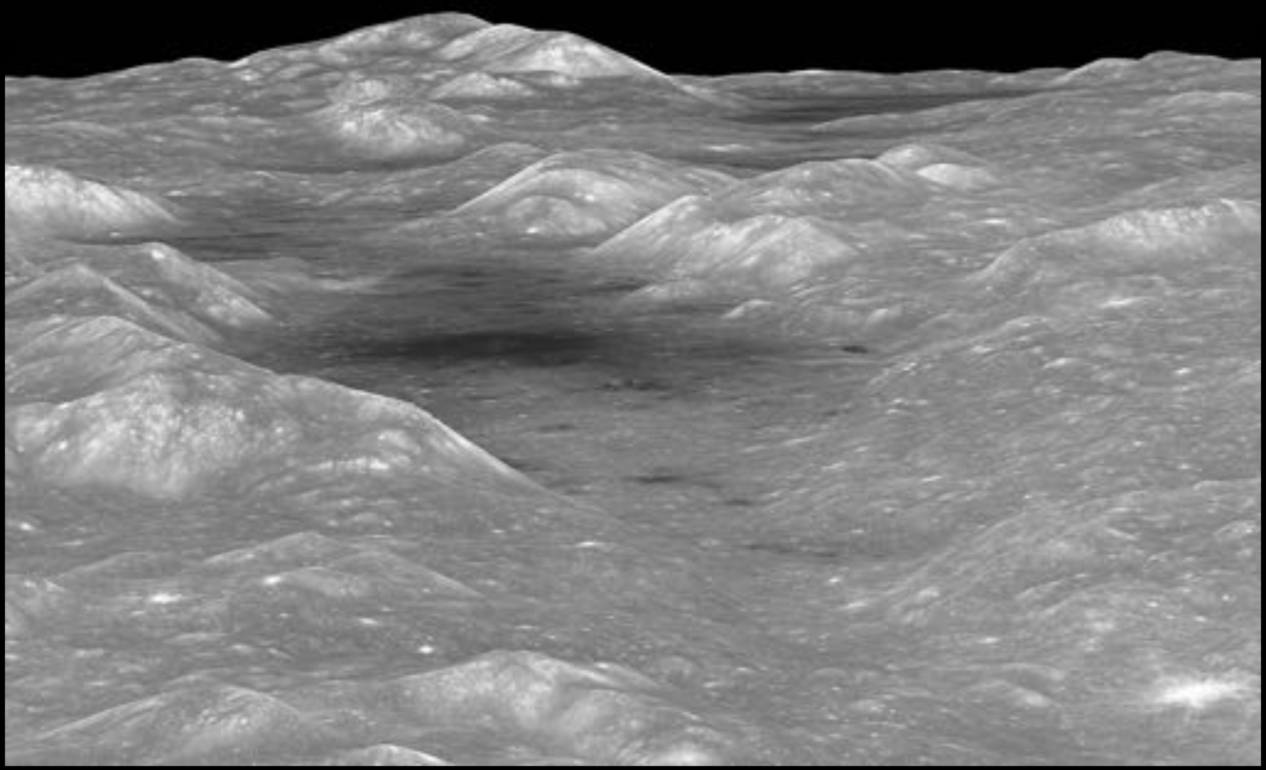
Advancing science of the Moon: Progress toward achieving the goals of *The Scientific Context for Exploration of the Moon* report



