Landing Sites for South Pole-Aitken Basin Sample Return

10 January 2018

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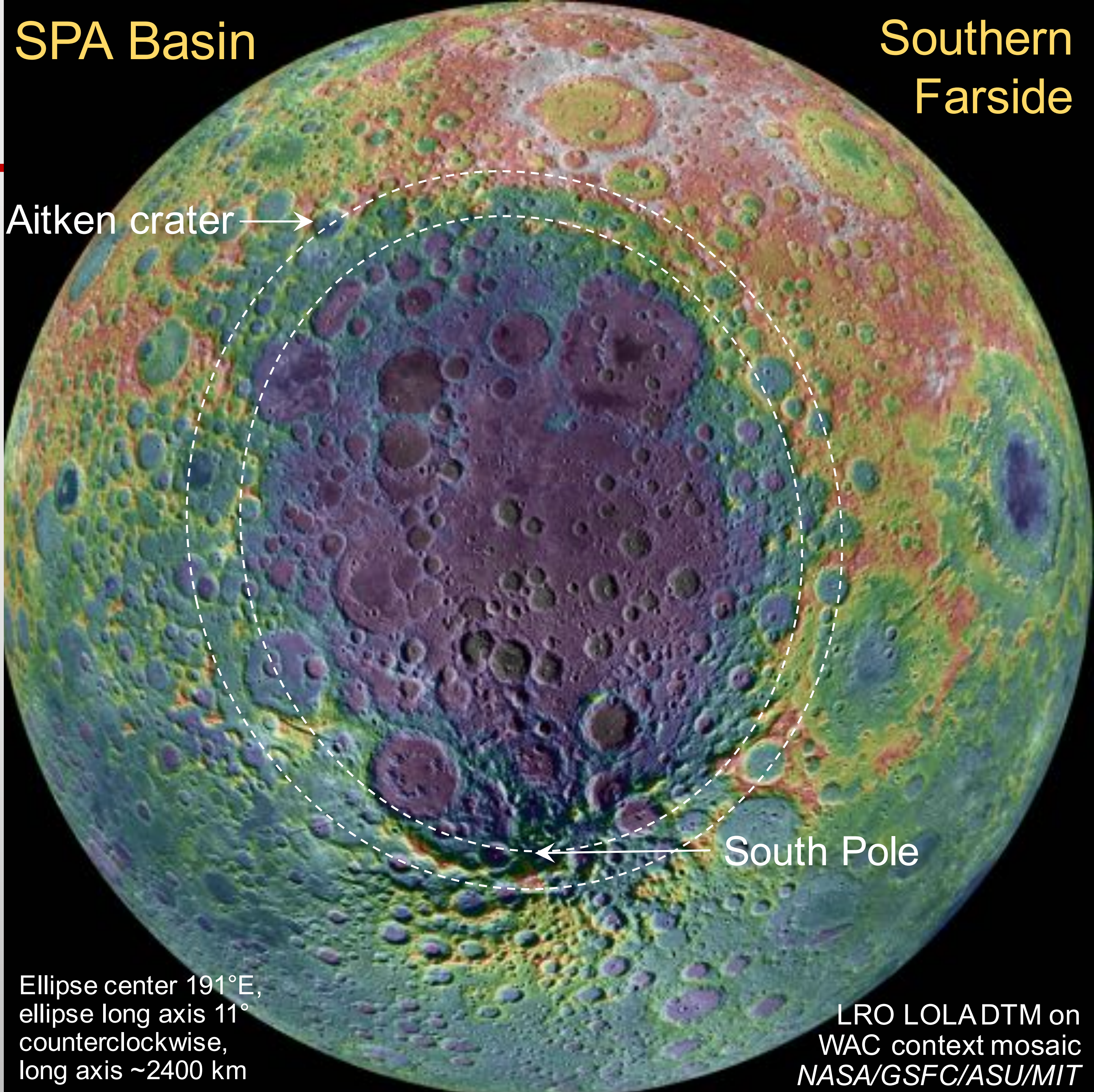
and C. Neal

Lunar Science for Landed Missions Workshop
January 10-12, 2018

Science Priority

- **Why sample return from SPA Basin?**
  - **Important for lunar science**
    - **impact history of the Moon**
    - **early magmatic evolution**
  - **Important for Solar System science**
    - **What happened in the first 500 Myr of Solar System history?**

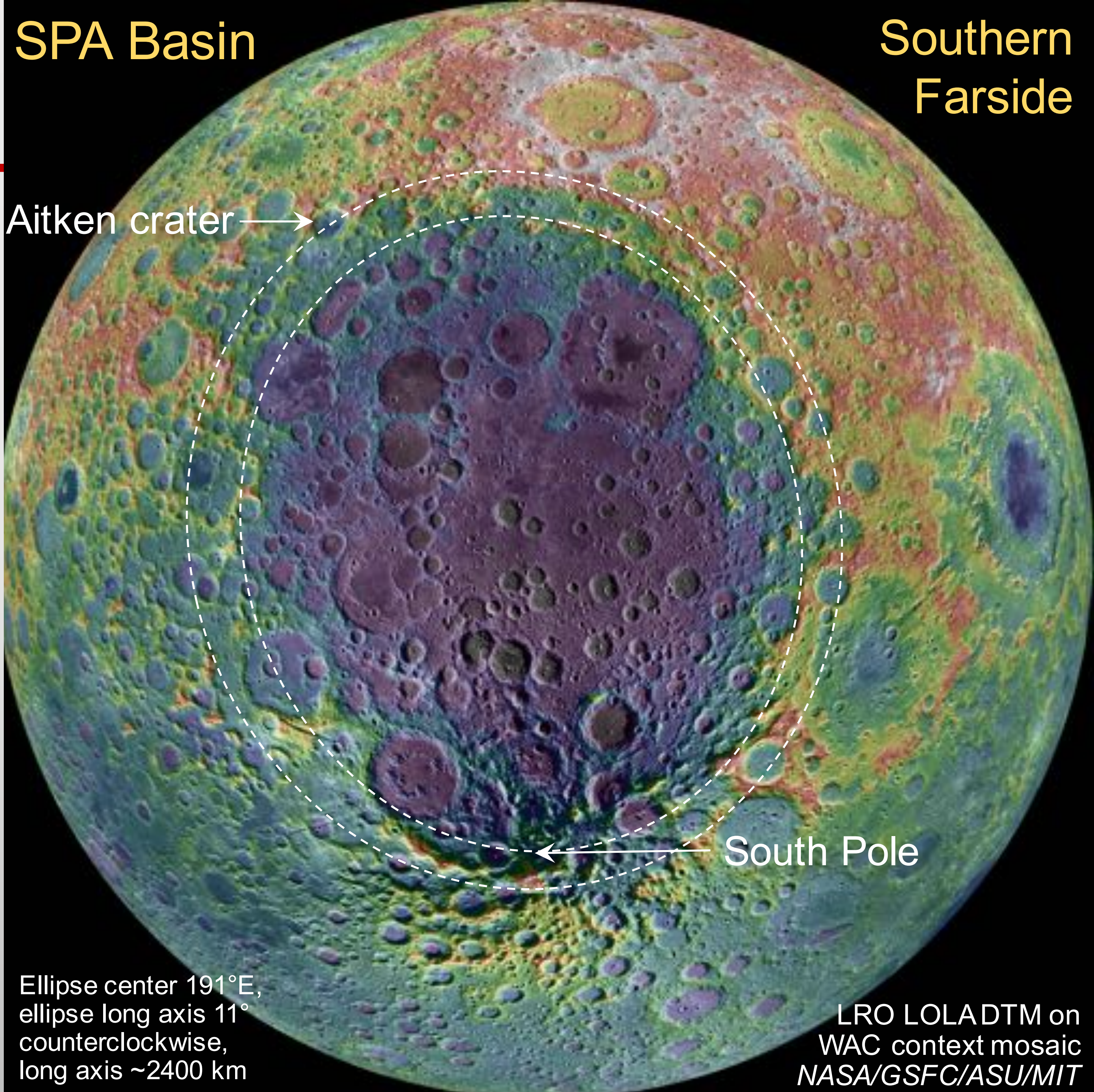
Sample Return from SPA is listed in the Decadal Survey as high-priority.



Science Priority

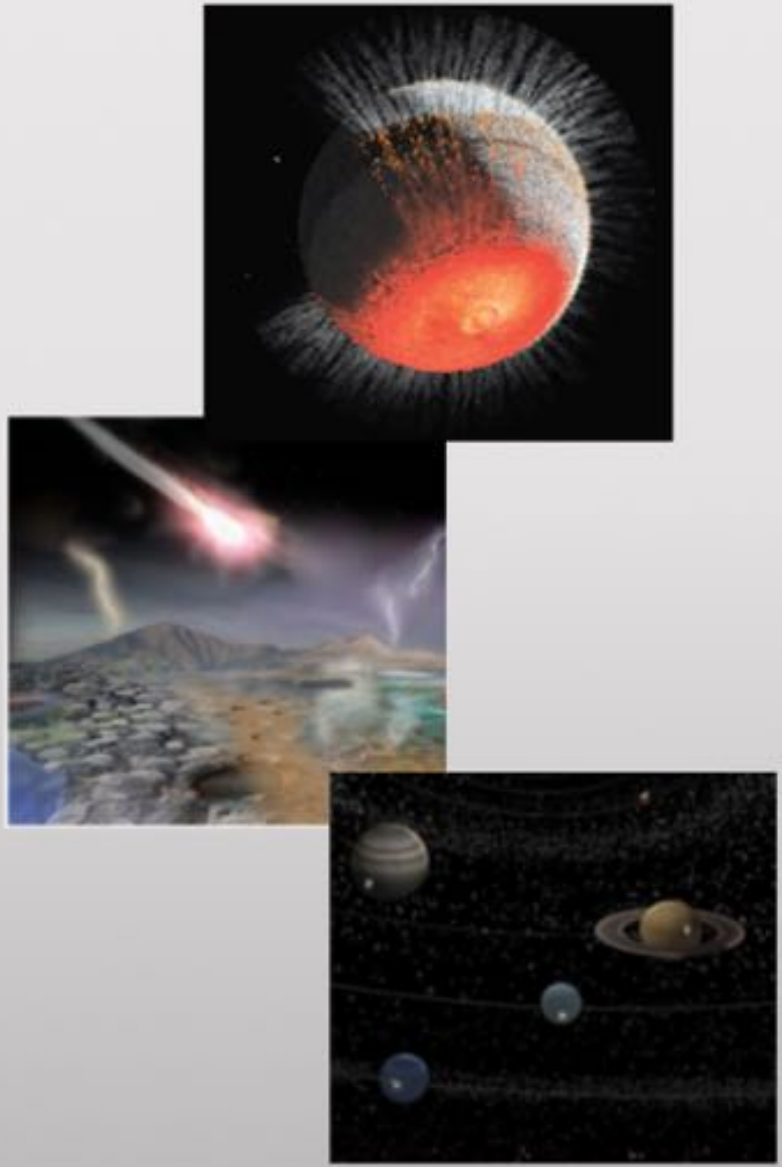
- **A unique location on the Moon and in Solar System**
- largest and oldest clearly recognizable lunar impact basin
  - SPA event completely resurfaced huge part of the Moon and reset ages over an enormous area.
  - As such, SPA *anchors the lunar impact-basin chronology*.

Critical Science objective is to determine basin formation age and "SPA chronology."



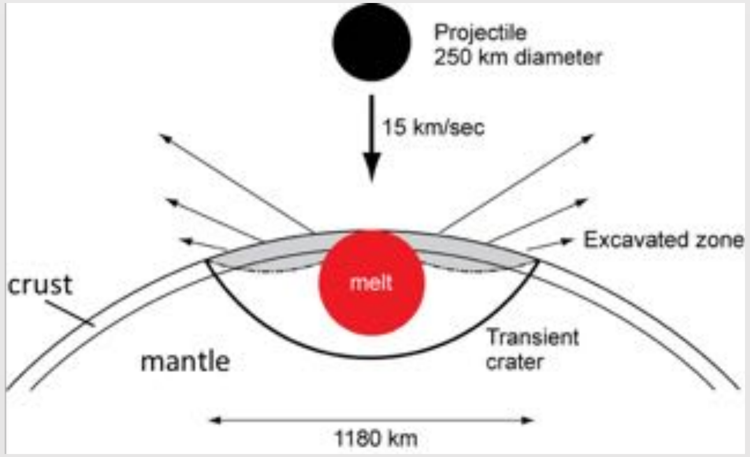
SPA-SR Compelling Science Questions

- **What was the heavy bombardment history of the Moon?**
  - *Cataclysm?   Duration?*
- **What are the implications for early Earth and the terrestrial planets?**
  - *Critical time for early life on Earth (and elsewhere?)*
- **What are the implications for early Solar System Dynamics?**
  - *Models: Nice, Grand Tack, Pebble Accretion, Extended decline of accretion*

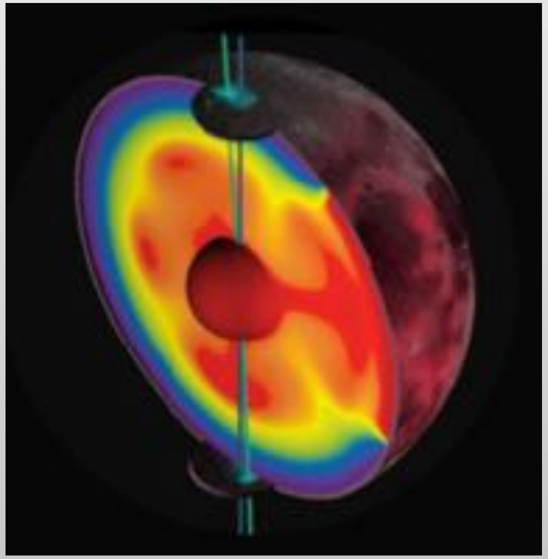


SPA-SR Compelling Science

- **Better understanding of the impact-basin-formation process**
  - How deep did SPA penetrate, how were the excavated materials distributed, how did the Moon's crust and mantle respond?

