First Steps Toward a USGS Assessment of Lunar Regolith as a Resource?

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Outline

- Quick Recap
  - USGS and Resource Assessments
  - Why regolith instead of ice
- 2020 ~~Plans~~ Proposal to NASA
  - Descriptive Model
  - Spatial and Deposit Density Model
  - Grade-Tonnage Model
  - Other constraints
  - Publication

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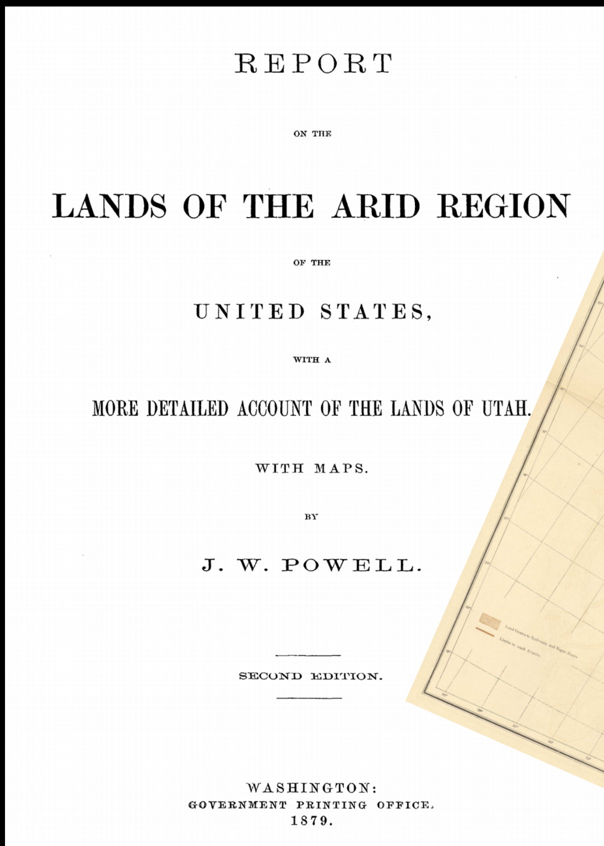
USGS: Doing resource assessments since 1879



REPORT

ON THE

LANDS OF THE ARID REGION

OF THE

UNITED STATES,

WITH A

MORE DETAILED ACCOUNT OF THE LANDS OF UTAH.

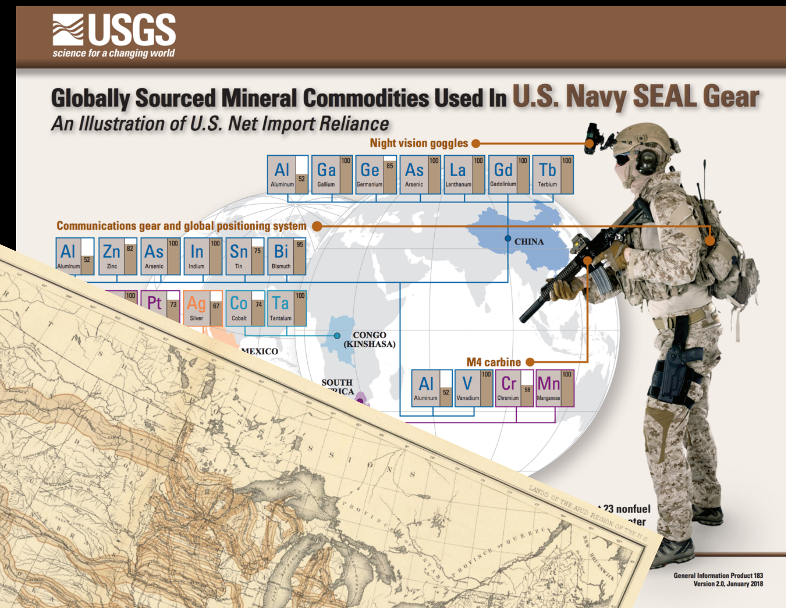
WITH MAPS.

BY

J. W. POWELL.

SECOND EDITION.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1879.



How does the USGS do resource assessments?