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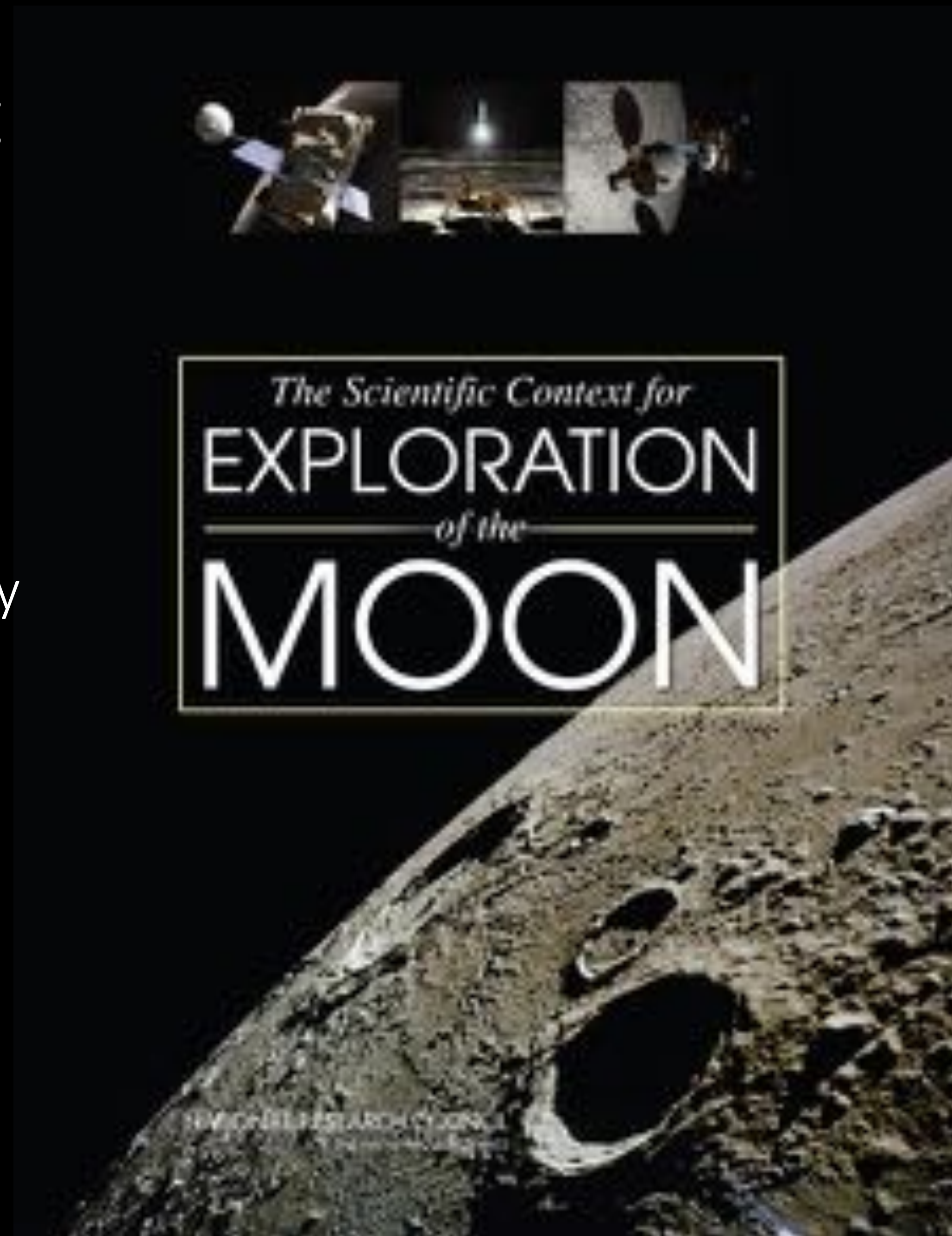
Advancing Science of the Moon Specific Action Team

The ASM SAT was requested by Jim Green and commissioned by LEAG; met in August in order to:

- Evaluate progress on lunar science goals since the 2007 *Scientific Context for Exploration of the Moon* (SCEM) report
- Consider concepts related to science implementation, as well as secondary science opportunities, outlined in the original SCEM report
- Note any new lunar science concepts that have become apparent since 2007

2007 SCEM report

- National Research Council study performed at the request of Associate Administrator of SMD
- Provide guidance on the science enabled by the newly established Vision for Space Exploration (ESMD-led lunar missions)
- "NASA needs a comprehensive, well-validated, and prioritized set of scientific research objectives for a program of exploration of the Moon"



8 Prioritized Science Concepts

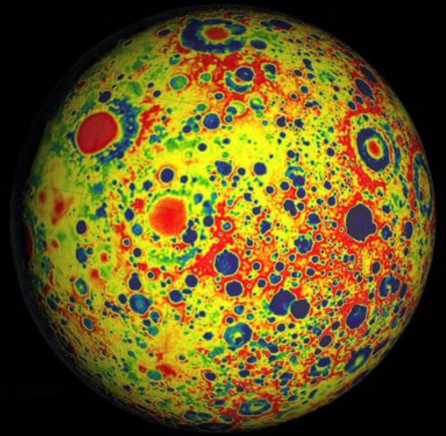
- 1: The bombardment history of the inner solar system is uniquely revealed on the Moon
- 2: The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body
- 3: Key planetary processes are manifested in the diversity of lunar crustal rocks
- 4: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history
- 5: Lunar volcanism provides a window into the thermal and compositional evolution of the Moon
- 6: The Moon is an accessible laboratory for studying the impact process on planetary scales
- 7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies
- 8: Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state