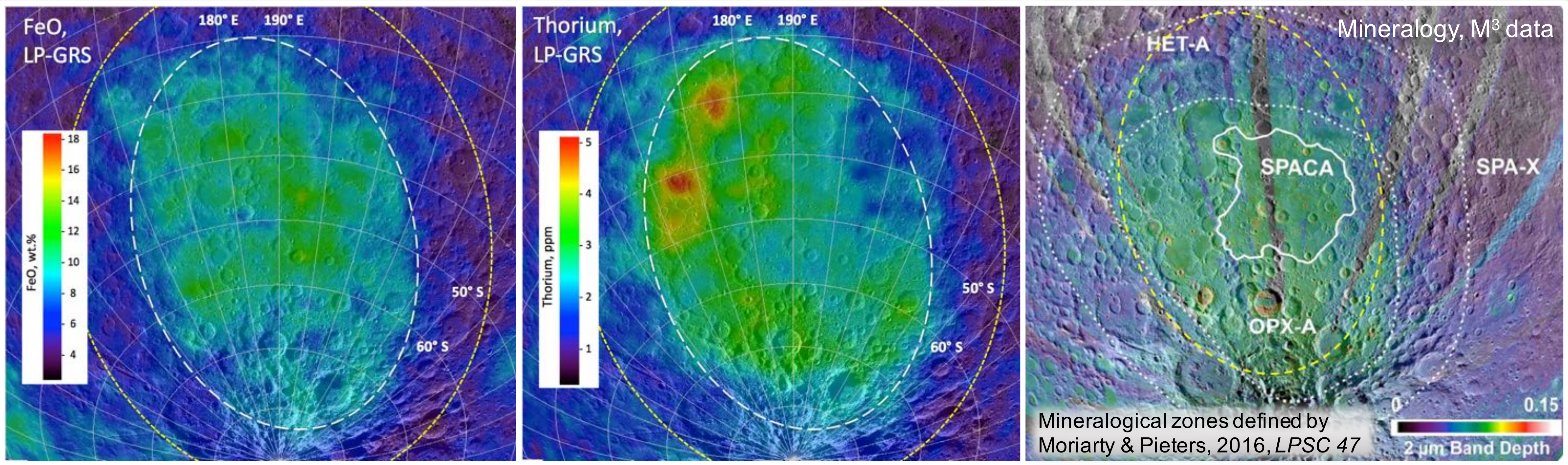


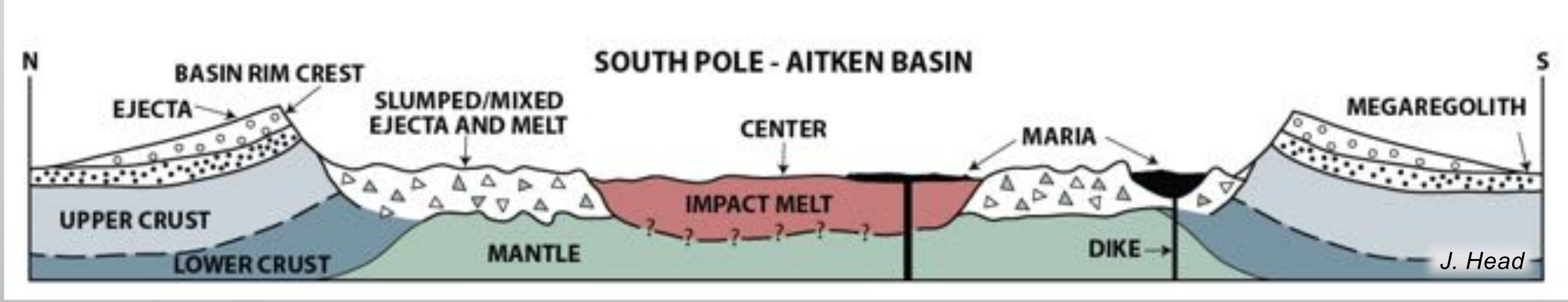
- **Elucidate Crust / Mantle / Core structure**
  - What are the processes that produced large-scale planetary heterogeneity?
  - When was the core dynamo active and at what strength?



- **Thermal Evolution of the Moon**
  - What is the distribution of heat-producing elements in the lunar interior and implications for thermal evolution?
- **Basalts as Probes of the Farside Mantle**
  - What is the heterogeneity of the farside vs. near-side mantle?

Chemical and Mineralogical Signatures





Magnetic Signature

- **Paleomagnetic studies of Apollo samples*** and spacecraft magnetometry of the lunar crust** indicate that an intense core dynamo was active between 4.2-3.6 Ga.
  - only one sample analyzed w/modern techniques that has an age > 3.9 Ga
- **Key questions:**
  - When was the dynamo initiated?
  - What was the source of energy that powered the dynamo?
    Core crystallization, precession, impacts?
- ***What materials are responsible for the magnetic anomalies?***
- ***Date the SPA impact melt rocks and determine their remanent magnetization!***

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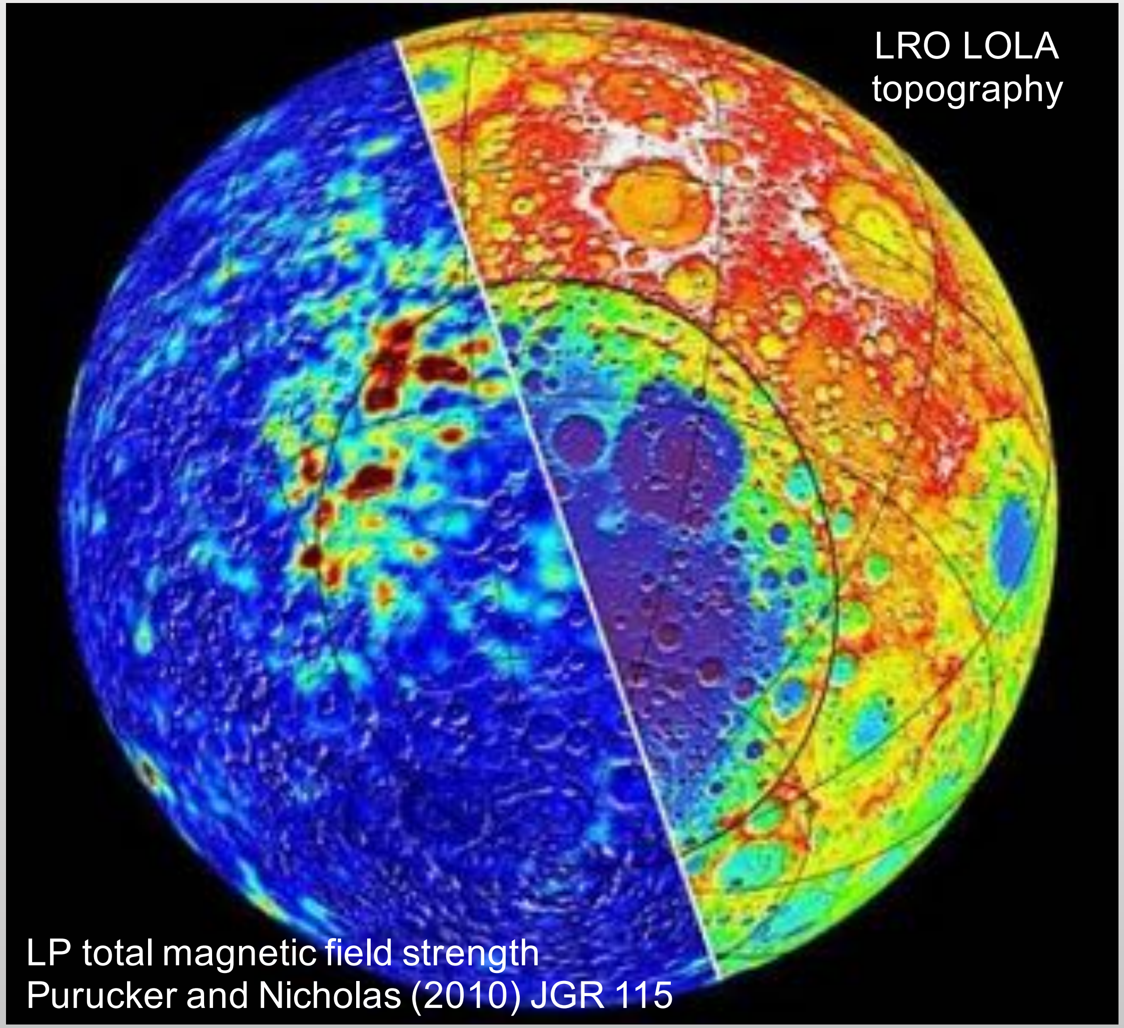
* Weiss & Tikoo, 2014   ***Richmond and Hood, 2008; Purucker and Nicholas, 2000*



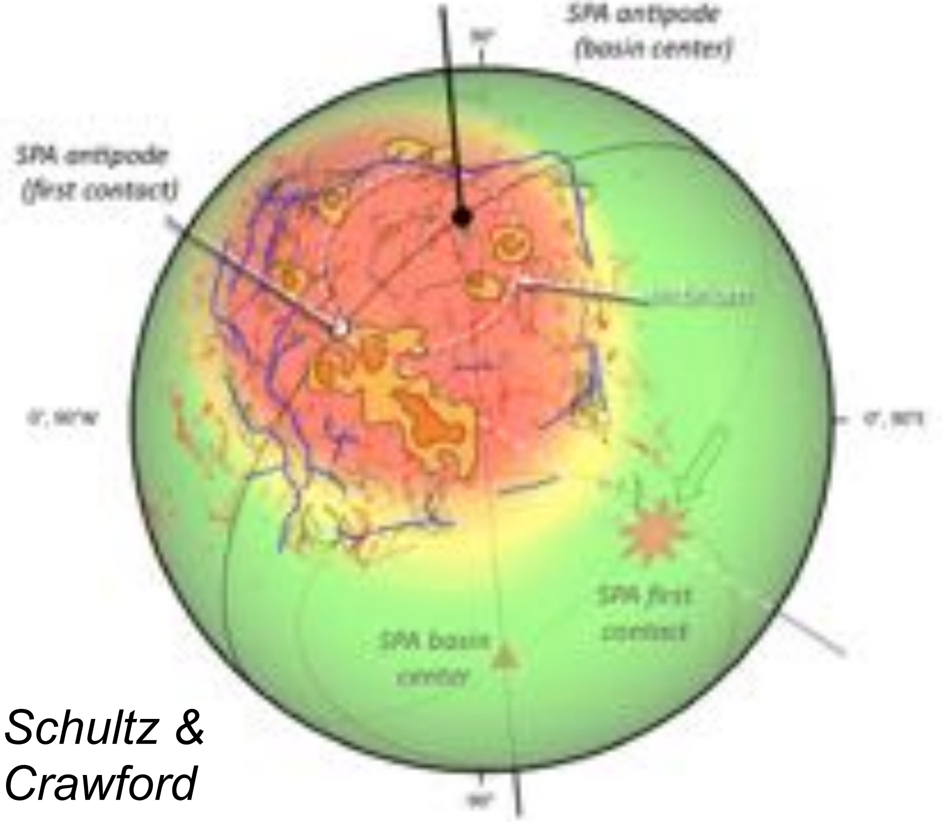
Wieczorek et al. (2012) Science 335

Possible Relationship to Magmatic Activity

46th Lunar and Planetary Science Conference (2015) 2416.pdf

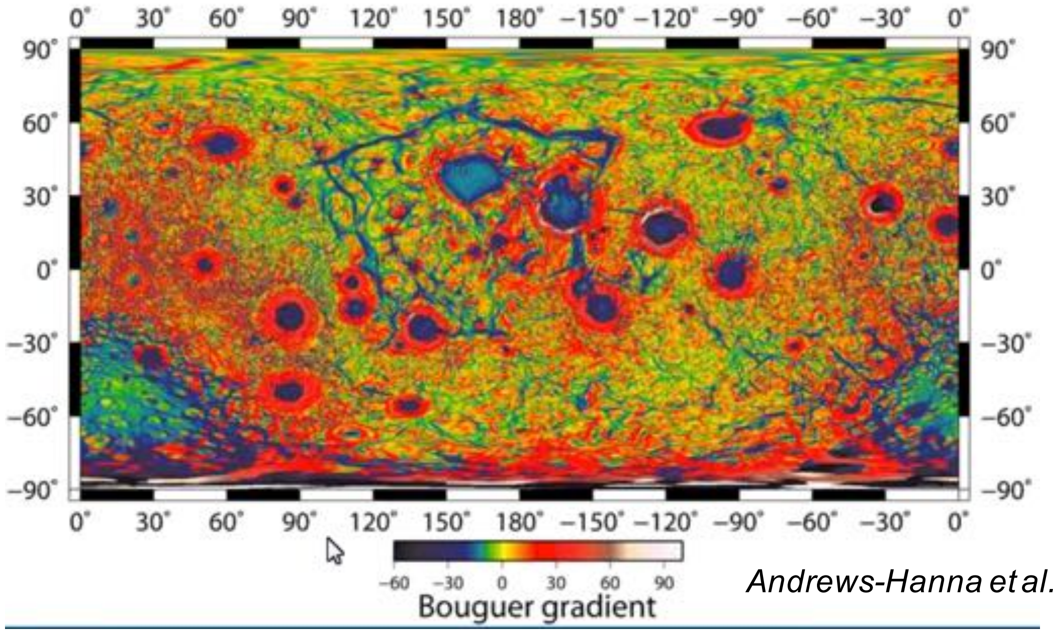
SPA-IMPACT ORIGIN FOR THE NEARSIDE DIKE SYSTEM ON THE MOON. P. H. Schultz[1] and D. A. Crawford[2], [1]Brown University, Providence, RI 02912 (peter_schultz@brown.edu), [2]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA.

- *Potential causal relationship of SPA to global magmatic activity on Moon.*



Schultz & Crawford

GRAIL gravity gradient map



Andrews-Hanna et al., 2014

Rift valleys possibly formed during an episode of crustal magmatism

Possible Relationship to Magmatic Activity

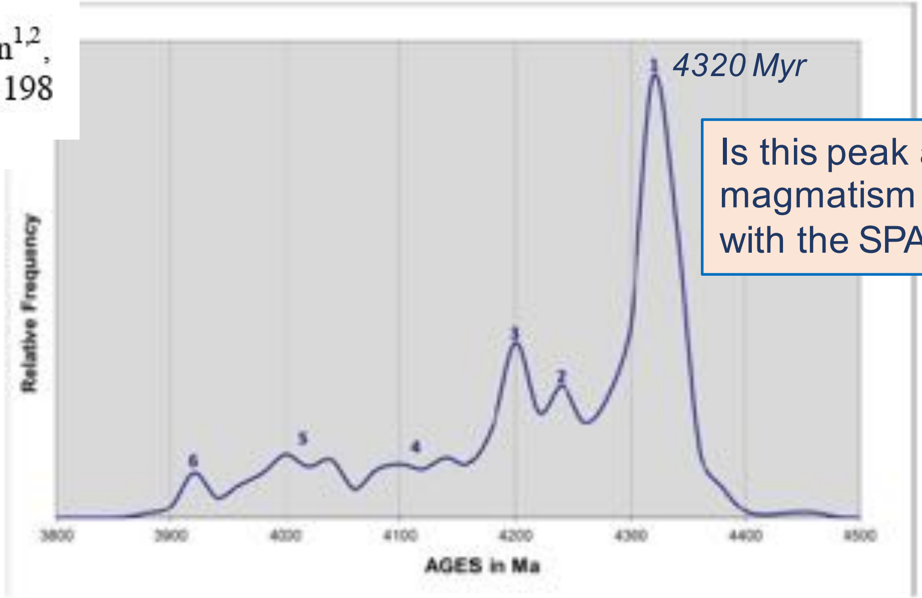
EVIDENCE FOR WIDESPREAD MAGMATIC ACTIVITY AT 4.36 GA IN THE LUNAR HIGHLANDS FROM YOUNG AGES DETERMINED ON TROCTOLITE 76535. Lars Borg[1], James Connelly[2], William Cassata[1], Amy Gaffney[1], Richard Carlson[3], Dimitri Papanastassiou[4], Jerry Wasserburg[4], Erick Ramon[1], Rachael Lindval[1], and Martin Bizarro[2]. [1]Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore CA 94550 USA. [2] Centre for Star and Planet Formation, University of Copenhagen, Denmark. [3]Department of Terrestrial Magnetism, Washington, DC 20015-1305 USA. [4]California Institute of Technology, Pasadena CA 91109 USA.

