface structure using active sounding, frequency **5 MHz**, echo observation range **5 km**, resolution 75 m, Detection of radio waves (**10k-30MHz**) from the Sun, the Earth, Jupiter, and other planets
Laser Altimeter (LALT)	Nd:YAG laser altimeter, **100 mJ** output power, height resolution 5 m, spatial resolution **1600 m** with pulse rate 1 Hz, Beam divergence 3 mrad
Differential VLBI Radio Source (VRAD)	Differential VLBI observation from ground stations, selenodesy and gravitational field, onboard two sub-satellites, **3 S-bands and 1 X-band**
Relay Satellite Transponder (RSAT)	Far-side gravimetry using **4 way range rate** measurement from ground station to orbiter via relay satellite, perilune 100 km, apolune 2400 km in altitude, **Doppler accuracy 1 mm/s**
Lunar Magnetometer (LMAG)	Magnetic field measurement using flux-gate type magnetometer, accuracy **0.5 nT**
Charged Particle Spectrometer (CPS)	Measurement of high-energy particles, **1-14 MeV(LPD), 2-240 MeV(HID), alpha particle detector, 4-6.5 MeV**
Plasma Analyzer (PACE)	Charged particle energy, angle and composition measurement, **5 eV/q – 28 keV/q**
Radio Science (RS)	Detection of the tenuous lunar ionosphere using **S and X-band carriers**
Plasma Imager (UPI)	Observation of terrestrial plasmasphere from lunar orbit, **XUV(304A) to VIS**
High Definition TV System	**Public Outreach**

Published Kaguya Science 1.

● **GRS**: First Results of High Performance Ge Gamma-Ray Spectrometer Onboard Lunar Orbiter SELENE (KAGUYA), Hasebe et al., *J. Phys. Soc. Jpn.* **78** (2009) Suppl. A, 18-25/ Germanium Gamma-Ray Spectrometer on SELENE(KAGUYA), N. Yamashita et al., *J. Phys. Soc. Jpn.* **78** (2009) Suppl. A, 153-156/ Radioactive element U distribution in addition to Th and K distributions, Karouji et al., *Adv. Geosci.* **19**(2010), 43-56. /Uranium on the Moon: The Global Distribution and U/Th Ratio, Yamashita et al., *GRL* **37**(2010) L10201. /Determining the Absolute Abundances of Natural Radioactive Elements on the Lunar Surface by Kaguya Gamma-ray Spectrometer, Kobayashi, S. et al., *Space Sci. Rev*. **154** (2010), 193-218./ Lunar Gamma-Ray Observation by Kaguya GRS, N. Hasebe et al., *Adv. Geosci*. **19** (2010) 57-68./ Neutron production in the lunar subsurface from alpha particles in galactic cosmic rays , Ohta et al., *EPS* **62** (2010) in press.

●**MI**: The global distribution of pure anorthosite on the Moon, M. Ohtake et al., *Nature* **461**(2009), 236-241. /Characterization of Multiband Imager aboard SELENE: Pre-flight and inflight radiometric calibration, Kodama et al., *Space Sci. Rev.* **152**(2010) 79-102./ Deriving the absolute reflectance of lunar surface using SELENE (Kaguya) Multiband Imager data , Ohtake et al., Space *Sci. Rev.* **154** (2010) 57-77.

● **SP**: Discoveries on the lithology of lunar crater central peaks by SELENE Spectral Profiler, Matsunaga et al., *GRL* **35** (2008), L23201./ Ultramafic impact melt sheet beneath the South Pole-Aitken basin on the Moon, R. Nakamura, et al., *GRL* **36** (2009), L22202. /Possible mantle origin of olivine around lunar impact basins detected by SELENE, Yamamoto et al., *Nature Geosci.* **3**(2010) 533-536..

●**TC**: Lack of exposed ice inside lunar south pole Shackleton, Haruyama et al., *Science* **322** (2008), 938-939./ Volcanic history of lunar far side revealed by Terrain Camera on SELENE, Haruyama et al., *Science* **323**(2009), 905- 908. /Formation age of the lunar crater Giordano Bruno, Morota et al., *MePS* **44**(2009), 1115-1120./ Mare Volcanism in the Lunar Farside Moscoviense Region: Implication for Lateral Variation in Magma Production of the Moon, Morota et al., *GRL* **36,** L21202./ Possible lunar lava tube skylight observed by SELENE cameras, Haruyama et al., *GRL* **36**(2009), L21206. /Timing and duration of mare volcanism in the central region of the northern farside of the Moon, Morota et al., *EPS* **62**(2010) , in press. /Timing and characteristics of the latest mare eruption on the Moon, Morota et al., *EPSL* **301**(2010), in press.

● **LRS**: Lunar radar sounder observation and founding of subsurface strata below the nearside lunar maria, Ono et al., *Science* **323**(2009), 909-911./ Distribution of the subsurface reflectors of the western nearside maria observed from Kaguya with Lunar Radar Sounder, Oshigami et al., *GRL* **36** (2009), L18202./ Detectability of subsurface interfaces in lunar maria by the LRS /SELENE sounding radar: influence of mineralogical composition, Pommerol et al., *GRL***37** (2010), L03201. / The Lunar Radar Sounder (LRS) onboard the Kaguya (SELENE) spacecraft, Ono et al., *Space Sci. Rev.* **154**(2010) 145-192./ Electrostatic solitary waves associated with magnetic anomalies and wake boundary of the Moon observed by KAGUYA,

Published Kaguya Science 2.

●**LALT**: Illumination conditions at the lunar polar regions by KAGUYA (SELENE) laser altimeter, Noda et al., *Geophys. Res. Lett*. 3**5** (2008), L24203 / , Lunar global shape and polar topography derived from KAGUYA-LALT laser altimetry, Araki et al., *Science* **323** (2009), 897-899. /Accuracy assessment of lunar topography models, H.S. Fok et al., *EPS* **62** (2010) in press.

●**RSAT**: Far side gravity field of the Moon from four-way Doppler measurements of SELENE (Kaguya)), Namiki et al., *Science* **323**(2009), 909-911. / Crustal thickness of the Moon: Implications for farside basin structures, Ishihara et al., *GRL* **36**, L19202./ An improved lunar gravity field model from SELENE and historical tracking data: revealing the farside gravity features, Matsumoto et al., *J. Geophys. R* es.**115**(2010), E06007. / Ground compatibility tests for gravity measurement of SELENE: Accuracies of two-and four-way Doppler and range measurements, Namiki et al., *Space Sci. Rev.* **154** (2010) 103-121./ Effect of Phase Pattern of Antennas Onboard Flying Spin Satellites on Doppler Measurements for Lunar Gravity Field, Q. Liu et al., *IEEE Trans., Aerospace Electron. Syst.*, in press (2010.

●**VRAD**: Pico-second accuracy VLBI of the twe-subsatellites of SELENE (Kaguya) using multi-frequency and same beam method, Kikuchi et al., *Radio Sci.* **44**(2009), RS2008. / Overview of differential VLBI observations of lunar orbiters in SELENE(Kaguya) for precise orbit determination and lunar gravity field study, Hanada et al., *Space Sci. Rev.* **154**(2010) 123-144. / Same-beam VLBI observations of SELENE (KAGUYA) for improving lunar gravity field model, Q. Liu et al., *Radio Sci.* **45** (2010) RS2004.

● **PACE**: Solar wind proton reflection at the lunar surface: Low energy ion measurement by MAP-PACE onboard SELENE (KAGUYA), Saito et al., *Geophys. Res. Lett*. **35** (2008), L24205. /First direct detection of ions originating from the Moon by MAP-PACE IMA onboard SELENE (KAGUYA), Yokota et al., *GRL* **36**(2009), L38185. / Solar-wind proton access deep into the near-Moon wake, Nishino et al., *GRL* **36** (2009), L16103./Pairwise energy gain-loss feature of solar wind protons in the near-Moon wake, Nishino et al., *GRL* **36**(2009), L12108./First in situ observation of the Moon-originating ions in the Earth's Magnetosphere by MAP-PACE on SELENE (KAGUYA), Tanaka et al., *GRL* **36**(2009), L22106. /Effect of the solar wind proton entry into the deepest lunar wake, Nishino et al., *GRL* **37**(2010), L12106. / In-flight Performance and Initial Results of PlasmaEnergy Angle and Composition Experiment (PACE)on SELENE(Kaguya), Saito et al., *Space Sci. Rev*. **154**(2010) 265-303. / Interaction between terrestrial plasma sheet electrons and the lunar surface: SELENE (Kaguya), observations, Y. Harada et al., *GRL* **37** (2010), L19202/ New views of the lunar plasma environment , J.S. Halekas et al., *Planet. Space Sci*. **58** (2010) in press.

Published Kaguya Science 3.

- LMAG: Plasmoid formation for multiple onset substorms: observations of the Japanese Lunar Mission "Kaguya", Nagai et al., *Ann. Geophys* **27** (2009), 59- 64, 2009./Thermal core-mantle coupling in an early lunar dynamo: Implications for a global magnetic field and magnetosphere of the early Moon, Takahashi et al., *GRL* **36**(2009), L24202./In-orbit calibration of the lunar magnetometer onboard SELENE (KAGUYA) , F. Takahashi, et al., *Earth Planets Space*, **61** (2009) 1269-1274. / Lunar magnetic field observation and initial global mapping of lunar magnetic anomalies by MAP-LMAG onboard SELENE (KAGUYA), Tsunakawa et al., *Space Sci. Rev.* **154**(2010) 219-251./ Magnetic Cleanliness Program Under Control of Electromagnetic Compatibility for the SELENE (KAGUYA) Spacecraft, Matsushima et al., *Space Sci. Rev.* **154**(2010) 253-564./ Non-monochromatic whistler waves detected by Kaguya on the dayside surface of the moon, Nakagawa et al., *EPS* **62** (2010) in press.
- RS: Studying the Lunar Ionosphere with SELENE Radio Science Experiment, Imamura et al., *Space Sci. Rev.* **154** (2010) 305-316.
- **UPI**: First optical observation of the Moon's sodium exosphere from the lunar orbiter SELENE (Kaguya), Kagitani et al., *Earth Planets Space* **61**(2009), 1025-1029./ The Upper Atmosphere and Plasma Imager/the Telescope of Visible Light (UPI/TVIS) onboard the Kaguya spacecraft, Taguchi et al., *EPS* **61** (2009) 17-23. / Variation in lunar sodium exosphere measured from lunar orbiter SELENE(Kaguya) , Kagitani et al., *Planet. Space Sci.* **58**(2010) 1660-1664./ Plasmaspheric EUV images seen from lunar orbit: Initial results of the extreme ultraviolet telescope on board the Kaguya spacecraft, Yoshikawa et al., *J. Geophys. Res.* **115** (2010) A04217./ Conjunction study of plasmapause location using ground－based magnetometers, IMAGE－EUV, and Kaguya－TEX data, Obana et al., *J. Geophys. Res.* **115** (2010) A06208. /First sequential images of the plasmasphere from the meridian perspective observed by KAGUYA, Murakami et al., *EPS* **62** (2010) e9-e12.
- HDTV: High Definition Television System on board Lunar Explorer KAGUYA(SELENE) and Imaging of the Moon and the Earth, Yamazaki et al., *Space Sci. Rev*. **154** (2010) 21-56.
- SOAC: Data Processing at KAGUYA Operation and Analysis Center, Hoshino et al., *Space Sci. Rev.* **154** (2010) 317-342.
- The Kaguya Mission Overview, Kato et al., *Space Sci. Rev.* **154** (2010) 3-19.

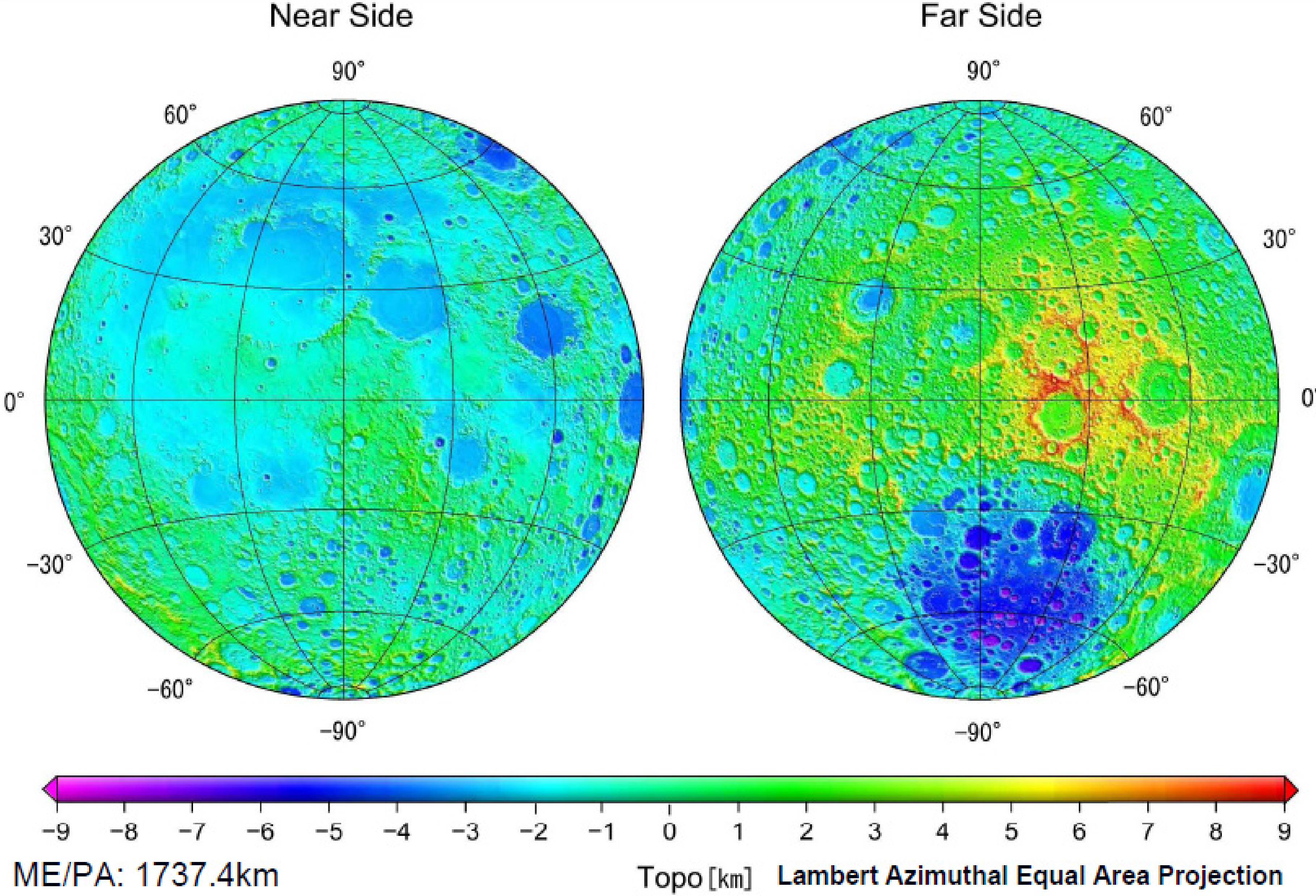
- Pre-launch studies: *Earth Planets Space* **60** (2008), 241-444. / *Adv. Space Res.* **42** (2008), 259-346.
- Proc. 26th Inter. Space Tech. Sci., *Trans. Japan Soc. Aeronaut. Space Sci. Aerospace Tech. Japan* **7** (2009) on line.

