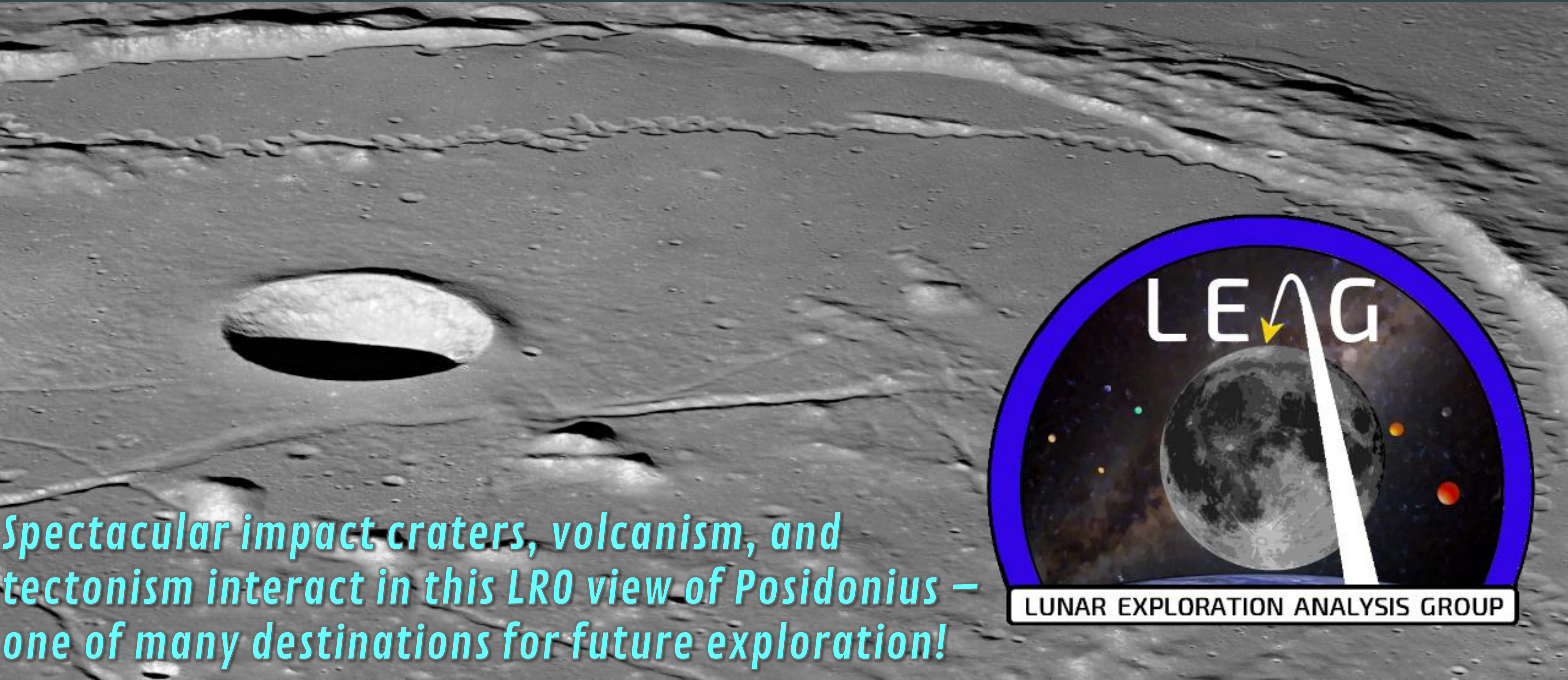
A WORLD FULL OF WONDER AND OPPORTUNITY

THE LUNAR EXPLORATION ANALYSIS GROUP VIEWPOINT FOR THE 2013-2023 DECADAL MIDTERM REVIEW

Clive Neal, LEAG Chair

Samuel Lawrence, LEAG Vice-Chair



Spectacular impact craters, volcanism, and tectonism interact in this LRO view of Posidonius – one of many destinations for future exploration!

OUTLINE FOR THE LEAG PERSPECTIVE

- LEAG Overview
- Review of Moon-related topics in “Visions and Voyages for Planetary Science in the Decade 2013-2022” (VV2011)
- Advances in Lunar Science Decadal Priorities since 2011
- Advances Beyond Decadal Priorities
- New Frontiers 4 Special LEAG Finding
- The Value of LRO Extended Science Missions
- New Opportunities for the Next Decadal

LEAG: REPRESENTING A LARGE VIBRANT COMMUNITY

The Lunar Exploration Analysis Group (LEAG) was established in 2004 to support NASA in providing analysis of scientific, commercial, technical, and operational issues in support of lunar exploration objectives, as well as their implications for lunar architecture planning and activity prioritization.

LEAG is jointly chartered by the Science Mission Directorate (SMD) and the Human Exploration and Operations Mission Directorate (HEOMD) and blends members of both communities, building bridges and synergies between science, exploration, and commerce whenever and however possible.

LEAG is a community-based, volunteer-driven, interdisciplinary forum. Membership is open to all members of the lunar exploration community and consists of lunar and planetary scientists, life scientists, engineers, technologists, human system specialists, mission designers, managers, policymakers, and other aerospace professionals from government, academia, and the commercial sector.

MEET YOUR LEAG EXECUTIVE COMMITTEE

- Chair: Clive Neal, University of Notre Dame
- Vice-Chair: Samuel Lawrence, NASA Johnson Space Center (Becomes Chair, March 2018)
- Past Chair: Jeff Plescia, JHUAPL
- Volatiles Chair: Dana Hurley, JHUAPL
- NGLSE Rep: Ryan Clegg-Watkins, Washington University in St. Louis
- LPI Director: Louise Prockter, Lunar and Planetary Institute/USRA
- LRO Rep: Noah Petro, NASA Goddard Space Flight Center
- ARTEMIS Rep: Jasper Halekas, University of Iowa
- ISRU Rep: Jerry Sanders, NASA Johnson Space Center
- Commercial Advisory Board Chair: Kurt Klaus, Lunar and Planetary Institute
- ESA Representative: James Carpenter, ESA

Ex Officio Members:

- Sarah Noble, NASA Headquarters, Science Mission Directorate
- Ben Bussey, NASA Headquarters, Human Exploration and Operations Mission Directorate
- Greg Schmidt, Solar System Exploration Research Virtual Institute

COMMERCIAL ADVISORY BOARD LUNAR EXPLORATION ANALYSIS GROUP

- CHAIR: Kurt Klaus, Lunar and Planetary Institute
- LEAG Chair: Clive Neal, Notre Dame
- LEAG Vice-Chair: Samuel Lawrence, NASA JSC
- Kyle Acierno, iSpace
- Dallas Bienhoff, Cislunar Space Development Corporation
- Dale Boucher, Deltion
- Joshua Brost, SpaceX
- Thomas Diedrich, Airbus
- Leslie Gerstch, MUST
- Sam Gunderson, Blue Origin
- Dan Hendrickson, Astrobotic
- Jeff Hopkins, Astrobotic
- Susan Jason, Surrey Satellites
- Jim Keravala, Off World Consortium
- David Kornuta, United Launch Alliance
- Bernard Kutter, United Launch Alliance
- Eva-Jane Lark, Investment Advisor
- Sean Mahoney, Masten Space Systems
- Maria Antonietta Perino, Thales Alenia Space Italia
- Bruce Pittman, NASA Ames
- Sridhar Ramasubban, Team INDUS
- Eric Reiners, Caterpillar
- Bob Richards, Moon Express
- Melissa Sampson, United Launch Alliance
- George Sowers, Sowers Space Solutions
- Kris Zacny, Honeybee Robotics

LEAG: SERVING THE COMMUNITY

- Annual LEAG Meeting
  - SSERVI Sponsors the LEAG Bernard Ray Hawke Next Lunar Generation Awards to positively encourage early-career networking and participation
  - 2016 LEAG Meeting at USRA Headquarters, 1-3 November 2016, 140 attendees
  - Very Special Guest: Rep. Jim Bridenstine, House Science, Space, and Technology Subcommittee
- LEAG Chair and Vice-Chair represent lunar exploration community to stakeholders as needed
  - E.g., Lawrence LEAG presentation at the Vision 2050 meeting: "The Opened Gateway: Lunar Exploration in 2050"
- LEAG Hosts Town Halls at key community meetings (LPSC) and NGLSE Networking Sessions at LPSC and LEAG meetings
- NEW for 2017: Annual in-person meeting of the Commercial Advisory Board
- Headquarters or field centers can request that LEAG form Special Action Teams to study topics of interest, if resources are provided
  - Always led by LEAG Chair or Vice-Chair to ensure programmatic continuity

LEAG SPECIAL ACTION TEAMS SINCE 2010

IN-PROGRESS

Lunar Capabilities Roadmap (Requestor: SMD) [G. Kramer and David Lawrence]

Advancing Science of the Moon Special Action Team (Requestor: SMD) [B. Denevi and S. Lawrence]

ISECG International Polar Mission Coordination VSAT2 (Requestor: HEOMD/ISCEG) [D. Hurley and S. Lawrence]

COMPLETED

- August 2016: Strategic Knowledge Gaps for the "Moon First" Human Exploration Scenario V2
- September 2015: European Response to the Volatile Specific Action Team Report
- January 2015: Volatiles Special Action Team
- March 2014: LEAG Resource Prospector Mission Special Action Team
- September 2012: Mapping the SKGs to the Lunar Exploration Roadmap
- March 2012: Strategic Knowledge Gaps for the "Moon First" Human Exploration Scenario
- March 2012: Science Value of a Cislunar Hab Research Facility Special Action Team
- June 2011: LEAG Robotic Campaign
- June 2011: LEAG Response to the Decadal Survey

THE LUNAR EXPLORATION ROADMAP:
OPENING THE GATEWAY TO THE SOLAR SYSTEM

The **LUNAR EXPLORATION ROADMAP** is the community-developed strategy to make steady concrete sustainable exploration advances along three themes :

- **BUILD** a firm foundation on the high frontier to decisively enable commercial opportunity
- **DISCOVER** fundamental knowledge exploring the surface of the most accessible target for planetary exploration
- **PIONEER** the trail to all other destinations beyond the Earth-Moon System

The **ROADMAP** includes technologies, time-phasing and mission choices

LEAG ANNUAL MEETING 2017: SCIENCE ENABLED BY GETTING TO THE SURFACE

- Conveners: Samuel Lawrence and Clive Neal
- Theme: Science Enabled by Getting to the Surface
- 10-12 October 2017, USRA Headquarters, Columbia, MD
- List of focused questions for discussion at the LEAG Website:
    - https://www.hou.usra.edu/meetings/leag2017/

2017 ONGOING LEAG COMMUNITY INITIATIVES

New Views of the Moon II

- Editors: Clive Neal, Lisa Gaddis, Samuel Lawrence, Brad Jolliff, Chip Shearer, Steve Mackwell
- Dramatic recent paradigm shifts in lunar science
- Goal is focused volume describing advances since 2006 publication
  - Integrated, trans-disciplinary chapters
  - US and international partners fully integrated
  - Scheduled for completion by 2019
- First Meeting: 2016 (Houston, LPI)
- Second Meeting: 2017 (Muenster, Germany)

Back to the Moon

- Leaders: Clive Neal and Julie Stopar
- Clear interest amongst science community and commercial entities in US lunar surface exploration
- US presently lacks surface access capability
- Goal is to define feasible, affordable, possibly nontraditional pathways to return the United States to lunar surface with robots and humans
- Meeting October 13, 2017 at USRA HQ
  - 160 indications of interest…and climbing!

Enabling Lunar Sample Return

- C. Neal and G. Schmidt
- Early 2018
- LEAG/SSERVI Activity

LUNAR MISSIONS: ACTIVE AND PLANNED

Active US missions

- LRO Cornerstone Mission
- ARTEMIS

Planned US Smallsat Missions

- Lunar Flashlight
- Lunar Polar Hydrogen Mapper (LunaHmap)
- SkyFire
- Lunar IceCube

Planned Missions

- **South Korea:** Korean Pathfinder Lunar Orbiter [2018]
  - US ShadowCam instrument
- **China:** Chang’e 5 [2017] , Chang’e 4, Chang'E-P1 (2021), Chang'E-6 (2023), and Chang'E-P2 (2025)
- **India:** Chandrayaan-2 [2018]
- **Roscosmos:** Luna 27 (2021), Luna 28 (2024)
- **ESA:** Luna 27 (2021), HLEPP (2025)
- **JAXA:** SELENE-R (2022), HLEPP (2025)
- **CSA:** HLEPP (2025)
- **US:** Resource Prospector (2022)

THE MOON IN VISIONS AND VOYAGES

- Moon included in the Inner Planets theme
  - Moon, Mercury, Venus
- Priorities for spacecraft missions to the Moon, Mars, and other Solar System bodies treated in a unified manner
- Numerous cross-cutting investigation themes relevant to lunar science, including:
  - Building New Worlds
    - Accretion, accretion timing, water supply, chemistry, and differentiation of inner planets?
    - How did their atmospheres evolve?
    - Role of early bombardment
  - Solar System Workings
    - Earth's biosphere endangerment and shielding
- Volatile Composition and Distribution
  - Nature of lunar polar volatiles
    - Chemical and isotopic compositions
  - Surface-bound regolith volatiles and seasonal variability
  - Lunar magmatic volatiles revealed in samples

THE MOON IN VISIONS AND VOYAGES

Important Science Topics to be addressed by Future Missions (Discovery)

- The nature of lunar polar volatiles
- The significance of recent lunar activity at potential surface vent sites
- The reconstruction of thermal-tectonic-magmatic evolution of the Moon
- The impact history of the inner solar system through the exploration of better-characterized and newly-revealed lunar terrains

- **Missions could include orbiters, landers, and sample returns**

Priority Lunar Mission Goals (New Frontiers)

- Sample return from the South Pole-Aitken Basin region (NF4)
- Lunar Geophysical Network (NF5)

Other Assessed Concepts

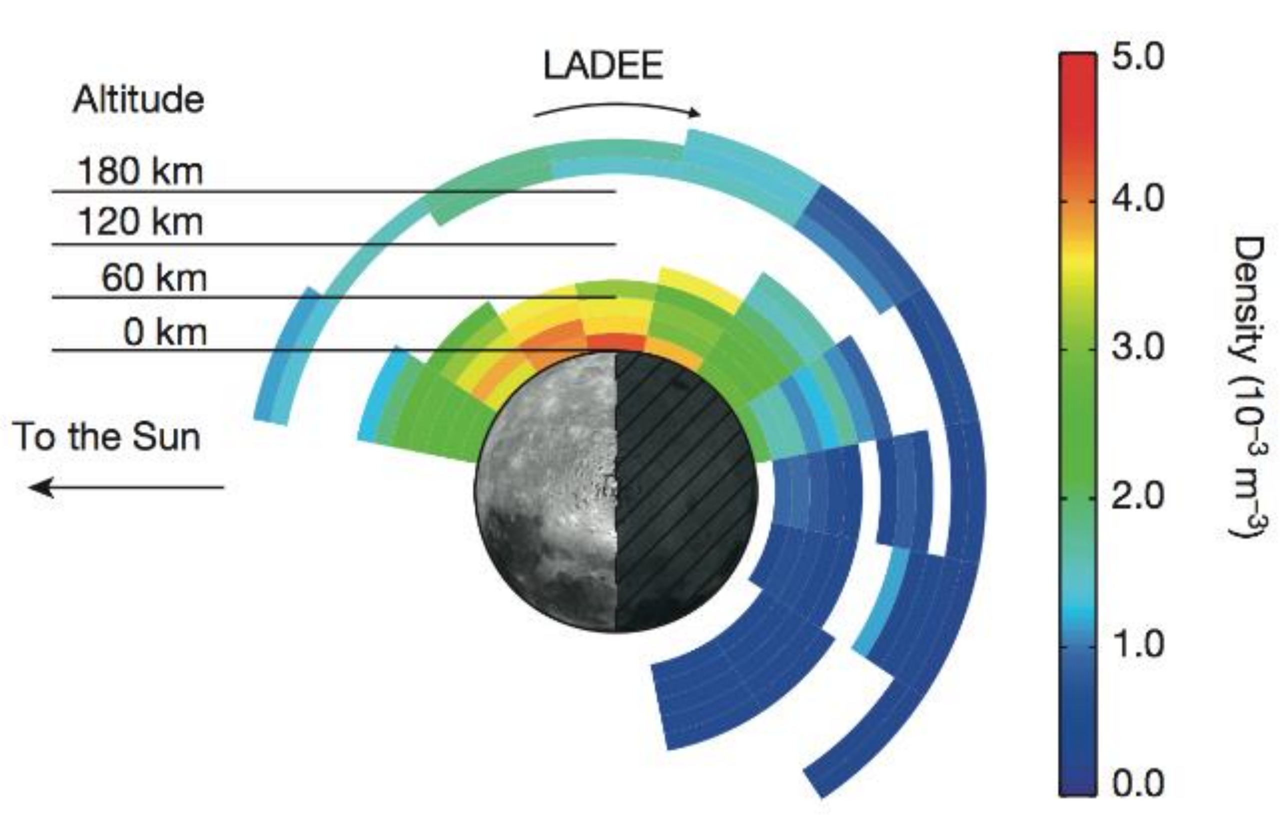
- Polar Volatile Explorer

PROGRESS IN LUNAR SCIENCE SINCE 2011

- **LRO continues to make fundamental discoveries about our Moon**
- Many Gravity Recovery and Interior Laboratory (GRAIL) results published in 2011-2013 timeframe
- LADEE mission (2013-2014) characterized the Moon's environment and surface-bound exosphere
- Sample research on Apollo samples and meteorites