44th Lunar and Planetary Science Conference (2013) 1563.pdf

WHAT LUNAR ZIRCON AGES CAN TELL? M. L. Grange[1,2], A. A. Nemchin[1,2], and N. E. Timms[1], [1]Department of Applied Geology, Curtin University, GPO box 198 (m.grange@curtin.edu.au), [2]Centre for Lunar Science and Exploration.

44th Lunar and Planetary Science Conference (2013) 1884.pdf

- Recent chronologic evidence for a spike in magmatic activity > 4.3 Ga…
- *What was the role of SPA?*



Is this peak a result of magmatism associated with the SPA impact?

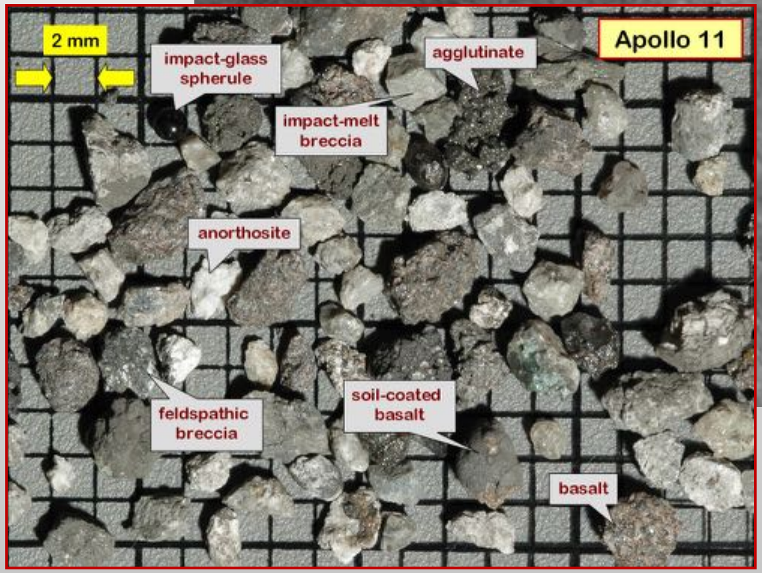
Grange et al., 2013

Figure 1: distribution of U-Pb ages of lunar zircon grains from Apollo 12, 14, 15, and 17 landing sites.

Answers: in Samples from SPA Basin

- *Samples of SPA basin hold keys to each of these questions:*
  - Ages
  - Compositions
    - major elements
    - trace elements
    - isotopes
  - Mineralogy
  - Magnetic Signatures

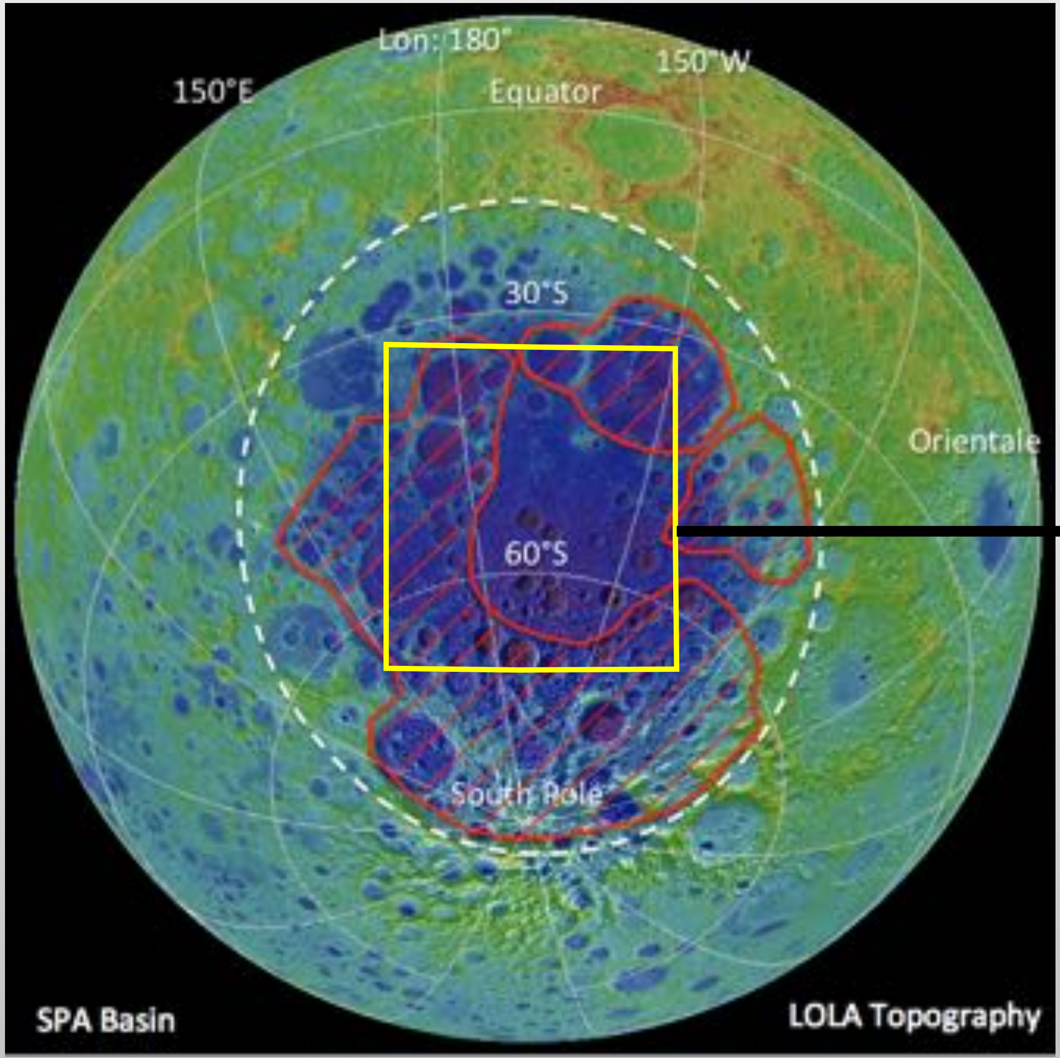
Answers require analyses in terrestrial laboratories.

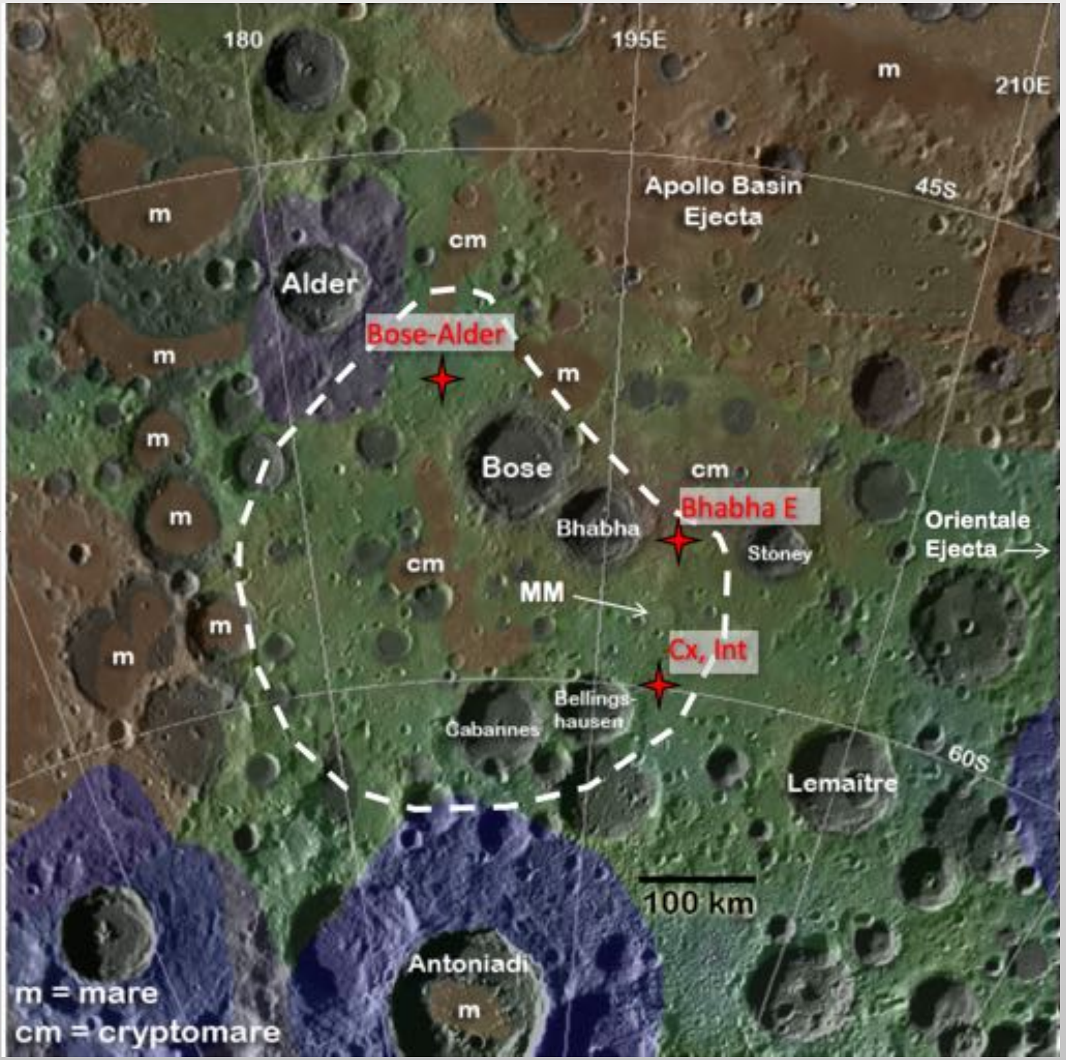


Rock fragments separated from Apollo 11 regolith

LROC NAC oblique view of interior of Mafic Mound, near the center of SPA basin.

Selecting a Landing Region





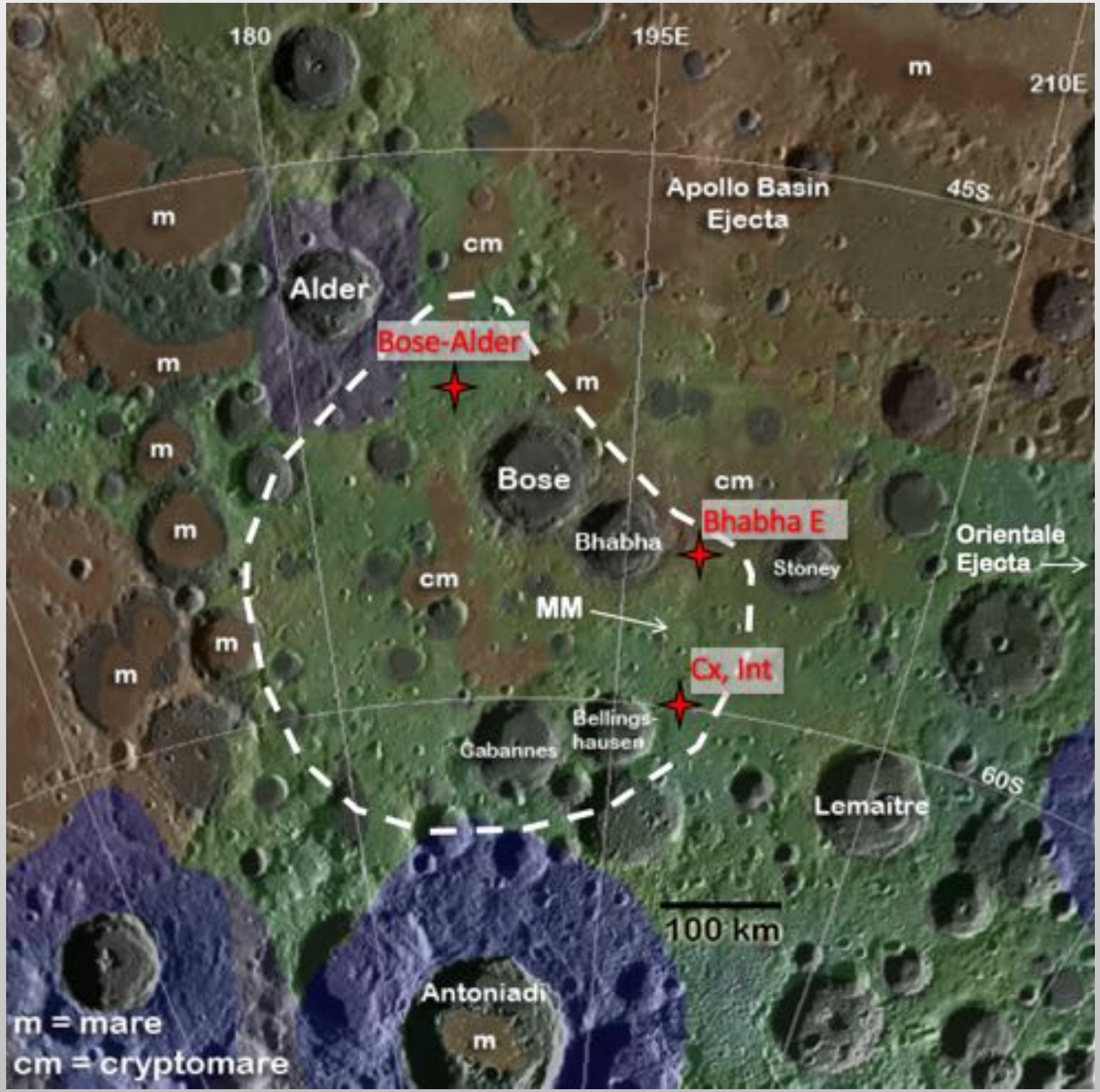
Many Potential Landing Sites in SPA

- Approach to sampling and selecting an appropriate landing site depends on science objectives and cost constraints.
  - e.g., automated sample return of regolith or sieved rock fragments
  - Apollo style sortie mission