- Key properties of USGS assessments:
  - Unbiased
  - Quantitative
  - Easy to understand by non-scientists
- Composed of 5 parts (called 3-part)
  - Descriptive Model of resource deposits
  - Spatial Model of study area
  - Deposit-Density Model of deposits in study area
  - Grade-Tonnage Model of deposit population
  - Economic Model

2018 Conclusions

- **Solar power, regolith, and ice demonstrate the range of situations the USGS methods could be used for**
  - *Solar power is a poor choice because the problem is too deterministic*
  - *Regolith is ready for a classic USGS assessment*
  - *Ice assessment would useful to highlight what we still need to learn, but without a descriptive model the uncertainties would be huge.*

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~~Plan~~ Proposal for a 2020 USGS Lunar Regolith Resource Assessment

- **Seeking NASA funding but source is ???**
- **We are here to seek community input on our proposal**
- **Proposed schedule:**
  - *Start work October 1, 2019*
  - *Submit for review by October 1, 2020*
  - *Publication in late 2020 or very early 2021 as a USGS Circular (aimed at a general audience, decision makers, students, and scientists in related fields)*
  - *2021 and beyond: continue with other assessments…*

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Descriptive Model

- Formation of lunar regolith is by impacts (from basin-forming to cosmic rays)

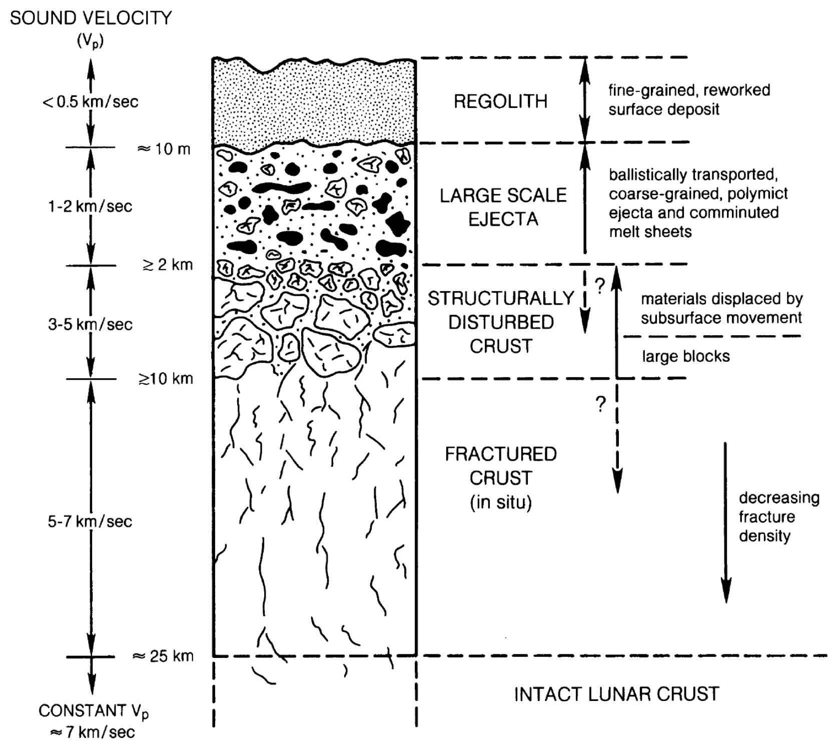

Fig. 4.22. Highly schematic cross-section illustrating the idealized effects of large-scale cratering on the structure of the upper lunar crust; see discussion of megaregolith in the text. A structurally disturbed lunar crust is also inferred from seismic measurements, e.g., from sound velocity (V_p) (*Toksöz et al.,* 1973). The depth scale in the figure is highly uncertain, because the total number of large craters and basins remains unknown. Highly variable depth effects must exist in different regions, depending on the degree to which an area has been affected by basin-sized impacts.