SIGNIFICANT ADVANCES: LUNAR ENVIRONMENT

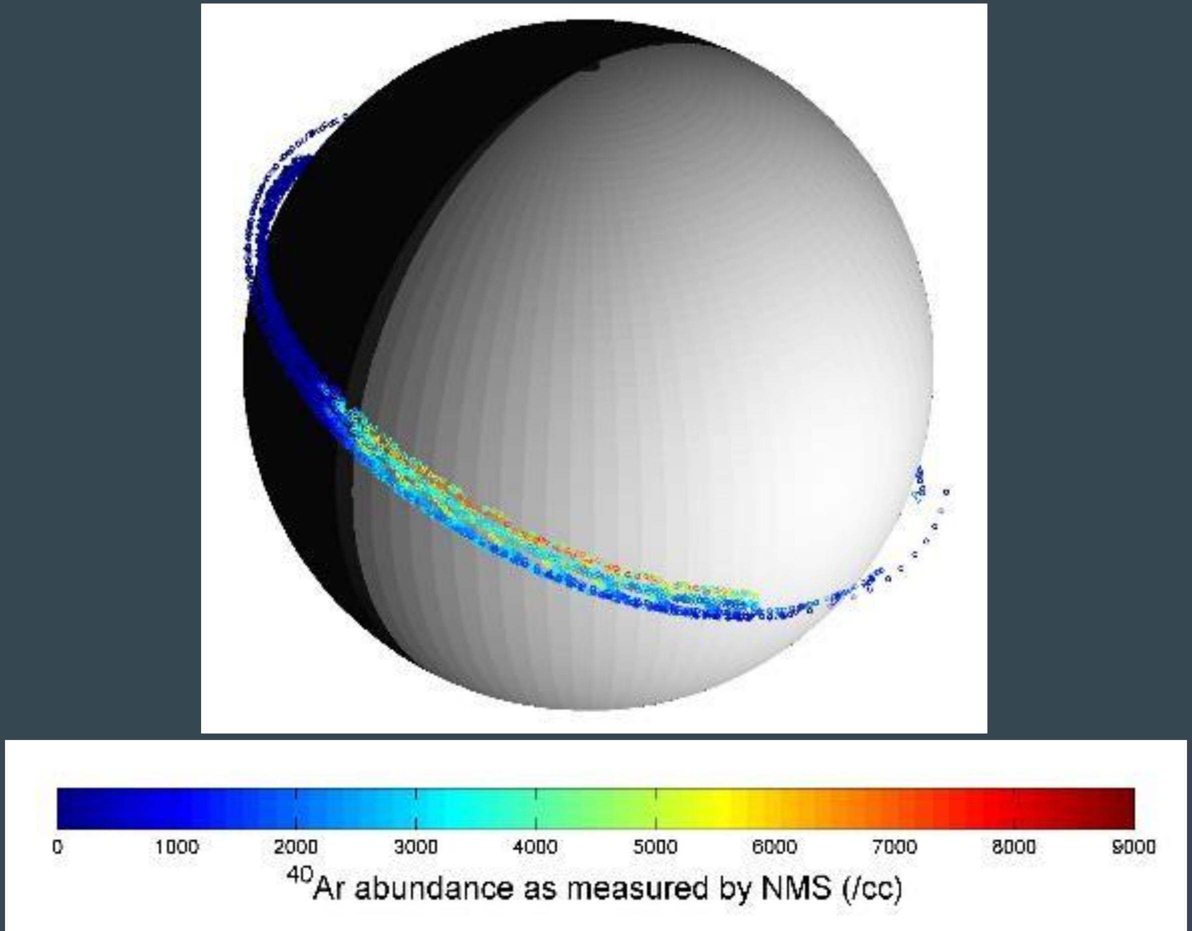
- Extensive further analysis of lunar orbital data sets from LADEE and LRO, theoretical modeling, and laboratory simulation of lunar environment leading to tighter constraints on environmental (charged particles, fields, regolith, dust, exosphere, surface volatiles) dynamics, including the volatile sources, sinks, and transport
- The Lunar Dust Experiment (LDEX) on the LADEE spacecraft has recorded over 11,000 unambiguous dust impacts since arriving at the Moon in October, 2013
- **These findings confirm that there is a dust cloud surrounding the Moon, which is sustained by the continual bombardment of interplanetary dust particles**



This figure shows the variation in density of impacts seen by LADEE at different heights above the surface and at different times of the lunar day.

SIGNIFICANT ADVANCES: LUNAR EXOSPHERE

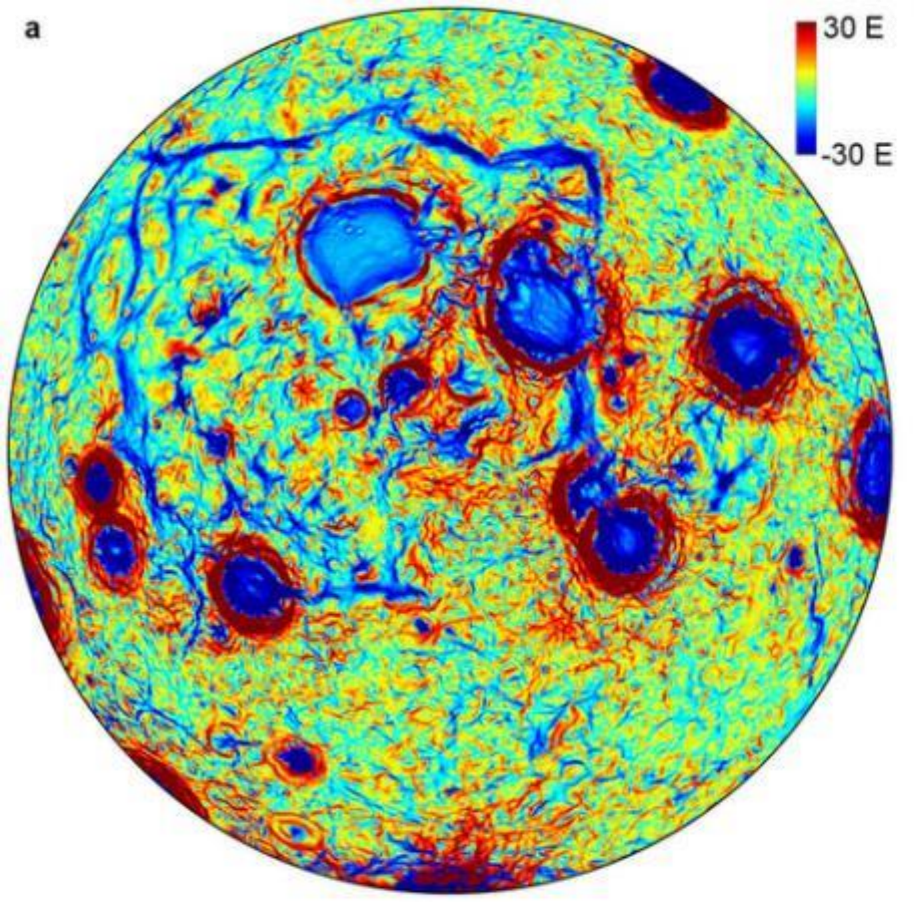
- The LADEE neutral mass spectrometer (NMS) detected argon, mapping out how argon moves over the course of a lunar day
- The NMS findings indicate that a very thin layer of Argon sticks to the surface on the cold nightside of the moon (much like frost is deposited during the night on Earth) and is released as the sun heats the surface. After release, these atoms do not immediately escape from the moon, as gravity keeps them within the orbit and they bounce off the warmer daytime surface where they can be detected by the NMS
- This data set provides the basis for higher fidelity models of the interaction of argon and other gases with the lunar surface, and by extension to other bodies in the solar system that have very thin atmospheres.



SIGNIFICANT ADVANCES: GRAIL

- **Although this mission occurred prior to V&V, most of the important results came out after V&V was drafted**
  - Achieves key goals set forth in SCEM report
  - Also critical for future mission planning

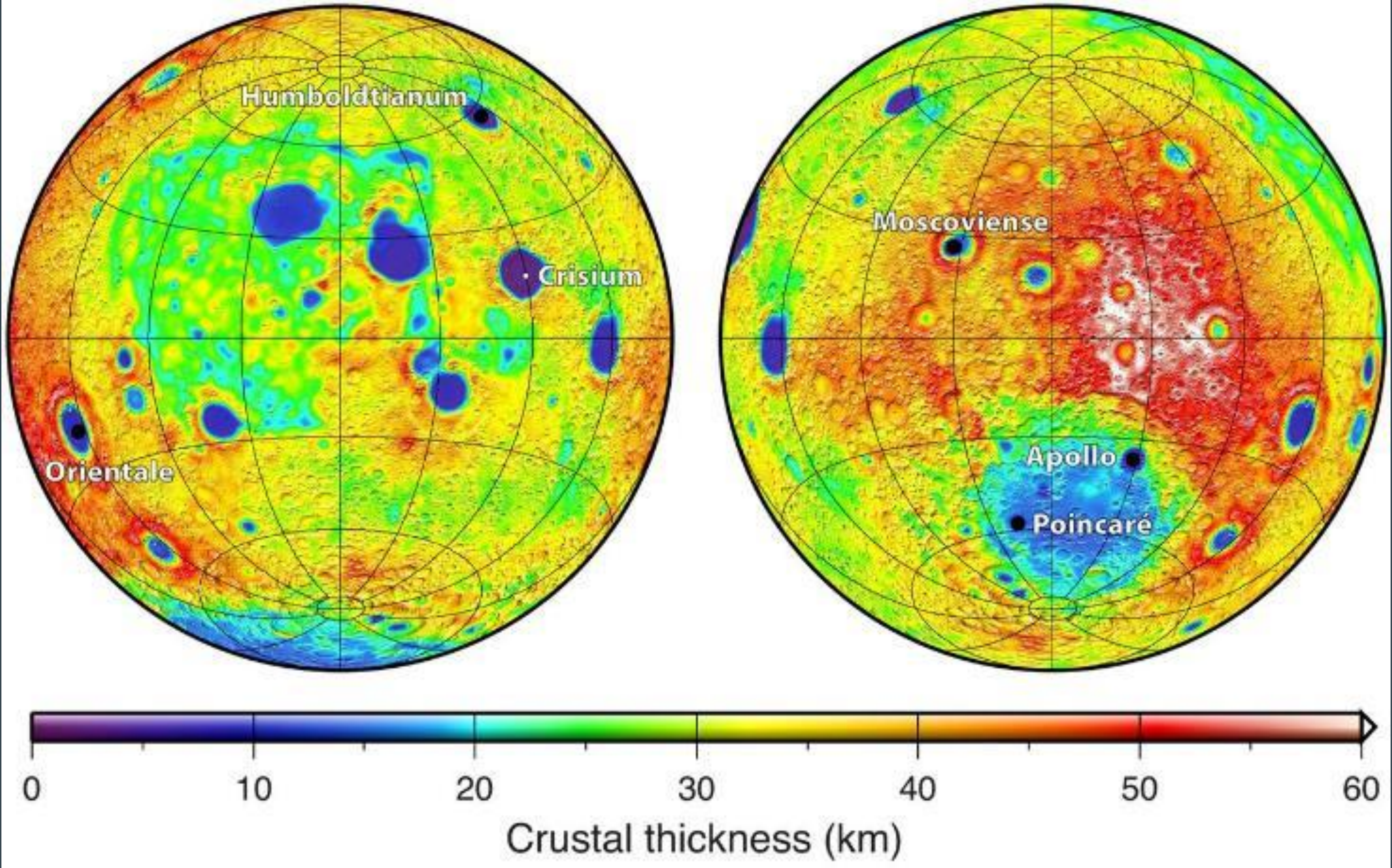
- Much important information about the lunar interior, such as existence of a small core, crustal thickness (less than thought) and density (lower than thought), and mass anomalies on a new and increasingly precise level of spatial resolution, including the identification in the gravity gradient map of the circum-Procellarum fracture network



J. Andrews-Hanna et al., Nature, 514, 68–71, 02 October 2014
doi:10.1038/nature13697

SIGNIFICANT ADVANCES: GRAIL CRUST THICKNESS

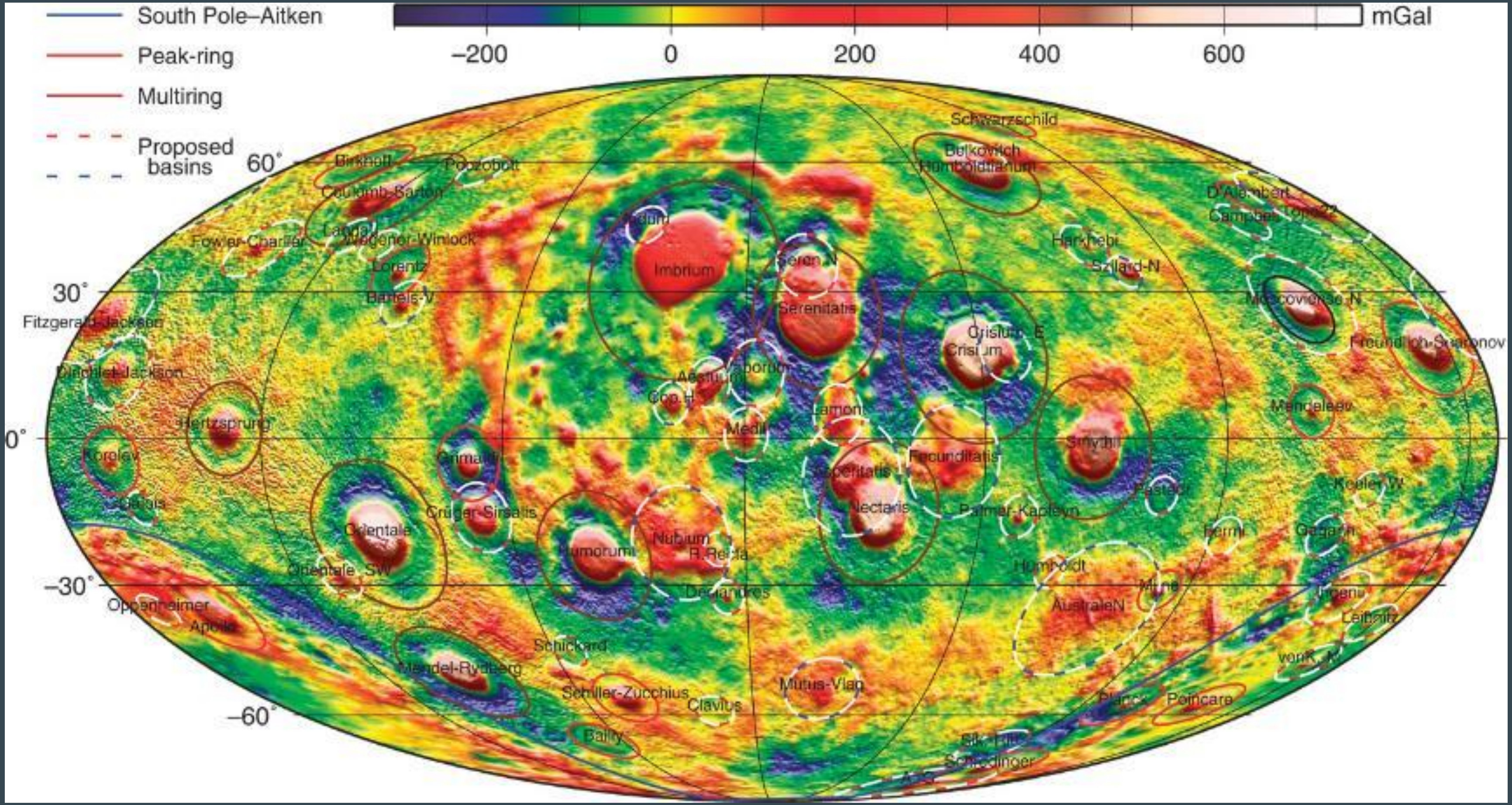
- GRAIL and LRO enabled determination of lunar crustal thickness
  - Bulk density lower than previously assumed
- Average crustal thickness varies from 34 to 43km thick
  - Previously thought to be ~50km thick
- Important for lunar geology, including models of interior dynamics and volcanic processes