HDTV Earth Views in May 9, 2008

and ENg

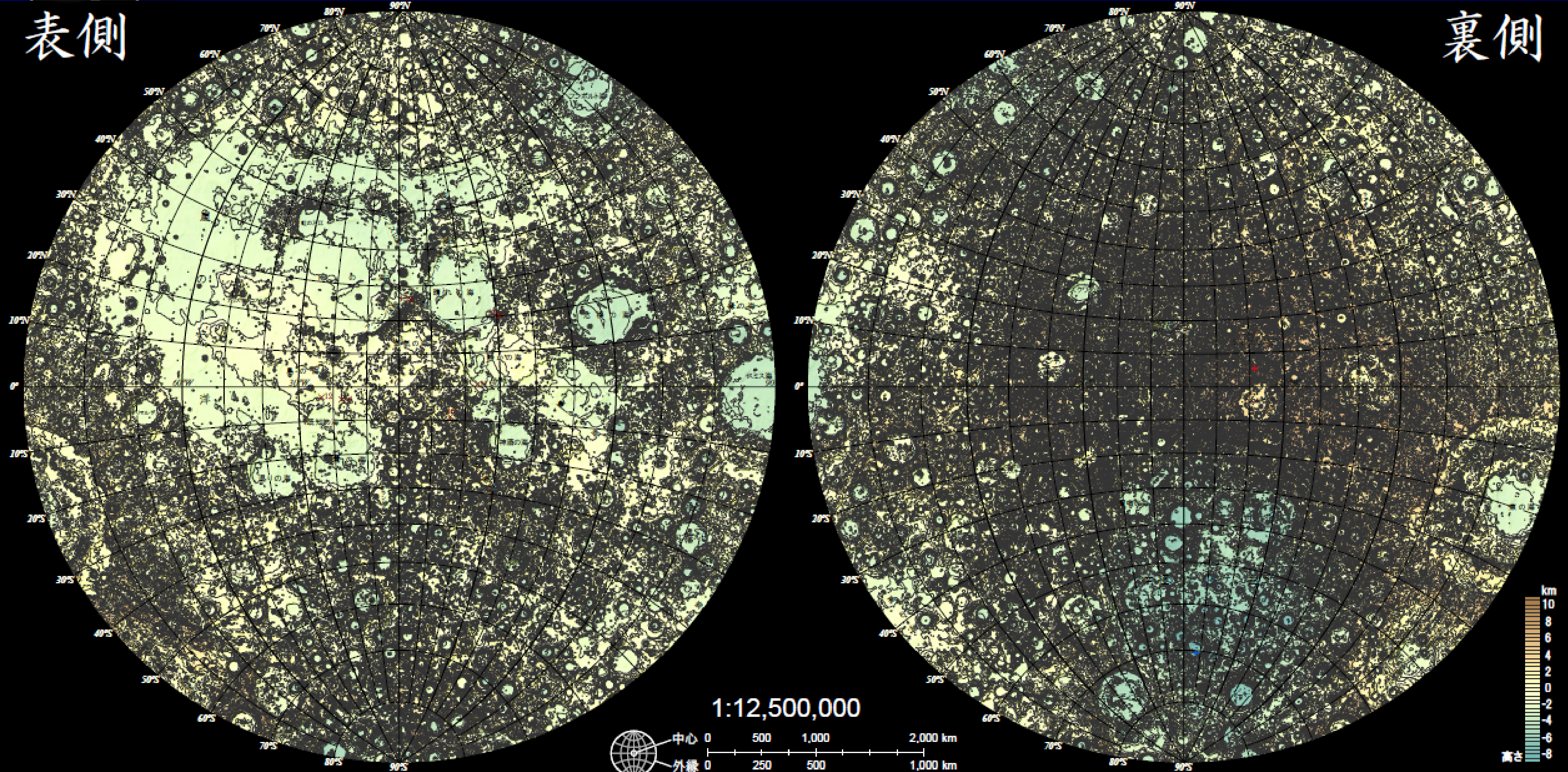
HDTV Crescent Earth in Jan. 27, 2008

Lunar Shaded Topographic Map (~30. June, 2008)



ME/PA: 1737.4km

Lunar topographic contour map



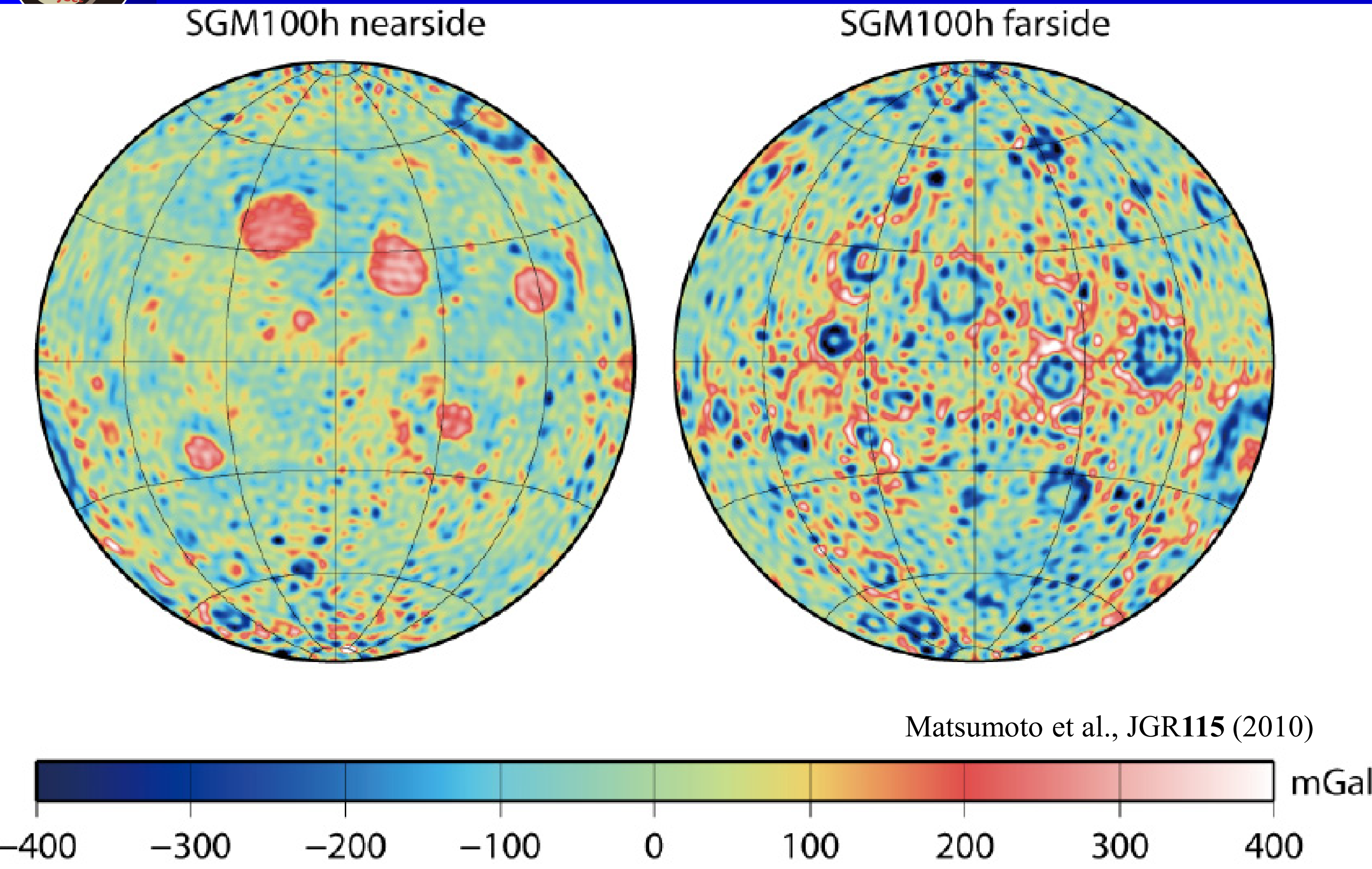
+ 最高地点 158.64˚W 5.44˚N 10.75 km
+ 最低地点 172.58˚W 70.38˚S -9.06 km
×11 アポロ宇宙船着陸地点（数字はミッション番号）

平射図法の縮尺は、地図の中心から離れるに従い大きくなります。地図の中心では、1:12,500,000 ですが、外縁では 2 倍に拡大され、1:6,250,000 となります。上のスケールバーには、中心と外縁での距離が示されています。

この地図は、JAXA の月周回衛星「かぐや(SELENE)」に搭載したレーザ高度計(LALT)の精度 4 m の観測データをもとに作成した月の地形図です。等高線間隔は 500 m（太い等高線は 2,000m ごと)、高さの基準は重心を中心とする半径 1,737.4 km の球です。
地図投影法は平射図法、経度 0°は地球から見える月中心を通る子午線です。
月の表側は玄武岩で覆われた平坦で薄暗い「海」と呼ばれる地形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います。「海」は円形もしくは楕円形をしているものが多く、衝突盆地の窪みに地下から溶岩が噴出して溜まったものと考えられています。モスクワの海などの例外を除き、月の裏側には「海」はほとんど見られません。たとえば月裏側の南半球には直径約 2,500 km の南極-エイトケン盆地と呼ばれる巨大な衝突盆地があり、月面で最も深く掘削された低地となっていますが、地形は平坦ではなく玄武岩も一部の領域にしか見られません。これは裏側の地殻が表側よりも厚く岩石の組成も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

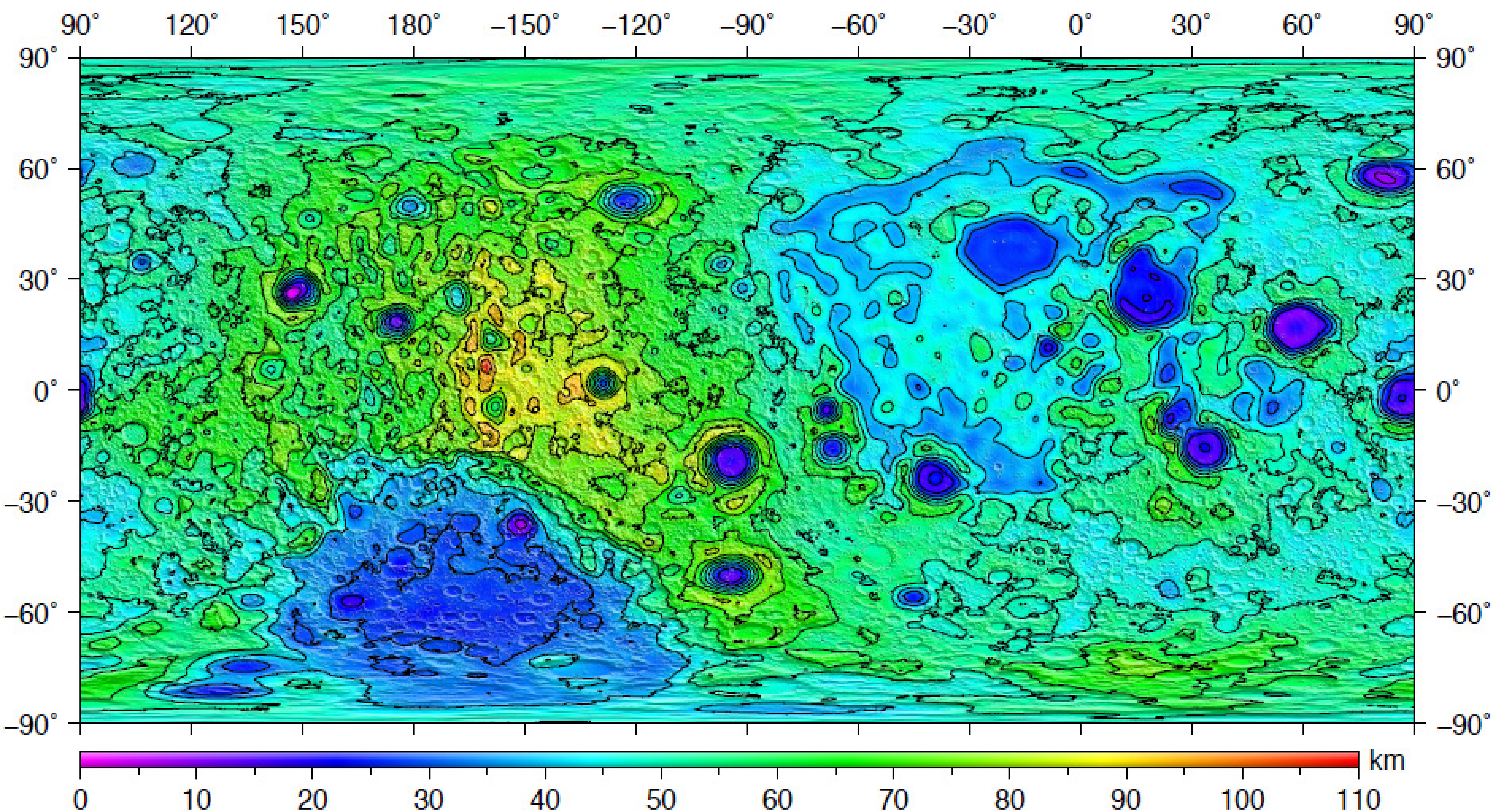
Gravity Model Version Up, SGM100h



Matsumoto et al., JGR**115** (2010)

Crustal Thickness

Ishihara et al., 2009, *GRL* **36 ,** L19202

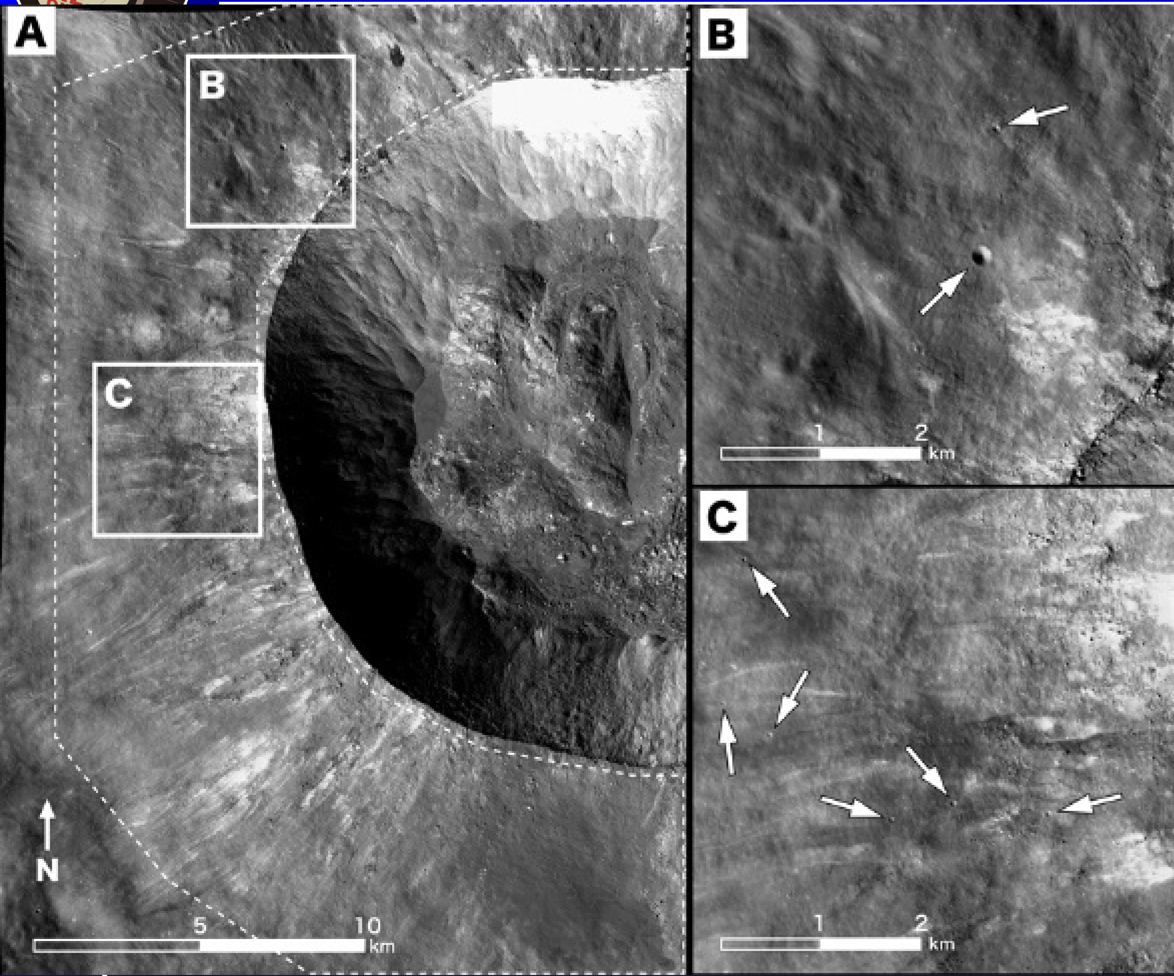


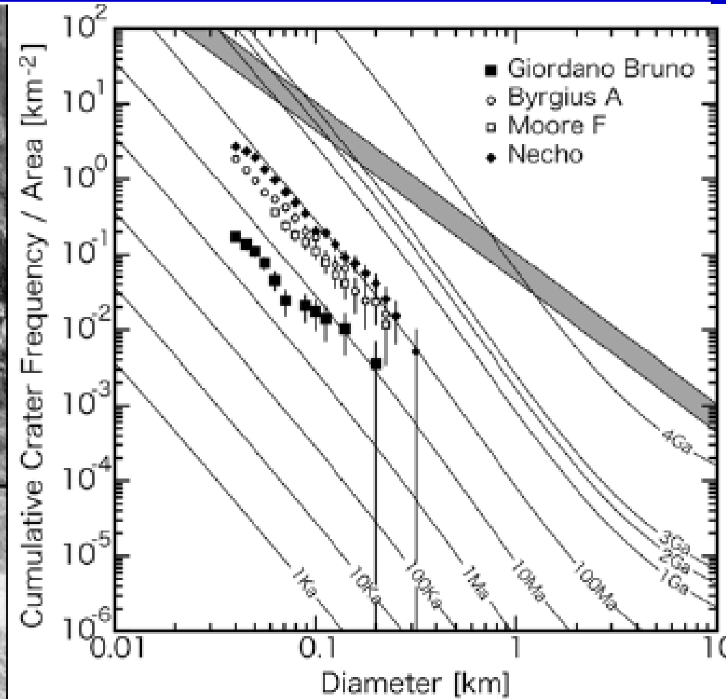
SELene

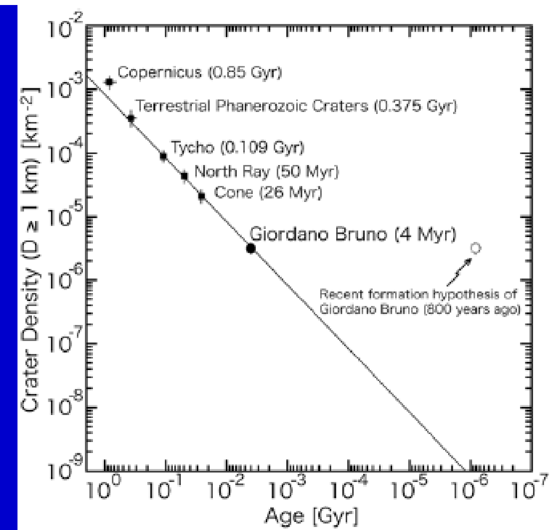
Max. : 110km in southern rim of Dirichlet – Jackson crater.(199.719E, 6.90625N)
Min.: 0 km benearth Mare Moscvience

Assum., densities of 2800 kg/m3 of crust , 3360 kg/m3 of mantle, and 3200kg/m3 of mare basalt