Hörz et al (1991) Lunar Sourcebook

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Spatial and Deposit Density Models

- **Regolith is everywhere as a surficial unit instead of being found in isolated “deposits”**
- **Need to divide the global “deposit” into sections that should have similar properties**
  - *Our current plan is to consider the properties (e.g., grade and tonnage) of the regolith for each of the ~200 units in the global geologic map of the Moon.*
  - *If this is too much detail, we will lump appropriately.*

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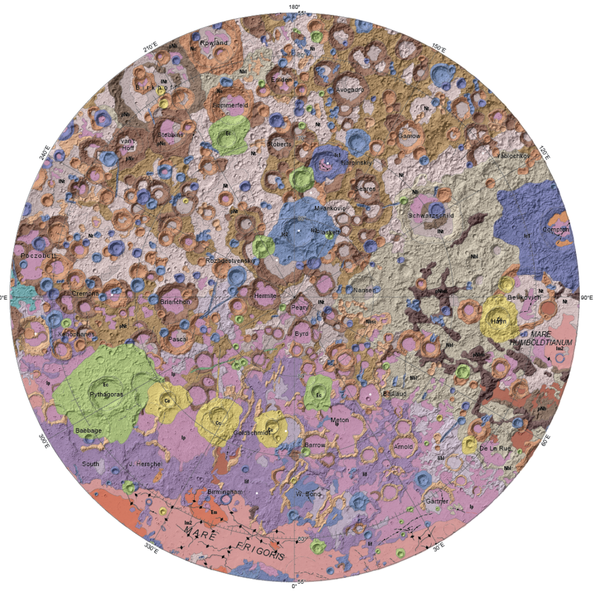


SCALE 1:6 078 683 (1 mm = 6.078683 km) AT 90° LATITUDE
POLAR STEREOGRAPHIC PROJECTION

NORTH POLAR REGION

Plains, terra, plateau, and mantle group

Unit	Description
EIp	Eratosthenian Imbrian plateau material
Ip	Imbrian plains material
Id	Imbrian dark mantling material
Ig	Imbrian grooved terrain
It	Imbrian terra material, undivided
Itd	Imbrian terra dome material, Hansteen Alpha
INp	Imbrian Nectarian plains material
INt	Imbrian Nectarian terra material, undivided
Nt	Nectarian terra material
Np	Nectarian plains material
Ntp	Nectarian terra mantling materials
pNt	pre-Nectarian terra, undivided

Basins group

Unit	Description
Ib	Imbrian basin
Ibm	Imbrian basin, massif
Iia	Imbrian Imbrium basin, Alpes Formation
Iiap	Imbrian Imbrium basin, Apenninus material
Iif	Imbrian Imbrium basin, Fra Mauro Formation
Iohi	Imbrian Orientale basin, Helvelius Formation, inner facies
Ioho	Imbrian Orientale basin, Helvelius Formation, outer facies
Iohs	Imbrian Orientale basin, Helvelius Formation, self-secondary facies
Iom	Imbrian Orientale basin, Maunder Formation, outer facies
Iork	Imbrian Orientale basin, Montes Rook Formation, knobby facies
Iorm	Imbrian Orientale basin, Montes Rook Formation, massif facies
Nb	Nectarian basin, undivided
Nbl	Nectarian basin, lineated material
Nbm	Nectarian basin, massif
Nbsc	Nectarian basin, secondary crater
Nnj	Nectarian Nectaris basin, Janssen Formation
pNb	pre-Nectarian basin, undivided
pNbm	pre-Nectarian basin, massif

Mare group

Unit	Description
Em	Eratosthenian mare material
Im1	Imbrian mare materials, lower
Im2	Imbrian mare materials, upper
Imd	Imbrian mare dome materials