Wieczorek, M. A., et al. (2012) *Science*, 1231530, doi: 10.1126/science.1231530

SIGNIFICANT ADVANCES: IMPACT BASINS

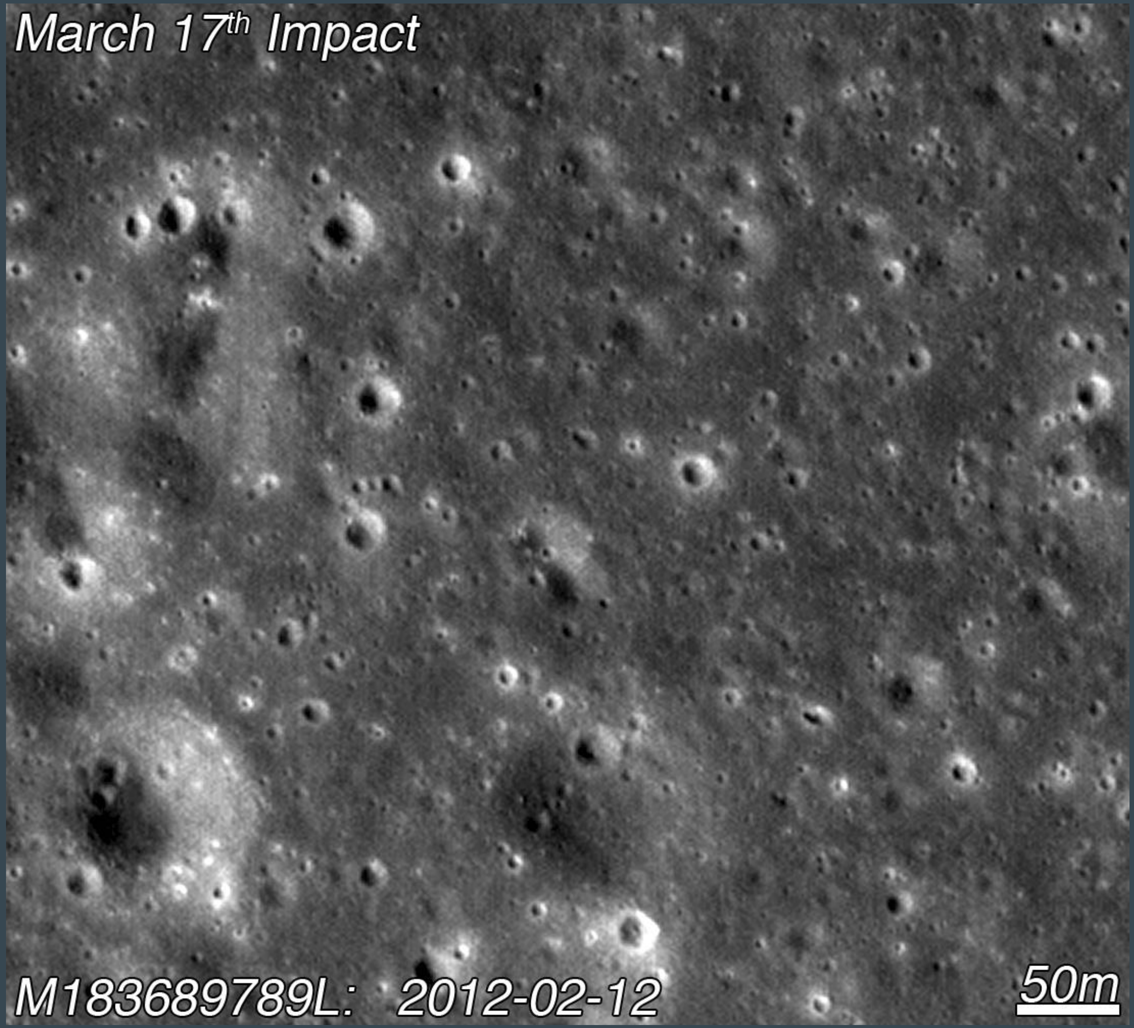
- GRAIL and LRO results yield definitive definition of the lunar inventory of impact basins



Neumann et al., *Science Advances* 30 Oct 2015:
Vol. 1, no. 9, e1500852
DOI: 10.1126/sciadv.1500852

SIGNIFICANT ADVANCES: RECENT IMPACTS

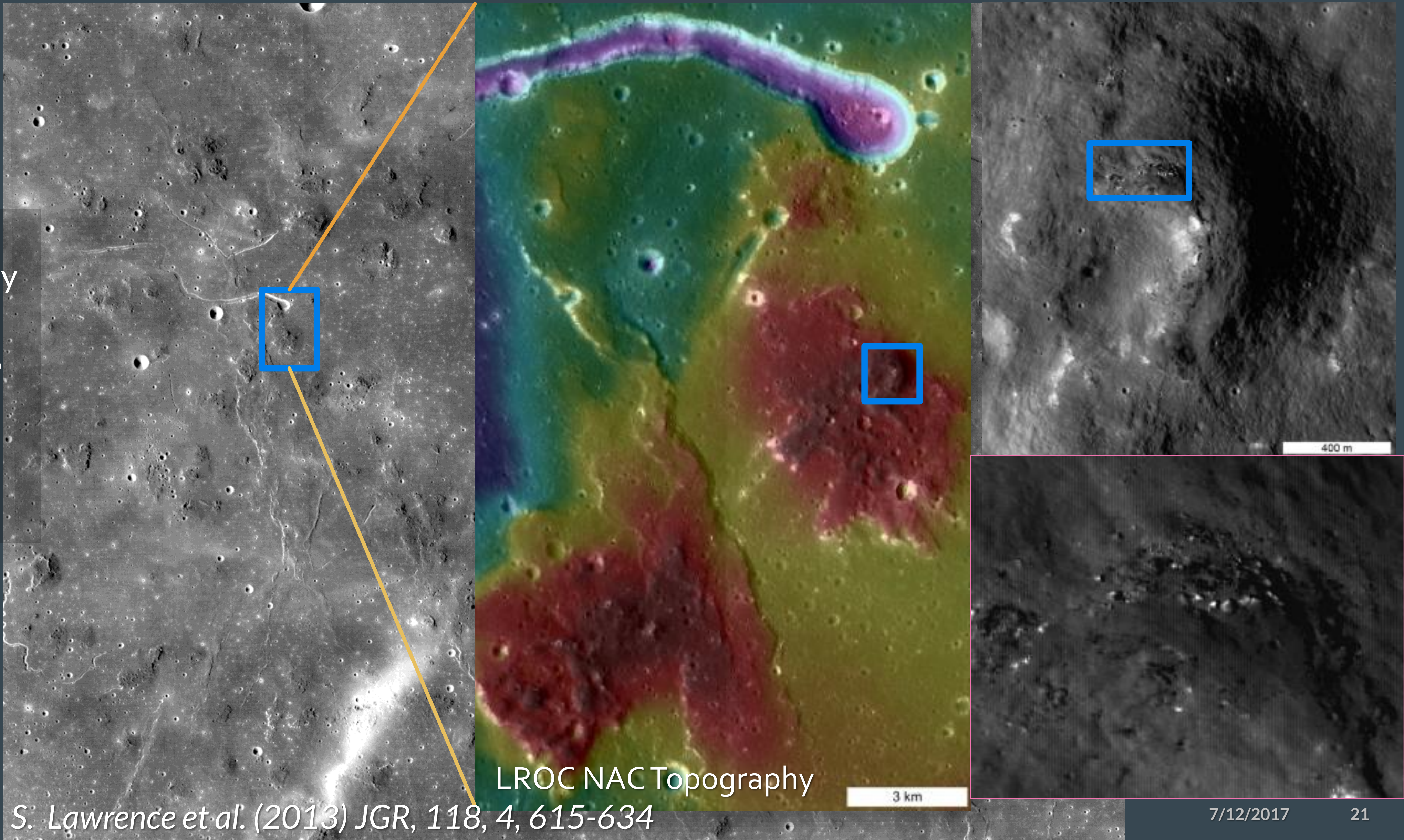
- LRO temporal pairs are creating critical new determinations of the lunar impact rate
- New impact craters are revealing exciting new details of ejecta distribution and the structure of the regolith



Robinson et al., 2015, Icarus, 252, 229-235, doi:10.1016/j.Icarus.2015.01.019

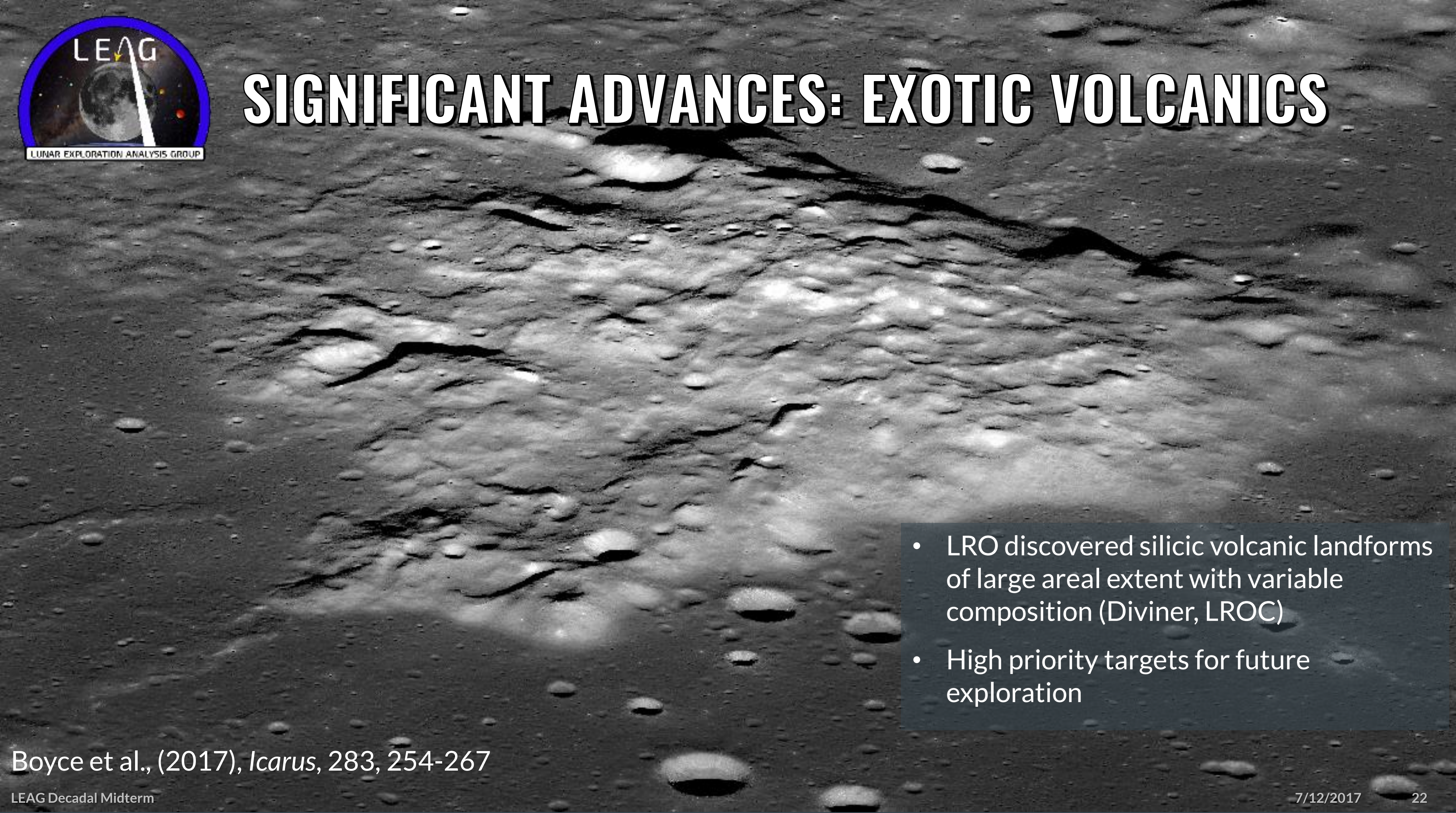
SIGNIFICANT ADVANCES: DIVERSE VOLCANISM

Our Moon has a stunningly diverse array of volcanic landforms: Large shield volcanoes, **spatter cones,** pyroclastic deposits, mare basalt provinces, silicic volcanics



S. Lawrence et al. (2013) JGR, 118, 4, 615-634

SIGNIFICANT ADVANCES: EXOTIC VOLCANICS

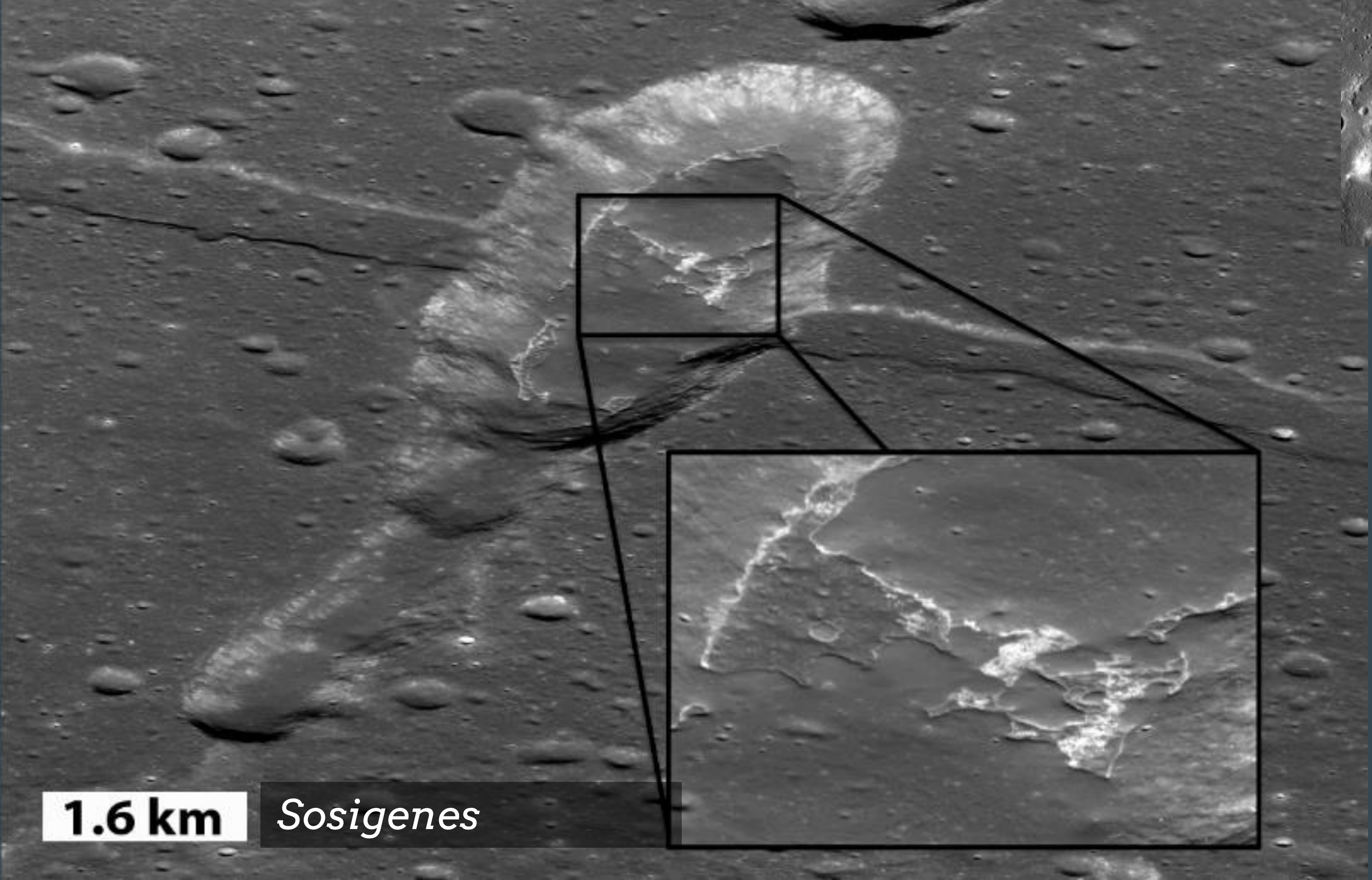


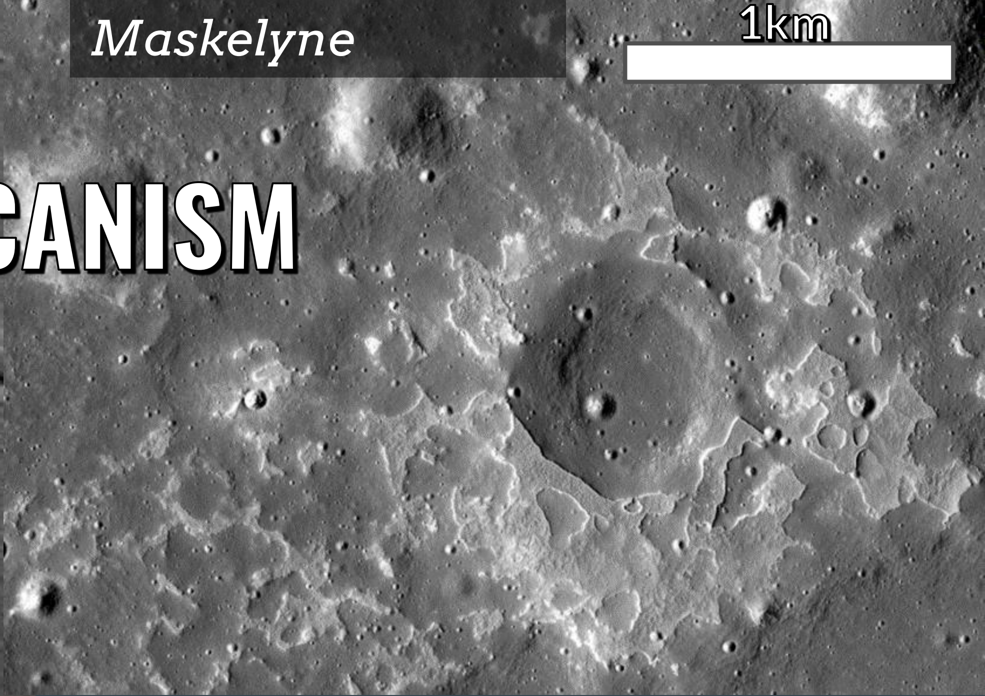
- LRO discovered silicic volcanic landforms of large areal extent with variable composition (Diviner, LROC)
- High priority targets for future exploration