Formation age of Giordano Bruno crater



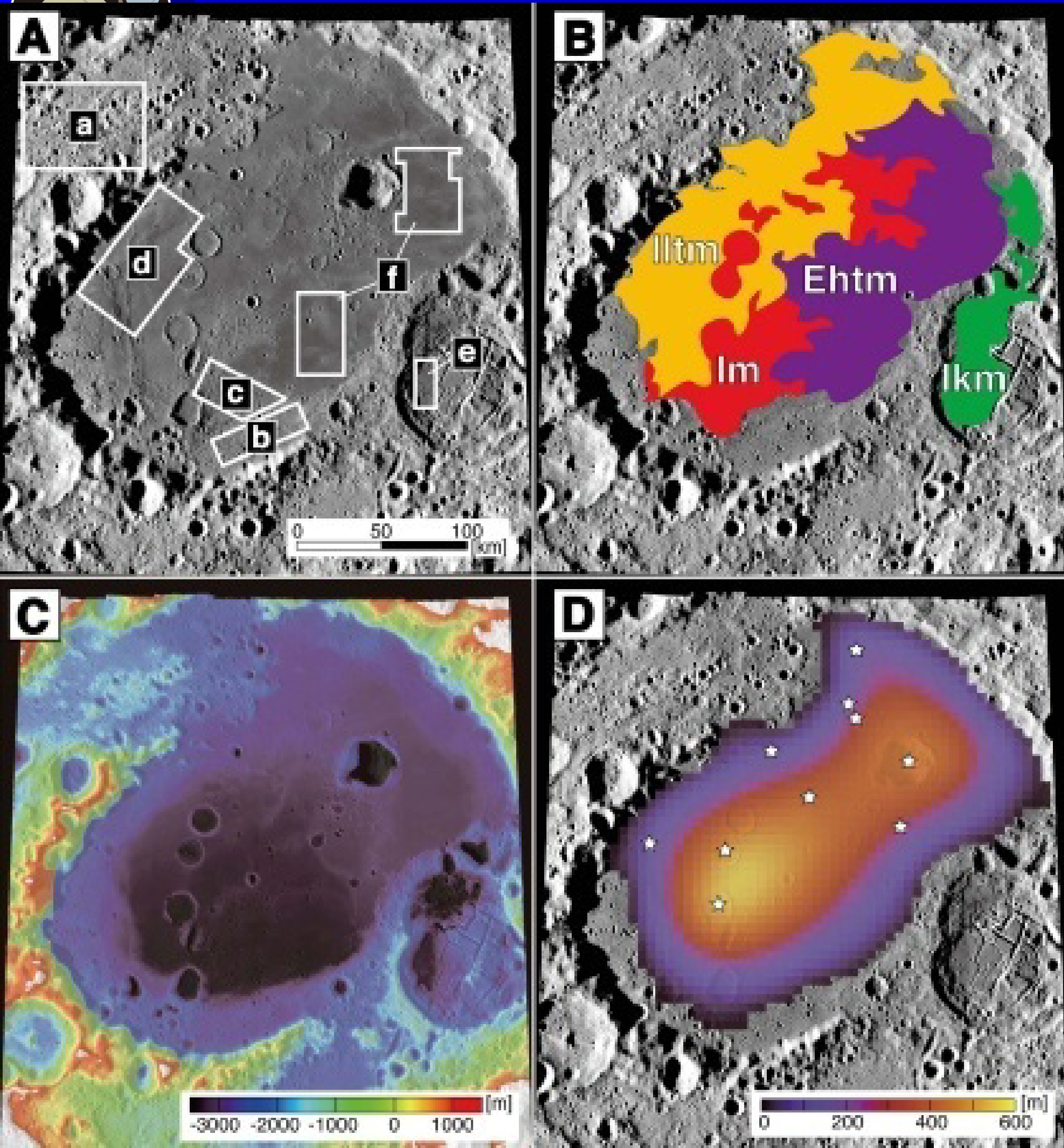


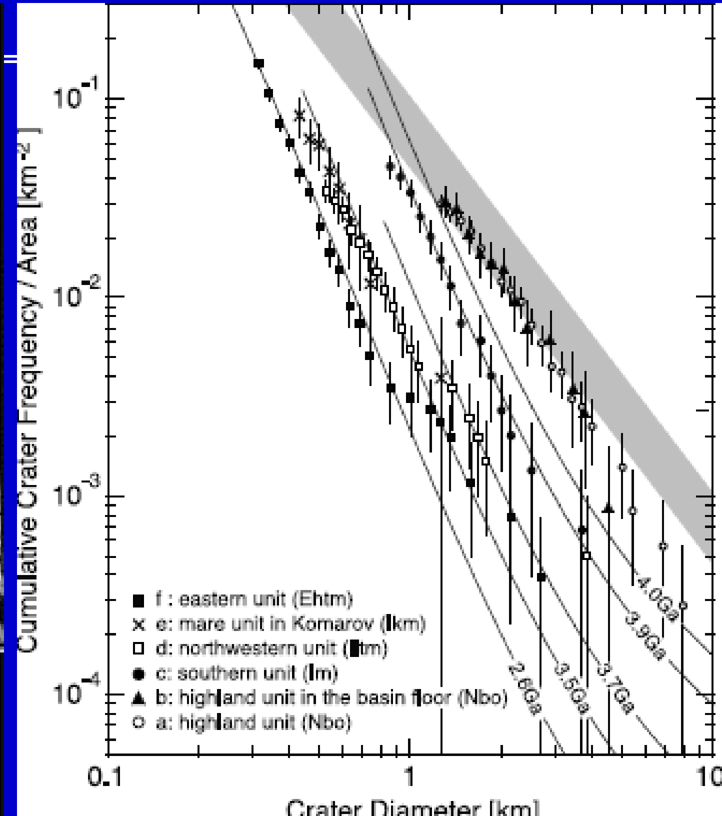


36N/103E, 22 km

Morota et al., *MePS* **44** (2009), 1115-1120

Basalt Thickness of Mare Moscoviense

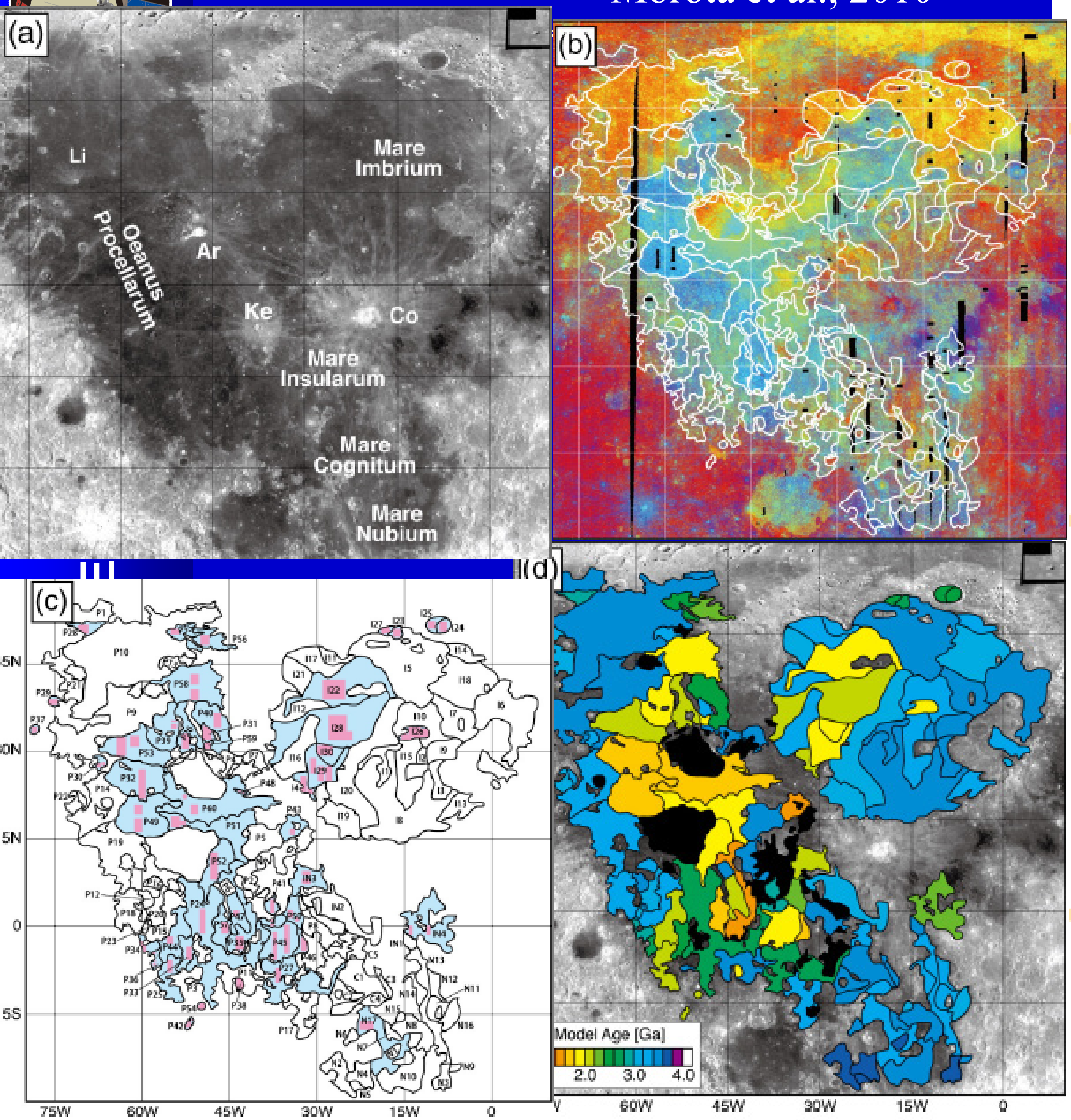


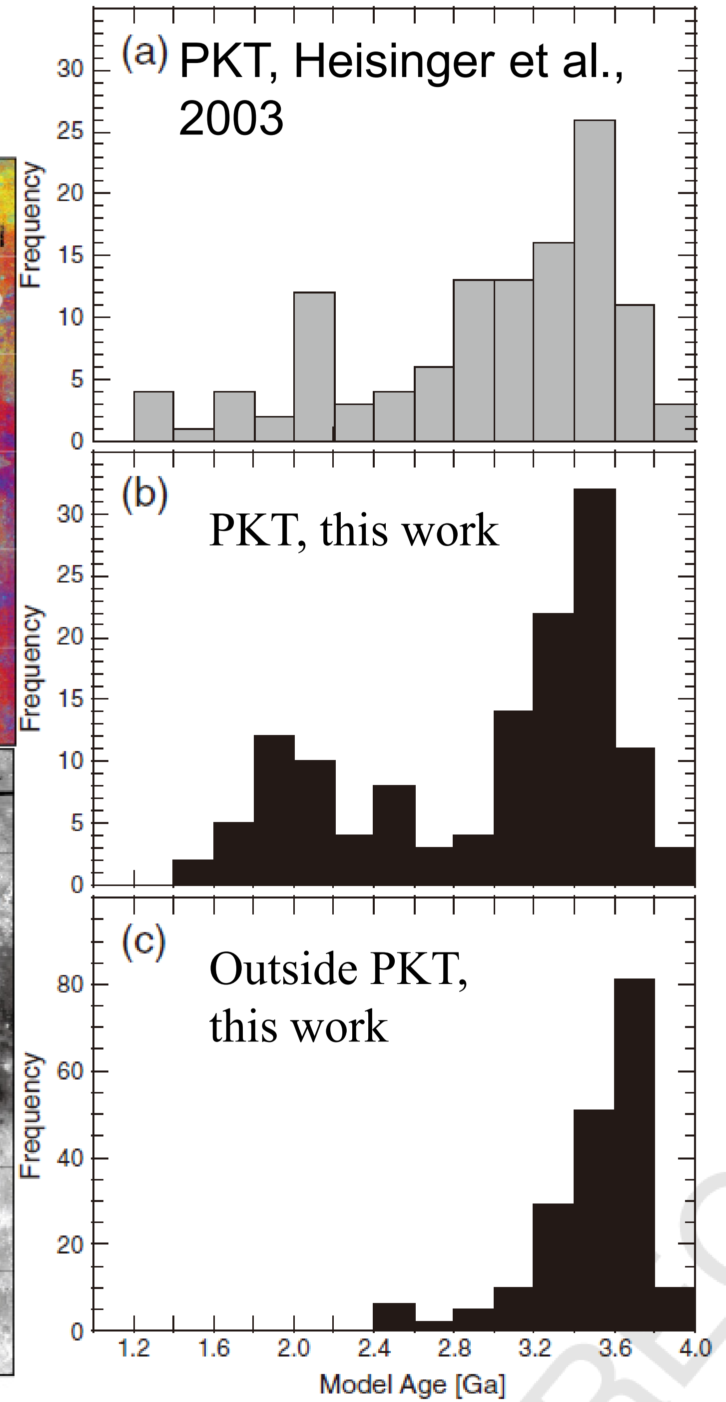


Morota et al., *GRL* **36** (2009), L21202

History of Mare Volcanism

Morota et al., 2010





Global map of mare basalts

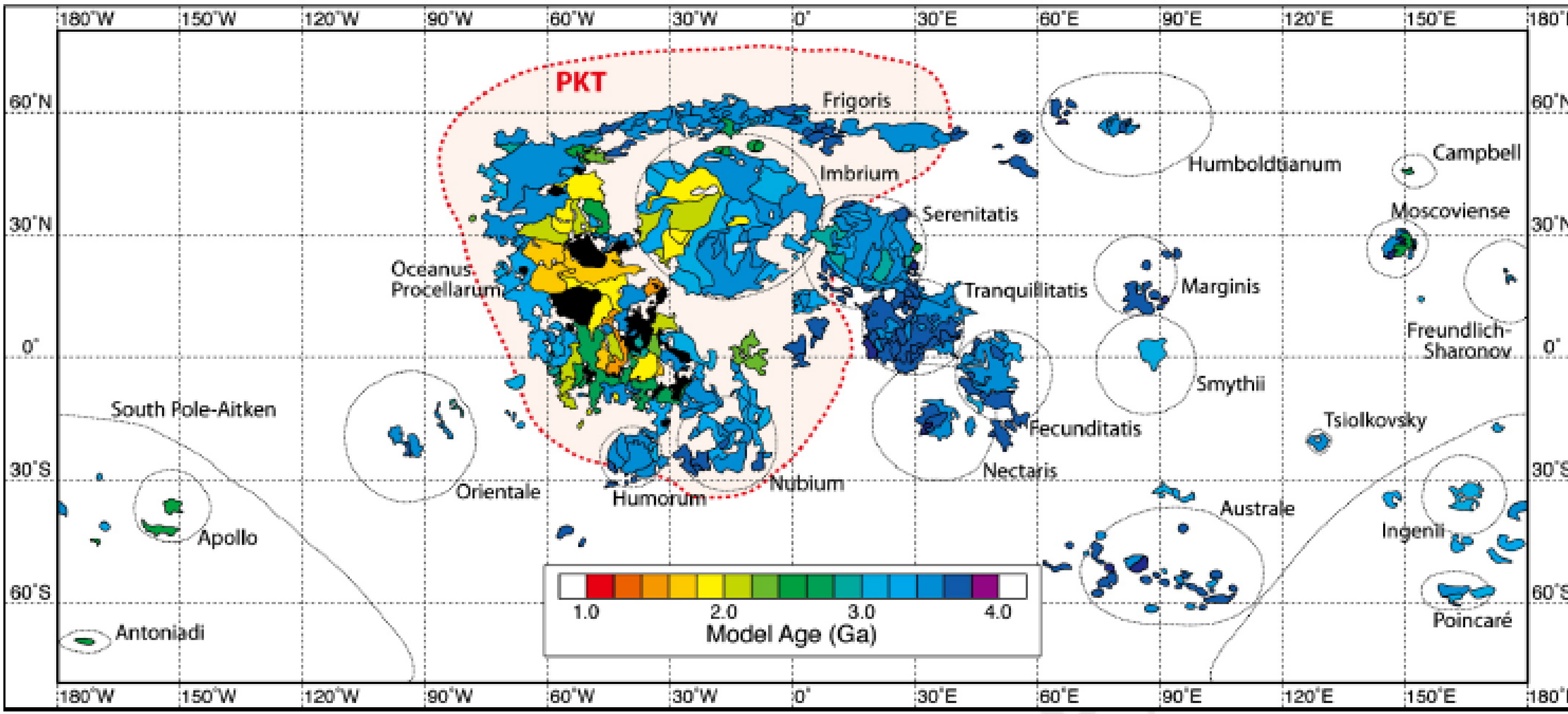
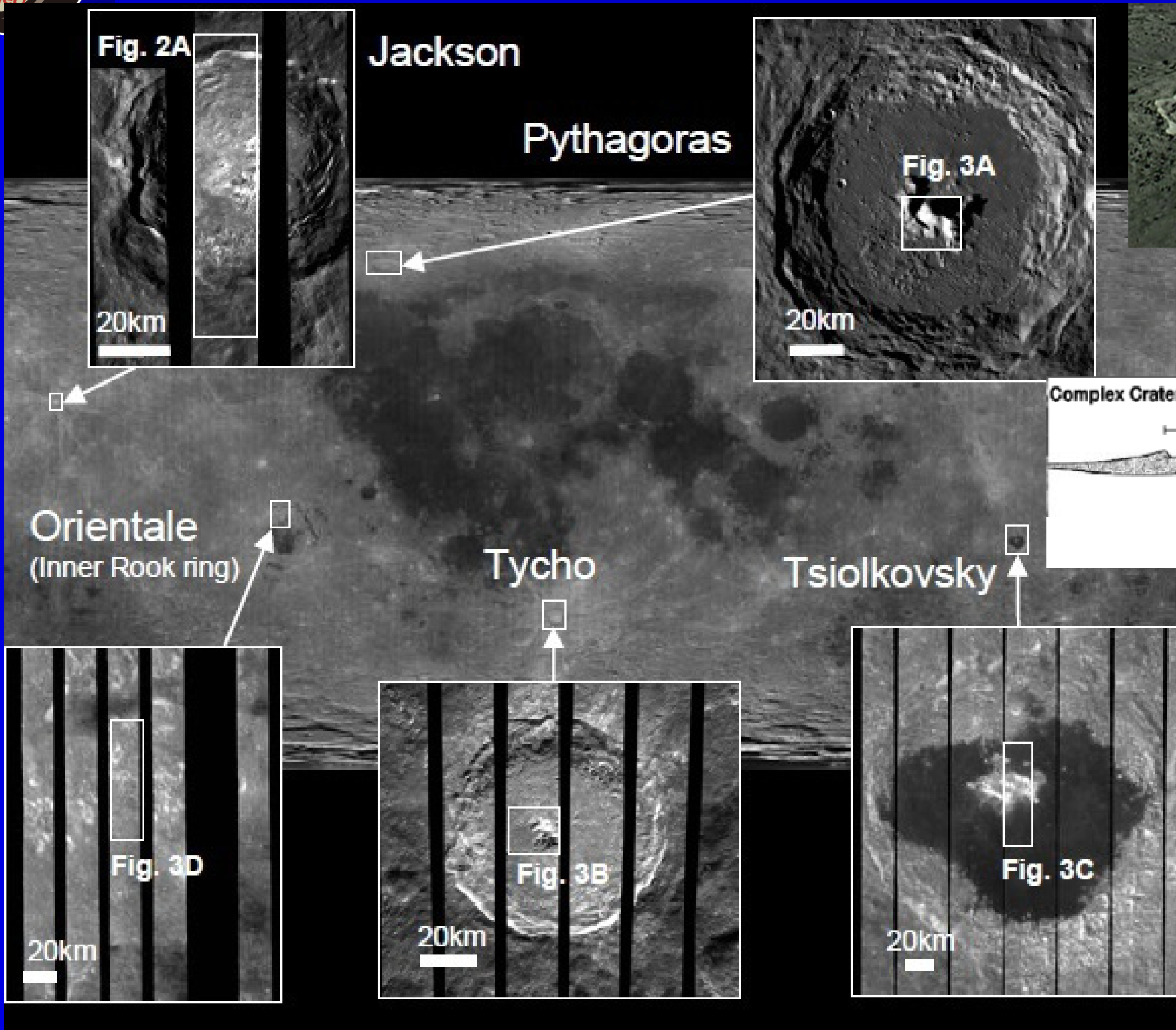
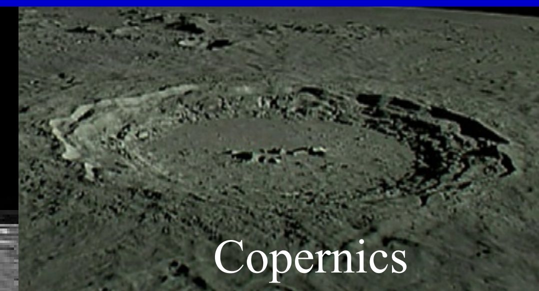