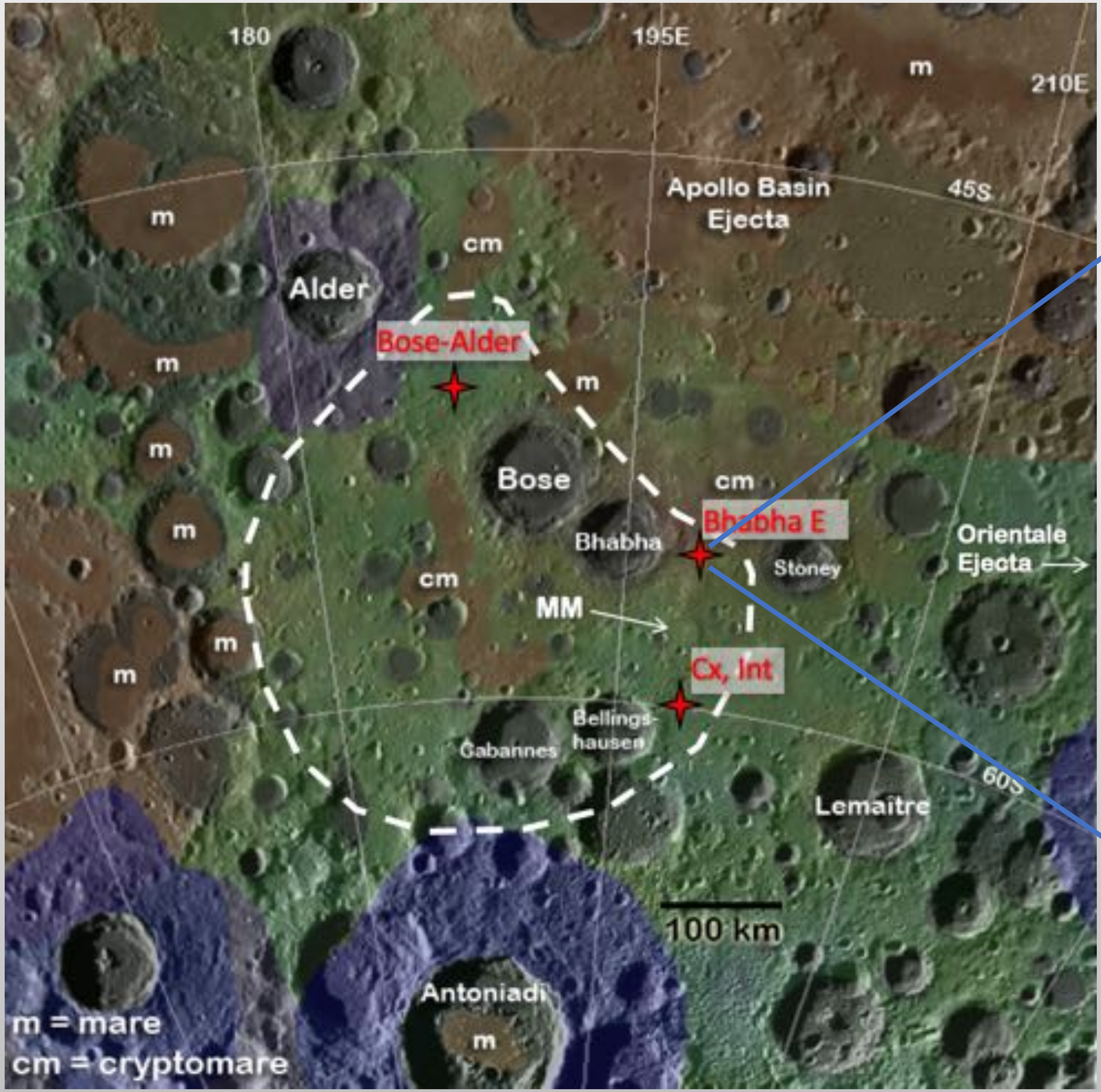
Figure:

Most of the area shown in green corresponds to Nectarian terra or plains materials.

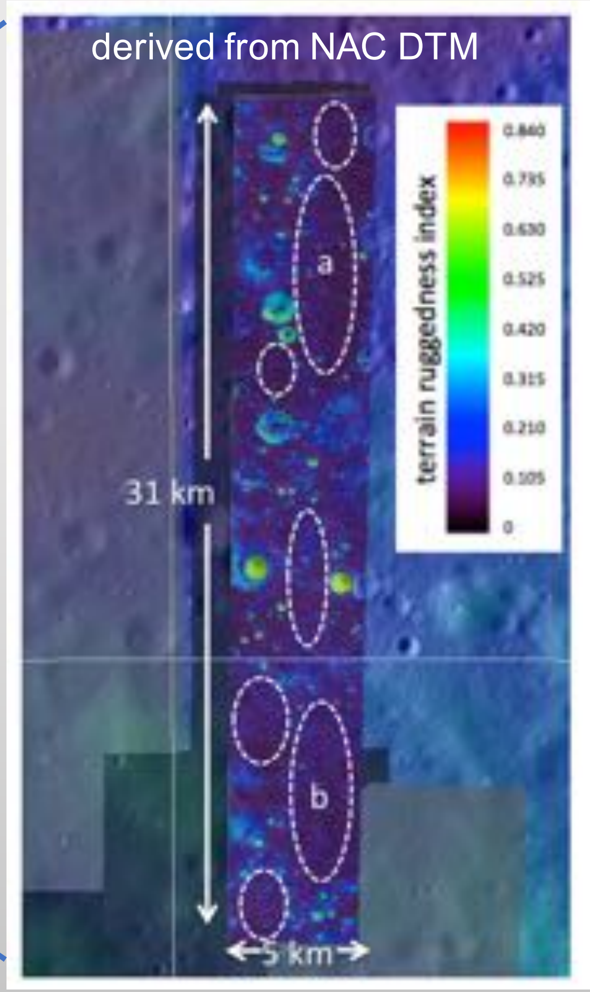
Diverse but mostly low-lying, smooth-appearing terrain.



Landing Site Safety Assessment

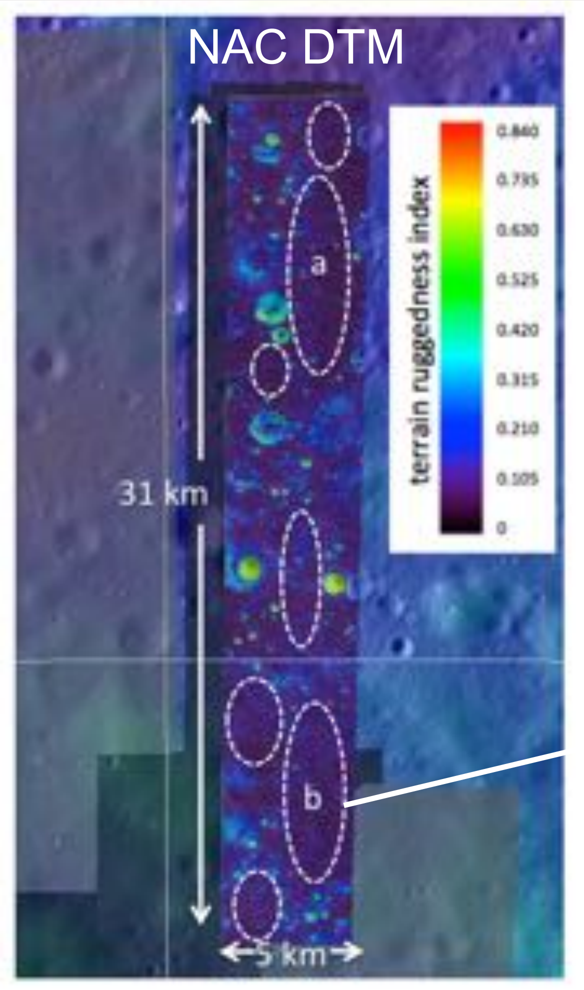


Terrain Ruggedness*

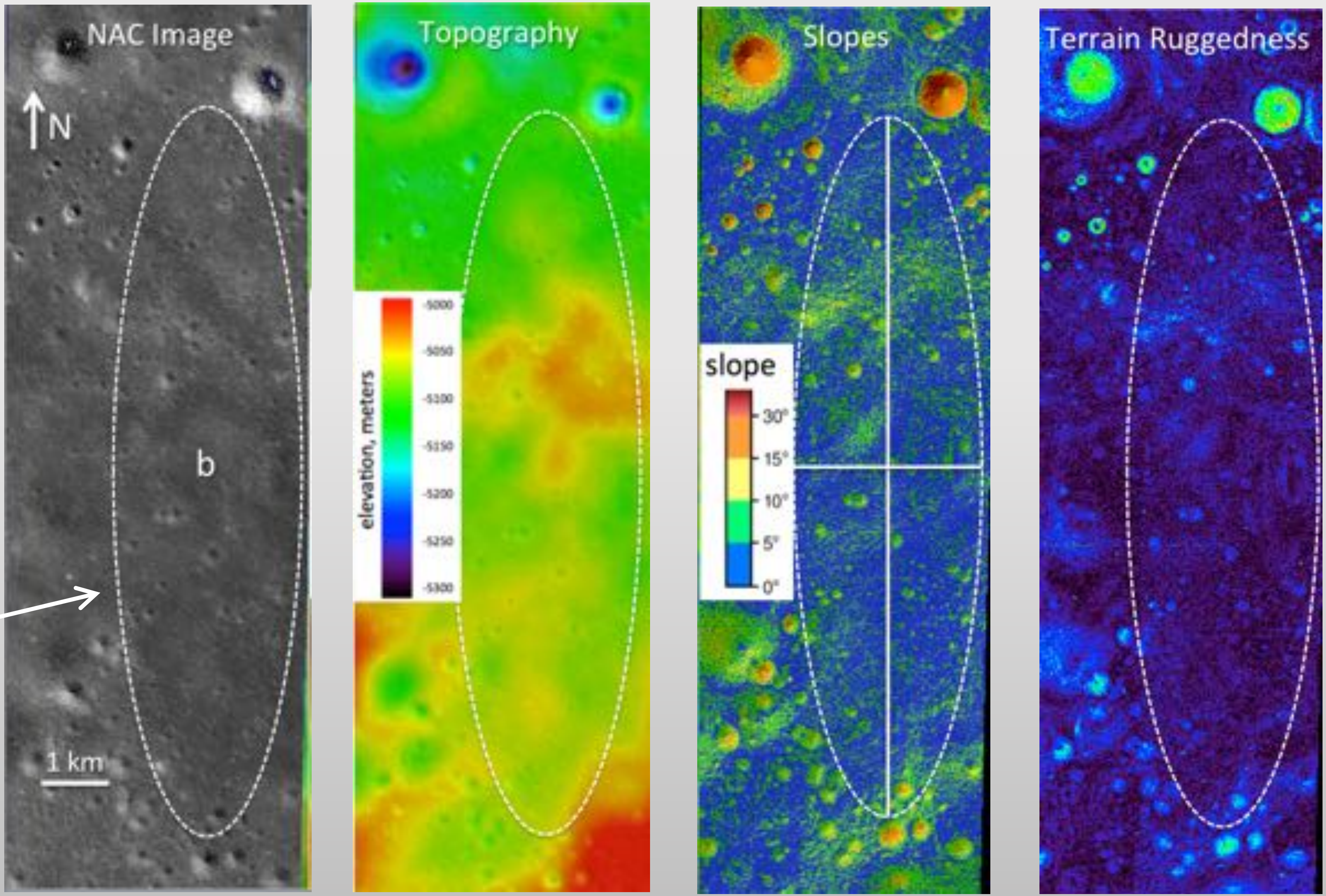


*Terrain Ruggedness Index: mean elevation difference between adjacent pixels in the DTM (Riley et al., 1999; Lawrence et al., 2015)

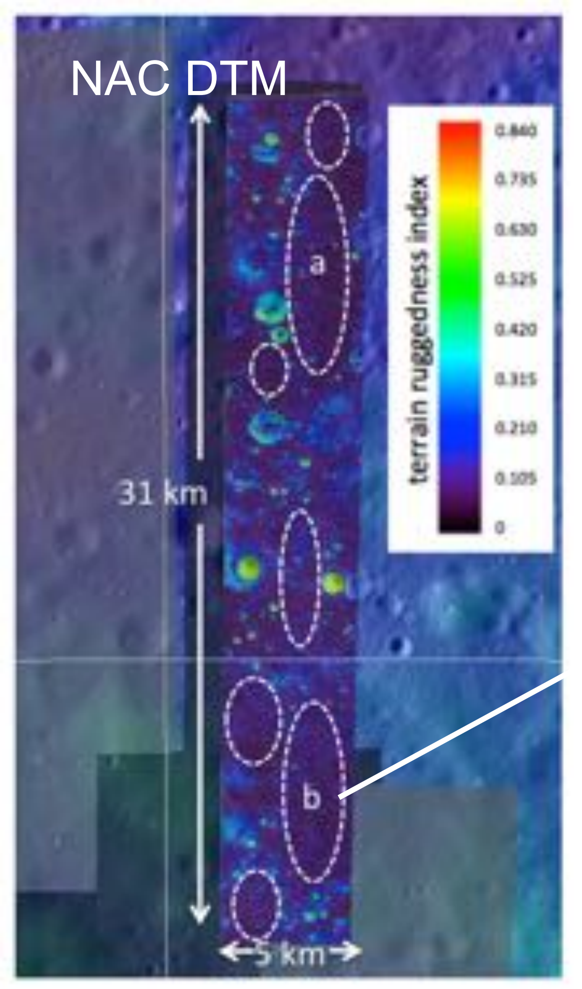
Landing Site Safety Assessment



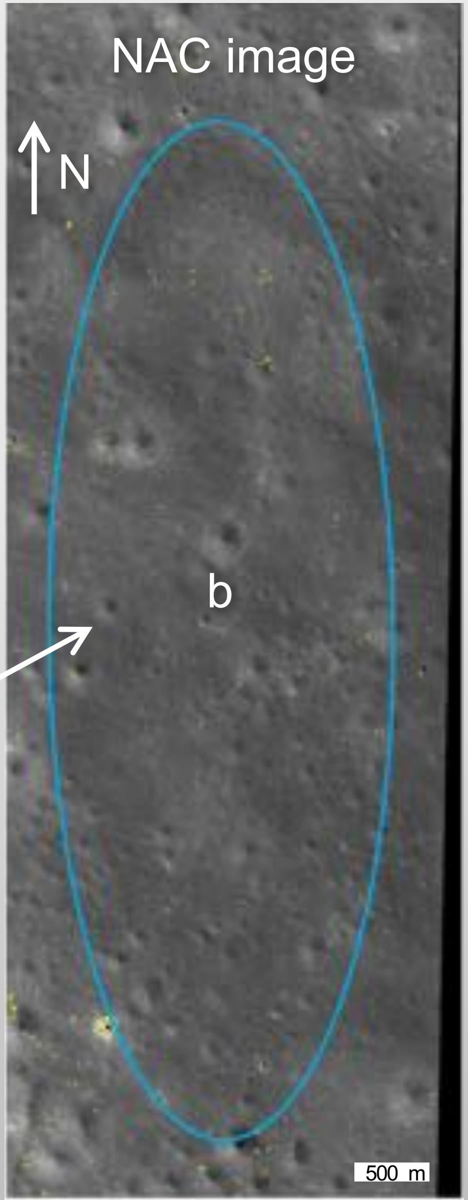
LROC NAC DTM Data



Landing Site Safety Assessment: Boulders



LROC NAC DTM Data



<u>Bhabha “b” Landing Ellipse</u>:

12.86 km^2

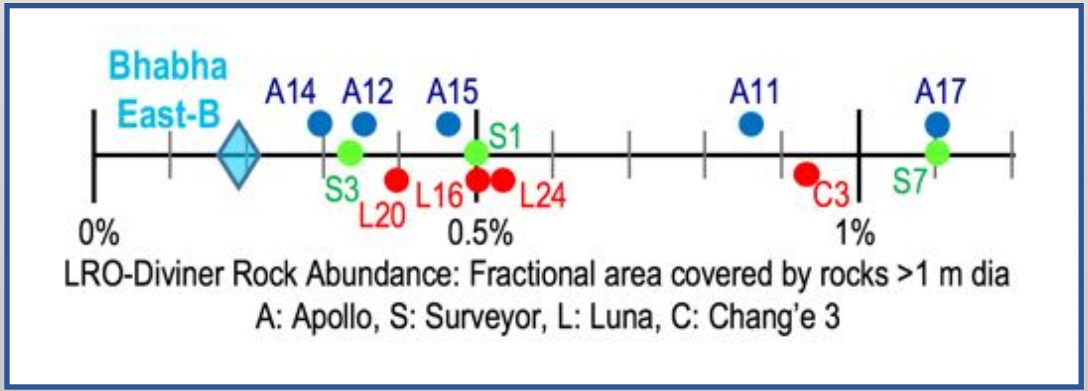
37 boulders within ellipse

Largest boulder: 3.5 m

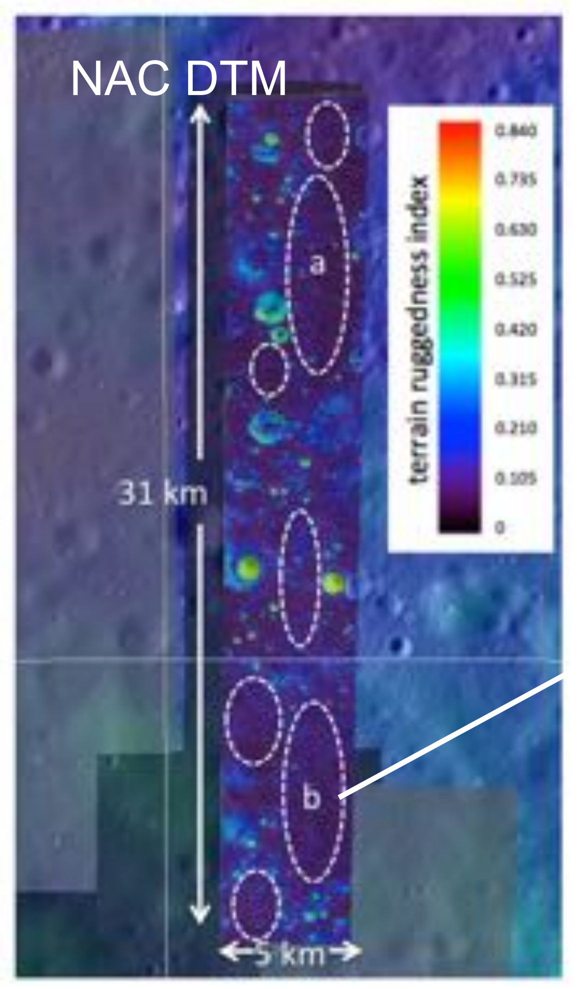
Diviner Rock Abundance: 0.002 (0.2%)

Calculated RA*: 6.4E-5 (0.00006%)

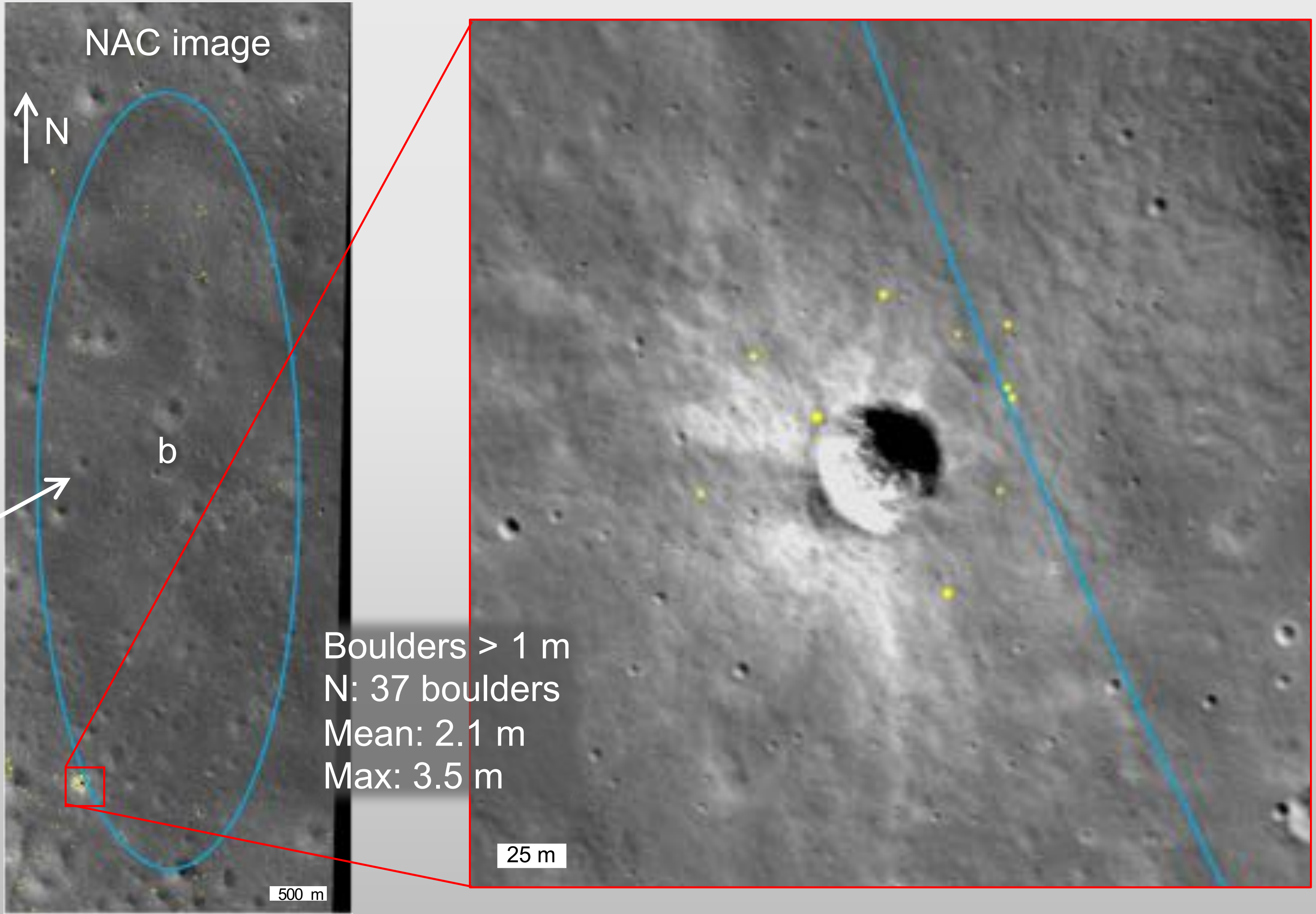
Diviner Rock Abundance comparison:



Landing Site Safety Assessment: Boulders

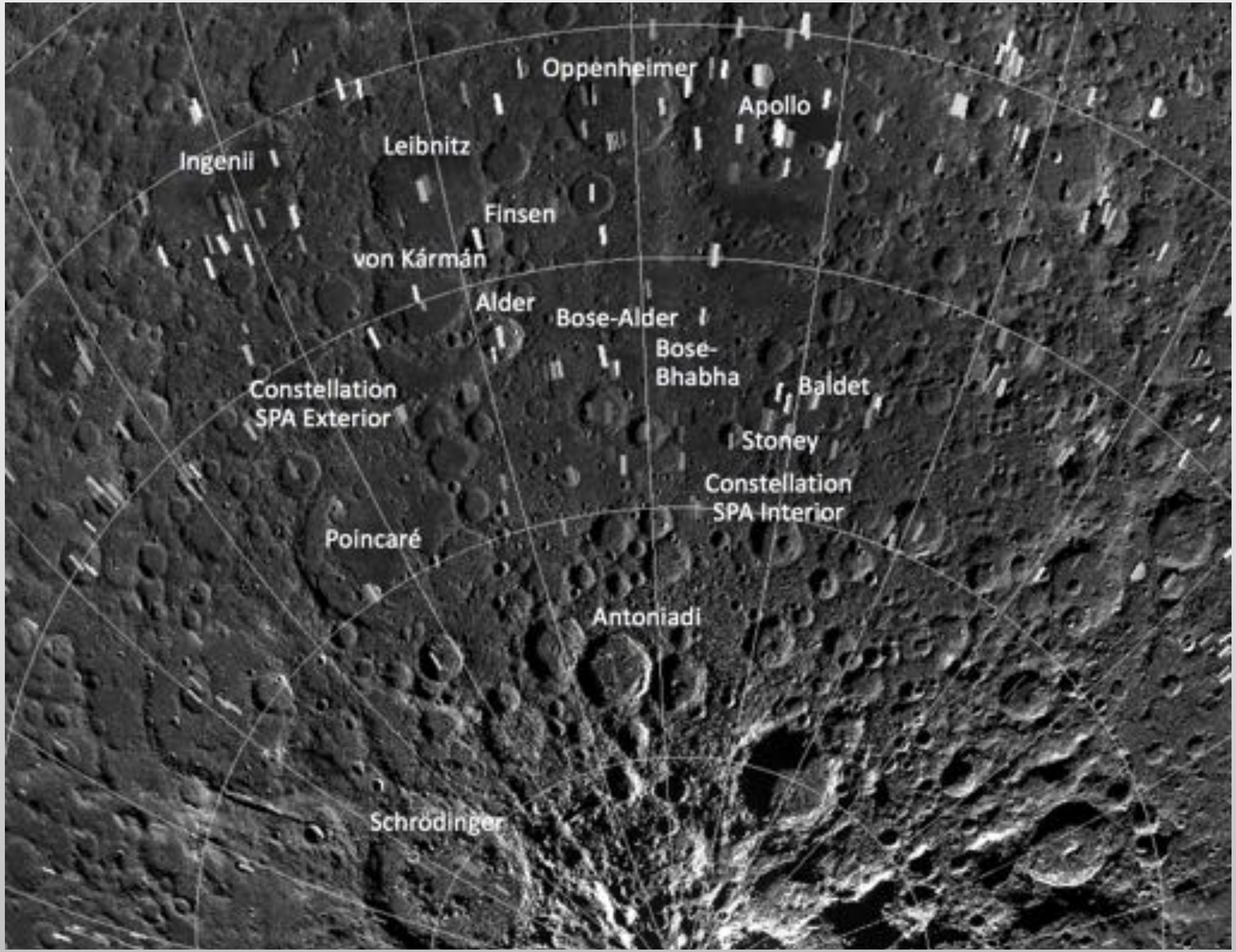


LROC NAC DTM Data



LROC NAC Geometric Stereo Coverage

- NAC Geometric Stereo observations needed for NAC DTM generation
  - Requires slewing LRO Spacecraft
  - Requires specific illumination conditions
  - Operationally expensive
- Good and growing coverage in key areas



Conclusions

- **SPA Sample Return Science**
  - **Determine age of samples that date formation of the SPA Basin.**
    - Test models of LHB timing and causes; establish >4 Ga lunar impact chronology.
  - **Numerous objectives for understanding early evolution of the Moon**
    - Including possible relationship between SPA formation and major igneous activity.
    - Testing concepts for early core dynamo and internal structure.
  - **Many possible landing sites**
    - Center of basin
    - South polar regions
    - Transient crater rim
- **Landing Site Planning and Hazard Avoidance**
  - **Highly accurate positional and coregistered data sets**
    - Enable detailed geologic studies to support landing site assessments.
  - **Imaging and topography at unprecedented scale (0.5-1.0 m)**
    - Provides essential data for automated landing and safe operations.

Sample return - from SPA - will address fundamental questions of early Solar System history, processes of giant impacts, and internal evolution of the Moon.

LRO provides the essential data for science evaluation and landing site terrain analysis.

Backup

Possible Ages from Crater Size-Frequency Analysis

Hiesinger et al., 2012, LPSC 43

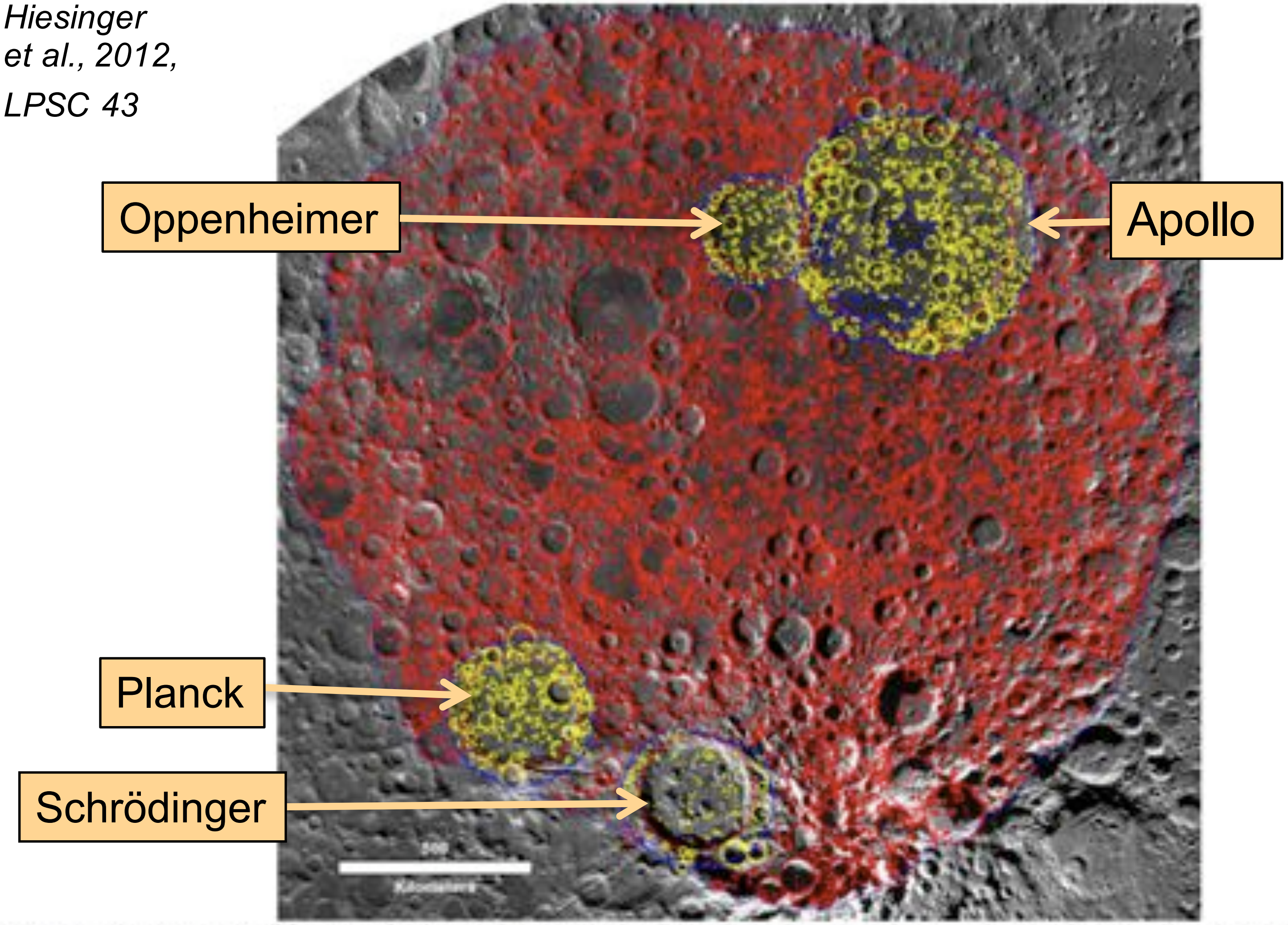
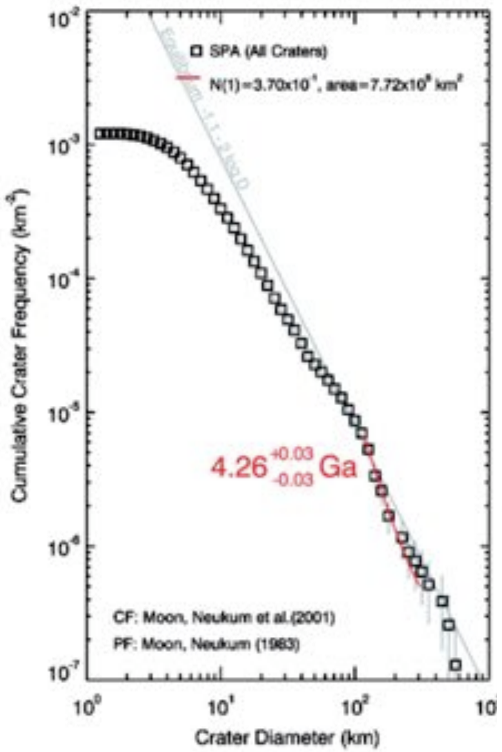


Fig. 2. Count area (blue) and counted craters (red) within the SPA basin. Craters superposed on Planck, Oppenheimer, Schrödinger, and Apollo craters/basins are shown in yellow. Stereographic map projection with the south pole approximately at the center of the lower image margin.