Crater group

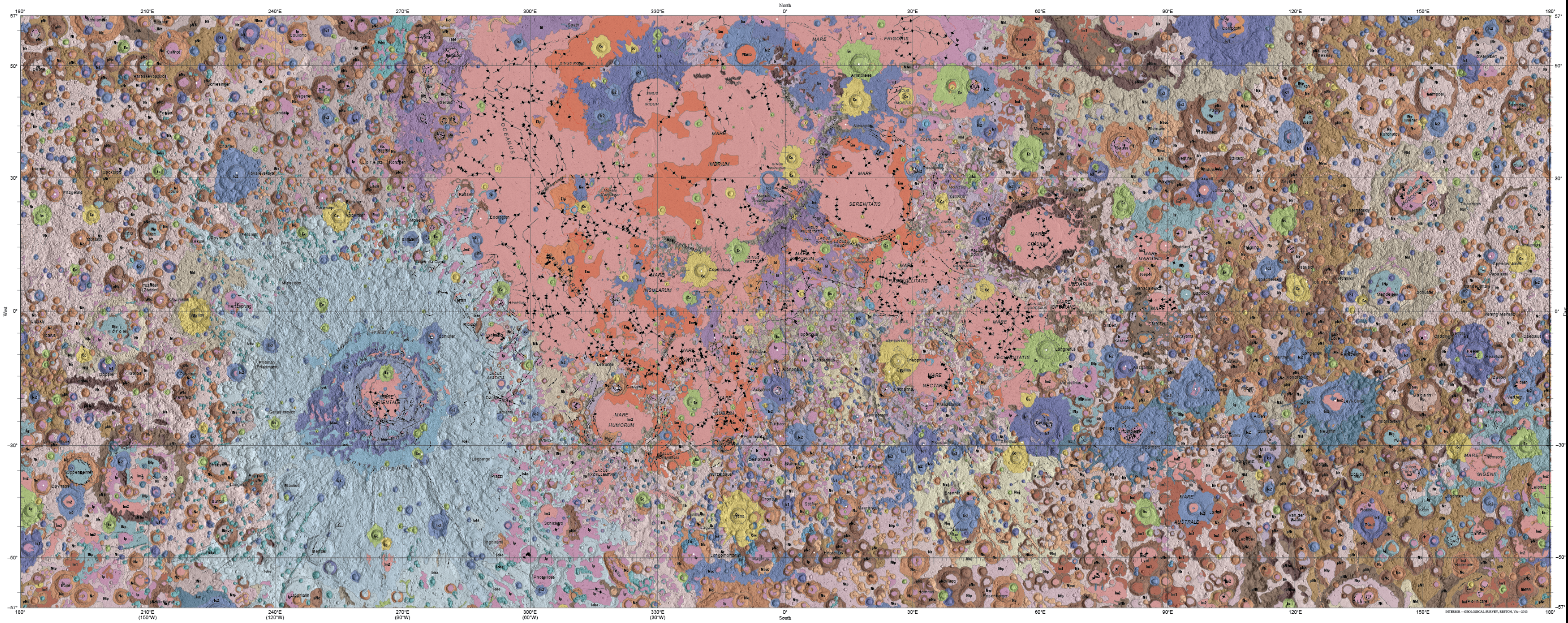
Unit	Description
Cc	Copernican crater material
Ccc	Copernican crater cluster
Ec	Eratosthenian crater material
Ecc	Eratosthenian crater cluster
Ic1	Imbrian crater material, lower
Ic2	Imbrian crater material, upper
Ic	Imbrian crater material, undivided
Icf	Imbrian crater material, fractured floor material
Iic	Imbrian Imbrium basin secondary craters
Nc	Nectarian crater material
pNc	pre-Nectarian crater material

Map Symbols

- contacts, undifferentiated
- basin ring
- channel (volcanic)
- crest of crater rim
- graben trace, certain
- lineament, undifferentiated
- wrinkle ridges

SCALE 1:6 078 683 (1 mm = 6.078683 km) AT -90° LATITUDE
POLAR STEREOGRAPHIC PROJECTION

SOUTH POLAR REGION



SCALE 1:10 000 000 (1 mm = 10 km) AT 0° LATITUDE
MERCATOR PROJECTION

Grade-Tonnage Models

- **Assuming that the fine component of the regolith is of most interest, we will use vol.% soil for "grade"**
  - *Is this a good assumption???*
- **The thickness of the regolith is used as the equivalent of "tonnage"**
  - *How do you define the bottom of the regolith?*