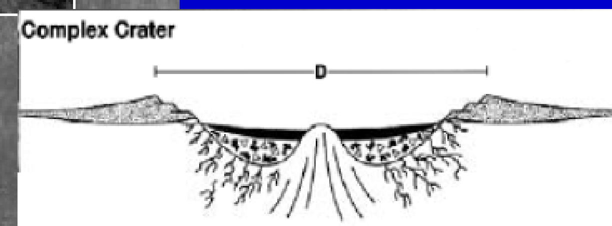
Fig. 5. Global map of the model ages of mare basalts on the lunar surface, including Oceanus Procellarum, Mare Imbrium, Nubium, Insularum (This study; Hiesinger et al., 2000, 2003), Mare Orientale (Greeley et al., 1993), Mare Serenitatis, Humorum, Tranquillitatis, Humboldtinum, Australe (Hiesinger et al., 2000), Mare Cognitum (Hiesinger et al., 2003), Mare Fecunditatis (Hiesinger et al., 2006), Mare Frigoris and other nearside maria (Hiesinger et al., 2010), Mare Moscoviense (Haruyama et al., 2009; Morota et al., 2009), and those within the South Pole–Aitken basin (Haruyama et al., 2009), the Freundlich–Sharonov basin, the crater Campbell, the crater Kohlschütter (Morota et al., in press), and the crater Tsiolkovsky (Tyrie, 1988).

Morota et al., 2010

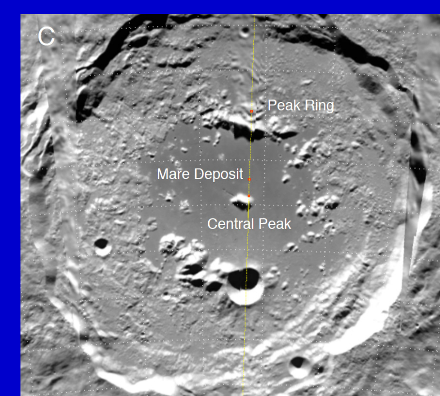
Lithology of central peaks of c.p. craters



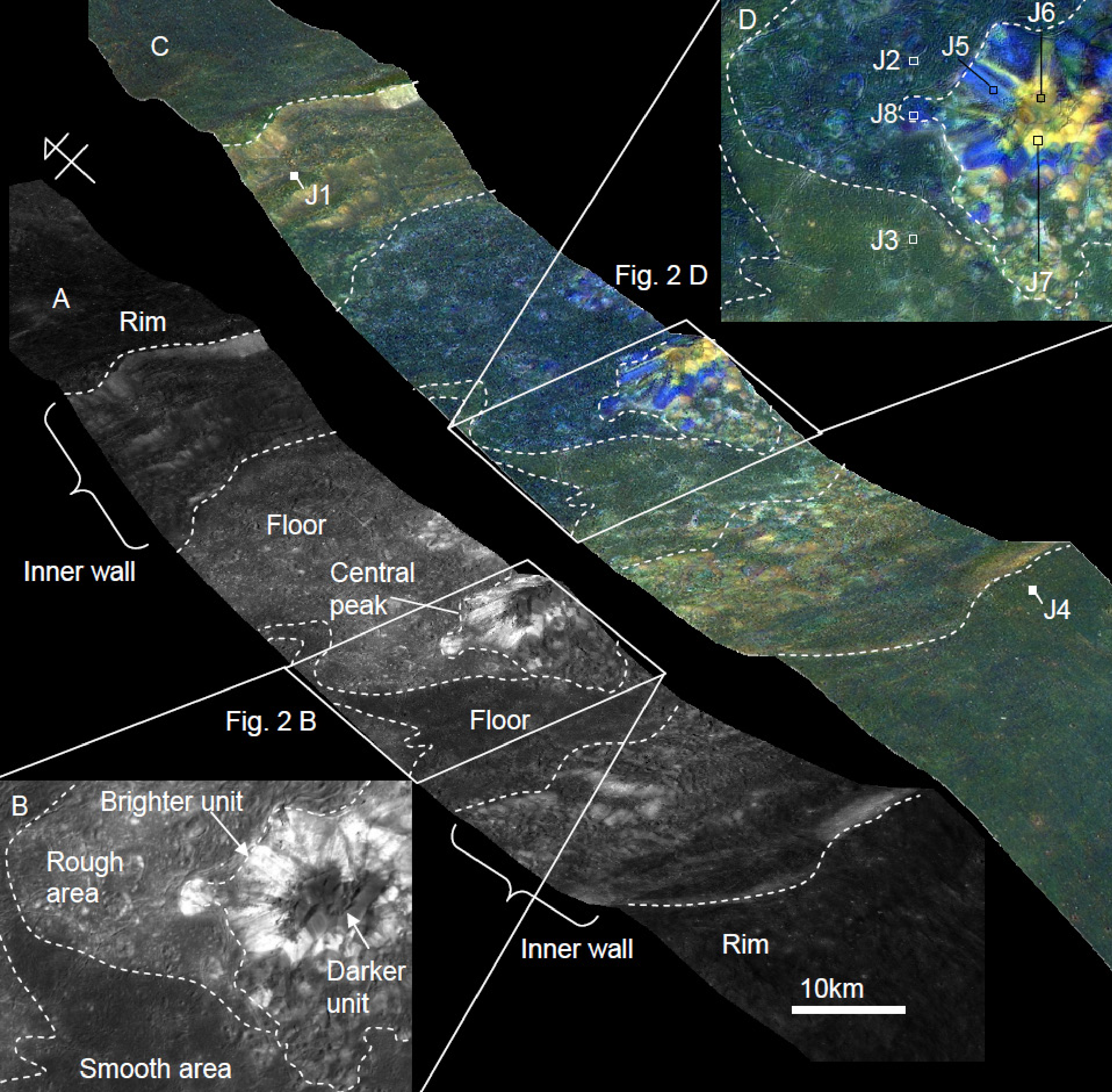




Antoniadi



Multi-band Imager of Jackson Crater



A: 750nm band

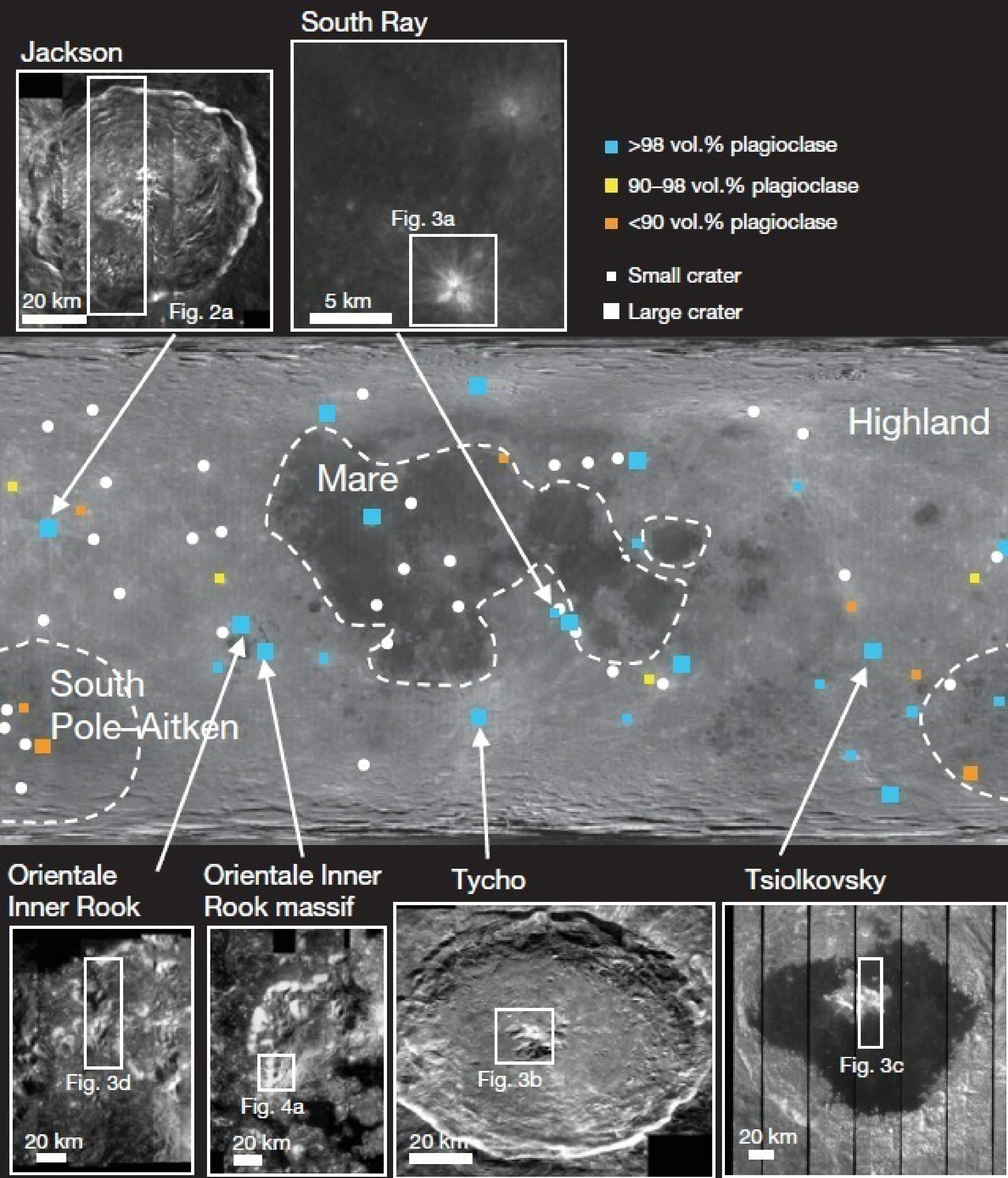
B: Close-up

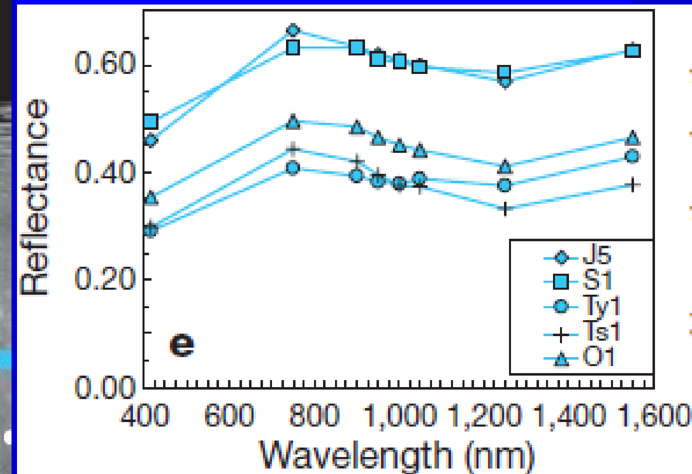
C: Color composite, 950nmR, 1050nmB, and 1250nmG