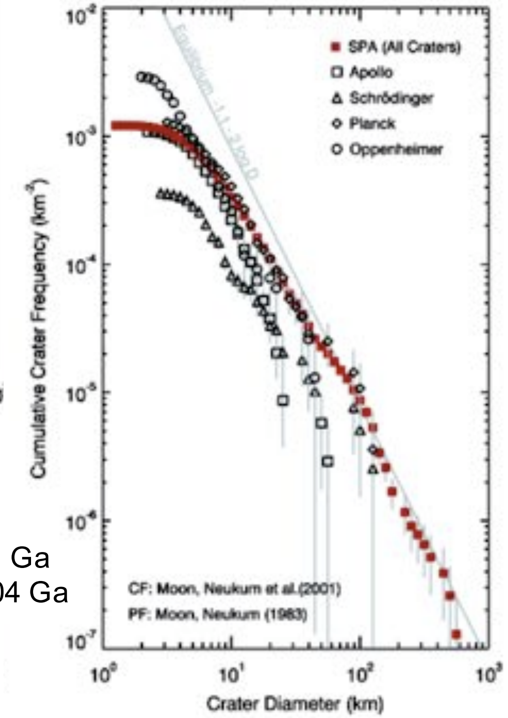
Model age of SPA basin



Apollo: ~3.91 Ga
Planck: 4.09 Ga
Schrödinger: 3.92 Ga
Oppenheimer: 4.04 Ga

Problem: Chronology poorly constrained >4 Ga

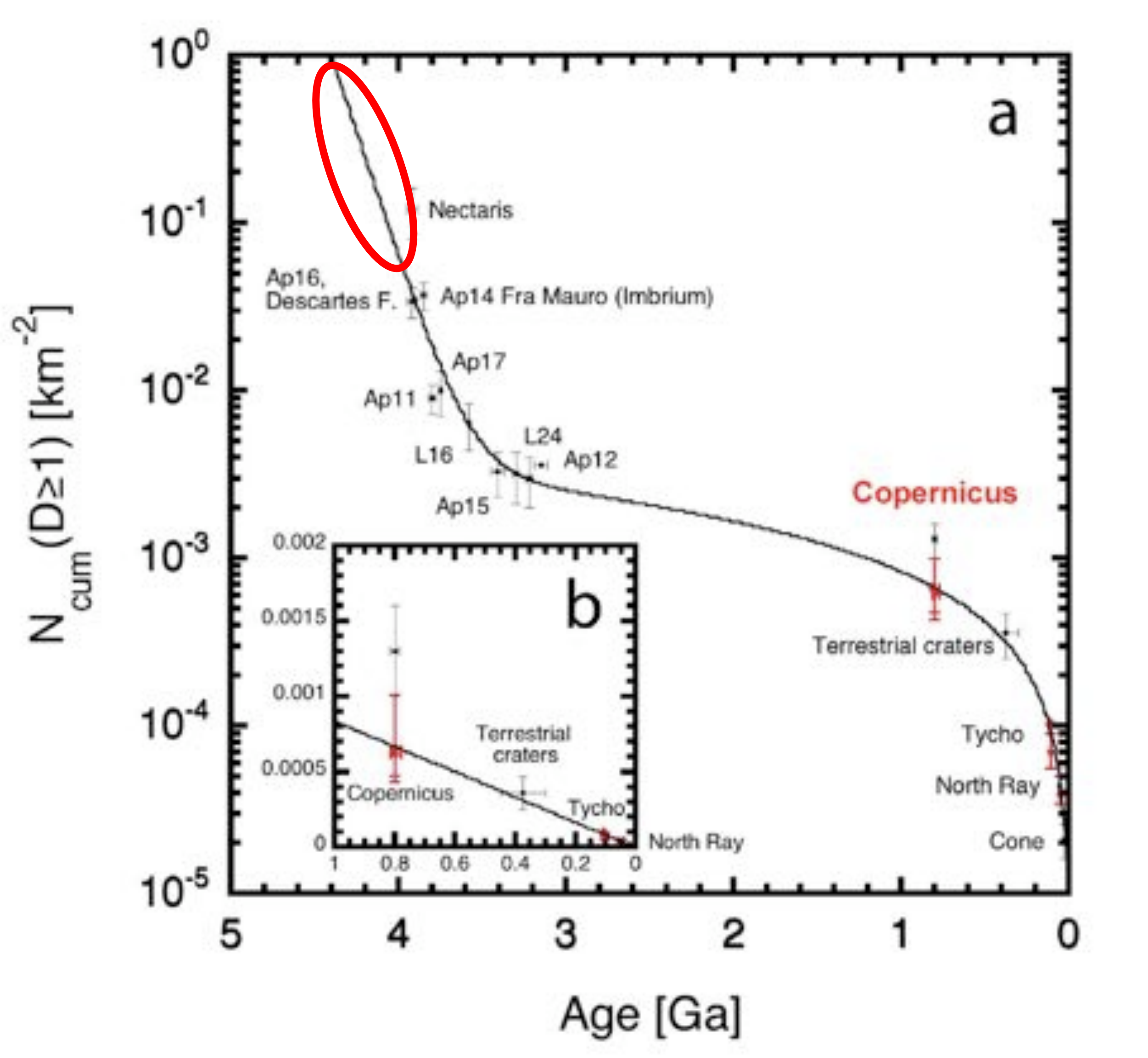
Relative ages of basins within SPA



Lunar Chronology: Key for planetary surface ages

Chronology:

How well do we know these ages?



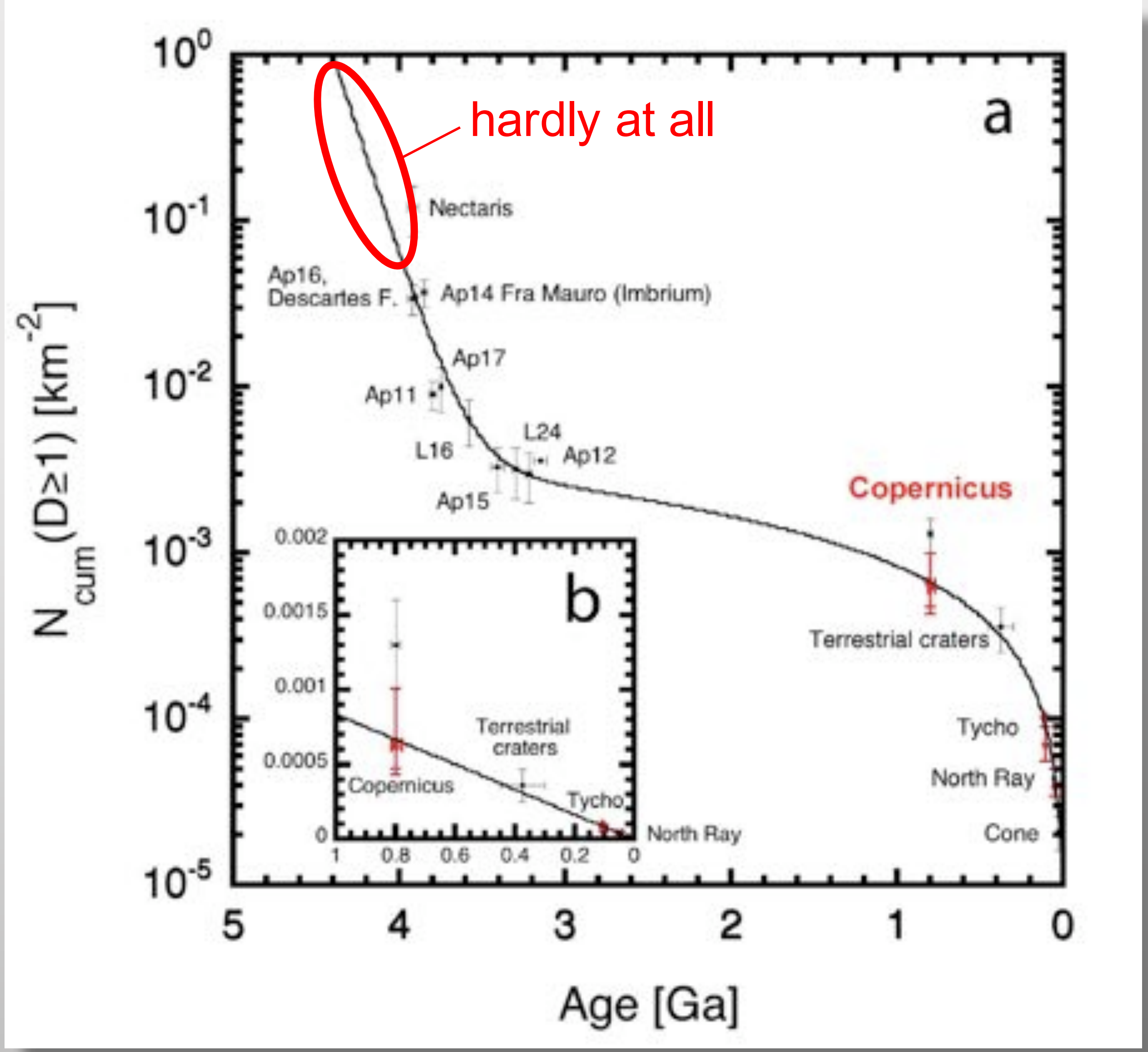
Lunar Chronology: Key for planetary surface ages

Chronology:

How well do we know these ages?

No "ground truth" data between >4 Gyr!

Samples are needed for age determinations!



Volcanic Resurfacing in SPA: Sparse (?)

Key Questions addressed by analysis of farside basalts:

→ age and compositional character of farside mantle

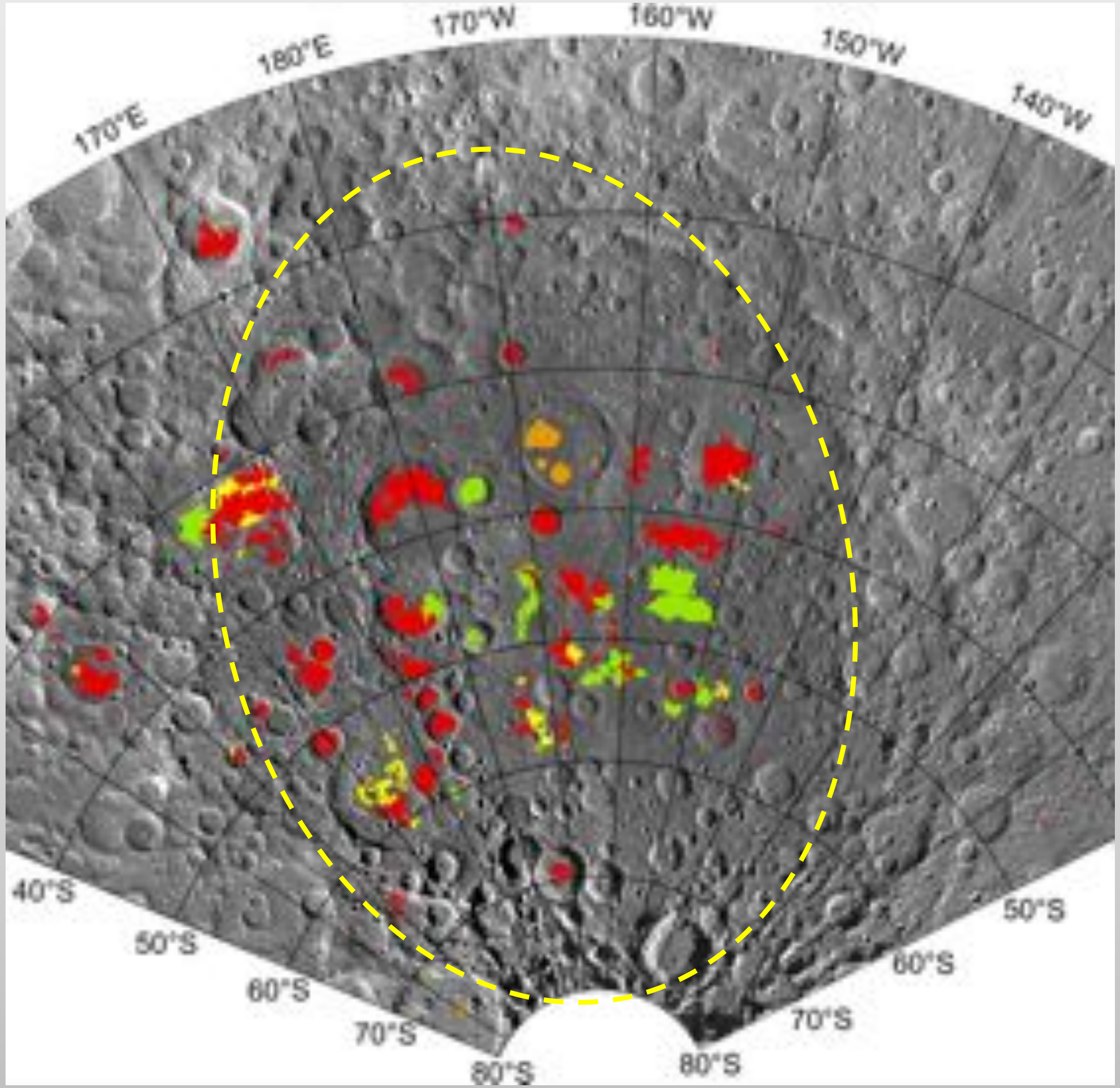
→ mixture of basalts vs. SPA impact melt in regolith

Red and yellow: mapped mare basalts

Green: mapped cryptomare

Orange: mapped pyroclastic deposits

Pasckert et al., accepted (2018)