Boyce et al., (2017), *Icarus*, 283, 254-267

SIGNIFICANT ADVANCES: POTENTIALLY RECENT VOLCANISM

Braden S.E. et al. (2014) Nature Geoscience, v. 7, p. 787-791

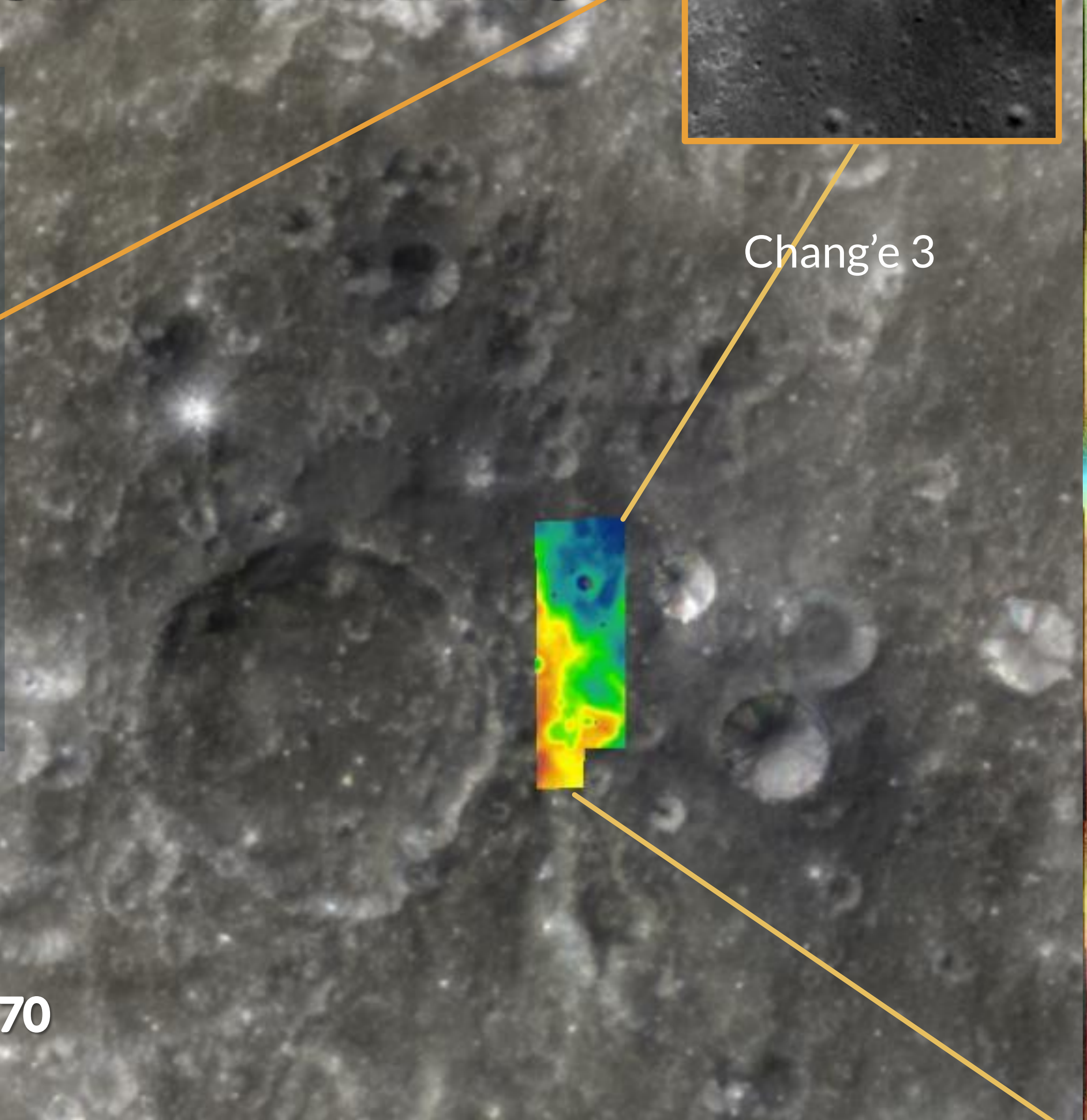


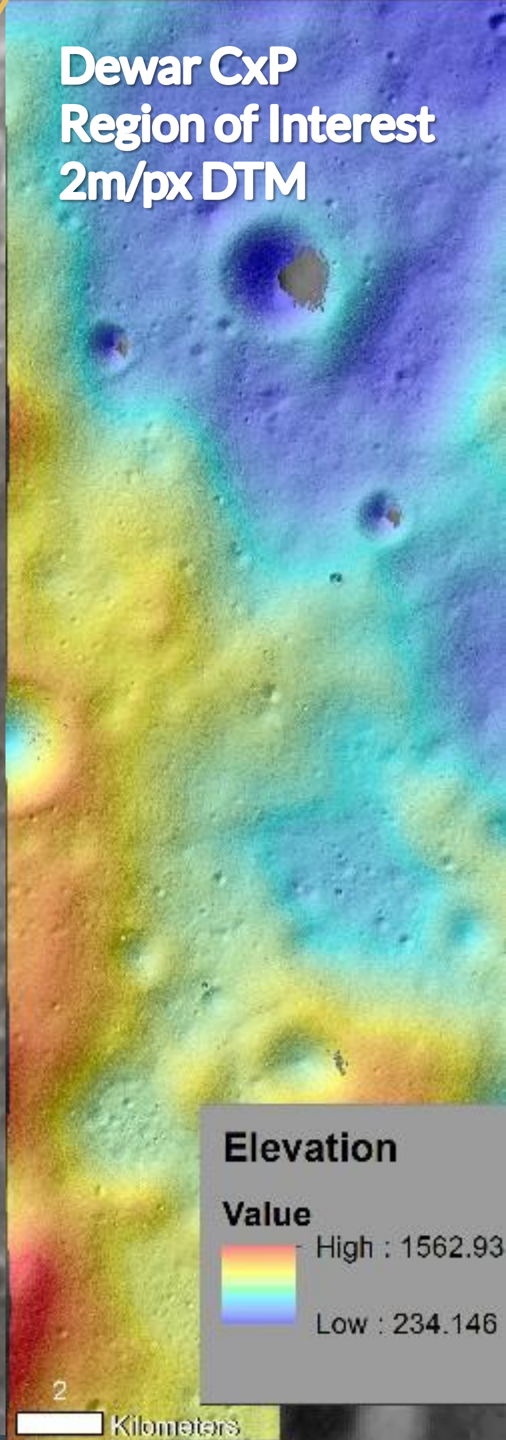


- Prospective discovery of recent lunar volcanism (Irregular Mare Patches) using LROC NAC Images
    - Compelling observational evidence for geologically recent (<<1 Ga) volcanic activity on lunar surface
    - Provocative, and therefore controversial, result currently a topic of vigorous debate
    - IMPs are high-priority targets for future robotic and human exploration

SIGNIFICANT ADVANCES: EXPLORATION PREPARATION

- LRO Mission is providing all data necessary to certify sites for safe landing
  - High-resolution images and stereo Digital Terrain Models for many locations on the Moon
- Possibility: provide post-landing operational support to spacecraft
- New targeting for international and GLXP mission teams
- **An incomparable Mission-Enabling resource**

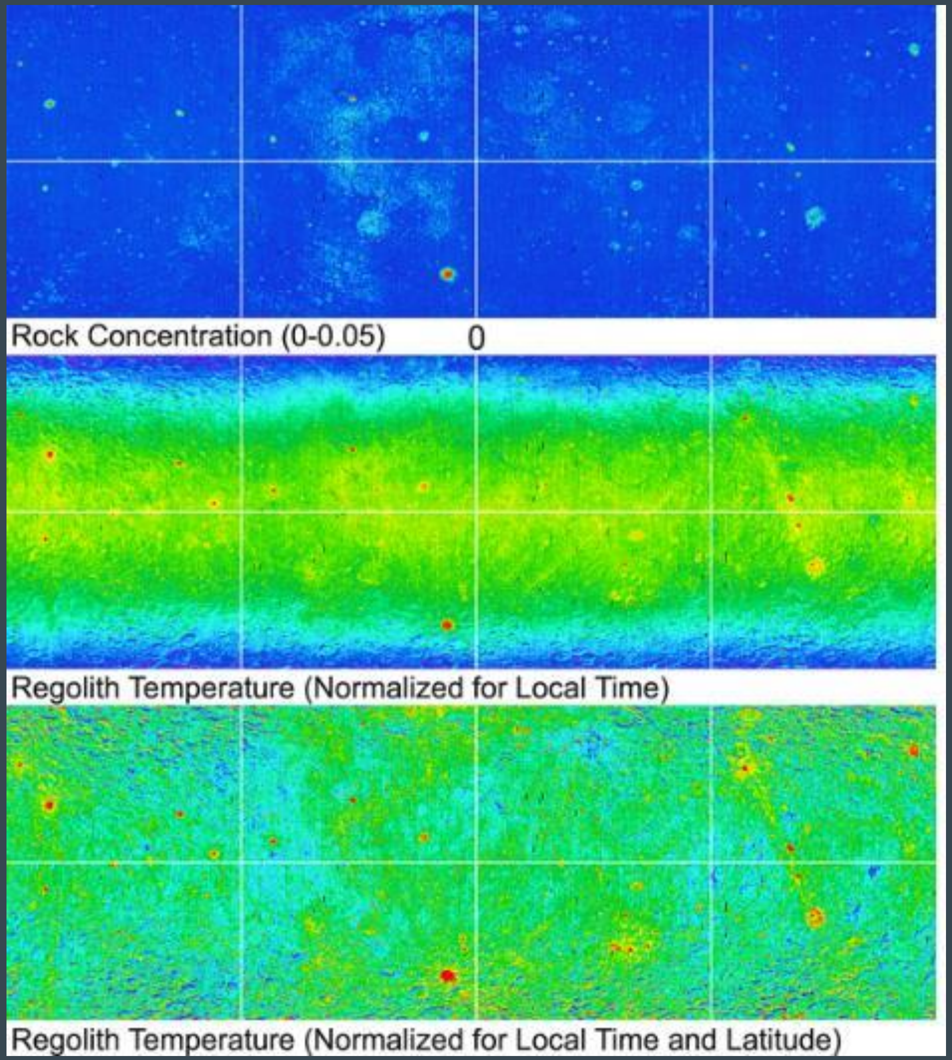




Dewar Cryptomaria
Whitten et al. (2015) Icarus , 257, p. 151-170

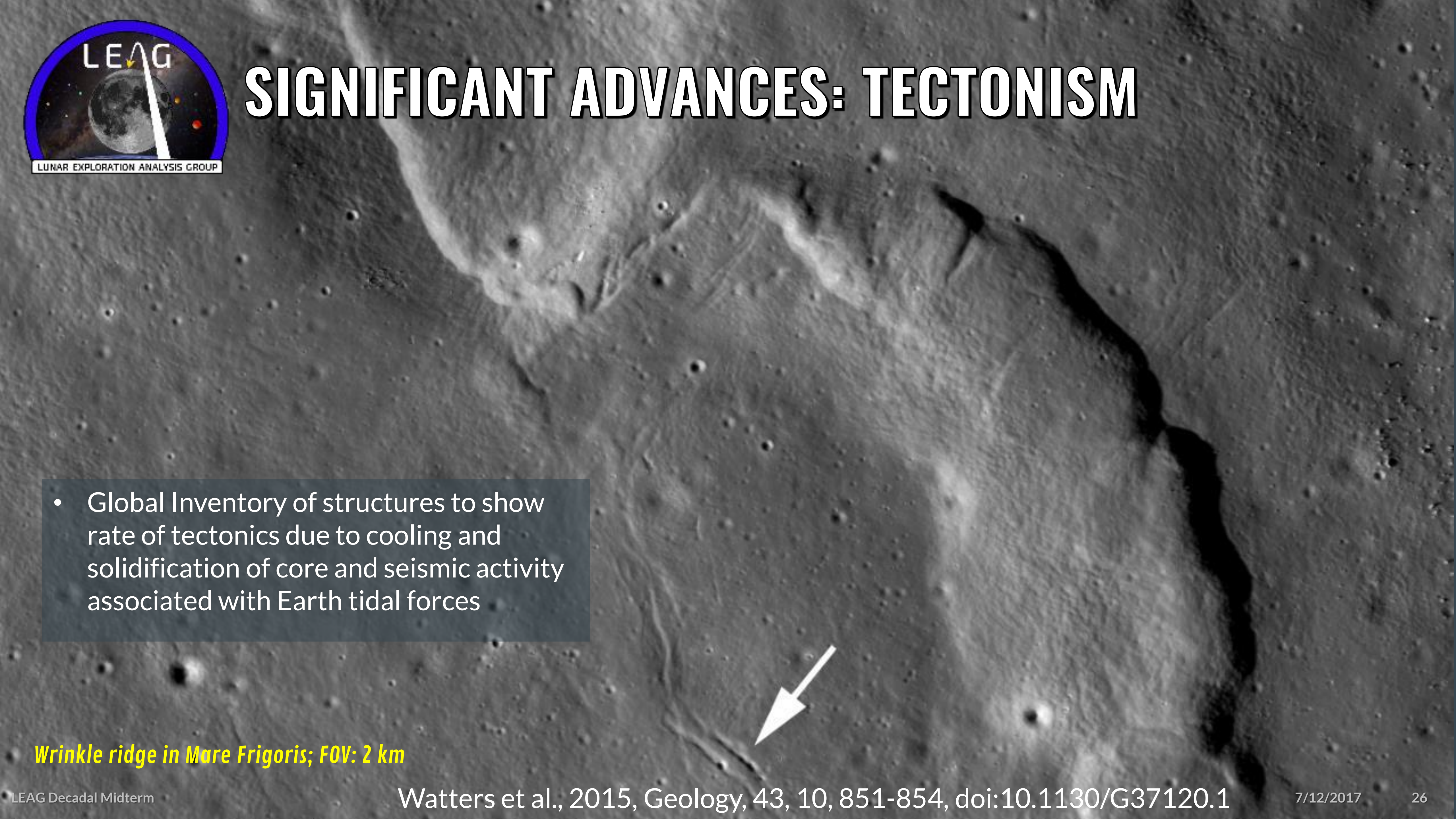
SIGNIFICANT ADVANCES: EXPLORATION PREPARATION

- Diviner thermophysical property results, including the global maps of Diviner Rock Abundance (DRA), are excellent tools for regolith property investigations and landing site selection