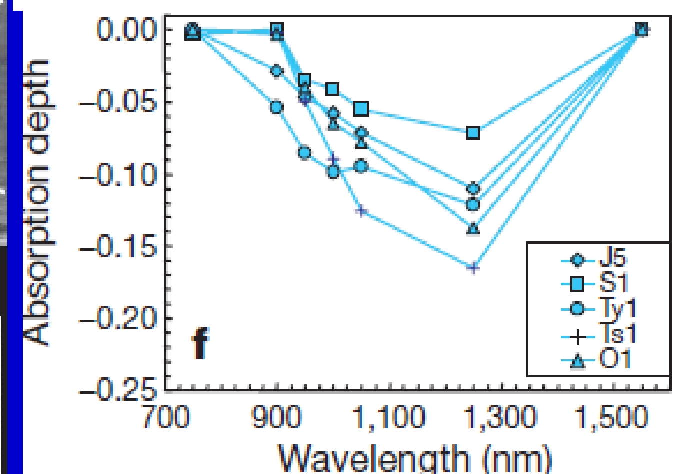
D: Close-up

Ohtake et al., 2009

Global distribution of rocks of high plagioclase abundance

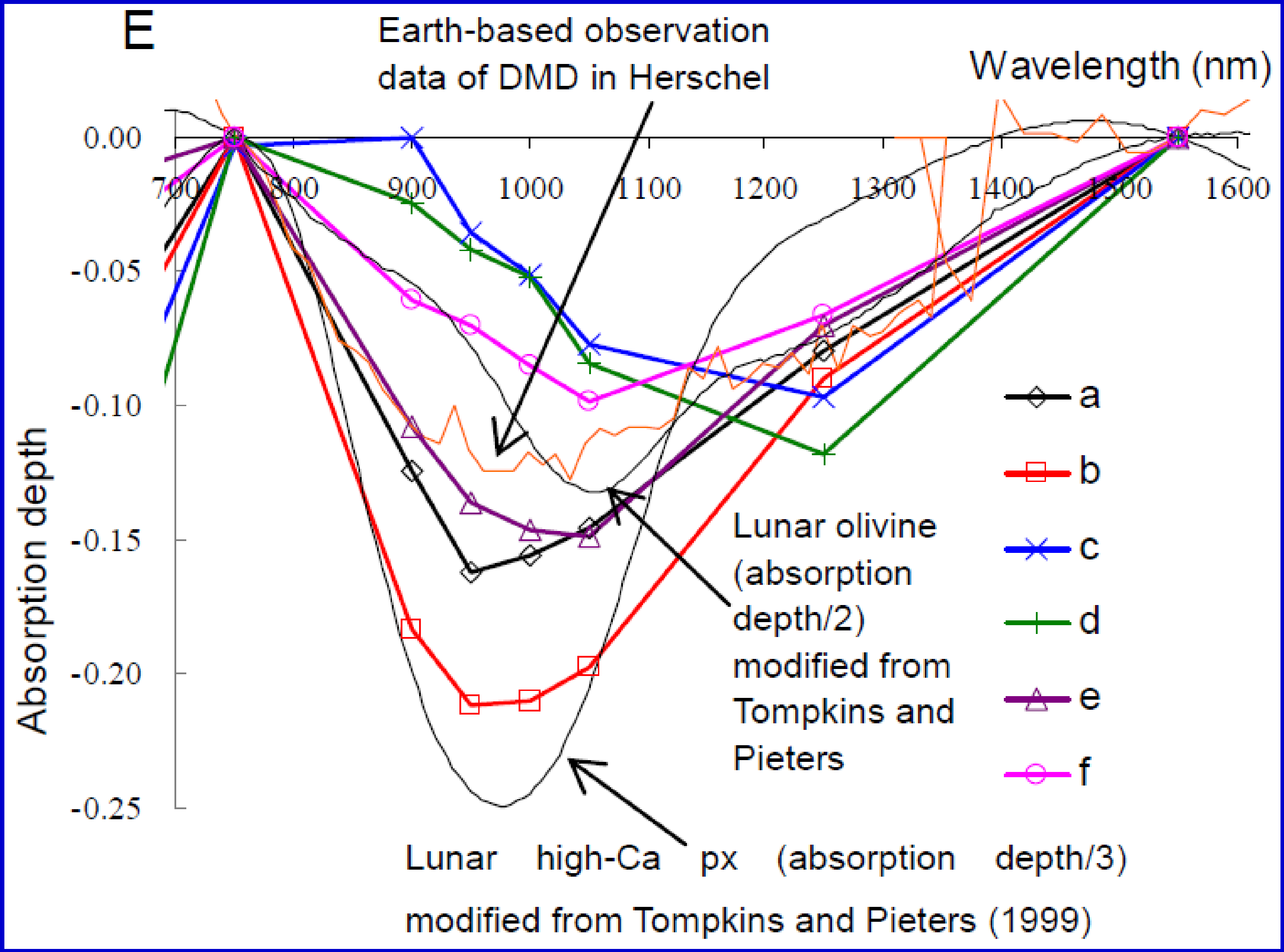






Ohtake et al., *Nature* **461**(2009), 236-241

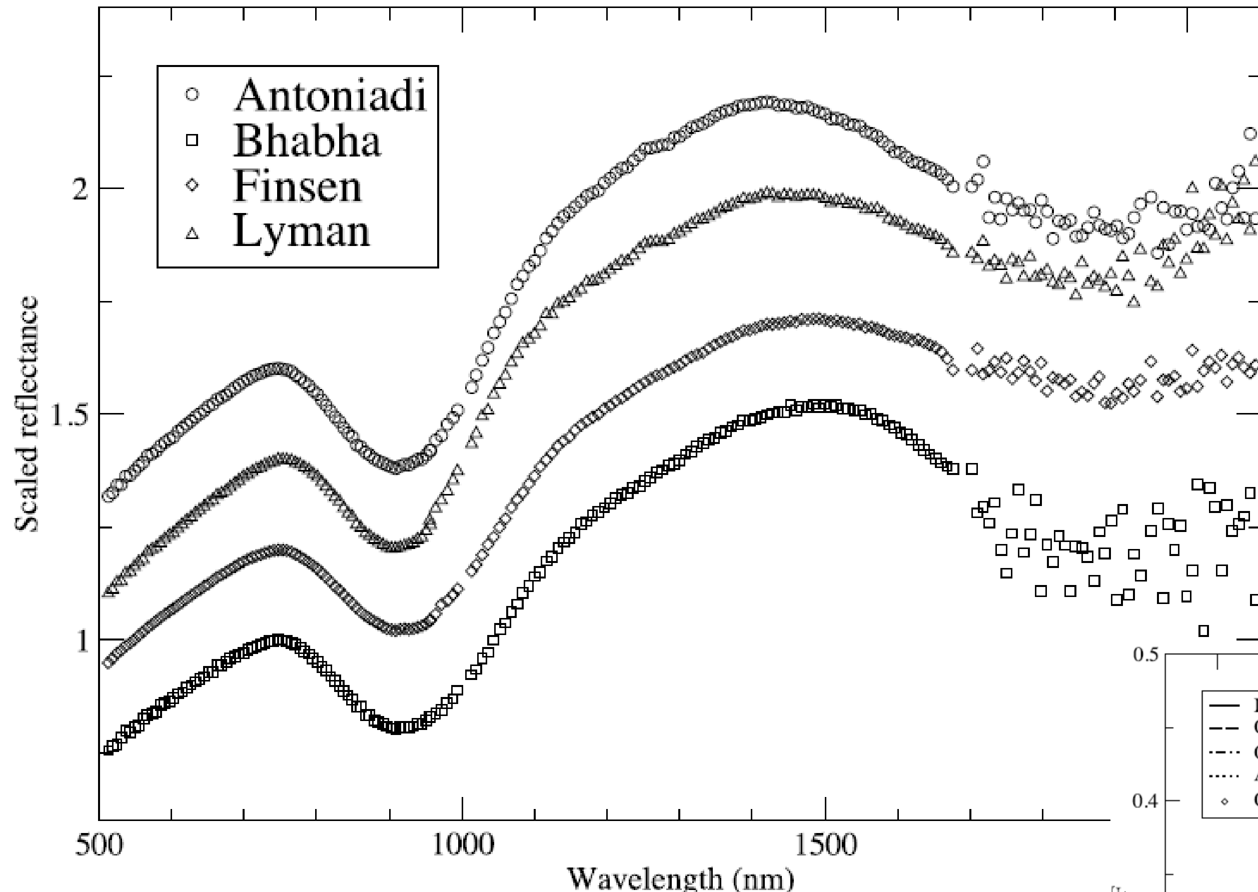
MI Reflectance 3.

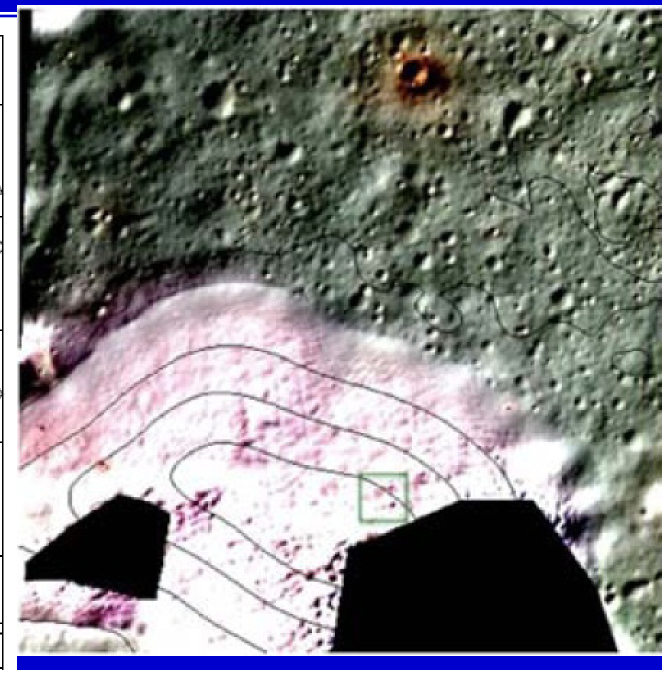


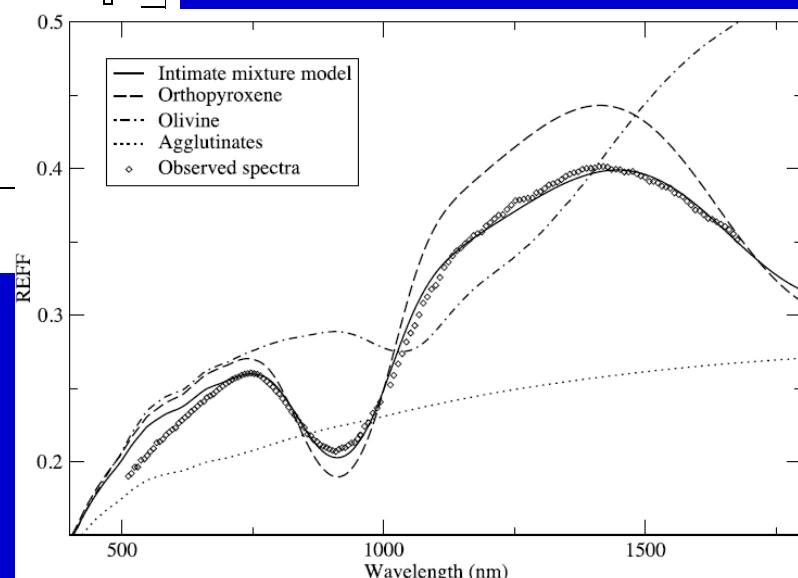
E. Multi-band Spectrum of points a-f in Fig. B

Ohtake et al., 2008

South Pole-Aitken lithology







SELeno

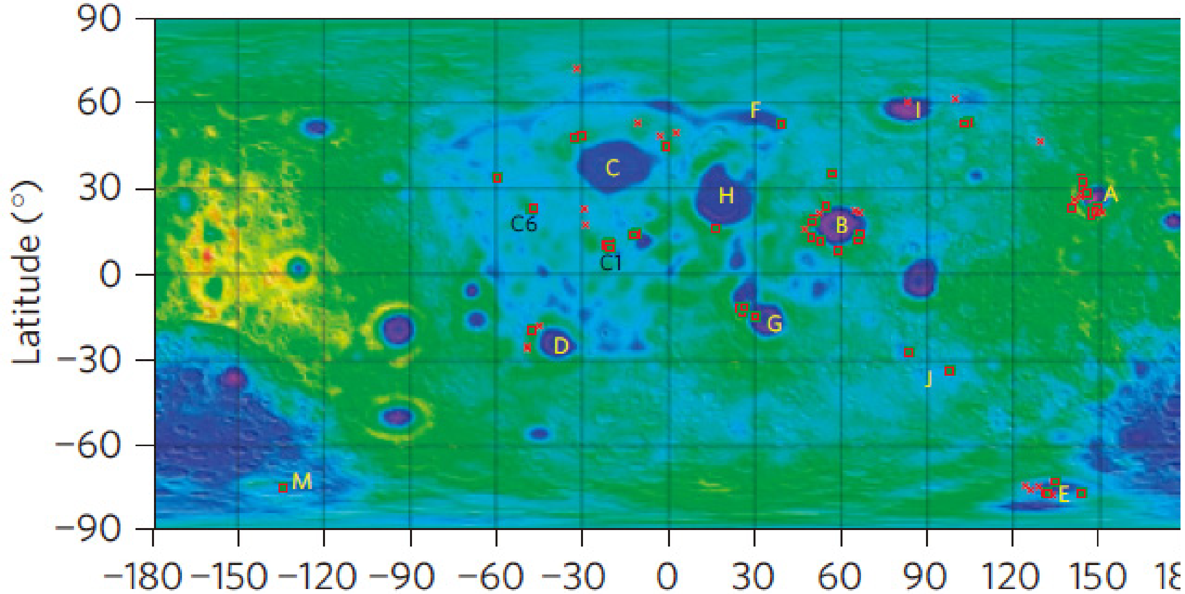
Nakamura et al., *GRL* **36**(2009), L22202

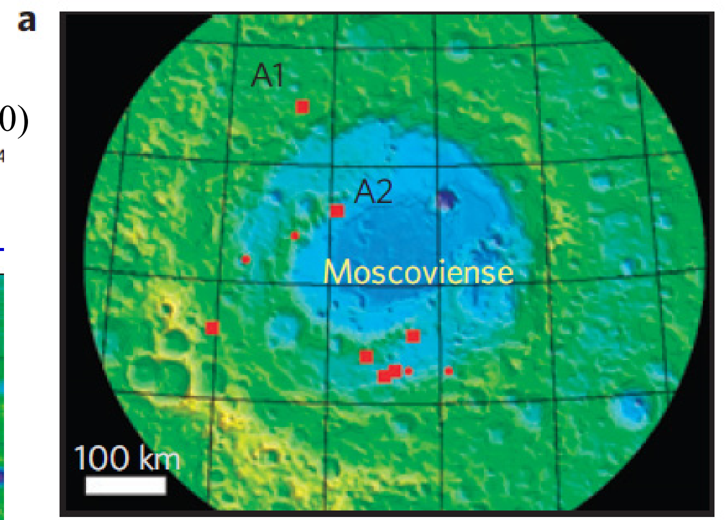
c.p. of Antoniadi crater:
74.1wt%Opx+ 11.1%Ol+14.8%Aggl.

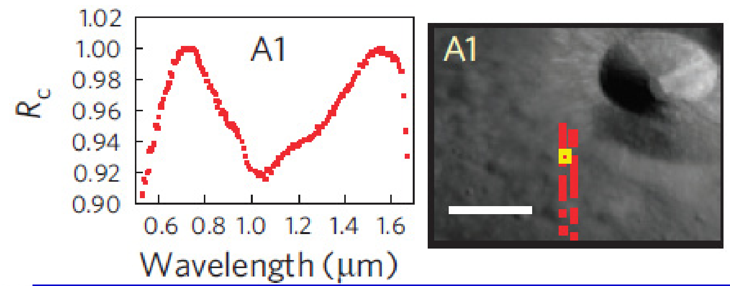
Possible mantle origin of olivine around lunar impact basins detected by SELENE

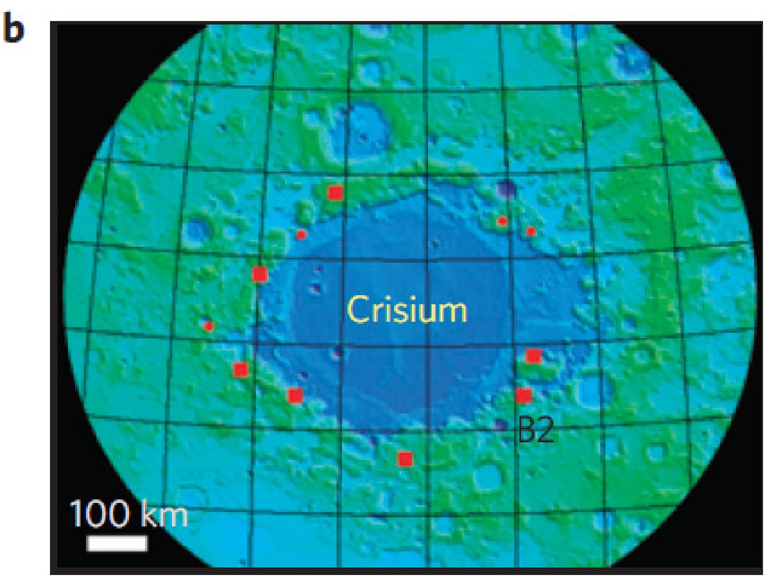
Nature Geosci. **3** (2010)

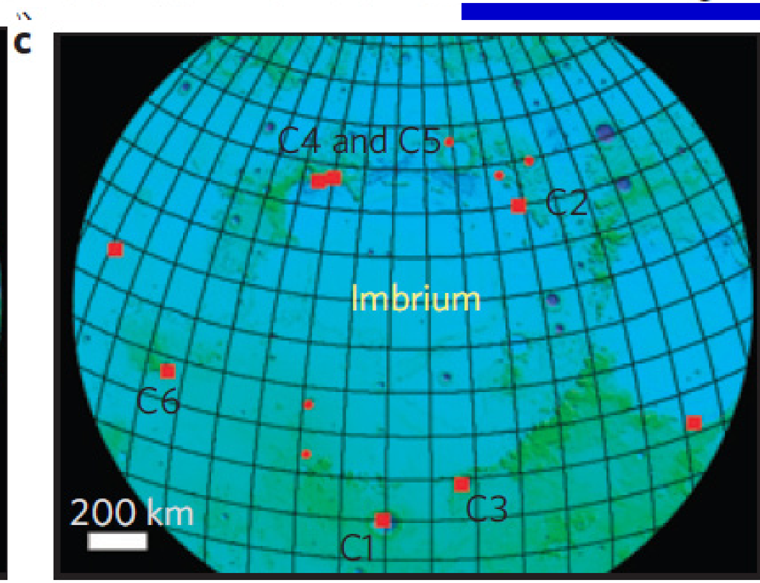
Satoru Yamamoto[1]*, Ryosuke Nakamura[2], Tsuneo Matsunaga[1], Yoshiko Ogawa[3], Yoshiaki Ishihara[4] Tomokatsu Morota[5], Naru Hirata[3], Makiko Ohtake[5], Takahiro Hiroi[6], Yasuhiro Yokota[1] and Junichi Haruyama[5]