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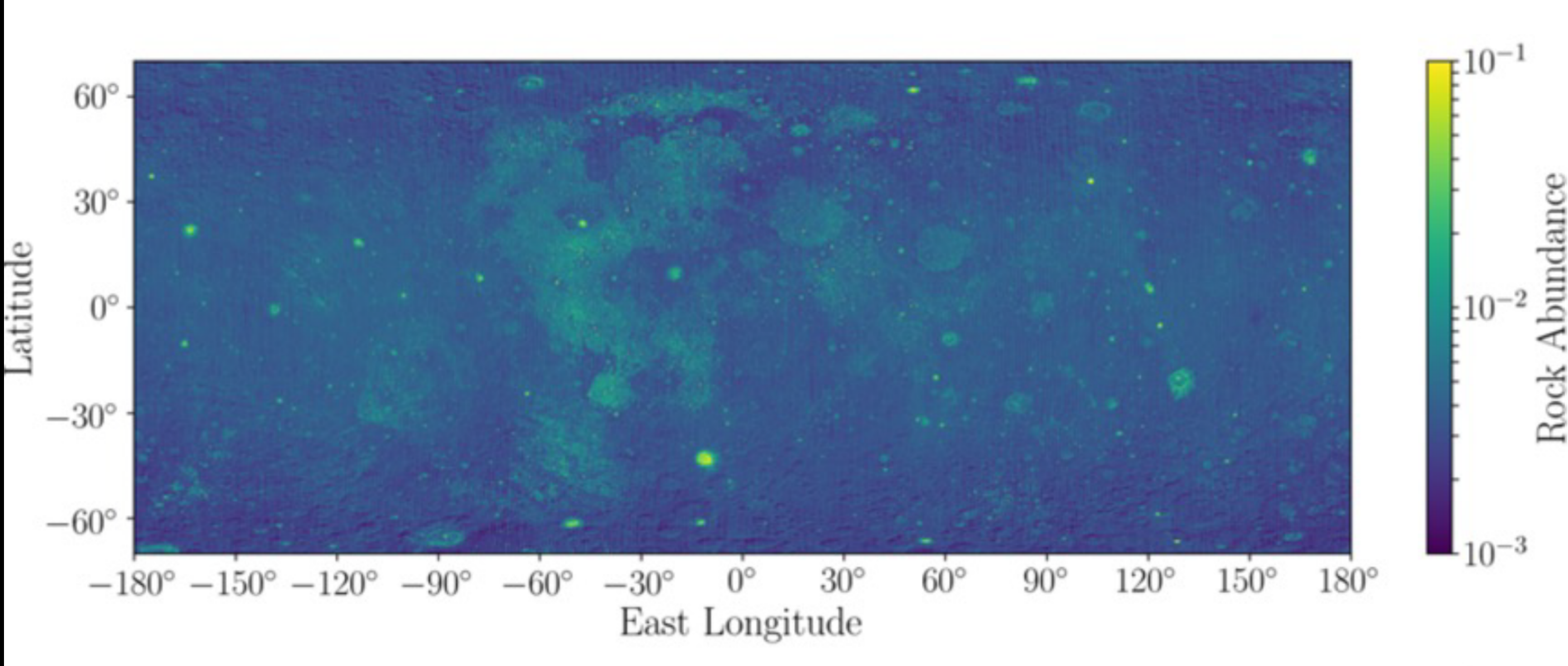
Regolith Grade

- **>1 cm particles not well represented in *Apollo* sample collection**
- **Thermal inertia from *LRO* DIVINER is the key data set (e.g., Bandfield et al., 2011; Hayne et al. 2017, Fig 12 below)**



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Regolith Thickness

- *Apollo* cores very useful (Carrier et al. 1991; below)
- Long wavelength radar (Campbell et al., 1997), crater morphology (Wilcox et al., 2010) also useful
- *GRAIL* gravity and *Kaguya* radar sounding are harder to interpret but could also help

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Regolith Thickness

(Carrier et al. 1991)