Bandfield et al. (2011) JGR, 116, E12, E00H02

SIGNIFICANT ADVANCES: TECTONISM



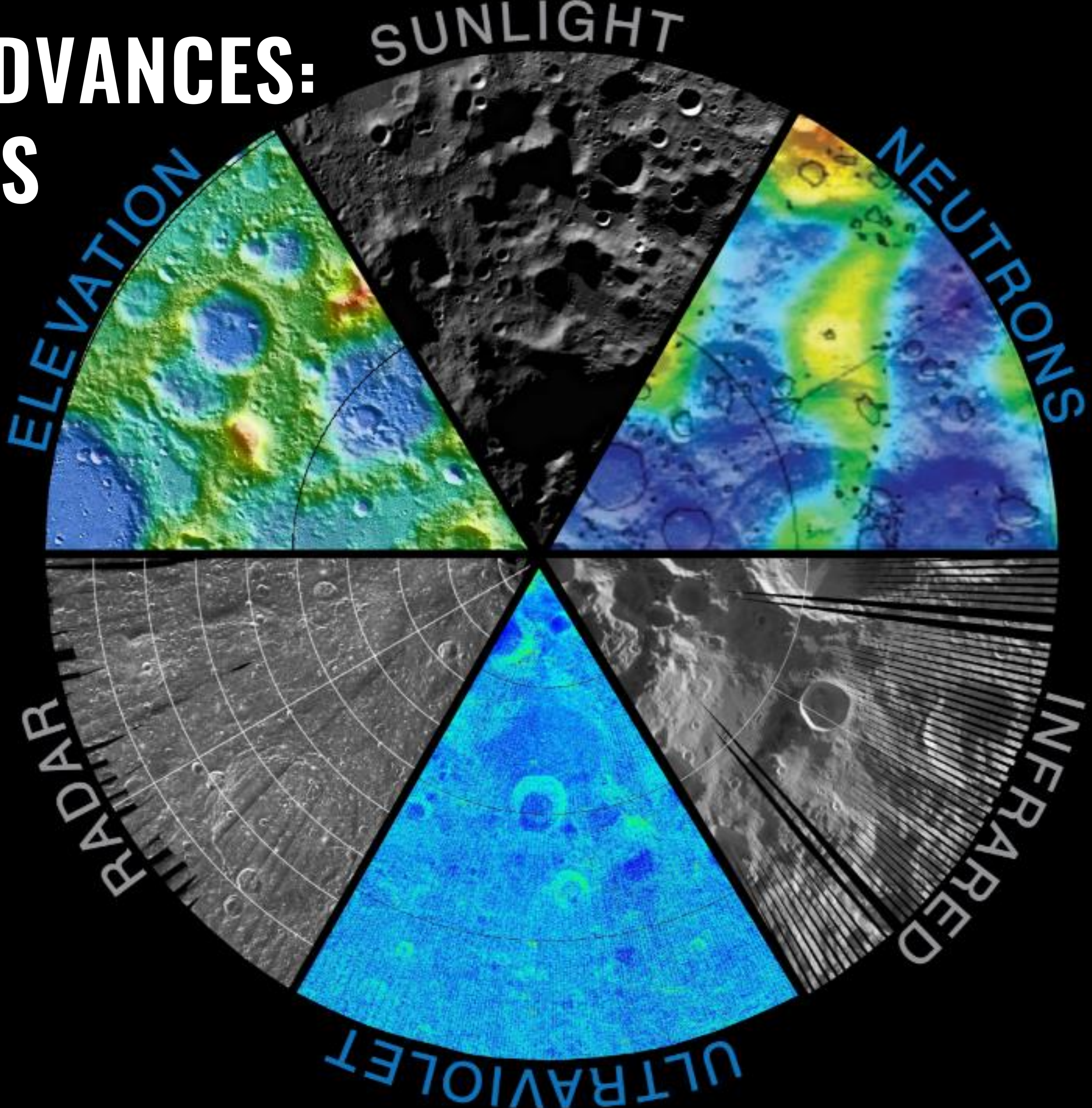
- Global Inventory of structures to show rate of tectonics due to cooling and solidification of core and seismic activity associated with Earth tidal forces

Wrinkle ridge in Mare Frigoris; FOV: 2 km

Watters et al., 2015, Geology, 43, 10, 851-854, doi:10.1130/G37120.1

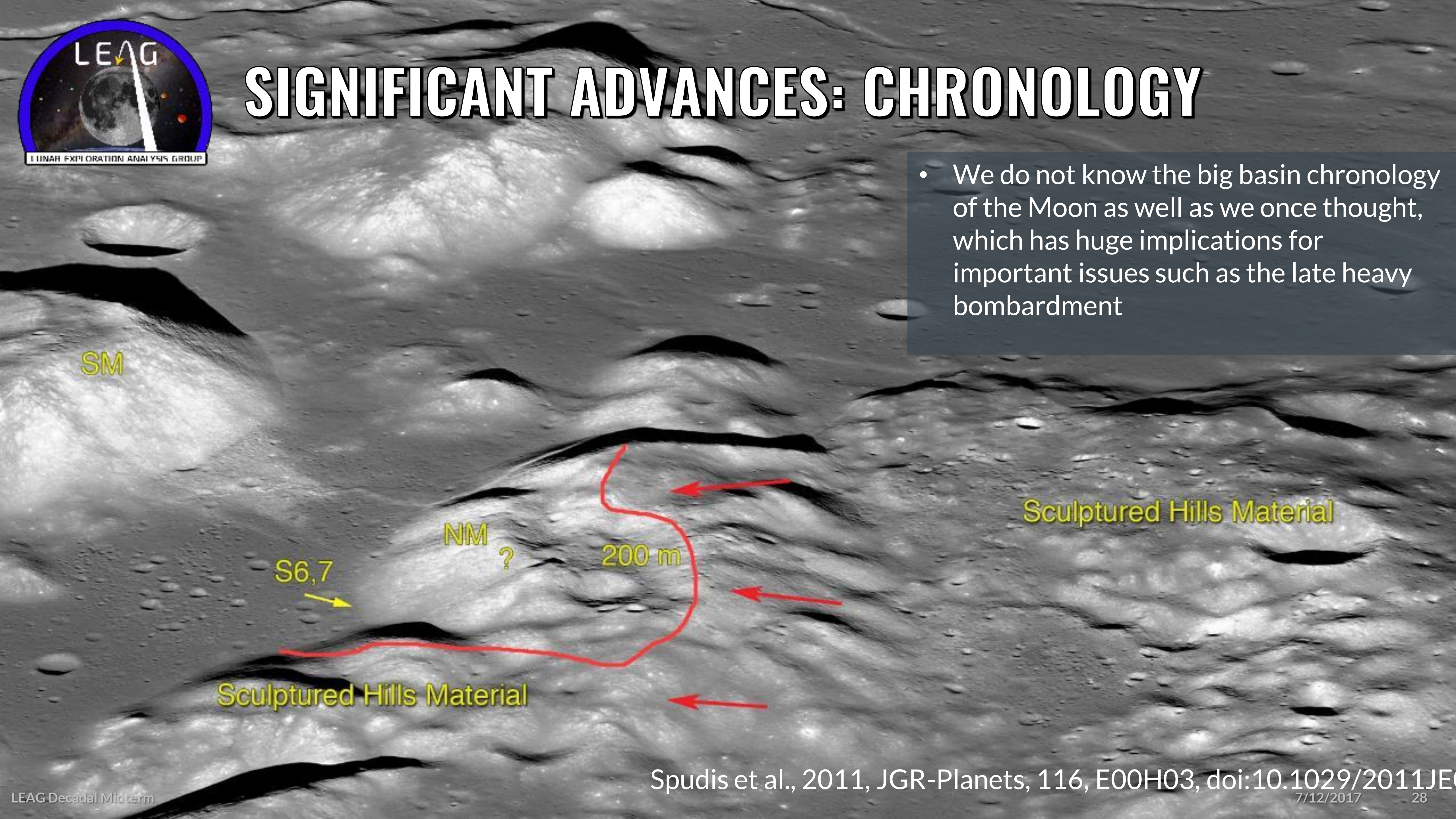
SIGNIFICANT ADVANCES: POLAR REGIONS

- LRO characterization of polar environment including surface and subsurface temperatures (Diviner) and illumination conditions (LROC), and the possibility of surface frosts (LAMP, LOLA)
- Non-comprehensive list:
  - Mazarico et al., (2011) Icarus 211, 2, 1066-1081
  - Speyerer and Robinson (2013), Icarus, 222, 1, 122-136
  - Mandt et al. (2016) Icarus 273, 114-120
  - Speyerer et al. (2016) Icarus 273, 337-345
  - Fisher et al, (2017) Icarus, 292, p. 74-85
  - Williams et al. (2017) Icarus, 283, p. 300-325.
  - Sanin et al. (2017) Icarus 283, P. 20-30
  - Patterson et al. (2017) Icarus 283, 2-19
- “We must follow up LRO results and get down to the surface to explore the poles in many places”



SIGNIFICANT ADVANCES: CHRONOLOGY

- We do not know the big basin chronology of the Moon as well as we once thought, which has huge implications for important issues such as the late heavy bombardment

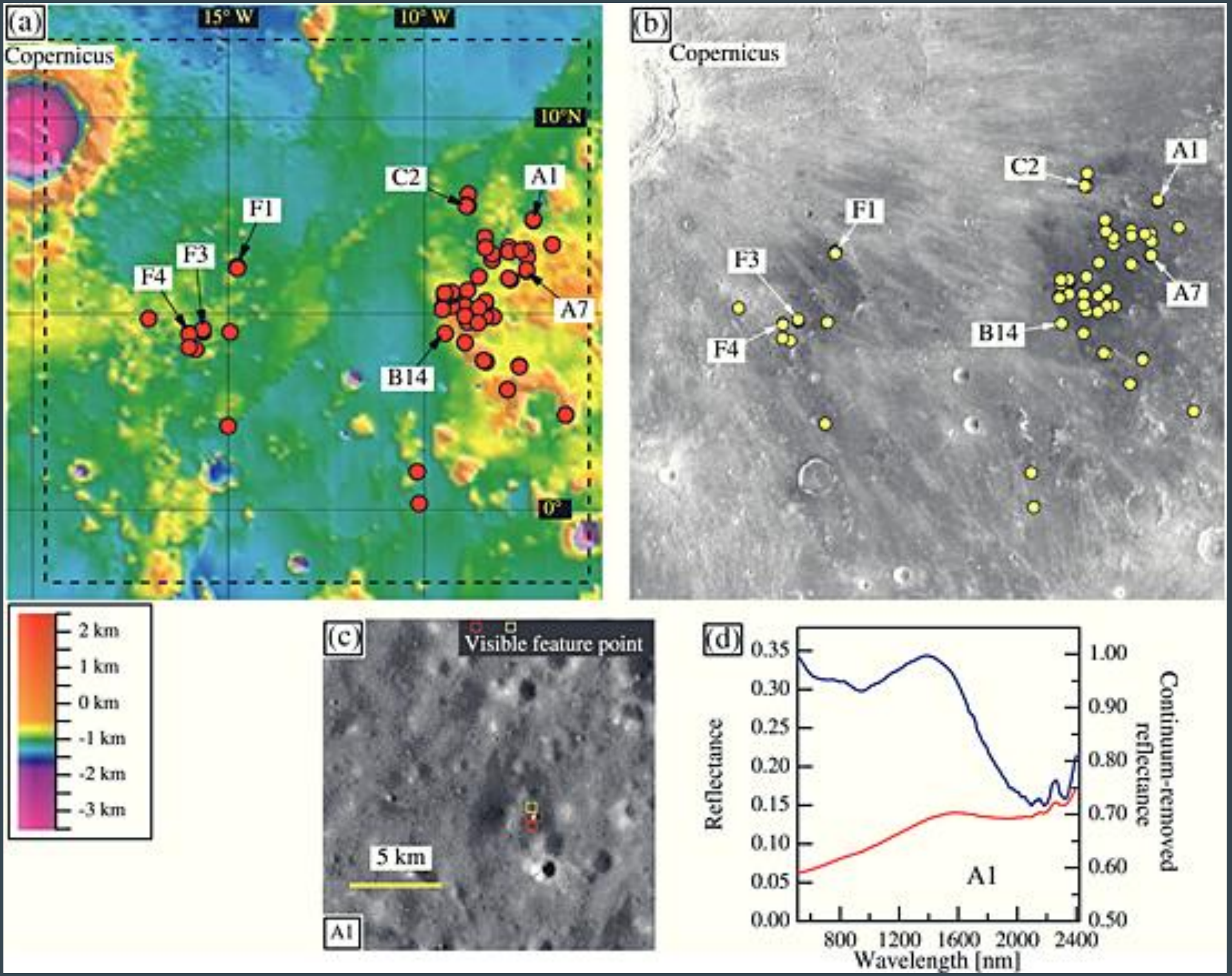


Spudis et al., 2011, JGR-Planets, 116, E00H03, doi:10.1029/2011JE

SIGNIFICANT ADVANCES: CRUSTAL COMPONENTS

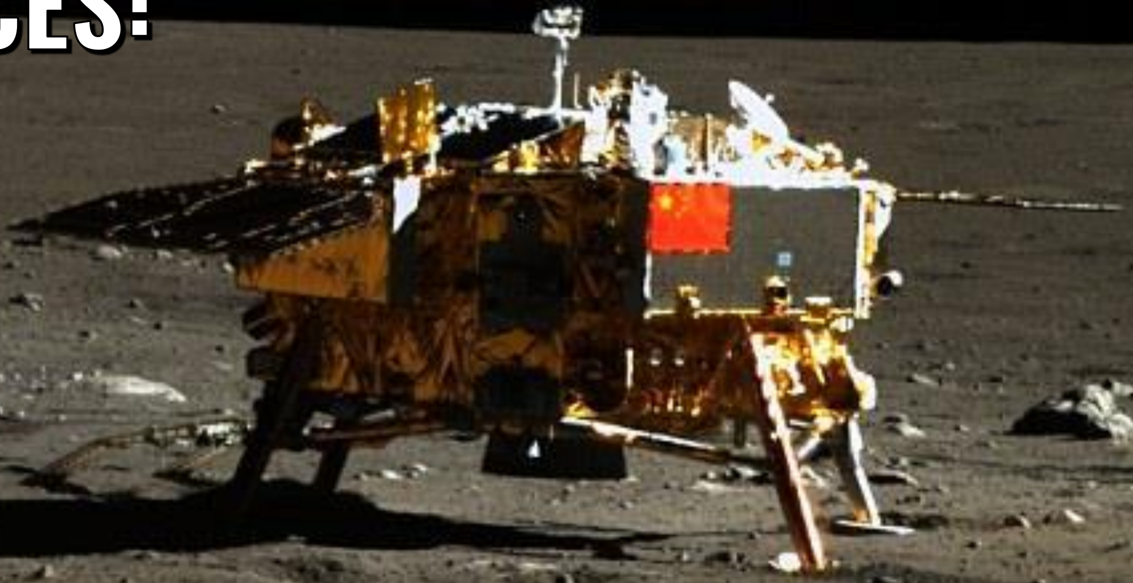
SPINEL-RICH PYROCLASTICS

- A Compositionally diverse lunar crust!
  - Ilmenite
  - silica-rich mineralogy
  - spinels
  - pyroclastic deposits
  - pyroxene varieties
  - nearly pure anorthosite.
- Exciting new science enabled by identification of surface mineralogy with first global UV bands (LROC), thermal data (Diviner)
- Continued discoveries about the diversity of the lunar crust using the high spatial and spectral resolution of M3 and the SELENE spectral suite data



Yamamoto et al., 2013, GRL, 40, 17, 4549-4554

SIGNIFICANT ADVANCES: GROUND TRUTH



- CE3 provided ground-truth measurements on a relatively young, intermediate- to high-Ti basalt flow in Imbrium basin.
- “We need more targeted landers to follow up and ground-truth the great orbital data we now have in hand”