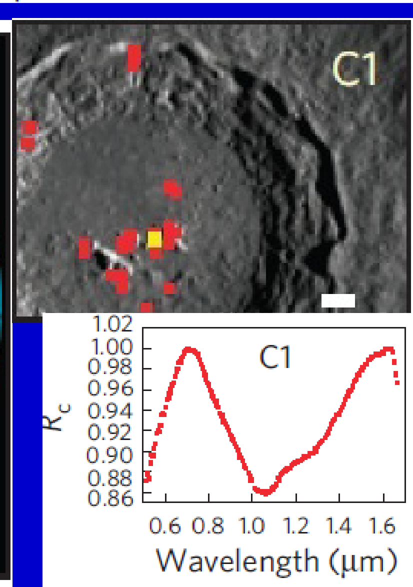






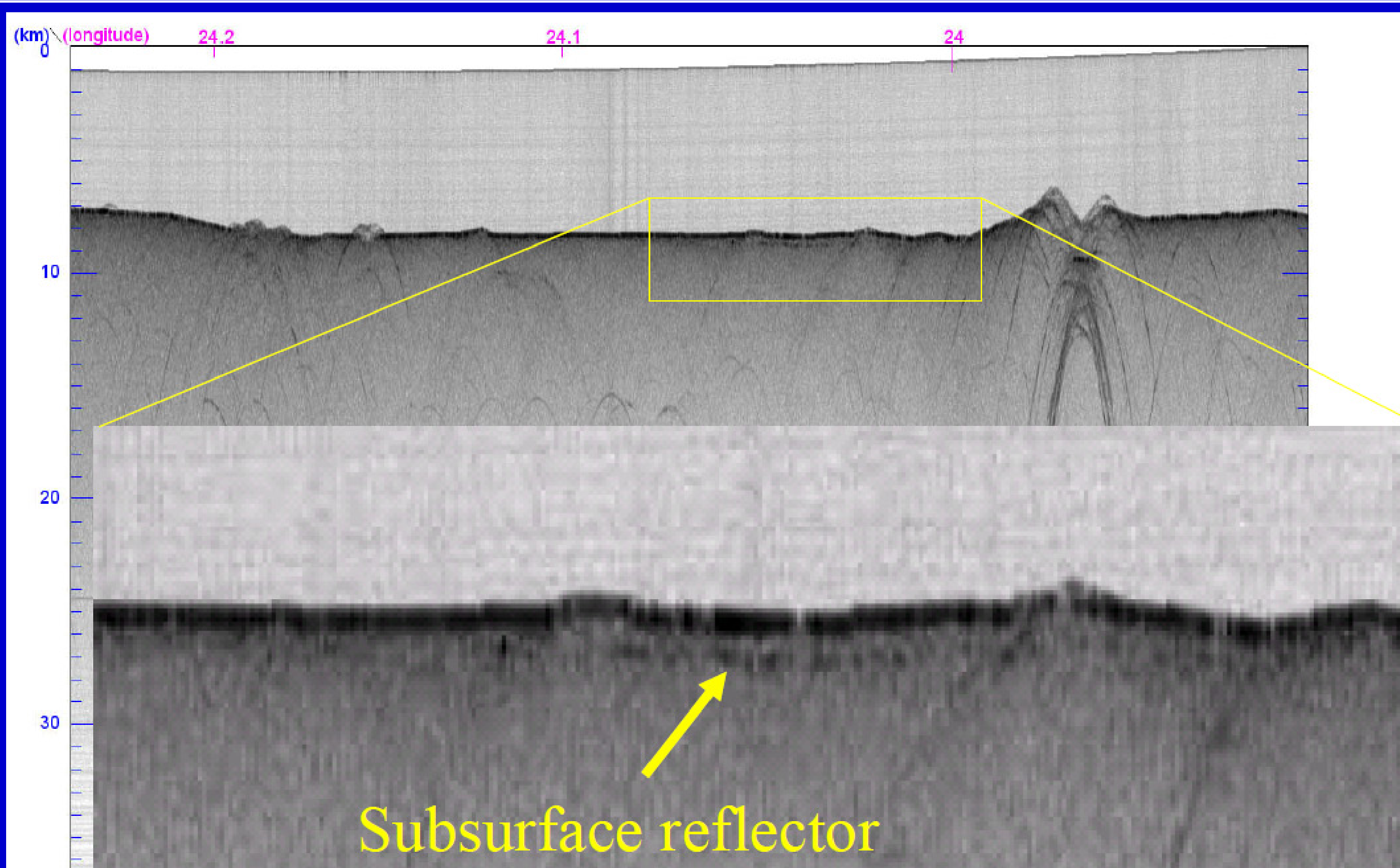






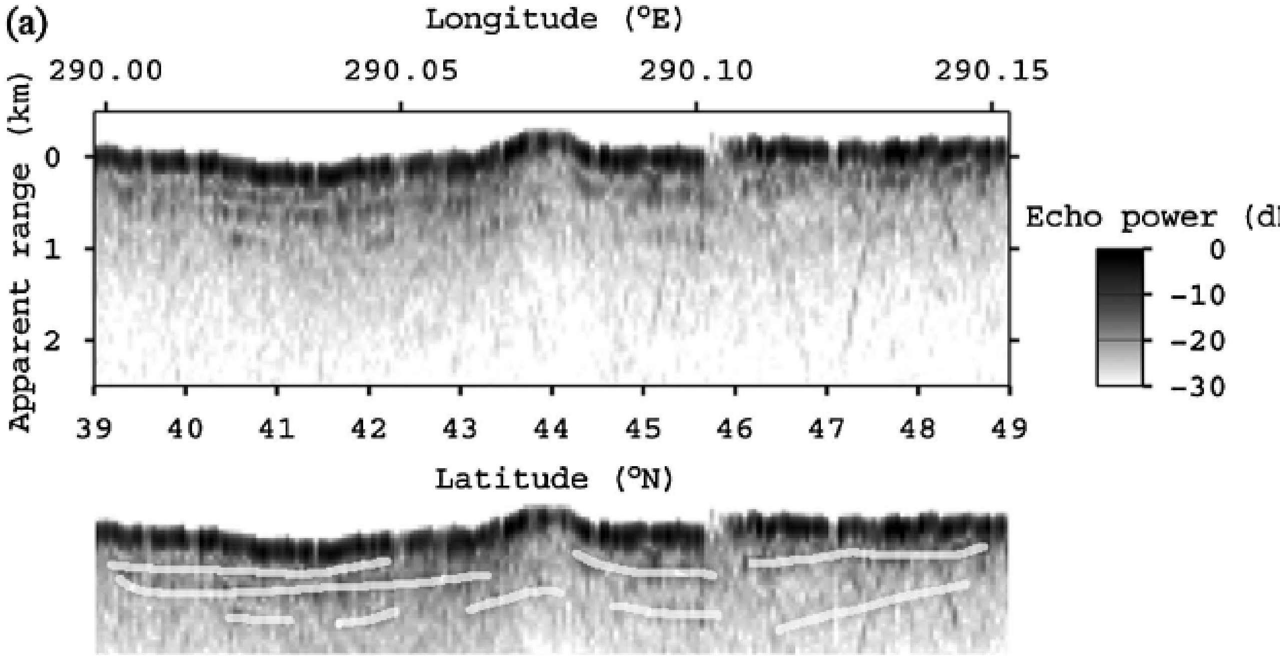
Subsurface Study of Mare Serenitatis by Lunar Radar Sounder

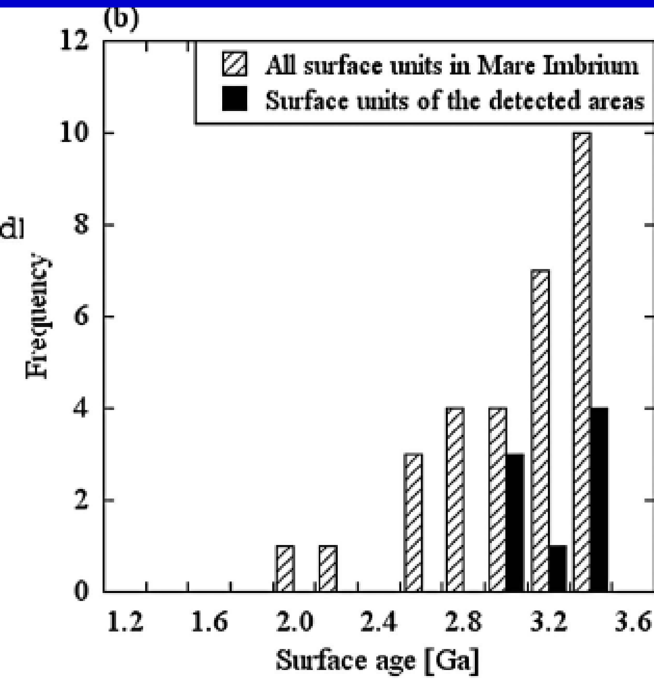
SELenological and ENgineering Explorer

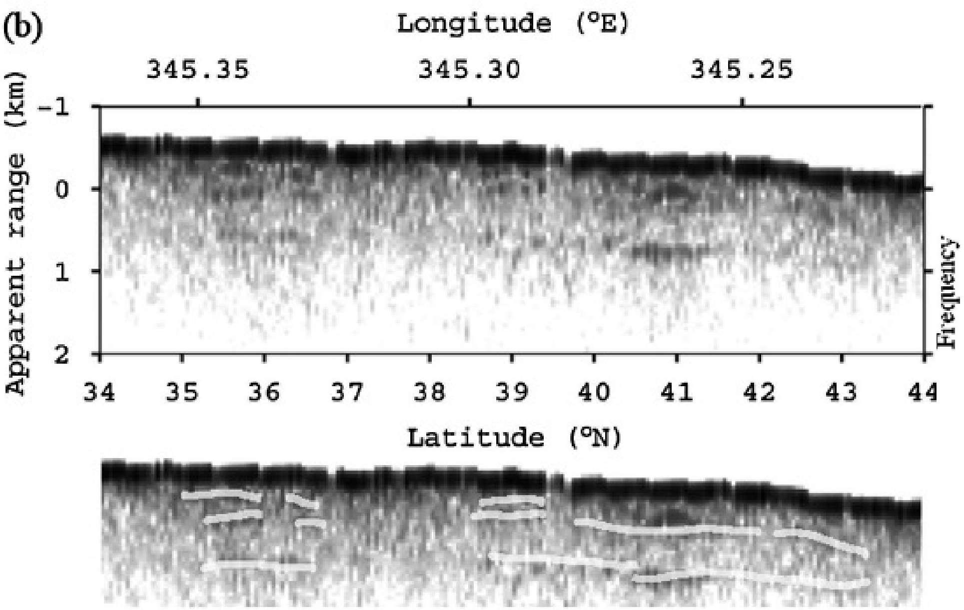


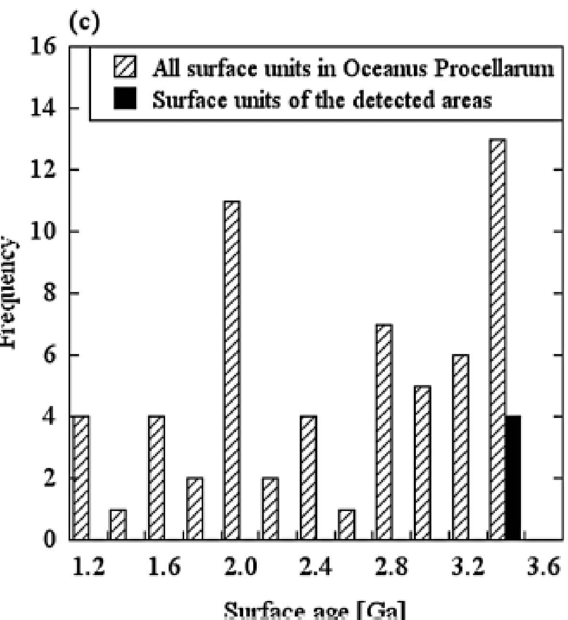
Ono et al., 2009

Mare Imbrium & Oceanus Procellarum by LRS



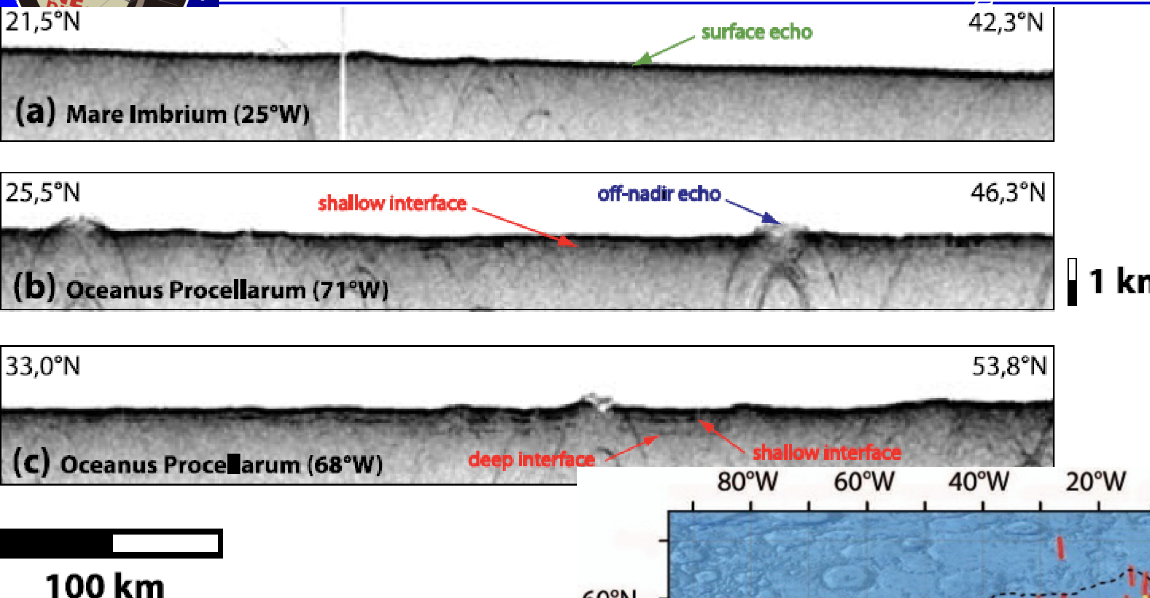




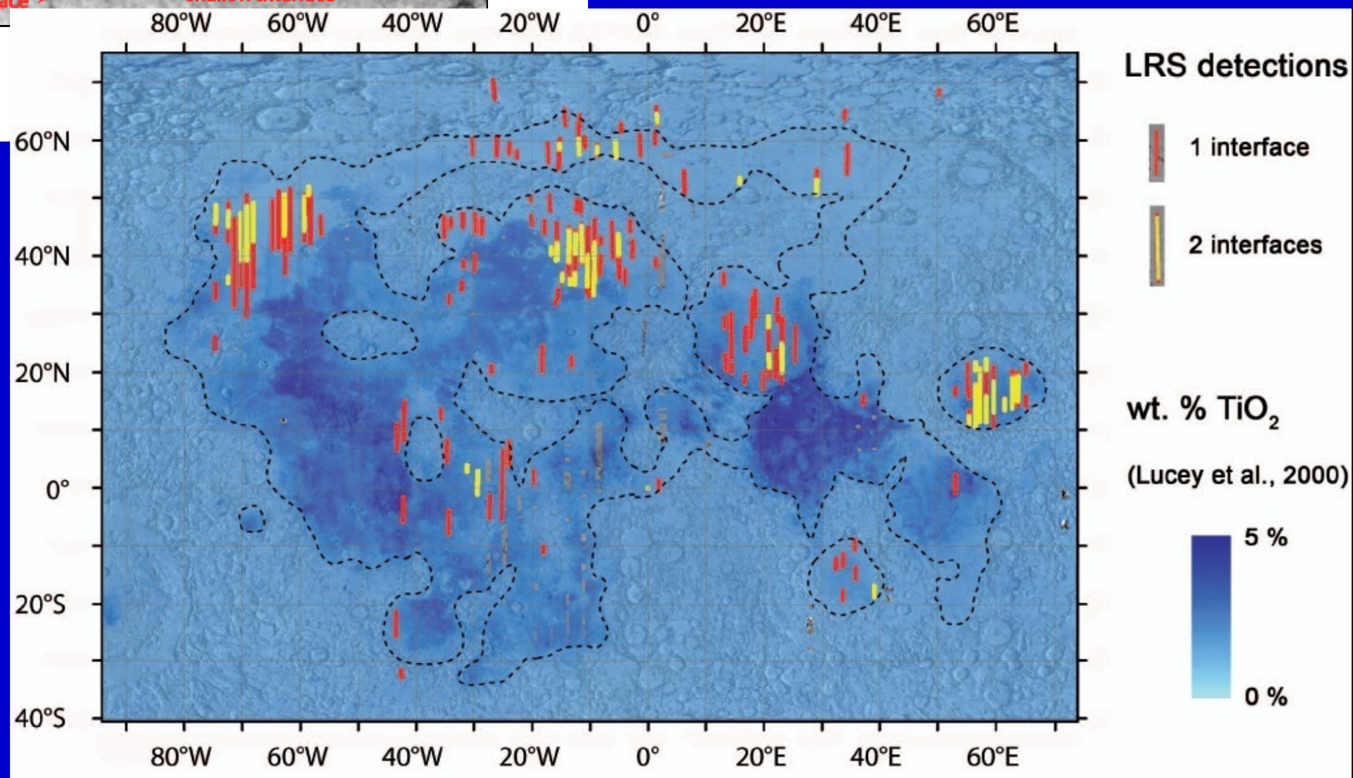


Oshigami et al., *GRL* **36** (2009), L18202.

Subsurface Interface Detectability with TiO_2 content

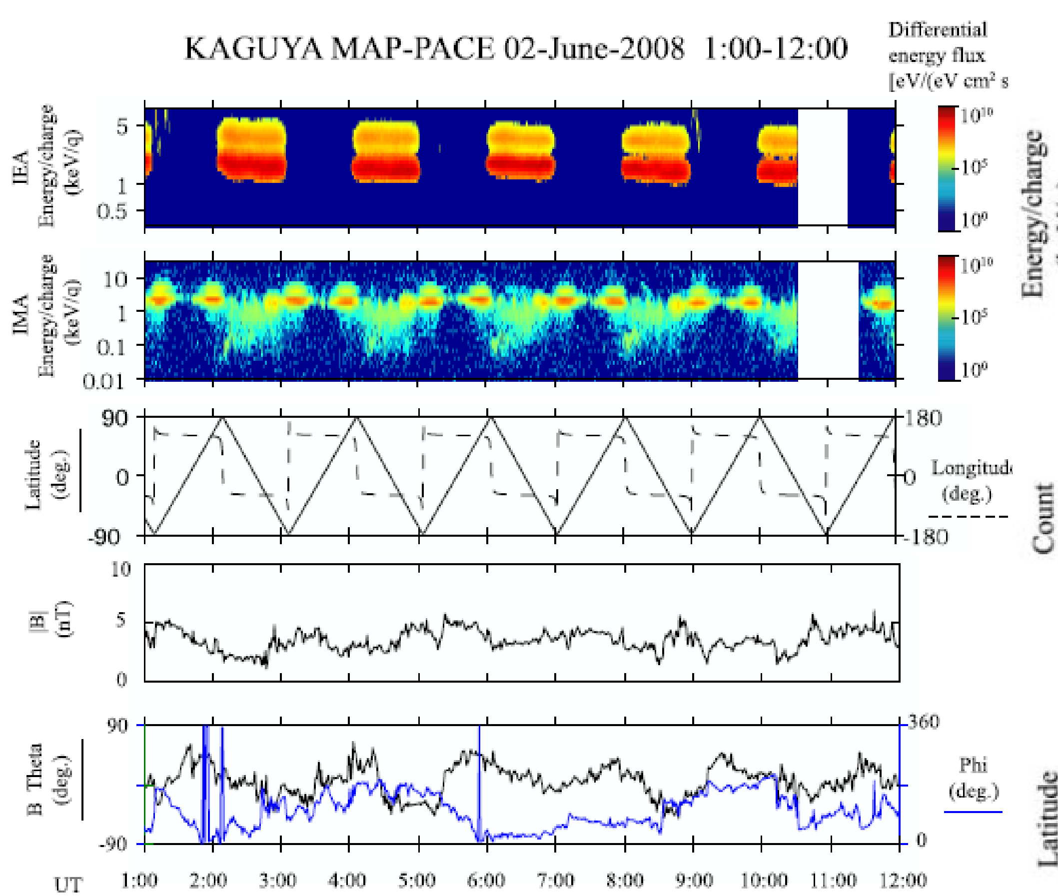


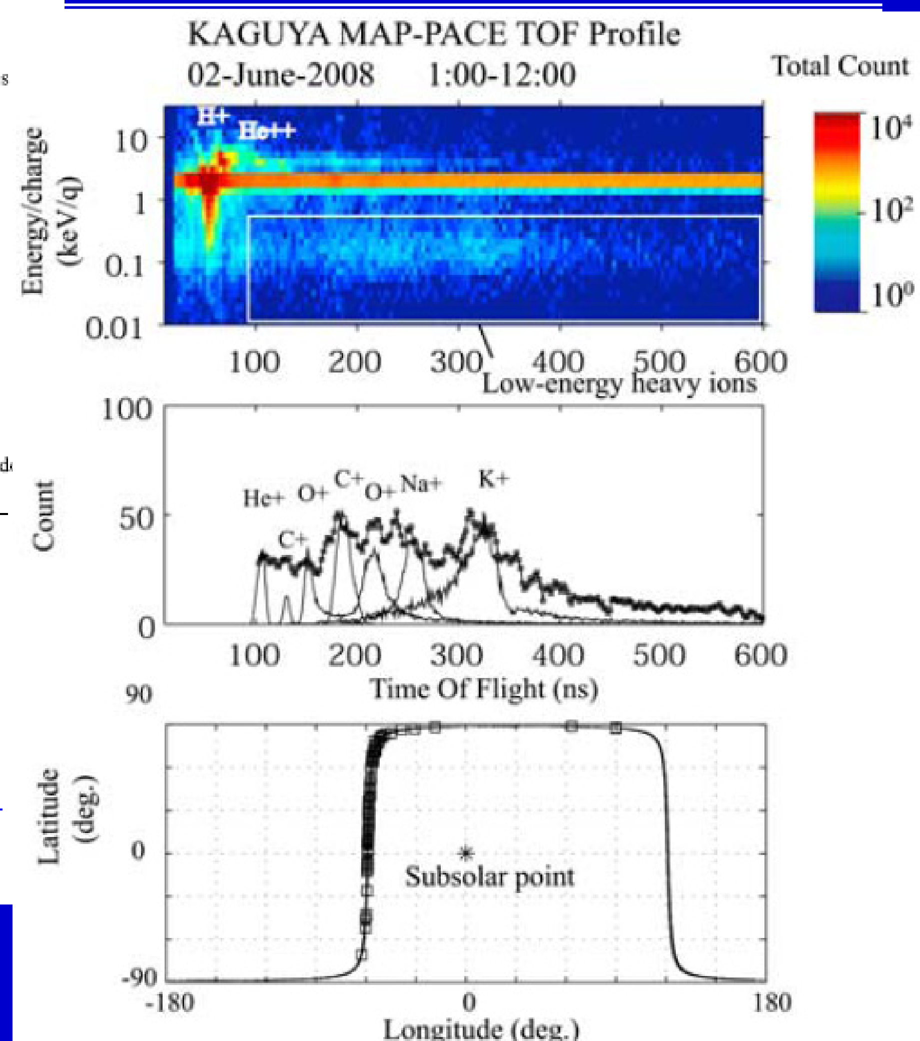
Pommerol et al., *GRL* **37**(2010), L03201