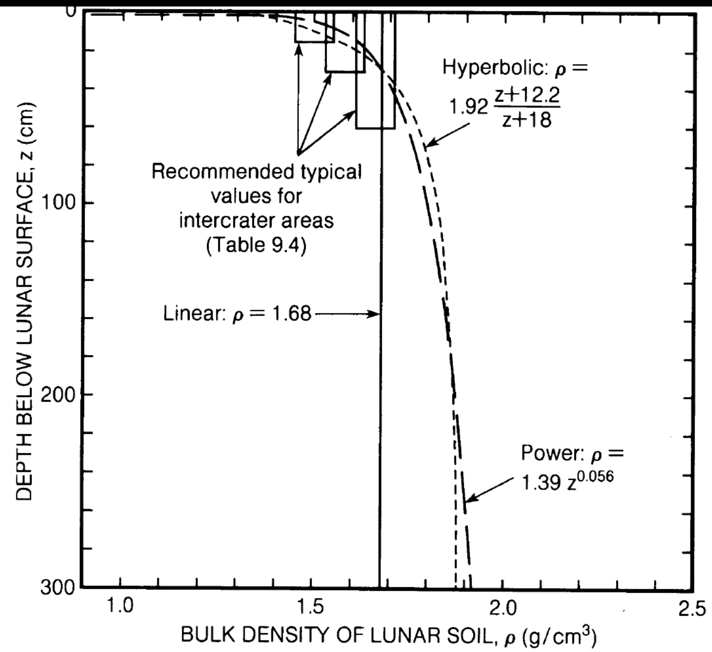

Fig. 9.16. Calculated *in situ* bulk density in the lunar soil layer as a function of depth below the surface, derived from data shown in Fig. 9.15. Three calculated density-depth relations are presented: linear (solid line), power-law (heavy dashed line), and hyperbolic (light dashed line). Boxes at the top of the plot show recommended near-surface bulk density values for intercrater areas.

Regolith Thickness

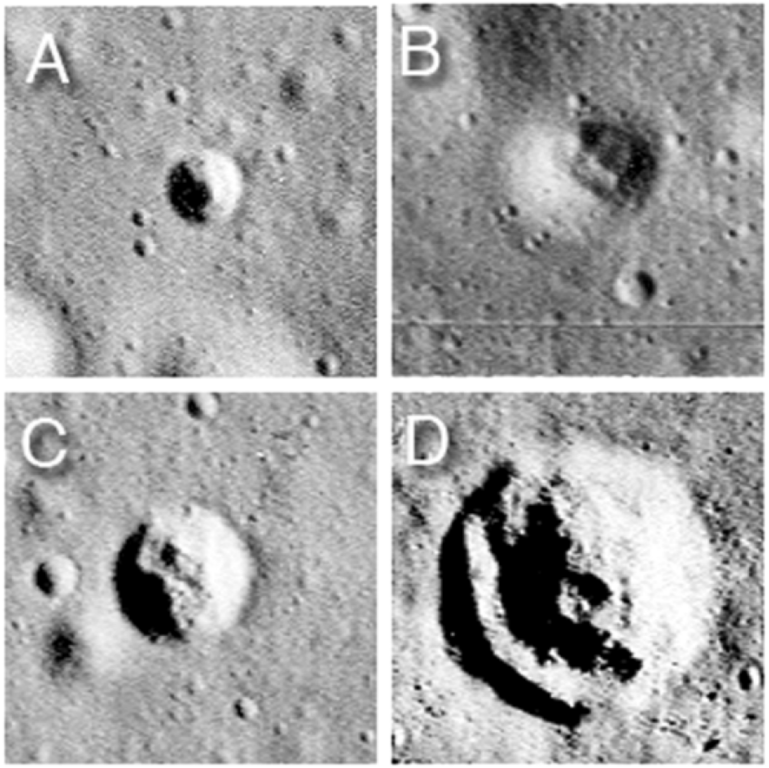

Fig. 1. Four classes of small craters as defined by Quaide and Oberbeck (1968). a) Normal, bowl-shaped morphology; b) central mound; c) flat-bottomed; d) concentric. Crater morphology is dependent on depth to a strength interface; craters trend A–D with decreasing depth of surficial layer. Each scene is 119 m across, from LO3-188-H2.