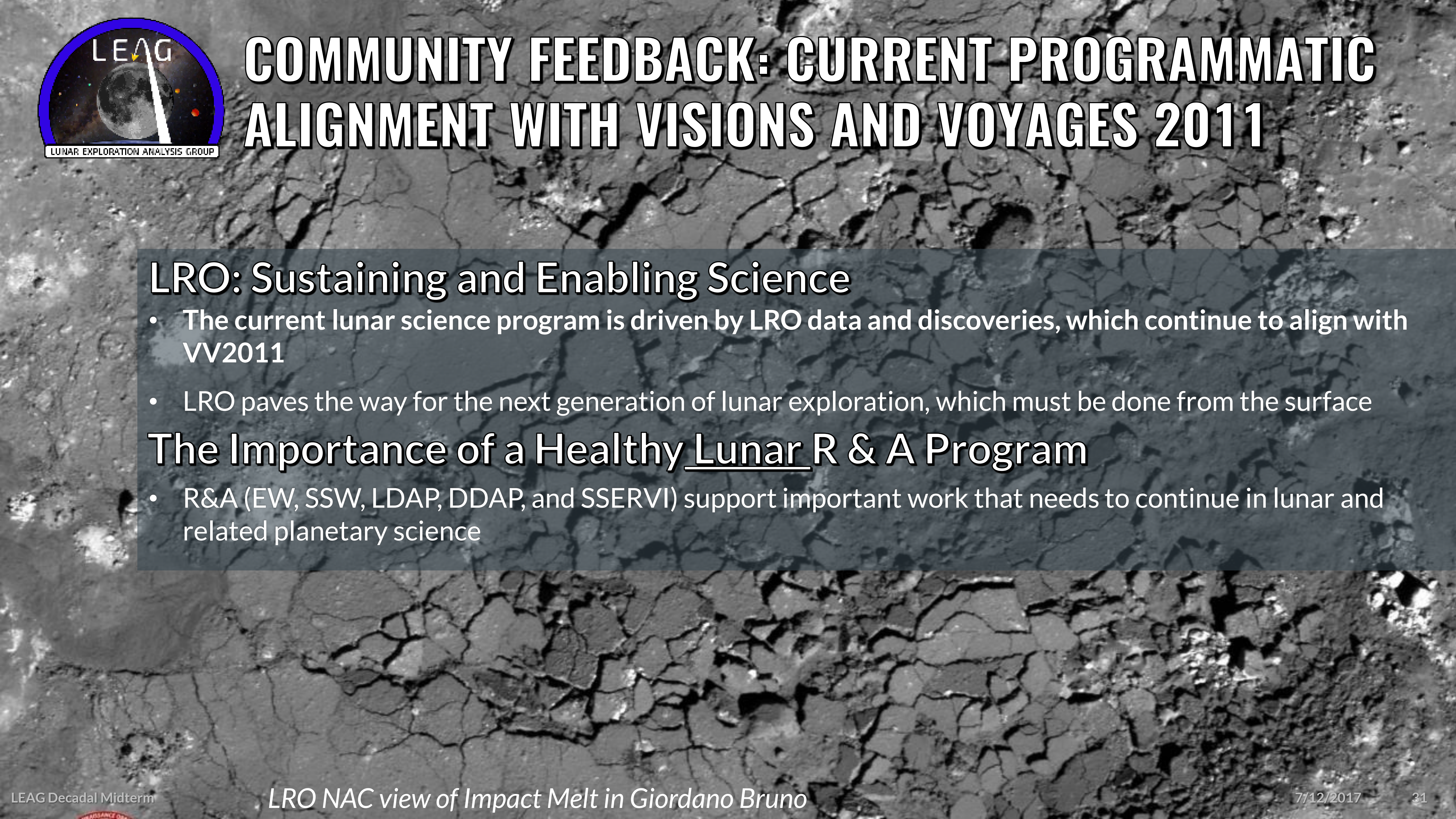
COMMUNITY FEEDBACK: CURRENT PROGRAMMATIC ALIGNMENT WITH VISIONS AND VOYAGES 2011

LRO: Sustaining and Enabling Science

- **The current lunar science program is driven by LRO data and discoveries, which continue to align with VV2011**
- LRO paves the way for the next generation of lunar exploration, which must be done from the surface

The Importance of a Healthy Lunar R & A Program

- R&A (EW, SSW, LDAP, DDAP, and SSERVI) support important work that needs to continue in lunar and related planetary science

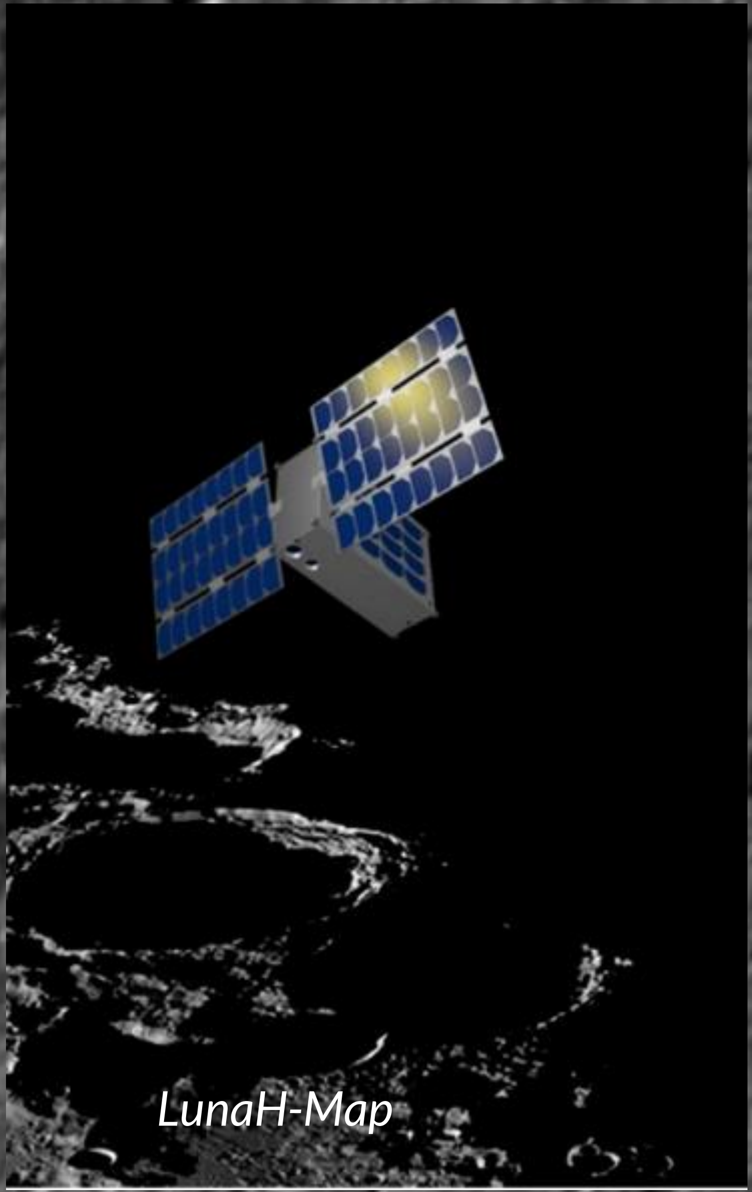


LRO NAC view of Impact Melt in Giordano Bruno

ADVANCES BEYOND VV2011: NEW PARADIGMS

LADEE in flight - Imaged from LRO 6 km away!

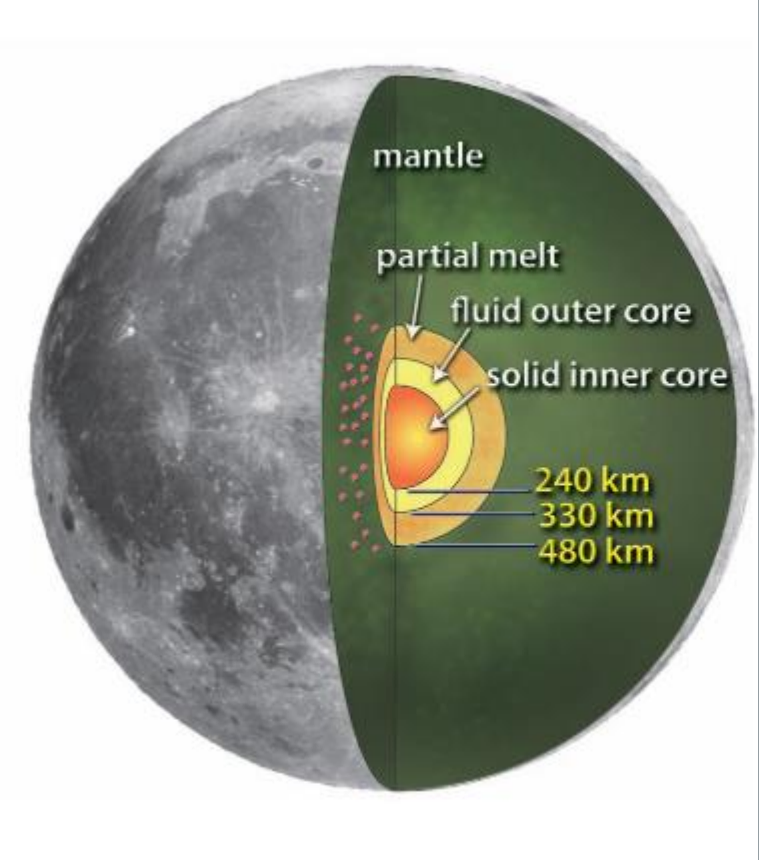
- The successful LADEE mission as well as the present slate of lunar SLS EM-1 smallsat missions demonstrate that the Moon is an ideal target for low-cost planetary missions based on new technology and management paradigms



LunaH-Map

ADVANCES BEYOND VV2011: ACTIVE LUNAR DYNAMO

- <u>Active lunar dynamo</u>. From lunar samples it is known that the Moon differentiated during its early history (first few 100 Ma).
- Using geophysical data, and depending on assumptions, the size of the lunar core is now constrained to be 220-480 km in radius (Weber et al., 2011; Weiss and Tiko, 2014).
- More important for understanding fundamental planetary processes, detailed laboratory measurements now possible with carefully prepared samples allow the character of the ancient lunar dynamo to be identified and constrained to be active from 4.25 and 3.56 billion years ago (Ga)
    - (Garrick-Bethell et al., 2016; Weiss and Tikoo, 2014; Tikoo et al., 2014).
- The Moon provides a unique opportunity to study the beginning and end of a planetary dynamo. This is a period of major events in early solar system history.



R. C. Weber, P.-Y. Lin, E. J. Garnero, Q. Williams, P. Lognonné, Seismic detection of the lunar core. Science 331, 309–312 (2011). doi: 10.1126/science.1199375; pmid: 21212323

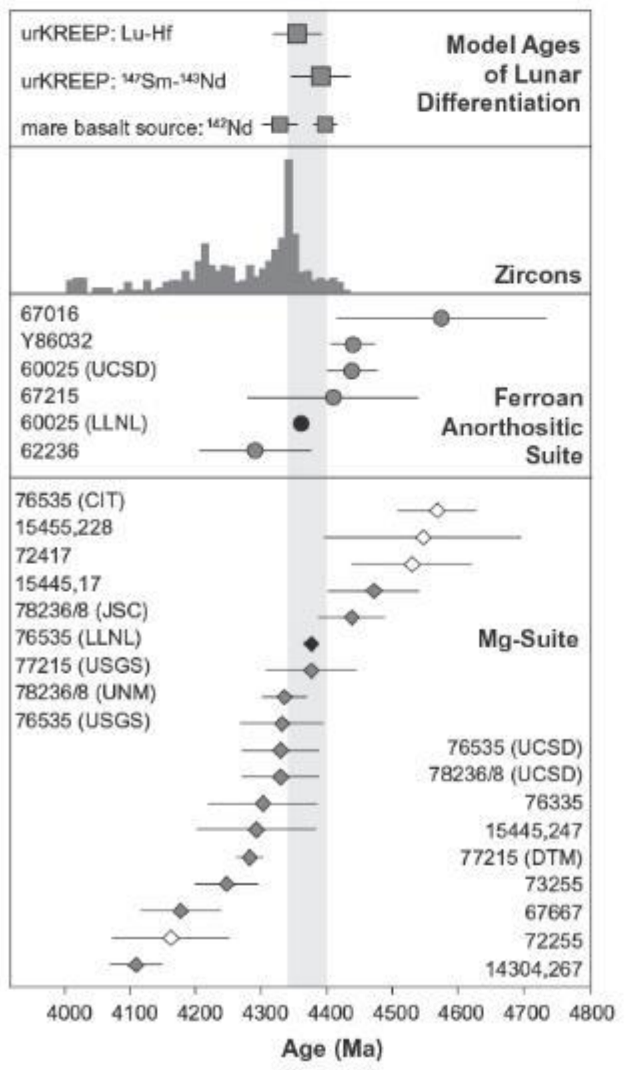
Weiss, B. P., and S. M. Tikoo (2014), The lunar dynamo, Science, 346, doi: 10.1126/science.1246753.

I. Garrick-Bethell, B. P. Weiss, D. L. Shuster, J. Buz, Early lunar magnetism. Science 323, 356–359 (2009). doi: 10.1126/ science.1166804; pmid: 19150839

Tikoo, S. M., B. P. Weiss, W. S. Cassata, D. L. Shuster, J. Gattacceca, E. A. Lima, C. Suavet, F. Nimmo, and M. D. Fuller (2014), Decline of the lunar core dynamo, Earth Planet. Sci. Lett., 404, 89–97.

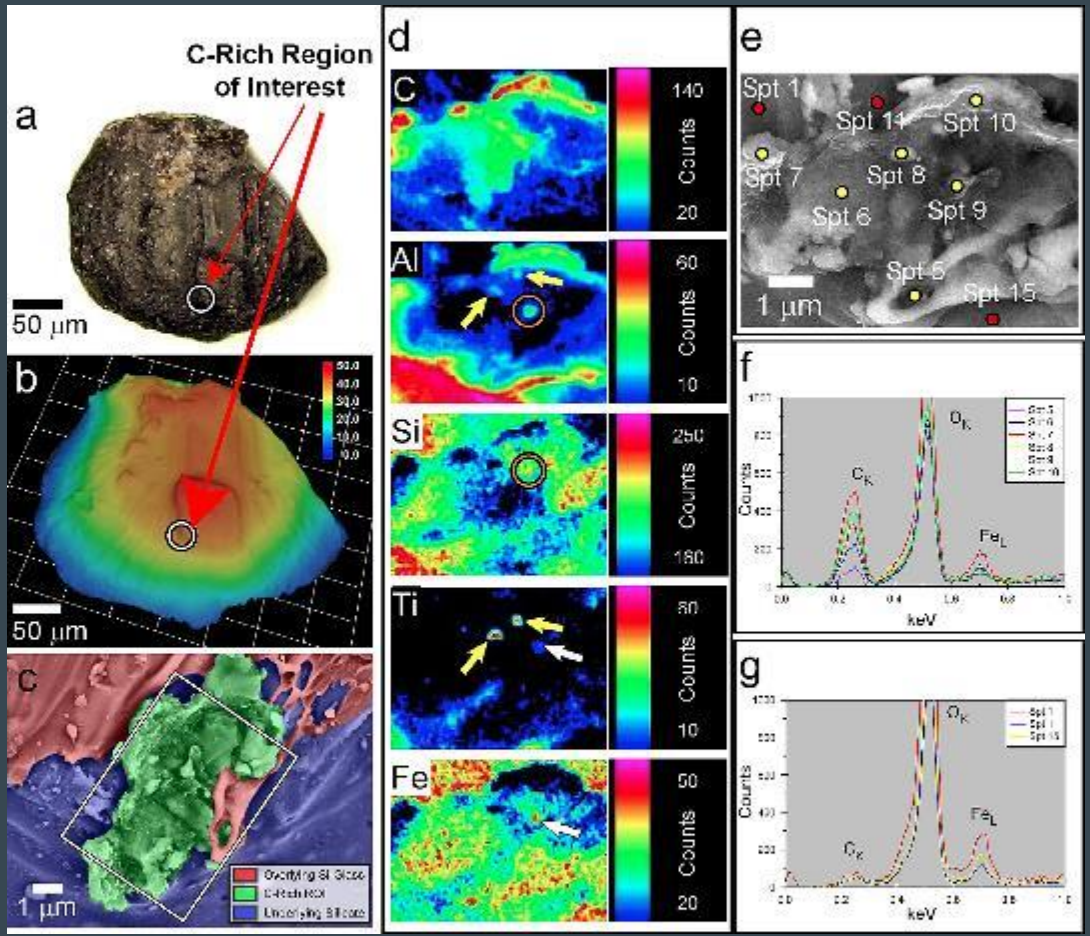
Garrick-Bethell, I., B. P. Weiss, D. L. Shuster, S. M. Tikoo, and M. M. Tremblay (2016), Further evidence for early lunar magnetism from troctolite 76535, J. Geophys. Res. Planets, 121, doi:10.1002/2016JE005154.