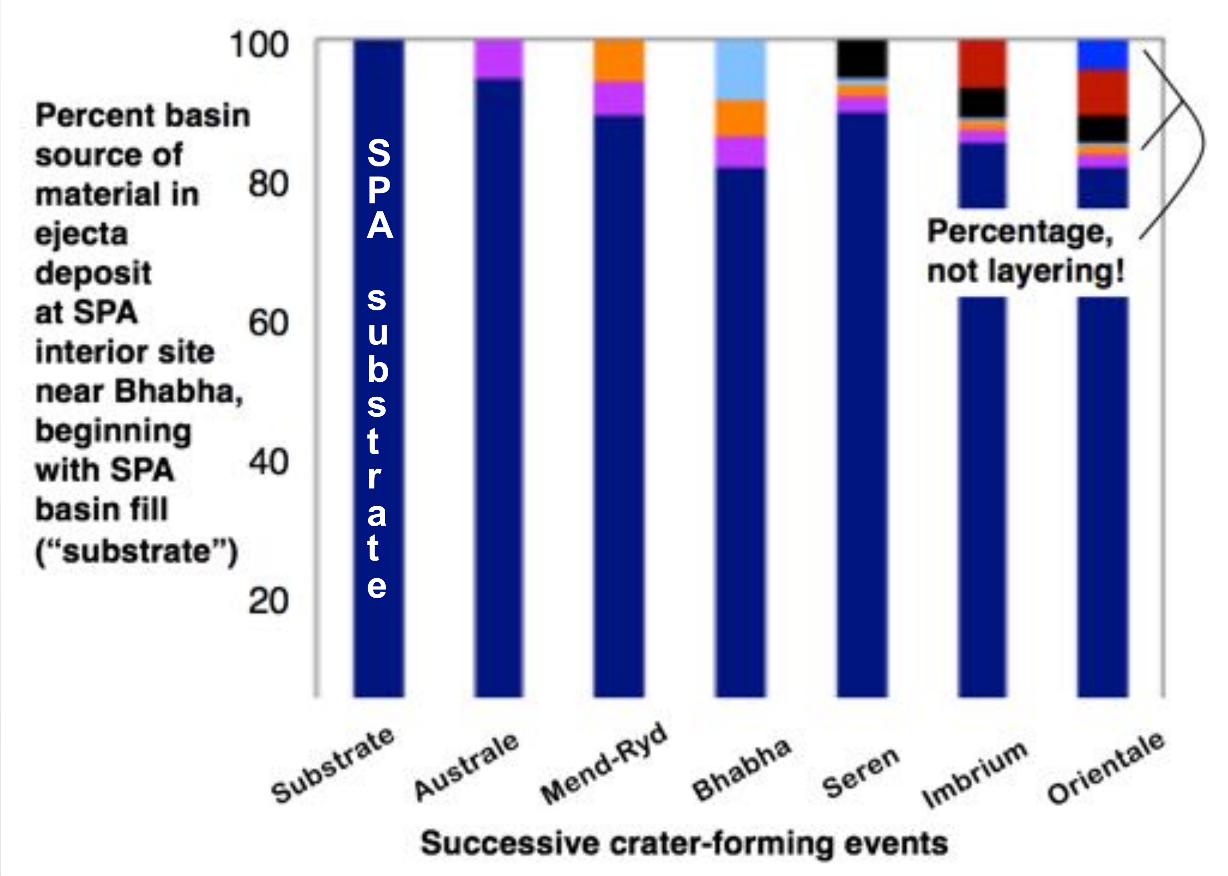
Rock fragments in Sample dominated by SPA substrate

Ballistic sedimentation

- Mainly digs up & redistributes material from SPA impact melt complex
- Rock material mostly SPA substrate, excavated and redistributed
- With significant (measurable) inputs from subsequent large impacts

Will sample abundant impact-melt rocks and breccia, as well as volcanic materials, mare and cryptomare.

Model for production of regolith by impact ejecta, showing proportions of materials contributed by various impacts

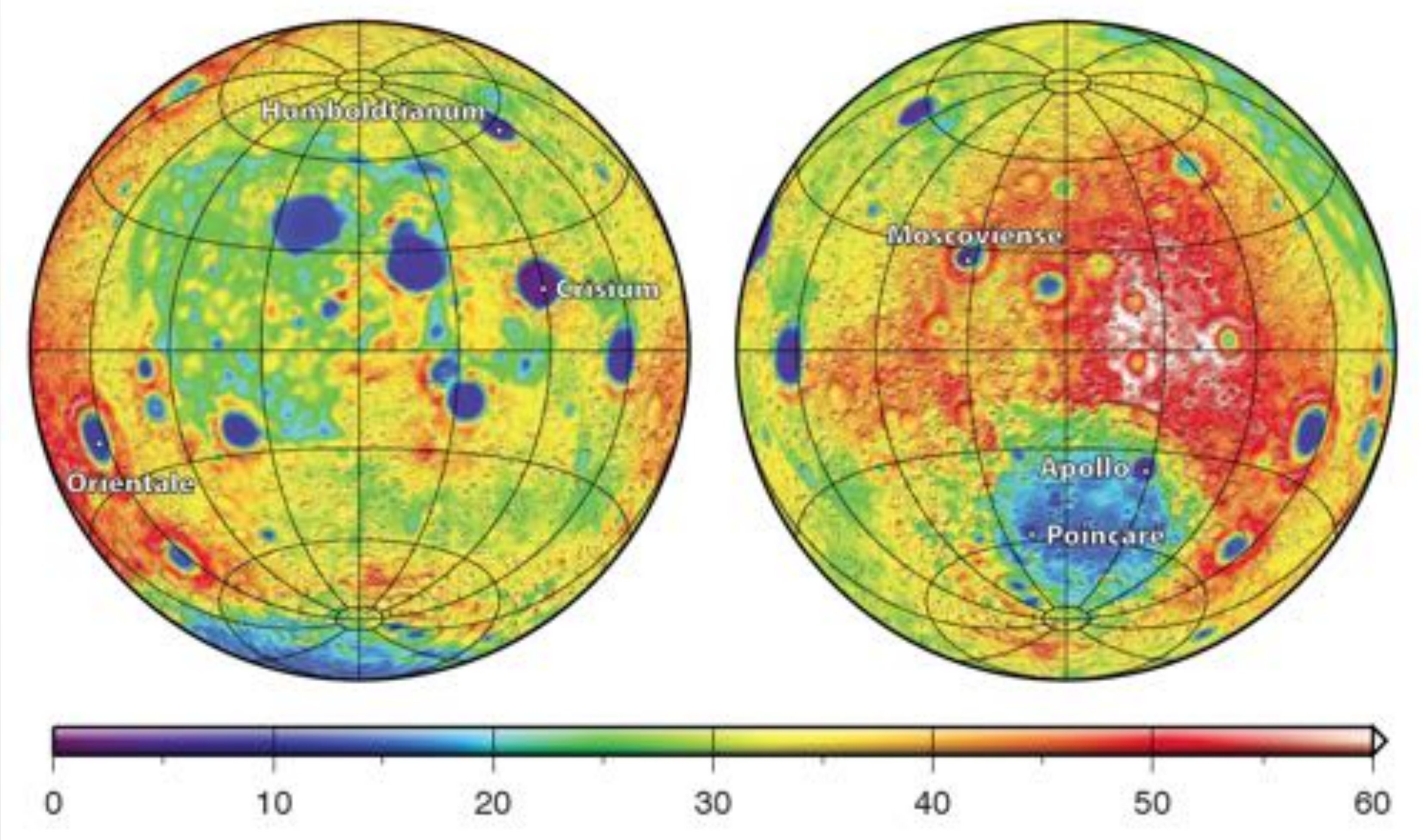


Haskin et al. (2003) *Lunar Planet. Sci.* **34**, #1434

Geophysics - GRAIL

- SPA
  ~10-20 km crustal thickness (likely impact melt body)
- Low Porosity
  ~ 6%
- High Density
  ~ 2800 kg/m^3

➢ *Need to know what are the rock types!*



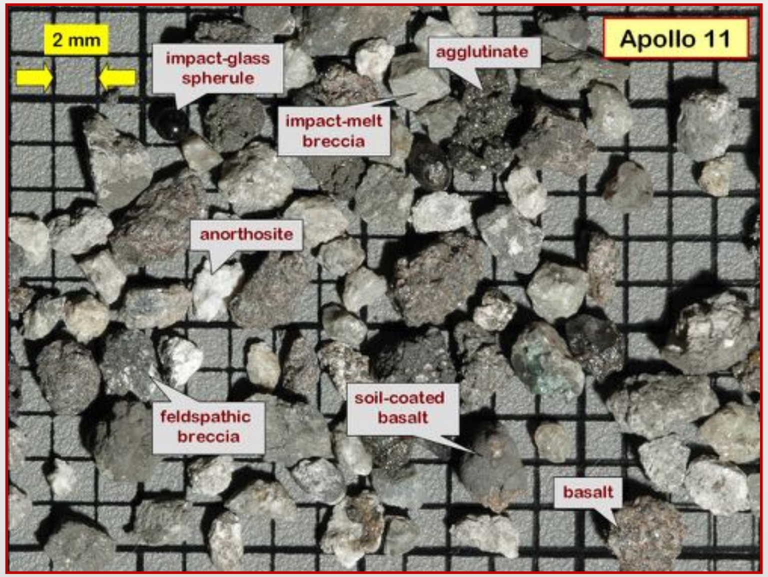
Crustal thickness superposed on topography. Model assumes crustal porosity of 12% and a mantle density of 3220 kgm^{-3}

Wieczorek et al. Science (2013)

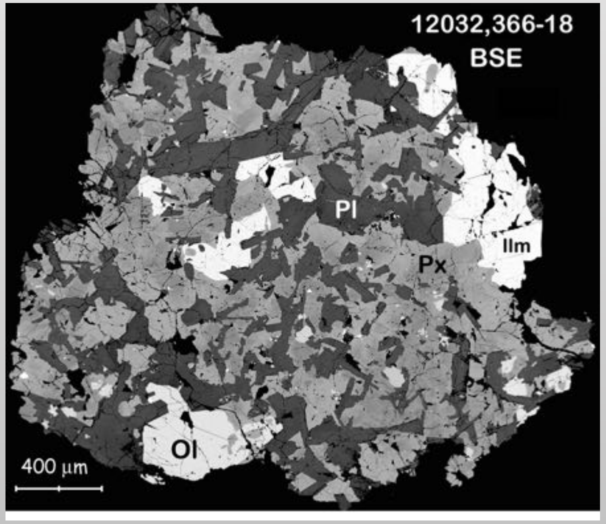
Sieve: concentrate rock fragments; collect unsieved regolith for context

Rock fragments carry unique, individual histories of igneous, impact, and volcanic events.

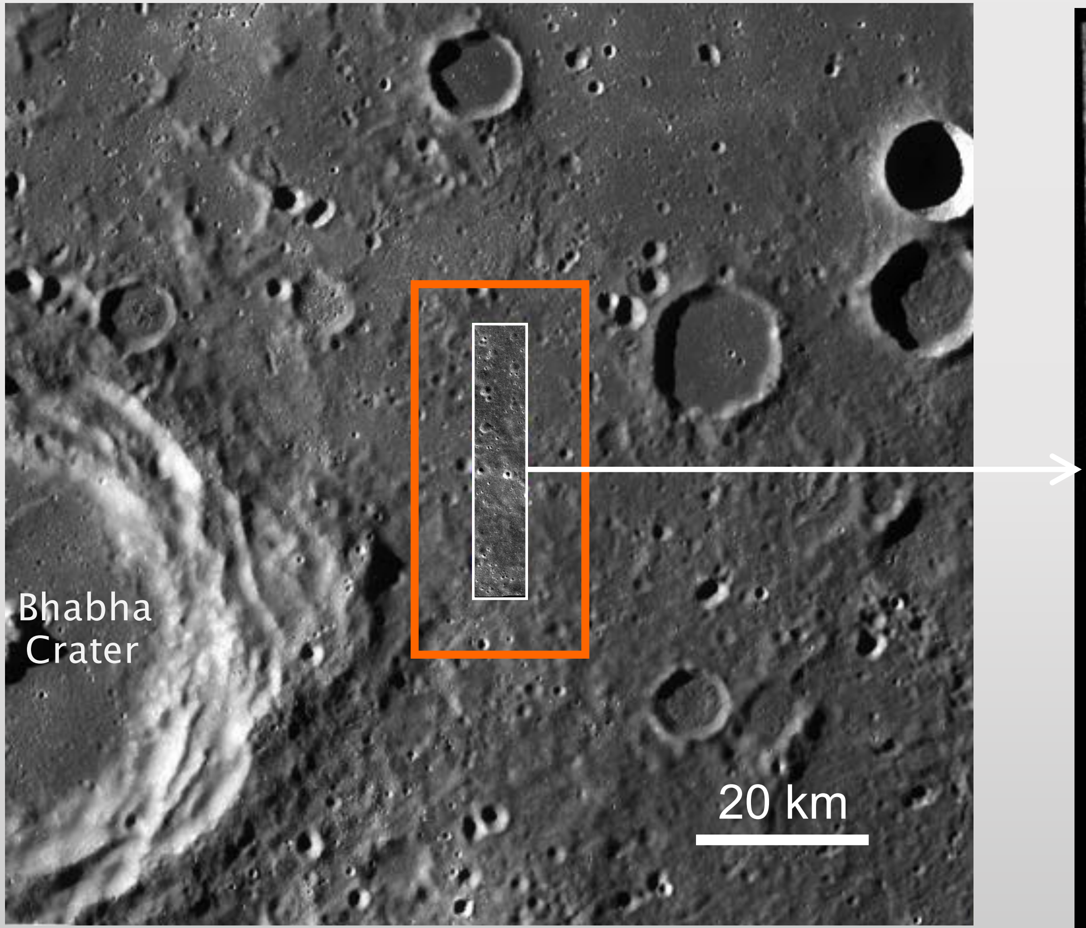
Rock fragments (2–10% by mass of regolith)
- represent local and distant events
- rock types are diverse because of impact mixing.

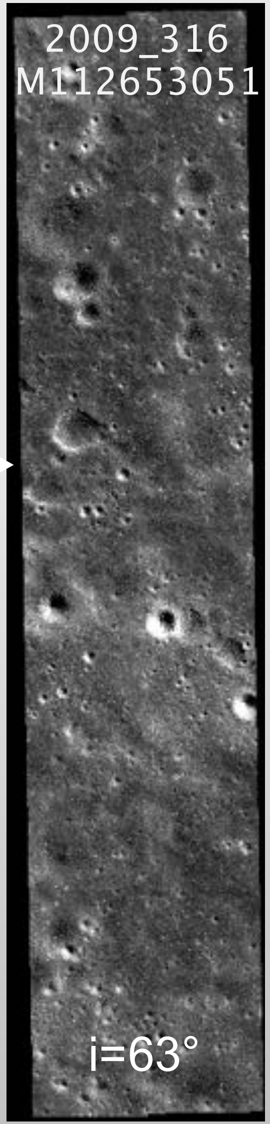


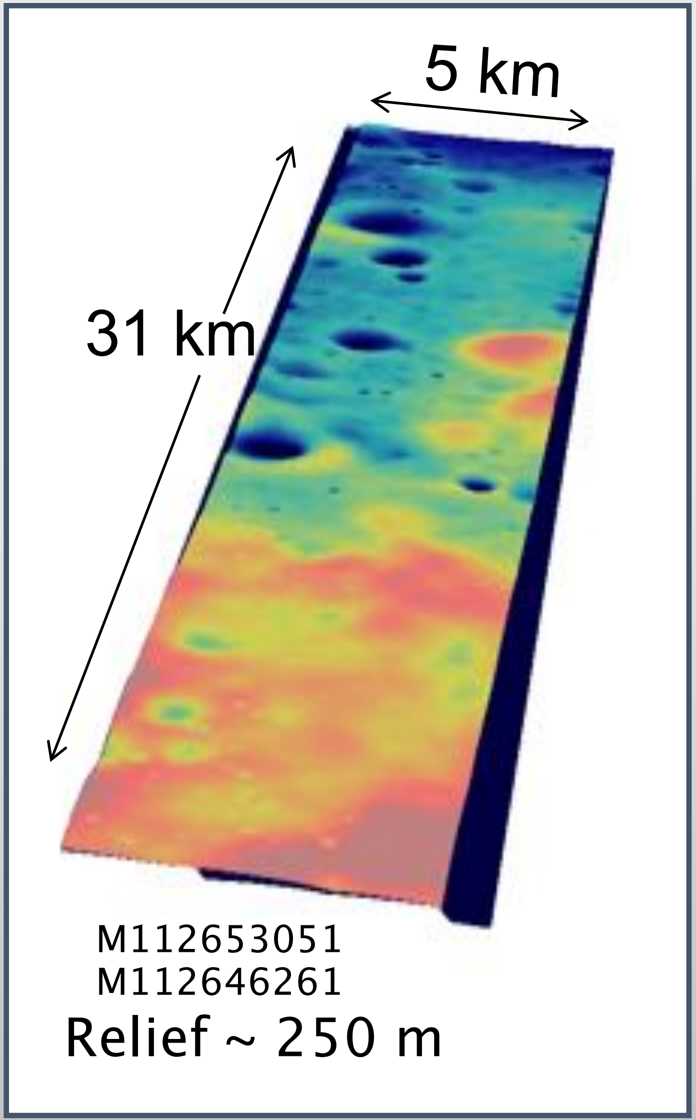
Sampling capabilities:
- Scoop to 10s of cm depth
- Sieve regolith to increase number of rocks by 25-50x
- 900-950 g sieved; 50-100 g unsieved
- Unsieved regolith for comparison with orbital data



Landing Site Safety Assessment: NAC DTMs







Bhabha - East Plains

Small is Beautiful!