Top 11 Goals

- 1a – test cataclysm hypothesis
- 1b – age of SPA
- 1c – precise lunar chronology
- 4a – composition and distribution of polar volatiles
- 3a – extent/composition of primary products of differentiation
- 2a – thickness of crust, variability
- 2b – stratification of the mantle
- 8a – lunar atmosphere
- 2c – size/composition/state of the core
- 3b – variety/age/distribution/origin of lunar rock types
- 8b – electrostatically transported dust

Advances in lunar science

- Since the SCEM report:
- Kaguya, Chang'e 1, Chandrayaan 1, LRO, LCROSS, Chang'e 2, GRAIL, LADEE, Chang'e 3
- Restoration and reexamination of older datasets
- Technological developments
- Advances in modeling
- New ideas!



Example: Goal 1a

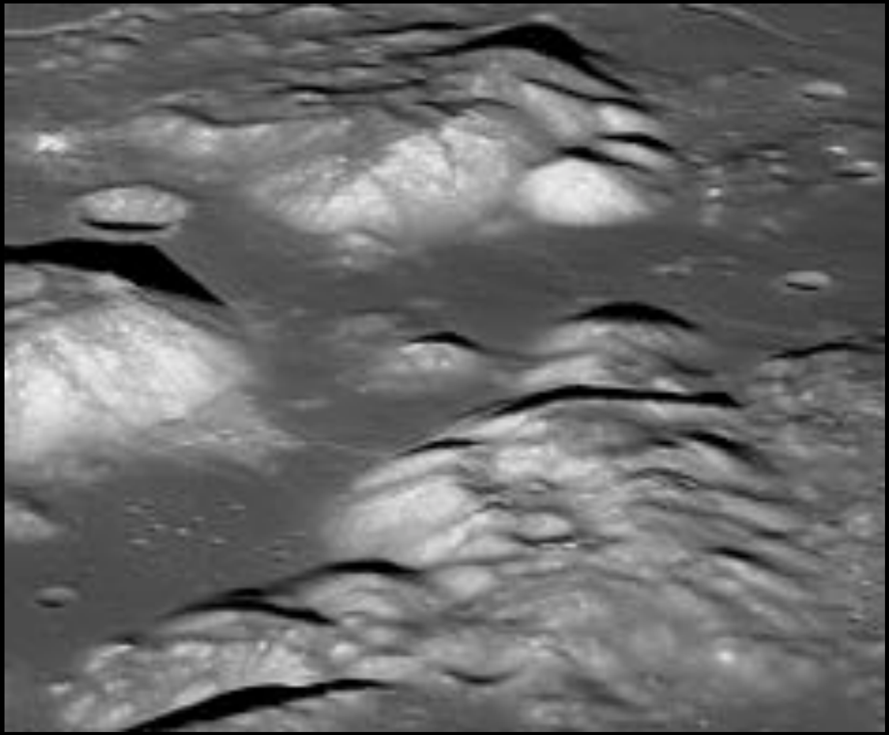
Test the cataclysm hypothesis by determining the spacing in time of the lunar basins

- If the Imbrium impact occurred on Earth it would have:
  - Vaporized the oceans
  - Sterilized the crust to depths of 100s of meters
- Was there a spike of large impacts around the time Imbrium formed?
  - Emergence of life on Earth
  - Migration of giant planets
  - Delivery of volatiles to the inner Solar System

Example: Goal 1a

Test the cataclysm hypothesis by determining the spacing in time of the lunar basins