ADVANCES BEYOND 2011: LUNAR MAGMA OCEAN CRYSTALLIZATION



- FAN age (60025) of 4,360 +/- 3 million years requires that either the Moon solidified significantly later than most previous estimates or the long-held assumption that FANs are flotation cumulates of a primordial magma ocean is incorrect.
  - Boyet M., Carlson R.W., Borg L.E., and Horan M. (2015) Sm-Nd systematics of lunar ferroan anorthositic suite rocks: Constraints on lunar crust formation. *Geochim. Cosmochim. Acta* **148**, 203-218
  - Carlson RW, Borg LE, Gaffney AM, and Boyet M. (2014) Rb-Sr, Sm-Nd and Lu-Hf isotope systematics of the lunar Mg-suite: the age of the lunar crust and its relation to the time of Moon formation. *Phil. Trans. R. Soc.* **A372**: 20130246
- The ^{176}Lu–^{176}Hf urKREEP model age = 4353 ± 37 Ma, which is concordant with the re-calculated Sm–Nd urKREEP model age of 4389 ± 45 Ma. The average of these ages, 4368 ± 29 Ma, represents the time at which urKREEP formed.
  - Gaffney & Borg (2014) A young solidification age for the lunar magma ocean. *GCA* **140**, 227-140

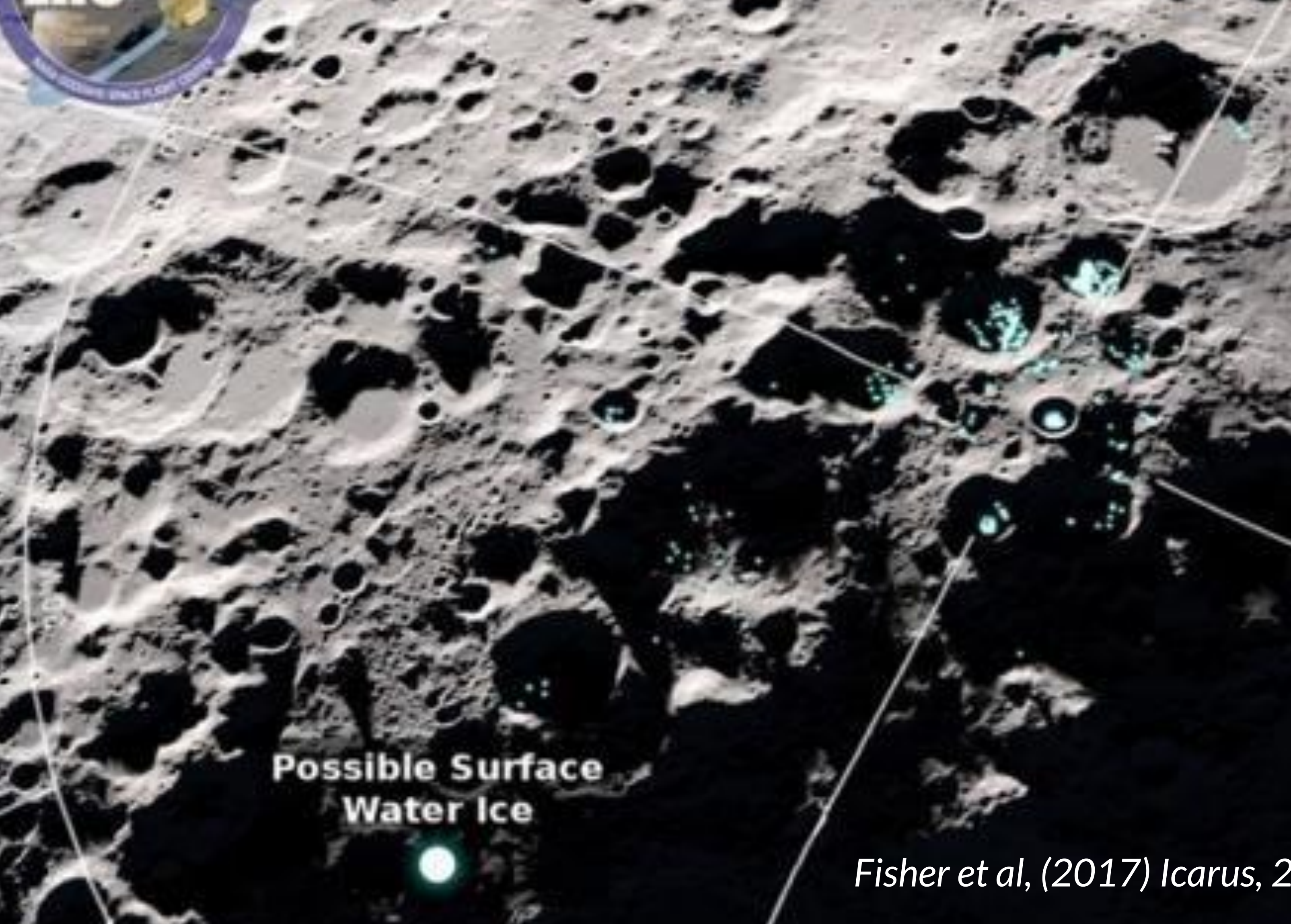
ADVANCES BEYOND VV2011: ORGANIC MATTER IN LUNAR SAMPLES



- Carbonaceous matter on the surfaces of black pyroclastic beads, collected from Shorty crater during the Apollo 17 mission, represents the first identification of complex organic material associated with any lunar sample. It formed through the accretion of exogenous meteoritic kerogen from micrometeorite impacts into the lunar regolith.
  - Thomas-Keprta et al. (2014) *Geochim. Cosmochim. Acta* **134**, 1-15.

ADVANCES BEYOND VV2011: LUNAR VOLATILES

- Visions and Voyages barely had time to incorporate the emerging knowledge of lunar volatiles
- In reality, the different forms of water now identified from the lunar interior, across the lunar surface, and sequestered at the poles have become areas of intense active research and are now known to represent different fundamental processes active on the Moon and other silicate bodies of the inner solar system (e.g. Hurley et al., 2017)
- This remains a strong area of intense interest for research and exploration across the international community

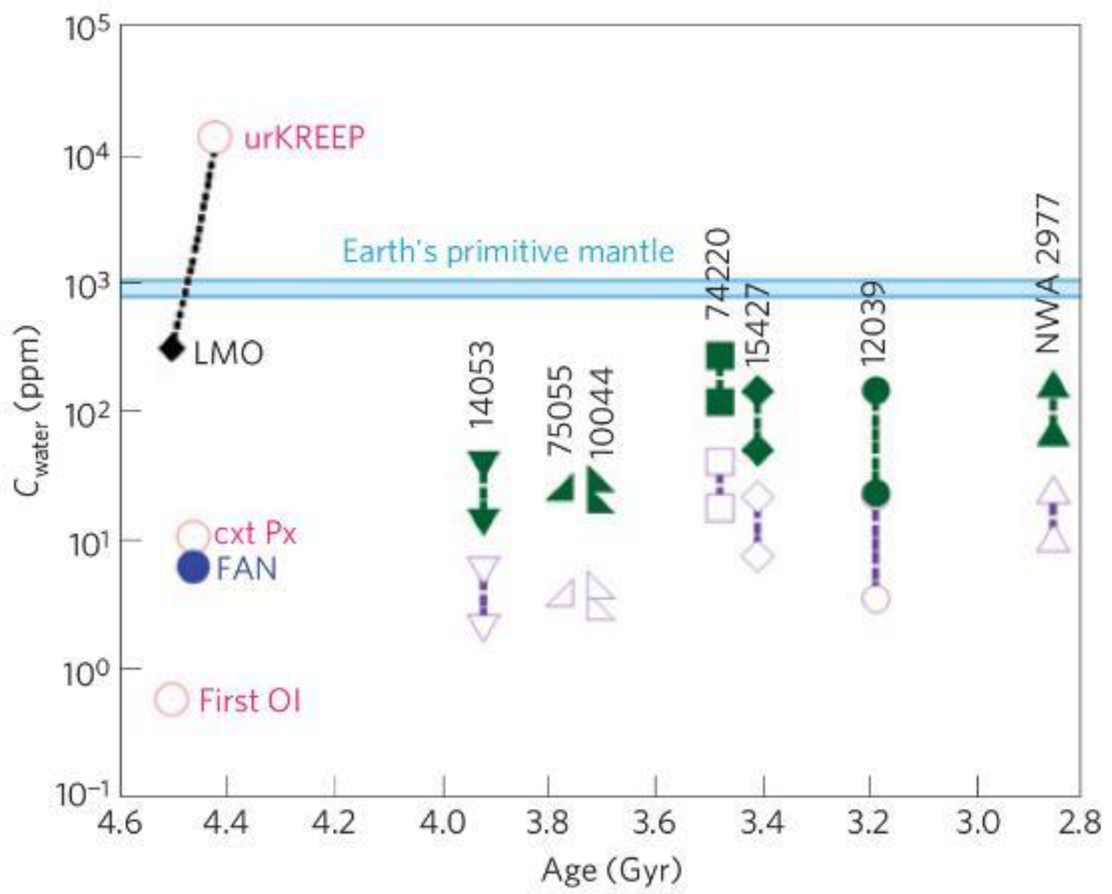


Fisher et al, (2017) Icarus, 292, p. 74-85, doi:10.1016/j.Icarus.2017.03.023

D. Hurley, A. Deutsch, E. Pendelton, 2017, EOS (in press)

ADVANCES BEYOND VV2011: LUNAR ENDOGENOUS VOLATILES

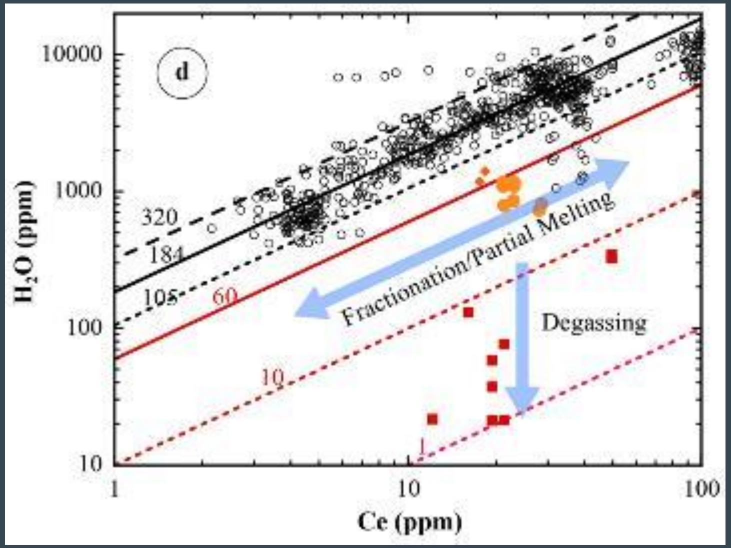
- **FTIR analysis of Ferroan Anorthosites, samples of the primary lunar crust, show they contain significant amounts of water**
  - Results indicate the plagioclase contained ~6 ppm H2O
- These data allow an estimate of the initial water content of the lunar magma ocean to have been ~320 ppm
- Water in the final residuum (urKREEP) could have been 1.4 wt%

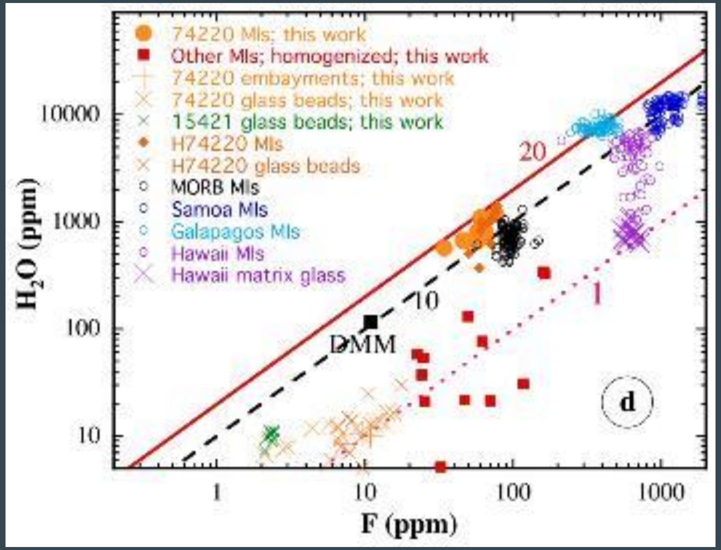


Hejiu Hui, Anne H. Peslier, Youxue Zhang, and Clive R. Neal (2013) Water in lunar anorthosites and evidence for a wet early Moon. *Nature GeoscienceLetters* **6**, 177-180

ADVANCES BEYOND VV2011: ENDOGENOUS VOLATILES

- Analysis of volatiles in melt inclusions in 74220, 15421, 10020, 12008, 15016.
- **Results by Hauri et al. (2011) for 74220 are not anomalous.**
- Approximate constancy of volatile depletion in the Moon relative to the Earth explained by assuming that both acquired volatiles from a similar source or by a similar mechanism, but the earth was more efficient in acquiring the volatiles.
- The H_2O, F and S concentrations in the primitive lunar mantle source to be similar to or slightly lower than those in terrestrial MORB mantle.





- Yang Chen, Youxue Zhang, Yang Liu, Yunbin Guan, John Eiler, Edward M. Stolper (2015) Water, fluorine, and sulfur concentrations in the lunar mantle. *Earth & Planetary Science Letters* **427**, 37-46

LRO: AN EPIC VOYAGE OF DISCOVERY

LEAG strongly endorses conclusions of the recent NRC "Review of Extended Missions and the Senior Review Process" Report, including the expansion of extended mission durations to 3 years

STRONG COMMUNITY SUPPORT FOR FURTHER LRO OPERATIONS

- "Interestingly, the longevity of LRO increases the potential for understanding 'baseline' for lunar surface activities (impacts, temperature and illumination regimes, other diurnal phenomena, etc.) thus increasing the probability of observing 'transient' anomalies caused for variations in the surrounding environment (sun, IMF, etc.)."
- "LRO is sustaining the US lunar science community"
- "Keep LRO going for as long as possible, especially for LROC NAC geometric stereo for digital terrain map development."
- "LRO is enabling for further missions to the Moon by obtaining all the information necessary for safe landing planning and assessment. High priority science targets have been - and continue to be - characterized in detail needed for precision landing and for landing at a site with good knowledge before hand of what to expect, where to traverse, etc. For example, characterization of the polar regions to find the best locations to pursue the science and resource definition associated with polar volatile deposits. "

COMMUNITY CONCERNS: TECHNOLOGY INCUBATION

- Many respondents identified challenges related to technology development
  - “Limited investments in programmatic and funding support for incorporating state of the art design, materials, and components in instrumentation, or qualifying state of the art technologies, especially electronics, for all subsystems. “
  - “Because we cannot qualify these new technologies rapidly enough (especially electronics) we are flying older and older components, which minimizes our capabilities and potential for new discoveries in new places, further eroding the science return for resources expended.”
  - “Also, by over-defining approaches to be used in instrumentation or mission concepts, we completely eliminate the inclusion of any 'breakthrough' capabilities.”
  - “Maybe the commercial opportunities could be used to rapidly flight-qualify components and instruments?”
  - “Insufficient flight opportunities for instruments – can this be rectified with commercial flight plans?”

COMMUNITY CONCERNS:
OCEAN WORLDS IN NEW FRONTIERS 4

SPECIAL LEAG FINDING ON OCEAN WORLDS IN NF4

- LEAG strongly supports the release of a draft-for-comment of the New Frontiers Announcement of Opportunity (AO), the formal AO to be issued in January 2017. However, the inclusion of new theme - Ocean Worlds (Titan and Enceladus) is a major cause for community concern. Such targets for New Frontiers missions were not prioritized in the current Decadal Survey and they were not added by a transparent community-wide process to properly reevaluate the overarching strategy and priorities, such as was done by the NOSSE (New Opportunities in Solar System Exploration) report of 2008. **Altering the New Frontiers candidate mission list by the inclusion of missions that were not considered by the Decadal Survey process undermines the credibility and balance of the entire Vision and Voyages report.** LEAG is concerned that the addition of the Ocean Worlds missions to the New Frontiers AO without an opportunity for community input would set a bad precedent and erode community confidence in the Decadal process. LEAG urges PSD to find another programmatic means to accomplish Ocean Worlds science in concert with the existing New Frontiers and Discovery programs.

- **Rationale**: The addition of a new mission target will significantly impact the work the community has been doing in planning for future New Frontier missions. A mission to Titan or Enceladus that would achieve New Frontiers class science requires years to develop to a mature concept. Therefore, the addition of the new missions at this late date raises the concern that many immature concepts would be proposed. While we understand that the Decadal Survey is but one source of input, the addition of Ocean Worlds creates the perception that proposals aimed at these additional targets would be at an unfair advantage and may get chosen even though they are at a more immature stage than those vetted by the decadal process.