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Wilcox et al., 2005

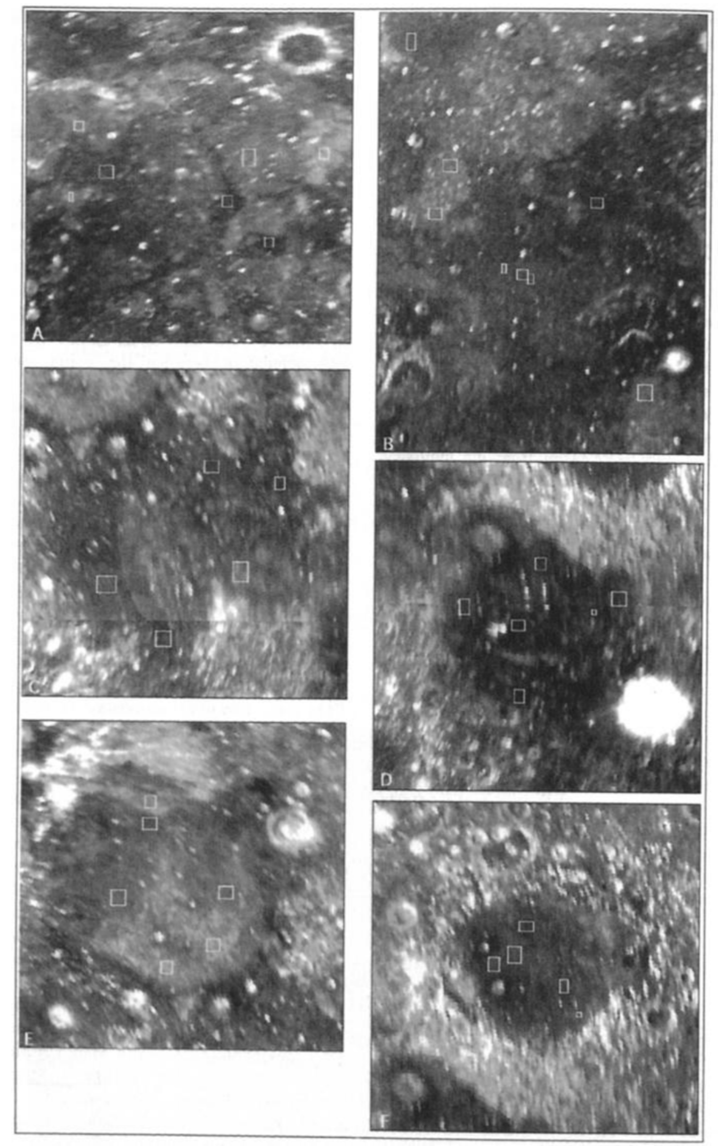
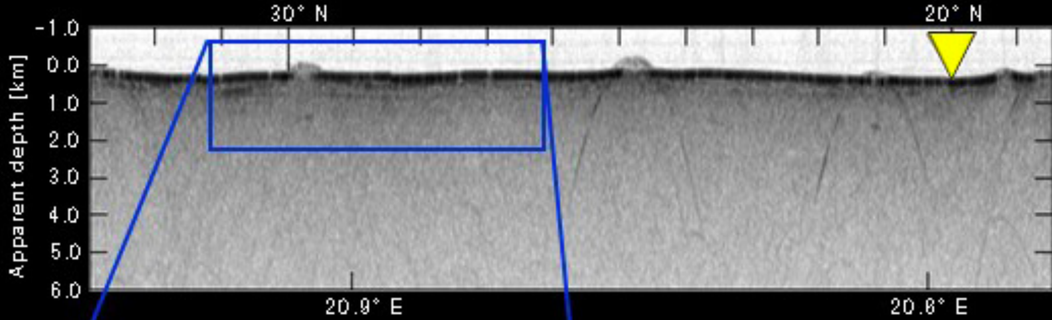
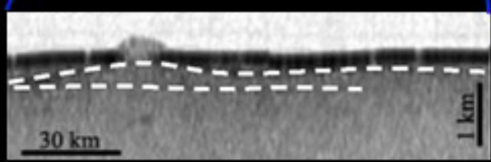


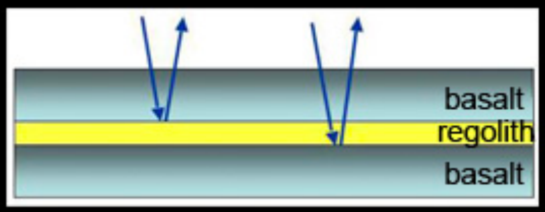
Figure 5. Locations of sample boxes for remote sensing data comparison. All maps are simple cylindrical projections of 70-cm depolarized radar data. (a) Mare Imbrium. Image area 25°-55°N, 325°-355°E. (b) Oceanus Procellarum. Ima [illegible] 5°-45°N, 353°-23°E. (d) Mare Fecunditatis [illegible] a 12°-42°N, 5°-35°E. (f) Mare Crisium. In [illegible]