SELenological and E

Sputtering surface ions by PACE

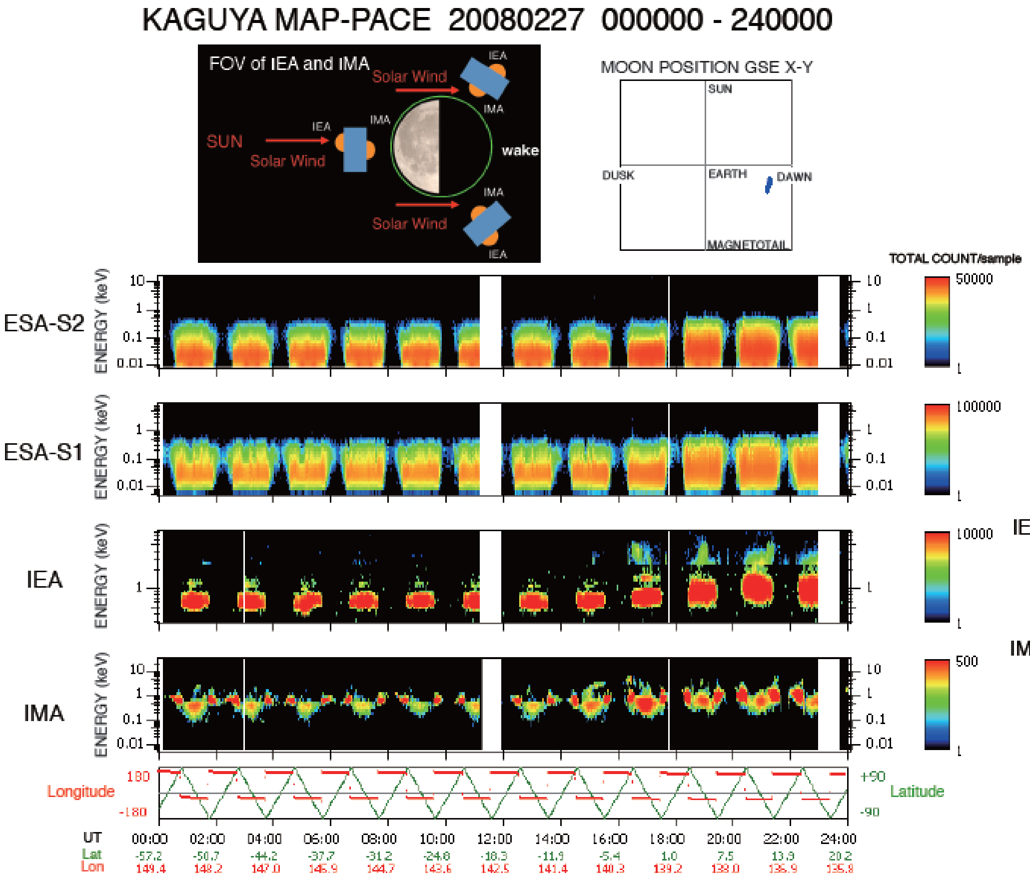


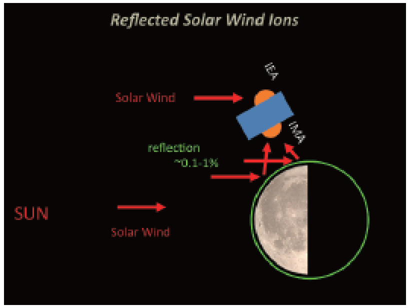


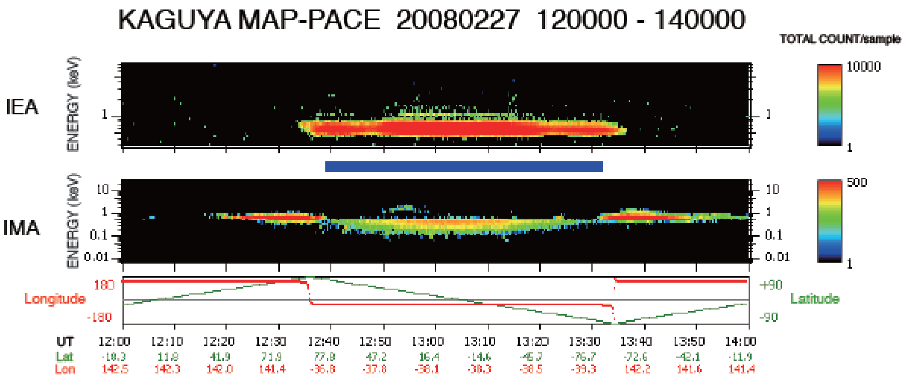
Yokota et al., *GRL* **36**(2009), L38185

Solar Wind reflection Observed by PACE

Solar Wind Ion Reflection on the Lunar Surface

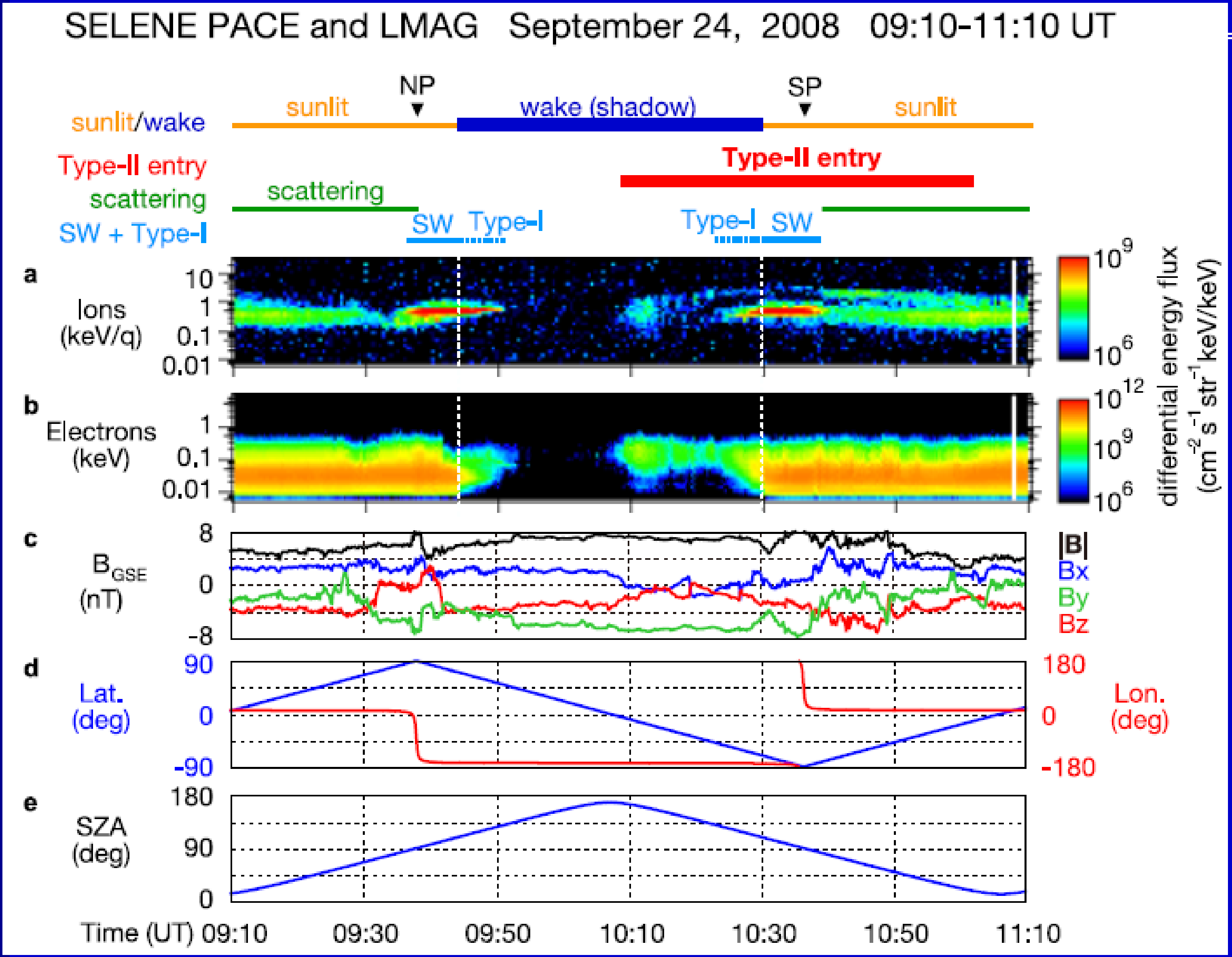






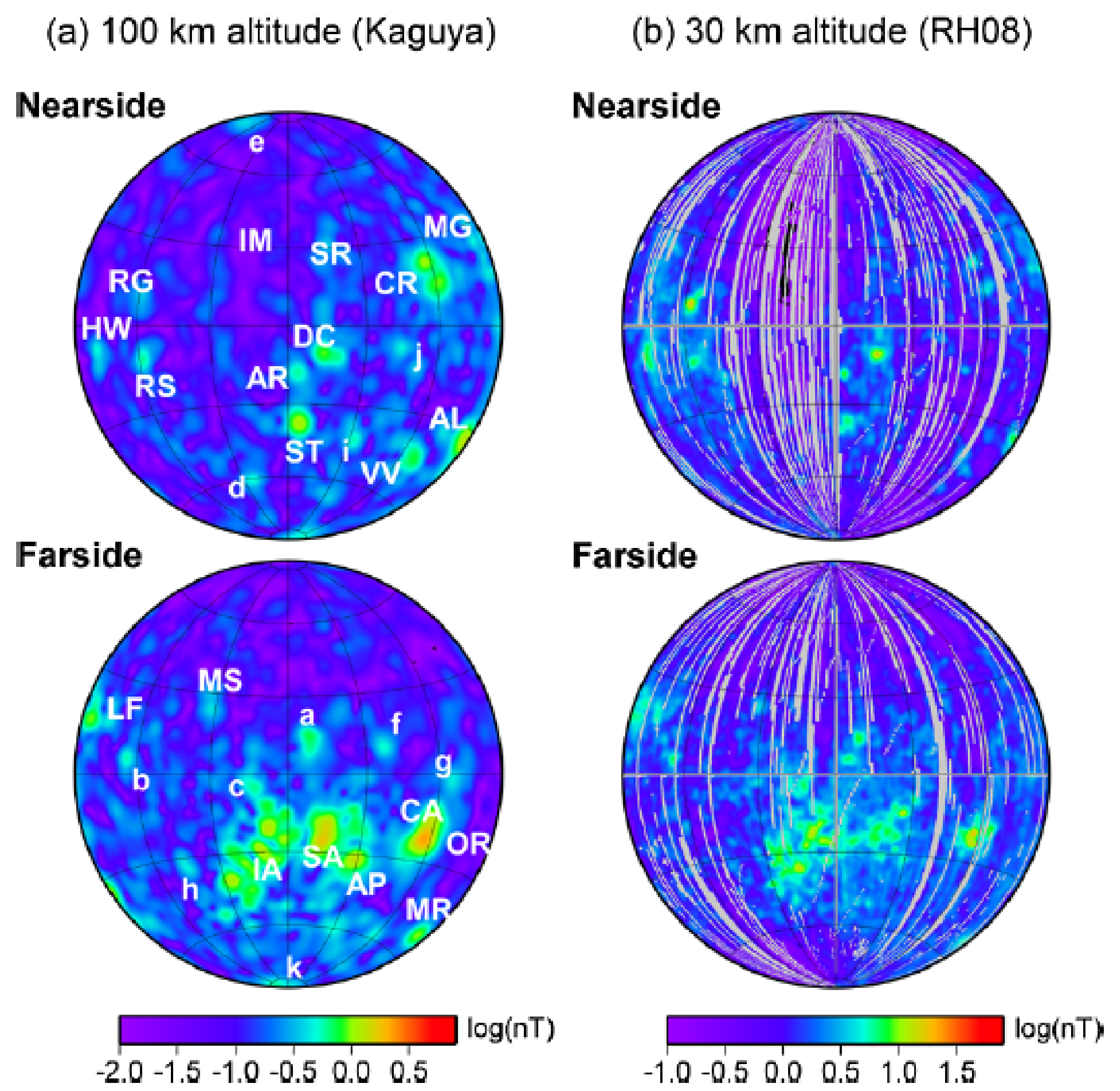
Saito et al., 2008

SW protons access into Moon wake



Nishino et al., *GRL* **36**(2009), L12108

Magnetic Anomaly by Kaguya LMAG



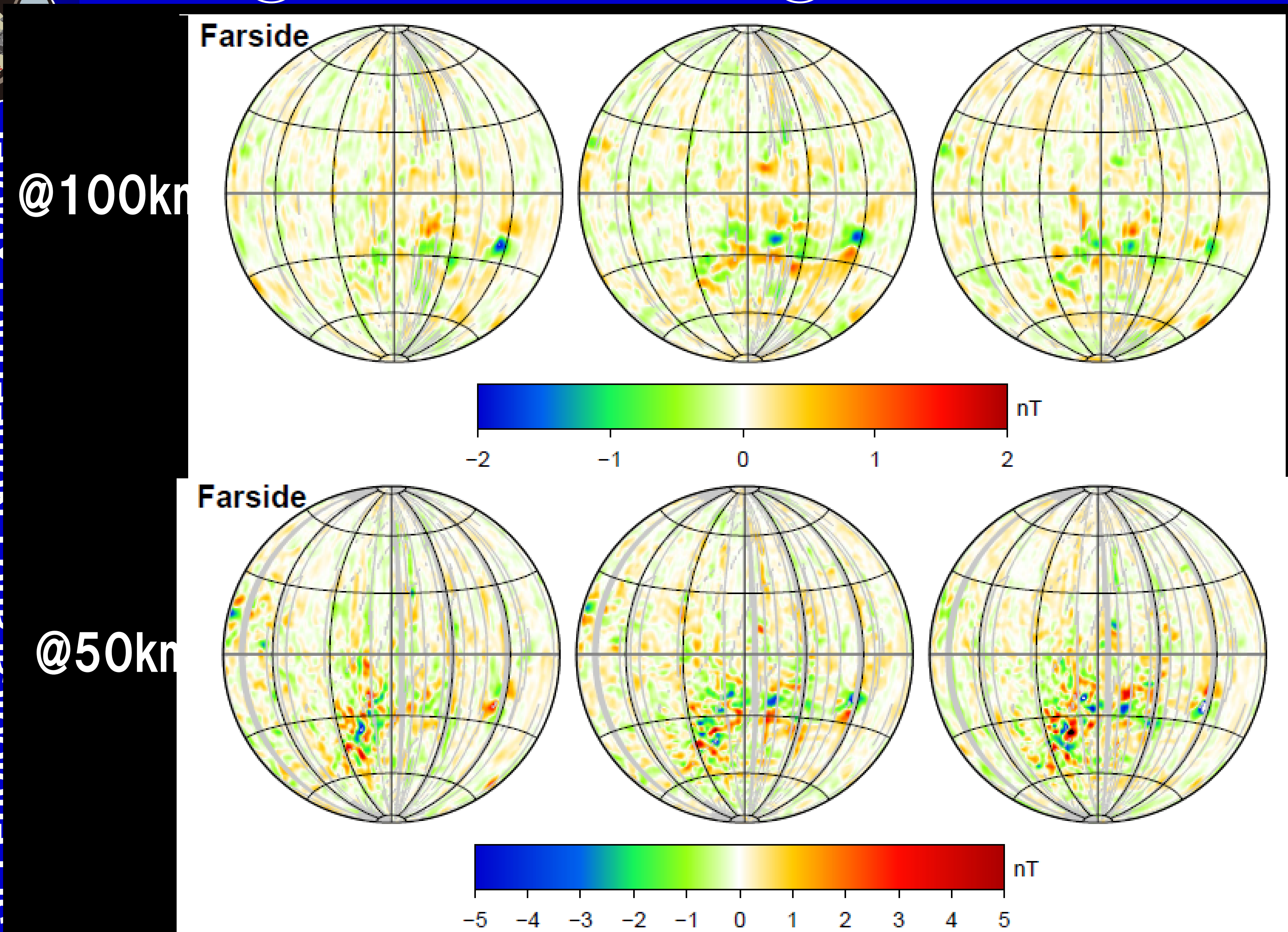
LP data (Richmond & Hood, 2008)