CONCERNS FROM THE COMMUNITY: NEW FRONTIERS PROGRAM

- Strong Concern about the New Frontiers cadence limiting mission opportunities

- South Pole - Aitken basin sample return remains a high priority for probing the early solar system impact bombardment history, with all of the attendant implications for solar system evolution and planetary history.
  - NRC New Frontiers Decadal Report recommend 5 medium class missions, including SPA-SR
    - Highest Priority mission (Kuiper Belt) implemented as New Horizons
    - 2nd highest priority was South Pole-Aitken sample return
    - Lower priority mission selected for NF2
  - Scientific Context for Exploration of the Moon again highlighted value of SPA-SR
  - SPA was again a finalist for 2009 NF3 competition
    - One of 3 new additions from NOSSE evaluation was selected for NF3 (OSIRIS-REX)
  - VV2011 again included SPA among 7 nonprioritized NF contenders

CONCERNS FROM THE COMMUNITY: DISCOVERY PROGRAM

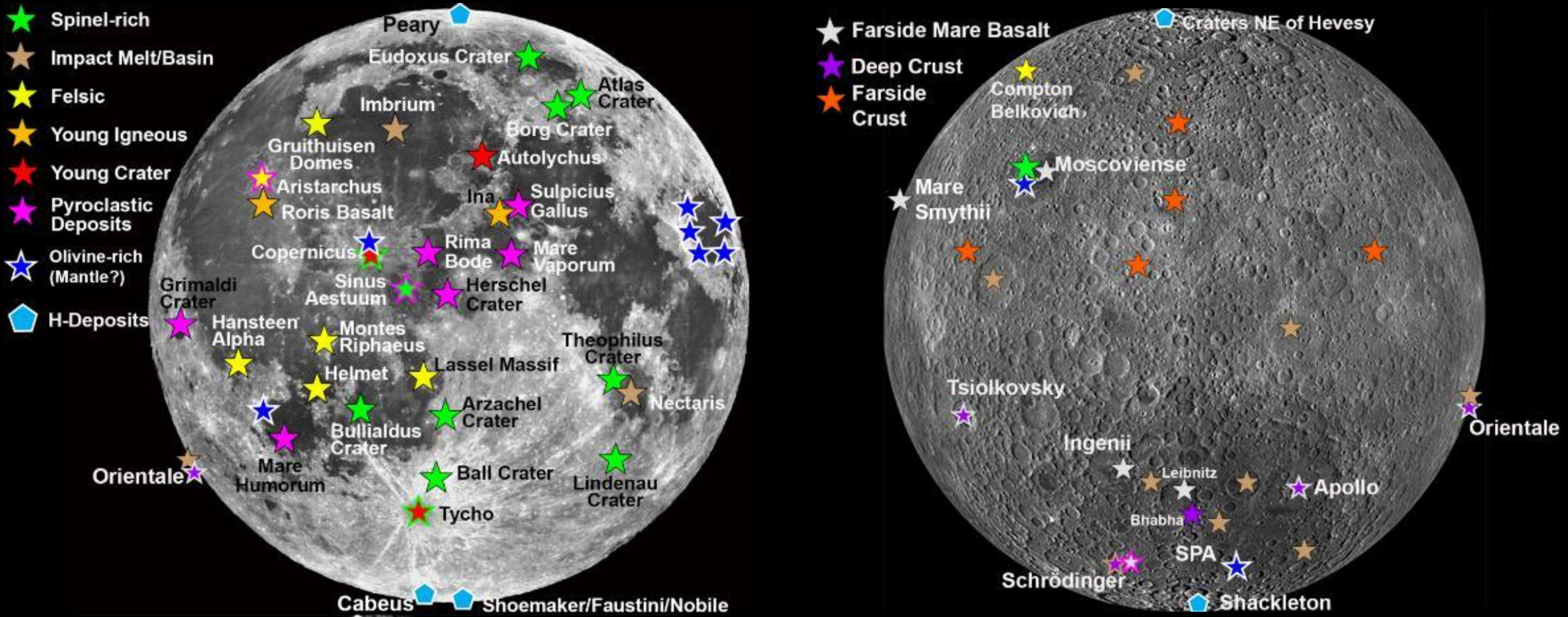
- **From VV2011: "The proximity of the Moon makes it an ideal target for future orbital or landed Discovery missions, building on the rich scientific findings of recent lunar missions and the planned GRAIL and LADEE missions"**
- **2010 Comment in Presidential space address** "We've been there before…Buzz has been there" **created <u>huge</u> problems for US lunar exploration community**
  - Flew in the face of new LRO/LCROSS results conclusively showing the immense science value and vast resource potential of Moon
  - **Widely interpreted as policy statement against all lunar exploration**
    - Made it nearly impossible for budding lunar mission teams to gain management buy-in and technology investment
  - <u>One clear result: only 3 lunar missions for Discovery 12, only 2 lunar missions submitted for Discovery 13/14 call</u>

- **Summary: Lack of submitted Discovery missions to Moon does <u>NOT</u> reflect lack of scientific value or community interest**
- **Moon-focused Discovery-class mission studies for orbiters, landers, and rovers should be supported to prepare for next Decadal**

HUMAN EXPLORATION OF THE MOON: GATEWAY TO THE SOLAR SYSTEM

- **The Moon is the most feasible and accessible destination for human exploration beyond Low-Earth Orbit**
  - Vast resource potential
  - Proximity enables high launch cadence
  - Surface exploration dramatically enhances capabilities for all other destinations
- **Moon is an incredibly compelling destination in its own right**
  - Human missions to the Moon will dramatically enhance planetary science for the entire Inner Solar System
- LEAG stands ready to help SMD and HEOMD define programmatic synergies that provide significant advances in planetary science objectives while meaningfully enhancing commercial opportunity, human surface exploration activities, and resource prospecting
- **HOWEVER: The Moon is an incredibly compelling scientific destination in its own right, and the clear desirability and feasibility of human lunar surface exploration should <u>not</u> preclude dedicated uncrewed US science missions**

NEW OPPORTUNITIES: SAMPLE RETURN



- Sample return from the Moon is pivotal for understanding many fundamental Solar System science questions, particularly the chronology of the inner Solar System

NEW OPPORTUNITIES: POLAR REGIONS

- Lunar PSRs provide a compelling, relatively accessible location for future planetary science studies of volatiles
- LEAG-ISECG SAT intended to help facilitate US and International polar mission coordination

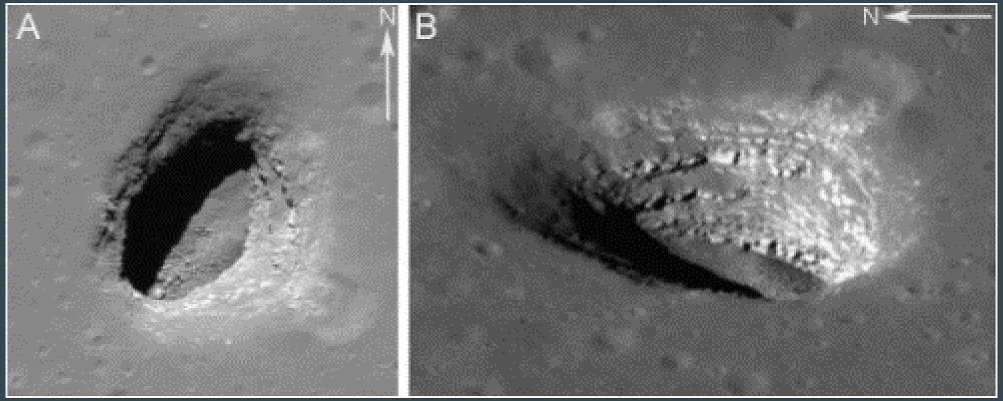
LROC NAC Polar Illumination map

NEW OPPORTUNITIES: POLAR VOLATILES EXPLORER

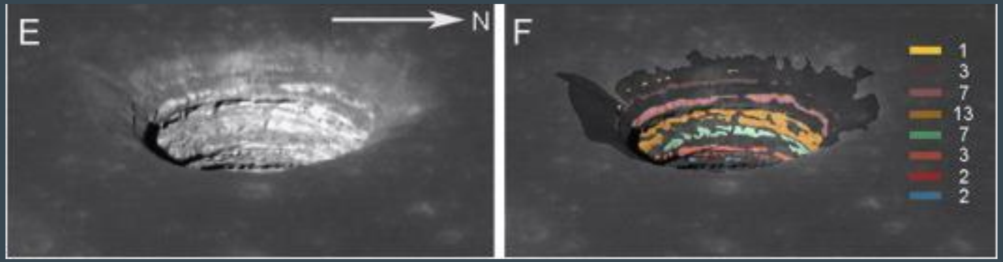
- Studied for Decadal but did not undergo CATE
- Science Objectives
  - Determine the form and species of the volatile compounds at the lunar poles
  - Determine the vertical distribution and concentration of volatile compounds in the lunar polar regolith
  - Determine the lateral distribution/concentration of volatile compounds in the lunar polar regolith
  - Determine the secondary alteration mineralogy of the regolith
  - Determine the composition and variation in the lunar exosphere adjacent to cold traps
- Lander+Rover with RPSs
- New Frontiers class mission

NEW OPPORTUNITIES: SUBLUNAREAN VOIDS

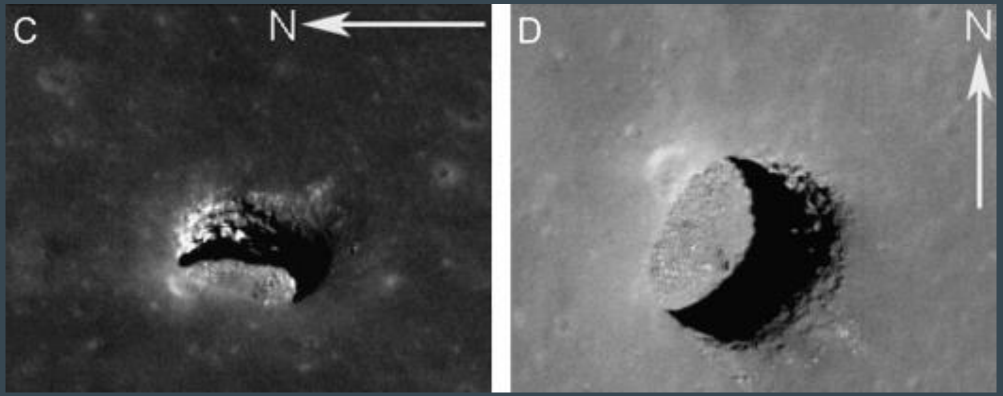
- At the time of VV2011 Moon caves (sublunarean voids) were only just being discovered
- Now there have been many discoveries, including both mare and impact melt sublunarean voids
- Sublunarean voids enable access to a stratigraphic section (in the walls of mare pits) and pristine, unshocked, unspace-weathered, in-place bedrock (under the overhangs)
- Sublunarean voids are also excellent locations for human habitats



Mare Ingenii



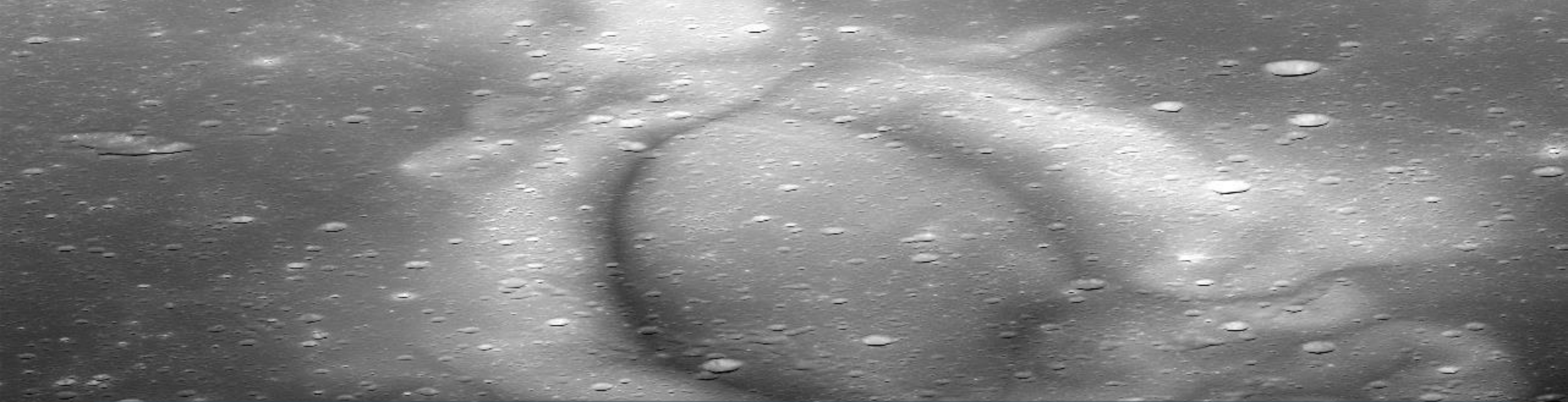
Mare Tranquillitatis



Marius Hills

Robinson et al., 2012, Plan. Space Sci., 69, 1, p. 18-27
Wagner et al., 2014, Icarus, 257-52-60

NEW OPPORTUNITIES: LUNAR SWIRLS



- Exploration of lunar crustal magnetic anomalies provides opportunities to investigate a broad range of key problems in planetary science:
  - Geophysics: the nature and origin of the magnetized crust (ancient dynamo, magnetized basin ejecta, comet impact)
  - Space Plasma Physics: mini-magnetospheres, electron vs. proton response to magnetic and electric fields
  - Geology/Surface Processes: origin of lunar swirls, space weathering, solar-wind implantation/hydration, dust motion/accumulation, comet impact

Glotch et al. (2015) Nat. Com., 6, doi:10.1038/ncomms7189
Denevi et al. (2016) Icarus 273, 53-67

PREPARING FOR THE FUTURE: THE ROLE OF COMMERCIAL SPACE SERVICE PROVIDERS

- Commercial providers are working to provide credible surface access capabilities (LEAG Commercial Advisory Board, 2017)
- Idea: NASA Transitions to customer, purchasing launch and landing opportunities
- Moon is ideal test bed to develop public-private partnerships for planetary exploration

Astrobotic Peregrine

Moon Express MX-1

SUMMARY: COMMUNITY SUGGESTIONS FOR THE NEXT DECADAL SURVEY

Technology Investments

- Landing systems
- Sliding autonomy for rover operations
- Long-lived distributed surface and orbital sensor networks.
- Need for lunar communication and GPS equivalent satellite network to support this
  - Equivalent to Mars program infrastructure (e.g., MRO)

Programmatic Innovations

- Combine Moon's proximity, desirability, and nascent commercial capabilities to establish a lunar exploration program based on public-private partnerships

MISSION PRIORITIES

- Sample returns
  - Incredible potential for chronology
    - ancient impact basin chronology
  - Volcanics
- Geophysical stations on the surface for magnetism, seismology, and heat flow
  - E.g., NF5 Lunar Geophysical Network
- Comprehensive array of In-situ missions to investigate some of the phenomenal geologic findings of recent missions, such as swirl properties and volcanism at sites such as Reiner Gamma, Aristarchus (crater and plateau), spatter cones at the Marius Hills, and the silicic pyroclastics at the Compton-Belkovich and Lassell Massif volcanic complex
  - Long-lived rovers
  - Stationary landers
  - Hoppers

- **Significant advances in lunar science since Vision and Voyages**
- **Recent missions, particularly LRO, have redefined our understanding of the Moon and created considerable momentum and enthusiasm for surface exploration**
    - **Strong community support for, and appreciation of, continued LRO operations**
    - **Valuable science to be obtained from future orbiters**
- **New science advances REQUIRE surface exploration**
    - Long-lived rovers
    - Sample returns
    - Landers
- Moon offers rich opportunities for public-private partnerships
- **<u>Still a lot of work to be done!</u>**

Lunar Reconnaissance Orbiter Wide Angle Camera – Hapke-corrected color

Only a
few days away
is a
whole world
full of
wonder
and
opportunity
just waiting
for us to
explore

Backup Slides

LEAG DECADAL Community INPUT PROCESS

Community feedback was solicited from the lunar exploration community through Lunar-L Listserv messages from LEAG Chair and Vice-Chair to community:

1. Describe the most significant discoveries in lunar science since the publication of Vision and Voyages and outline how these have addressed the strategies, goals, and priorities for lunar science as outlined in VV2011

2. Assess the degree to which NASA's current planetary science program addresses the strategies, goals, and priorities for lunar science as outlined in Vision and Voyages (2011) and other relevant NRC and Academies reports (e.g., the Scientific Context for the Exploration of the Moon

3. What are the new discoveries that have been made since the publication of VV2013 that are not included in VV2011?

4. Please describe the value of the Lunar Reconnaissance Orbiter extended missions in addressing VV2011 lunar science strategies, goals, and priorities.

5. What new and exciting lunar science topics need to be in the next decadal survey?