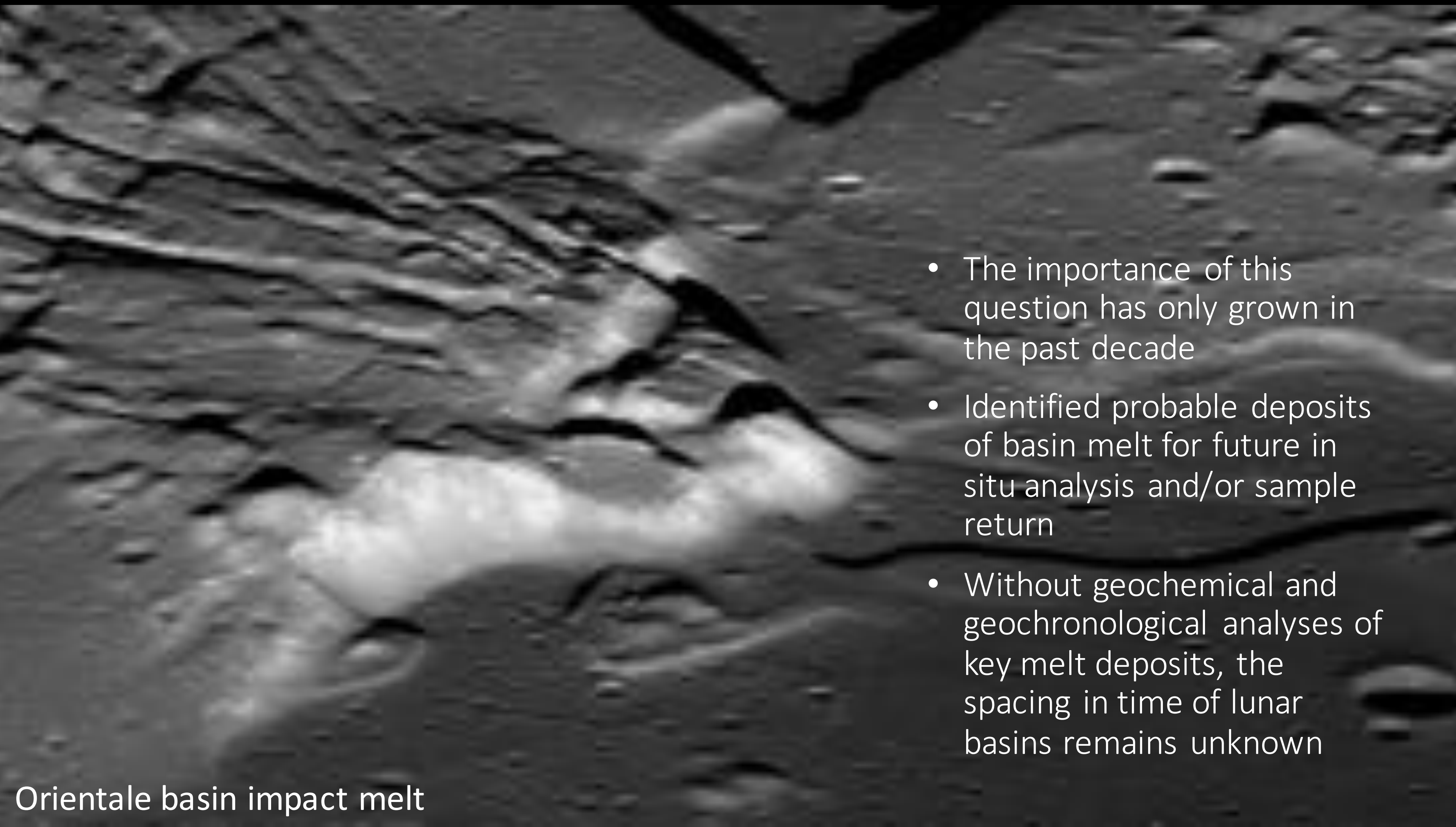
- Had been general consensus about relationship of samples to Imbrium, Serenitatis, and Nectaris
- Serenitatis:
  - Sculptured Hills deposits deposited as Imbrium ejecta rather than Serenitatis (Spudis et al., 2011; Fassett et al., 2012)
  - U-Pb dating of Sculptured Hills material supports Imbirum origin, Ar distribution less straightforward (Mercer et al., 2015; Thiessen et al., 2017)
- Nectaris:
  - Youngest clasts in aluminous Descartes breccias are coeval with KREEP-rich crystalline melt rocks that are the best candidates from Imbrium ejecta, support geological interpretation of Descartes formation as Imbrium ejecta (Norman et al., 2010)
- If Sculptured Hills and Descartes Formation are Imbrium ejecta, removes age constraints on basins older than Imbrium and reopens the pre-Imbrian impact history to debate



Oblique view of Sculptured Hills at Apollo 17 site

Example: Goal 1a

Test the cataclysm hypothesis by determining the spacing in time of the lunar basins



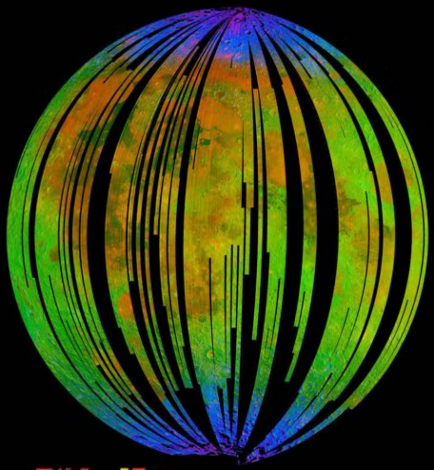
- The importance of this question has only grown in the past decade
- Identified probable deposits of basin melt for future in situ analysis and/or sample return
- Without geochemical and geochronological analyses of key melt deposits, the spacing in time of lunar basins remains unknown