Campbell et al., 1997

Regolith Thickness







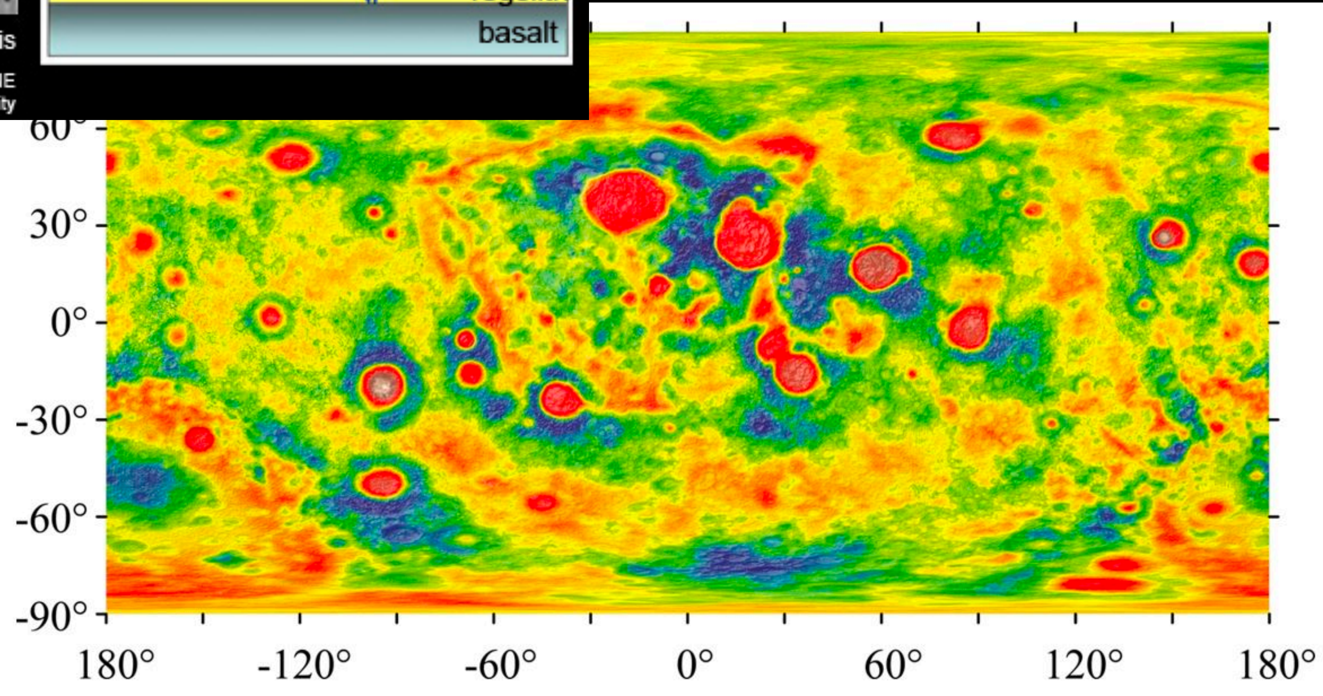
LRS radargrams of substructure of Mare Serenitatis

(C)JAXA/SELENE

Analysis: Tohoku University, Nagoya University, Kyoto University

JAXA

Soderblom et al., 2015



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Statistical Modeling

- **Use Monte-Carlo methods to combine probability distribution functions to obtain quantitative assessment**
- **Key is the quality of the functions fed into the model**
  - *Quantified uncertainties is the key*
  - *Data from Apollo, Surveyor, Lunakhods are just barely adequate for formal statistical analysis*
  - *Uncertainties in remote sensing data are quantifiable*
  - *Relative homogeneity of regolith properties helps*

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“Economic” Model

- **This can add technical and other constraints**
  - *What slopes are traversable?*
  - *How deep can you dig?*
  - *How far can you move?*
  - *Do you need to be in sunlight?*
- **At the next SSR, we hope to be looking for a few specific scenarios for utilizing bulk regolith to include in our assessment.**

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Beyond “first steps”

- **USGS is methodical, meticulous and reliable**
- **This first assessment lays the groundwork for further assessments**
  - *Adding mineralogical and compositional information (e.g., ilmenite for O_2 extraction)*
  - *Foundational data and methods for more complex resources (e.g., water ice)*
  - *Data management and analysis infrastructure uses modern digital tools that will facilitate timely addition of new data from space missions and laboratory studies*

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How can we make it happen?

- Proposal is for $250K in FY20
- USGS will continue discussions with various entities within NASA
- We will seek internal USGS funds to make at least some forward progress in FY20
- We welcome community input on this proposal…