Tsunakawa et al., 2010

SELenological and ENgineering Explorer

LMAG@100km vs LMAG@50km（Farside）

SELENological and ENgineering Explorer

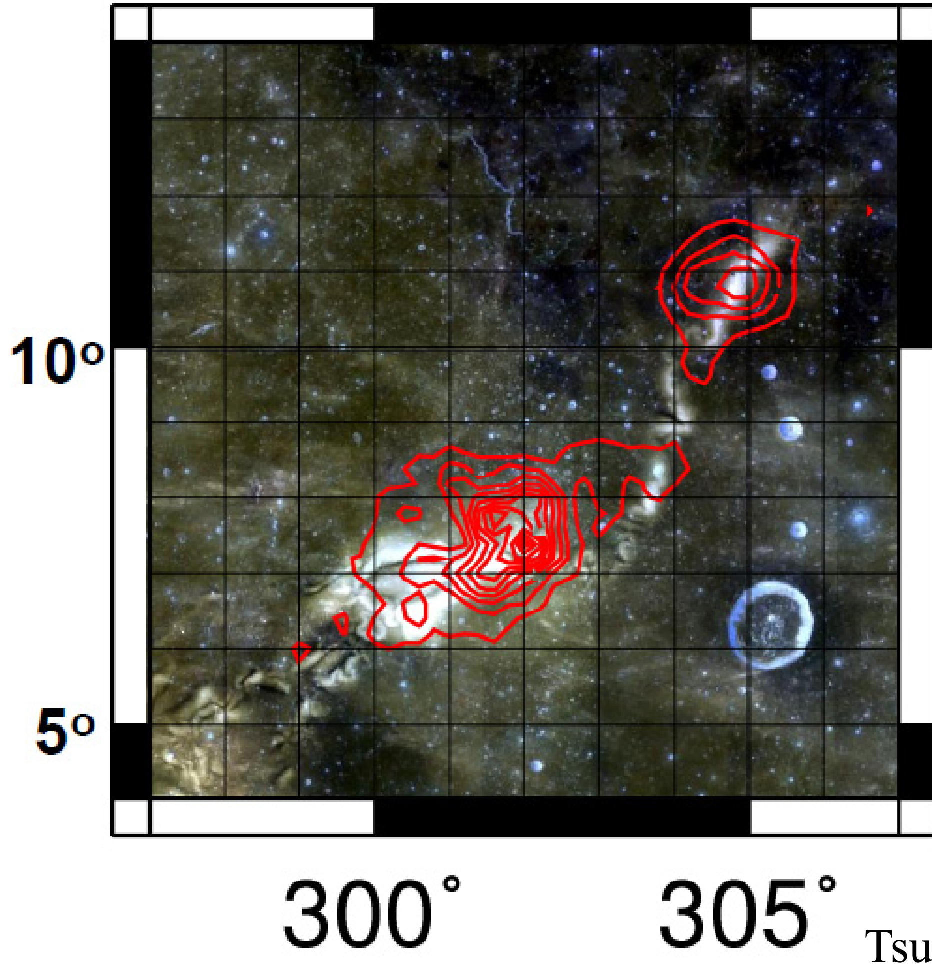


Tsunakawa et al., 2009

Magnetic Anomaly Research

SELenological and ENgineering Explorer

強い磁場は太陽風の衝突を防ぐ(ミニ磁気圏)



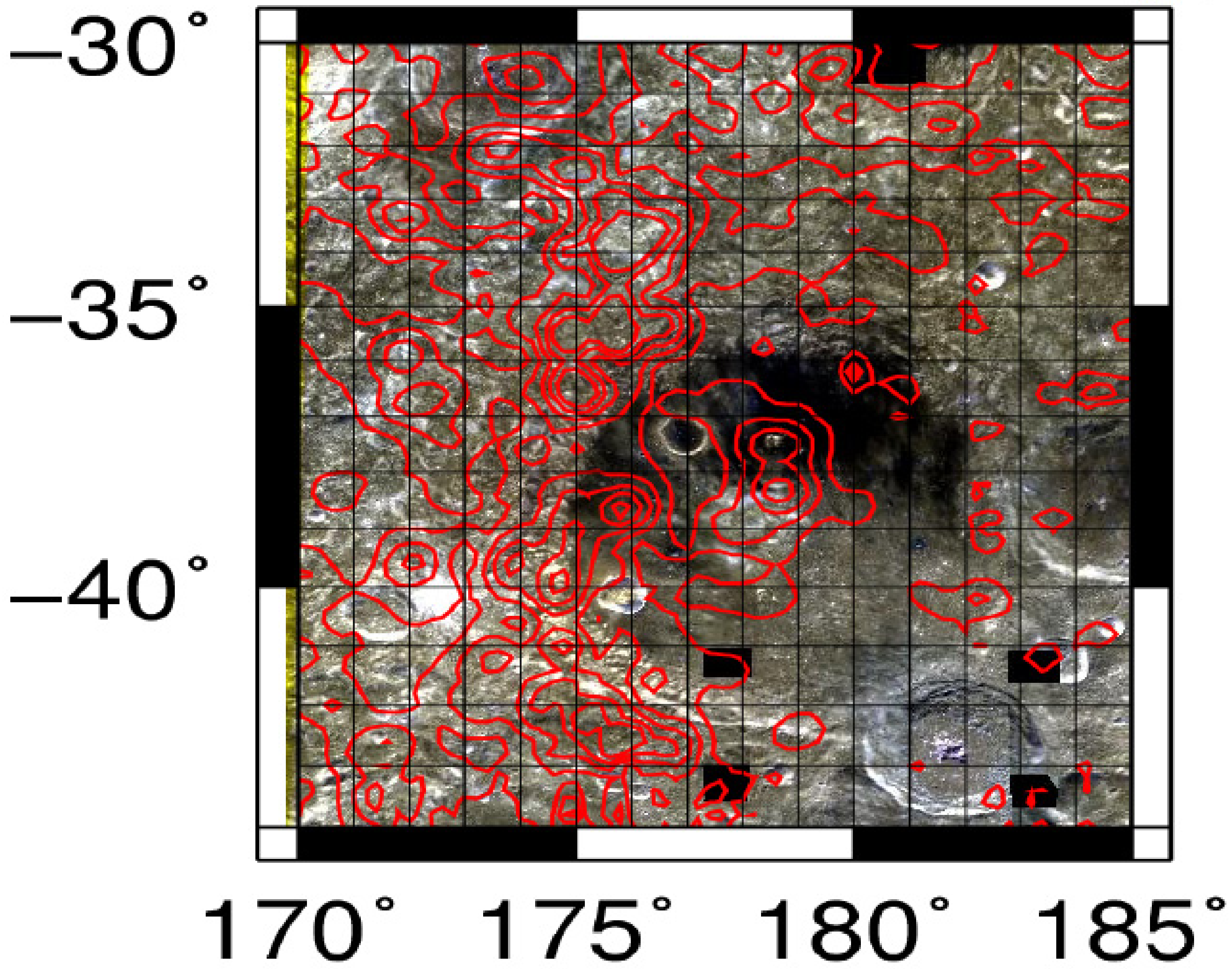
最大 663 nT@月面
太陽風は数nT

ミニ磁気圏が月面を
明るく保つ

Tsunakawa et al., 2010

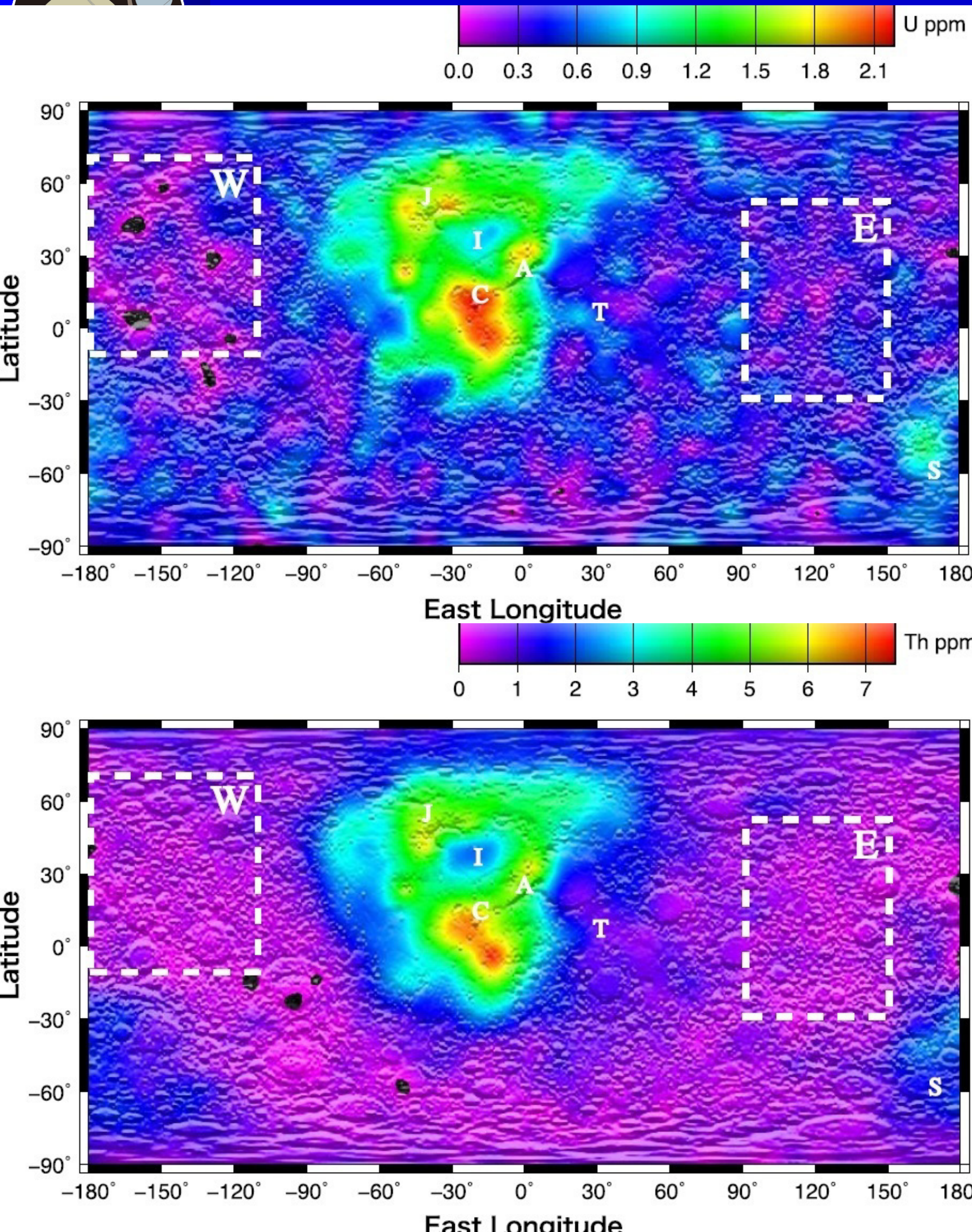
スワール:ライプニッツクレータ

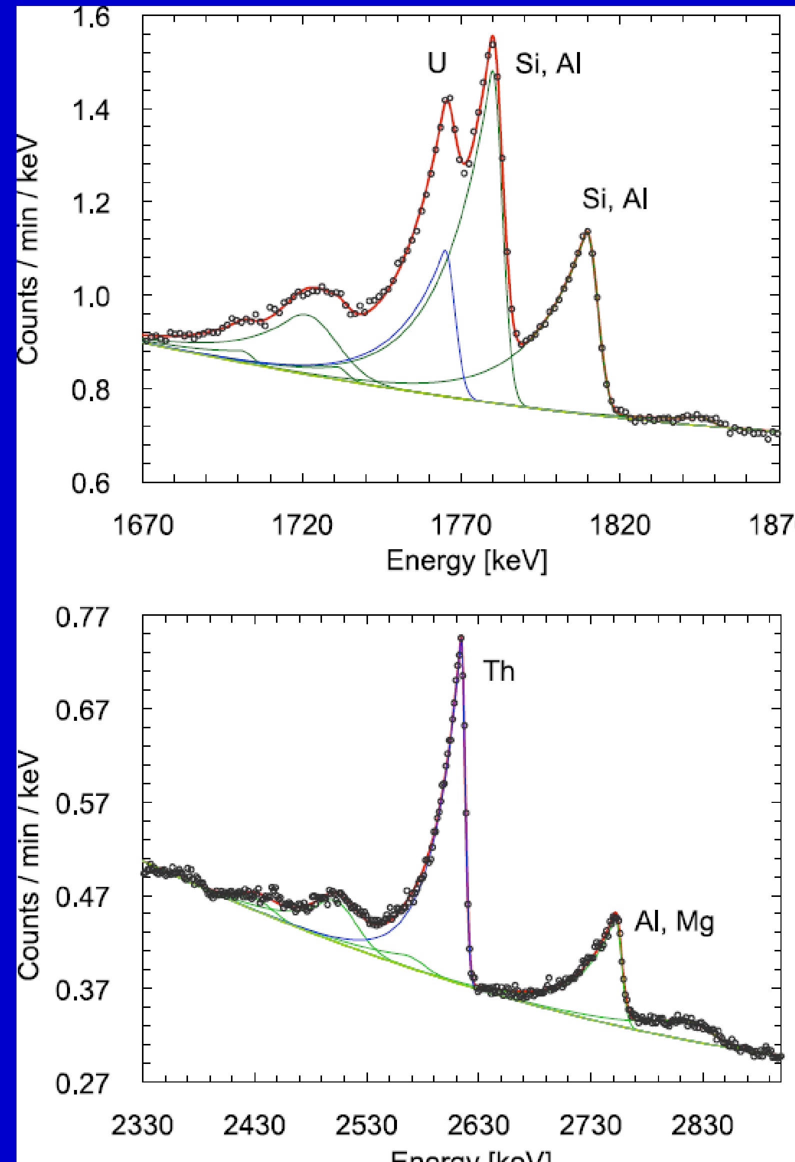
最大 99.6 nT@月面



Uranium & Thorium distribution

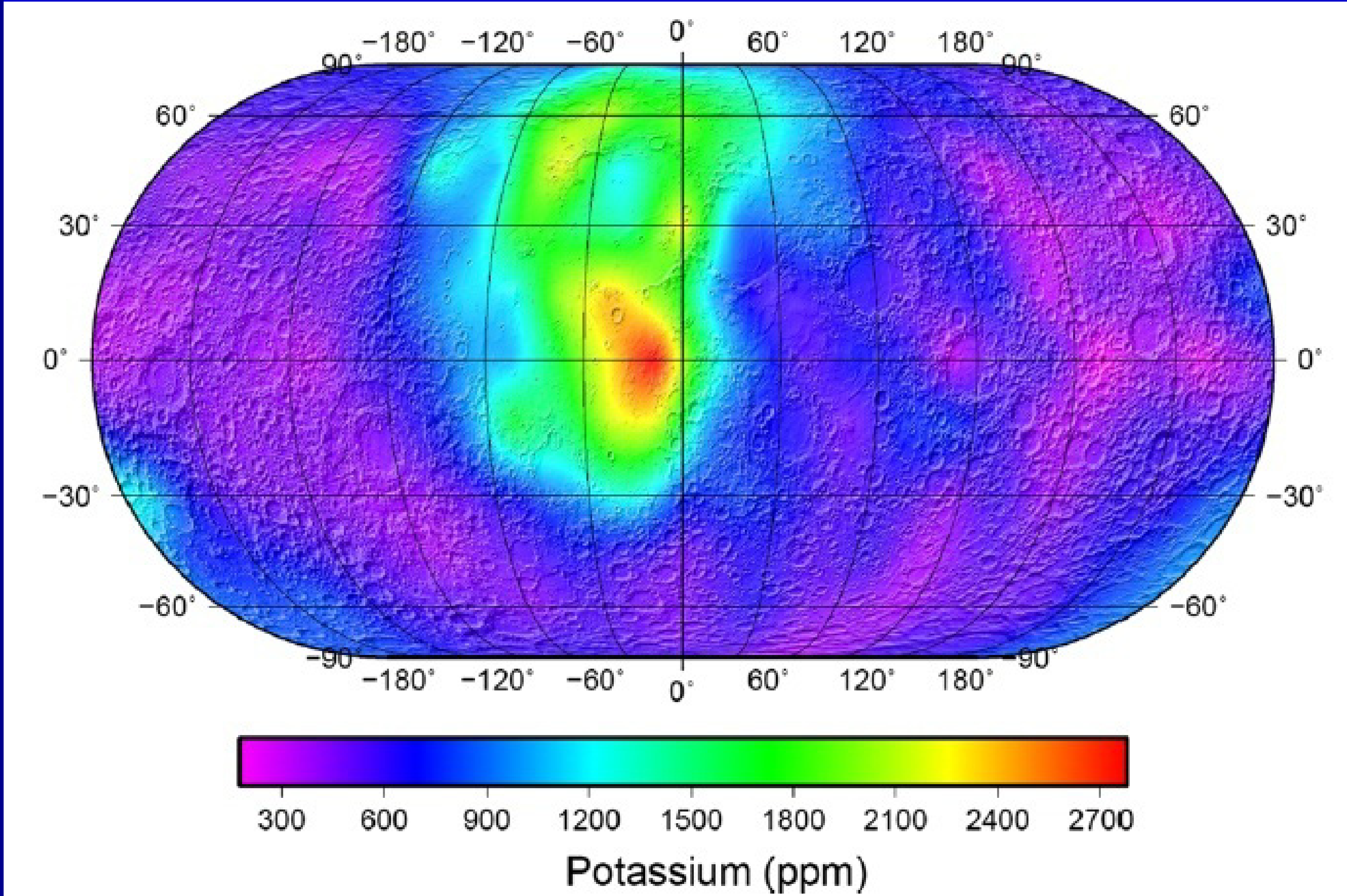
Yamashita et al., 2010





Potassium distribution

SELenological and ENgineering Explorer



S. Kobayashi et al., SSR **154**

New findings in Kaguya Science

SELenological and ENgineering Explorer

- Farside gravity anomaly --- RSAT
- Farside topography --- LALT
- Crustal thickness-- RSAT/LALT/VRAD
- Pole topography/Illumination rate-- LALT
- Farside volcanic activity-- TC
- Mare formation process-- LRS
- Pure anorthosite identification -- MI/SP
- SPA lithology -- SP/MI
- Olivine distribution in craters' rim-- SP
- Solar wind interaction -- PACE/LMAG
- Mini magnetosphere -- LMAG/PACE
- K/U/Th Distribution -- GRS