Orientale basin impact melt

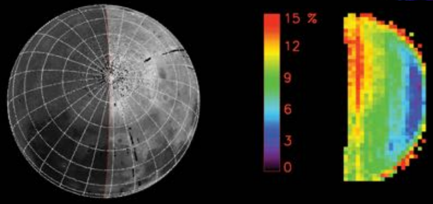
ASM SAT Report

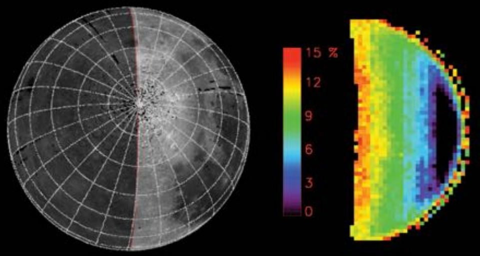
- Progress toward each goal evaluated
- Each section ends with summary of progress still needed
- No effort to reprioritize
- Identified new Concepts and Goals

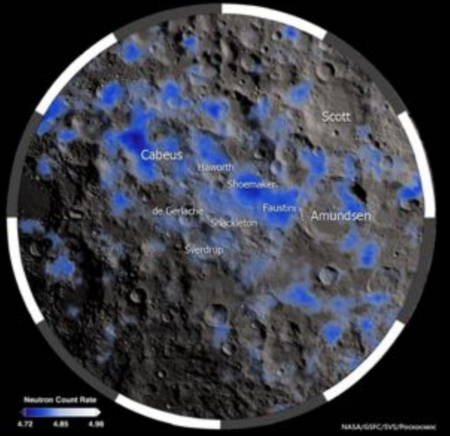
The lunar 'water' cycle



- Volatiles scattered across four Concepts of SCEM report
- Work from the last decade points to cycle with three components:
  - Primordial (interior) water
  - Surficial water (linked to solar wind)
  - Polar water (sequestered)
- Identify and characterize these lunar volatile reservoirs and evaluate their interrelations
  - Composition and variability of endogenous volatiles entrained in volcanic products
  - Sources of mid-latitude surface hydroxyl and water, determine how it migrates
  - Determine source(s) of polar volatiles