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Chemie der Erde 66 (2006) 163–185

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INVITED REVIEW

Big returns on small samples: Lessons learned from the analysis of small lunar samples and implications for the future scientific exploration of the Moon

C.K. Shearer*, L.E. Borg

Analytical approach	Resolution or special handling requirements
Petrographic analysis by optical microscope and SEM	10 mm to 1 μm resolution and sample surface preparation.
EMP	<10 μm resolution and sample surface preparation.
TEM	1 μm to 10 nm resolution and extensive sample preparation.
SIMS	1–40 μm resolution and sample surface preparation.
INAA /ICP-MS	Manipulation and irradiation/dissolution of 50–500 μm glass beads.
XANES	10–40 μm resolution and sample surface preparation.
TIMS	Manipulation and dissolution of 50–500 μm glass beads.

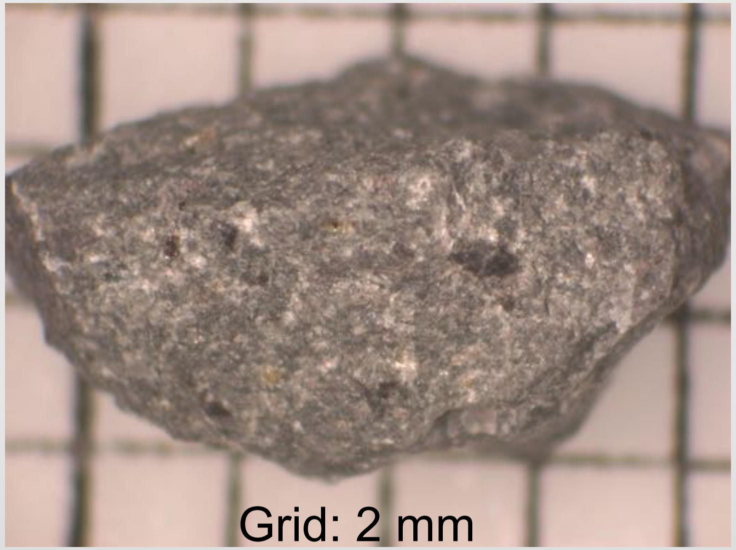
Table 1. Calculated minimum sample size requirements for various radiogenic isotope techniques

Sample	Ar–Ar age	Rb–Sr age	Sm–Nd age	Initial Hf	ϵ_{Nd}^{142}
FAN 62236	27 mg	1165 mg	1610 mg	7.1 g	833 mg
Mg-ste norite 78236	8.8 mg	59 mg	10 mg	59 mg	21 mg
Mare basalt 15475	7.1 mg	15 mg	10 mg	37 mg	20 mg

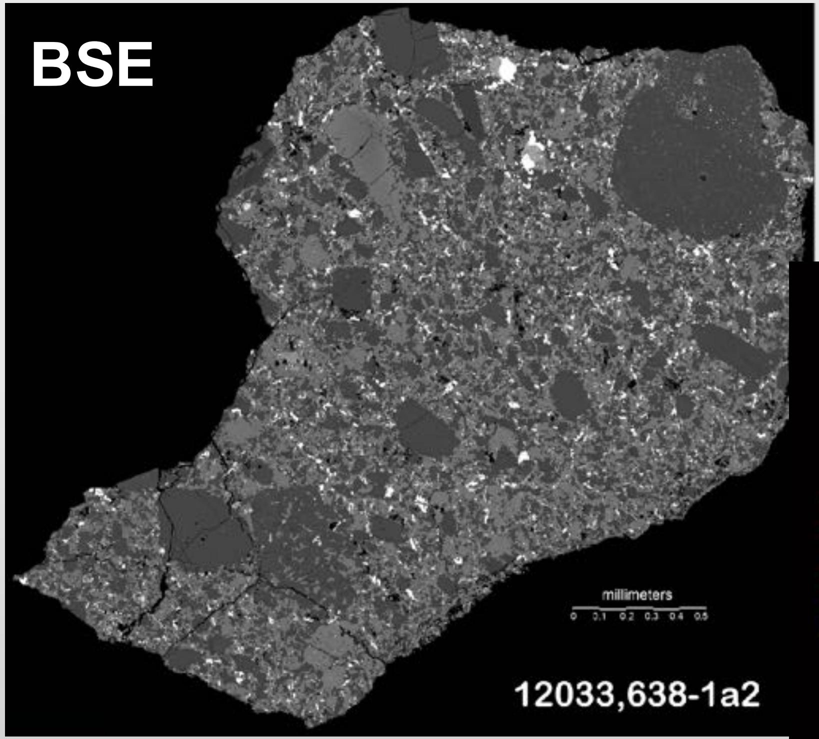
The amount of sample necessary for Ar assumes 5 × 10–15 mole ^{40}Ar background, sample/background = 100, 15 heating steps, and a sample age of approximately 4.0 Ga.

Example of Analyses of a Small Rock

12033,638-1



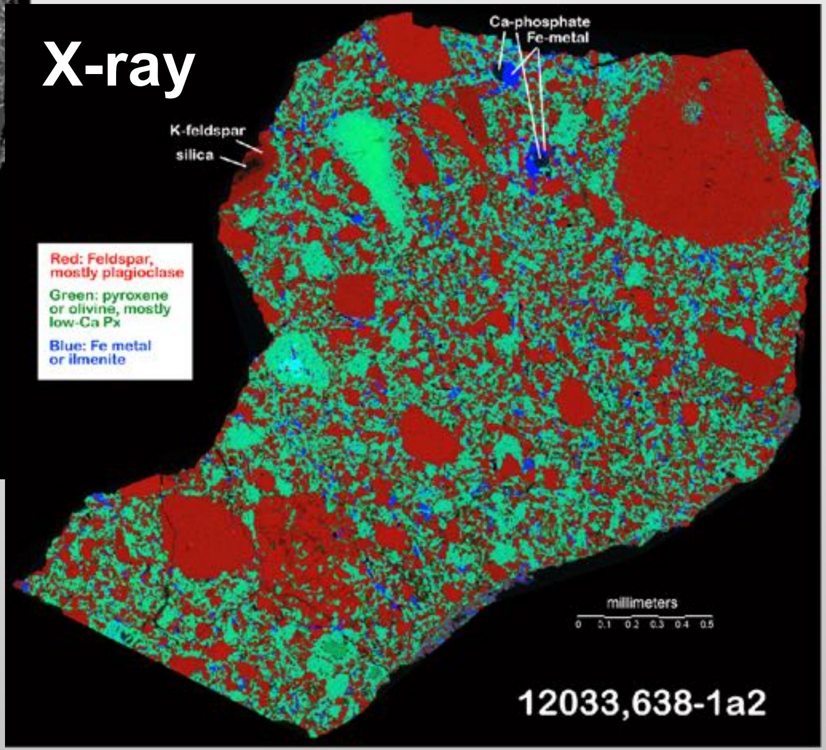
Chemistry: INAA: 20 mg



Petrography

Mineralogy

Mineral Chemistry



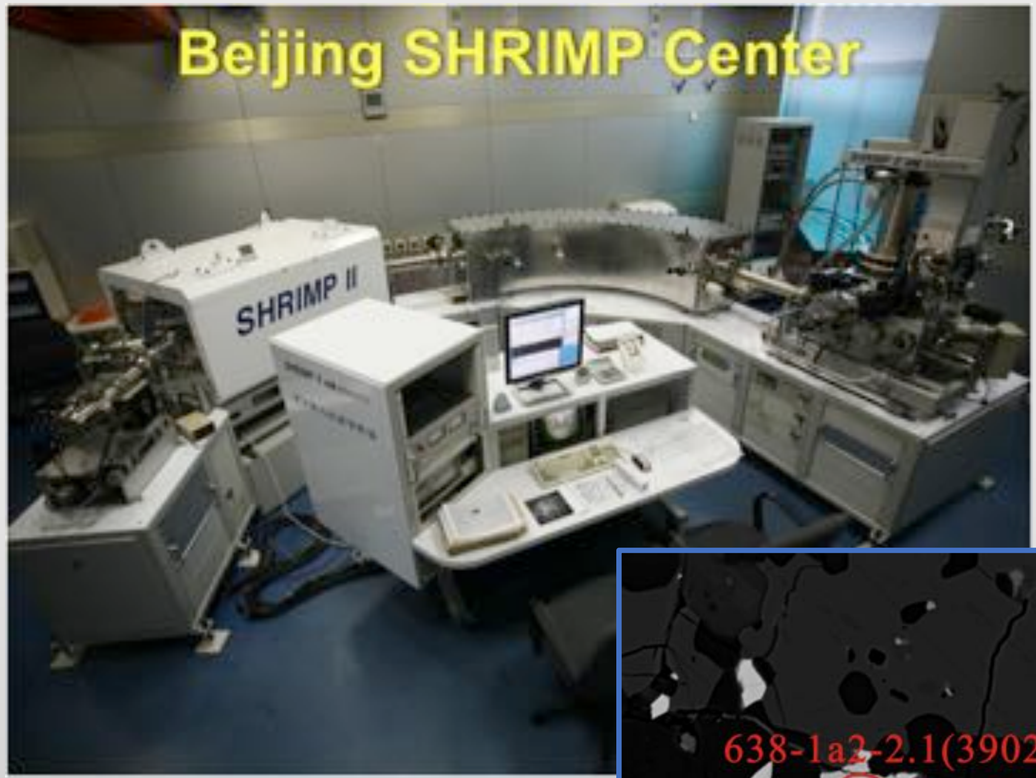
R: Al; G: Mg; B: Fe

Rock is a mafic impact-melt breccia, rich in incompatible trace elements. *New Apollo type.*

Example of Analyses of a Small Rock

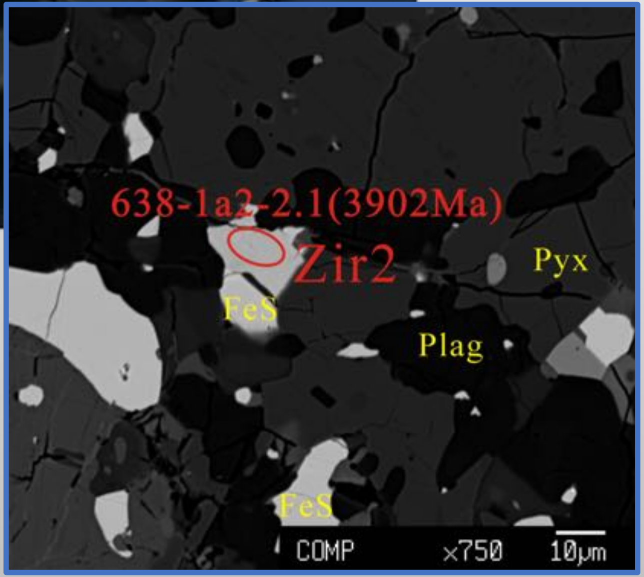
Comparative zircon U–Pb geochronology of impact melt breccias from Apollo 12

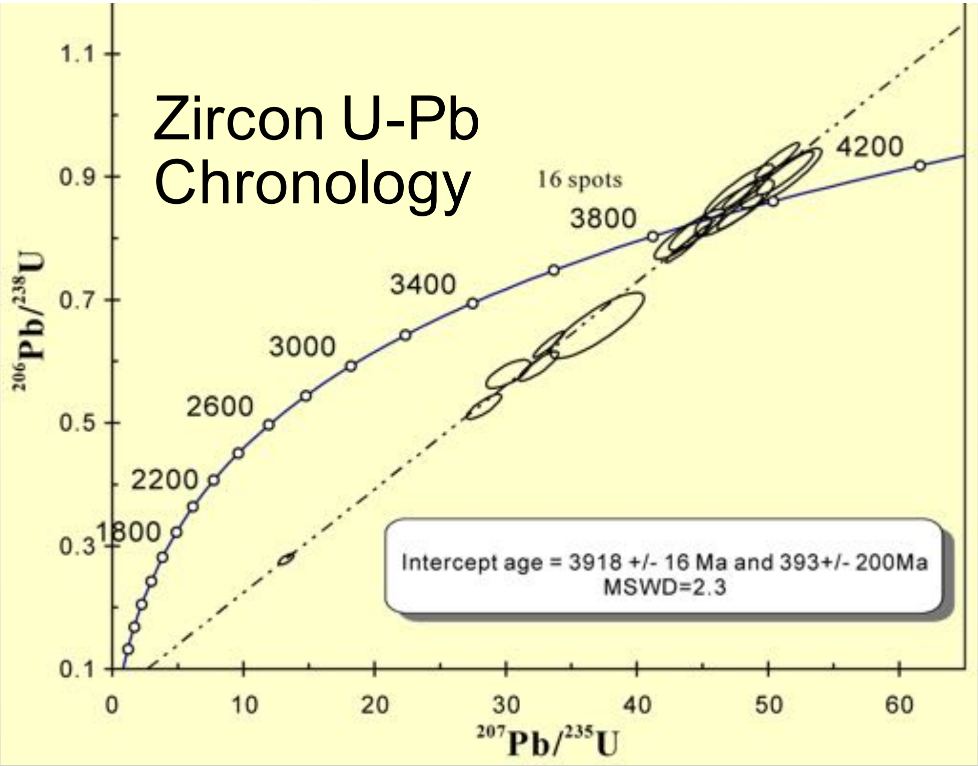
Earth and Planetary Science Letters 319-320 (2012) 277–286



Big Instrument,
Small Rock!

Spot size of primary beam: 10 μm





Crystallization Age: 3918 ± 16 Ma;

Interpretation: Age of Imbrium