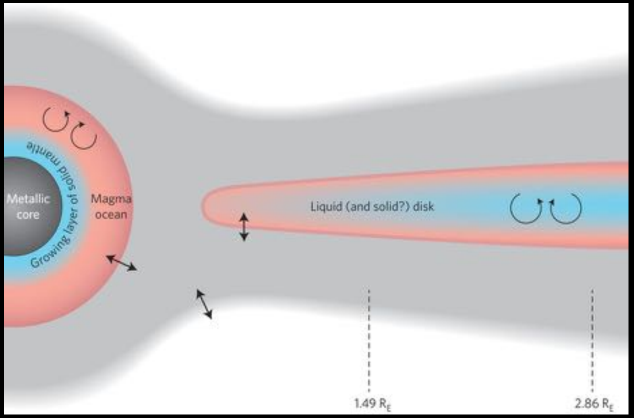






The origin of the Moon

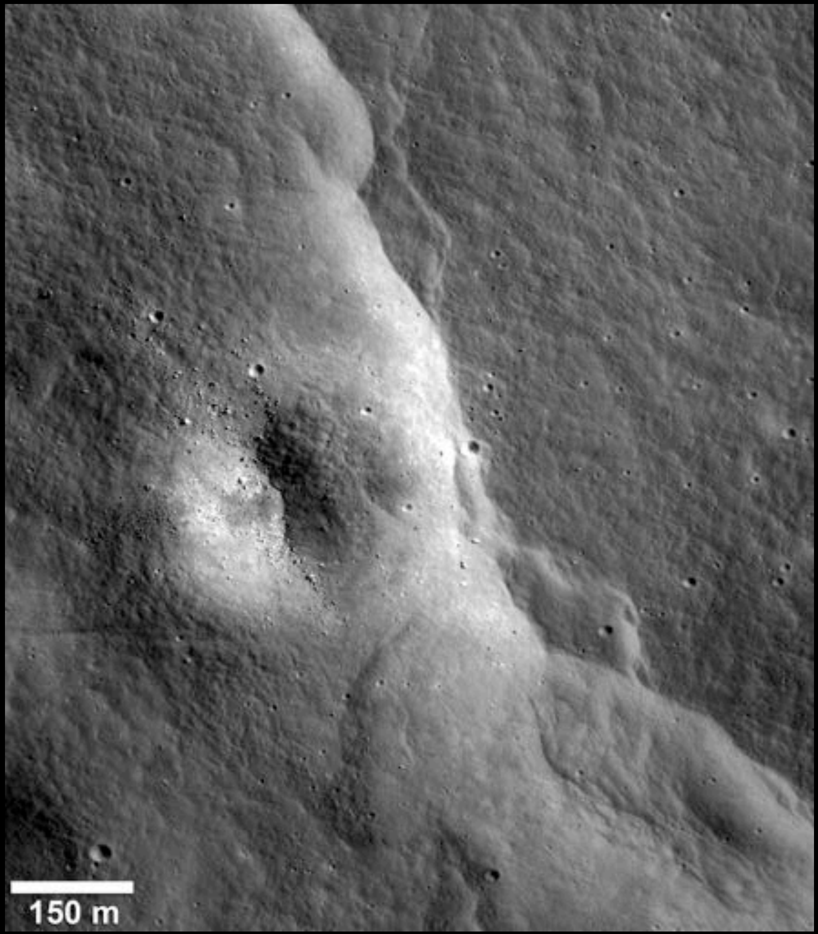
- A key goal of studying the Moon: better understand the origin and accretion of planets
- Moon's deep interior is a vault containing critical information about its initial composition during and immediately after accretion
- Specific goals:
  - timing of the collision
  - mechanisms, timing, extent of volatile depletion in the Moon
  - composition of the impactor
  - conditions and processes in the protolunar disk
  - conditions and processes at the surface of the lunar magma ocean, composition and longevity of an early atmosphere



Elkins-Tanton, 2013

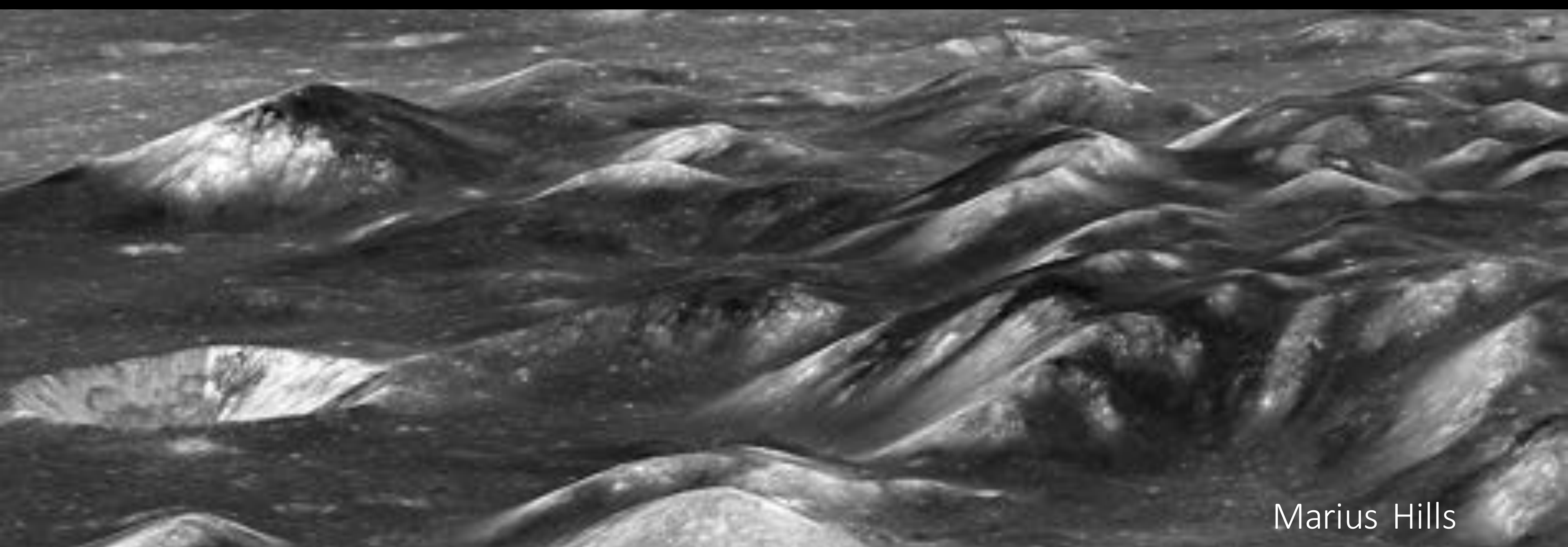
Lunar tectonism and seismicity

- Greatly expanded high-res imaging led to discovery of abundance of lobate scarps
- Without plate tectonics: number, distribution, level of seismicity of lobate scarps, provide information on Moon's interior structure, thermal history, and mechanism(s) of heat loss
- In addition to global contraction, may be due to stresses from tides and recession – active today
  - Lobate scarps explain shallow moonquakes?
  - If so, regions with active scarps would be targeted for seismic analyses, but avoided for landed assets such as outposts



ASM SAT report conclusions

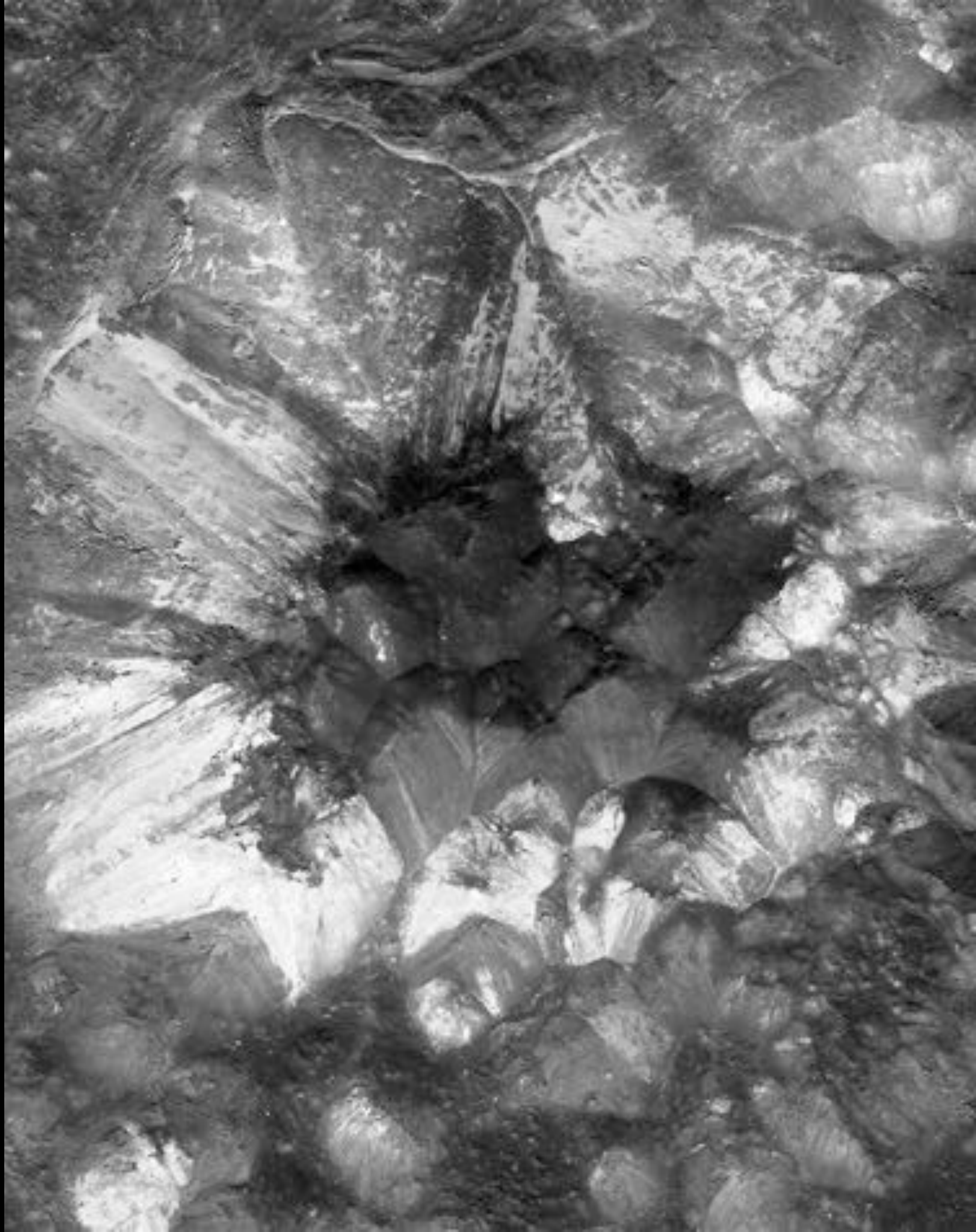
- Concepts and goals outlined in the SCEM report remain relevant after a decade of progress in lunar science
  - Nearly all had at least some progress; none were "done"
- New concepts and goals have emerged
- Lots learned, lots to do



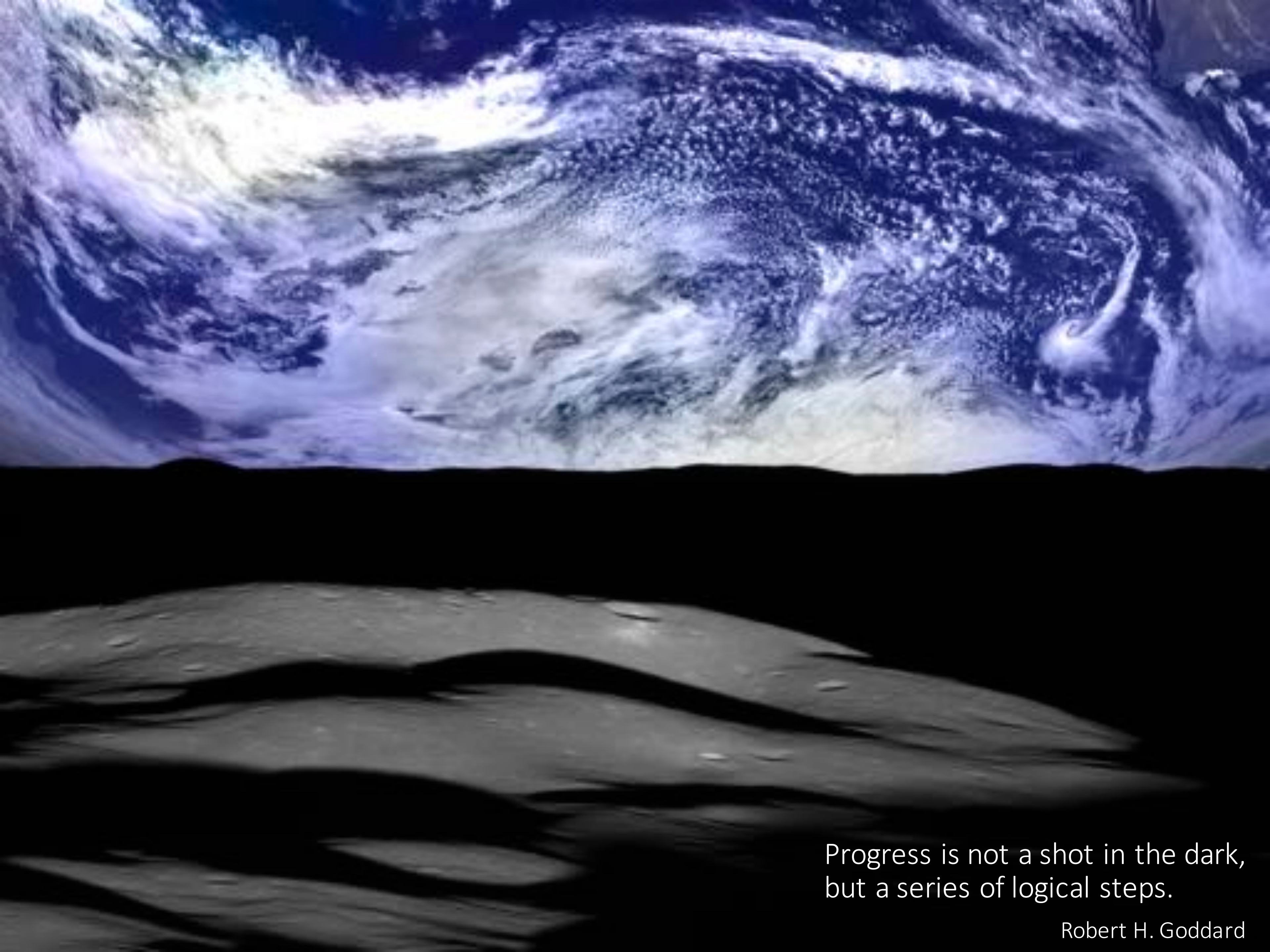
Landed missions for Lunar Science

We are now in a much stronger position to take advantage of laded missions and identify ideal landing sites to address the SCEM goals

While there is still real progress to be made from orbital missions, the advancement of many of these goals requires landed missions



Jackson Central Peak


Progress is not a shot in the dark,
but a series of logical steps.
Robert H. Goddard